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Cues for Vibro-tactile Route Guidance

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Declaration

This research thesis is my own work and has been carried out at the Department of Pervasive Computing, Johannes Kepler University, Linz, Austria. It has not been submitted to any other institution in order to request for another degree.

Linz (Austria), November 3, 2009

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Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Diplomarbeit selbstständig und ohne fremde Hilfe verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt bzw. die wörtlich oder sinngemäß entnommenen Stellen als solche kenntlich gemacht habe.

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Kurzfassung

In der heutigen globalisierten und schnelllebigen Welt stellt Mobilität einen immer wichtigeren Faktor dar. Eine der Herausvorderungen dabei ist die zuverlässige Orientierung an unbekannten Orten. Unterstützende Technologien existieren z.B. in Form von Navigationsgeräten, wobei die meisten dieser Geräte Informationen über den auditiven oder visuellen Kanal übertragen. Die dazu benötigten Sinne Hören und Sehen sind zwar gut erforscht und werden ständig benützt, haben aber auch ihre Nachteile: Nachrichten können von der eigentlichen Aufgabe wie beispielsweise dem Lenken eines KFZ ablenken oder überhört bzw. übersehen werden. Zusätzliche Probleme treten für blinde oder sehbehinderte Menschen auf, und auch für nicht beeinträchtigte Menschen gibt es Situationen in denen einzelne Sinne überlastet oder nicht verfügbar sind (laute Umgebungen, Dunkelheit, Nebel,. . .).

Dies motiviert den Einsatz einer anderen Modalität: dem Tastsinn. In der Literatur wurde bereits bewiesen, dass es möglich ist Menschen nur durch taktile Reize von Wegpunkt zu Wegpunkt zu führen wenn diese hunderte Meter voneinander entfernt sind. Diese Experimente wurden allerdings auf freiem Feld bzw. im Wald mittels Positionsbestimmung über GPS durchgeführt.

Das Ziel dieser Arbeit war es zu zeigen, dass (*i*) präzises Führen auch im kleineren Maßstab, mit Wegpunkten, die nur $1.5m$ voneinander entfert sind, möglich ist, dass (*ii*) Distanzinformation in den taktilen Reizen zu präziserer Navigation (kürzere Wege in schnellerer Zeit) führt und, dass (*iii*) multimodale Wahrnehmung im Sinne von gleichzeitigem Hören und Spüren der Vibrationen ebenfalls zu höherer Präzision beiträgt.

Im Zuge dieser Arbeit wurde Software entwickelt um mit den Daten des Positionierungssystems taktile Reize zu berechnen und diese an einen Taktorgürtel zu schicken. Insgesamt wurden 7 Experimente mit 4 verschiedenen Reiztypen an 10 Testpersonen durchgeführt.

Die Ergebnisse zeigen, dass (*i*) präzises Führen auf kleinem Raum möglich ist. (*ii*) Es konnte nicht bewiesen werden, dass die zusätzlich übertragene Distanzinformation zu einer Verbesserung der Präzision führt, es wurde allerdings das gleiche Ergebnis wie bei Reizen ohne Distanzinformation erreicht. Dennoch wurde durch die Distanzinformation ein positiver Effekt erzielt: ungefähr die Hälfte der Testpersonen konnte einschätzen wann sie den nächsten Wegpunkt erreichen werden. (*iii*) Ein positiver Effekt der multimodalen Wahrnehmung konnte ebenfalls nicht gezeigt werden.

Zukünftige Arbeit sollte sich mit dem Lerneffekt bei Reizen mit Distanzinformation konzentrieren.

Abstract

In today's modern and fast-paced world mobility is getting more and more important. One of the challenges with that is orientation in unknown places. Supporting technologies exist e.g. in the form of navigation devices, where most of them convey information through the auditory or visual channel. The modalities hearing and seeing have the advantage of being well explored and commonly used, but can also be problematic: their use can be distracting, information may be overlooked due to information overload, they are limited for people with impaired vision or the blind, and there are situations where they can be blocked (e.g. noisy environments, darkness, fog,...).

This motivates the use of another modality: the sense of touch. Related works have already shown that it is possible to guide people between points that are several 100s of meters apart. In their research GPS was used for tracking and a large field and a forest served as the testing ground.

The goal of this work was to show that (*i*) accurate route guidance is possible on a much smaller scale with waypoints which are only $1.5m$ apart, (*ii*) encoding distance information in the tactile cues will improve walking accuracy (participants should walk faster and with less detours) and provide situation awareness, and (*iii*) multimodal notification (by means of hearing the noise of vibrating tactors) will further increase accuracy.

In the course of this work software was developed to get position information from the indoor tracking system, calculate tactile cues and send them to a vibro-tactile belt. In total 7 experiments testing 4 different types of cues have been conducted with 10 participants.

Results showed that (*i*) indoor route guiding is possible. (*ii*) It could not be proven that distance information improves performance but equal performance to the baseline experiments was reached. However, a positive effect was achieved: almost half of the participants could estimate when they were near to the next waypoint. (*iii*) A positive effect of multimodal notification could not be proven as well.

Future work should focus on exploring the impact of a learning effect on cues with distance encoding.

Contents

Chapter 1

Motivation

This diploma thesis deals with vibro-tactile cues, more specifically with the use of these cues to support people in finding their way while walking. One may wonder why it is necessary to use vibrational guidance cues when we were able to find our way without them until now. For that I want to outline which methods or supportive devices we use for orienting ourselves today, which issues exist with these approaches and how vibro-tactile cues may help to solve them. A special emphasis is put on how these cues may help blind or visually impaired people to more autonomous mobility.

Mobility: Mobility is getting more and more important in our modern society. Our cities and buildings are growing, city maps tend to grow into vast grids where it is difficult to find specific streets or buildings. The interiors of shopping malls, airports, train stations or office blocks are like a maze for people who visit them for the first time. Since mobility is rising, chances that we visit new places are higher than in the past, also traffic volume, both car and pedestrian traffic, is growing steadily. For many people it is part of their daily routine to visit places where where they do not know the necessary directions and the best way to get there. The increasing amount of ways of transportation and temporarily unsuitable routes due to traffic jams or accidents makes this task even more challenging.

1.1 Conventional Approaches to Orientation and their Drawbacks

In our neighborhood, on the way to work or to relatives no help is required, one knows the way by heart. But as soon as we go someplace new we need a way of finding out where to go exactly and which is the best way to get there considering factors like distance and duration. Additionally it would be great to get help if we get lost underway. Conventional methods to find our way around depend on the means of transportation.

1.1.1 On the Road

When going longer distances by car we use **road signs** to drive from city to city. In combination with **maps**, where one looks for the shortest way to the goal beforehand, making mental notes of places one has to pass, this is an old but working approach. Another source of information, often the last resort due to inconveniences, is asking **passersby** or local people for directions.

An easier and more modern approach is using a **GPS car navigation system** that provides visual as well as auditive feedback. Programming a route is as easy as providing the device with the destination and maybe extra options like avoiding toll roads. The information provided by the device is always related to the current position of the user and highly detailed.

Problems: Above noted approaches have several issues. When driving a car asking passersby is difficult, because it involves stopping and nobody may be around. Road signs are stationary and may be overlooked. Sometimes there are so many signs that it is difficult to find the one containing information relevant for the current situation. Maps should not be read while driving and reading them correctly can be a time consuming matter, also for long trips one would have to remember more details about the route than possible.

When using a navigation system one should theoretically be able to merely rely on its directions without further efforts, but in reality GPS positioning is sometimes not as exact as required: e.g. tunnels or high skyscrapers prevent the GPS signal from reaching the receiver. Another drawback is that while driving it is not recommended to intensively use a graphical GPS system. However, using voice output instead or complementary works well.

