SHEFFIELD HALLAM UNIVERSITY

Haptic Interaction with a Guide Robot in Zero Visibility

A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of Philosophy

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Declaration

I hereby declare that this thesis embodies the results of my own work done as a part of EPSRC funded REINS project and that it has not been submitted anywhere for any award apart from that of Doctor of Philosophy at Sheffield Hallam University

I have made acknowledgement of the work of others and have made reference to work carried out in collaboration with other people.

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Ayan Ghosh Date

Abstract

Search and rescue operations are often undertaken in dark and noisy environments in which rescue teams must rely on haptic feedback for exploration and safe exit. However, little attention has been paid specifically to haptic sensitivity in such contexts or to the possibility of enhancing communicational proficiency in the haptic mode as a life-preserving measure. The potential of robot swarms for search and rescue has been shown by the Guardians project (EU, 2006-2010); however the project also showed the problem of human robot interaction in smoky (non-visibility) and noisy conditions. The REINS project (UK, 2011-2015) focused on human robot interaction in such conditions. This research is a body of work (done as a part of the REINS project) which investigates the haptic interaction of a person with a guide robot in zero visibility. The thesis firstly reflects upon real world scenarios where people make use of the haptic sense to interact in zero visibility (such as interaction among firefighters and symbiotic relationship between visually impaired people and guide dogs). In addition, it reflects on the sensitivity and trainability of the haptic sense, to be used for the interaction. The thesis presents an analysis and evaluation of the design of a physical interface (designed by the consortium of the REINS project) connecting the human and the robotic guide in poor visibility conditions. Finally, it lays a foundation for the design of test cases to evaluate human robot haptic interaction, taking into consideration the two aspects of the interaction, namely locomotion guidance and environmental exploration.

Acknowledgements

I would like to start by offering huge thanks to my primary academic supervisor Prof. Jacques Penders. His patience, support and encouragement has helped me through the undulating emotional process of academic research and writing. With his guidance, I have achieved many great feats, for that I am eternally grateful. I also would like to thank my second supervisor Dr. Peter Jones for his comments and support that gave my work an interdisciplinary focus.

I owe thanks to all REINS project team members at Sheffield Hallam University and The King's College, London who challenged and supported my work. Thank you to all the team members, Dr. Alan Holloway, Mr. Heath Reed, Dr. Alessandro Soranzo, and Alireza Janani. I would also like to thank Dr. Lyuba Alboul for helping me at various instances and all other members of Robotics research group of Sheffield Hallam University.

Lastly, I would like to thank my friends and family for their unrelenting encouragement and support. Their kind words and encouragement over the years have elevated me to new heights. And, of course, I want to thank my wife Meenakshi, my father and my mother, whose love and care have kept me mentally strong throughout this adventure.

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Chapter 1

Introduction

This chapter introduces the main context of making use of robotic guides in zero visibility. It also reports on the motivation behind the research, main research questions addressed and presents the main outline of the thesis.

1.1. Context

Search and rescue scenarios are often complicated by low or zero visibility conditions because of smoke or dust. In the early stages of a fatal fire incident, the situation is usually very far from stable and therefore a dynamic risk assessment by the search and rescue teams (also called fire-fighters) is essential. The term '*dynamic risk assessment (DRA)'* is used to describe the continuing assessment of risk that is carried out in a rapidly changing environment[1]. On the arrival of the initial attendance, the Incident Commander of the team needs to gather information, evaluate the situation (Zúñiga 2012) and then apply judgement to decide the appropriate course of action. Initial strategy to locate and extinguish the seat of fire or conduct a primary search depends on the amount of smoke at the location of the fire incident.

1.1.1. The smoke conditions on arrival-initial stage

In the vast majority of cases, there is either no smoke or light / moderate smoke, on arrival of the firefighting teams at the scene[2], as depicted in figure 1. The smoke becomes heavy and dense as time progresses.

1

HM Government. 2008. Vol 2 Fire and Rescue Manual. [ONLINE] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7643/incidentcommand.pdf. [Accessed 1 January 2017].

2

William R. Mora. 2003. U.S. Firefighter Disorientation Study. [ONLINE] Available at: http://www.trispeceyegear.com/wp-content/uploads/2010/08/FirefighterDisorientationStudy.pdf. [Accessed 1 January 2017].
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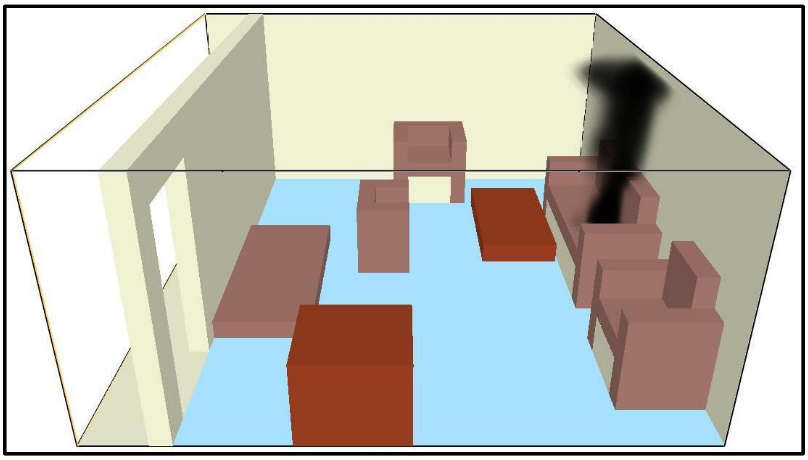

Figure 1, Smoke Condition at the time of the Arrival of the Fire-fighting team

1.1.2. The smoke conditions after arrival

In most of the cases heavy smoke develops during the course of the incident and lasts longer than 15 minutes, leading to prolonged Zero Visibility Conditions (figure 2). The principal consideration of the incident commander, at that time, is the safety of all personnel. On assessing the hazards and health and safety of personnel in the scene, they commonly take some risk to save lives.

After initial assessment (Zúñiga 2012), the incident commander needs to reduce any remaining risks to an acceptable level, by introducing further control measures, such as use of protective equipment like safety harnesses, safety glasses, etc. When fire-fighters enter a smoke filled environment, they may also use a breathing apparatus due to the presence of toxic fumes in the environment. The amount of air supply contained in the breathing apparatus suffices for about 20 minutes (Casper & Murphy 2003), meaning that the zero visibility condition lasts longer than the breathing time of the apparatus and the crew needs to be out of the danger zone before the air supply runs out. This implies considerable time pressure for all the crew and their commanders (Casper & Murphy 2003) to locate the seat of the fire. The chances for rescues reduce considerably over time and in order to save lives fire fighters are required to act swiftly.

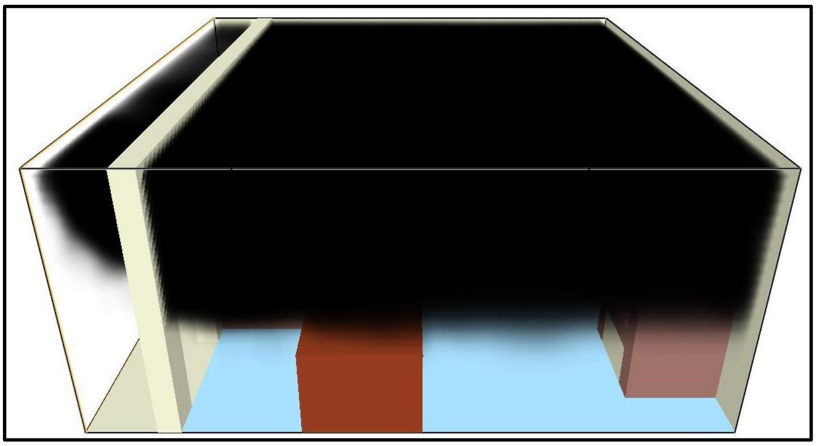

Figure 2, Smoke condition after 15 minutes of arrival of the Fire-fighting team

The deteriorating and unknown conditions make it very difficult for a firefighter to safely traverse the obstacle laden environment. Therefore in attempts to carry out evacuations under extreme conditions, firefighters are subjected to stress and when they exceed air supply or are trapped, they can be highly vulnerable. This can lead to disorientation and firefighters can get lost. Disorientation, can be defined as a loss of direction in absence of vision, and is one of the serious hazards for rescue personnel. William R. Mora[3]in his studies, states that lack of vision played a major part in most firefighter fatalities.

1.2. Motivation

1.2.1. Warehouse Structure

Disorientation can depend on various occupancy types, construction types and structures of different sizes and ages[3]. These structures include places of assembly, office buildings, warehouses, high-rise apartment buildings and commercial structures. Industrial warehouses in particular are of major concern for firefighters because they typically consist of large open spaces along with storage areas consisting of vertical racks. Modern warehouses are usually single storey buildings in which stairs are not very common; they can be as large as 400 x 200 m^2. Some are large and divided into

[3] William R. Mora. 2003. U.S. Firefighter Disorientation Study. [ONLINE] Available at: http://www.trispeceyegear.com/wp-content/uploads/2010/08/FirefighterDisorientationStudy.pdf. [Accessed 1 January 2017].

sections separated by fire resistant walls (resistant for several hours). The typical dimensions of sections are in the order of 100 x 200 m^2.

In the event of fire, the fire is typically confined to a certain area whereas the smoke may cover the entire warehouse. Searching for victims is dangerous because sometimes covering the enormous dimensions of the warehouse in zero visibility can be very dangerous. There might be some debris on the floor, but one may assume that in the majority of the warehouses, things are kept in order. Thus, the ground is easily passable; however if the situation deteriorates and the risk levels are high, fire fighters do not enter the building.

Examples of Warehouse fire incidents

In a warehouse fire of 1991 in Gillender Street London (UK), two fire fighters died and in the 1999 warehouse fire in Worcester (USA), six fire fighters lost their lives. In November 2007 a tragedy happened in Warwickshire (UK), when four fire fighters were killed in a vegetable warehouse blaze (Penders et al. 2011).

In the Worcester case, first a crew of two fire fighters reported being lost 22 minutes into the incident; 30 minutes later, an emergency team consisting of four fire fighters got lost as well. The Worcester warehouse was a six storey building with largest dimensions 40 x 50 m^2, where thick smoke developed (Note that this floor space is only a tenth of the floor space of a section of the modern warehouses). The communication link was interrupted and emergency teams were not sure where the crew got lost.

In December of 2005 two firefighters died in a fire of a 3-story house in the city of Tübingen in Germany. Their retreat path was blocked by a burning wall, and they were not able to find a new way out before the air of their respiration apparatuses was gone. Their bodies were found 3 meters away from a window connecting to the outside part of the building (Denef et al. 2008).

1.2.2. Background of the research problem

To overcome the problem of disorientation in a zero visibility environment, in the '*GUARDIANS'* project (Penders et al. 2011), a group of robots provided localisation and navigation and could in principle lead the fire fighters. A basic assumption was that if the group of robots could tackle the navigation and localisation problems, the rescue workers would welcome them as assistants. As an interface, the project put into trial, a wireless visual display (a visor with LEDs mounted in the mask of the fire fighter) (Penders et al. 2011), giving locomotion directions to the fire fighter.

Trials were held with professional fire fighters of South Yorkshire Fire and Rescue. In the trials, the firefighting teams were required to advance, being directed by the visor mask, along with a set of distracting additional tasks. They performed on the whole quite well despite of the distracting additional tasks. However, adherence to the direction indicators of the wireless visual display was poor, meaning they had a large amount of information to be processed (Denef et al. 2008); on occasions, subjects moved ignoring the directions indicated.

Afterwards, it was pointed out that confidence about position and bearing is extremely important in real fire incidents. In the trial setting, attempts were made to disrupt the familiarity with the wall, which acts as a point of reference. Consequently, the fire fighters suggested there was a lack of realism and that the aid did not provide any indication of bearing that they were confident with. Being away from a wall or a physically stable point of reference is apparently problematic for fire fighters and they suggested that the interface would be more useful if it could provide directions to and from the wall (Penders et al. 2011).

To summarise, it became clear that fire-fighters by no means were prepared to give up their procedural routine or the feeling of security given by these routines; they simply ignored instructions that contradicted their procedural routines. This experience led the '*Guardians*' project team to reconsider the whole concept of interfacing with a fire fighter when providing guidance. They very strongly indicated that they rely on mutual physical contact, haptic and tactile feedback and it was decided that the area needs further exploration.

Based on these disappointing findings of the '*GUARDIANS'* project, a different consortium decided to design a feedback system that complements the protocols of fire fighters to enhance the search and rescue tasks and not be disruptive.

The result was the '*REINS'* project (EPSRC funded), which aimed to explore the possibility of designing a robot guide which will aid the fire-fighters to explore and safely navigate through an unpredictable space without feedback via sight or hearing. In addition to conditions of zero visibility, the audio cues are negated because the oppressive search environments have a lot of ambient noise; it is difficult to interpret audio feedback.

1.3. The research claim

Previous research has shown that robots have been deployed as guides in environments of zero visibility for fast navigation and safe exit. These robot guides are technically capable of large/small scale mapping of the environment and solving localisation problems autonomously.

However, not much attention has been given to the interaction with these robots and the interaction design. The haptic sense (addressed in more detail in later chapters) is a natural fall-back option for interaction with the immediate environment in the absence of the visual as well as the auditory sense. This research investigates the interaction, which means if a human being is subjected to conditions of zero-visibility with a robot guide, how haptic sense is used as a mode of communication between the two.

This work is a part of the 'REINS' project (mentioned in section 1.2.2); some team members have focused on designing a haptic interface that connects the human with the robot guide and programming the trajectories of the robot. My research and this dissertation investigated the haptic interaction between the robotic guide and human being (henceforth called 'handler') as an independent piece of work, through developing a thorough understanding of haptic interaction in real world scenarios (e.g. visually impaired person and guide dog). The research also builds on test cases to evaluate the effectiveness of the design (done by other team members) looking through the entire context of the interaction and following a user-centric approach. As an outcome of the evaluations, the design guidelines and recommendations are identified to improve the usability and user-experience in regards to the haptic interface. These guidelines are used by designers and solution developers of the team for design evolution of the interface for the zero visibility conditions.

To summarise this research is concerned with the effectiveness of the haptic interaction between the robot and the human.

1.4. What is the research not about?

In order to present the research in more clear and concise manner, it is important to note what the research does not reflect. First, the research does not focus on designing any algorithm for a mobile robot which involves extracting knowledge of the environment through various sensors. Second, the research also does not focus on developing a motion planner for safe navigation of the robot guide considering the zero visibility of the environment. Third, defining control strategies for human-robot interaction is beyond the scope of this thesis. Fourth, the thesis does not address the issue of practical implementation of any simultaneous localisation and mapping (SLAM). For guidance, the research assumes the robot guide is technically capable of mapping and navigating through the unknown environment with conditions of zero visibility. However, interacting with the robot guide under such circumstances can be demanding and strenuous. As previous research did not shed much light on the interaction, the thesis aims at bridging that gap.

The research does not investigate any local or global navigation abilities of the guide robot. Developing large scale maps that could aid the navigation of the robot in zero-visibility is beyond the scope of this research.

1.5. Research questions and the methodology

The main aim of this thesis is *to study the haptic interaction with the robot and usability of the designed interface in the conditions of zero visibility*. This has led to the following sub-questions, which are addressed in the subsequent chapters:

Fire-fighters as well as visually impaired people resort to the haptic sense to interact with the real world. Visually impaired people even make use of dogs to be guided. The first research question is formulated as:

Research Question 1. *What can we learn about haptic interaction in zero visibility by studying the fire-fighting protocols and the use of guide dogs by visually impaired people?* (addressed in Chapter 2)

Addressing research question 1 can give us an insight into human-human haptic interaction (between fire-fighters) and human-animal (haptic interaction) and help us use that insight into human-robot haptic interaction. However, the haptic sense has been used in assistive robotics before where people are at ease in a tranquil environment and not deprived of auditory feedback. We intend to use haptic sense in a context where the handler is subjected to a sensory deprived stressful setting. Therefore, when assisting, the robotic guide should in general not increase the physical or cognitive load of the handler. The end-users (fire-fighters) are a set of skilled people and they undergo rigorous training. Their haptic senses are highly trained in accordance with the existing protocols. To develop a successful cooperation with a guide robot in these circumstances, a major pre-requisite is haptic sense is sensitive enough to convey information from the robot and it could be trained for the interaction. The second research question is formulated as:

Research Question 2. *How sensitive and trainable is the haptic sense?* (addressed in Chapter 3)

Once the second question is addressed, then there are two different aspects to the next phase of the research. The basic requisite for a robotic guide is to direct the handler from one point to the other successfully without collisions. This is referred as '*locomotion guidance*' henceforth. When the handler is guided into an unknown environment and wants to search the immediate environment (especially in search and rescue tasks), the robotic guide could be used as an aid. '*Exploration*' involves making use of the same robot as a tool for scanning and searching the immediate environment. Although these are integrated aspects of the task condition we are building towards, the locomotion and haptic exploration problems are logically separable so that they can be pursued either in parallel or sequentially. The design of the haptic interface therefore needs to contribute to these aspects and this thesis evaluates the effectiveness of the interface. The third and fourth research questions are formulated as:

Research Question 3. *How can the physical interface cater for locomotion guidance in zero visibility conditions?* (addressed in Chapter 5)

i. How can various test cases be designed to explore the use of the interface under various predefined circumstances for navigation?

Research Question 4. *How can the robotic guide be used as an exploratory tool?* (answered in Chapter 6)

i. How can information from the robotic guide be transferred to the human (feedback system) at the time of the exploration in a meaningful way using haptic sense?

1.6. Thesis structure

Broadly the thesis consists of the following: Introduction (Chapter 1), Acting in zero visibility (Chapter 2), Exploring the sensitivity of haptic sense (Chapter 3), The *'REINS'* interface (Chapter 5 and Chapter 6) and Conclusion (Chapter 7). The following paragraphs summarise individual chapters and the work included in the thesis.

Chapter 1 provides the context and motivation for the dissertation and lists the fundamental questions behind the research.

Chapter 2 describes the real world scenarios in zero visibility and their influence on the work.

Chapter 3 If the haptic sense is to be used as a medium of communication between the handler and robotic guide, it is important to study how reliable it is. This chapter demonstrates the extreme sensitivity and trainability of the haptic sense in the absence of vision.

Chapter 4 presents a snapshot of the previous studies and existing work that focus on Human-Robot interaction in zero visibility. It also focuses on modelling assistive technology in absence of visibility and how our system fits into that.

Chapter 5 presents an analysis of the haptic *REINS* interface (connecting the human being and the robot guide) design. It also reports on the experiments performed to test the interface concerning guidance, in which the robot takes the handler from one way point to the next. We discuss evaluating the haptic interface to enable a handler to follow the guide and considerations that led to the design.

Chapter 6 concerns a haptic feedback system, focusing on how it has to behave when the robot is used as an acceptable exploratory tool.

Chapter 7 concludes and summarises the thesis and briefly discusses some possible lines of future work.

1.7. Publications made through the thesis

- Ghosh, A.; Penders, J.; Jones, P.E.; Reed, H., "Experience of using a haptic interface to follow a robot without visual feedback," in Robot and Human Interactive Communication, 2014 RO-MAN: The 23rd IEEE International Symposium on, vol., no., pp.329-334, 25-29 Aug. 2014

- Ghosh, A., Alboul, L., Penders, J., Jones, P. and Reed, H., 2014. “Following a robot using a haptic interface without visual feedback” In: ACHI, Barcelona, Spain 23-27 March 2014, pp. 147-153.
- Jones, P, Ghosh, A, Penders, J, and Read, H, (2013), "Towards human technology symbiosis in the haptic mode,".In: International Conference on Communication, Media, Technology and Design, Famagusta, North Cyprus, 2-4 May 2013. 307-312.
- Ghosh, A, Penders, J, Jones, P, Reed, H, and Soranzo, A, (2014), "Exploring Haptic Feedback for Robot to Human Communication." International Conference Disability, Virtual Reality and Associated Technologies, Gothenberg, Sweden.
- Penders, J. and Ghosh, A., 2015. Human Robot Interaction in the Absence of Visual and Aural Feedback: Exploring the Haptic Sense. Procedia Computer Science, 71, pp.185-195

Chapter 2

Interacting in zero visibility

This chapter is dedicated to the research question: ***What can we learn about haptic interaction in zero visibility by studying the fire-fighting protocols and the use of guide dogs by visually impaired people?*** *We look at how fire-fighters navigate a space in order to understand the task in hand and what sense they use in the absence of vision. We explore the interaction of visually impaired people with their guide dogs and we use that model as a reference, to develop a model for interaction with the robotic guide in zero visibility that could cater for the task in hand.*

2.1 Reflecting upon Fire-fighting Protocols for search and navigation with breathing apparatus

According to Denef et al., (2008) navigation in general can be defined as '*a human practice constructed out around technical possibilities such as indoor positioning of orientation tools, but also around cognitive capabilities of the navigator*' and, '*a deep understanding of the context*' is required to provide good and supportive navigation technologies. Therefore it is important to take a deep look at the existing navigation practices and protocols prevalent among fire-fighting teams in ever changing spaces and get an insight into their experiences, if we aim to develop a robotic guide for these conditions. Chapter 1 indicates that there are significant challenges for these teams to effectively work in highly oppressive search environment due to:

- Poor visibility due to heavy smoke
- Limited audibility due to ambient noise. Research done by Reischl et al. (1979) show that noise levels during firefighting exceed safe limits. Firefighters have protection for noise abatement.
- Toxic environment because of presence of deadly gases; e.g. hydrogen cyanide, phosgene, carbon monoxide (LEVINE 1979; Sammons & Coleman 1974; Dyer & Esch 1976). Fire sites may have carbon monoxide levels as high as 3000 ppm (Barnard & Weber 1979).

Firefighters carry breathing apparatus that suffices air supply for 20 minutes (Penders et al. 2007).

- The protective gear gets heated up because of extreme temperatures at the fire scene.

Hence, firefighting teams usually operate in units for fast navigation and exit. Each unit comprises of three personnel, two firefighters and one lead, functioning with established protocols.

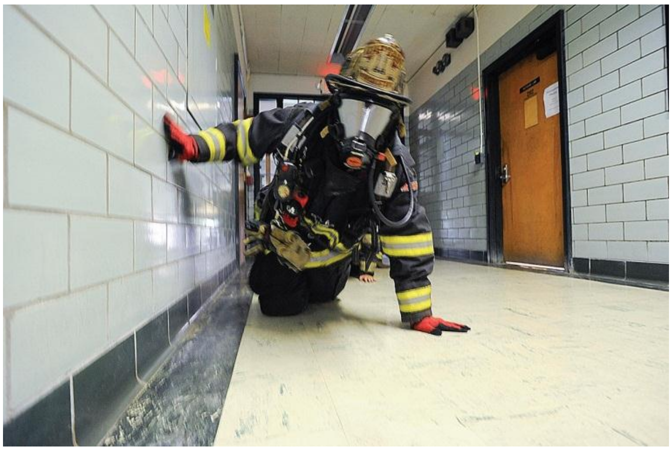

Figure 3, Fire-Fighters proceeding along the walls (Denef et al, 2008)

Whenever two firefighters enter a building, the unit lead stays in a safe place outside. They are connected through a '*lifeline*' (Ramirez et al. 2009), a rope latched to the belt of one of the firefighter and held on the other end by the unit leader so that it can be used to find the way back to the start point. Because of the danger of losing bearing and orientation, fire fighters proceed along the walls (figure 3) of a building and they report recognition points and obstacles; each member in the unit will try to memorize their findings.

In the United Kingdom, procedures for large buildings are that a first unit will lay-out and fix the main guideline (or lifeline) along a wall, refer to (Figure 4). Subsequent units aiming towards the scene of operations follow the guideline, which has a pair short ropes knotted onto it at regular intervals, to define positions along it. Timing the guideline-following by the firefighters, it is found that they progress at a rate of 12m in about one minute.

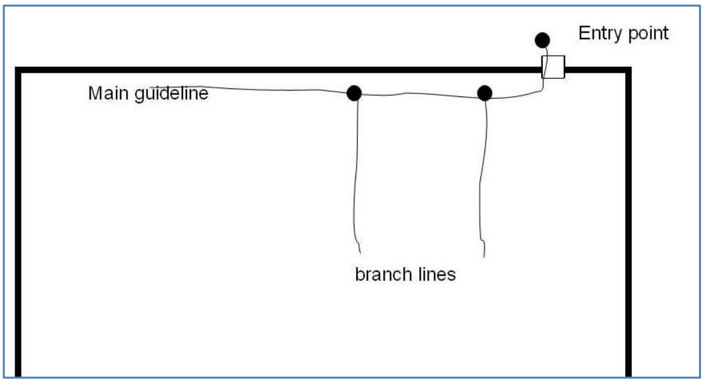

Figure 4, Guideline laid along the wall

Figure 5(a) Fire-fighters proceed along the wall and tied to each other with a rope (b) fire-fighters use dorsal side of their hand to scan hanging obstacles

If a team of two firefighters proceeds along the wall, they are tied to each other with the help of a rope (as shown in figure 5(a)) and the person behind places his one hand on the shoulder of the person in front: the medium of communication between two human beings. When the space far from the wall needs to be explored, one member stays close to the wall while moves away from the wall, explores the area more freely and comes back (as shown in figure 6). While, no verbal interaction takes place between them, they remain safely connected with the guideline, their basic aid for locomotion.

At the time of exploration standing on a rear foot, they use the front foot to stamp ahead in a fan-like pattern in order to feel for obstacles and to test the floor before a real step is made. Meanwhile one hand will be moved up and down in front of the head and upper body to feel for hanging obstructions and in particular loose hanging wires, as shown in Figure 5(b). The firefighter always uses the dorsal side of his hand to protect him from accidentally grabbing an uncovered electric wire with the palm, as the contraction of his muscles will move his hand away.

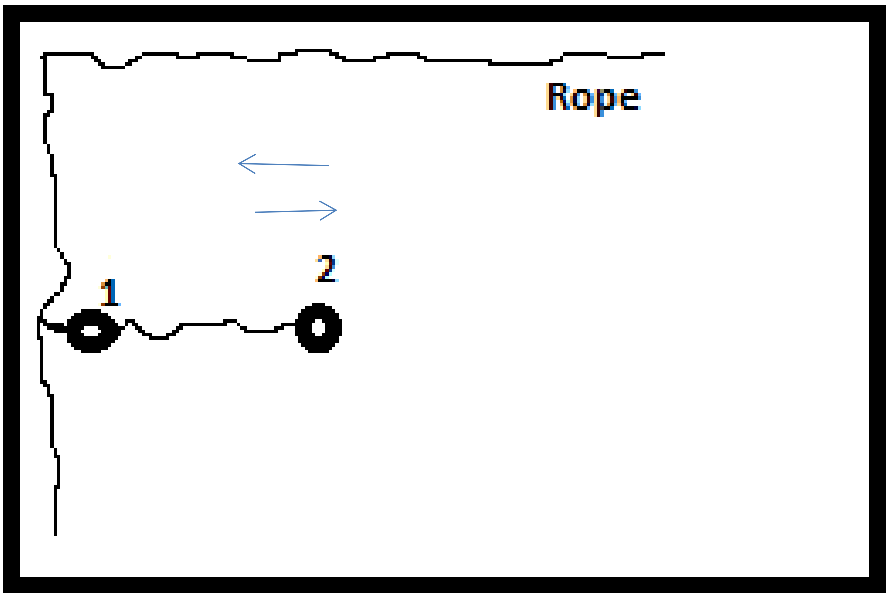

Figure 6, When one member stays close to the wall and the other member (connected with a rope) explores the area far from the wall and comes back

After scanning the designated area, the unit returns to the point through which they entered, using the guideline as their pathfinder. Denef et al (2008) reconstructed the path of one firefighting unit (as shown in Figure 7).

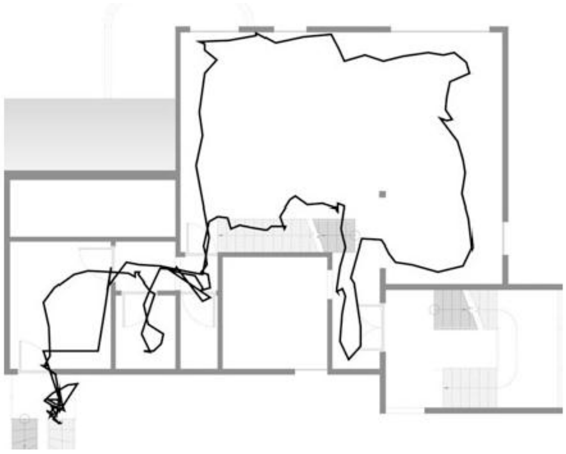

Figure 7, path of a firefighting unit as reconstructed by Denef et al (2008)

2.1.1 What can be learnt about navigation in zero visibility from firefighters?

The navigation practices of firefighters involve complex structures of behaviour, which are very sensitive to change and developed out of experience over long periods of time (Denef et al. 2008). Here we list the lessons learnt, which can help us understand the interaction in zero visibility:

- Navigation of firefighters is a collaborative activity and teamwork is an essential element. We are exploring the context of using a robotic guide in zero visibility conditions, where the handler and the guide can develop cooperation and operate as a team, similar to a team of two fire-fighters. The human being must be able to observe the behaviour of the robot in relation to the environment where it is acting.
- When proceeding into an environment with no or limited visibility fire fighters have to rely heavily on their proprioceptive awareness, which can be defined as a variation of the sensory modality of touch that involves the sensation of joint movements and joint position senses (Lephart et al. 1997). Firefighters undergo rigorous training and their proprioceptors develop, meaning they gather their skills (looked in more detail in Chapter 3). Therefore a haptic interface seems a natural solution to connect the handler and the semi-autonomous robot. The primary focus is on creating the haptic feedback and investigating whether it has enough bandwidth to aid the human being.

- There is a high level of division of labour among fire-fighters while they scan a room, stay close to the walls, and move to the middle of the room to get a sense of the environment and build an impression of the space. Therefore, we summarise that in relation to a firefighter's navigation of an unknown environment, there are two different aspects (as mentioned in Chapter 1): locomotion guidance (using the wall or rope as a reference) and exploration of space (moving hands and feet). We define locomotion guidance as: '*to be ably guided along a path from one point to the other'*. Exploration of space is defined as: '*to be able to gauge the environment around'*. And they make use of their proprioceptive senses to achieve these tasks. The envisaged handler-robot partnership will allow an integration of **two haptically-mediated functions**: a) safe locomotion guidance through an obstacle-strewn environment and b) exploration and discrimination of encountered obstacles according to particular object properties such as weight ('discrimination').
- Boesch & Boesch (1989) defined cooperation as '*individuals acting together to achieve a common goal*' and Naderi et al., (2001) proposed that cooperative interactions can be categorised along three dimensions namely: (i) similarity of the actions performed or congruence (ii) timing or synchrony and (iii) spatial coordination. While a team of two fire fighters navigates the space, the cooperative interaction between them can be described as congruent (similar actions aiming at a goal), simultaneous and homospheric (being in spatial proximity). We believe the cooperative interaction between handler and the robotic guide would also be categorised as congruent, simultaneous and homospheric.
- Firefighters have a remarkable ability of building a mental model or cognitive map of the environment while navigating in the absence of vision. The term '*cognitive mapping*' is extensively used in literature (Kitchin 1994) when we look at the process of orientation in unknown environment. Researchers from fields as diverse as psychology, geography and urban planning have explored how humans process and use spatial information to create a cognitive map for navigation and way finding. Cognitive psychologists have broken navigation down into its component steps and as an interplay of neuro-cognitive functions,

such as '*spatial updating*' and '*reference frames*' or '*perception-action couplings*' (Denef et al. 2008). Researchers have found that navigation in humans can be of two types: landmark-based and path integration. In landmark-based navigation, auditory, visual, tactual or olfactory landmarks provide information about current position and orientation. Firefighters use recognition points, obstacles or knotted ropes at regular intervals along the guideline as landmarks. In path integration the person gathers information while moving to update current position and orientation relative to some starting point (Gallistel 1990). Path integration primarily concerns proprioceptive information. It is believed that, the proprioceptive information from the robotic guide can contribute to the path integration of the handler and his perception of space and help him construct a cognitive map of the environment, thereby giving a sense of security during navigation.

2.2 Reflecting upon navigation for visually impaired people

Firefighters undergo rigorous, systematic and careful training in a low visibility and their cognitive capabilities learn to function more effectively in such an environment. Furthermore, when we try to understand proprioceptive and haptic senses in the absence of vision, prime examples are visually impaired and blind people, who are in a unique position to appreciate and are more proficient at attending to nonvisual stimulus and making better functional use of nonvisual senses (Hollins 1989). The blind community has long been believed to be a motivation for research about zero visibility. It is thus important to have an insight into the use of non-visual senses and how it helps the community.

2.2.1 Use of non-visual senses

Visually impaired people live in a different perceptual world than people with sight (Hardwick et al. 1998). When we use our eyes to see, the brain translates that information into images and deprivation of this visual input to the brain can cause permanent damage in the visual cortex (Hardwick et al. 1998). When vision is absent, distorted or reduced, one's functioning in the sighted world can be challenged by changes to how one accesses the information. Even studies have revealed that people, with visual impairment, have difficulty in constructing a cognitive or mental map of the environment (Perez-Pereira & Conti-Ramsden 2013), because a comprehensive quantity of spatial information is taken through the visual system in comparison with sensory systems used by the visually impaired (auditory, tactile, etc). But these people can compensate for their lack of sight with other senses. The improvement in the remaining senses is an outcome of learned behaviour; in other words visually impaired people learn how to use these senses more efficiently and have the ability to retain in the memory things they have learned (Fraser 1917).