1.1.2 By Foot

Basically the same methods as when steering a vehicle also apply for the walking scenario, with some changes in suitability. Sometimes it is a good choice to follow **signs** even as a pedestrian, an example being the stroll from the main square of a city to a nearby castle. Also when looking for certain places like the toilet or the elevator in a building following signs tends to be a good solution. **Asking people** for help is much more convenient while walking since we can easily stop and are more flexible when not sitting in a vehicle. On the other hand, **navigation devices** are not commonly used yet. However, the recent trend to have Google Maps or similar products available on modern mobile phones may change this soon.

Problems: When walking outside of a building we often can not rely on signs that lead us to our goal. Signs may only be an option when visiting important places, otherwise signs are sparse. Even finding out which street one is currently walking in can sometimes be difficult, finding out how to get to another street is impossible. A sign is stationary and must be discovered by the person interested in this information (pull information).

Graphical navigation systems have the advantage of always residing at the same spot and notifying us in the right moment (push information). They may be practical in a car where they are mounted, but when walking such a device must be held in a hand. Miniaturization will one day make displays available everywhere, as demonstrated in [1] where sunglasses with miniature displays are capable of displaying e.g. guidance information to the user, but this technology is not yet ready for the mass market. Since it is necessary or advisable to stop for studying the map to avoid stumbling or bumping into people, this slows us down. By using voice output the slowdown can be avoided, but it is also not optimal: the output must compete with ambient noises and music we listen to and when we want to talk to somebody an ear is blocked by an earplug.

1.1.3 Blind People

To navigate in unfamiliar places is, for obvious reasons, particularly difficult for blind people, as they can not easily study maps or visually orient themselves. Current position and movement direction, the structure of buildings, the meaning or even presence of objects, stairs, elevators can not be obtained autonomously.

When walking without a human guide they use different means of orientation; the most common being the **long cane** or blindman's stick, used for sensing obstacles, curbs, and guiding lines carved out of the asphalt. When only using a long cane the person needs to know her surroundings very well, knowing the location of cross-walks and sidewalks is mandatory, exploration of never-visited regions nearly impossible.

Guard dogs are trained to obey commands like "turn left", "search for the next door", or "cross the street" and are able to find cross-walks, stairways or doors. When guiding, they are aware of the space required for the blind person to walk, avoiding crashes with lampposts, mailboxes, or low-hanging branches [2]. That way a blind person, together with her guard dog, can safely navigate in unknown regions, but, as with the long cane, the person's situation awareness solely depends on her knowledge of the surroundings. Once lost, there is no easy way to find the way back alone.

Indoor and outdoor navigation for blind people is a very active field of research. I will mention two short examples: Ross and Blasch [3] presented an outdoor guiding system using GPS, voice output and a 3 by 3 matrix of "shoulder tappers" on the back for giving directional information. In [4] Hub et al. developed an enhanced long cane with cameras for object tracking, a keyboard for interaction and voice output and WLAN-based tracking. Information about objects was gathered from an annotated 3D-model of the building and its objects.

Furthermore, there are commercially available **navigation devices** especially designed for the blind and visually impaired, two examples being the "UltraCane"[1], a long cane with ultrasonic obstacle detection by Sound Foresight Ltd., and "Trekker" by Humanware[2], which tells its users, amongst other things, their current location, points of interest or landmarks, and intersections either through an earplug or a braille display, solving the big issue of lacking situation awareness.

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[1] "UltraCane" by Sound Foresight Ltd., URL: `http://www.batcane.com`, last retrieved September 2, 2009

[2] Trekker by Humanware, URL: `http://www.humanware.com/en-europe/products/blindness/talking_gps/trekker/_details/id_88/trekker.html`, last retrieved September 2, 2009

Problems: Any information that is presented visually, maps, road signs and visual displays, are of no use for blind people. Most devices that allow blind people to navigate can not be used hands-free and require a lot of care, an example for that being guide dogs. Neither long cane nor guide dog provide situation awareness. Current GPS navigation systems may remedy this problem, but voice output is not an ideal solution as blind people depend on the sense of hearing to be aware of their surroundings [5]. Wearable braille keyboards make the device non-hands-free. Moving in unknown areas is still a real challenge.

1.1.4 Information Overload

Another problem with signs and navigation devices is that they use the auditory and visual channel, two channels that are heavily in use already. Ambient noises like people chatting and laughing, honking cars, braking tramways, or even just music we listen to may drown information arriving via the auditory channel. Blinking advertisements, moving cars and people may distract us from relevant signs. In extreme cases, it may be impossible to get visual input even for people with normal sight: consider somebody walking in dense fog, trekkers caught in a white out in the mountains or a person in a burning building filled with smoke.

1.1.5 Summary

Today's electronic navigation devices are helpful already, for a comprehensive overview of the current state of the art of driver assistance see [6], but they can be too intrusive for walking scenarios. Obviously blind people are more willing to use costly, heavy or complicated solutions, as they depend on such aids. For them navigation devices are not only gadgets providing more comfort, but a significant improvement in the quality of life, because then they can move around more independently without the need of human guides. Our research shall contribute to better and less obstrusive interfaces for both blind and people with normal vision.

To condense the most important points (more details in Table 1.1): all traditional methods (passersby, maps, signs) require users to actively look for them and extract the information they want. Visual and auditory GPS take less effort by providing exactly the information users need for their journey, but they have the problem of using strained

				On the Road				By Foot				Blind People				
	Sit. Awareness	Attention[a]	Non-distractive[b]	Availability	Ease of Use	Hands-free	Personalized[c]	Availability	Ease of Use	Hands-free	Personalized	Availability	Ease of Use	Hands-free	Ears-free	Personalized
Passersby	+	−	+	o	−	+	+	+	o	+	+	o	−	+	+	+
Maps	+	−	+	+	o	−	−	+	o	−	−	−				
Road Signs	o	−	+	+	+	+	−	o	+	+	−	−				
Visual GPS	+	o	o	+	+	+	+	+	+	−	+	−				
Auditory GPS	o	+	o	+	+	+	+	+	+	+	+	+	+	+	−	+
Long Cane	−	−	−									+	o	−	+	+
Guide Dog	−	o	−									+	o	−	+	+
Tactile Belt	−	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

[a] can easily get users' attention

[b] is not distractive and does not block other information channels

[c] information is tailored to users' needs

Table 1.1: An overview of the pros and cons of different approaches to route guiding

senses. It may happen that cues are overlooked because of busy surroundings, or the other way round: cues may mask important events in the surroundings.

1.2 Possible Improvements Through Vibro-Tactile Cueing

As described in more detail in Chapter 2 and 3 the vibro-tactile channel has amongst others the following properties: It is (*i*) **available for blind people** (and people with normal vision that are temporarily blind because of e.g. fog), (*ii*) **hands-free** (required when driving a car), (*iii*) **ears-free** (for ambient noises for the blind, music, or talking to people), (*iv*) **not commonly used** (it therefore has a high potential in getting users' attention). On the other hand tactile cues do not negatively effect e.g. visual tasks (see Section 3.3), which are two problems we encountered with visual and auditory guiding.), (*v*) **intuitive**, (*vi*) **private** (no other person can feel vibrations from somebody else's tactor belt). Therefore it is a good candidate for the (additional) use in a navigation system and other applications.

A good navigation system should be able to fulfill the following requirements as listed in Table 1.1.

1. Provide situation awareness so that users know their location.
2. Be easy to learn and use.
3. Be usable hands- and ears-free.
4. Provide information tailored to users' needs.
5. Easily get users' attention even when they are currently busy.
6. Do not be distractive or block information channels.

Tactile Feedback Only: Our assumption is that the tactile feedback could enhance unobstrusiveness by allowing the user to follow vibro-tactile cues without constantly looking at a display or the necessity of acoustic signals. Unfortunately navigation systems providing situation awareness are difficult to realize using only tactile feedback due to the small bandwidth of the sense of touch in comparison to seeing and hearing. The direction to the next waypoint can effectively be conveyed and all requirements except situation awareness can be fulfilled.

Combined Solutions: However, situation awareness is an important feature for the perfect navigation device. This further supports the idea of using vibro-tactile cues in combination with already existing systems, e.g. an ordinary graphical navigation system with voice output could be used in combination with a vibro-tactile belt. This would add redundancy to the overall flow of information by adding an additional notification channel.

1.3 Hypotheses

The goal of this work was (*i*) to show that highly precise vibro-tactile guidance is possible even for courses contained within one room, (*ii*) to tackle the disadvantage of having no situation awareness when using navigation systems using only vibro-tactile cues and (*iii*) to investigate the effect of multimodal notification. It has already been pointed out that vibro-tactile cues should optimally be used as an additional source of information since its bandwidth is limited, but for the experiments the sole use of vibro-tactile guidance was chosen. This allowed a focus on research of this type of guidance by avoiding other factors of influence.

A first step was the design of the hardware and software system, which is described in detail in Chapter 5, to proof the following hypotheses.

I Encoding of distance information into vibro-tactile messages will allow persons to find waypoints faster and more exact when compared to a simple baseline cue due to more situation awareness.

II A navigation performance degradation is expected when removing the auditory sensory channel as information carrier (blanking the noise caused by the vibration elements). This is motivated from earlier work, e. g. [6, p. 225], where it has been found that the noise generated by vibration elements provided an additional information source.

Outline

This work is structured as follows. After the motivation in this chapter a the basic knowledge of the field of haptics is explained: Chapter 2 discusses properties of the human skin relevant to sensing vibro-tactile stimulations, Chapter 3 deals with the basics of vibro-tactile information transmission. Then related work concerning land navigation, vibro-tactile cues or notification patterns is analyzed in Chapter 4. Conclusions and findings from these papers were used as a starting point for our research.

Chapter 5 discusses the hardware used and gives an in-depth look at the software that was written to conduct the experiments, which are explained in detail in Chapter 6 and 7. Results from the first series lead to planning the second one, both chapters include a conclusion of the related experiments in regard to the hypotheses. Chapter 8 concludes the work by reflecting the approach and the results and gives a short outlook on the possibilities of a complete vibro-tactile guidance system.

Chapter 2

Properties of the Human Skin

Gescheider et al. stated in [7] that human sensory systems work with channels, where each channel is tuned to sense a specific region of the energy spectrum. This is also true for the sense of touch – in glabrous skin it consists of four channels, where each channel is tuned into a specific region of the frequency spectrum. Vibrations are perceived as soon as their intensity is higher than the threshold for at least one channel. In reality, most vibrations will activate several channels at once and for our work it is not very important how many channels are currently activated or which channel contributes to the sensation. We are interested in the combined perception of vibrations as illustrated in Figure 2.1.

All channels together are capable of sensing a broad spectrum of frequencies from about 0.4 to $1000Hz$, where the threshold of perception is at a low point around $250Hz$, but the fact that humans are capable of sensing vibrations is just a side effect of the real role these channels play in human perception. Their purpose is not to enable us to recognize that an object is vibrating at a rate X, but to extract much more sophisticated facts out of our surroundings. Every channel has a special purpose from a neurophysiological point of view: properties of the four different mechanoreceptors corresponding to these channels are explained in much detail by Johnson [8]. Gescheider et al. did further research on temporal and spatial summation and concentrated on the frequency domain of the different receptors in [7]. In the next section the most important facts are summarized, key data is listed in Table 2.1.

2.1 Mechanoreceptors in the Skin

Four types of mechanosensitive transducers embedded in our skin react on cutaneous motion and deformation like indentation and stretch, each one in a different way. In some publications they are referred to by their adaption rate which is either slow (SA) or rapid (RA), or by the transducer names: Merkel discs (SA-I), Ruffini corpuscles (SA-II), Meissner corpuscles (RA-I) and Pacinian corpuscles (RA-II). Generally, slowly adapting channels are able to sense constant forces, while rapidly adopting channels only react on temporal changes.

As apparent in Figure 2.1, the overall curve of the threshold of perception has its low point approximately between 200 and $250Hz$, as the Pacinian channel is the most sensitive to vibrations: $10nm$ of skin motion at $200Hz$ is enough to stimulate them [8]. Lower and higher frequencies have a higher threshold and are therefore more difficult to sense. As a result most vibro-tactile interfaces work in this frequency range, also our work will deal with this area of the frequency spectrum.

2.1.1 Merkel Disk

Merkel discs are a special cell type at the end of the SA-I afferent fiber and are located in the basal layer of the epidermis. Even if the receptive field diameter of the fiber is 2 to $3mm$ big, edges as small as $0.5mm$ can be detected. This channel has the best spatial resolution and enables us to detect edges, corners and curvature. Its response to skin intendation is linear up to a depth of $1.5mm$, much more than for other channels. Higher level information our brain extracts from these perceptions is the recognition of **tactile patterns** and **textures**[8]. Frequencies sensed are below $100Hz$, the frequency with the least threshold being around $50Hz$.

2.1.2 Ruffini Corpuscle

The Ruffini corpuscle is located in the connective tissue of the dermis and senses about the same frequency spectrum as Merkel disks. It is six times less sensitive to skin indentation, but two to more times more sensitive to stretch than Merkel discs. Relatively few information about e.g. objects held in the hand are collected, the main perception through this channel is how much the skin is stretched. This information plays two roles

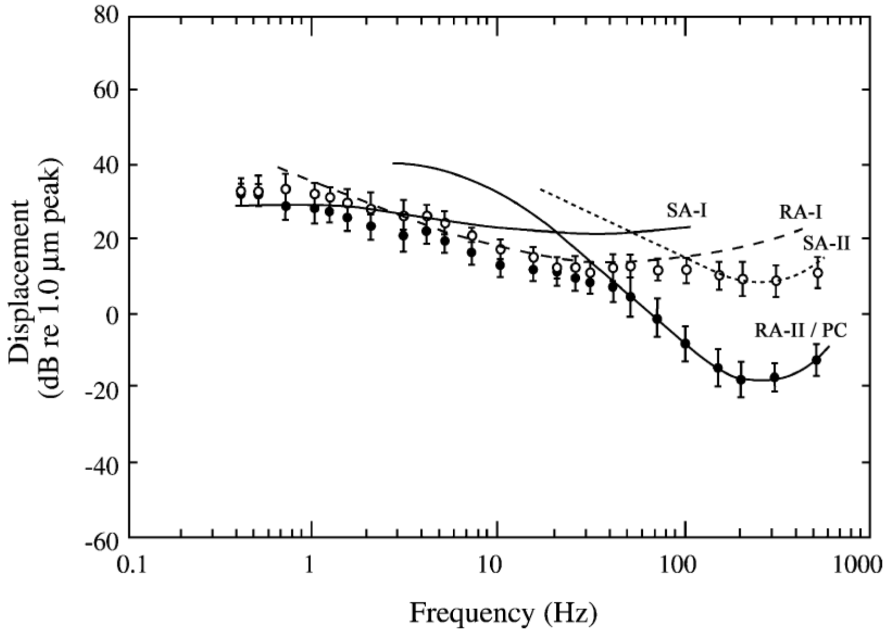

Figure 2.1: Four-channel model of mechanoreception adapted from [7]. Filled data points represent the overall threshold curve for large contactors ($3cm^2$), the unfilled ones for small contactors ($0.01cm^2$) where the Pacinian channel is not active. RA-I = Meissner, RA-II = Pacinian, SA-I = Merkel, SA-II = Ruffini;

in human perception, first, it allows to sense the **direction of local motion or force**, and second, in the case of the hand it allows for a perception of **finger position**[8].