Researches have shown that people missing one sense not only just learn to use the others better; their brain has the ability to change and adapts to the loss as time progresses and they gain experience. If one sense is lost, the areas of the brain dedicated to handling that sensory information do not go unused — they get used for processing other senses. Karns et al. (2012) provide evidence of this reshaping in the brains of deaf people. People who are born deaf use areas of the brain typically devoted to processing sound (primary auditory cortex) to instead process touch and somatosensation. Perhaps more interestingly, this neural reorganization affects how deaf individuals perceive sensory stimuli, making them susceptible to a perceptual illusion that hearing people do not experience. A large body of evidence shows that when the brain is deprived of input in one sensory modality, it is capable of reorganizing itself to support and augment other senses, a phenomenon known as cross-modal neuroplasticity (Merabet & Pascual-Leone 2010; Gilbert & Walsh 2004). Most of the research on cross-modal neuroplasticity has focused on blind individuals, who often have enhanced auditory abilities (Bedny et al. 2011). Brain imaging studies show the visual cortex in the blind is taken over by other senses (Gougoux et al. 2005), such as hearing or touch, and contributes to language processing (Bedny et al. 2011). Because of this, visually impaired people can read Braille alphabet with more ease than sighted people, perfectly familiar with the alphabet (Perez-Pereira & Conti-Ramsden 2013). Warren (1978) in his book says, that '*the blind have, through need, learned to attend better to auditory stimuli and therefore can make more use of the available auditory information than can sighted people*'.

2.2.2 Navigation and way-finding in the absence of vision

The task of navigation gets complicated in case of visual impairment, as one of the main problems being acquiring knowledge of the surrounding environment. However, they use much richer information, such as the environmental sound, the gradient of the slope, direction of the wind to facilitate path integration (Loomis et al. 1993). They have higher mental faculties of attention, giving them a sense of security and ease during navigation.

While walking they drive before them a slight wave of air, which, on striking a solid object, is thrown back upon the face producing a slight sensation. The sensation comes as a warning to the blind pedestrian. Visually impaired people thus can avoid contact with obstacles in their homes or with trees and posts on the sidewalks by the impression made upon their faces from the sudden condensation of air, making them aware of the presence of such obstacles. This facial sensation is not necessarily confined to persons who are blind but is occasionally experienced in the dark by people with sight (Perez-Pereira & Conti-Ramsden 2013). This is called the “obstacle sense”, or “facial vision”, that allows the blind to feel the presence or absence of obstacles (Warren 1978).

The sense of hearing coupled with the faculty of attention enables visually impaired people to move through the streets with comparative ease and safety. They note the vehicles that pass along the highway and can readily recognize the various sounds made by various automobiles. Listening to various sounds, the trained ears learn to estimate distance, to judge direction and get warned of a possible danger. So basically, unlike sight, which is a comprehensive sense and gives synchronous information about the environment as a whole, the other senses represent the environment in parts. Researchers have shown that the presence of obstacles can be mediated by audition, from echo-detection and echo-location (Warren 1978; Hardwick et al. 1998).

2.2.3 Mobility aids for navigation using proprioceptive awareness

Mobility is defined as '*the ability to travel safely, comfortably, gracefully, and independently*'(Hardwick et al. 1998). The task requires more time (Rieser et al. 1986) and more cognitive effort (Byrne & Salter 1983) for the visually impaired. Although senses, other than sight, can develop to a remarkable degree, simple aids such as the guide dog and the white cane remain the dominant aids for mobility within the community. The use of haptics and proprioceptive feedback is well received by the visually impaired community. The long cane, which was invented in the 1940s, is still the most widely used mobility aid among visually impaired users (Hardwick et al. 1998). It allows the detection of obstacles and drop-offs within a 1-meter range. This short range forces the user to be prepared to stop or to correct course quickly, and thus limits walking speed (Hardwick et al. 1998). The cane is easily identified by other travelers, warning bystanders to get out of the way but also marginalizing the blind (Brabyn 1985). Despite its shortcomings, the long cane is a wonderful instrument providing surprisingly rich information. It is generally used by making arcs, tapping on each end (Brabyn 1985). The sounds emitted by tapping can be used for echolocation. The contact dynamics also provide information about the texture and slope of the ground. This and '*cues through the soles of the feet*' are a rich sources of information (Lenay et al. 1997).

The guide dog is also a popular mobility aid (Naderi et al. 2001) and effective, but must be trained by professionals and cared for by their owners. Their cost is approximately $12,000 to $20,000 in order to train guide dogs and their working life is of approximately five years (Shoval et al. 2003). Using a cane means finding a route while the dog can obviously see the route; it's quicker and far less stressful and far more reliable. Clark-Carter et al., (1986) identified that guide dog users attain optimum efficiency during independent mobility. We therefore study the interaction between a visually impaired person and a guide dog during mobility; we model that interaction and use that model as a reference in studying how a person interacts with the robotic guide in zero visibility.

Guide dogs for visually impaired people

A domain rich with experience on haptic feedback and proprioception is the use of guide dogs for the visually impaired (Figure 9). In this section we give a general description of using a guide dog. The information is based on interaction with dog trainers of Guide-Dogs-for-the-Blind but it can also be found in the literature (Marston et al. 2007, Marion & Michael 2008).

Handling a guide dog

For clarity, the guiding link between user and dog is called a handle, and the user is usually referred to as the '*handler*' (as mentioned before). The dog is also on a lead, but this lead does not serve when the dog is guiding.

Figure 8, the handle taken apart

Figure 9, Person being guided by a guide dog

The interface: the handle

The handle is attached to a harness on the dog's back and shoulders. The dog is walking at the handler's side, 2/3 of the dog's body being ahead of the handler (Figure 9) - the dog is half a pace ahead. The handle is a rigid U shaped instrument (with a square '*bottom*' for the actual handle) (Figure 8) and this is the only guiding instrument used during walking. The handle is shaped so as to hardly need any grip from the handler and is rigid so as to immediately let the handler know when the dog stops.

The handle is not used to push the dog, nor does the dog drag the handler along with it. The default condition is that dog and handler walk at the same pace: the handler feels the dog's movements and direction while the dog monitors the handler's walking and other aspects of the behaviour as they proceed together. As the dog slows down to stop at or negotiate obstacles the handler feels this through the handle. The handle is also used by the handler to communicate particular commands and actions to the dog: it can be used to stop the dog, slow it down, prohibit certain things etc.

The dog can see the handler as well as feeling them through the handle. On being guided by a guide dog, one of the project team members noted: '*I walked blindfolded with the dog along a busy walkway outside. Pretty soon I began to feel even the slight changes of speed and direction. The trainer who walked with me said that it is important to swing my hands so that the dog also gets some feedback on your active participation of walking.*'

In addition to the handle, there is a series of verbal and gestural commands that dogs are trained on: directional commands ('*left'*, *'right'*, etc.) and control commands ('*no'*, *'leave'*, *'steady'*, etc.); these can be used in conjunction with commanding through the handle. When stationary, the dog watches the handler`s legs and arms to receive a command (as referred in Figure 10(c)). To start walking, the handler takes the right leg back and swings the right arm forward saying '*forward*' and then the dog starts to walk again.

To the general description, notes are added from an interview (with a different font) with a visually impaired female adult, who is referred as ‘N’ henceforth. 'N' currently has a guide dog called Jasper and she has had other guide dogs in the past. She travels to work daily by tram with Jasper's help.

'*N*' uses a number of verbal commands and gestural signals with Jasper (as per training) although she finds that the number of gestural signals has dwindled as their relationship has developed; currently she is mainly relying on verbal commands. The handle is used primarily as a simple guidance tool although she occasionally communicates through it (she might need to jiggle it or waggle it in order to emphasise something).

Locomotion guidance

Locomotion guidance concerns moving from point to point in a nearly straight line without collisions and it includes collision avoidance. Dogs are trained to guide according to a strict protocol: they walk in a straight line, in the middle of the pavement; they slow down and negotiate minor obstacles on the pavement, refer to (Figure 10). The dog may begin to take evasive action in advance if a slight deviation is required; which means that the handler will have avoided an obstacle without even knowing it. In a supermarket people with trolleys traverse the aisles, concentrating on shopping and not paying attention to what is going on behind them. The dogs are trained for this: the dog stops when there is no way through without brushing the handler against the obstacle.

On the street, people are on the move and more aware of what is coming up ahead and tend to get out of the way. The dog continues in a straight line until faced with a '*choice*' of directions. At that point, the handler will have to prime the dog as to the required direction. For instance, the dog will stop at the kerbside when there is a road to cross, refer to (Figure 10(c)). It is down to the judgement of the handler to initiate a crossing: the handler will have to command the dog forward. However, the dog will not move forward if it is aware of a hazard, so the handler will have to wait and then issue a further command etc.

It is told in the interview that if the pavement is blocked, for example, Jasper will take N. to the kerb, implying the need to cross the road at that point. This deviation from the normal route, will be interpreted by N. as Jasper taking evasive action, although she can check this by telling Jasper to go ahead as normal (in which case it can again refuse). The thing that makes N. most anxious is crossing roads.

Thus, on interviewing '*N*' and looking at the experiments performed by Naderi et al., (Naderi et al. 2001), we conclude that locomotion guidance involves the following actions:

- Start: Locomotion in any direction from a still position.
- Stop: Motionlessness lasting for more than 2 seconds.
- Obstacle avoidance: Change in direction by some angle followed by a similar change in opposite direction.
- Turning: Sharp change in the direction of walking.
- Slowing down: Decrease in the speed of walking.
- Stepping: Locomotion that results in continuation of walk on a higher level or lower level.

Navigation and exploration

Generally speaking, guide dog and handler only follow fixed routes with which the handler is familiar; indeed prospective handlers are trained on the routes (eg the safest route and way to walk) before they have a dog. A dog trainer says, '*Clients would be taught that if they did not know where they were then to stop and ask someone. Most clients have a fixed number of set routes and do not venture off those, some clients work their dogs in lots of environments and they generally tend to have better orientation/spatial awareness and/or residual vision to support their other skills'*.

'*N*' uses Jasper for a number of familiar routes (e.g. getting to work) although these routes may vary slightly albeit in predictable ways: for example, in coming to work she may get off at different tram stops but the route to work from each stop is familiar. Unlike some guide dog users, '*N*' announces her destination to Jasper (for example '*let's go home*') and Jasper will head off in the right direction and guide '*N*' there, subject to her control and command at junctions etc. On leaving the tram to make her way to work N. will tell Jasper to '*find right*' - that is, turn right out of the tram and find the appropriate starting point for the journey to the workplace. On arriving at the specified destination Jasper will find the entrance door or whatever looks most like an entrance door on arrival.

Figure 10, The dog always walk along straight lines at the centre of the walkway(left) and sits down at the curb or crossings (middle) and watches the handler's legs and arms to receive a command (right).

[N.] While being guided, N. knows where she is all the time on the street due to her '*mental map*' of the route and her ability to read all kinds of environmental cues about location and direction etc. There are occasional times (e.g. crossing the park) where such cues are sparse or absent for some moments. She has only ever got lost once, although - due to the familiarity of the route overall - she was quickly able to find her way back again. She notes that people think to help her by giving distance indications but these are of no use to a blind person.

The cooperative interaction and the division of labour between the handler and the guide dog

Leading a visually impaired person is fundamentally a cooperative task, where both participants play important roles. Similar to a firefighting unit, the cooperative interaction between a guide dog and a visually impaired person is congruent, simultaneous and homospheric (being in spatial proximity). Apparently, the guide dog is not taking the handler to a destination - the handler is taking the dog to the destination. The team is depending on the handler's spatial awareness and ability to read clues and cues from the environment. The handler (not the dog) has to find the destination; we call this *navigation*. Navigation concerns making choices, deciding in which direction to go and that requires a (mental) representation of the environment of some sort. It also requires a link between the current position and that representation, if this link is fails the person is lost. Navigation requires some sort of localisation in the representation of the environment.

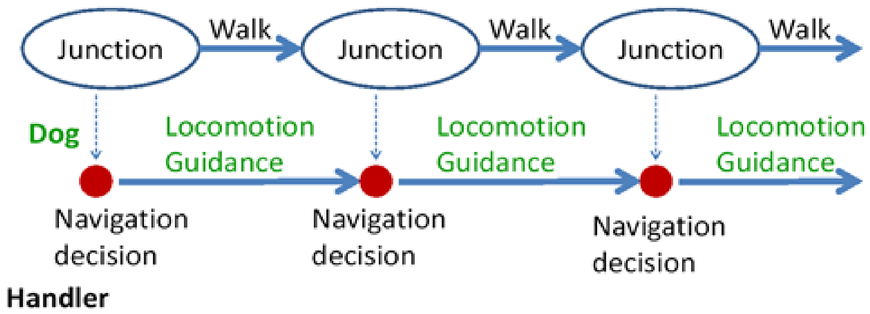

Figure 11, Handling a guide dog: task analysis

The handler initiates an action by movement or verbal command (sometimes) whereas the dog always initiates by movements. The task of the guide dog is, as the above shows, to negotiating a passage; this activity takes place in locomotor space as it is called in (Veraart & Wanet-Defalque 1987) and we call the task which the dog performs *locomotion guidance.* Locomotion guidance by the dog and navigation decisions taken by the handler are complementary activities each performed by a 'specialised' agent of cooperative action, refer to (Figure 11)

2.2.4 What can be learnt about navigation in zero visibility from visually impaired people and their interaction with guide dogs?

- In the absence of vision, the human brain can be activated by non-visual senses given systematic training and can be improved with time and experience. For the successful operation of the robot device, the handler will need to develop particular haptic skills and proficiencies relevant to the locomotion guidance and exploration. Studying the use of guide dogs, it is concluded that the haptic sense and proprioceptive awareness is highly sensitive and trainable to a remarkable degree and we further investigate that in the following Chapter.

- Inspired by the study of the handle connecting the handler and the guide dog, we connect the human user and mobile robotic guide with a rigid interface (a ‘*stick*’). The communication between the user (handler) and the guide will take place through the interface.
- It is perceived in the context of the dissertation that the interaction is a communicational landscape emerging between the human being and the robot. It is a presumption that the human being, by nature, will try to '*read*' the situation (Harris 1996) and base decision making upon the '*view*' obtained. We also expect that the handler wants to remain the dominant and initiating partner, at least from his/her perspective. If not further specified this leads to the question whether (a) the handler is leading the robot or (b) whether the robot is leading the handler. However, as the analysis of a guide dog and handler team above shows we can distinguish between (a) and (b). This seems a natural basis for a mixed initiative mode of operation and division of autonomy between them. At the point of exploration, the human being has the autonomy (decision maker) and uses the robot as a tool to explore the immediate environment, whereas, between two points of exploration, the robot acts as an autonomous guide and is the decision maker ensuring a safe passage, exactly like a guide dog between two points navigation. As shown in figure 12, the task of exploration is carried out by the human while locomotion guidance is restricted to the robot. In each of these phases shown in the figure 12 the dominant actor is marked in red, which basically signifies the entity having autonomy.

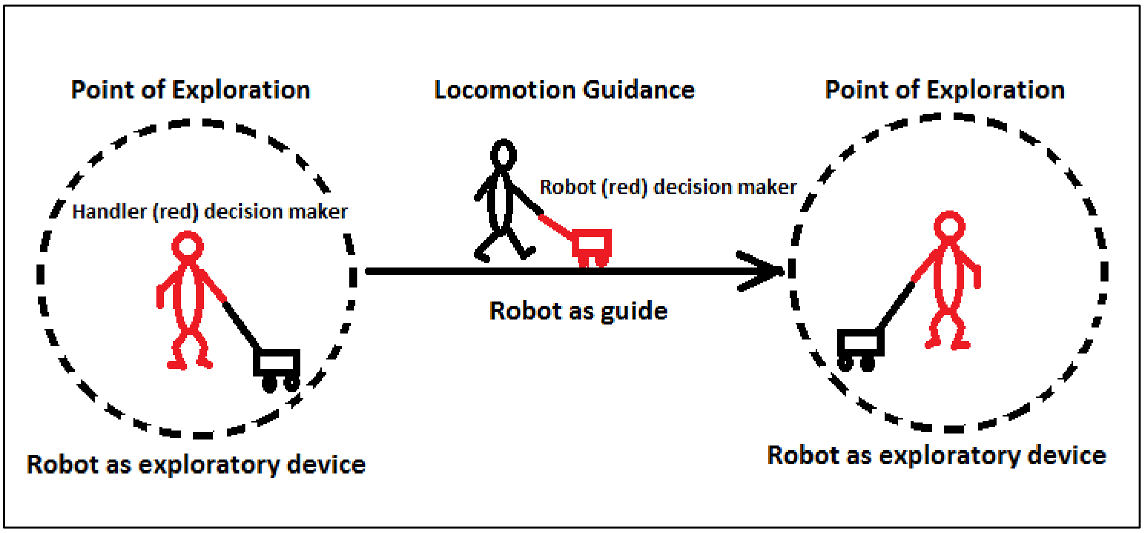

Figure 12, Division of Autonomy between handler and the guide robot

2.3 Chapter closure

Collins et al., (2013) note that the human robot relationship draws similarities from various kinds of existing bonds humans share with other humans, animals or objects (as shown below). Human - human bonds are explained by Hazan and Zeifman (1999) whereas human animal bonds have been discussed by Walsh (2009).

Keeping this in mind, in this chapter, we reviewed two real world scenarios where interactions take place in zero visibility and we reflected upon the conclusions that could influence the interaction between the human being and the robotic guide. Providing technical solutions is not really difficult, however, since interaction is the study of this thesis, providing a meaningful basis for the study is the real challenge. These learnings are the key factors for the study and can help understanding the effectiveness of the design of the haptic interface connecting the human and the robot.

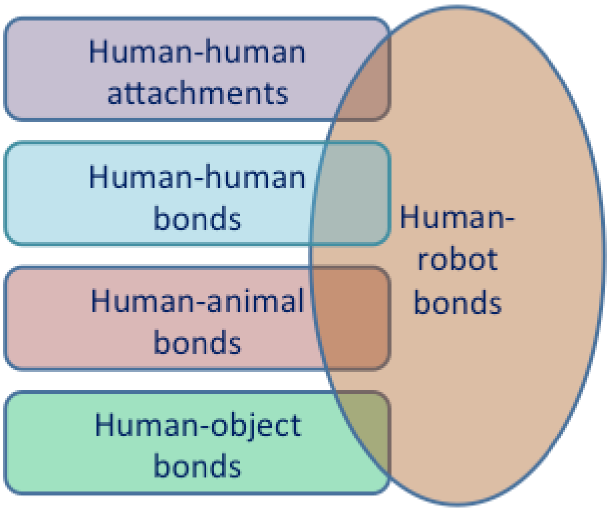

Figure 13, Human robot bonding (Collins et al., 2013)

One of the learnings is that the firefighters and visually impaired community rely heavily on their proprioceptive senses and it can develop to a remarkable extent, given systematic training.

Chapter 3

Exploring the haptic sense

This chapter is dedicated to the research question: ***how sensitive and trainable the haptic sense is?*** *We review the haptic sense in this chapter and conduct an experimental study to demonstrate the extreme sensitivity and trainability of haptic communication and the speed with which users develop and refine their haptic proficiencies. We discuss how these initial explorations may shed light on the more general question of how a human mind, on being exposed to an unknown environment with zero visibility, may enter into collaboration with an external information source in order to learn about that environment, using haptic sense. Part of this chapter is published as*

Jones, P, Ghosh, A, Penders, J, and Read, H, (2013), "Towards human technology symbiosis in the haptic mode,".In: International Conference on Communication, Media, Technology and Design, Famagusta, North Cyprus, 2-4 May 2013. 307-312.

3.1 Human senses

Human senses, physiological tools for perceiving environmental information, as described by Aristotle, are broadly classified into: sight or vision, audition, olfaction, taste or gustation and touch or traction. The sensory system actually extends beyond five senses. These five senses are called exteroceptive (Gibson 1966), as they are directed outward for receiving stimuli from the outside world. There are senses that involve sensitivity to internal events, such as body temperature, hunger and thirst, sleep cycle, heart rate, etc. Other important senses are the kinaesthetic sense and sense of equilibrium, which are proprioceptive; involving position and motion of the body. The characteristics of these senses have been investigated over decades by scientists. Each of the sense modalities, is characterised by many factors, such as the types of received and accepted data, the sensitivity to the data in terms of temporal or spatial resolutions, the rate at which information is processed, ability of the receiver to adapt to the data that is received (El Saddik et al. 2011b). Data pertaining to the surrounding environment is acquired using these senses and transformed into usable representations, creating new possibilities for efficient interactive experiences with machines (Petersen et al. 2004). It is extremely important to realise the potential of the human senses, so that they are naturally integrated in human-machine interaction as well as in the interaction design process.

The haptic sense can be stimulated through heat, vibration, pressure etc. The human haptic system perceives two types of information (El Saddik et al. 2011c), kinaesthetic or proprioceptive and tactile or cutaneous. Though they are not mutually exclusive, this thesis is mostly concerned with the kinaesthetic awareness of a human being. When exploring the haptic sense, the challenge is how to utilise its potential in the interaction context; and what influence the use of these senses has on interactive experience. In this chapter, we study the sensitivity and trainability of the haptic sense.

3.2 Haptic sense

Haptics, the word originates from the Greek word '*Haptos*' and it refers to the science of manual sensing (exploration for extraction of information) and modification of the environment through body and touch. (Gibson 1966) describes Haptics as '*the sensibility of the individual to the world adjacent to his body by the use of his body*'. This word was introduced by researchers in the field of experimental psychology to refer to the active (tactile-kinaesthetic action) exploration (Klatzky & Lederman 2009) of real objects by humans. Robles-De-La-Torre (2006) notes: '*In experimental psychology and physiology, the word haptic refers to the ability to experience the environment through active exploration, typically with our hands, as when palpating an object to gauge its shape and material properties. This is commonly called active or haptic touch, in which cutaneous and kinaesthetic capabilities have important roles.*'

Furthermore, active touch is closed loop and enables bidirectional flow of energy due to acting and sensing. It is not limited to the zone of physical contact. It involves voluntary and exploratory movements essentially resulting in kinaesthetic perceptions, linked to the cutaneous perceptions, and generating tactile-kinaesthetic action. It may or may not be accompanied by other sensory modalities such as vision or audition. Prinz (2013) states that '*haptic senses may play a role in giving the world a sense of objectivity. Sight and sound are spatial senses in that they can be used to locate objects along spatial dimensions, but it is not clear phenomenology that these senses alone give us the impression of the objects existing in a space that is external to the mind. Haptic* *senses, because they often exploit bodily movement, may present space in a way that is more decidedly external* ' and also convert the visual information into a meaningful action (seeing and reaching for an object), thereby contributing to our '*impression that things are out there*'.

Gibson (1962) notes that the term haptics was first proposed by Révész (1950), following observations of '*the performances of the blind*', to denote '*an unrecognized mode of experience ... which goes beyond the classical modalities of touch and kinesthesis*'. More specifically, the term is intended to capture 'active touch' (an activity) as opposed to 'passive touch, or *being touched* (Gibson 1962)' (a sensation). 'Active touch', Gibson emphasises, '*in an exploratory rather than a merely receptive sense*' (Gibson 1962).

The haptic sense is distributed over the entire body, unlike other senses, which are centralised around specific parts of a human body. Although relatively under-explored in comparison with sight and hearing, the sense is '*critical for normal human functioning at many different levels, from controlling the body to perceiving the environment, as well as learning about and interacting with it*' (Robles-De-La-Torre 2006). Consequently, there is now intense psychological interest in the cognitive dimensions of haptic sensing generally as well as in the development of haptic proficiency in blind and visually impaired adults and children.

3.2.1 Human haptics and haptic perception

Human haptics focuses mainly on the aspects related to human perception of the sense of touch, relative locations of body parts in space and the cognitive components of the body-brain haptic system. When a person touches an object, the interaction force or pressure applied on the skin, is conveyed to the brain by the associated sensory system and it leads to perception. As mentioned earlier, haptic perception can either be tactile (through the skin) or kinaesthetic (through the movements of the position of joints and muscles). It is a mental process that constructs the whole image after the perception of the parts, a sharp contrast to visual perception, which concerns observing the whole image and then the parts (Noë 2004). For instance, to sense the shape of a cup, one must run his/her fingers across its shape and surfaces to build a mental image of the cup (El Saddik et al. 2011a).

When it concerns active touch, the most significant mechanical component of the human body is essentially the upper limb (hand-arm) system, as it plays an important role in gathering information about the world. Radman (2013) states that '*The body is knowledgeable in its own terms and the hand possesses its authentic know-how. A "trivial" movement thus give birth to mental happenings* '. This component consists of the upper arm, the forearm, and the hand, which, as a whole, possessing twenty-eight degrees of freedom for dexterous exploration and manipulation (El Saddik et al. 2011c). The sensory (or somesthetic) system includes large numbers of various classes of receptors and nerve endings in the skin, joints, tendons, and muscles. Typically, a physical stimulus activates these receptors and causes them to convey sensory information to the central nervous system. The brain, in turn, analyses and '*perceives*' this information and issues appropriate motor commands to activate the muscles and initiate hand or arm movements.

Kinaesthetic information can be expressed through active and free movement of the hand, whereas tactile information is conveyed when the human hand is passive and stationary while in contact with an object. Therefore, kinaesthetic awareness involves the position and motion of the hand and arm, as well as the forces acting on them, to give a sense of the total contact forces, surface compliance, and weight (Haggard & Flanagan 1996).

3.2.2 Kinaesthetic awareness using haptic sense

The anatomic definition of kinaesthetic awareness is the perception of movement and position of one's body parts (muscles, bones and joints) in space (Rasch & Burke, 1972) at any given point of time (even when the body remains stationary). It gives one the ability to know posture accurately and assess weight. When an object is picked up, the tension in one's muscles generates signals that are used to adjust posture. Kinaesthetic awareness is the bodily intelligence that allows a person to react intuitively without having to think about every single movement (Rasch & Burke, 1972; Floyd & Thompson, 2004). It also acts as a vocabulary for describing the body in motion and how it conditions our experience of the world in the interactions with and through interactive technologies.

Our kinesthetic sense therefore conditions the manner in which we experience the world in framing our embodied actions, by providing a sense of spatiality and bodily-motor potential in our relation to the physical and socio-cultural world. The motor abilities are developed into motor skills when they meet the cultural world, responding to the perceptual signals human body receives (Noland, 2007). Fogtmann et al., (2008) cite Ponty (1945) that kinaesthetic awareness is mediated by '*Motor-memory*'. It can be defined as a combination of motor skills and kinaesthetic memory to guide human actions (Noland, 2007).

The psychological aspect of motor skills, known as psychomotor abilities, is the cognitive part of the motor system. Psychomotor skills are a result of organized muscle activity in response to stimuli from the environment. Whereas the physical part of motor learning is concentrated around reflex actions, psychomotor skills are complex movement patterns that have to be practiced (Boucher, 2004).

When engaged in any form of sport, the notion of psychomotor abilities is present most of the time. In combat sports like boxing, fencing, taekwondo, etc., elements such as tactics and psychomotor abilities are of greater importance than any other skill. It is not only vital to know how to execute a certain action, but also to know where and when to apply it, which is also the case for fire-fighters. This is the empathic part of our innate bodily intelligence (Czajkowski, 2006).

3.2.3 Sensitivity of haptic sense

Research has highlighted the extraordinary speed and sensitivity of the haptic sense (Bushnell et al. 1991) and has also demonstrated, comparable set of spatial abilities in people without vision as can be found in those with vision' (Golledge et al. 1996; Ungar et al. 1996; Espinosa et al. 1998; Ungar 2000). Bushnell et al., (1991) demonstrate that haptic sense is 20 times faster than vision and sensitive to a vibration up to 1 KHz (Bolanowski Jr et al. 1988); humans are able to distinguish between two successive stimuli 5ms apart. Thus, there has been growing interest in haptic sensing and its technological applications (for reviews and commentary see, e.g., (Hayward & Astley 1996; Henriques & Soechting 2005; Robles-De-La-Torre 2006)).

Haptic sensing of weight and force, as well as other object properties such as size, volume and texture, have been extensively studied since the early 19th century (e.g. the pioneering work of Ernst Weber (1996)). The sensitivity of the haptic sense can be demonstrated by the ability of a person to discriminate between objects in the environment haptically. In general, discrimination abilities using haptic sense have been shown to be extraordinarily acute and easily trainable. Indeed, in a study of haptic discrimination of textured surfaces, Lamb (1983) concluded that:

'*Any incremental change in the period of the dots produced d' values greater than zero; in other words, the subjects could detect to some degree any change in the period of the dots, no matter how small. There was no evidence of "threshold" behaviour in this discrimination task*'.

d' represented the discriminative performances of various subjects between two different surfaces using active or passive touch.

In terms of the discrimination of weight more specifically, studies have differentiated between the perception of '*inertial mass*' (the feeling of the force needed to move an object) and '*gravitational mass*' (the feeling of holding an object in the hand), showing that '*gravitational mass*' generally feels heavier (Tiest & Kappers 2010). Studies have also shown the inter-relation between perceptions of weight and perceptions of size, volume, colour and texture (Kahrimanovic et al. 2011; Jones 1986).

After looking at the literature, in order to have an understanding of the haptic sense and address its potential in interactive systems in our own context, the study reported in this thesis involves designing an experiment based on haptic perception in humans, their kinaesthetic awareness and the sensitivity of the haptic sense.

3.3 Testing the Haptic Sense

3.3.1 Experiment rationale

As the main aim is developing a robotic guide for skilled handlers, the focus is making use of their '*motor memory*' and '*motor learning*'. Skilled handlers perform a task enough number of times to form a nerve pathway that activate muscle contractions and therefore the movements become automated (Rasch & Burke 1972). The skills associated with one's motor abilities are timing, tactics, response speed and ability, type of action and level of attention (Czajkowski 2006).

Subjects are to make judgements of ‘inertial mass’, experienced by using a mobile mechanical device to collide with, and push, objects of various weights. However, the weight discrimination studies referred to above have all involved *direct* touch contact with objects. In contrast, this study involves *indirect* haptic sensing in that subjects can only ‘feel’ the weight of objects through the mediating presence and role of the mobile device.

Kinaesthetic Interaction can be divided into three categories, individual, joint and opposed; the last two are variations of Kinaesthetic Empathy Interaction. Individual kinaesthetic interaction is where one person is interacting with space or artifact, while Kinaesthetic Empathy Interaction is focused around movements involving other people (Fogtmann 2007). The experimental design is an example of individual kinaesthetic interaction as it involves making use of a mobile device as a prototype for the robot.

The study is interested in the extent to which users would be able to use their haptic sense to discriminate between objects in terms of weight (sensitivity) and how quickly such mediated haptic powers would develop and improve over a short period of time (trainability or motor learning). The main aim is to determine whether the haptic sense is acute enough to be used for interaction with the robotic guide. Furthermore, the study eliminates the influence of the perception of other object properties (size, volume, texture, etc) on the perception of weight, since no tactile manipulation of objects is possible and subjects are deprived of both visual and auditory feedback (by blindfold and headphones).

Five subjects over the age of 18 are recruited to take part in the experimental study of haptic discrimination. Each subject underwent two sets of trials, during which their behaviour was monitored and video recorded. The subjects are given the task of pushing the mobile device by means of the handle attached while blindfolded and wearing headphones. On each push the subjects are asked to report on whether they could feel anything in front of the mobile device and, if so, how heavy it was. (exact instructions are given below).

The task as outlined requires the subjects to develop communicational proficiencies which involve a number of different types of semiological integration (Harris 2009), including:

1. '*environmental integration*' – '*The integration of an individual's activities with objects and events in the physical world*' (Harris 2009).

2. '*transmodal integration*' – '*The integration of verbal with non-verbal communication', visual with oral communication, etc.*' (Harris 2009). Here, the subjects had to integrate verbal descriptions of weight ('light', 'medium', 'heavy') with haptic feedback from the device. In fact, using such terms represents a complex integrational challenge. It is neither simply to do with 'linguistic' knowledge – in this case, knowledge of 'English' vocabulary - nor with the 'psychological' ability to make perceptual discriminations. Jones & Collins (2009) cites Harris (1981):

'*Even the use of ordinary grading words, like heavy, good, unusual, typically involves a simultaneous assessment of facts and terminological appropriateness, correlated in such a way that when doubts arise it often makes little sense to ask whether they are factual doubts or linguistic doubts. They may in one sense be a mixture of both, but not necessarily a mixture that could even in principle be sorted out into two separate components*'.

Clearly, then, the same object may be 'light' for the purposes of one task but 'heavy' for the purposes of another. In practice, then, subjects had to create from their own experiences what appeared to them to be an appropriate integration of their own feelings with the words given. Thus, subjects would have to introduce some semantic order into their understanding and use of these terms as an inseparable dimension of developing the haptic discrimination skills themselves. In effect, then, the *words used to* *describe weight*, no less than the mobile device for ‘feeling’ weight, would need to be transformed into ‘transparent technology’ in order for successful task performance.

3.3.2 Transparent technology and haptic sense

As Clark (2008) explains, the concept of ‘*transparent technology*’ derives from the Heideggerian notion of ‘*transparent equipment*’ – ‘*equipment ... that is not the focus of attention in use*’ Clark (2008), a ‘*classic example*’ being ‘*the hammer in the hands of the skilled carpenter*’. As Clark argues, the user does not ‘feel’ the equipment in his or her hands:

‘*Instead, the user “sees through” the equipment to the task in hand. When you sign your name, the pen is not normally your focus (unless it is out of ink etc.). The pen in use is no more the focus of your attention than is the hand that grips it. Both are transparent equipment*’ (Clark 2008).

A ‘transparent technology’, then, ‘*is a technology that is so well fitted to, and integrated with, our own lives, biological capacities, and projects as to become (as Mark Weser and Donald Norman have both stressed) almost invisible in use*’(Clark 2003). In contrast, an ‘opaque technology’ is ‘*one that keeps tripping the user up, requires skills and capacities that do not come naturally to the biological organism, and thus remains the focus of attention even during routine problem-solving activity*’ (Clark 2003).

‘*Transparent*’ tools are those ‘*whose use and functioning have become so deeply dovetailed to the biological system that there is a very real sense in which – while they are up and running – the problem-solving system just is the composite of the biological system and these nonbiological tools*’ (Clark 2003).

The classic illustration of ‘*transparent technology*’ in this sense, and of particular relevance to the study, was the use of a cane by a blind person (or ‘*cane traveller*’) for navigational purposes (Clark 2003) as described by Bateson (1972):

‘*But what about “me”? Suppose I am a blind man, and I use a stick. I go tap, tap, tap. Where do I start? Is my mental system bounded at the handle of the stick? Is it bounded by my skin? Does it start halfway up the stick? Does it start at the tip of the* *stick? But these are nonsense questions. The stick is a pathway along which transforms of difference are being transmitted. The way to delineate the system is to draw the limiting line in such a way that you do not cut any of these pathways in ways which leave things inexplicable. If what you are trying to explain is a given piece of behaviour, such as the locomotion of the blind man, then, for this purpose, you will need the street, the stick, the man; the street, the stick and so on, round and round. But when the blind man sits down to eat his lunch, his stick and its messages will no longer be relevant – if it is his eating that you want to understand*'.

If I am conscious of the world via a stick, then the stick is not simply a tool that '*I*' use, but part of '*me*', a limb of my extended arm-hand system and a sense organ of my extended mind. User and tool thus become '*human-technology symbionts*' - '*thinking and reasoning systems whose minds and selves are spread across biological brain and nonbiological circuitry*' (Clark 2003).

Clark offers a remarkable illustration of the work of Berti & Frassinetti (2000) with neurologically impaired human subjects. The subjects in question suffered from 'unilateral neglect' within the visual system with the result that areas within the visual field were inaccessible to them. But when subjects were given a stick to reach objects with, it was found that '*the use of a stick as a tool for reaching actually extends the area of visual neglect to encompass the space now reachable with the tool*'(Clark 2008). He quotes from Berti and Frassinetti: '*the brain makes a distinction between "far space" (the space beyond reaching distance) and "near space" (the space within reaching distance) ... simply holding a stick causes a remapping of far space to near space. In effect the brain, at least for some purposes, treats the stick as though it were part of the body*' (Berti & Frassinetti 2000).

As Clark explains, this human ability to render our technological aids 'transparent' in this way has profound consequences for how we understand not simply our physical and mental abilities but, more fundamentally, how we understand what it is to be human. In broad terms, it means that we need to '*foreground embodiment, active sensing, and temporally coupled unfoldings*' in our perspective on human action and cognition (Clark 2003). But more specifically, it involves a view according to which tools are not so much 'used' by people but 'incorporated' (Clark 2003) into novel dynamic systems of embodied activity and interaction to form part of the users themselves.

In the study of object discrimination using the device-on-a-stick we were interested in witnessing and analysing the emergence of such a human-technology symbiosis or '*synergism that can develop between artifacts and human agents*' (Neuman & Bekerman 2000) in individual haptic interaction. More specifically, then, this involved providing a suitable task context in which the mobile device would be transformed in use into 'transparent technology'.

3.3.3 Description of the experiment

Fig 14 shows a schematic view of the mobile device and its functional components (a prototype for the ultimate mobile guide robot). The mechanical device consists of a fixed handle (henceforth 'rein') attached to a wooden trolley to use the arm-hand system of the human body (Fig 14(a)). The wooden trolley rolls on four wheels, two at the sides (radius 7cm), one at the back (3cm) and one (3 cm) in the front (Fig 14(b)). The trolley is designed to have two degrees of freedom, moving only forward and backward. The trolley is surmounted by a smooth, rigid skirt (Fig 14(c)) which envelops the body and wheels of the trolley (Fig 14(a)). The skirt is fitted with sensors (not in use for this experiment), signals from which are received and recorded by a computer. The skirt, in principle, sits on top of the mobile robot and the goal is to yield the force exerted from objects using it's sensory array and translate into a vibratory feedback for the handler (to be explained in chapter 6).

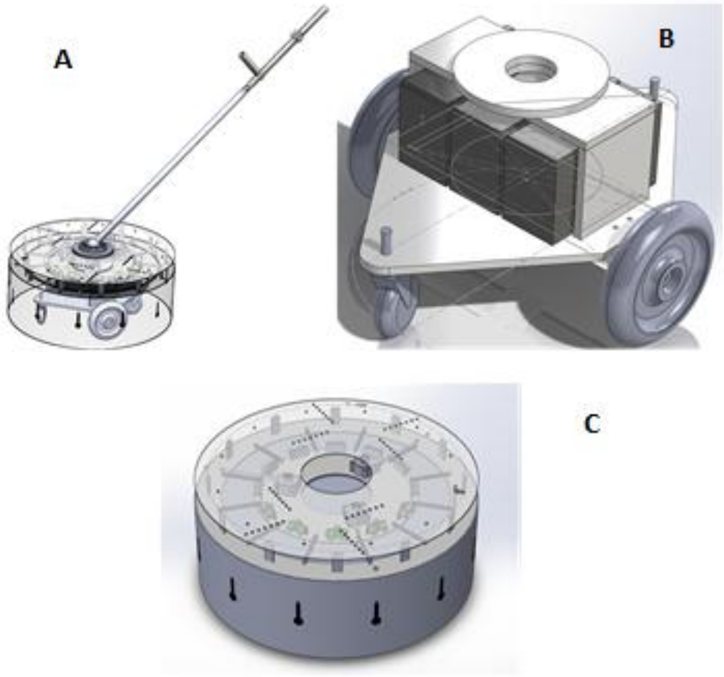

Figure 14, (a) Mobile device consisting of a wooden trolley, a rigid handle and a skirt (b) wooden trolley (c) skirt that fits on the wooden trolley

Target objects

In this simplified setting for haptic discrimination, a hollow wooden box, measuring 30.48x30.48x29.21 centimeters and weighing 3.2 kilograms empty is used as the basic target object. The weight of the box is altered during the experiment by adding pre-arranged weights (keeping the physical dimensions same, so that the subjects cannot make assumptions by looking at it), giving the following set of weight values for the target objects:

- 3.2 kg (the empty wooden box)
- 5.2 kg (the box plus 2 kg weight)
- 10.2 kg (the box plus 7kg weight)

Protocol

Each subject was asked to undergo two trial sessions with twelve trials in each session with a short break between sessions. The whole trial period lasted for approximately 30 minutes for each subject. At the start of the first session, subjects were instructed on how to perform the task. Subjects were allowed to see the mobile device (but not the box or weights) and to push it several times before blindfold and headphones (playing a sound track less than 70dB) were put on. Subsequent communication with subjects was conducted via pre-arranged haptic signals.

Subjects were asked to grasp the fixed rein and to gently push the mobile device away from them a short distance without stepping forward (Figure 15). On each of the twelve trials in each session, subjects would encounter one of the following four randomly assigned target states (as mentioned below). Though the target states are randomly presented, the distribution is uniform across all subjects.

a. No object in front.
b. Wooden box (3.2 kg)
c. Wooden box plus 2 kg (5.2kg)
d. Wooden box plus 7 kg (10.2 kg)

For states (b-d), the wooden box was placed in direct contact with the skirt before the trial began (as in Figure 15) in order to eliminate (or at least reduce the chance of) perceptible collision cues. Subjects were asked to report what they could feel on each trial using, as far as possible, the verbal expressions below (verbal report):

A. *Nothing*: meaning no object could be felt in front of the device.
B. *Light*: meaning there was a light object in front of the device.
C. *Medium*: meaning there was a medium weight object, quite easily movable, in front of the device.
D. *Heavy*: meaning there was a quite heavy object, possibly not movable, in front of the device.
E. *Not sure*: meaning the subject was not sure if there was any object in front of the device or not.
F. *Not sure which*: meaning the subject could feel an object but was not sure of the weight.

Before the commencement of every trial, the fixed rein was gently placed in the subject's hand – this was the pre-arranged haptic signal for the subject to push and report. After each report, the rein was taken back, by the experimenter for a few seconds while the next trial was set up.

Figure 15, Subject pushes the device with the target object in front.

For each trial we recorded the following:

- response time in seconds (from push to report)
- a verbal report indicating the subjects' ability to match the type of action with their level of attention

Each verbal report ('Nothing', 'light', etc) was noted against the relevant target object state (No object, wooden box, etc) so that we could examine the accuracy of the verbal report.

Results

Speed of Haptic Sense - Response times

Table 1, figure 16 and figure 17 show the average response times of every subject for the first and the second trial sessions. The mean response time for the second set is less than the first set in each case, indicating that the subjects have already learnt from the first trials using their psychomotor abilities and responded with more confidence in the second session of the trials.

	Trial Set 1	Trial Set 2	Overall
Subject 1	5.93	5.00	5.465
Subject 2	7.72	6.02	6.87
Subject 3	6.13	3.83	4.63
Subject 4	3.93	2.9	3.415
Subject 5	4.34	2.21	3.275

Table 1, Mean response times in seconds

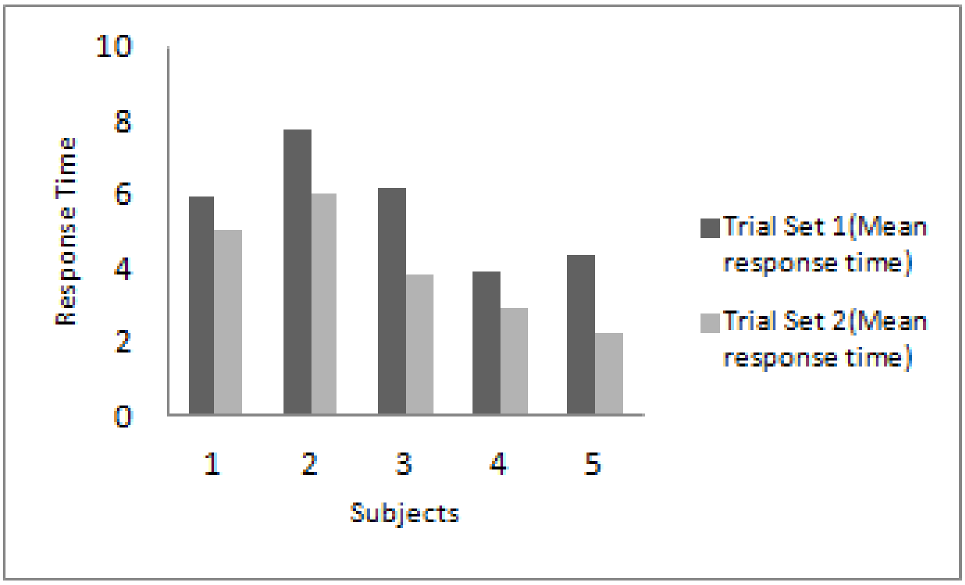

Figure 16, Bar-Graph showing the Mean Response Times for two sessions

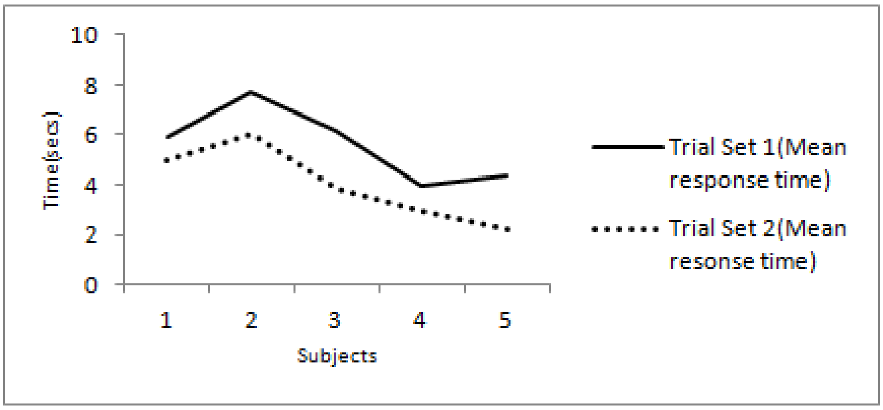

Figure 17, Line-Graphs showing the mean response times of the subjects for two sessions

Sensitivity of Haptic Sense - Accuracy of the verbal report

We took a verbal report to be accurate if there was a match between target state and verbal expression as follows:

Target state	Verbal expression
a	A
b	B
c	C
d	D

Table 2, Match between target states and verbal expressions

We counted verbal responses E and F as inaccurate for the purposes of calculating the accuracy rate. The accuracy rate for each subject was calculated on the basis of the number of accurate reports per trial set. Figure 18 shows that the accuracy rate improved from the first trial set to the second trial set for each subject.

Figure 19 shows accuracy rate by each target state (a)–(d) for each trial session. Accuracy increases over the two trial sessions for all target states. However, accuracy rates for states (a) (No object) and (d) (Heavy object) are very high indeed, with rates for states (b) (Light object) and (c) (Medium object) being lower but improving in the second trial. Figure 20 shows mean accuracy rate for each target state over all trials, indicating that the general accuracy for each target state is over 60%.

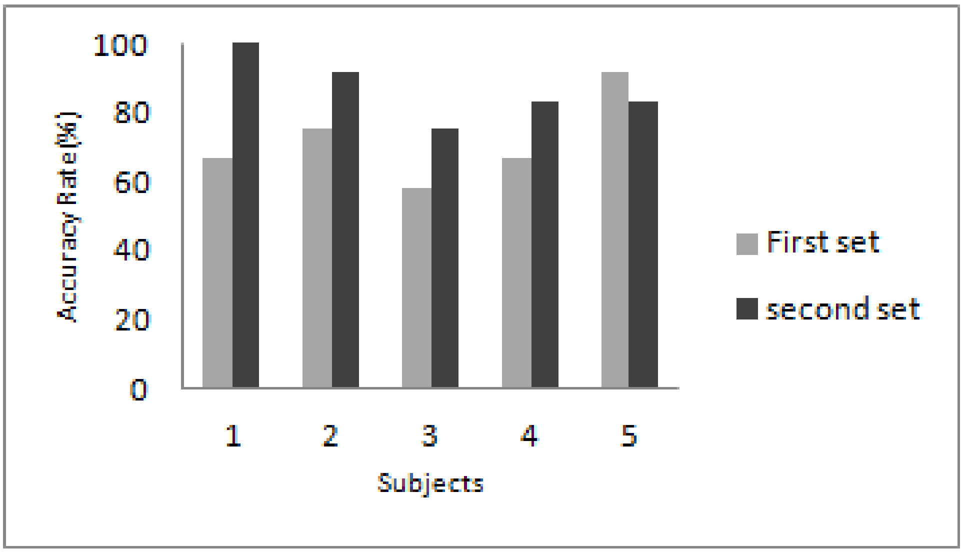

Figure 18, Percentage accuracy for all subjects

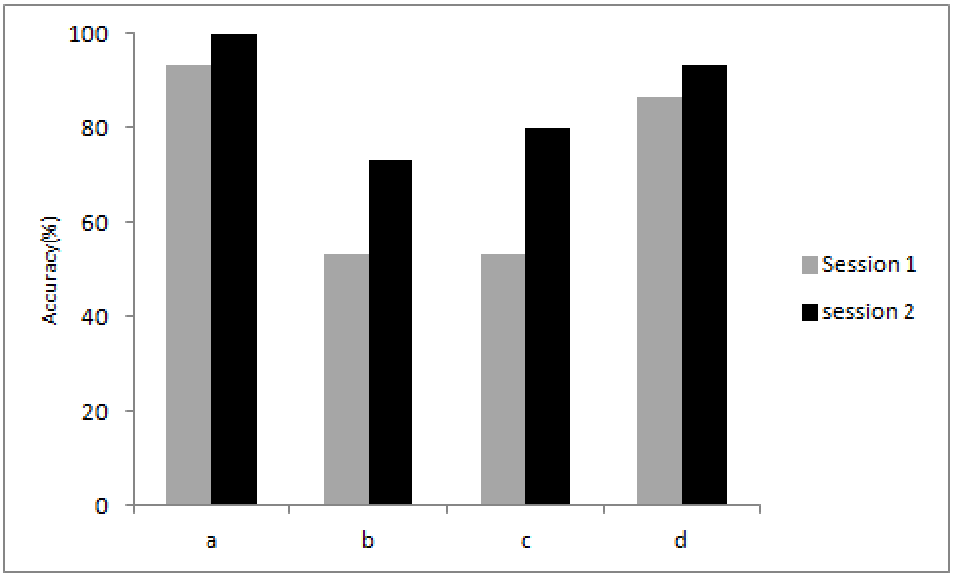

Figure 19, Mean accuracy by target state (a)-(d)

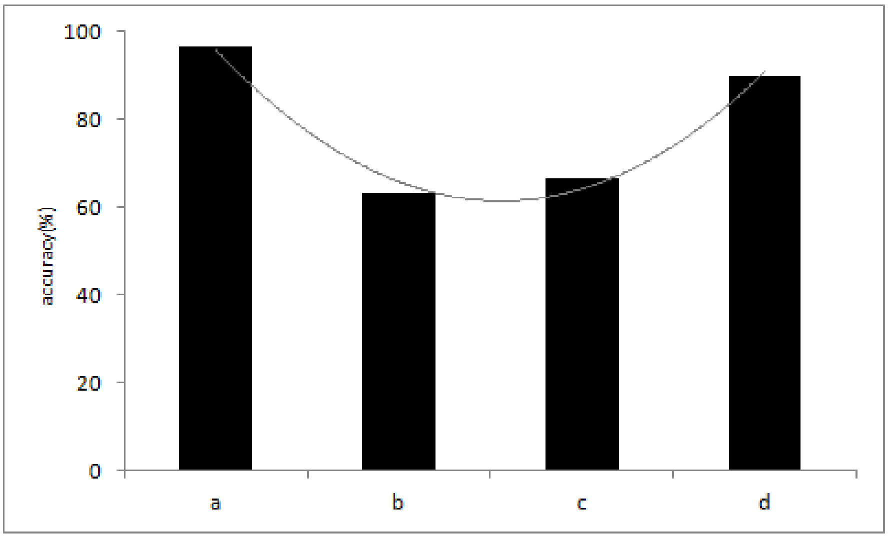

Figure 20, Mean overall percentage accuracy for each target state.

3.4 Discussion

Prior to the experimental trials, the level of difficulty that the given task would pose for the volunteer subjects, was not known. However, as the results clearly show, the subjects found the task to be manageable and made rapid strides in task competence over the two trial sessions. Subjects are able, by and large, to make use of haptic sensing and to coherently and successfully integrate verbal descriptions with haptic perceptions of different object weights as represented in the four target states. The proprioceptive information from the position of the fingers and wrist is used to hold the handle and the kinaesthetic information from the tension of the muscles helped them distinguish between weights. The results overall, then, appear to demonstrate clearly and unequivocally that haptic proficiency is sensitive to distinguish and develops very rapidly, even under very unfamiliar and difficult task condition and, consequently, that skills of haptic discrimination are easily trainable. In other words, the subjects were learning fast in a very unfamiliar environment and consequently show improvement. They are, as one would ordinarily say, 'familiarizing themselves' with the task and task environment.

In *integrationist* terms, familiarization of this kind is a communicational (or semiological) process since it has to do with the development of sign-making capacities in the human subject to familiarize yourself with an environment or set of circumstances means getting better at *'reading'* the environment for meaningful cues relevant to your *'current programme of action'*. It means being able to discard or ignore those environmental properties which are currently irrelevant or insignificant. The speed, confidence and accuracy of the verbal reports of the subjects have improved during second phase of the experiment. Therefore, we would argue, by an increasing capacity that they 'read' the environment for relevant cues in this way via the fixed rein. We are witnessing here a growing 'integrational proficiency': a capacity for creating contextually meaningful verbal signs through the simultaneous integration of haptic perception via fixed rein ('*environmental integration*') with verbal labels for weight discrimination ('*transmodal integration*'), all the while in a communicative relationship with the experimenters ('interpersonal integration').

But the process as described is just the process of development of 'transparent technology' in the sense of Clark (2003, 2008). Improved accuracy in discrimination of target weights, in the absence of any other factor being changed, can only mean that the properties of the mobile device itself are become invisible – literally *intangible* – against those of the target object. The fixed rein becomes haptic *background* as the object environment becomes haptic foreground. In other words, the results show the fixed rein being transformed by active subjects, over a few minutes, into 'transparent technology'.

But as they 'feel' the different target states, where, one may ask, do the subjects end and where does the mobile-device-on-a-stick begin? Since the subjects have no direct physical or perceptual contact with the target objects, then it is only the system human *agent* - *rein* - *mobile device* - *target object* which includes all the 'pathways' (Bateson 1972) necessary to the action of the system, i.e. feeling and discriminating accurately between object weights. In making themselves aware of their environment via the fixed rein, then, the 'partnership' of human subject and technology in this case is an emerging symbiotic system of acting, feeling, and thinking. Tool and tool user are becoming 'human-technology symbionts'. At the same time, the subjects are creating novel semantic values for the weight words via their integration in context with haptic feedback from the rein. The 'verbal technology', as much as the mechanical, must also, then, become 'transparent' to the task.

3.5 Conclusion

In this chapter, a small scale experimental study in haptic discrimination using a mobile wooden device fitted with a stick is reported. The aim was to account for if the haptic sense conditions our experience with the world, where our motor abilities are developed into motor skills with training and learning (Noland 2007). We have demonstrated the sensitivity and trainability of the haptic sense. We have also argued that the development of haptic proficiency involves a process of development of ‘transparent technology’, a process in which a human-technology symbiosis emerges. We have also argued that the development of transparent technology is understandable, in semiological terms, as a growth in integrational proficiency on the part of the human agent.

Chapter 4

A look at previous work on guide robots in zero visibility

In this chapter we review previous studies with the focus on guidance in zero visibility, outlining how my work fits within related research. The chapter highlights the previous work done on robot guides used in conditions of zero visibility and how people interact with them.

4.1 Introduction to guide robots

Literature on the subject of guide robots in low-visibility is rather sparse. However, there are several works on robotic assistance for the visual impaired people, because travelling independently is an important aspect of modern life. A part of blind and visually impaired community has been successful at independent travel, whereas majority seldom travel on their own. In fact, a robotic guide is considered as one of the potential travel aid solutions to investigate their mobility and travel experiences, the problems encountered and their spatial knowledge (Hersh 2016; Hersh & Johnson 2010). Work on guide robots started with MELDOG (Tachi et al. 1985), which is good example with full perception about environment, where they study the companionship in communicating between a robot and the handler in a known environment (Tachi et al. 1985). The robot was not connected to the handler using a rigid handle because of the inflexible nature of the machine. Instead they adopted a communication wire system with ultra-sonic sound (Tachi et al. 1981). Here, handler takes the initiative and controls the robot using switches connected through a wired line. The robot stops on each land mark and waits for next command of the handler. When there is an obstacle, the warning signal is transmitted back to the handler through electrocutaneous stimulation. In this study, the robot navigates a predefined path without real time probing of the environment. In an unknown environment, however companionship in communicating between a robot and a master is a continuous process. Moreover, Loomis et al. (2006) developed personal navigation system to guide the blind people in familiar and unfamiliar environment. However, in both the cases of MELDOG (Tachi et al. 1985) and Loomis et al (2006) navigator could follow only commands given by user to reach the destination.

Allan Melvin et al. (2009) developed a robot called Rovi to replace a guide dog; however the paper does not extensively report trials with users. Rovi had digital encoders based on retro-reflective type infra-red light that recoded errors with ambient light changes. Though Rovi could avoid obstacles and reach target, it did not have the capability to provide guidance in an unknown environment(Marston et al. 2007). The auditory navigation support system for the blind is discussed in (Loomis et al. 2006), where, visually impaired human participants (blind folded participants) were given verbal commands by a speech synthesizer. However, speech synthesis is not an option for search and rescue scenarios, as the environment has a lot of ambient noise.

Ulrich & Borenstein (2001) developed a guide cane (as shown in figure 21) without acoustic feedback running on unpowered wheels; it uses Ultra Sound to detect obstacles. The user has to push the guide Cane - it has no powered wheels- however it has a steering mechanism that can be operated by the user or operate autonomously. In autonomous mode, when detecting an obstacle, the wheels are steering away to avoid the obstacle. The guide cane has been tested with 10 subjects three of whom were blind and cane users, the other seven were sighted but blindfolded. Basic conclusion: walking with the guide cane was very intuitive and required little conscious effort, nothing more is reported on the subjects' experiences. The guide cane only uses obstacle avoidance. This work would have been more informative if the author had considered the orientation of the subjects to move forward.

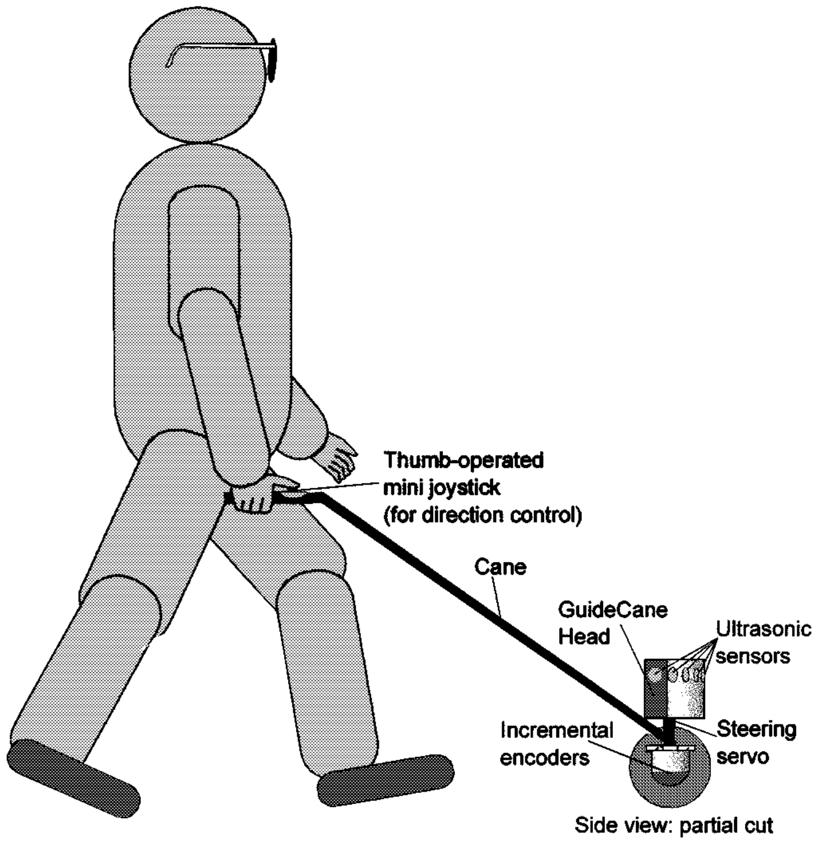

Figure 21, Guide cane developed by Ulrich and Borenstein (2001)

The robotic shopping trolley developed by Gharpure and Kulyukin (2008; 2010; 2006) is also aimed at the visual impaired. This trolley guides the (blind) shopper - who is holding the trolley handle - into the vicinity of the desired product and subsequently instructs the shopper on how to grab the product using voice instructions. The guidance is fully robot driven. Experiments with visually impaired subjects were performed in a supermarket. An interesting comment from the subjects was: '*Instead of just following the robot, doing nothing, I would like to know what products I am passing by*'.

Mori and Kotani (1998) developed a robotic travel aid for the visually impaired called '*Harunbo*', which had a motorised wheel chair base with a vision system to get information about navigation and orientation, a sonar range sensing system to get information about mobility and an optical obstacle sensory system for obstacle avoidance. The interface is a horizontal bar attached to the rear part and the handler was supposed to hold that while walking in order to maintain balance.

Most guide robots work on the principle that the robot changes direction when it detects an obstacle and communicates the change to the user haptically via a handle or audibly. Researchers have concentrated mostly on different methods for obtaining information about the environment and there has been less research effort on communicating this information to the handler. Thus communication and interaction with the robot guide remain the major issue. It can be viewed as a flexible, creative and dynamically adaptable process. It is also perceived that interaction with a guide robot is a communicational landscape emerging between the human being and the robot. In this view the interaction not necessarily requires a set of a-priory fixed (command) codes.

4.2 Interaction with guide robots

Goodrich (2007) defines Human Robot Interaction, as '*communication between robots'* and largely influenced by proxemics, the interaction is broadly classified into two categories:

• '*Remote interaction — the human and the robot are not co-located and are separated spatially or even temporally (for example, the Mars Rovers are separated from earth both in space and time).'*

• '*Proximate interaction — The humans and the robots are collocated (for example, service robots may be in the same room as humans Proximate interaction with mobile robots may take the form of a robot assistant, and proximate interaction may include a physical interaction.).* '

Interaction with a guide robot is an example of proximate interaction (homosperic - as mentioned in chapter 2) and in addition it is believed to be congruent and simultaneous. The biggest challenge in such an interaction is how communication takes place between the guide and the handler.

It is clear from the work done by researchers before (Gharpure & Kulyukin 2008; Kulyukin & Kutiyanawala 2010) that even during the interaction in less stressful settings, experienced by visually impaired people in supermarkets, there is reluctance to give up dominance and a desire to get to know more about the actual situation.

4.2.1 Mixed initiative approach

As mentioned in Chapter 2 (figure 12 in chapter 2 page 39), it is argued that full autonomy of the robot will not be appreciated by the handler; he/she by nature tries to read the situation (Harris 1996) and adapt the team's (robot and human) behaviour in accordance to that reading. Thus some sort of accountability is implicitly required from the robot and we have to opt for a '*mixed initiative*' or '*shared control'* approach in which the handler is able to direct the robot and make decisions. Reduced autonomy for the robot also seems to imply limited responsibilities for the robot. In mixed initiative approach, trust the handler has on the robot, relies on the messages received from the robot.

An example of the *mixed initiative approach* is reflected in the work of Shim et al (2004). A robotic cane 'RoJi', consisting of a long handle, two steerable wheels, a sensor unit and a user interface panel, was developed with two operational modes; the robot control mode (RCM) and the user control mode (UCM). The obstacle information is transferred to the handler in the form of audio signals. The handler is the dominant partner and can initiate either RCM or UCM. The cane's RCM is an autonomous navigational mode whereas the UCM allows the handler operate the robot, based on auditory information provided, using the buttons on the interface panel. The work of Aigner and McCarragher (1999) also reflects the idea of *mixed initiative*. They have developed a robotic cane with a shared control framework meaning the framework combined an autonomous mode (Aigner & McCarragher 2000) with a human interaction mode. It has the ability to steer around obstacles in autonomous control mode using ultrasonic sensors. The handler can interact with the cane using a joystick mounted on the handle. The handler is given the ultimate control and can override the sensor data, in case there is a conflict. However, these papers do not report much on handle design, interface panel and trials with the handler.

4.3 Modelling guide robot systems

In the past, researchers have mainly focused on the technical aspects of guide robot systems for travel by blind and visually impaired people and the human dimension lacked desired attention. This led to the use of advanced technologies without consideration of the wider context of the involvement of end-users in all stages of the design process and never gained popularity within the visually impaired community. Therefore it is important to adopt human-centred, user-centred and participative design approach (Kontogiannis & Embrey 1997), with careful consideration of the human as well as the technology system and the context in which the system would actually be used.

Guide-robot systems fall under the category of assistive technology for visually impaired people. Assistive technologies, in general, have a diverse range of users and potential users and also are required in various applications. Hence, there is a strong need for a simple modelling framework to reveal the generic structure of assistive technology systems and analyse the complexity (Marion & Michael 2008). It should give an understanding of the functioning of assistive technology systems in the social context. According to Marion & Michael (2008) *'A thorough review of the literature'* reveals *'that the development of assistive technology has only been studied by a limited number of researchers'* and there are only a few modelling approaches for assistive technology.

The USERfit model developed by Poulson and Richardson provides a user-centered approach for designing assistive technology (Poulson & Richardson 1998). As shown in Figure 22 below, the model consists of four basic stages, namely, *problem definition*, *functional specification*, *build* and *test*. The fundamental feature of this model is that it stresses user participation. However, Wu et al. (2008) consider that USERfit is only fit for '*pure customisation'* (Lampel & Mintzberg 1996) of assistive technology design and hence, the model is less cost effective.

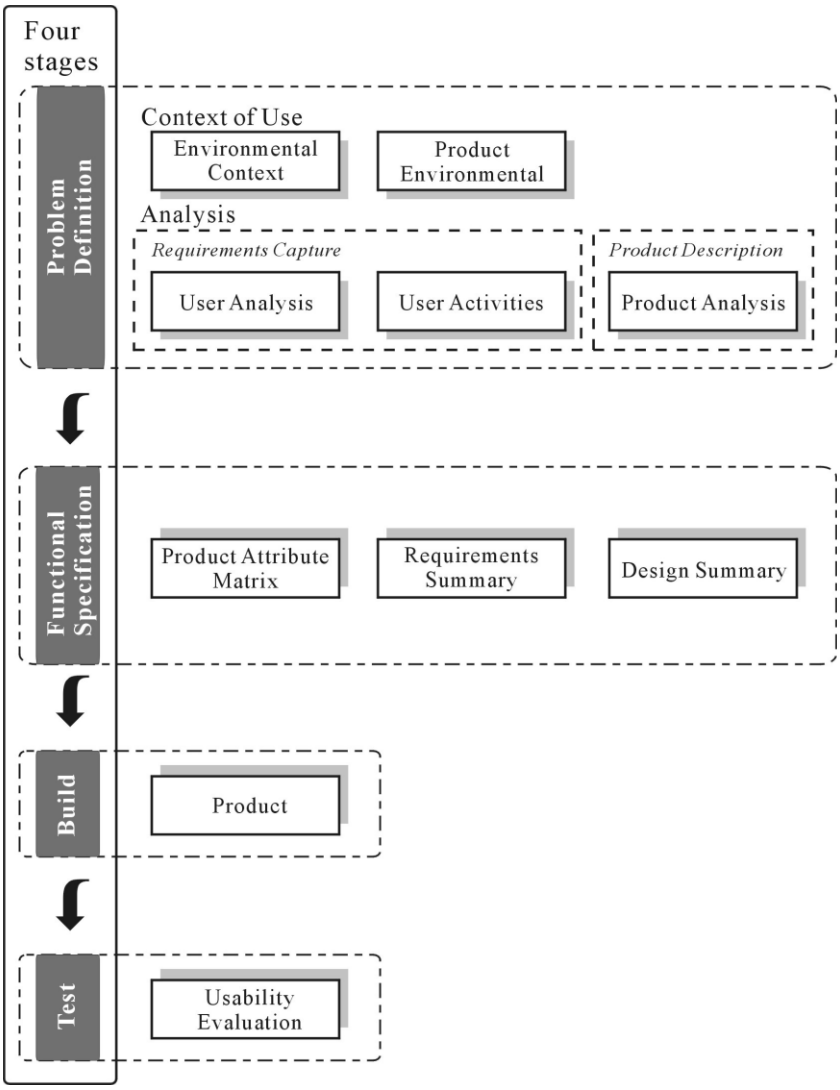

Figure 22, Design process of USERfit model (Poulson & Richardson 1998)

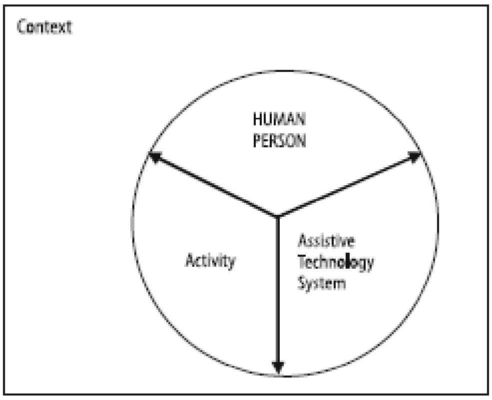

Figure 23, the human activities assistive technology (HAAT) model (Hussey & Cook 2002)

The human activities assistive technology (*HAAT*) model, described by Cook and Hussey, in their book *Assistive Technologies: Principles and Practice* (Hussey & Cook 2002), can be used for designing and developing assistive technology devices. Hersh & Johnson (2008) refers that it is one of the better known frameworks for assistive technology. The pictorial representation of the model is shown in Figure 23. The *HAAT* model defines assistive technology through four components. The first component is the *context* which represents the physical and social attributes of the environment. The second component is the *human person* (or handler, as termed in this thesis) involved. It includes the physical, cognitive or affective properties of the handler along with his/her skills and abilities. The third component is the *activity* representing the task that needs to be completed. The final component is the *assistive technology*, which is an external aid to provide basis to improve handler's performance in the presence of a disability. *HAAT* model is an extension of the original human performance model comprised the three components of “human, activity, and context” (Bailey 1989).