2.1.3 Meissner Corpuscle

Meissner corpuscles consist of several cells located in the superficial dermis just below the epidermis. In contrast to the slowly adapting receptors, they have poor spatial resolution but quite high density – 43% of the mechanoreceptors in the finger are Meissner corpuscles. Static skin deformation is ignored, but they are four times more sensitive to dynamic skin deformation than Merkel discs (SA-I). This results in a robust neural image of **skin motion** and further on **detection of slip** of or sudden forces on objects held in the hand. This constant feedback about slip, so called **grip control**, allows us to delicately handle objects with our hands. Frequency-wise this channel senses vibrations between 10 and $200Hz$.

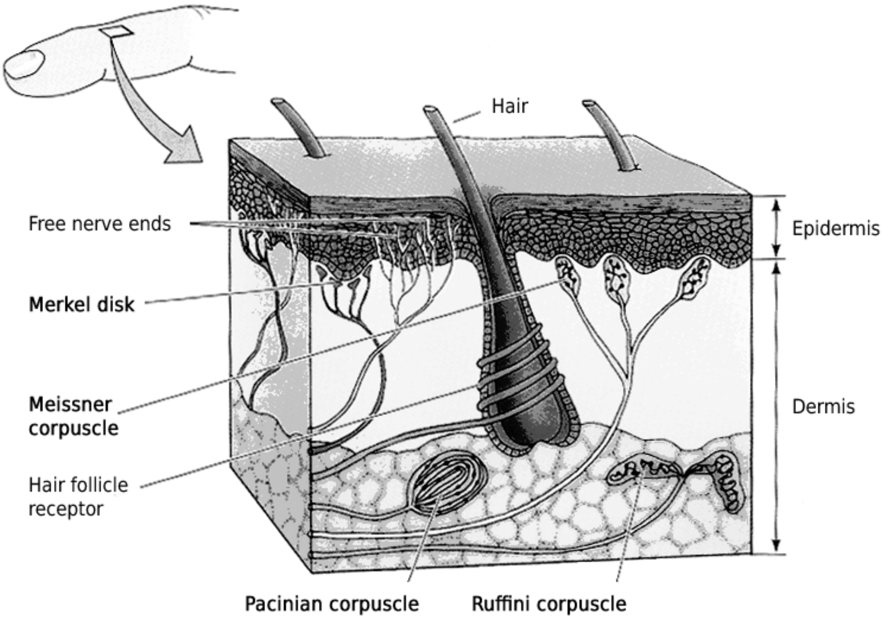

Figure 2.2: The four types of mechanoreceptors in the human skin (in bold typeset), adapted from [9]

2.1.4 Pacinian Corpuscle

Pacinian corpuscles can be found in the dermis and subcutaneous. They are large, layered onion-like structures with as many as 70 layers, enclosing a single nerve ending that is sensitive to deformation in the nanometer range. To protect this nerve from overstimulation it is enclosed in protection layers, which filter lower frequencies, and is not located directly below the surface of the skin. Its neurological purpose is the **perception of distant events** that are transmitted in the form of vibrations between 70 and $1000Hz$ with the minimum threshold between 200 and $250Hz$. The central nervous system can then for example sense the surface we are scratching with a shovel just by the vibrations submitted through its handle.

Summation and Age Effects: Gescheider et al. showed in [7] that the Pacinian channel is the only one of the four channels capable of temporal and spatial summation. The larger the contactor size and the longer the duration (up to 1 second) of a stimuli, the lower the detection threshold. Tactile sensitivity of this channel is therefore strongly dependent on the number of stimulated corpuscles. All channels, like other senses like hearing and seeing, are negatively affected by aging. The influence on the Pacinian channel is about twice as big as on the other three tactile channels. Dying cells have about the same effect as a reduction of contactor size since the detection threshold depends on the number of activated receptors. After 80 years the threshold is around $24dB$ higher.

	Merkel discs	Ruffini corpuscles	Meissner corpuscles	Pacinian corpuscles
Location	basal epidermis	dermis and subcutaneous	superficial dermis	dermis and subcutaneous
Rate of Adaptation	slow (SA-I)	slow (SA-II)	rapid (RA-I)	rapid (RA-II)
Spatial Resolution	good	fair	poor	very poor
Mean Receptive Area	$11mm^2$	$59mm^2$	$13mm^2$	$101mm^2$
Sensory Units	25%	19%	43%	13%
Response Freq. Range	$0.4 - 100Hz$	$0.4 - 100Hz$	$10 - 200Hz$	$70 - 1000Hz$
Min. Threshold Freq.	$\sim 50Hz$	$\sim 50Hz$	$40Hz$	$200 - 250Hz$
Force Thresholds	$1.3mN$	$7.5mN$	$0.58mN$	$0.54mN$
Temporal Summation	no	no	no	yes
Spatial Summation	no	no	no	yes
Age Degradation[a]	$10 - 12dB$	$10 - 12dB$	$10 - 12dB$	$24dB$
Low-level Purpose	local shape, pressure	skin stretch, local motion or force	velocity, local shape, slip	vibration, slip, acceleration
Higher Purpose	texture	finger position	grip control	vibrations

[a] Increase of threshold at age 80

Table 2.1: Features of the four types of mechanoreceptors on the human hand. Adapted from [10] (most parts) and [7].

2.2 Vibro-tactile Localization on the Abdomen

2.2.1 Why the Abdomen?

Most research on the tactile channel as summarized in Section 2.1 is focused on the fingers, the area of the human body with the highest density of mechanoreceptors. When our focus changes from researching the tactile sense to giving vibro-tactile feedback, the hand is no longer the most suitable body part. This has several reasons, the most important one being that we are constantly using our hands, so attaching any feedback device onto them would be impractical. Pedestrians, car drivers, trekkers, firemen, they all need hands and feet to accomplish their tasks. Even in the hypothetical situation when the device for giving tactile feedback is unnoticeably small, it may be difficult to sense information when the hand is in use, e.g. somebody is carrying a heavy object in his hands.

There are at least four restrictions for a useful body part for vibro-tactile navigation cues.

1. We do not want to use body parts that are in contact with our surroundings, dismissing fingers, hands and feet.
2. Unobstrusiveness dictates we should only use body parts usually covered by clothing, since we want to integrate the technology there, avoiding the effort of wearing an extra piece of equipment. This again dismisses fingers, hand, feet, and in addition head and neck.
3. Another reason for not placing tactors on or near the head is that vibration may leak into the ear, causing unwanted noise [11].
4. Karnath et al. [12] state that position in the three-dimensional space is more intuitively represented by the torso than by limbs in constant motion, Craig and Sherrick [13] suggest to use back, abdomen or thigh instead of fingers. Cholewiak et al. [14] suggest using the trunk as it provides more spatial awareness of our orientation than other body parts, quoting Van Erp's research on the kinesthetic ego center [15]:

   > The trunk midline constitutes the physical anchor for calculation of the internal egocentric coordinate frame for representing body position with respect to external objects.

2.2.2 Properties of the Abdomen

Tactor Positioning: Cholewiak et al. showed in [14] that localization performance is not influenced by the vertical location of tactor elements (the two tested places were 2.5 and $12.5cm$ above the navel respectively) or the type of the tactors (pneumatic and electromechanic). Also response thresholds do not vary much for different locations, even if the underlying tissue is either tendon, bone, gut or muscle. Instead human's ability for localization is highly influenced by the position around the waist. Best performance was achieved for the two anatomical keypoints (also called *anatomical reference point*) navel and spine, with declining performance to the left and right side. They also shifted a belt with 8 tactor elements slightly, so that navel and spine had the highest possible distance to next tactors, which resulted in a performance drop of correct localizations from 92% to 87%.