Hersh & Johnson (2008) extended the basic structure of *HAAT* model encompassing a much wider range of attributes components. They have termed this extended model as *the comprehensive assistive technology* (CAT) model. It is applicable to any assistive technology system as it can be given a tree-like structure (as shown in figure 24) that does not use an excessive number of branches at any level. The tree-structure approach is very flexible, easy to modify, can be simplified by omitting variables that are not important in the particular context and helps fine-grained analysis of each component.

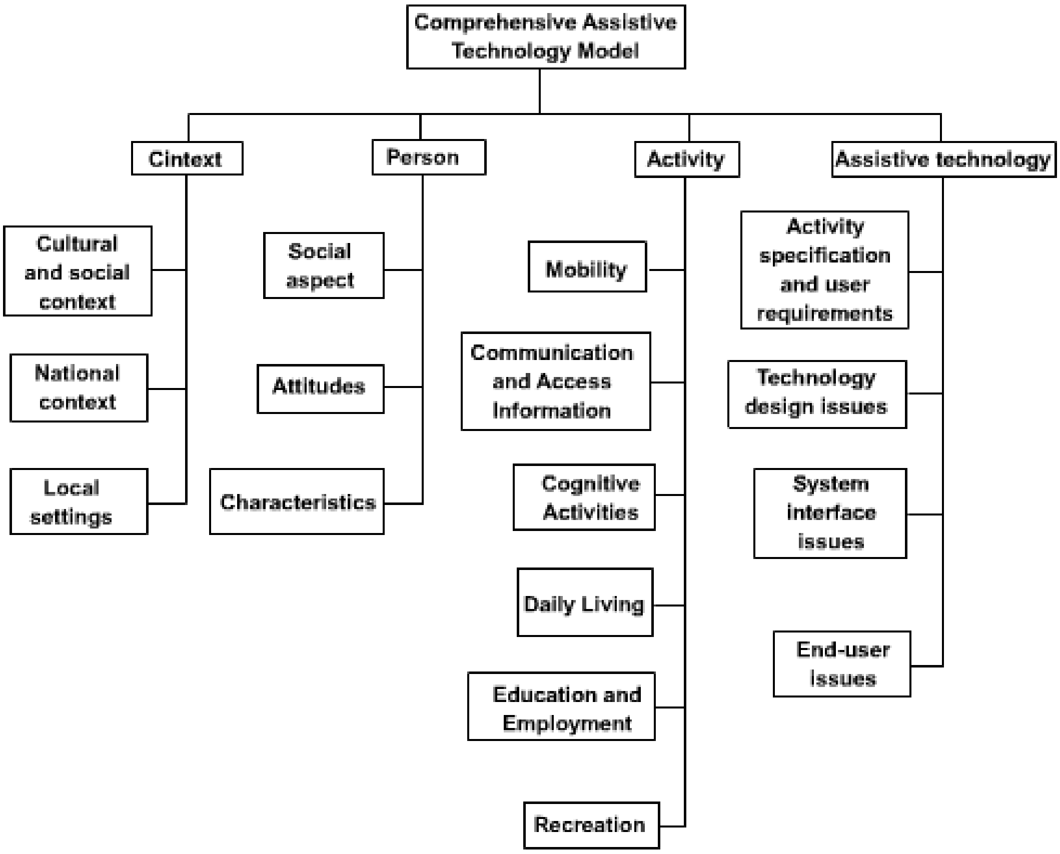

Figure 24, three-level Assistive technology investigative framework using CAT model (Hersh & Johnson 2008)

The top level has four branches as in HAAT model (Hersh & Johnson 2008). According to Marion & Michael (2008), these components share interfaces with each other and hence, the assistive technology has interfaces with the context, person and activity components. Focusing on the assistive technology component, it is further subdivided into four components: human-technology interface (catering for two way interaction between handler and assistive technology), activity output (contributing to the functional performance of the technology), environmental interface (helps detecting environmental data and links it to the processor) and processor (translates information among other three components and controls the activity output). A more formal representation of assistive technology system component is shown in Figure 25, in the form a block diagram and can be applied to the analysis and synthesis of assistive technology.

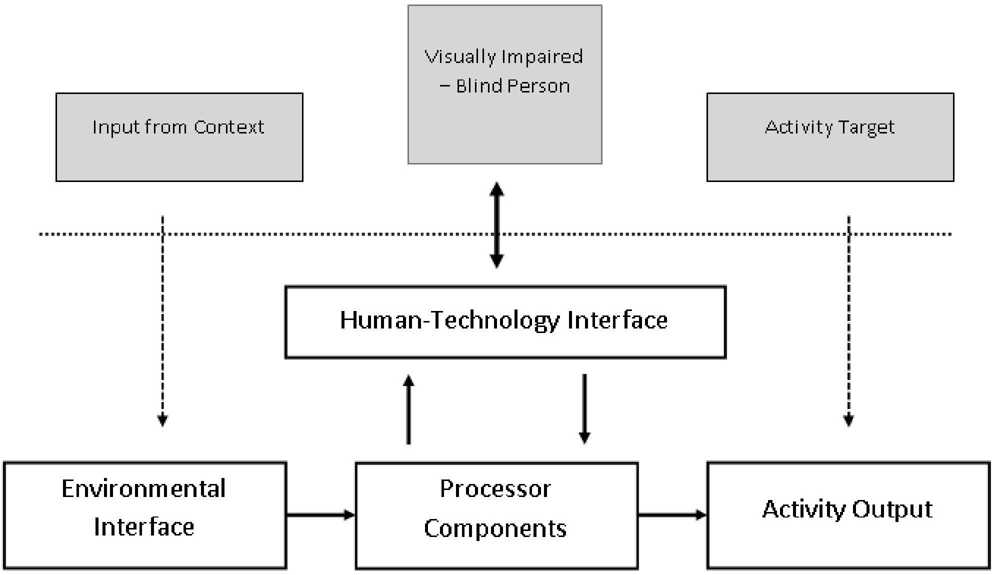

Figure 25, Block diagram of Comprehensive Assistive Technology Model (Marion & Michael 2008)

In chapter 2, we have looked into the interaction between a visually impaired person and a guide dog in detail. Guide dogs provide support for safe and independent travel for visually impaired people and give them confidence. The CAT model assistive technology block diagram can be used to analyse the effectivity of guide dogs (as shown in Figure 26) and get an insight about features required in a guide for zero visibility condition. In addition, Figure 27 shows the Guidecane system (Ulrich & Borenstein 2001) developed by Ulrich and Borenstein including the interface and processor component used for obstacle detection and route planning.

It is observed that both cases are examples of '*shared control*' or '*mixed initiative*' system. It is important that the handler has the ability to be the dominant partner and override the guide, when he or she feels that it is necessary. The handler has the power to be in control of the global navigation whereas the main task of the guide is to steer around obstacles and proceed in the desired direction.

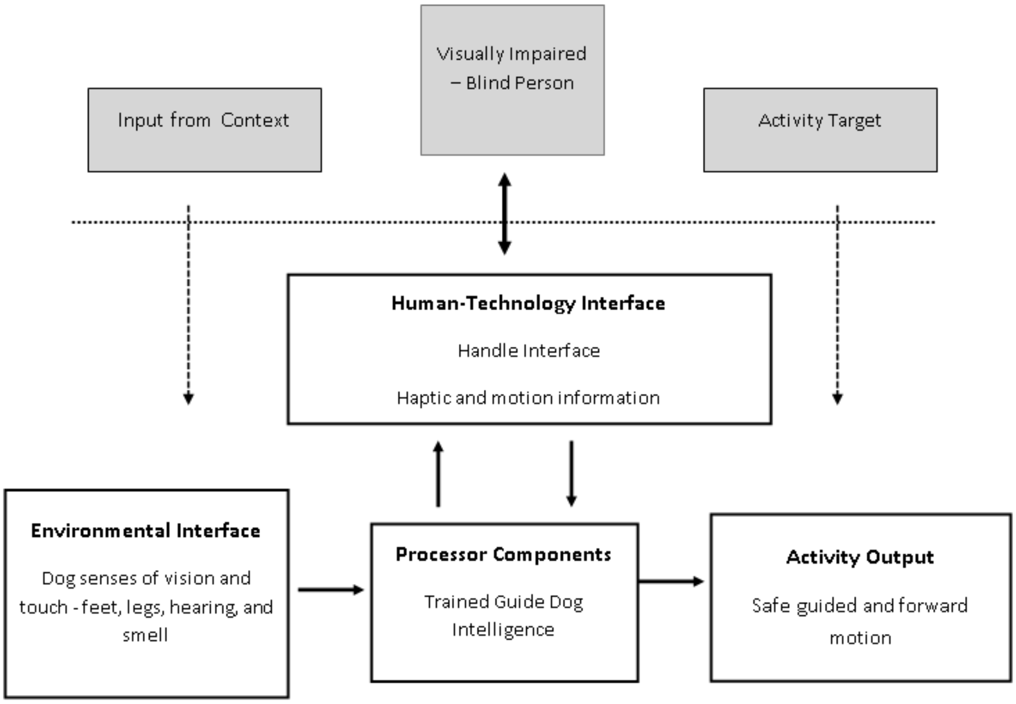

Figure 26, Assistive Technology System Block diagram - Guide Dogs (Marion & Michael 2008)

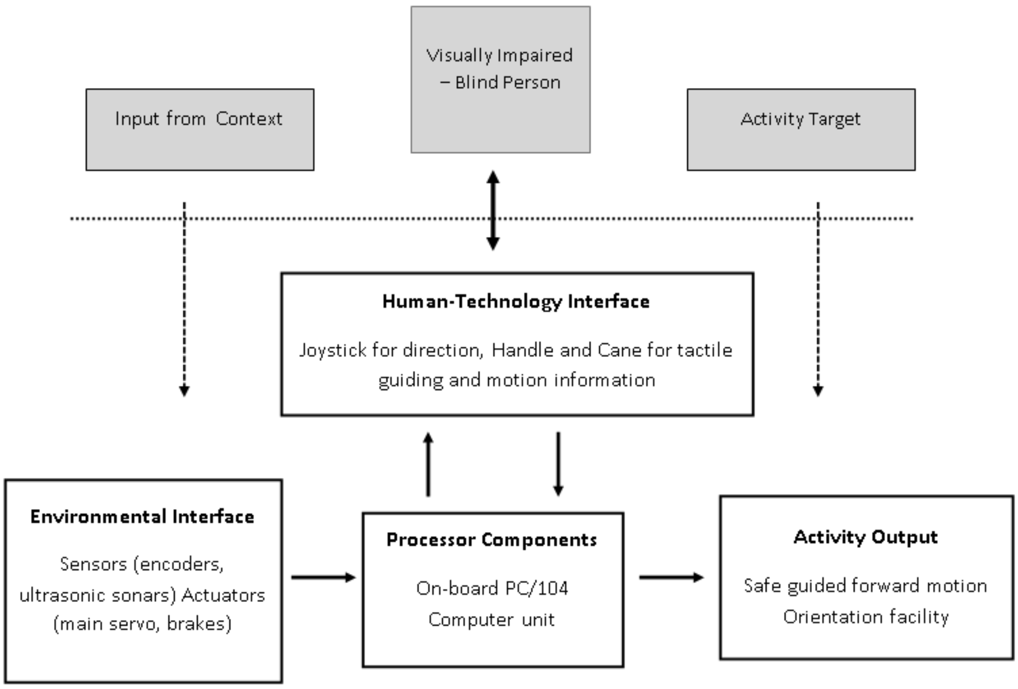

Figure 27, Assistive Technology System Block diagram - GuideCane (Marion & Michael 2008)

4.4 Using CAT assistive technology block diagram to analyse the use of a guide robot in zero visibility

As we have seen in Chapter 2, the task in-hand can be simply classified into two logically separable subtasks - locomotion guidance and environmental exploration. A consequence of this type of simple decomposition of the task is that we find solutions to these problems separately. And then a conceptual integration of the solutions can give an insight into solving the basic research question of this thesis.

According to Ungar (2000), mobility for visually impaired people can be categorised into locomotor space (also called '*far space*') and haptic space (also called near space). '*Locomotor space'* is the space handler is required to travel whereas haptic space is the space immediately around the handler's body (plus a short-range assistive device such as a long cane). Thus we can summarise that locomotion guidance is an activity which is to be carried out in locomotor space and environmental exploration is to be realised in haptic space.

As we have mentioned in chapter 1, this work is a part of a project, which aims at designing a robot guide, it is required to have the capability to act as an aid for the user to explore and move through an unpredictable space without feedback via sight or hearing. It is intended that the robot guide in this project, when given autonomy for safe locomotion guidance, has a wall-following algorithm to follow the contour of the wall, using an array of ultrasonic sensors, there-by partially copying the wall-following behaviour of firefighters (as shown in figure 28). Safety is one of the fundamental requirements to judge whether a guide robot is practical or not (Song & Huang 2001). A guide robot not only needs to avoid unexpected obstacles during locomotion, but is also required to ensure that the handler, who is being guided, follows a safe path.

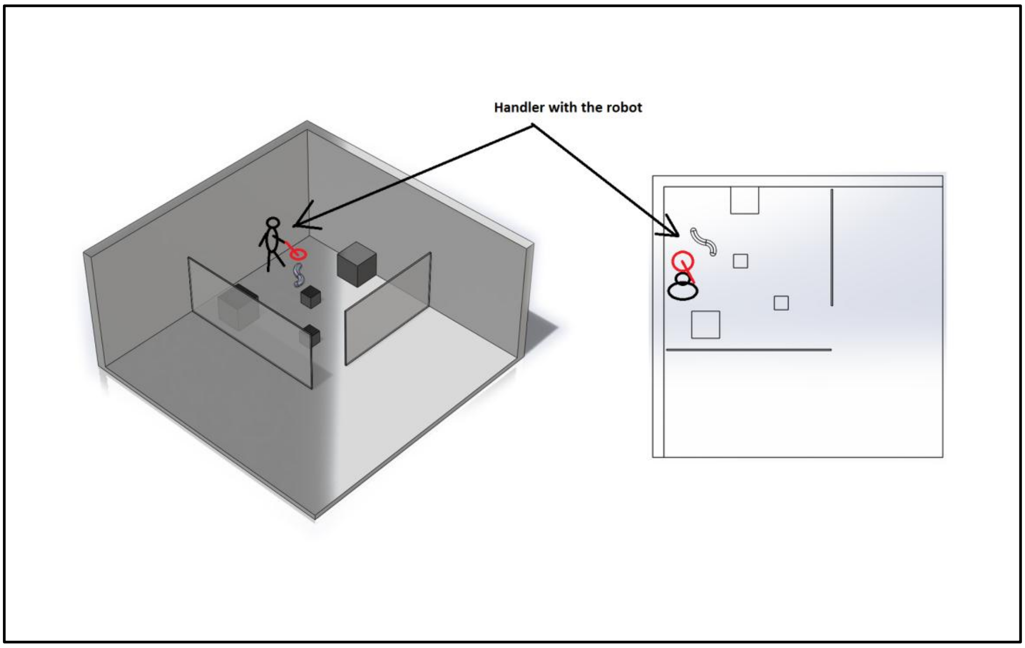

Figure 28, Locomotion guidance using robot guide

Another important aspect of interacting with the guide robot is that the handler should be able to construct a cognitive map (Kuipers 1983b) of the space in which he or she is situated, and the locations of the objects perceived. By the term cognitive map, it is meant that the knowledge of an environment, which is acquired by integrating observations, gathered over time and can be used to find routes and determine the relative positions of space. Kuipers (1983a) notes '*the most fundamental processing problem solved by a cognitive map is to store the description of the route traveled in the environment so that it can be reconstructed later*' and he describes cognitive map as '*"Map in the Head," inspected by the "mind's eye"*'. Ungar (2000) notes that a person with vision has at least three advantages: the coincidence of body-centred and external reference frameworks during locomotion; the ability to look forwards and backwards along a route and thus integrate the locations of spatially separated landmarks. Thus, to learn a map, the handler must travel through the space, gathering local observations. However, the absence of vision hinders cognitive map acquisition (Passini & Proulx 1988) and its construction heavily relies on the body as a frame of reference (Corazzini et al., 2010), also termed as egocentric (Ungar, 2000). Moving through space, the egocentric frame of reference gets updated sequentially. Therefore, the guide robot needs to communicate the most appropriate information about the immediately surrounding environment to the handler through the interface, which would contribute to his acquisition of the '*mental map*' of the space traversed.

For the purpose of using the robot as a tool for environmental exploration, a bumper is mounted on the robot with displacement sensors to give the handler a sense of the object the robot has bumped onto (as shown in figure 29). The locations of the objects in the exploratory space must be maintained in the handler's memory. It is important to identify the relevant information (concerning the displacement of the bumper), the handler would need and the challenge is to map those information channels onto the user-interface. The main objective is to deliver relevant information while not overloading the handler, through a haptic experience.

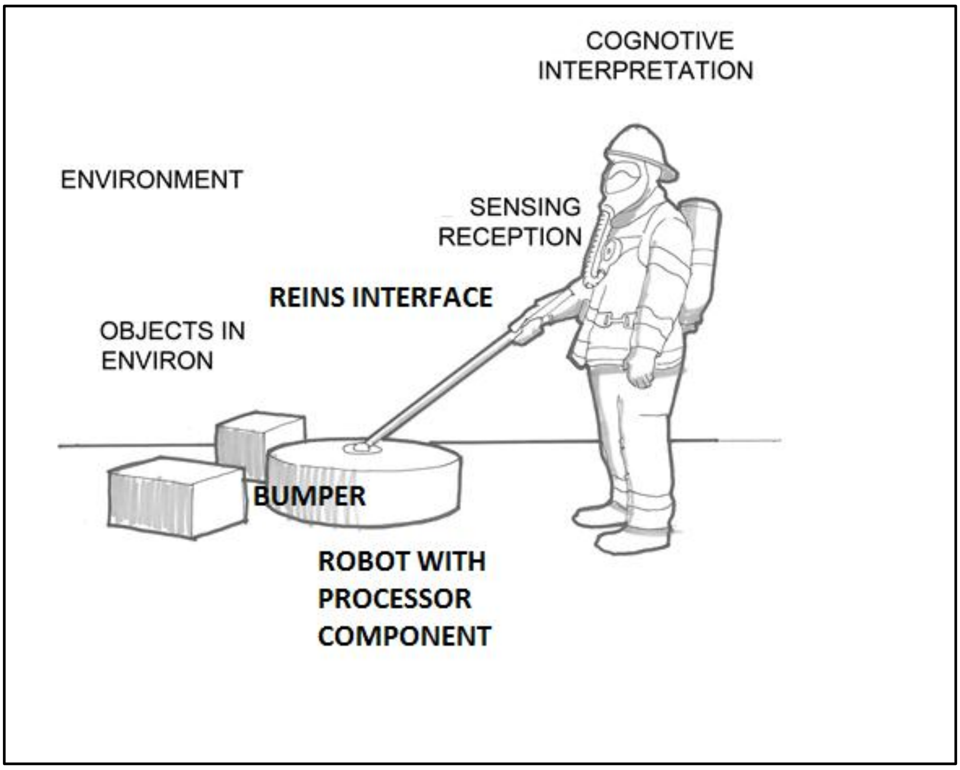

Figure 29, Environmental exploration using robot

As shown in figure 30, the CAT model assistive technology block diagram is used to understand the guide robot system. As it is clear that the interface connects all the components of the model, it is important to study the designed haptic interface through which the user interacts with the robotic guide. Designing a system requires careful research and planning for the user interface. In the following chapters of the dissertation, the haptic interface is studied and analysed to see how it can contribute to the interaction. The interface in principle has to have two important features, the information to be communicated to the handler, and the means of communicating this information and should not be complicated.

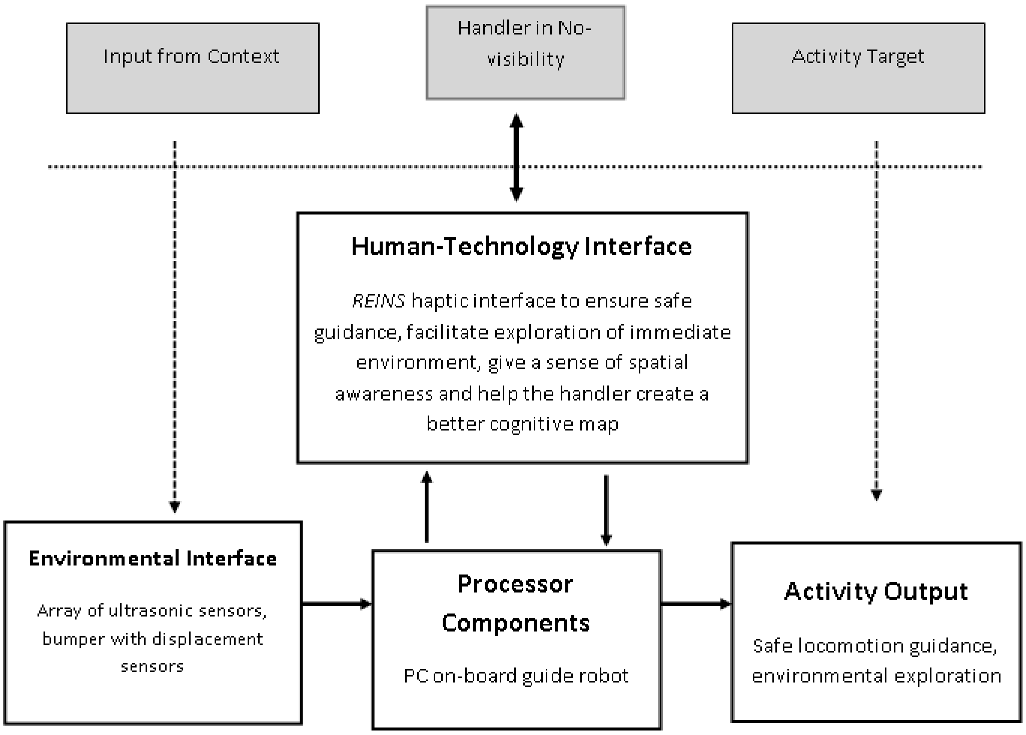

Figure 30, Block diagram of REINS guide robot using CAT model

4.5 Conclusion

It is proven that simple aids, such as the long cane and Braille script, can be efficient and have gained popularity, as they communicate the right information and utilize the natural capacities of the human senses (Marion & Michael 2008). This means that the focus should be on creating a haptic experience through a simple interface relevant to the research question mentioned in Chapter 1. Chapter 5 presents a critical evaluation of the design of the haptic interface and explains how it can aid locomotion guidance for the handler. Chapter 6 presents a study of the feedback system of the interface, when the robot is used as an exploratory tool for environmental exploration.

These chapters can provide a base for building a bridge of empathy (Fulton Suri 2003) between the designers of the guide robot system in zero visibility and the handlers of the system.

Chapter 5

Evaluating the haptic interface for locomotion guidance

This chapter is dedicated to the research question: ***how does the design of the haptic interface aid locomotion guidance for the handler?*** *A discussion on evaluation of the design and considerations that led to the design is presented. We look through the experimental study to demonstrate how the interface can be of assistance in locomotion guidance by the robotic guide. Parts of this chapter have been published as:*

Ghosh, A.; Penders, J.; Jones, P.E.; Reed, H., "Experience of using a haptic interface to follow a robot without visual feedback," in Robot and Human Interactive Communication, 2014 RO-MAN: The 23rd IEEE International Symposium on, vol., no., pp.329-334, 25-29 Aug. 2014

Ghosh, A., Alboul, L., Penders, J., Jones, P. and Reed, H., 2014. Following a robot using a haptic interface without visual feedback. In: ACHI, Barcelona, Spain 23-27 March 2014, pp. 147-153.

5.1 Introduction

Direct physical contact is often used to guide a person to the desired location (e.g., leading a person by the hand) or to adjust a person’s posture required for a task (e.g., a dance instructor working with a dancer) (Chen & Kemp 2010). As mentioned in the previous chapter, interaction with a guide robot is an example of proximate (Goodrich & Schultz 2007) interaction and when the handler is in close proximity to a robot, physical contact becomes a potentially valuable channel for communication. Examples of other proximate interaction with robots are cobots guiding human movement (Gillespie et al. 2001), and dancing robots that respond to physical interaction with a human dance partner (Takeda et al. 2005).

In this chapter, we discuss evaluating the design of an interface, connecting the handler with the robot, to enable a human being to follow a robot in an environment with zero visibility. Being guided along an unknown path without visual feedback poses several challenges to a human being, in particular if the guide is a robot.

Chapter 3 has also highlighted the extraordinary speed and sensitivity of the haptic sense. This provides enough ground to explore how to make better use of the haptic sense. Eventually, a well-designed haptic interface suitable for guidance in zero visibility conditions might also be useful in everyday conditions and may free the reliance on a visual sense and related mental resources so that they can be used for other tasks. The research therefore, have a bias towards an interface solution that utilises the haptic sense 'implicitly' and presents information in a non-symbolic or non-performative form; the paradigm is the handle of a guide dog discussed in Chapter 2. Explicit or symbolic signals like, one tug on the interface means right, while two tugs mean left, are not preferable. We believe that implicit feedback induces a lower cognitive load for the handler and can certainly aid the aim of developing a transparent tool (Clark 2008).

Leading a robot is far from a simple physical locomotion problem (Young et al. 2011; Gockley et al. 2007). However, having a robot lead a person raises considerable additional issues, concerning the degree of autonomy granted to the robot. Based on the analysis of the interaction between a visually impaired person and a guide dog we distinguish between locomotion guidance and navigation. While the visually impaired human handler determines global navigation (i.e., final destination and en-route decision points) the guide dog provides locomotion guidance between these decision points (as mentioned in Chapter 2). Locomotion guidance is affected through a simple haptic interface between dog and handler - that is a rigid handle held by the handler and attached to the dog's harness. The handler and the guide dog interact with each other to achieve the activity of guided and safe mobility.

Young et al. (2011) describe walking a robot using a dog-leash. They note that leading a robot consists of a delicate interplay between the human leader and the robot, requiring ongoing communication and interaction. This includes (for both the robot and the handler) monitoring the other’s movement direction and speed (Young et al. 2011). The dog-leash is used in conditions of good visibility and a relatively low level of environmental noise.

5.2 The haptic interface: design and history

As it was discussed in chapter 4, the first step towards this aim is to build an interface that will lead the handler along a safe path. Kim et al. (2010) cites Armstrong's work (Armstrong 1975), which developed a framework for measuring mobility performance. One of the two main components to measure performance was the ability to move from one place to another safely. Looking at visually impaired people, one of the most greatly used mobility aids is the long cane, despite modern devices (Clark-Carter et al. 1986; Burton & McGowan 1997), because it extends the sensing range of the handler, facilitating safe navigation and exploration of the immediate environment (Gallo et al. 2010). While walking forward with the long cane, the handler sweeps it from side to side to create a '*3D spatial window'* (LaGrow et al. 1997; Blasch & l'Aune 1992; Blasch et al. 1996) and through this window the environment is '*previewed'* to ensure safe locomotion. Blasch et al. (1996) distinguished this '*preview'* into three types, of which, the one of interest is '*foot placement preview'* meaning that the surface on which the foot is placed, is safe.

Looking at this, it is believed that when a guide robot is used, it also creates a spatial corridor avoiding obstacles and the safest path for the handler would be the path that the robot already has traversed; thus the working definition of safety for this dissertation is '*handler should follow the trail of the robot as close as possible and his feet are placed as close to the spatial corridor created by the robot, as possible'*. Hence the experiments, reported below, look at the following behaviour of the handler in terms of the ability to closely match the live path of the robot.

Obviously, in order to be able to follow the robot, the handler needs to know where the robot is relative to current position and orientation of the self. Initially the project looked at three distinct interfaces: a wirelessly connecting device, for instance: a Nintendo Wii, a short rope/rein or leash, and a stiff handle. A major problem for any wireless device lies in how to indicate the position of the robot with respect to the follower. A rope does indicate the direction of the robot but only when there is no slack. the final choice has been for a stiff handle via which the position (direction and distance) of the robot is immediately clear to the follower.

In Chapter 2, the thesis presumes that the human being wants to remain the dominant and initiating partner, at least from the perspective of the handler. However, the interaction model from our perspective is such that the robot has the autonomy during locomotion guidance whereas the handler has the autonomy during environmental exploration. This seems a natural basis for a mixed initiative mode of operation. This is implemented to the experiments in the human-robot scenario and the task of the robot is restricted to locomotion guidance. This leaves quite some space for the human to exert initiative and overall dominance.

5.3 Grip specifications for the interface

The first requirement is that the robot needs to act as an aid to provide locomotion guidance from one point to the other. The second requirement is using the robot as a tool for exploring the environment and the obstacles. Therefore the robot and the interface must have the potential to provide rich feedback, so that the handler intuitively reacts to changes in the direction caused by the movement of the robot wheelbase. Looking at both the aspects and the broomstick interface designed by Young et al., (2010), a *robot-on-a-stick* seems to a very natural solution. But this leads to a further question about what would be the appropriate way for the handler to hold the stick. Visually impaired people, while using a long white cane, do hold the cane in one hand. However, they also apply a special grip with the dominant hand (for instance stretched the index finger) and/or keep the elbow touching the body (Bongers et al. 2002). Traditional orthopaedic canes are suitable for pistol grip (Murphy 1965).

Inspired by the work of Young et al., (2010), a prototype similar to the *robot-on-a-stick* was designed (as shown in Figure 31), keeping in mind that it would also serve a tool for environmental exploration and sweeping the area of interest. The prototype is an extended cane, comprising of a round plate on four non-motioned passive omni-directional wheels and a broom-stick as the handle. The omni-directional wheels made the disc easily manoeuvrable in any direction (on the floor).

The research carried out '*in the wild*' first phase pilot trials asking people to hold it with their dominant hand and move the device in a sweeping pattern (as shown in figure 32).

Figure 31, Robot-on-a -stick prototype wit omni-directional wheels

It is observed that manipulating the disc with the dominant hand is not as easy as handling a white cane. Holding the stick blind folded, a lack of accuracy in sensing the direction has been noticed; several subjects immediately put their second hand on the stick to compensate (as shown in Figure 34). The broomstick interface developed by Young et al., (2010) is even held using two hands (as shown in figure 33). This could be well explained by Guiard's kinematic chain (KC) model (Guiard & Ferrand 1996; Guiard 1987). Leganchuk et al. (1998) cites that according to this model, the two hands function as serially assembled links, with the non-dominant hand as the base link and the dominant hand as the terminal link. Fundamental to this theory is the fact that both hands are cooperative in nature. The non-dominant hand acts as the frame of reference for the action of the dominant hand (Guiard & Ferrand 1996).

Figure 32, in the wild trials with the first prototype

Figure 33, Broom stick interface (Young et al. 2010)*, an inspiration for the design of interface shown Figure 34*

Figure 34, Subjects tend to hold the prototype with two hands

However, feedback from the subjects, during pilot trials, revealed that using two hands can bring discomfort when being guided by a robot in an unknown environment without visual feedback and they would not like to engage the second hand. Secondly subjective feedback from fire-fighters revealed that they would not want to keep both of their hands engaged. Instead they would want to make use of one hand to its full potential, so the other hand is free. Therefore, the intention is to have the interaction to be unimanual in a way that the dominant hand is optimally used while the non-dominant hand is left free.

And in case of unimanual interaction, anecdotal feedback from subjects reveal, holding the handle, as shown in Figure 34, is not a favourable solution, because the wrist joint is a complex system interposed between the forearm and the hand (De Lange et al. 1985), offering the hand a unique combination of movements, like *dorsopalmer flexion*, *radioulnar deviation* and combination of these two, *circumduction*. Hagert (2010) gives an account for proprioception of the wrist joint in his work. The arrangement of small bones and ligaments gives too much flexibility to the wrist for a stable proprioceptive feedback. However, the lower arm is remarkably stable in terms of proprioceptive feedback and hence, lower arm is the appropriate part of the body for the interface to be attached. Murphy (1965) notes that the crutches offer more support and stability. From this we concluded that a crutch like design of the handle, in which the stick is fixed to the lower arm, is preferred (as shown in figure 35).

Figure 35, Crutch-Like design of the handle

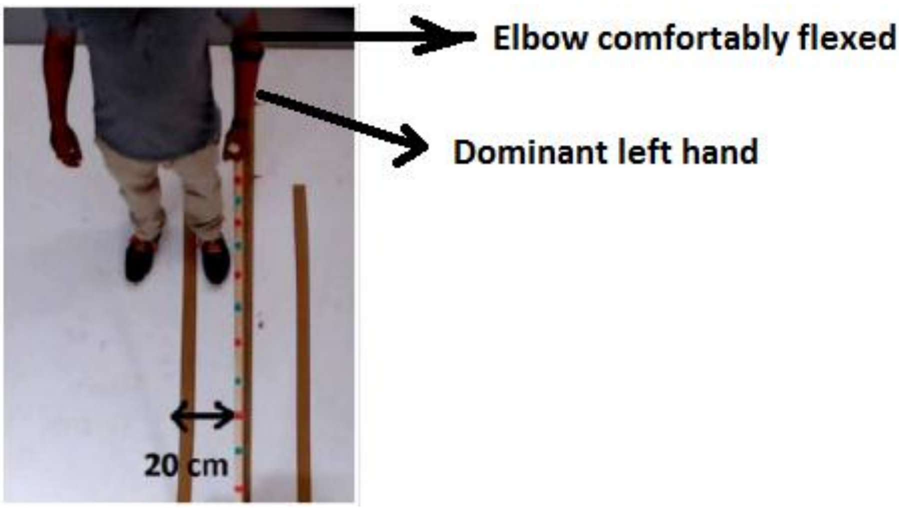

Figure 36, Left-handed person holding wooden prototype with comfortably flexed elbow

Thus a second crutch-like prototype is designed, which can be strapped on the lower arm. Strapping it to the lower arm helps transmission of stable proprioceptive forces while the hand is used to grip the small stick on the handle. The handle is about 1.3 meters long (about 55 inches), which is the approximate size of a long cane (Rodgers & Emerson 2005). We have observed that when the handle is held straight with the dominant hand with elbow slightly flexed, the distance between the handle and the center line of the handler's body is roughly 20 centimeters (as shown in Figure 36).

As our working definition of ensuring a safe path says the path followed by the handler should closely match with the trail of the robot, we need to carefully envisage implementation of the interface on the robot in such a way that it ensures as much path matching as possible.

5.4 Implementing the interface on the robot

It is well-known that if one end of the handle is fixed to the base of the robot with no degrees of freedom and other end attached to the handler, the rotational motion of the robot at the point of the turns will create a torque, abruptly pushing handler and therefore creating large deviations from the path of the robot. To minimise that effect, a simple crutch-like prototype with a ball-in-a-cup mechanism at the base (as presented in Figure 37) was developed to enable some second phase of preliminary experimentation in the wild. There is a provision for a detachable pin ball to restrict the movement of the ball in the cup (as shown in Figure 37). This would help us to carry out comparative analysis of the ball-in-a-cup joint with a fixed joint.

For the purpose of experimentation, the ball-in-a-cup joint is attached to a pioneer 3AT robot. This mechanism allows full freedom in the horizontal plane as well as some limited freedom in the vertical direction. The pilot studies have revealed that there have been instances where the handler did not feel safe following the robot. The handler lost track of the relative position of the robot with respect to his own position, although he was attached to the robot. As a consequence, the handler did not feel comfortable following the robot when it was trying to avoid any obstacle on its way (as presented in Figure 38).

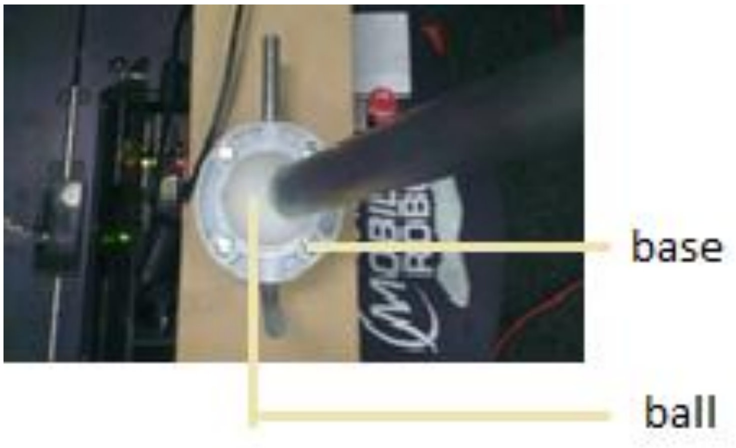

Figure 37, Ball -in - a - cup joint with detachable pin

Figure 38, Handler losing track of the position of the robot with ball in a cup joint attached on a Pioneer 3AT robot

To overcome this problem, a third prototype was designed for third phase testing, fixing the base and introducing a spring in the middle of the handle to allow smoother following at the turns (as presented in Figure 39 (right)). The effect of the spring system could be neutralised by a metal tube which could slide and sit over the spring (as presented in Figure 39 (left)).

Figure 39, spring system in the handle

But pilot studies have revealed that the spring can cause a slack, which can also be problematic and unsafe. The handler can lose track of position as well as the orientation of the robot. There have been instances when the handler bumped into the robot itself because the handler could not get a real feel of how fast the robot was moving. Figure 40 (left) shows an example where the handler starts following the robot, a slack being caused in the spring (Figure 40 (middle)) and the handler bumps into the robot (Figure 40 (right)).

Figure 40, subjects following the robot with spring system in the handle fitted on a pioneer 3AT robot

These findings led to the design of a fourth prototype (Figure 42) to ensure safety, comfort and rigidity. The prototype consists of a mechanical feedback spring system at the base, as presented in Figure 41. The spring system allows rotation of the handle on the horizontal plane.

When the spring system has zero tension, the handle is aligned with the center line of the robot. When the handle is being rotated, the spring system induces tension on the handle, which increases with the rotation angle. The system also comes with a pin enabling someone to lock and nullify the action of the springs, giving us the option to carry out a comparative study between a flexible joint and a fixed joint. Thus, this handle provides two testing options:

- *The handle is attached to a fixed joint (rigid)*: meaning the handle is fixed at base using the pin.
- *The handle is attached to a flexible joint (spring)*: meaning the handle can rotate in the horizontal plane, and rotation induces tension on the handle.

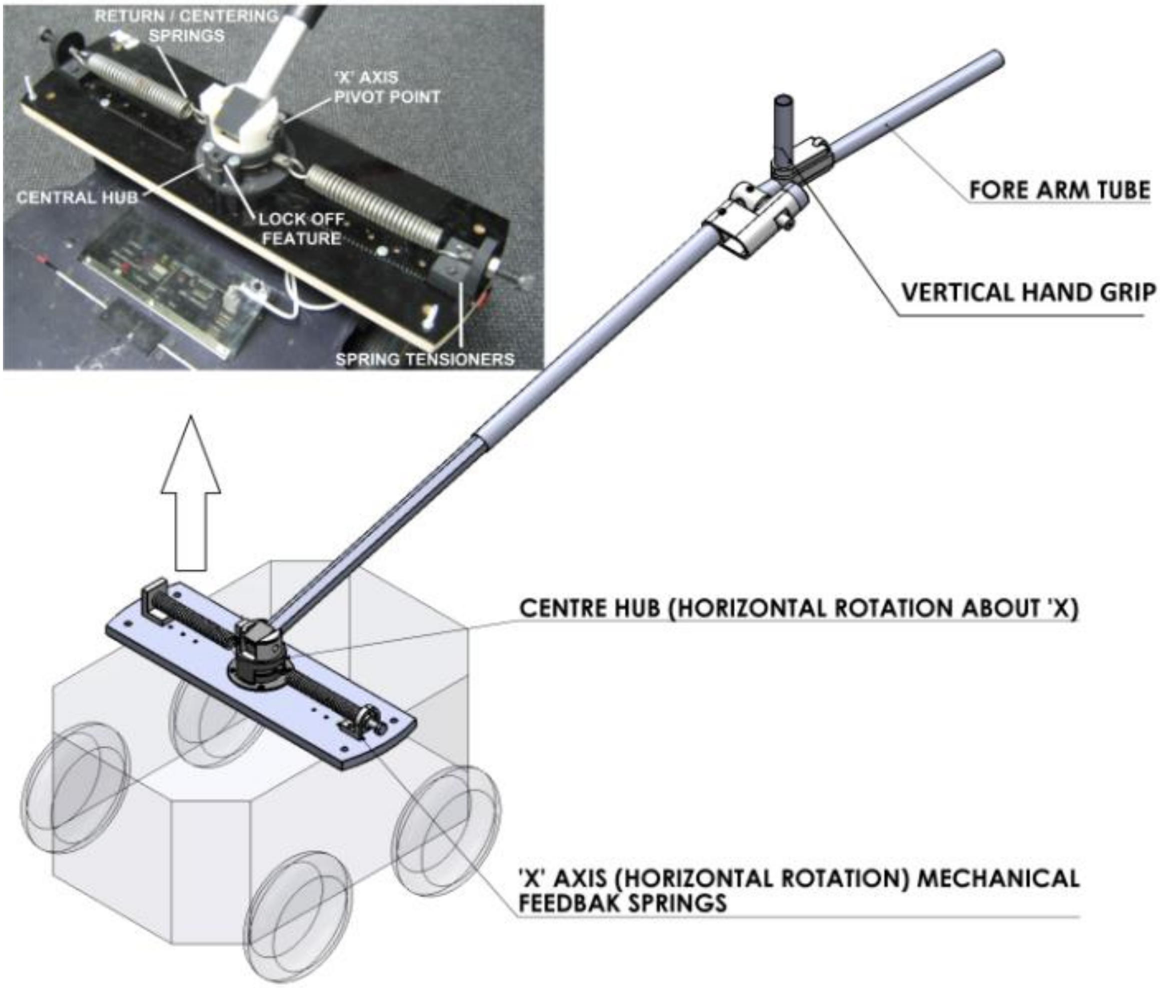

Figure 41, Handle with flexible joint at the base

5.5 Preliminary evaluation for fourth phase testing

The primary evaluation purpose was to test usability: whether the handler could easily follow the robot.

5.5.1 Robot and sensors

For the experiments, the handle is mounted on a Pioneer-3AT 4-wheel robot. The robot was programmed to follow fixed pre-programmed trajectories autonomously. The wizard of the robot could remotely choose a trajectory and start/stop the robot. The robot operated with a linear speed of 0.6m/s and the angular speed was set at 0.5 rad/s (at the turns). Although these parameters are not investigated extensively, these values are below a normal walking speed, usually a linear speed of 1m/s or more, because the handler is expected to traverse an unknown environment. The ROVI robot discussed by Melvin et al. (Allan Melvin et al. 2009) moved at 0.2m/s, a speed which we experienced as very slow and thereby making the handler wait for the robot to act.

Figure 42, Handler attached to the handle with flexible joint

At all times, the walking pattern of the follower was being observed and the degree of displacement of the follower with respect to the center line of the robot was being recorded using a Hokuyo Laser Range Finder, which was fixed exactly at the middle of robot's rear bumper (as shown in Figure 43). Data collection proceeded at a speed of 10Hz or 10 observations per second. The positions of the robot at every instance of time were measured by odometry sensors. The data was sent to the operator's workstation using a Lantronix 802.11g WiPort modem.

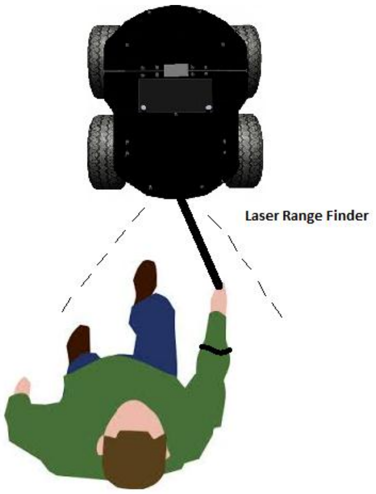

Figure 43, Handler following the robot with a laser range finder at the rear bumper.

5.5.2 Testing Protocol

We studied the effect of two different settings of the interface on the following behaviour of right-handed participants. On each of the trials, the subjects were asked to use the stiff handle in one of the following modes:

- *The handle attached in a fixed joint (rigid)*
- *The handle attached with a flexible joint (spring)*

The overall aim of the study is to evaluate the use of an autonomous robot guide. However, autonomous behaviour can occur in many variants; for the study, we confined the robot to five pre-programmed repeatable behaviours. This is implemented to mimic autonomous locomotion guidance from one point to the other.

In the absence of visual clues, handlers have to rely on what is called path integration (Mittelstaedt & Glasauer 1991) to create a cognitive map, which accounts for the locomotion. Path integration uses the available vestibular, kinesthetic and motor command information in order to maintain self-orientation and position during locomotion in the absence of vision (Amorim et al. 1997; Etienne & Jeffery 2004). According to the '*TOUR'* model presented by Kuipers (1978), the current position of the handler is represented by a small working memory called the *"You Are Here"* pointer within the cognitive map. And at the current position, he gets a '*view*' of his sensorimotor world using his non-visual senses (Kuipers 1983a). An '*action*', such as change of location or orientation, can change the current '*view*' and shift the '*you are here*' pointer (Kuipers 1983a), helping one to create an abstract path in the mind. The '*spatial semantic hierarchy*' model of a human cognitive map created by Kuipers (2000), categorises an action into '*travels*' and '*turns*'. Kuipers (2000) notes that "*A turn is an action that leaves the agent at the same place*" and "*a travel takes the agent from one place to another*". Therefore we tried to create simple trajectories for the robot with a mix of '*travels*' and '*turns*' also varying the magnitude of the '*turns*', so that we could analyse if the handle can contribute to the cognitive map of the handler.

Thus, the robot was made to move autonomously in one of the following pre-programmed trajectories below:

- *path A*: Straight travel (approximately 8 meters).
- *path B*: Straight line (approximately 5 meters) + longer turn (right/left) + straight travel (approximately 3 meters).
- *path C*: Straight travel (approximately 5 meters) + shorter turn (right/left) + straight travel (approximately 3 meters).

When the robot moves in a straight line, the set linear speed is inspired by the normal walking speed of a person. However, for setting the robot's angular speed we do not have an intuition; therefore we designed a smooth or longer turn (close to 45 degrees) and a sharp or shorter turn (close to 70 degrees). The preliminary and informal tests were carried out with team members (four) as subjects; each of them performing 8 trials for each of the paths A, B and C, with different handle settings. Subjects were blindfolded and asked to put headphones on. Before the commencement of each trial, the handle was attached to the subject's forearm and a gentle pat was the pre-arranged haptic signal from the experimenter, used to indicate the start of each trial. For each trial we monitored the following:

- the position coordinates (odometry sensors) of the robot in the experimental space, at a frequency of 10 Hz .
- the degree of displacement of the subject from the trajectory of the robot.

The data collected were used to examine the spatial correspondence of the robot's path and the follower's path.

5.5.3 Results

Robot following straight travel:

The first trial with each subject aimed to observe how the person follows the robot. The handle is mounted in the middle of the robot, while the crutch like part of the handle is attached to the right fore-arm of the follower (right-handed) with elbow slightly flexed, thereby making him/her stand about 15-20 cm left of the centre line of the robot (as presented in Figure 44). In the figures below, we show trajectory plot of the trajectories of the robot and the handler across several trials. The plot is based on the data collected (10 Hz) on board of the robot. The movements (straight/left/right) of the robot and follower are shown in the diagrams.

The robot is around a meter (length of the handle) in front of the follower. So while the robot starts at time t_0 at position (0, 0) the follower is at time t_0 at position (-1, 0). Figure 45 shows a graphical plot of the straight path (path A) for two cases (subjects using both handle settings). We do not observe much difference in the following behaviour. So it is concluded that when the path is straight, there is no impact of handle settings (fixed or flexible joint) on the following behaviour: the follower follows the robot, slightly (15-20 cm) off the robot's centre.

Figure 44, Handle mounted on the middle of the robot and attached to the handler

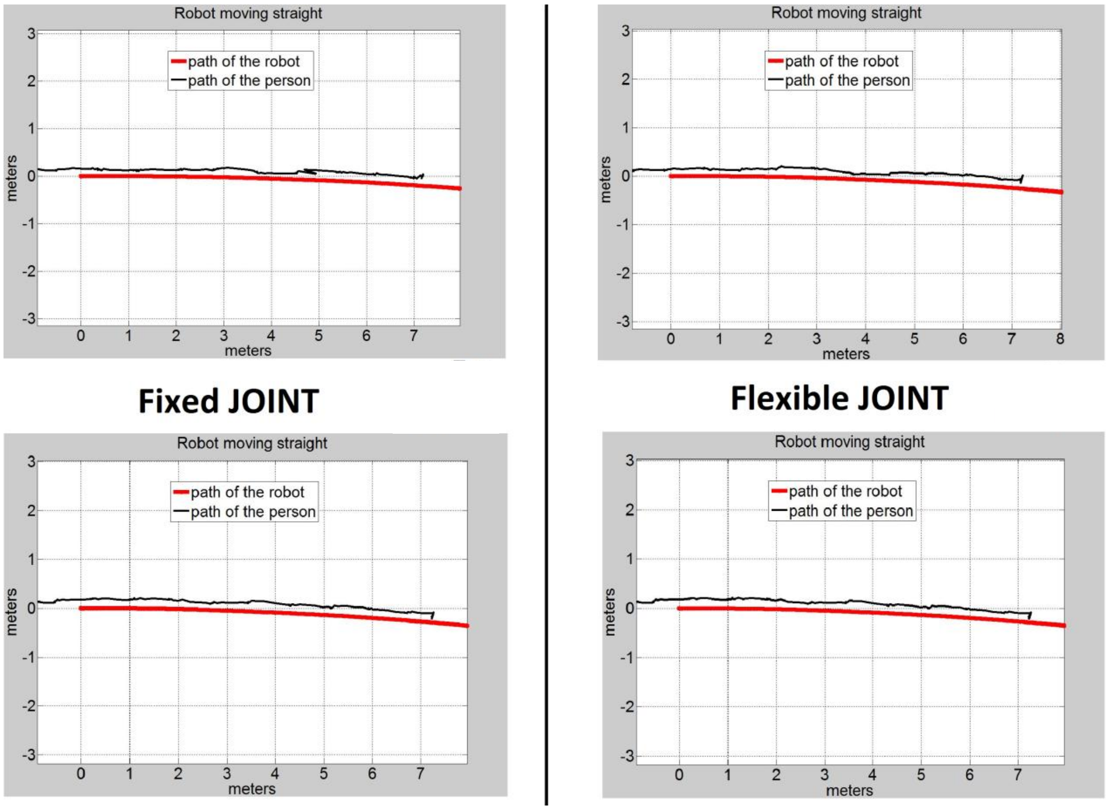

Figure 45, Trajectory plot of the straight path followed by the robot and the handler with fixed joint (left) and sprung joint (right).

Robot turning left:

Figure 46 and Figure 47 show a trajectory plot of the paths for two cases (subjects using both handle settings) while the robot takes a sharper and smoother turn to the left respectively. In both the cases, it is visible across the trials that there is a very obvious difference between the follower's experience with fixed joint (Figure 46 (left) and Figure 47 (left)) and the sprung joint (Figure 46 (right) and Figure 47 (right)) and the impact of these two different handle settings on the follower's following behaviour. When the joint is fixed the handler is forced to deviate more from the centre line of the robot. The follower gets deviated close to 0.5 m off the path followed by the robot. With the flexible joint this effect is rather minimal and there is a higher degree of matching of paths.

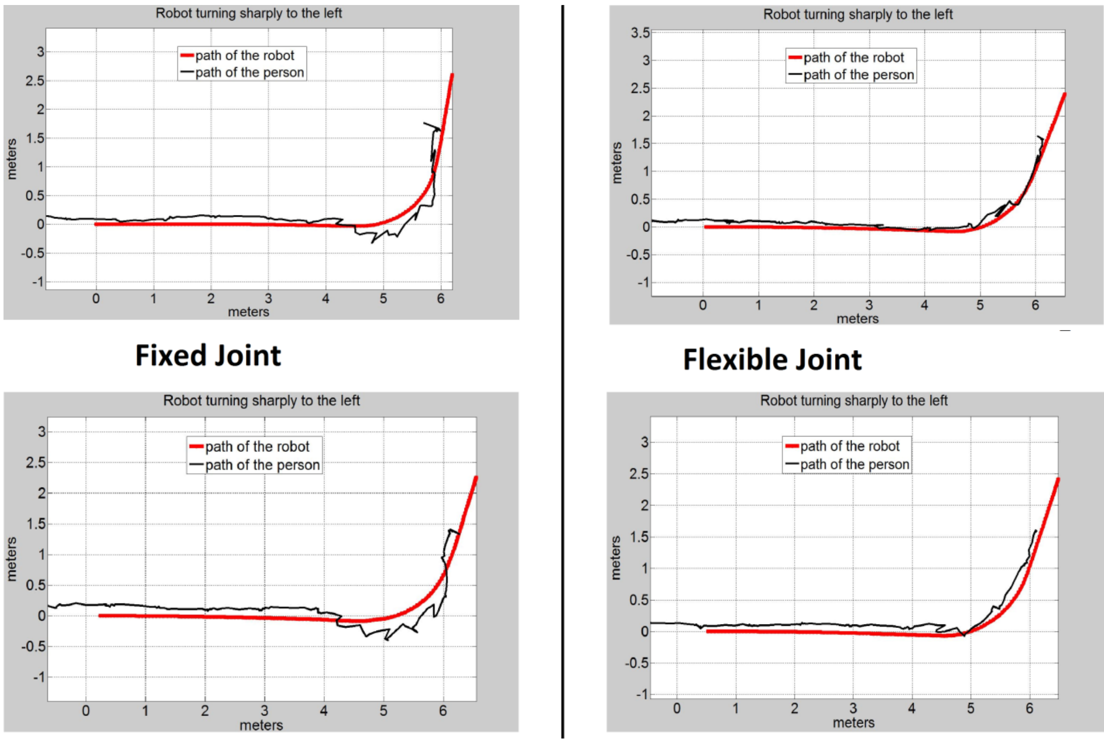

Figure 46, (left) Trajectory plot of the path when robot takes a longer left turn with fixed joint and (right) Trajectory plot of the path when robot takes a longer left turn with sprung joint

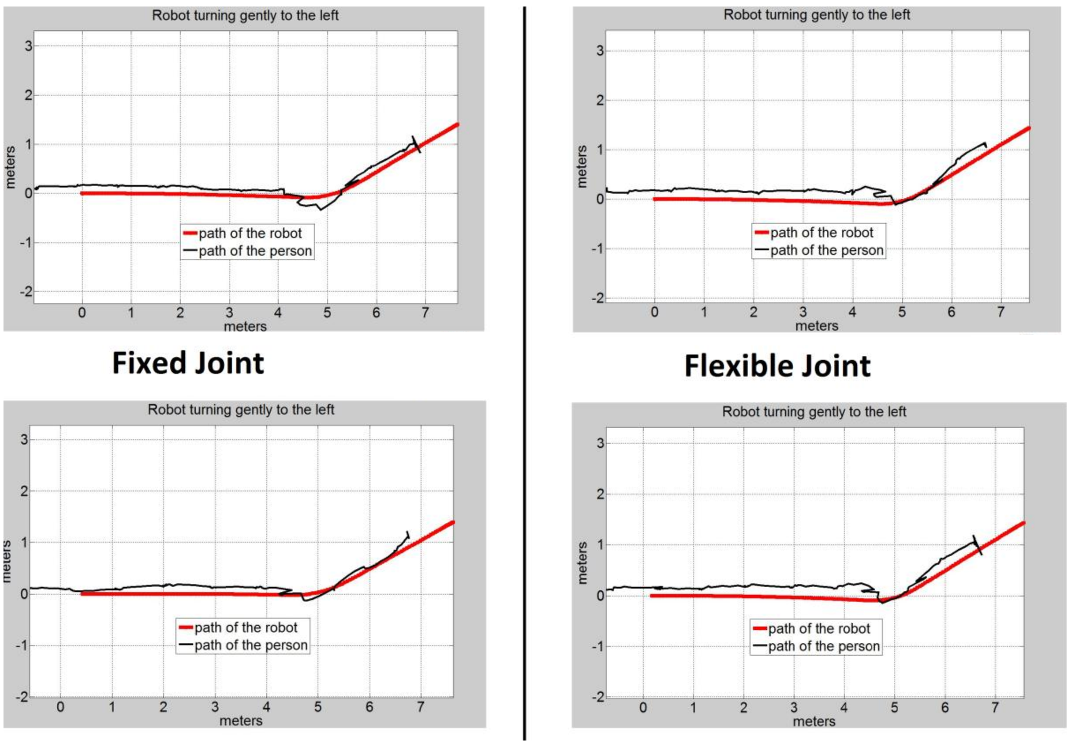

Figure 47, (left) Trajectory plot of the path when robot takes a shorter left turn with fixed joint and (right) Trajectory plot of the path when robot takes a shorter left turn with sprung joint

Robot turning right

It became evident from the experiments that there is an acute difference in the following behaviour when the robot is turning right and when the robot is turning left. If we have a look at all the trajectory plots of paths of robot turning right (both sharper turn and gentler turn), we notice something in common. Surprisingly on right turns, the follower's paths deviate abruptly at certain points considerably more from the path of the robot (at the point of turn) than on left turns (Figure 49 and Figure 50). However, if the paths are plotted with the abrupt deviations removed (the blue dotted lines in figures 49 (left and right) and figures 50 (left and right) indicate the paths if there is no abrupt deviation), we can visualise the effect of two different handle settings; flexible joint offers a smoother following.

Our subjects have their right hands as the dominant one. When they are taking a left turn, there is room to flex their elbows (Figure 48 (left)) and the arm has much more freedom for movement; hence the following behaviour looks more comfortable. However, during a right turn, the handler is holding the handle in the right hand and the crutch like handle pushes the handler's elbow towards the body. Thus he is forced to take a step out (Figure 48 (right)). These effects are persistent during gentle turns as well (as shown in Figure 50).

Figure 48. The elbow posture of a right handed handler during left (left) and right (right) turns.

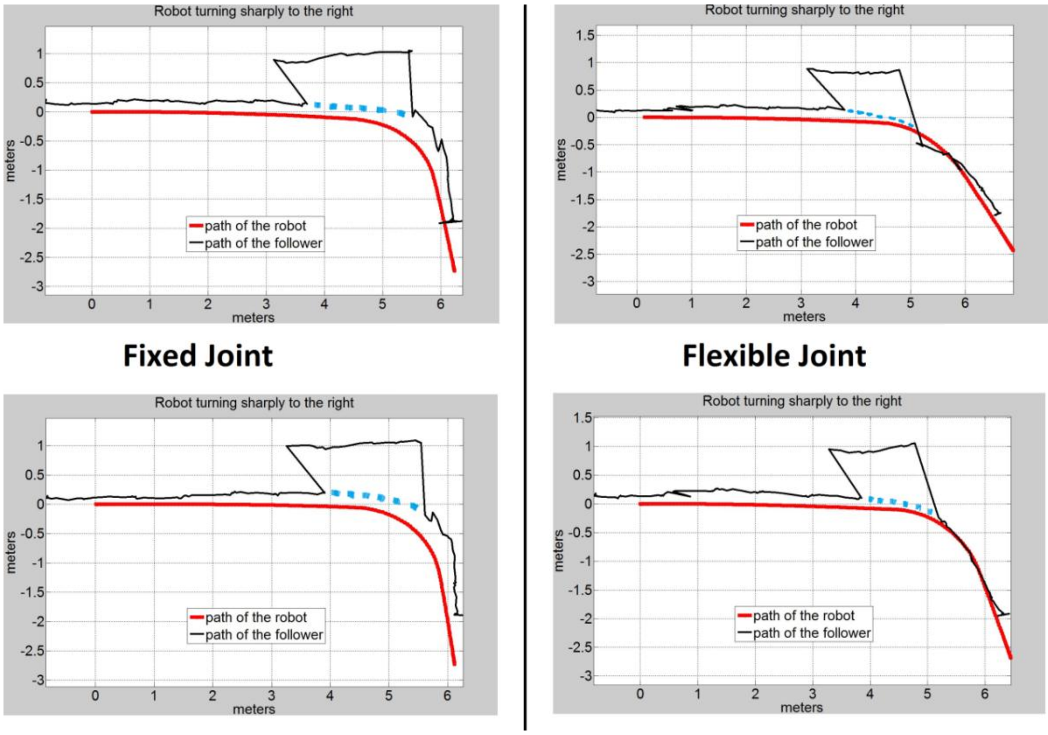

Figure 49, (left) Reconstruction of the path when robot takes a longer right turn with fixed joint and (right) Reconstruction of the path when robot takes a longer right turn with sprung joint

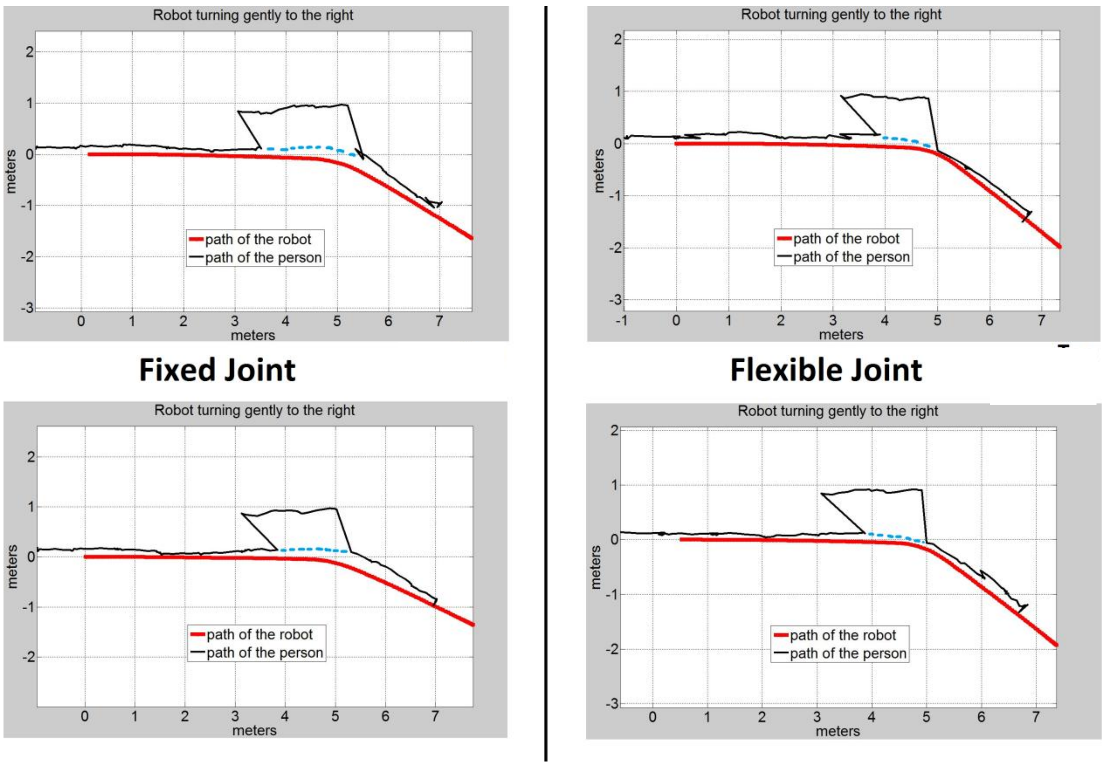

Figure 50, (left) Trajectory plot of the path when robot takes a shorter right turn with fixed joint and (right) Trajectory plot of the path when robot takes a shorter right turn with sprung joint

5.6 Discussion on preliminary evaluation

The findings of the experimental trials raise a number of issues about the design of the handle and user experience that deserve further investigation. First of all, it seems clear that when the handle is attached with a flexible joint (spring) the follower's path better matches the path of the robot; there is only little displacement of the human follower from the robot's trail. For right turns, deviations start very abrupt, but remain lesser with the sprung-joint. In the turns the handler is exerting some force on the robot and this causes the robot to slip and maybe slide. The reconstructed paths in figures 45-50 are based on odometry data and will contain some error, nevertheless the overall patterns can be recognised in the videos taken in final phase of evaluation later.

In terms of the subjective experience of the follower, the initial anecdotal evidence suggests that the flexible handle setting affords a smoother and more comfortable guided experience, although the firmer and more abrupt tug delivered by the inflexible handle may give the handler a keener awareness of spatial orientation and location.

5.7 Evaluation of final phase testing

Based on the results of first preliminary evaluation, we followed up and carried out a final phase of more formalised evaluation. We confined the robot to five pre-programmed repeatable behaviours. Thus the robot was made to move autonomously in one of the following pre-programmed trajectories similar to theprevious phase:

- *Path A*: Straight travel (approx. 5 meters) + longer right turn + straight travel (approx. 3 meters).
- *Path B*: Straight travel (approx. 5 meters) + gentle right turn + straight travel (approx. 3 meters).
- *Path C*: Straight line (approx. 5 meters) + longer left turn + straight travel (approx. 3 meters).
- *Path D*: Straight line (approx. 5 meters) + gentle left turn + straight travel (approx. 3 meters).

The robot was designed to take a shorter turn (close to 45 degrees) and a longer turn (close to 70 degrees). On straight lines, the robot operated with a linear speed of 0.6m/s; in the turns linear speed was also 0.6m/s and the angular speed was set at 0.5 rad/s resulting into a circle arch with a radius of about 1.25 m.

The trials were performed in a sports hall and were also recorded on video. The camera was placed approximately 3m height and about 20 m opposite the starting position of the robot, producing an elevated front view of the robot being followed by the test subjects. We set out to define and carry out more formally structured trials. The purpose was to test usability of the robot as a guide and whether a person could comfortably and safely follow the robot. In an attempt to define a numerical criterion, we observed how closely the path of the follower matches the live path of the robot.

5.7.1 Testing protocol

Six subjects took part in the experiment. Each subject was asked to undergo two sessions with four trials in each session (using, in random order, either the rigid or the spring handle setting on -in counter balanced order- the paths A-D described above). At the start of the first session, the subjects were instructed on how to perform the task and were asked to sign a consent form. Subjects were blindfolded and asked to put headphones on. Before the commencement of each trial, the handle was attached to the subject's forearm and a gentle pat was the pre-arranged haptic signal from the experimenter, used to indicate the start of each trial.