Further experiments in [14] using 7 tactors in a half circle either from navel to spine or from side to side (with the same distance between tactors as for the 12-tactors experiment) showed that when using the anatomical reference points as end points of the circle, the performance was equal to the performance with 12 tactors. However when using only one anatomical reference point plus the two sides (hips), the performance increased significantly. In this case the two end points seemed to work like additional reference points and therefore increase accuracy. Also the number of possible locations was reduced at the endpoints, leading to a smaller possibility for misclassification.

The Golden Number of Tactors: Overall accuracy of localization for 12, 8, and 6 tactors around the waist were 74%, 92%, and 97% in [14]. Even if the recognition rate for navel and spine were around 100% in all three cases, performance dropped dramatically the more the tactor was on either the left or the right side of the body. This result suggests that proximity between tactors is a very important factor, apparently a number of 12 tactors is too much for the resolution of our skin.

To find out the optimal number of tactors, *information transmission* or *uncertainty reduction* as described in [16] can be used: The maximum amount of information that can be transmitted is the logarithm to the base 2 of the total amount of tactors, the actually submitted information is the logarithm to the base 2 of the correctly identified tactors.

Even if 12 tactors allow for 12 tokens encoded in 3.58 bits in comparison to only 3 bits in the case of 8 tactors, about the same amount of information was transmitted with 8 and 12 tactors. Even when only using 6 tactors the total transmitted information was only a little less compared to using 12, but with significantly better accuracy. More details are available in Table 2.2.

There are two explanations for the increase in performance when using a reduced number of tactors. (*i*) Separation of tactor elements directly influences localization performance and (*ii*) differentiating between less options causes less cognitive load. However, (*ii*) is less significant, experiments in [14] with 7 tactors in a half-circle always achieved worse results than the experiment with 8 tactors in a full circle.

Tactors	Accuracy (%)	Theoretical Bandwidth (bit)	Actual Bandwidth (bit)
12	74	3.58	2.71
8	92	3	2.65
6	97	2.58	2.46
7	85	2.8	2.22

Table 2.2: Results from three localization experiments with different numbers of tactors mounted on a waistbelt from [14]. Tactors were distributed around the waist except the number of tactors was 7, where tactors were spread from the left side over the belly to the right side, leaving out the back. Bandwidth (information transmitted) is measured in terms of bits, calculated from the logarithm (to the base 2) of the number of alternatives.

Learning Effects: Localization performance improved at about 2% for each of 10 learning sessions (with 6 trial blocks each) in [14], so a small learning effect for vibro-tactile cues exists.

Chapter 3

Vibro-tactile Information Transmission

This chapter will give a short overview about general properties and parameters of the vibro-tactile channel. All these properties and parameters should be considered when designing tactile feedback systems.

3.1 Properties

Available for the Disabled: The tactile channel is truly ubiquitous in the sense of being available for everybody, even for the physically challenged or the blind, who may not have access to specific senses or methods of input. The only existing constraint is that paraplegic people, depending on which part of the spinal cord is damaged, have a strongly decreased sense of touch [17, p. 288].

An Additional Channel: The tactile channel is not used often yet: most human-computer interaction uses the visual or auditory channel and only small bits of information are transmitted through the sense of touch. An example are cell phones, where the information content of the fact that the phone is vibrating is rather small: somebody is calling or an SMS has arrived, depending on how many different melodies (vibration patterns) the user set up. The influence of multimodality, using the tactile channel in addition to the normally used ones, is outlined in Section 3.3.

Easy to Learn: Feedback from test persons and empirical results from both our experiments and various publications (e.g. waypoint navigation with a tactor belt in [18] or pedestrian guidance in [19]) show that well-designed tactile cues can be unterstood and successfully used after a very short period of familiarization. Such a display is intuitive and can be used without much practice. The belt system in [18] was understood promptly by the test participants and good performance was achieved from the beginning with only a mild learning effect.

Private: Vibrations can only be felt by the person who wears the vibrating device or tactor. In surroundings where it is not completely silent other people will not even be able to hear that a flow of information is taking place.

Works Even In Vibration-Rich Environments: Van Erp et al. successfully used a tactor belt on a fast boat and a helicopter in [18]. In both environments whole body vibrations with main components up to 15Hz were present but still navigation solely relying on tactile cues worked perfectly, whereas a visual display in a fast boat is very difficult to read at high speeds.

Low Data Rate: Unfortunately its capabilities to convey information are very limited, especially in comparison to the senses seeing or hearing: the range of frequencies that can be sensed is only between $0.4Hz$ and $1000Hz$ (see Table 2.1), numbers for changes in frequency that can be discriminated vary wildly between 2 and 50% in different publications [20]. In comparison, the frequency range sensed by the human ear is $20Hz$ to $16000Hz$, at $1000Hz$ a frequency change by only 0.3% ($3Hz$) can be discerned [17, p 346].

3.2 Parameters or Dimensions

When transmitting information via the vibro-tactile channel, information must be encoded into the vibration. The term *tacton* was introduced by Brewster and Brown in [21] as “structured tactile message for non-visual information display”. Most publications in the field of vibro-tactile notification adapted this term, Riener et al. also use *tactogram* in several publications, others, e.g. Brown et al. in [16], use *(vibro-)tactile message.*

1. *Spatial location:* Location of vibration is a very distinctive feature, even if the spatial resolution of the skin is highest for the fingertips, resolution around the belly or on the forearm is good enough for useful applications: van Erp et al. [18] and Elliott et al. [22] used a belt with 8 tactors encoding directional information for a waypoint finding task on the belly; Brown et al. [16] encoded three appointment types in three locations on the forearm (elbow, wrist and the middle between these two), where the three different locations were identified correctly with an accuracy of over 96%.

   Jones et al. [23] built a tactile display comprising of a 4 by 4 tactor matrix stimulating the lower back. Through this vest directional and instructional cues for outdoor navigation were sent to the users, who were able to follow these cues "with almost perfect accuracy". They also showed that tactile pattern recognition works better on the back than on the forearm.

2. *Frequency:* No recent works related to route guiding used frequency to encode information, but use constant frequencies instead, with $250 Hz$ being the optimal frequency. Jones and Sarter [20] summarized the result of several publications dealing with the use of frequency in tactile cues: it is unclear how many different frequencies can be distinguished, suggestions for the forearm range from three up to eight different frequencies. Caution was advised when using frequency as a parameter, especially because frequency and intensity influence each other, making it dangerous to assign them to different variables.

3. *Intensity (or strength):* This parameter is also not commonly used in related work, but is used for Vibratese [24], a nowadays extinct tactile language introduced by Gerald in the late nineteen-fifties. At most three different values (level of intensity) should be used [25].

4. *Roughness (amplitude modulation):* 3 different roughnesses, e.g. a $250 Hz$ signal with an amplitude modulation of $30 Hz$, were used in [16] to signal the importance of an appointment, but they showed that the recognition error rate with over 40% is very high for 3 levels, the use of a maximum amount of two levels is recommended, which reduced the error rate to around 17% in that case.

5. *Duration:* This property ist mostly not used alone (vibrations of different length separated by a break), but indirectly in complex on-off-patterns. Patterns allow for more encoded information than just varying the length of one pulse.

6. *Pattern (or rhythm):* Different patterns, pulses of varying durations, have been used to encode the type of an appointment [16], the distance to a waypoint (van

Erp et al., 2005; Elliott et al., 2007) and direction (Lin et al., 2008). Much more information on patterns is provided in the next chapter.

7. *Tempo (of pattern/rhythm):* Patterns can be played at different speeds. Lin et al. transmitted distance information by having two speeds for every pattern that actually encoded the direction [19].