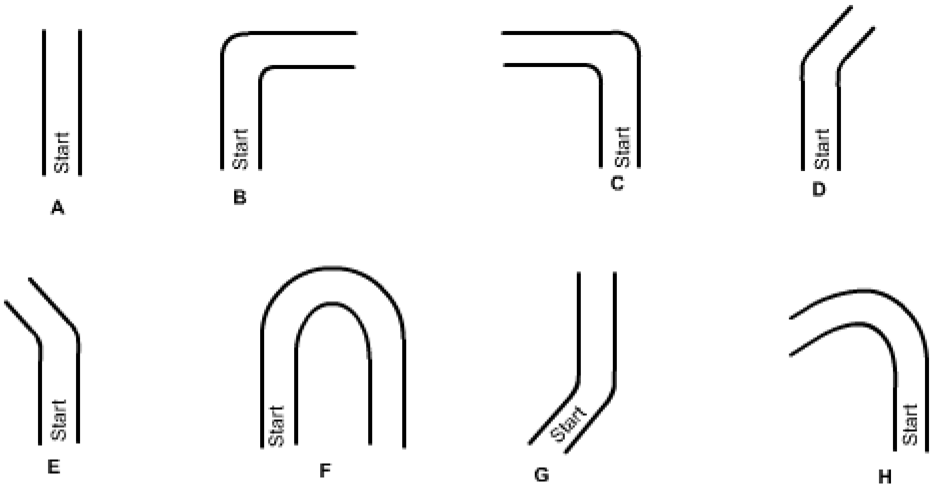

Figure 51, Picture (shown to participants during trials) used in pictorial assessment technique for spatial awareness

In order to make the subjects familiar with the experimental environment before the commencement of the first session, the subjects were given a trial run, on which they were asked to follow the robot moving in a straight-line for 8 meters (approximately) blindfolded.

We also used a non-verbal pictorial assessment technique to understand if the subjects have a '*mental map'* (Kuipers 1978) of the path guided by the robot, when they are using the interface (sense of spatial awareness). The subjects were asked to report which path they believed to have followed choosing, as far as possible, one of the eight options shown in Figure 51, where

A = straight line;

B = straight line plus sharp right turn;

C = straight line plus sharp left turn;

D = straight line plus gentle right turn;

E = straight line plus gentle left turn;

F = straight line plus semi-circular path plus straight line

G = gentle right turn plus straight line

H = straight line plus a very acute left turn

Subject	1	2	3	4	5	6
Fixed Joint						
Path A	D	D	D	D	D	G
Path B	D	D	not sure	D	D	D
Path C	C	C	C	C	H	E
Path D	E	E	E	E	C	E
Flexible Joint						
Path A	D	D	D	D	D	G
Path B	D	D	D	D	D	D
Path C	E	C	C	C	Robot malfunction	E
Path D	E	G	E	E	C	B

Table 3, Subjects' responses on pictorial representation of paths provided

5.7.2 Results

Mental map of the path followed

The subjects were asked to point at one out of eight options (pictorial representations of various paths) given to them. Every option (one out of eight refer to Figure 51) chosen after each trial, was noted against the relevant path followed. Table 3 shows subjects' responses on their senses of spatial awareness. As is evident from the table, the subjects were mostly accurate in determining whether the turn was a left or right turn, however they were less accurate in distinguishing between the gentle and longer turns, right turns - whether long (path A) or short (path B) - were nearly all experienced as the same, left turns show more diversity.

Does the Follower's path match that of the robot?

The paths reconstructed on the videos frames, in the figures 52-54 using video analysis software package Dartfish; annotations may contain some inaccuracy, nevertheless overall patterns can be recognised. In the reconstruction the position of the robot and the feet of the person were marked in each frame. These points are joined using a spline function, the result of which was projected on all frames. Measurements in the frames have been based on rough calibrations in the frame using the known size of the robot and distances between the floor markers. Observing the experiments, we concluded that the flexible joint does offer much better path matching than the fixed joint across all the trials, for all participants. If we look at Table 4, which lists the deviations from the path of the robots at turns for subjects 3, 4, 5 and 6, we observe that in case of flexible joint the deviations are considerably less. Figure 55 presents the mean deviations across all subjects for all the paths (Path A, Path B, Path C and Path D).

Figure 56 gives the mean time delays (t in seconds) for four subjects with different handle settings. *t* is the delay between the point in time when the robot starts to turn and the time when the follower starts to turn. While the fixed setting of the handle alerts the follower of the movements of the robot more immediately, thereby resulting in abrupt tugs in the turns, the flexible handle setting allows for a build-up of tension within the spring mechanism, meaning that the forces on the subject accumulate gradually, thereby causing a delay between the start of the robot's turn and the follower reacting to it. That delay makes for a smoother turn and one that is spatially more accurate.

It became clear that there is an acute difference (as indicated in the previous phase of trials) in the following behaviour when the robot is turning right, refer to Figure 52 and Figure 53 and when the robot is turning left refer to Figure 54, summarised in table 4. On right turns, the follower's path deviates considerably more from the path of the robot with subject 3 (scoring on the higher ends concerning confidence etc) reaching a maximum of 0.44 deviation and subject 4 (lower confidence score) maximum 0.47 m. In the left turns the maxima reduce to 0.18m for subject 3 and 0.36m for subject 4. In the right turns, deviations start very abrupt, but remain smaller with the sprung-joint, because all subjects were right-handed.

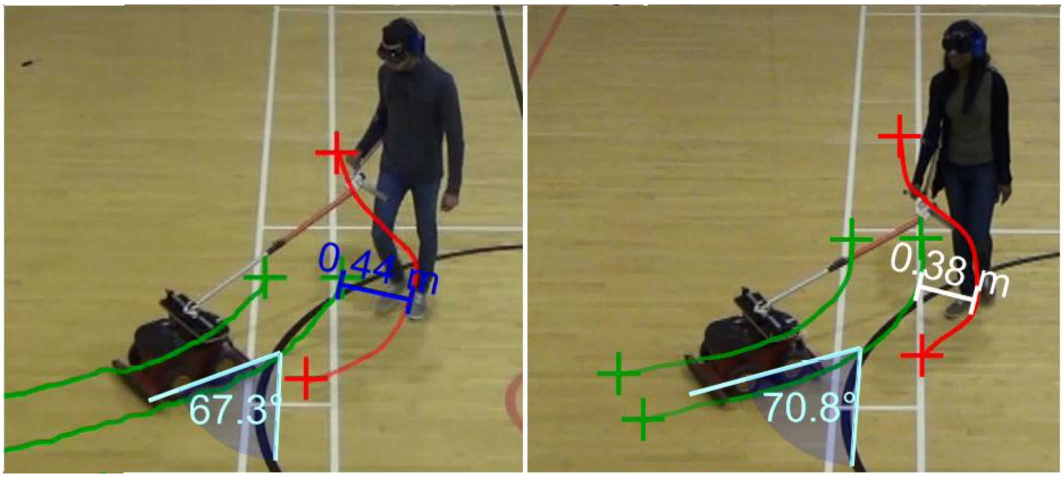

Figure 52, Subject 3 (left) and 4 (right) longer turn to the right with fixed handle setting

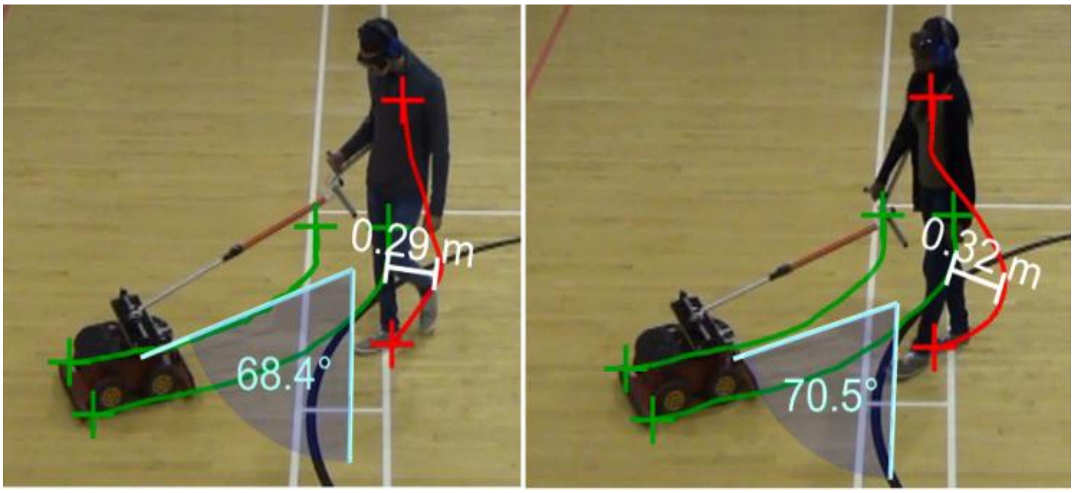

Figure 53, Subject 3 (left) and 4 (right) longer turn to the right with flexible handle setting

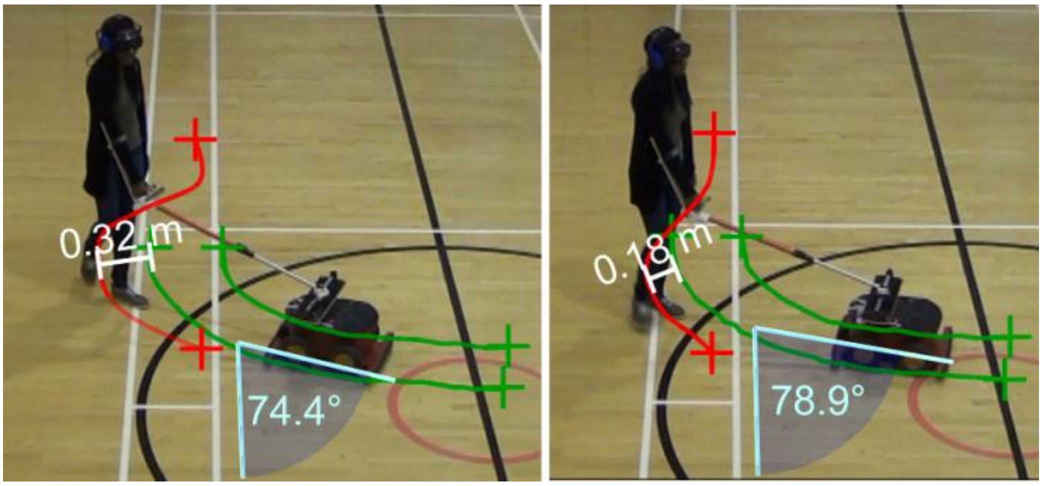

Figure 54, Subject 4 longer turn to the left with fixed (left) and flexible (right) handle settings respectively

Subject 3				
	Rigid Joint		Sprung Joint	
	angle	deviation	angle	deviation
Path A(longer right)	67	0.44	68	0.29
Path B(shorter right)	43	0.37	48	0.09
Path C(longer left)	69	0.18	-	-
Path D(shorter left)	48	0.10	55	0
Subject 4				
	Rigid Joint		Sprung Joint	
	angle	deviation	angle	deviation
Path A(longer right)	70	0.38	70	0.32
Path B(shorter right)	45	0.47	46	0.27
Path C(longer left)	74	0.32	78	0.18
Path D(shorter left)	53	0.36	55	0.28
Subject 5				
	Rigid Joint		Sprung Joint	
	angle	deviation	angle	deviation
Path A(longer right)	68	0.40	67	0.14
Path B(shorter right)	43	0.39	44	0.15
Path C(longer left)	71	0.24	-	-
Path D(shorter left)	48	0.18	51	0
Subject 6				
	Rigid Joint		Sprung Joint	
	angle	deviation	angle	deviation
Path A(longer right)	67	0.44	67	0.23
Path B(shorter right)	45	0.44	48	0.35
Path C(longer left)	70	0.42	73	0.28
Path D(shorter left)	48	0.29	54	0.22

Table 4, Table representing angle of turn (degrees) and deviation (meters) from the path of the robot, for four subjects (two different handle settings)

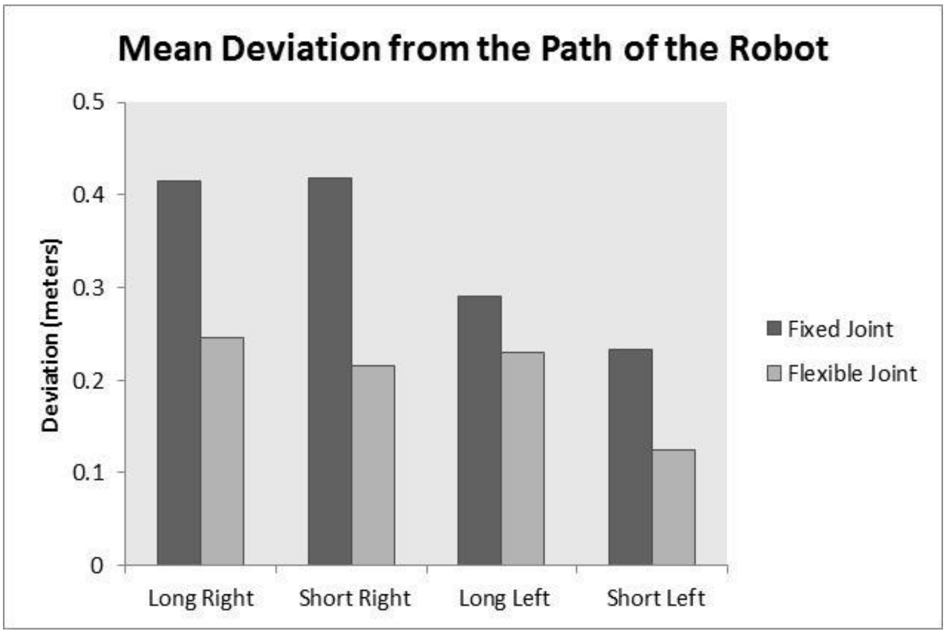

Figure 55, Mean deviation for four subjects with fixed/sprung handle settings..

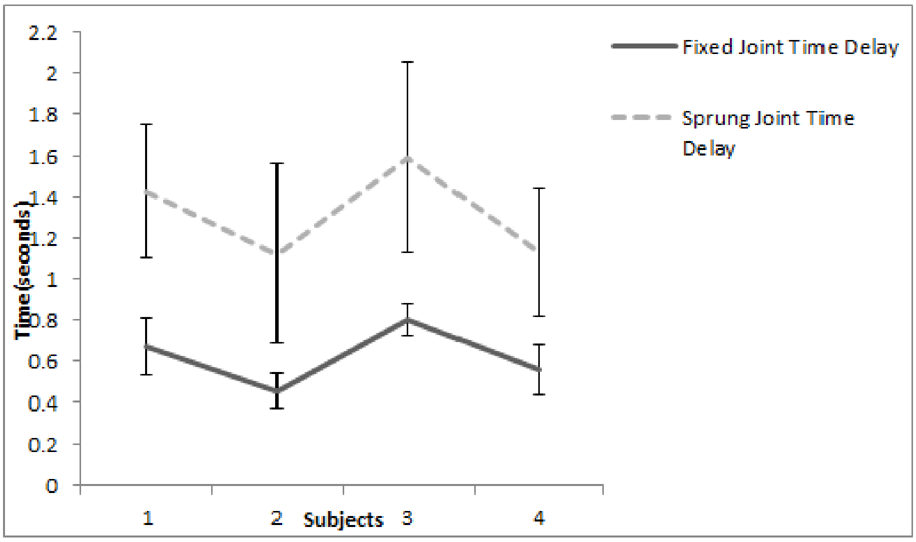

Figure 56, Mean T (time delays in seconds) for four subjects with fixed/sprung handle settings.

5.8 Discussion

First of all, it seems clear that when the handle is attached with a flexible joint (spring) the follower's path better matches the path of the robot; there is only little displacement of the human follower from the robot's trail.

The trajectory plots and video annotations suggest that the flexible handle setting results in a smoother and more comfortable guidance experience, although the firmer and more abrupt tug delivered by the inflexible handle may give the handler a keener awareness of spatial orientation and location. This is evident from the mean time delays (as shown in Figure 56). The flexible handle setting allows for a build-up of tension within the spring mechanism in real time, meaning that the forces on the subject accumulate gradually, thereby causing latency between the start of the robot's turn and the follower reacting to it (the start of the subject's turn). That delay makes for a smoother turn and one that is more accurate spatially, however, it leaves open how immediately and accurately the follower is alerted of the movements of the robot through the haptic interface. In future it would be interesting to compare right and left handed subjects in order to confirm my intuition that on a left turn a left handed person is also forced to step out and mirrors the pattern of a right turn by a right handed person.

5.9 Conclusion

We have presented a haptic interface attached to an autonomous robot for locomotion guidance. We have reported on a small scale experimental study of different settings of the interface. The trial data show that:

a) The handle interface with spring mechanism affords a more effective solution to the '*matching path*' problem, although this conclusion needs to be qualified in the light of our observations about the interactional nature of the path.,

b) Subjects show accurate spatial awareness in relation to gross orientational parameters (left versus right) but whether they are capable of more fine-grained assessments of direction (e.g. magnitude of a turn) and orientation is unclear.

Chapter 6

Evaluating the haptic interface for environmental exploration

This chapter is dedicated to the research question: ***how does the design of the haptic interface aid environmental exploration for the handler?*** *A discussion on evaluation of the design and considerations that led to the design is presented. We look through the experimental study to demonstrate how the interface can be of assistance in environmental exploration by the robotic guide. Part of this chapter has been published as:*

Ghosh, A, Penders, J, Jones, P, Reed, H, and Soranzo, A, (2014), "Exploring Haptic Feedback for Robot to Human Communication." International Conference Disability, Virtual Reality and Associated Technologies, Gothenberg, Sweden.

6.1 Introduction to using the robot as a tool for exploration

According to Oxford dictionary, the word '*exploration*' means the act of searching an unfamiliar area. Exploration in the context of search and rescue entails not only finding out what is out there; but also to be able to find the way out. It has been concluded in Chapter 2, that exploration of the haptic space is of life importance for a fire fighter and this exploration problem is logically separable from the locomotion problem, dealt with, in the Chapter 5.

The guide designed in the project consists of a powered robot and additionally it is intended as an exploration tool to trace the objects encountered. '*Tool use'* is a paradigm explored by researchers over the years. Seed & Byrne (2010) cites Beck's (1980) definition of tool use as '*to alter…the form, position, or condition of another object, another organism, or the user itself when the user holds or carries the tool during or just prior to use*'. According to Johnson-Frey (2003) tool use introduces a set of difficulties as the physical characteristics of the tool, its relationship to the body and with the environment can impact its effective utilisation. The tool functions as an extension of the physical body (Rademaker et al. 2014) and action space involving psychological processes such as perception, attention and cognition (Seed & Byrne

2010). Maravita and Iriki (2004) state that this extension is followed by changes in specific neural networks, that hold an updated map of body shape and posture called '*Body Schema*'. To act efficiently in space, the human brain needs to localise objects of interest. In the absence of vision, visually impaired people use a long cane as a tool to detect and localise objects (Schenkman & Jansson 1986), by tapping the tip of the cane. Schellingerhout et al. (2001), redesigned the tip of the cane to improve obstacle detection.

Interacting manually with objects in the environment, associates the sensorimotor systems to the handler. Reaching towards a target object involves its extrinsic spatial properties (location, orientation, etc.) and knowledge of the limb's relative position (Johnson-Frey 2003). By contrast, grasping the objects, involves its intrinsic properties, such as shape, size, texture and knowledge of the position of hands and fingers. It is important that tool use affects the way in which the handlers interact with the surrounding environment (Baccarini & Maravita 2013). We can modify our relationship with external space in terms of body/space representation by using a tool; tool use induces a spatial remapping and suggests a direct expansion of the so-called *peripersonal space* (roughly what we called the haptic space above) to the whole space reachable by the tool (Baccarini & Maravita 2013). The primary goal is to use the robot as a tool to detect obstacles and understand the aspects of their intrinsic properties (such as their immovability). Seed and Byrne (2010) state that animals have a remarkable ability of physical reasoning and using a tool with the right physical properties to solve a problem. In the first phase '*in the wild*' pilot trials, subjects were asked to make use of the first prototype (an extended cane attached to circular base with omni-directional wheels), mentioned in the previous chapter and shown in figure 31 (chapter 5, page 82), to detect the movability of various objects. They automatically figured out how to use the prototype as a tool by pushing it against the objects (as shown in figure 57).

Figure 57, Using 'robot-on-a-stick' prototype as a tool

However, the disc with rigid handle provided implicit feedback to the handler while the handler was operating it. The tool we are aiming for is a mobile robot with a haptic user interface, which is a powered device and to make effective use of it, physical contact with the objects is essential. To enable physical contact between the robot and objects, a mechanical impedance filter - '*bumper*' for short - is designed by the design team (as shown in Figure 58), which sits on the guide robot and is attached to the handle (mentioned in the previous chapter). The fundamental design is based on a bumper mechanism system consisting of an inner platform suspended by springs which are connected to the outer skirt (as shown in Figure 59). Mechanical displacement of the bumper is proportional to the applied impact force while bumping on to an object and displacement is measured by triangulating the length by three CRTs (Cable Reel Transducers) (as presented in Figure 59). An estimate of applied force and contact point on the skirt/bumper is then calculated. The design team performed tests to calibrate the system with objects (as presented in Figure 60) and designed a graphical interface to know the location of impact on the bumper (Janani et al. 2013).

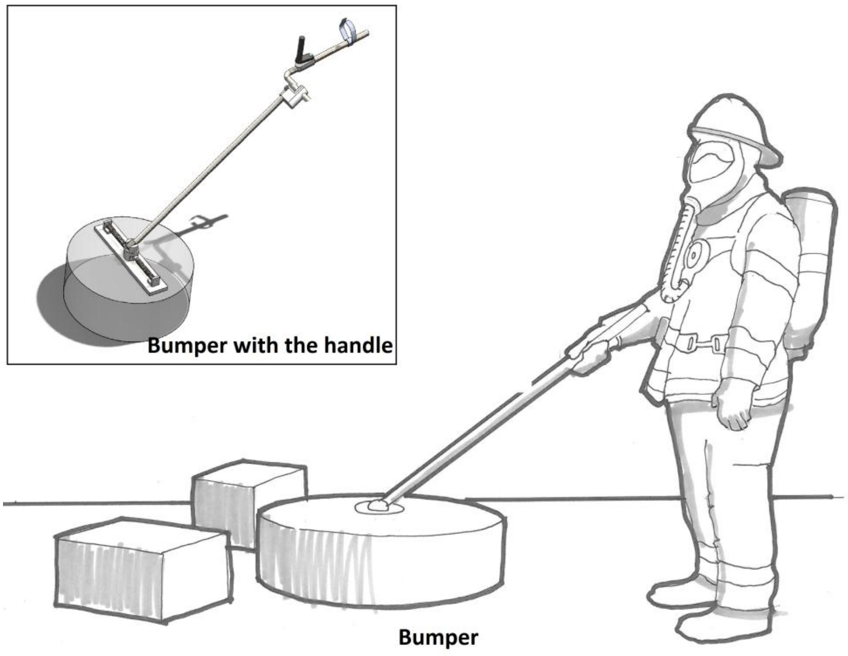

Figure 58, Mechanical Impedance filter - 'bumper'

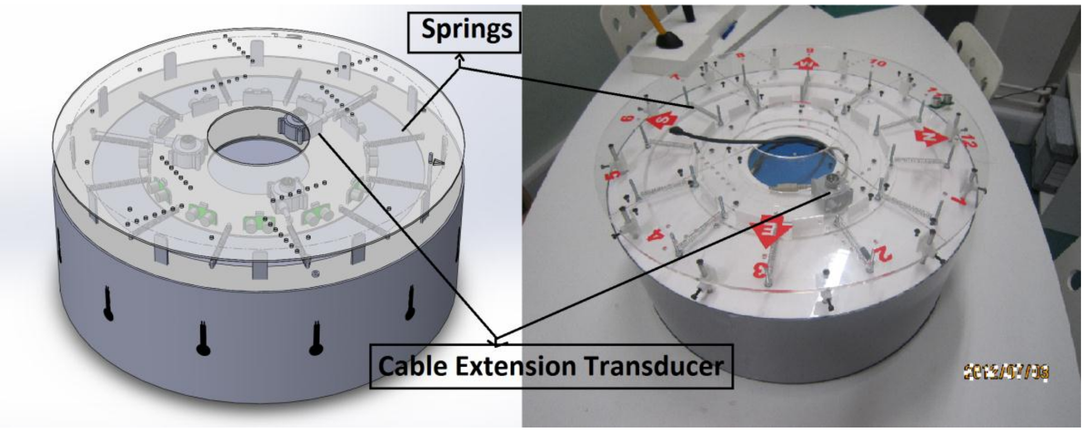

Figure 59, Bumper with 3 CRT and Springs

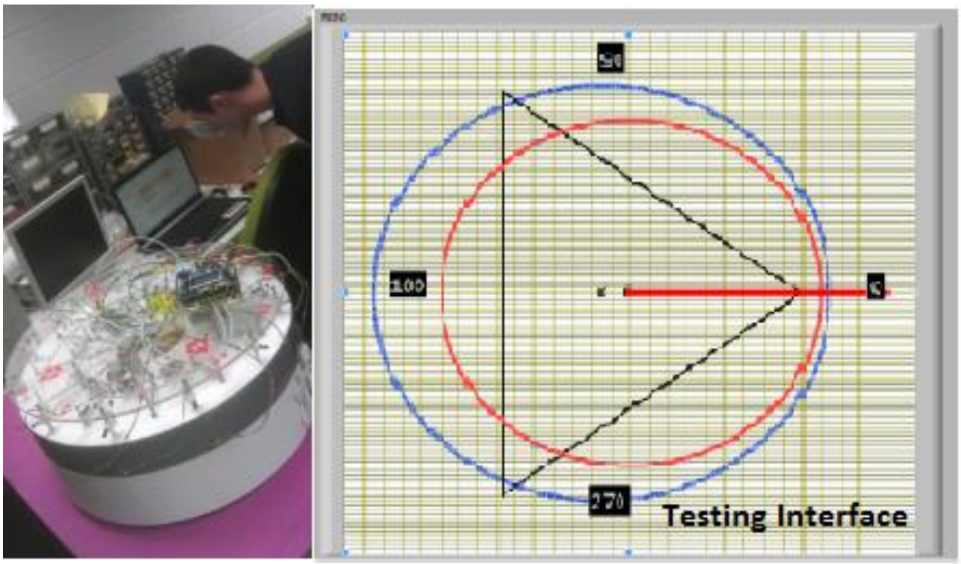

Figure 60, Reins team performing tests with bumper

Ultimately the idea is to transmit this information about the location of impact to the handler in the form of haptic feedback. A major issue with a powered robotic device is that there is no room for active haptic sensing by the human and the feedback to the handler has to be made explicit. Therefore a design issue is what information concerning the displacement of the bumper should be presented to the handler and how to present this. It is important to focus on creating feedback from a powered robot to the handler and the received feedback should enable safe exploration of the environment. For situations where limited/no visual or audio response is available, it is believed that haptic feedback such as vibration is a viable alternative. Ng et al., concluded in their work (Ng et al. 2007) that vibro-tactile feedback offers far superior communication of information than electro-tactile feedback.

6.2 Vibration as a form of haptic feedback

Mechanoreceptors on the skin respond to mechanical pressure or distortion. There are four main types of mechanoreceptors in glabrous skin: Pacinian corpuscles, Meissner's corpuscles, Merkel's discs, and Ruffini endings (Gemperle et al. 2003). However, Pacinian corpuscles are sensitive for mechanical vibration. Pacinian corpuscles have a threshold frequency that a vibration stimulus must overcome in order to trigger a signal to the brain (Gray & Sato 1953). A perceptible frequency range of humans was found in (Gemperle et al. 2003) from 20-400 Hz. If a vibration is not strong enough to cause the Pacinian corpuscle to reach this threshold, the brain would not be able to sense the vibration. There have been many studies on using vibroactuators for different purposes in navigation. For example, the study in Tsukada & Yasumura (2004) presented an active belt which is a wearable tactile display that can transmit directional information in combination with GPS directional sensor and vibration motor. Another research on cooperative human robot haptic navigation in (Scheggi, Aggravi, and Morbidi 2014), used a wrist belt with vibro-tactile sensors to guide a human to a target location. Moreover, haptic feedback was used to navigate people by using a mobile phone in (Pielot et al. 2011). Furthermore, vibro-tactile way-point navigation was presented in (Pielot et al. 2010) in pedestrian navigation.

Now the question arises which part of the body is most appropriate for communicating the feedback? The tactile sensitivity varies widely by body location with movement (Post et al. 1994) and therefore it is important to choose the most appropriate location. Research done by Karuei et al. (2011) reflects that wrist, arms and spine are the most preferred locations for wearable haptic systems. Several works have been done in the past to provide vibrotactile feedback in the forearm (Ng et al. 2005; Cholewiak & Collins 2003; Scheggi, Aggravi & Prattichizzo 2014). Following these considerations, it was decided that a haptic cuff, with vibration motors, could be designed as a part of the haptic interface that would sit on the forearm of the handler and be attached to the crutch like part of the handle (as shown in Figure 61).

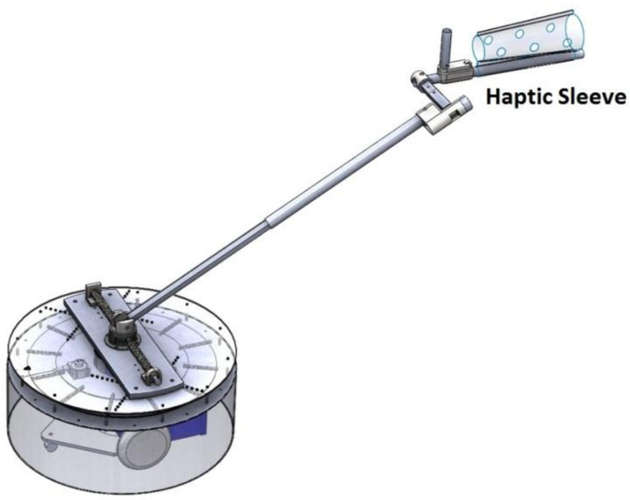

Figure 61, Handle with haptic cuff

However, using a tool may pose challenges because it increases the cognitive load of the handler (Byrne 2004). Therefore, it is very important to carry out a systematic evaluation of the vibration messages so that the right design is formulated and it does not add on to the cognitive load of the handler. For the preliminary phase of experimentation, the design team designed a wearable cuff with six vibration motors (as shown in Figure 62).

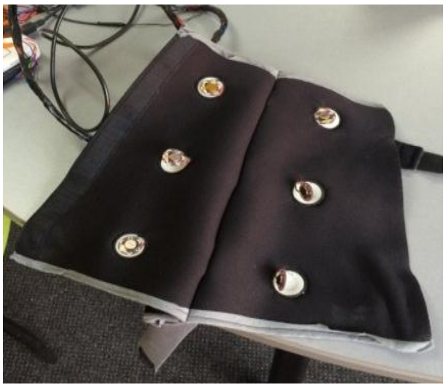

Figure 62, Wearable feedback cuff

The cuff was designed in such a way that three vibration motors sit on the dorsal (outer) side of the forearm whereas the other three sit on the palmer (inner) side of the forearm. The distance between two vibration motors is roughly 10 cm. The vibration motors used are '*Lilypads*' that have 20mm outer diameter and thickness of 0.8 mm[4]. The motors vibrate for short periods (3 seconds) on the lower arm of the handler. The motors are individually controlled; however, all motors operate at the same frequency and intensity. They are connected through a microcontroller and operated using a software interface developed in Labview.

6.2.1 Testing Protocol

Figure 63 shows a person wearing the cuff on the lower arm. The first question is whether subjects are able to distinguish which individual motors are activated; in addition the aim is to study whether different combinations of concurrent vibrating motors are recognisable. After one or more vibration motors were turned on for 3 seconds using a wizard of Oz interface, the subjects were asked to report on the

[4] https://www.kitronik.co.uk/pdf/310-101_datasheet.pdf

positions of the motors, by pointing out the options shown in the picture (Figure 64). To make it easier to understand, we named the positions as following: motors close to the wrist, Under Arm Bottom (UB) and Over Arm Bottom (OB), in the Middle as Under Arm middle (UM) and Over Arm Middle (OM) and close to the Elbow as Under Arm Top (UT) and Over Arm Top (OT), refer to Figure 65. Every subject was given noise cancelling ear protectors to neutralise all possible auditory cues.

Six subjects, aging between 22 and 55 without any medical condition, took part in the experimental study. Each subject was asked to undergo four sessions with twelve trials in each session (48 trials in total for each participant). Before the commencement of the trials, the subjects were briefed about the experiment and went through a pre-trial in order to make them accustomed with testing environment and the apparatus. In the first trial set any of the six vibration motors is activated, but only one at the time.

Figure 63, The cuff on trial and the trial's feedback display.

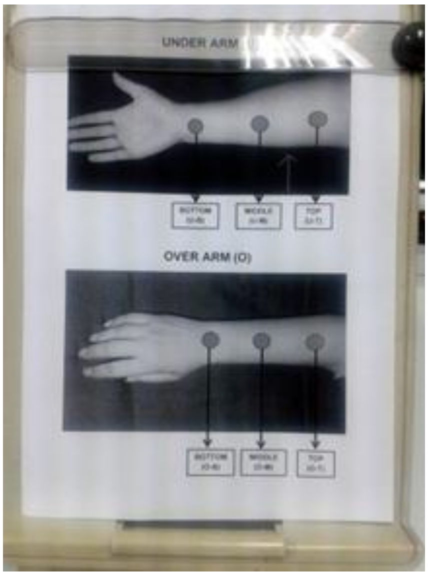

Figure 64, the picture placed in front of the subjects for pointing out the positions.

In the second trial set two motors are activated concurrently but in varying patterns and in the third set three motors are activated concurrently in varying patterns. The final session consists of a mix of single, double or triple motor activations in a counter balanced order.

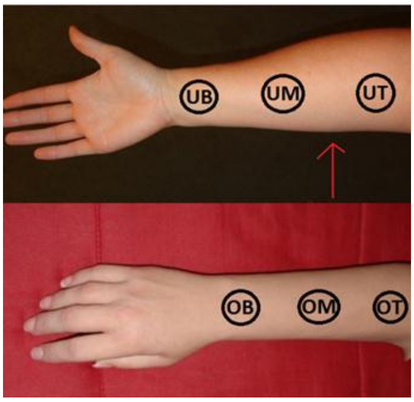

Figure 65, Position of the vibration Motors

6.2.2 Results

For the purpose of analysis, the motor positions are numbered as follows:

Position of the vibration Motors	Number

Under Bottom (UB)	1
Under Middle (UM)	2
Under Top (UT)	3
Over Bottom (UB)	4
Over Middle (UM)	5
Over Top (UT)	6

Table 5, Number assigned to each position of Vibrating Motors

Figure 67, 68 and 69 show the errors subjects made in identifying the specific motors across all trial sets. The figures show motor positions on the horizontal axis; the vertical axis shows the number of errors made when the respective motors were activated. Figure 67, shows the errors with single active vibrating motor, the figure 68 shows errors with two active vibrating motors and the figure 69 shows error proportions with three vibrating motors. We notice that there is an increase in the number of errors as the number of vibrating motors increases. It is evident that the subjects were most accurate in determining the positions of vibrations when only a single vibration motor was turned on.

Mean numbers of errors for the each participant under 3 conditions are as follows:

Condition 1 (single vibrating motor): 1.83

Condition 2 (2 motors vibrating concurrently): 3.5

Condition 3 (3 motors vibrating concurrently): 6.5

Figure 66, shows the total number of errors for each trial condition across all trials. These results indicate the increasing difficulty in accurate identification of vibrating motor(s) over the three conditions. The binary logistic regression of participant accuracy indicated a significant effect of the number of motors $z = 4.52$, $p < 0.001$. Conversion of the log-odds indicated that the number of motors active introduced an increase of 12.5% to error rates.

It would appear, then, that the task becomes much more challenging with three vibration motors switched on and also that some of the triple-combinations are more readily identifiable than others. Although the precise reasons for this extra level of difficulty are not clear, anecdotal evidence suggests that identification difficulties may be associated with distribution or proximity of the motors on the arm but we were unable to establish this from the present data.

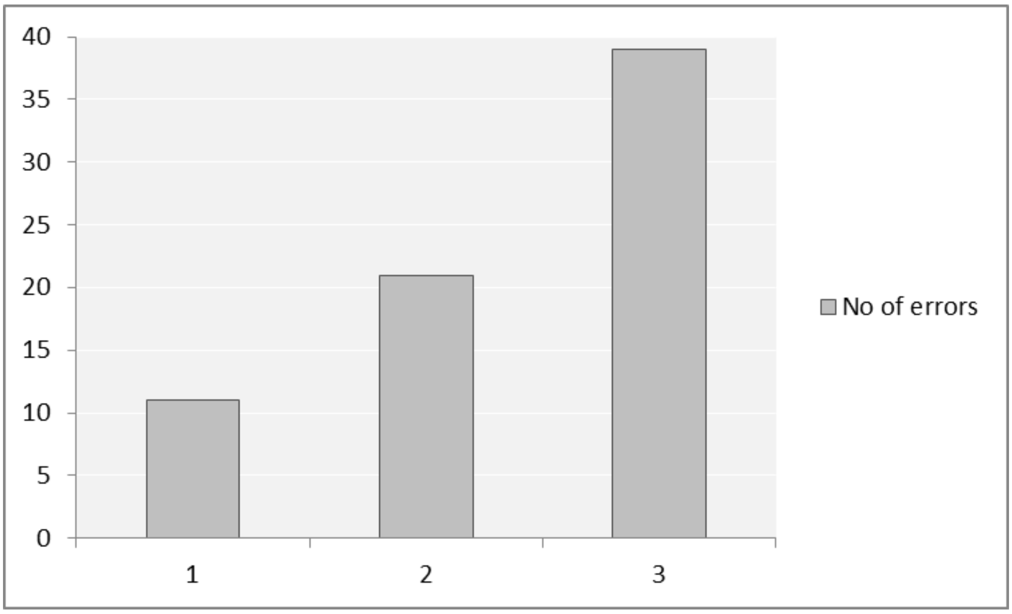

Figure 66, Total number of errors across all trials w.r.t number of active motors

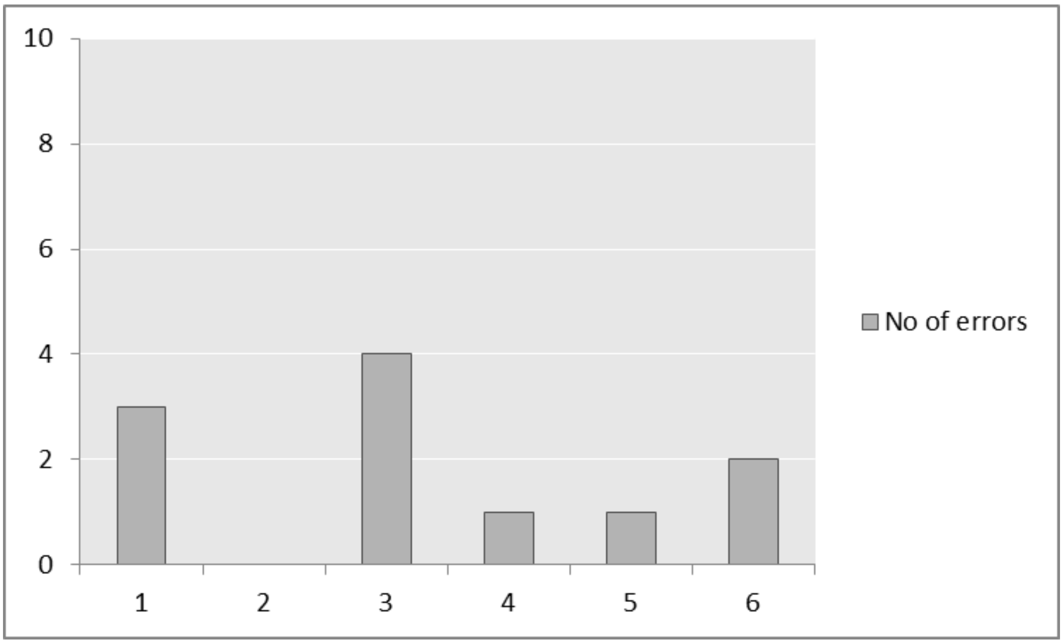

Figure 67, Number of errors across all single active motors

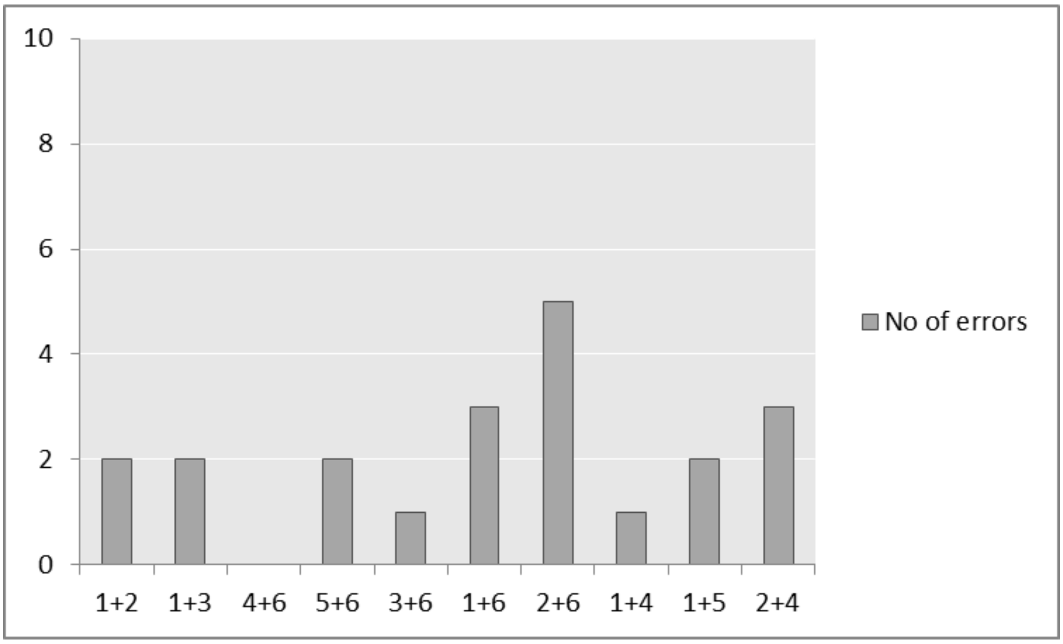

Figure 68, Number of errors across all double active motors

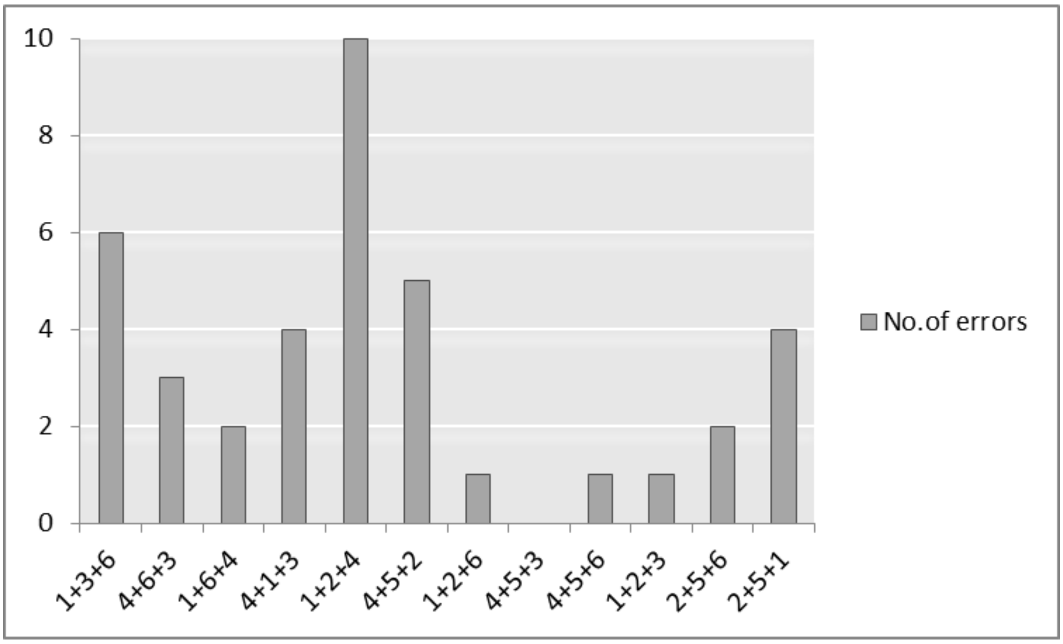

Figure 69, Number of errors across all triple active motors

6.2.3 Discussion on preliminary evaluation

The findings of these experimental trials raise a number of issues that need to be taken into account for further re-design of the cuff and the message-sending configurations of vibrating motors. The trial data show that subjects were easily able to distinguish when individual vibration motors were activated but that the difficulty of the task increased when motors were combined. Combinations of three motors, in particular, were especially difficult to identify accurately. In terms of subjective experience, a few subjects pointed out that the activation time of the motors (3 seconds) is relatively long for transfer of a message. They also pointed out that a gap of 10 cms between two motors is small, as it was difficult for them to perceive when motors are activated concurrently; they often perceived the combined signal as if it was a single but more intense signal.

6.3 Evaluation of the final phase testing of the feedback cuff

Based on the findings of the previous experiment, the cuff was redesigned (as shown in Figure 70) to transmit messages. A next step is to define and design feedback signals (a sort of haptic alphabet) that correspond with displacements of the impedance filter. Since the robot is intended as an exploration tool, the displacement of the robot's bumper has to be presented to the handler. We apply four vibrating motors attached to a cuff with wider gap between them. The cuff is strapped around the forearm of the handler and the motors vibrate on the skin for a shorter duration (1 second).

The overall aim of final phase evaluation is to investigate whether activation of the vibration motors induces an adequate spatial sense to the handler. In other words, is the handler able to associate the vibration of a particular motor with a particular spatial direction?

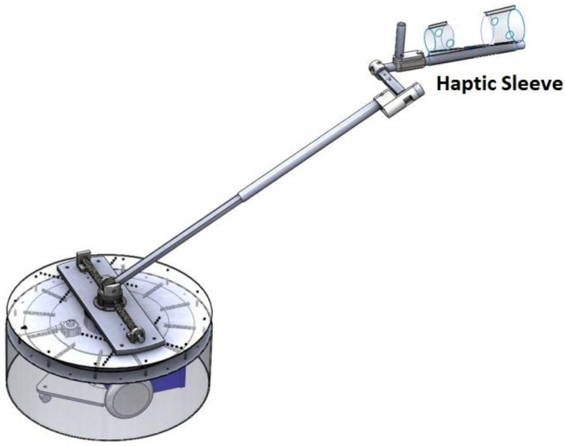

Figure 70, Reins interface with redesigned cuff

If the results are positive, they will strengthen the basic idea of using vibration motors to represent the physical location of impact between the robot bumper and obstacles. We first define and design the feedback signals (vibration patterns) and indicate how the signals are intended to be associated with the bumper. The robot is let to bump onto an obstacle with the aim of alerting the handler to the presence of the obstacle but also to indicate the position of the obstacle relative to the handler. The main question therefore is whether the handler can associate a vibration signal with a spatial direction.

As mentioned earlier the newly designed cuff consists of two sets of two motors only; one set attached to the palmer and one to the dorsal of the forearm, as shown in Figure 71. This means that we have a potential alphabet/vocabulary of four separate digits corresponding to each motor being activated separately.

6.3.1 Associating Vibration Motors and the Bumper

When a handler is navigating an environment, certainly when unknown, then new data/information about the area in front is the most relevant. The robot and handler will usually move into the forward direction and accidentally bump into an obstacle. This means that the front half of the bumper is the most useful part for exploration. Data about the area behind has been collected before (in previous steps) and up-dates are relatively unimportant.

Figure 71, two sets of two vibration motors; left, attached to the inner side of the arm; right, attached to the outer side

Following this rationale we focus on representing data about the front half of the robot bumper in the heading direction. We have an alphabet of four signals: four vibration motors, L1, R1, L2 and R2 in Figure 72 (right). We assign a vibration motor to four distinct points on the bumper: points A-D in Figure 72(left). When an arm is outstretched, we assumed it is most intuitive to associate the front points A and B on the bumper with vibration motors L1 and R1 (in Figure 72) that sit closer to the palm. When holding the handle as in Figure 7, but also when the right hand is stretched naturally with the thumb up, the palmer of the forearm is on the left while the dorsal is on the right, thus motors L1 and L2 are associated with left and R1 and R2 with right. Similarly, for a left handed person L1 and L2 sit on the dorsal side of the forearm while R1 and R2 on the palmer side.

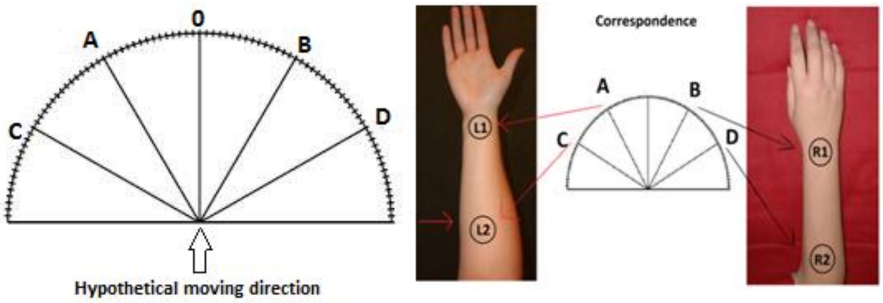

Figure 72, (Left) Points of impact on bumper which are to be provided to the handler (Right) Corresponding vibration motors on right arm

6.3.2 Spatial cognition using the feedback cuff

Maravita & Iriki (2004) state that the tools, when we extend our reaching space, can become incorporated into a plastic neural representation of our body. The authors in (Cooke et al. 2003) also cite that tools effectively increase the integration of biologically relevant visual stimuli in a body-centred representation of space. In case of zero visibility, the feedback cuff should integrate haptic stimuli in body centred representation of space. The question arises what exactly is a body centred representation of space?

How humans represent space in memory is still a subject of ongoing discussions within psychology. Central to these discussions, is the distinction made by Klatzky (1998) between egocentric and allocentric representations of the environment. Egocentric means a coordinate system, which is centred on the body of the handler, whereas, an allocentric coordinate system is located and oriented on external objects (Sadalla & Montello 1989). These two coordinate systems have different relative importance. For scene recognition, the egocentric system is the most important, whilst for reorienting, it is the allocentric system which is dominant (Klatzky 1998). The spatial tasks that are intensely studied in this context are: recognising scenes, reorienting and updating (Meilinger & Vosgerau 2010). The discussions focus on whether both types (egocentric and allocentric) are needed for a particular task and whether these different types of representations combine in human memory. Burgess (2006) developed a two-system model of parallel egocentric and allocentric representations of objects.

However, when the environment is unknown and there is no visual or audible feedback, we assume that the allocentric spatial representation is missing. In order to make prompt navigation decisions, the handler needs some mental representation or mental map of the close surroundings, which we believe is egocentric in nature and gets updated continuously. Wang and Spelke (2000) argue that representation of targets is relative to the self and the representation is updated as the navigator moves through a novel environment.

Studies in cognitive psychology report that humans can form images of unseen environments; images are egocentric, representing the environment from a particular point of view. Amorim et al., (1997) demonstrate that humans have two different types of processing modes in their memory during non-visual navigation; namely task centred processing mode and object centred processing mode. In object centred mode the object's perspective is kept track of at every instance of the navigation thereby making it challenging in terms of cognitive load. The object centred mode involves slower body movements and locomotion. In the task centred mode, a human being is expected to mentally trace the path without worrying about the objects. Above we have distinguished exploration (object centred) from locomotion (task centred). The processing modes are a prerequisite for path integration (Etienne & Jeffery 2004; Mittelstaedt & Glasauer 1991) which uses available vestibular and kinaesthetic cues and motor command information to maintain self-orientation and position during navigation in the absence of vision.

Experimental investigation of 'path integration' usually comprises a learning phase, where the subjects view the scene; and a test phase, where the subjects are asked to walk blindfolded to a target point. It has been shown that providing subjects with landmarks during the test phase of path integration improves their performance (Kalia et al. 2013).

In the human robot interface the vibration motors are associated with impact points on the bumper. The aim is that this interface induces a spatial presentation for the handler. Below we discuss the design of a simple experiment to test the effectiveness of the spatial presentation.

6.3.3 Design of the test

Ideally the robot's feedback enhances the handler's exploration capability by contributing to the (implicit) mental mapping ability of the handler. Above, we have emphasised on the intuitiveness of associating the vibration motors with impact points on the bumper. Since object centred processing mode is demanding, it is important to design a simple experiment to see whether a handler is able to point out to a particular direction in space, on receiving a haptic signal (vibrating motor activation). The experiment is an adaptation of the work of Gescheider (1965) who conducted a set of experiments to compare localisation of sound, based on both acoustic and cutaneous feedback. Another inspiration for the experiment comes from Haber et al., (1993): they state that pointing methods using body parts (e.g., nose, chest, or index finger) or extensions of body parts (e.g., hand-held cane or short stick) lead to more accurate responses. For the study, we have used a wooden replica of the handle shown in Figure 73. The replica has also a crutch like design exactly like the haptic interface discussed in Chapter 5; it is 1.2 meters in length, from the point of hold to the tip. As explained in the previous chapter, when the handle is held straight, the distance between the handle and the centre line of the handler's body is roughly 20 centimeters. We provide the handler with a dummy handle and we replicate the impact points on the bumper (points A-D in Figure 72) as locations painted on the floor in the form of a semi-circle, in front of the handler where they point, refer to Figure 74. Since we are only interested in the front half of the bumper, we resort to a semi-circle rather than a full circle.

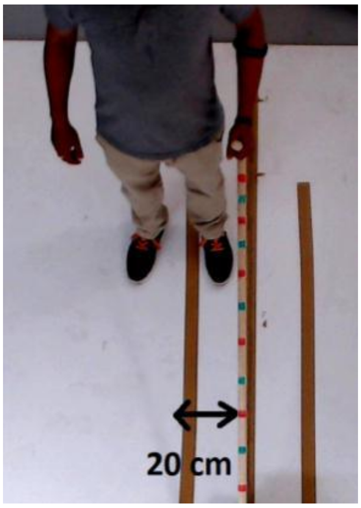

Figure 73, Subject holding the wooden handle replica straight

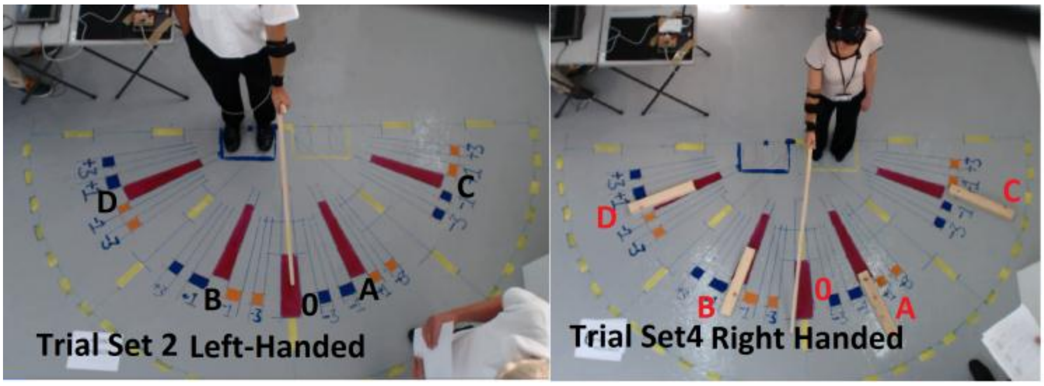

Figure 74, the experimental layout, a protractor painted on the floor as well as a marked position for the subject

The four vibrating motors are attached to the forearm of the subjects, as shown in Figure 71. The motors are connected through a National Instrument DAQ card and activated using a Wizard of Oz interface developed in a NI-Labview 2009 environment. The motors are individually controlled by the wizard; however, all motors get activated for a time period of one second and all operate at the same frequency (200 Hz approximately) and intensity (vibration amplitude 0.8 G approximately). To assign a specific message to each of the motors (as shown in Figure 72), a pictorial representation of the bumper, drawn in the form of a semi-circle, is used. While investigating whether subjects would be able to correctly indicate the location as well as the orientation of the previously seen object after the walk without vision, Amorim et al., (1997) recall the '*rectilinear normalization*' effect observed in several studies, where navigation and orientation judgements tend to be carried out in (and distorted toward) a normalised right-angle grid. Sadalla and Montello (1989) found that angles that are close to 0^0, 90^0 or 180^0 are the most accurately remembered. They also found that turns between 0^0 and 90^0 were all over estimated, while turns between 90^0 and 180^0 were all underestimated. If one stands on the centre of a semicircle, one quarter (90^0) lies on his left and the other (90^0) on his right. We intend to have two target points in each quarter. Therefore the radius of the semicircle is 1.7 meters within which certain target points (in red) are marked out. The semi-circle is divided into 54 sectors (to facilitate scoring each participant on the given task), where the angle for each sector is 3.3 degrees (approximately) (as shown in Figure 75). The target points, corresponding to the impact points on the bumper, are as follows (Figure 72):

- Target point 0: perpendicular radius to the base of the circle
- Target point A: approximately 22.5 degrees on the left of Target point 0 (7th sector on the left of Target point 0) (reference Figure 75)
- Target point B: approximately 22.5 degrees on the right of Target point 0 (7th sector on the right of Target point 0)
- Target point C: approximately 67.5 degrees on the left of Target point 0 (20th sector on the left of Target point 0)
- Target point D: approximately 67.5 degrees on the right of Target point 0 (20th sector on the right of Target point 0)

6.3.4 Scoring convention followed

The target points have sector markings on either side, to give a score and analyse the accuracy of the participants (Figure 75). Footprints were marked 20 centimeters on the either side of the Target Space 0 (adapted to the dominant hand of the participant) where the participants are asked to stand, in order to make sure that their feet position is fixed during the course of the experiment and the body maintains same orientation throughout. Sectors are made and numbered (reference Figure 74), both to the right and to the left of each target point to enable precise scoring of the participants' performance by interpreting the recorded videos. The video camera is mounted on the ceiling, providing a view as shown in Figure 74.

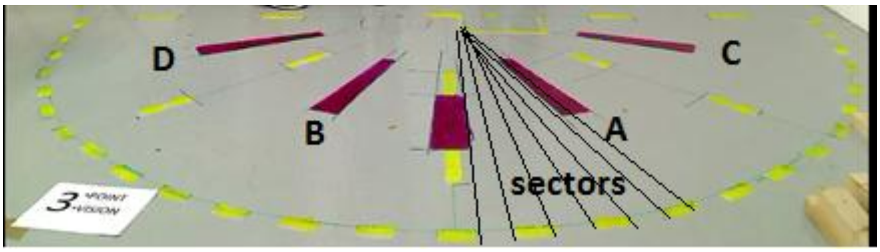

Figure 75, reconstruction of the sector markings on the image

The overhead camera provides an orthogonal projection of the handle on the floor (reference Figure 74); errors are estimated to be minimal when a participant pointed at the marked red sector of a target point. Therefore a score of zero is given, meaning he is accurate and points on the target point. If the participant points to any sector either to the left or the right of the red area, an absolute score is given based on the respective markings of the sectors. A sign convention is followed (as shown in Figure 76); movement in clockwise direction represents positive whereas movement in anticlockwise direction represents negative. The higher the absolute value of the score, the less accurate the participant is in judging the target space. Figure 75 shows a representation of the sectors between Target point 0 and Target point A.

As mentioned earlier, the trials are all video recorded and scorings are done afterwards, by interpreting the videos. After every motor is activated, the actual position of the replica handle is compared with the intended position (marked target offset corresponding to the motor activation) using the marked sectors. When a participant pointed at the marked red area of a target space, a score of zero (0) is given, meaning the result is accurate. If the participant pointed either to the left or the right of the red area, depending on the sector where they have pointed, a deviation score is determined. Therefore, it is evident that the higher the score more is the deviation from the target points. For example, in Figure 76 L1 is activated, the stick should have been at A (market as the offset of interest in Figure 76), but the stick actually points at the third sector, right of A. The sign convention is that a clockwise deviation is positive whereas anticlockwise deviations are negative. Thus in case of Figure 76 the participant scores +3, the original score.

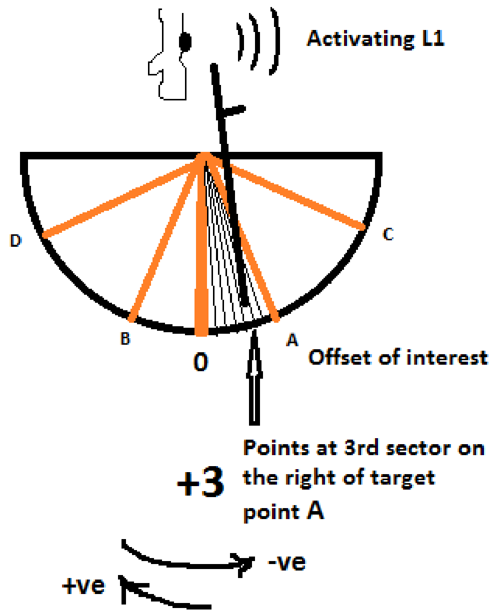

Figure 76, schematic diagram of the floor layout

The primary reason behind the experimental design is to study if the participants can reliably associate the vibrating motor activations with the marked target points that correspond to the impact points of the bumper. In the process the haptic stimuli should integrate with the egocentric representation of space. As the tool used in this case is a handle and the target points are represented by displacing it from the point of rest, the question arises whether the cognitive faculties of the participants represent space (displacement) relative to their body position or to position of their arms when the handle is at rest. Inspired by the work of Johnson-Frey (2003) therefore, we introduced two different scores for each trial; '*original score*' and '*relative score*'. To calculate the '*relative score*', the resting position of the replica handle, before a particular motor activation, has also been scored with respect to Target point 0, (resting position score) in the same way. Using the resting position score we can compensate the scores: for instance, if the right handed participant (Figure 4 right) scores +3 for a specific target direction, then the relative score would be +2 (*original score* - *resting position score*) for the same target. The '*original*' score is the score directly based on the position of the handle in the painted protractor. The '*relative*' score is produced by compensating the original score with the rest position observed before each move. Thus we are able to evaluate whether the initial resting position has any impact on a participant's performance.

6.3.5 Testing protocol

Nine participants, aging between 22 and 55 and without any medical condition, took part in the experimental study. They were asked to stand in front of a semi-circle. Before the commencement of the experiment, we have carried out the following for each participant:

- Briefing about the experiment.
- Asked to sign a consent form.
- Given a disposable sleeve to wear on the lower arm for hygiene reasons.
- Standing on the marked footprints, they are asked to hold the handle with the naturally dominating hand in order to find out if the participant is left handed or right handed.

Each participant undertook 6 sets of trials (8 trials per set i.e. 48 trials in total for one participant). The trials are carried out in both non-blindfolded and blindfolded states: a) (non-blindfolded state) to ensure that the participants undergo a training session and establish whether they can reliably associate a cuff signal with a pointing action with the handle; b) (blindfolded state) to establish whether subjects can carry over their spatial discriminations using memorised locational information and encoded actions from the learning trial session. The trials, carried out, are as follows:

Trial 0, the first set (referred as trial 0) is a pre-test to understand each participant's (without having idea of target spaces) spontaneous interpretation of instructions given. Participants were blind-folded and asked to hold the handle, stand on the marked area for footsteps and carry out the following instructions:

a. A small movement of the handle to the near left (a briefing is given before the start, that the act should be performed on receiving a haptic signal like a gentle tap on the left shoulder, in order to reduce the cognitive load of interpreting verbal commands at the time of the trial).
b. A small movement of the handle to near right (given a gentle tap on the right shoulder).
c. A large movement of the handle to the far left (given two gentle taps on the left shoulder).
d. A large movement of the handle to the far right (given two gentle taps on the right shoulder).

Here, the subjects showed their personal interpretation of the verbal descriptions of the intensity of the movement (‘*small*’, ‘*large*’) and direction (‘*near left*’, ‘*far left*’).

The next set of trials (trial set 1 to 5) uses the same experimental layout; however, participants are to be prepared before that. They are made to wear the disposable sleeves prior to attaching the vibration motors correctly. In order to make sure that the vibrating motors (L1, L2, R1, R2), are fitted uniformly for all participants, L1 and R1 sit on either side of the wrist (carpus) and then the length between carpus and elbow (olecranon) is measured. L2 and R2 sit on the part of the lower arm that corresponds to the two third of the length previously measured (as shown in Figure 77).

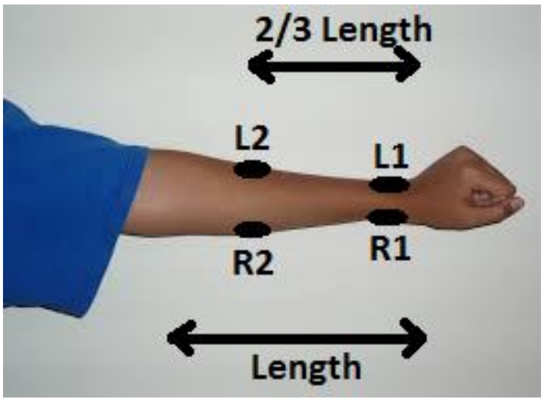

Figure 77, Positioning of vibrating motors on one's arm

Once the vibration motors were attached, each motor was activated and participants are asked to point to the activated motor. This was to ensure that the motors were working and participants could indeed feel the vibration of each motor. Once the motors were attached appropriately, the participants are made to hold the handle and return to the area of the semi-circle where footsteps are marked. At the time of the briefing, the following conventions are narrated:

- When no vibrating motor is activated, the handle is to be held relaxed with elbow slightly flexed, pointing in front. This is termed as their neutral position (close to Target point 0)
- When L1 is activated, the handle is to be moved as close as possible to Target point A (actual near left, small movement).
- When R1 is activated, the handle is to be moved as close as possible to Target point B (actual near right, small movement).
- When L2 is activated, the handle is to be moved as close as possible to Target point C (actual far left, large movement).
- When R2 is activated, the handle is to be moved as close as possible to Target Space D (actual far right, large movement)

When participants have an idea of small and large movements with the handle (egocentric in nature), the remaining five sets of trials are carried out in the following way:

Trial 1 is mainly meant for familiarisation with the task of associating vibration motor activations with target points. Participants are not blindfolded and asked to carry out the task as described above.

In *trial 2* (testing without training), Participants are blindfolded and asked to carry out the task as described and no help is given. This is a trial set where participants have performed without receiving much training.

Trial 3 is meant for training and learning. Based on the work of Tan et al (Tan et al. 2002), we have introduced more kinesthetic cues in the experiment to improve their spatial memory performance. Participants remained blindfolded and blocks of wood are placed in the target areas A to D (as shown in Figure 78), so that they can feel a feedback when the tip of the handle (Serino et al. 2007) is gently tapped on the blocks. Subjects are asked to carry out the trial as described above; the instructor guided the subjects to find the right target spaces to avoid them hitting the blocks hard. The idea is to make the participants remember the points with the help of kinaesthetic cues (Tan et al. 2002).

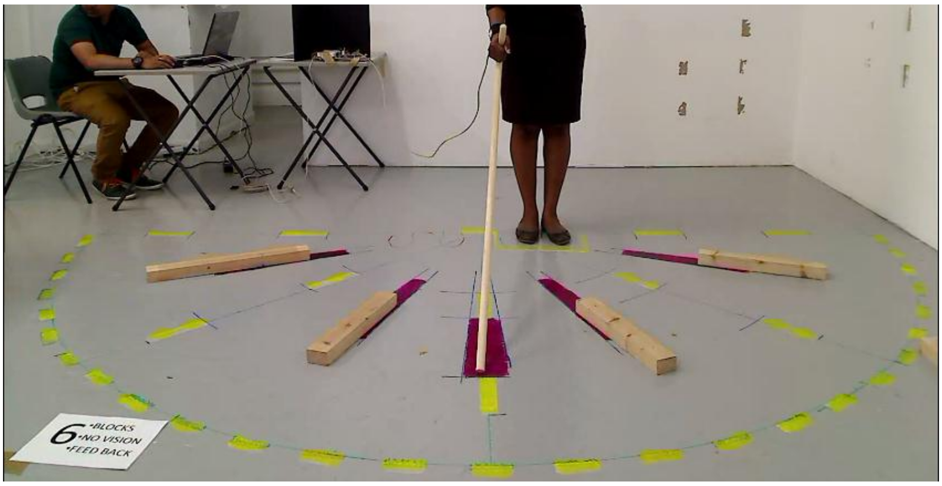

Figure 78, wooden blocks placed on the target states A-D

Trial 4 is also meant for learning without instructions from the instructor, where subjects remained blindfolded and wooden blocks remained in the target areas A to D. Subjects are asked to carry out the experiment as described above and no help is given.