3.3 Multimodal Notification

Multimodal input or output uses not only one, but several channels, e.g. visual and auditory output. Considering an information flow in the other direction, from user to computer, an example of multimodal input would be speech and gesture input as used in [26]. Every channel has its weaknesses, but the complementary input of a well-designed multimodal system can compensate parts of these weaknesses. By reason of Wicken's Multiple Resource Theory (MRT) cognitive workload should be reduced [27]. Also in most situations when a human-machine interface is used, the main task is not to monitor the information provided by the machine, but it is also necessary to observe other information channels: a pedestrian can not only follow tactile guidance cues but amongst other things also has to watch his surroundings and pay attention to the noise of approaching vehicles.

In several publications evidence of multimodal stimulation enhancing the overall performance of a certain task can be found. Oviatt [26] combined gestures with voice input for a map-viewing application which led to a decrease in errors between 19% and 41%. van Veen and van Erp [28] showed that vibro-tactile cueing helps flying a helicopter more accurately by avoiding course drift: the pilots did not fly blind but with normal (during the day) and degraded vision (wearing night vision goggles at night) plus the additional tactile cues. In both cases, even when flying during the day, course drift was reduced due to the additional information. Elliott et al. [22] also investigated the performance of a system using both visual and tactile feedback: the mental effort of navigating was compared for a handheld visual GPS device by Garmin[1] and a "Personal Tactical Navigator" (PTN, mentioned in more detail in Section 4.2). The tactile solution required significantly less mental effort, but the time required for completing the course was shortest when only using the Garmin, slightly worse (+0.7%) when using both, and worst (+5.3%) for PTN only. When asked most soldiers said they would use PTN for

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[1] Garmin Ltd., URL: `http://www.garmin.com`, last retrieved September 8, 2009

navigation and Garmin for confirming location and waypoint distance, therefore clearly preferring the multimodal feedback over either single case.

However, encoding different information in several parameters has its pitfalls: Brown et al. [16] experimented with vibro-tactile feedback and observed a drop in percentage correct score from 80% to 50% for the parameter roughness when adding a third parameter (location) to the existing two (pattern and roughness), where all three parameters conveyed different information. The simultaneous use of several senses also affects each others performance: Gallace et al. [29] summarized recent research on the mutual influence of different information processing channels: (*i*) tactile change blindness (the ability to detect changes in tactile patterns gets worse when the pause between patterns gets bigger) is affected by activity on the visual channel. In an experiment the onset of the second tactile pattern was coincided with a visual stimulus, which negatively affected the outcome. (*ii*) This does not work the other way round: visual change blindness is not affected by simultaneous tactile stimuli, which suggests that tactile stimuli do not negatively affect unrelated visual tasks.

3.4 Guidelines for the Design of Tactile Cues

The following guidelines, which should be kept in mind when designing tactile cues, have been compiled from all the mentioned research.

1. Even if the recognition rate for individual parameters of cues (e.g. rhythm alone) are very high, combining more parameters or dimensions will most probably reduce the individual recognition rate.
2. Parameters can only hold a limited amount of information, every parameter has a certain point when adding more options will not increase but instead maybe even decrease the total transmitted information. This happens when the error rate lowers the overall transmitted information more than the additional option raised it. This happened e.g. for the roughness parameter in [16], where reducing the values from three to two for the roughness parameter resulted in an increase in information transmission, or [14] where Cholewiak et al. [14] showed that using 8 and 12 tactors around the belly does not increase the transmitted information, but only the error rate.

3. This makes the creation of a more-dimensional cue non-trivial. There are many combinations to consider and test. It is important to optimize cues for the amount of transmitted information, not the theoretical amount of information that could be transmitted (combinations of all possible values). See Section 2.2.2.
4. Findings concerning multimodality as summarized in [29] suggest the use of different sensory modalities redundantly to improve performance. Using different modalities for unrelated information is not recommendable, even if the tactile channels seem to not negatively influence visual tasks.

Chapter 4

Approaches to Route Guidance

In this section three examples for outdoor route guiding systems will be presented, where one of them was developed for blind people, fitting their special needs. We will take a look at the hardware used, parameters for vibro-tactile cueing, results for the respective research questions and lessons that have been learnt. Bringing route guidance indoor is even more complicated, as positioning of the user must be more accurate and technology like GPS does not work in buildings. The tracking hardware used in [30], current research on WLAN tracking and commercially available products like Ubisense[1] are a step in the right direction, but as it is not the goal of this work to develop a position tracking system no further details are given here.

4.1 Van Erp et al. 2005 – Pedestrians, a Helicopter and a Fast Boat

Van Erp et al. conducted two studies very similar to [31] in [18], one to experiment with different distance encodings in a pedestrian situation, a second as a proof of concept that tactile notification also works on a helicopter and a fast boat.

Hardware: The wearable system consisted of a minicomputer (486 DX Tiqit matchbox PC), a digital compass (Honeywell HMR2300) and a GPS receiver (Garmin GPS 35-HVS) which were packed in a backpack. Additionally a tactile belt with 8 tactors, splitting the 360^o of freedom into 8 times 45^o, was worn around the waist.

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[1] Ubisense, URL: `http://www.ubisense.net`, last retrieved September 10, 2009

Parameters: *Direction* was simply encoded by location (which tactor was activated), with a special behavior of the tactor in the front: it had two different pulsing modes, one for course deviations between 10^o to 22.5^o and a faster one for 0^o to 10^o.

Four *distance* encodings were used in the first experiment: Two three-phase models with pauses of $2s$ (at the start), $6s$ (in the middle) and $4s$ (near the next waypoint) between one second pulses and two monotonic models. Both had two modes and either used absolute or relative distances for determining e.g. if the pause should be 2 or 6 seconds long. Monotonic cueing worked like this: pauses were 10 seconds long in the beginning, except for within 15 meters of the starting point, where the pause was only 2 seconds, and were reduced by 1 second for every 10% the user came closer to the next waypoint. A vibration of all tactors for one second represented reaching the waypoint in all cases.

Routes: Routes for the first experiment were between $360m$ and $390m$ in length, all using the same two locations as first two waypoints, with six waypoints total. They were placed in an open field of grass of about $110m$ by $90m$, with no visual indications for the waypoints. A waypoint was considered reached when the participant came within a $15m$ radius around it.

For the second experiment, conducted on water and in the air, routes consisted of only four waypoints and were significantly longer (around $17km$ and $40km$), the radius for reaching a waypoint was $50m$ and $100m$ respectively.

Lessons Learnt: All distance encoding schemes used in experiment 1 resulted in a lower effective walking speed between 4.2 and $4.4km/h$, whereas test persons achieved a speed of over $4.6km/h$ in a control condition with a one-second pulse every two seconds, the difference being statistically insignificant. The main reason for this seems to be the long distance between pulses, test participants recommended not to use intervals longer than 4 seconds.

Even if test persons reached the goal the fastest using the control model, they had no means of knowing how far they still had to go. This posed problems in the second experiment because of a relatively small waypoint radius in relation to the high speed. A boat driver suggested to add an indication when the next waypoint is nearing, consequently, a good distance encoding model would be desirable.

4.2 Elliott et al. 2007 – Route Guiding for Soldiers

This work [22] dealt with analyzing the performance of a device called Personal Tactical Navigator (PTN), in comparison to and in combination with (*i*) a Garmin hand-held GPS device and (*ii*) a map together with a compass, during an outdoor waypoint finding task. The PTN consisted of a GPS receiver, a digital compass and a tactor belt with 8 tactors. All routes consisted of four waypoints, spaced $600m$ apart.

Parameters: *Direction* was encoded by location of the activated tactor, *distance* encoding worked as follows: if the next waypoint is more than 50 meters away, the frontmost tactor vibrates for $200ms$ each $2s$, all other tactors vibrate each second. If the distance is between $15m$ and $50m$ the frontmost tactor makes a double pulse ($100ms$ vibration, $200ms$ pause, $100ms$ vibration) every second, all other two double pulses per second. If the goal is reached all tactors vibrate for 3 seconds. The frontmost tactor behaves differently for two reasons: to make it different from the other ones and to lower the amount of vibro-tactile stimulation when the user is on the right track.