Trial 5, (testing after training), subjects remained blindfolded, the wooden blocks are removed and subjects were asked to carry out the experiment as described, no help was given (similar to *trial 2*). Table 6 below presents a summary of the sets

Trial Number	Code	Description
0	Verbal Instruction (Blindfolded)	Participants showed their personal interpretation of the verbal descriptions of the intensity of the movement ('small', 'large') and direction ('near left', 'far left').
1	Familiarisation (Non-blindfolded)	Familiarisation with the task of associating vibration motor activations rightly with target points. Participants are not blindfolded and asked to carry out the task as described above.
2	Blindfolded testing	Participants are blindfolded and asked to carry out the task as described without any training
3	Training and learning using kinaesthetic cues with feedback (Blindfolded)	Blocks of wood are placed in the target areas A to D, so that participants can feel a feedback when the tip of the handle is gently tapped on the blocks with guidance from the instructor.
4	Training and learning using kinaesthetic cues without feedback (Blindfolded)	Blocks of wood are placed in the target areas A to D, so that participants can feel a feedback when the tip of the handle is

		gently tapped on the blocks without guidance from the instructor.
5	Blindfolded testing after training with kinaesthetic feedback	Participants are blindfolded and asked to carry out the task as described.

Table 6, Summary of trial sets

To counterbalance the order in which the vibration motors are activated, four sequences of 8 selected motor activations (two activations of each motor) are prepared in advance of the experiment. For each of the trials sets (1 to 4) one of the four sequences is selected randomly. However, for every respective participant, the sequence presented in trial 5 (blindfolded testing after training with kinaesthetic feedback) is the same as used in trial 2 (blindfolded testing). The idea is to carry out a comparative study between these to trial sets to understand if there is any effect of training with the wooden blocks (kinaesthetic feedback).

6.3.6 Results

Reliability of the haptic messages communicated via the feedback cuff

Since the purpose of the experiments is to investigate whether the design choices do contribute to the spatial awareness of the handler, the first point is to see whether subjects can haptically associate between target zones A to D with the transmitted vibration messages. Therefore, we have done a comparative study between three testing trials - that is *trial 0* (interpretation of verbal instructions) where participants do not have idea of target points and they only interpret verbal instructions '*near or far, left or right*', *trial 2* (*blindfolded*) where participants performed after a familiarisation trial session and *trial 5* (*blindfolded after kinaesthetic feedback*) where participants use memory of the previous trial with kinaesthetic cues - to understand how reliably participants can associate signals on the forearm with pointing at the right target directions, when they are blindfolded. The remaining trial sets are meant for either familiarisation or training, hence they are not taken into consideration.

None of the subjects made a real error: as the vibration motors were activated, subjects never pointed to a wrong target point. Figure 79 and Figure 80 show mean absolute original scores and relative scores for all participants across three above mentioned trials. According to the scoring convention followed, it is evident that lower the score, the more accurate a participant is in judging a target point on receiving a motor activation. The scores do not show huge deviation (less than 2) from the points of interest. The error bars also show that there is no significant difference vibration motor among points A, C and D in terms of accuracy. However, participants tend to most accurate while pointing at target point B.

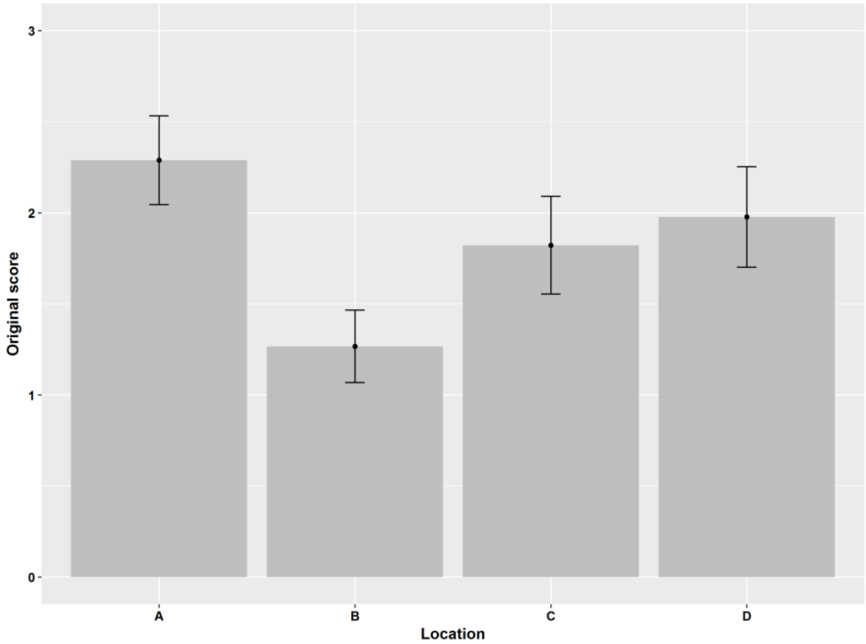

Figure 79, Mean original scores in absolute values, L1 associates with target A, R1 with target B, L2 with C and R2 with D.

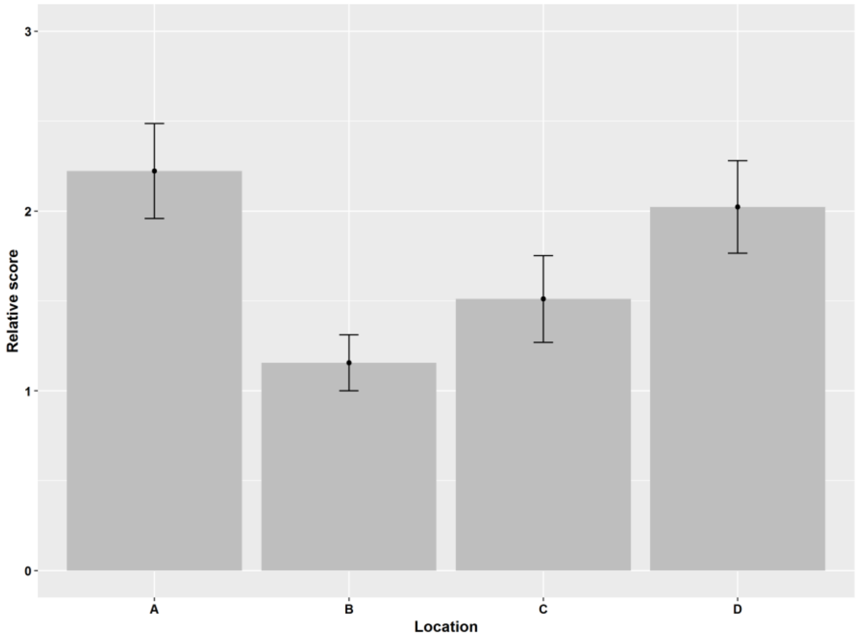

Figure 80, Mean relative scores in absolute values, L1 associates with target A, R1 with target B, L2 with C and R2 with D.

Effect of position of arms in egocentric representation of space

As mentioned in section 6.3.4 the target points are represented by displacing the handle replica from the position of rest to corresponding marked offsets on the floor. So the question arises whether the displacement is to be calculated from the *Target point 0* or from the exact resting position of the handle before the motor activation. This helps us understand if the egocentric spatial representation uses body position or the hand position as the point of reference. Therefore, we introduced '*relative score*', which is calculated by scoring the resting position and subtracting that score from the '*original score'*. Figure 81 presents the box plot of original scores and relative scores for all participants across three testing trials for visualising the distribution. Red dots in the figure signify the outliers; the differences in the ends of upper whiskers are 2 and the lower whiskers are 1). Although the median (which is 0) is the same for both score types, the difference of interquartile range for the upper quartiles (which is 2 for original score and 1 for relative score) in two box plots is one. Thus, when the relative score is considered the errors seem lower.

A Wilcoxon signed ranked test between original and relative scores indicate that initial position of the handle had a significant effect on the error score of participants as accounting for their baseline starting position reduced their performance error, $V = 1636, p < 0.001$.

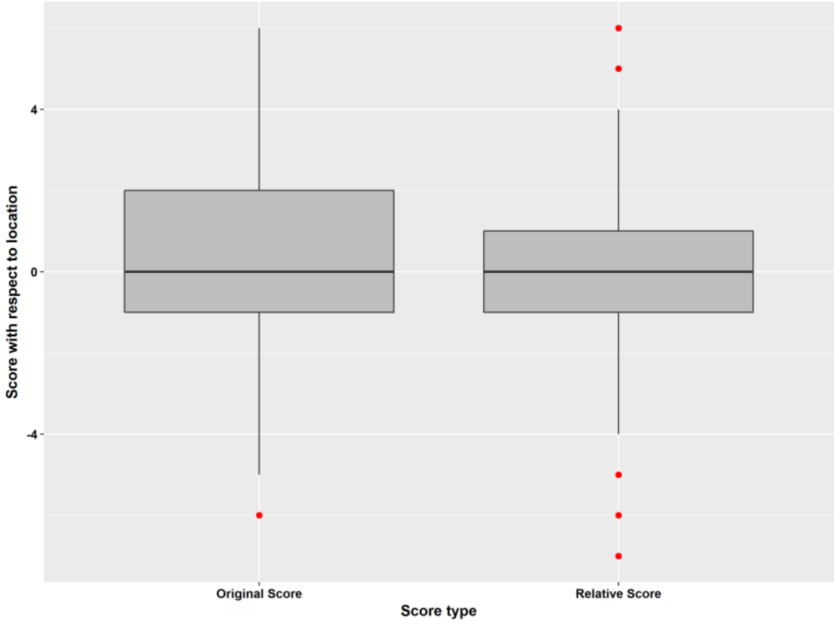

Figure 81, Box plots by score types

Effect of training with kinaesthetic cues

We intend to improve the participants' spatial memory performance by introducing two training sessions with kinaesthetic cues (*trial 3* and *trial 4*). The idea is to make sure participants remember the target points of interest more accurately, after being subjected to training. Figure 82 shows the mean original scores for all participants under three testing conditions (*trial 0, trial 2* and *trial 5*). Figure 83 shows the mean relative scores for the same. Both the figures show a similar pattern; none of the error bars overlap. Therefore it is conclusive that the participants make more errors when they have no idea of the target points and only interpret verbal commands, errors are minimised when they are familiar with task and finally errors are the least after they are trained with kinaesthetic cues.

The mean original scores for *trial 2 (blindfolded)* and *trial 5 (blindfolded and kinaesthetic feedback)* are 1.37 and 1.88 respectively. A Wilcoxon signed ranked test was conducted to compare participant score in *blindfolded* and *blindfolded &*

kinaesthetic feedback conditions. It indicates that there is a near significant effect of training on participants score $W = 3062.5$, $p = 0.0535$.

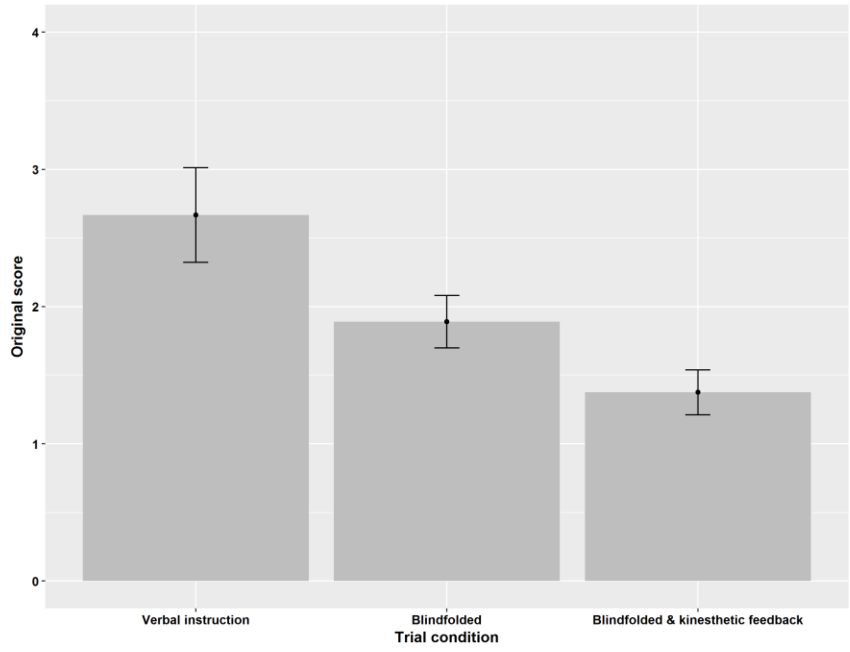

Figure 82, Mean original score for three testing trials

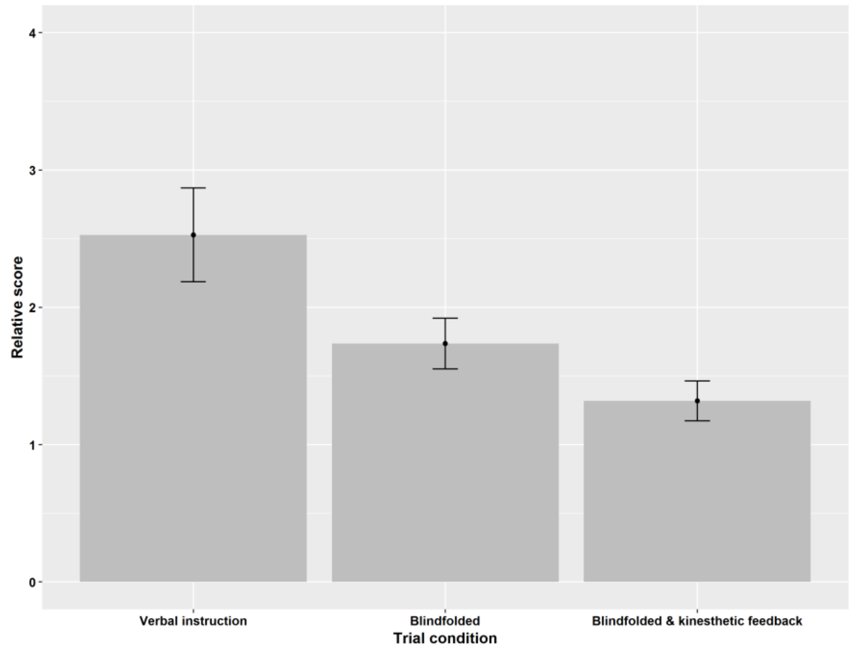

Figure 83,Mean relative scores for three testing trials

6.4.7 Discussion and conclusion

Prior to the experimental trials, we had no idea of the level of difficulty that the task would pose for the volunteer subjects. In the beginning, the participants showed their personal interpretation of the verbal descriptions of movement (‘small’, ‘large’) and direction (‘near left’, ‘far left’). However, as the results clearly show, the participants found the task to be manageable, without huge errors. Therefore a feedback system using vibrating motors can be used as a part of the haptic interface connecting handler and the guide robot, to transmit messages from the impact points of the bumper. It is also evident that the participants made rapid strides in task competence over the trial sessions. Accuracy in determining the four specified target points improved over the sequence of trials, when training sessions with the wooden blocks were introduced providing direct haptic feedback for the participants. As we have mentioned in Chapter 2 that the system is to be used by skilled handlers, it is clear that they would have better egocentric spatial representation if they receive prior training about the various impact points of the bumper using kinaesthetic cues. Furthermore, results show that there is significant impact of initial resting position of the handle on participants' performance of judging the target points by displacing the handle. This is also an important design consideration for using the robot as a tool for exploration and defining the location of the impact points of the bumper, because these points in principle would contribute to the cognitive map of the handler; the results look more convincing when the points are spatially represented with respect to handler's arm position rather than the position of his body.

Chapter 7

Conclusion and future work

This chapter revisits the research questions and presents the conclusion of this thesis and future research work.

7.1 Revisiting the research questions

The fundamental research question that needed to be addressed was '*How can haptic sense be utilised for interaction with a robotic guide in zero visibility conditions*?' Several phases of research and evaluations have been conducted focusing on the problem. The fundamental research question was further broken down into sub questions. Reflections on each sub question and the respective answers are discussed as follows:

Research Question 1. *What can be learnt about interaction in zero visibility studying real world scenarios and how can these interaction models contribute to the research?*

Chapter 2 studied the protocols followed by the firefighters and the way they haptically communicate with each other. It also highlighted how visually impaired people make use of the haptic sense to navigate and the communicational landscape that is shared between them and the guide dogs at the time of the navigation. The learnings from studying these two real world scenarios helped us understand the interaction in zero visibility in a more comprehensive manner. Both the scenarios are excellent examples of collaborative activity, which gives us a ground to believe that when the handler interacts with the guide robot, they need to develop cooperation and operate as a team to achieve the task. There is a high level division of labour between two fire-fighters even though they work as a team, navigating a space in the absence of visibility. Having a look into their protocols, it was concluded that their task can be logically separated into *locomotion guidance* and *environmental exploration*. Therefore the question arises that when these two tasks are to be accomplished with the help of a guide robot, how can the division labour happen. The answer lies in interaction that takes place between a visually impaired person and a guide dog, which is an example of shared control and division of autonomy. The visually impaired person is always in control of the situation; embarking on his venture of navigating the route which he already has a mental map; he initiates the navigation and also takes navigation decisions after reading the clues and cues from the environment. The guide dog only provides guidance avoiding hazards from one point of decision (for e.g. - a junction) to another point of decision. Similarly the guide robot can act as an autonomous guide providing locomotion guidance and ensuring safe passage. At the time of exploration, the handler can be the dominant partner and make use of the same robot as a tool to examine the immediate environment.

Furthermore, in both cases, the interaction is homospheric, which means it takes place in close spatial proximity. While being in close proximity, fire-fighters use a rope as a form of connection between them whereas the visually impaired handler and the guide dog are connected by a rigid handle. Thus, the guide robot and its handler need to be connected using an interface, which in principle should be a rich enough medium to facilitate the flow of relevant information (feedback) between them. Due to the conditions, the feedback information cannot exploit visual and auditory senses of the handler; hence the natural choice becomes the haptic sense. Looking at the blind community, it is evident that a haptic interface is sensitive enough to gauge the environment and can be trained when other senses are absent.

Another important aspect learnt from the study is that both fire-fighters and visually impaired people have remarkable abilities of constructing a mental model of the environment (cognitive map). Thus the interface that connects the handler with the robot should contribute to the process of the relatively accurate construction of handler's mental model.

Research Question 2. *How sensitive and trainable the haptic sense is?*

Chapter 3 focuses on the haptic sense in a more detailed manner, which would be '*the sensibility of the individual to the world adjacent to his body by the use of his body*' in the literature. Haptic sense is linked with kinaesthetic (through the movements of the position of bones, joints and muscles) and cutaneous perceptions (through the skin) that are distributed all over the body and allows one to actively interact with the world. Though they are not mutually exclusive, this thesis is mostly concerned with the kinaesthetic awareness of human being and how its potential can be exploited in the context of interaction with the guide robot. Kinaesthetic awareness, proprioceptive in nature, is the perception of the relative position of one's body parts in space. Haptic sense, especially the kinaesthetic awareness, is mediated by one's motor abilities and has the potential to develop into a '*motor skill'*. Previous research (Bushnell et al. 1991) has highlighted the extraordinary speed and sensitivity of the haptic sense. However, the chapter aimed at highlighting the sensitivity and trainability of the sense, in the context of the handler's interaction with the guide robot. A small scale experiment was carried out, keeping in mind that if participants can use their haptic sense to discriminate between objects in terms of weight (sensitivity) and how quickly the sense improves over a short period of time (trainability). A semiological perspective was also integrated within the experimental design, associating the verbal descriptions of weight (‘light’, ‘medium’, ‘heavy’) with haptic feedback from the device. As an apparatus, a prototype of the intended guide robot system was used, which consisted of a wooden trolley attached to a handle (could be fixed on a participants' arm) and a bumper prototype that sat on the trolley. Participants (blindfolded and headphones on to remove visual and auditory feedback) were asked to use the apparatus to push wooden boxes of the same shape and size, containing varying weights and associating the predefined verbal labels (‘light’, ‘medium’, ‘heavy’) with what they felt. Although they had no idea of the weights, the results show that they learnt to coherently and successfully integrate the verbal labels with the weights during the course of the experiment. The proprioceptive information from the position of the fingers and wrist is used to hold the handle and the kinaesthetic information from the tension of the muscles helped them distinguish between weights. Over subsequent trials the accuracy of the participants showed improvement, meaning, they were learning fast in a very unfamiliar environment and their motor abilities were developing into motor skills (given training).

Research Question 3. *What is the physical connection between the robotic guide and the handler and how to evaluate the effectiveness of the connection?*

The literature on the subject of guide robots in low-visibility is rather sparse. However, there are several works on robotic assistance for visually impaired people, which is highlighted in chapter 4. It reflects on the literature where the human and the robot operate in a mixed initiative or shared control approach. Chapter 4 also looks into the *Comprehensive Assistive Technology* (CAT) model for understanding assistive technology and uses the model to analyse our situation of haptic interaction with the designed guide robot system, emphasising the importance of designing a suitable interface (the haptic interface). The interface is required to communicate the right information to create a haptic experience relevant to the main subject of the study. Chapter 5 presents a critical evaluation of the design of the haptic interface and explains how it can aid locomotion guidance for the handler. The first step towards developing an interface with robot guide is the fact that it ensures the safety of the handler. It was observed that when the robot traverses a path avoiding obstacles, it creates a spatial corridor safe for the handler. Thus, the working definition for safety for this thesis is '*handler should follow the trail of the robot as close as possible and his feet are placed as close to the spatial corridor created by the robot, as possible*'. The second most important aspect of having an effective interface is the fact that it contributes to the cognitive map of the handler. However, before testing the interface on these two grounds, chapter 5 carried out pilot trials in phases to infer its implementation on the robot and the grip specifications. A crutch like grip and a spring system at the base seemed the best solution for the problem being looked at. A preliminary phase of the evaluation was conducted, attaching a laser range finder at the back of the robot, to analyse the handler's following behaviour when attached to the robot. In the experiment the robot was pre-programmed to navigate fixed trajectories. The operator would start and if necessary stop the robot remotely. One could say that the robot emulated an autonomous behaviour as it was not tele-operated by the handler. The pre-programmed trajectories consisted of straight travels and turns, based on the TOUR model from literature. The turns varied, short turns were about 45 degrees while the longer ones were close to 70 degrees. The robot operated with a linear speed of 0.6m/s, while for the turns the angular speed was 0.5 rad/s. As an outcome, an evaluation metric was defined in terms of how closely the path of the handler matched the live path of the robot. Based on metric and keeping the above mentioned two aspects in mind (path matching and sense of cognitive map), lastly a more refined experimental design was realised. Results have shown how the spring system (flexible joint) at the base, during locomotion guidance by the robot, allows the participants to follow a safer path and the kinaesthetic feedback from the interface gives them a keener awareness of spatial orientation and location.

Research Question 4. *How can the robotic guide be used an exploratory tool?*

We have already discussed about a mixed mode of operation, where the autonomy is shared between the handler and the guide robot. Chapter 6 reflects on how the handler can use the powered guide robot as a tool to encounter obstacles in the environment. While being used as an exploration tool, physical contact with the obstacles is essential and to enable physical contact, a bumper was designed, which can estimate the point of the contact. The question arises about how the information about the impact can be transmitted to the handler in the form of haptic messages. Vibro-tactile feedback seemed to be a natural solution, as the mechanoreceptors on the skin respond to mechanical pressure or distortion. However, the tactile sensitivity of the human body varies by location. Previous research (Karuei et al. 2011) reflects that wrist, arms and spine are the most preferred locations for wearable haptic systems. Following this consideration, a haptic cuff for the forearm had to be designed; this would be attached to the crutch-like part of the interface. The initial haptic cuff consisted of six vibration motors, three of which sat on the palmer side of the forearm and other three on the dorsal side. An experiment was designed to validate the vibration messages in such a way that they do not add on to the cognitive load of the handler and the number of messages is optimised. Results show that the error rates are lowest when a single motor is active, followed by two concurrent active motors and highest during three concurrent active motors. Therefore it is evident that the cognitive load is lowest for haptic messages concerning single motor activations and subjective feedback also revealed that participants found it difficult to gauge the exact locations of the motors when they are close to each other. The results have led to the redesign of the haptic cuff with four vibrating motors, two on the palmer side and two on the dorsal side. The next phase evaluation is to investigate whether activation of the vibration motors induces an adequate spatial sense to the handler. The rationale behind the next phase evaluation was to see if results would give an insight into using vibration motors to represent the physical location of the impact between the robot bumper and obstacles. The robot was allowed to bump into an obstacle with the aim of alerting the handler to the presence of the obstacle but also to indicate the position of the obstacle relative to the handler. The main question for the next phase of study therefore was whether the handler can associate a vibration signal with a spatial direction. A Wizard of Oz experiment was designed with participants with a wooden handle replica having a crutch-like design and the redesigned cuff attached to their forearm in a way that the attachment was uniform for all. Initially they were asked to associate their spatial cognition with pre-defined verbal label (*near, far*, *right*, *left*) and their performances were recorded to have a base for comparative analysis. Then they were asked to point at marked targets on the floor on receiving a haptic message generated by a single motor activation from the wizard. The participants were blindfolded during the experiment to eliminate visual feedback and even trained with kinaesthetic cues through trial sessions so that their motor memory transforms into motor skills. Results show that participants can spatially discriminate among the target points to interpret the haptic messages, and their performances even improve after they have received training. Results even show pointing towards a target point involves knowledge of the limb's relative position, which is an important design consideration for the entire guide robot system consisting of the mobile robot, the bumper, the handle and the haptic cuff. Therefore this chapter gives an insight into how the system can contribute to one's task of spatially exploring the immediate environment.

7.2 Contributions of the thesis

The thesis presents a body of work that investigates the interaction of a human being with a robotic guide in zero visibility. The main contributions of this thesis are:

- Understanding interaction in zero visibility, which is an outcome of reflecting upon real world scenarios where people interact in zero visibility (such as interaction among firefighters and between visually impaired people and guide dogs).

- Understanding the haptic sense that could be used for interaction in zero visibility and designing experiments to study the sensitivity and trainability of that sense.
- Analysing and evaluating the design of a physical interface (designed by the consortium of the project) connecting the human and the robotic guide in zero visibility.
- Laying a foundation for design of test cases to evaluate human robot interaction in zero visibility, taking into consideration the aspects of locomotion guidance and environmental exploration.

7.2.1 Papers published from the work

- Ghosh, A.; Penders, J.; Jones, P.E.; Reed, H., "Experience of using a haptic interface to follow a robot without visual feedback," in Robot and Human Interactive Communication, 2014 RO-MAN: The 23rd IEEE International Symposium on, vol., no., pp.329-334, 25-29 Aug. 2014
- Ghosh, A., Alboul, L., Penders, J., Jones, P. and Reed, H., 2014. "Following a robot using a haptic interface without visual feedback" In: ACHI, Barcelona, Spain 23-27 March 2014, pp. 147-153.
- Jones, P, Ghosh, A, Penders, J, and Read, H, (2013), "Towards human technology symbiosis in the haptic mode,".In: International Conference on Communication, Media, Technology and Design, Famagusta, North Cyprus, 2-4 May 2013. 307-312.
- Ghosh, A, Penders, J, Jones, P, Reed, H, and Soranzo, A, (2014), "Exploring Haptic Feedback for Robot to Human Communication." ICDVRAT, Gothenberg, Sweden.

- Penders, J. and Ghosh, A., 2015. Human Robot Interaction in the Absence of Visual and Aural Feedback: Exploring the Haptic Sense. Procedia Computer Science, 71, pp.185-195

7.3 Reflections on the research

Some reflections of the research are detailed below:

- The thesis has presented research work about share of the autonomy between the handler and the guide robot to achieve the task, and how it could be logically separated into locomotion guidance and environmental exploration. Both these problems have been dealt with separately in this thesis. The biggest challenge would be conceptually integrating them under one system, in such a way that the handler (the dominant partner in the collaboration) can switch between them. Secondly, a more important question arises; once the handler decides to shift from one mode to the other, how will transition take place and how will the handler react to the transition. Thirdly the guide robot system (the mobile robot, the bumper, the handle and the feedback cuff) design concerning environmental exploration is still in its early stages. Interesting would be when actual data in regards to impact on the bumper is transmitted in the form of vibration messages. It would be interesting if the new research could shed light on this context.
- The guide robot operates at a linear speed of 0.6m/s and 0.5rad/s at the turns. Reflecting on the thesis and considering the fact that an unknown environment is traversed in absence of visibility, it would be interesting to investigate how the robot guide could adapt to the walking speed of the handler.
- Experiments were performed concerning locomotion guidance and participants' performances were analysed on two different handle settings. However, their subjective experiences (confidence) were not captured based on these settings. A more refined and fine grained experimental design to test the handle could be done. Another complicating factor might

be the slippage caused by the resistance forces the handler exerts on the robot while following; a measure of which can reveal the confidence of the handler.

- The fire-fighters use their front leg in a fan-like motion to form an arc and explore the environment ahead of them (similar to the motion of the cane used by visually impaired people). But, in order to explore specific obstacles, they tap their feet on them (in case of visually impaired, the tip of the cane is tapped). The ultrasonic sensors on board the mobile robot, can create a spatial window to detect the presence of obstacles, however, to explore them physically, what should be the motion of the robot? Therefore research can be continued, to shed light on these questions, seeking answers.

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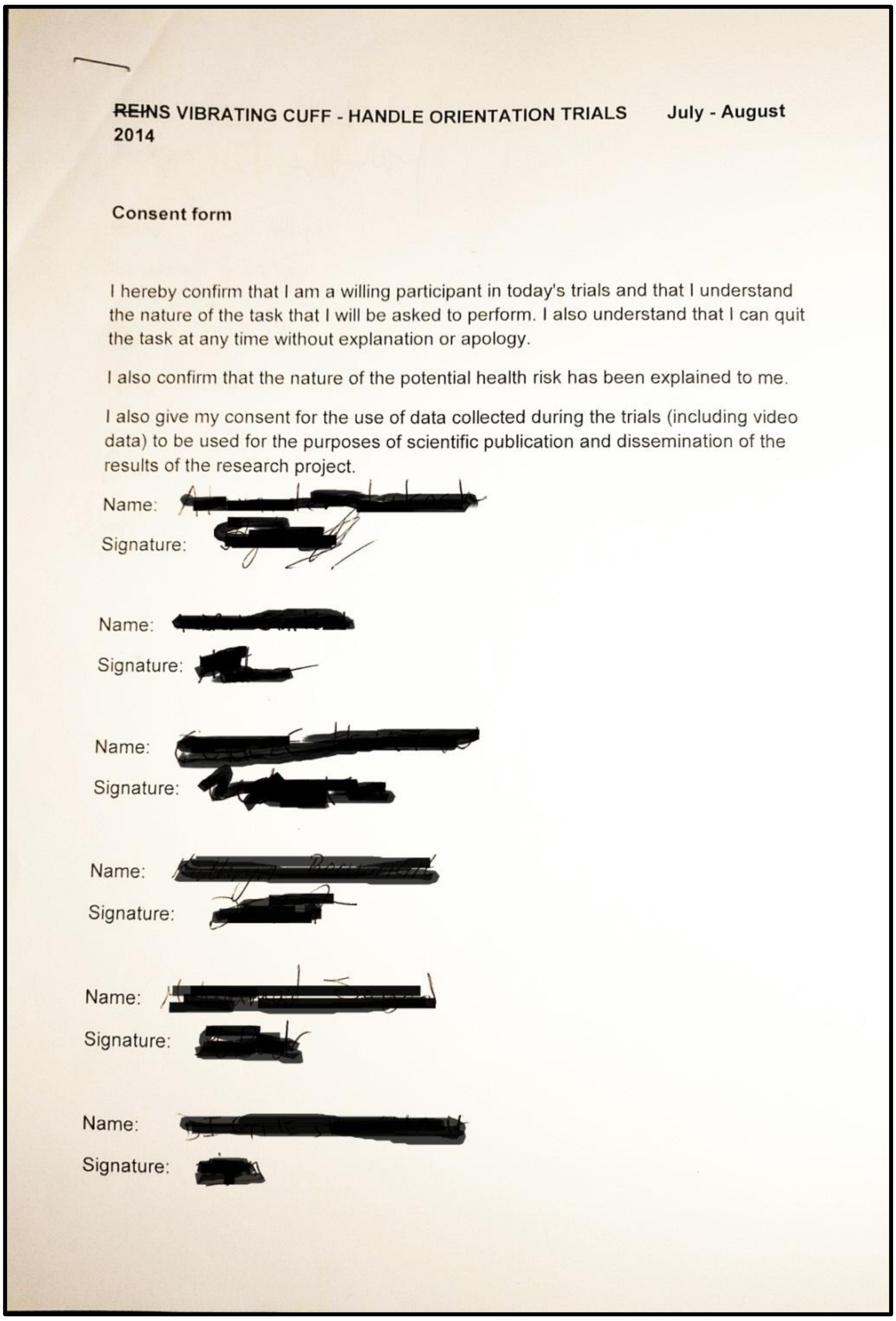
Appendix

Consent form used for participants for all trials



REINS VIBRATING CUFF - HANDLE ORIENTATION TRIALS July - August 2014

Consent form

I hereby confirm that I am a willing participant in today's trials and that I understand the nature of the task that I will be asked to perform. I also understand that I can quit the task at any time without explanation or apology.

I also confirm that the nature of the potential health risk has been explained to me.

I also give my consent for the use of data collected during the trials (including video data) to be used for the purposes of scientific publication and dissemination of the results of the research project.

Name: [redacted]

Signature: [redacted]

Name: [redacted]

Signature: [redacted]

Name: [redacted]

Signature: [redacted]

Name: [redacted]

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