Experiments: In the first daylight experiment the tactor belt performed well for: finding all waypoints (results were 95% when using Garmin and 86% for a compass system), quickly reaching the goal (test persons using the compass system needed more time). The course deviation was worse than for the other two devices, but the test persons noted they went off course with the belt to avoid natural obstacles because it was so easy to find the right track again with the belt.

Target Spotting at Night: A second experiment took place at night in a forest and also required the soldiers to detect targets. The belt was evaluated against the same handheld textual GPS device and an additional helmet-mounted visual display. Soldiers using the tactor belt could navigate faster and also find more targets than soldiers wearing the helmet. When giving feedback later, they gave significantly higher ratings for the tactor belt over both other systems for looking out for terrain obstacles, allowing hands-free operation, ease of staying on route, being simple to learn, being simple to use, effectiveness for night operations, effectiveness for urban operations, effectiveness for wooded terrain, and effectiveness in enemy territory. So the belt has the big advantage of being intuitive, hands-free and eyes-free, but the big disadvantage of providing no position or distance information, thus reducing situation awareness. This further confirms Table 1.1.

Lessons Learnt: Results of the second study showed that navigation speed was slower with the PTN than with the visual GPS device, in contrary to the expectation that glancing at the display would slow them down. Target detection was about equal, even if results for the Garmin were thought to be worse, since attention has to be paid to the display.

The lack of situation awareness when using the tactile solution was considered problematic, soldiers gave good feedback to the Garmin device here, which always visualized the current location.

Other ideas for improvements by the soldiers were to make the tactile belt smaller, lighter, more integrated into garment, and to use stronger vibrations. A very popular demand was to use both devices simultaneously, PTN for guidance and Garmin for situation awareness. They noted that tactile guidance would be most useful in combat situations, when there is no time to look at a display.

4.3 Pressl and Wieser 2006 – Route Guiding for Blind People

A navigation system tailored to the needs of blind people has been proposed by Pressl and Wieser [30]. Their goal was to track and help visually impaired pedestrians to navigate in an urban environment.

Hardware: Position tracking was done by the no longer available PTN (Pedestrian Navigation Module) by Vectronix AG. It uses a combination of GPS and dead reckoning to overcome the limitations in accuracy of GPS: with the help of a magnetometer triad and a gyrocompass, course determination can be calculated, a barometric altimeter detects height which is needed e.g. in buildings to detect the current floor.

Pressl and Wieser suggested to use vibrating wristbands with varying intensity of vibration for obstacle warnings and a one-hand keypad with braille output as second user interface device. However, they did not conduct empirical studies with that kind of devices.

Route Calculation and Guidance: The main interest of their research was the creation of an annotated map together with the implementation of complex route guiding. The navigable map held geometric, topologic as well as thematic information at a very high resolution, e.g.: streets, sidewalks, cross-walks, lamp posts, dust bins and points of interest (restaurants, medical care,...). Routes were not only optimized for the shortest distance but also to be as safe as possible, e.g. to not use cross-walks without a traffic light.

Guidance instructions were divided into four groups: direction instructions (e.g. left, straight ahead), maneuver instructions (e.g. turn left, go until), objects (e.g. traffic lights) and obstacle warnings (e.g. dust bin).

Lessons Learnt: When planning route guiding applications for blind people their special needs must be considered: the information must be very fine-grained to be helpful. It is not enough to tell the user to turn left in 2 blocks but to support him all along the way.

Chapter 5

Hardware and Software Setup

5.1 Hardware

Many technologies exist for tracking a user's position. Some popular ones are GPS and its counterpart Galileo for outdoor tracking and Ekahau (WiFi), InterSense (Ultrasonics) and Ubisense (UWB[1]) for indoor tracking.

A detailed picture about the current state of the art for vibro-tactile human computer interaction can be found in the following two publiations. Pasquero [32] gives an in-detail survey of different types of tactile displays and Chouvardas et al. [33] give a good overview on fields in which tactile information transmission is currently used for and for which purpose.

In short, the following components were used in the system architecture. A quick overview of how the interaction works between them can be found in Figure 5.1.

- *Position Tracking:* InterSense IS-900[2]
- *Vibro-tactile Feedback:* Engineering Acoustics Inc. Tactor Control Unit (TCU) connected to a belt with 8 C-2 tactors[3]
- *Masking of Ambient Noises:* AKG K-55 closed-back headphones for noisy environment[4] and an MP3-player

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[1] Ultra Wideband

[2] IS-900 series by InterSense Inc., URL: `http://www.intersense.com/IS-900_Systems.aspx`, last retrieved October 8, 2009

[3] Tactors and control units by Engineering Acoustics Inc., URL: `http://www.eaiinfo.com/Tactor%20Products.htm`, last retrieved October 8, 2009

[4] AKG K-55 headphones, URL: `http://www.akg.com/site/products/powerslave,id,256,pid,256,nodeid,2,_language,EN.html`, last retrieved October 8, 2009

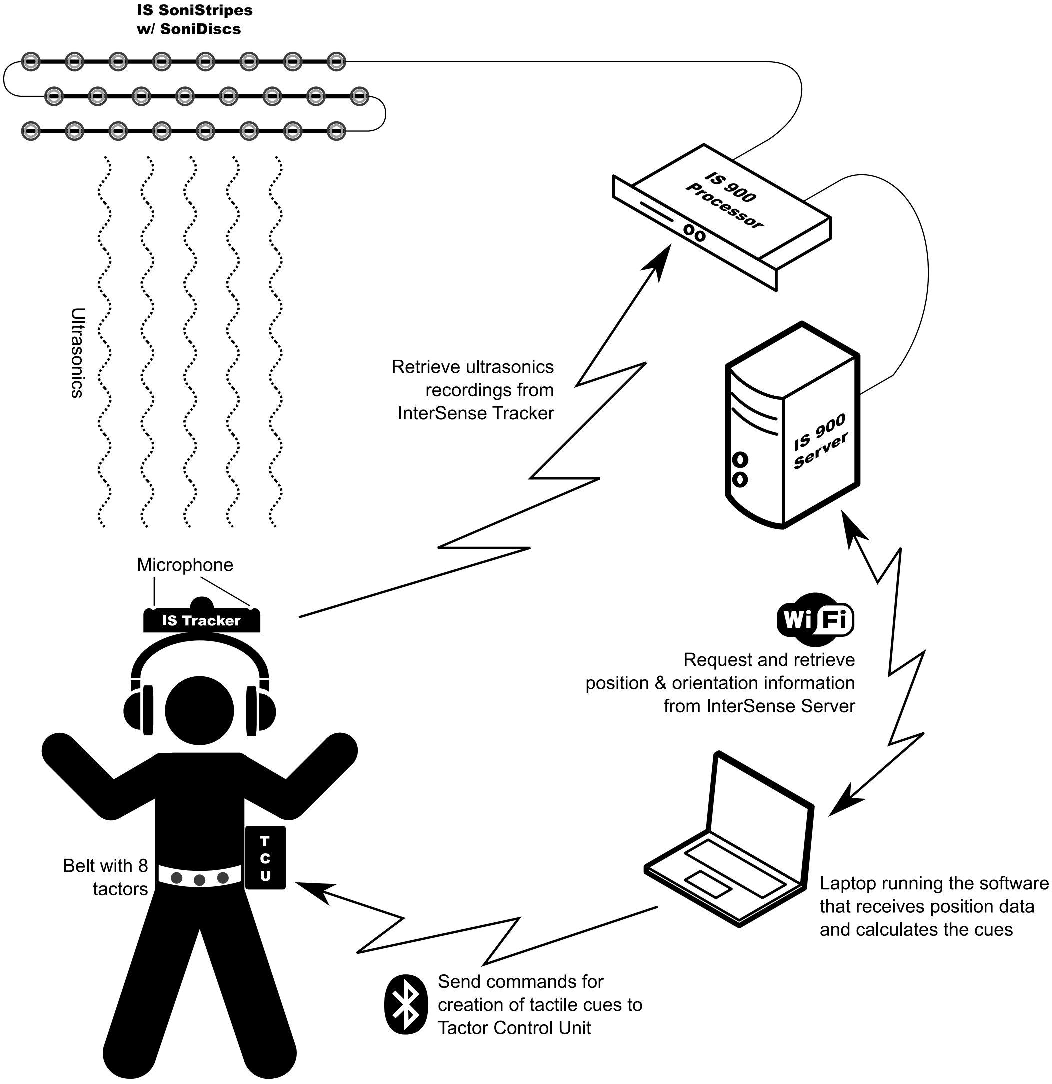

Figure 5.1: Diagram showing the interaction between the different pieces of hardware used in our work. Different modes of information transmission are represented as follows: zigzag lines are wireless, dotted waves are ultrasonics, curved lines are wired connections.

- *Orchestration:* A laptop running Linux using Bluetooth and WLAN to retrieve the participants' position, calculate the cues and send them to the tactor controller.

5.1.1 Tracking of Position and Orientation

For highly precise and accurate indoor position and orientation tracking of our participants we used the InterSense IS-900 6-DOF[5] ultrasonic positioning system. It consists of SoniStripes with SoniDiscs mounted on the ceiling which emit ultrasonics, a wireless tracker with two ultrasonic microphones, a processor (base station) which receives the recordings of the trackers' microphones and does all the calculations, and a PC running server software which allows software access to the data calculated by the processor.

The tracker had to be carried along by the participants and was mounted on top of the headphones which were worn throughout all experiments and playing "masking music" in most of them (see Figure 5.2, right image). The system provides x/y/z-coordinates and the orientation in 3D space: yaw, pitch, roll. For our purposes it was enough to use the x and y coordinates and the orientation (yaw) of the user.

Limitations: InterSense requires its own infrastructure and is, like most other products for exact position tracking, very expensive. Due to the system requiring its ultrasonics emittors to be mounted on the ceiling in a high density (SoniDiscs are mounted in distances of about $1m$ in our laboratory) it is difficult or too expensive to deploy in bigger environments like a construction hall. A line of sight from the SoniDiscs to the trackers is required and battery life is very short: after one day filled with experiments the battery is drained. Intervals at which the server software provides new data records averages to around $400ms$.

Tracking is only possible when the tactor is directly below the area where SoniDiscs are installed. This is a reasonable limitation, but we were confronted with problems of a random nature: in general the system worked well, position tracking was exact to about $10cm$, but sometimes the data was several meters off. These problems occured seldom at first (once every few times a participant walked a course) but just before starting the second series of experiments the rate jumped up to several times for all courses. On two days the system completely refused to work and could not get a fix on the trackers.

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[5] Degrees of Freedom

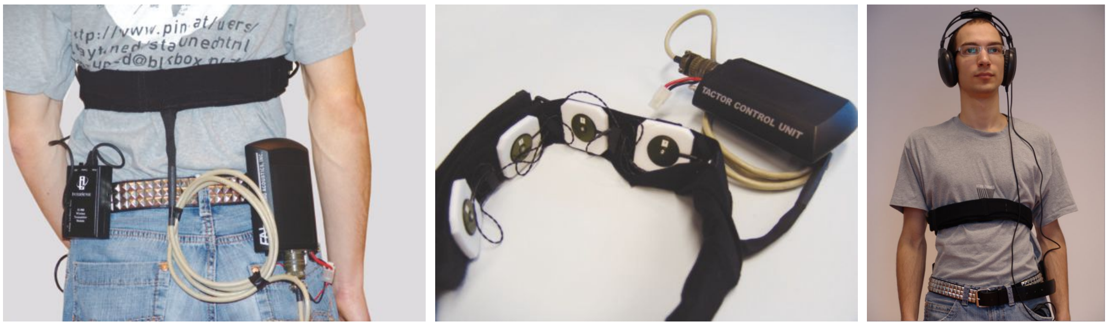

Figure 5.2: The waist-belt system consisting of the vibro-tactile belt, the InterSense transceiver, and the belt controller; a detailled view of the waist belt and the Tactor Control Unit; the author wearing the belt and the headphones during an experiment (from left to right).

5.1.2 Vibro-tactile Feedback

Guidance cues were emitted by a vibro-tactile waist belt, built up from 8 high-precision C-2 tactors creating a strong, punctuated vibration force (see Figure 5.2, middle image). Each of the tactors has a diameter of $30.48mm$, a height of $7.87mm$, and uses electromechanical voice-coils to generate vibrations with a resonance frequency in the range between 200 and $300Hz$. In order to allow precise delivery of orientation information, the vibration elements were spaced equally. As abdominal girths vary between people we used two differently sized belts, one with a length of $72cm$ and one with $85cm$.

To create a cue most of the times several commands must be sent to the TCU, e.g. to set the frequency and which tactors should vibrate. A short excerpt of the commands the TCU accepts is *setTactors* (use a bitmask to set which ones of the 8 tactors are vibrating), *setSinFreq1* (set the frequency of the first oscillator from two), setAttenuation (set attenuation from maximum intensity of vibration force).

Limitations: Frequencies at which the 8 tactors vibrate can only be set to different values for two fixed groups of four tactors, not for every single tactor. It is therefore not possible to let two arbitrary tactors vibrate at different frequencies. Intensity and roughness (frequency modulation) can only be set globally for all tactors as well.

The firmware only supports quite simple commands like set the frequency, set the intensity and set which tactors should vibrate. Commands must be sent in intervals no shorter than $50ms$, otherwise they will not be executed at all as the internal buffer is overwritten before the old command has been executed. This limits the complexity of cues when time is critical. A workaround for this, storing predefined sequences on the controller, is not feasible because there is room for only 16 sequences.

A detailed description of the communication with the belt is given later in Chapter 5.2.4.

5.2 Software

The software was written in C++ using the cross-platform application and UI framework Qt[6] under Linux. Qt does not include support for serial communication, I used the third-party class QextSerialPort[7] for that. For communication between threads the signals and slots[8] concept is used frequenctly.

Its purpose is to act as glue for the used hardware components, to visualize the user's trace in a room and to calculate the cues that are sent to the user. For this purpose the software communicates with the InterSense server over WLAN to retrieve the users' position and orientation. The task of the user is to walk along a predefined course consisting of several waypoints, a waypoint is considered reached as soon as it is contained within the circle with a diameter of $40cm$ representing the user. Based on the user's position and orientation, the position of the next waypoint and the selected type of cue, which can be chosen in the GUI, a tactile cue is calculated. (An overview of how the cues work can be found in Chapter 7.2, more in-depth explanations are given in Chapters 6.2.4 and 7.1.6, which describe the setups of the different experiments.) Then the necessary commands are sent to the Tactor Control Unit via a serial over bluetooth connection.

Classes and structures can be divided into three logical parts, which are all weaved together by *ShapeTactilizer*:

1. Position tracking: *Intersense*, *IntersenseRecord*, *IntersenseThread*, *ReplayThread*
2. Vibro-tactile output: *TactorController*, *TactorThread*

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[6] Qt framework by Nokia, URL: `http://qt.nokia.com`, last retrieved October 8, 2009

[7] Class for serial communication with Qt, URL: `http://qextserialport.sf.net`, last retrieved October 15, 2009

[8] Signals and slots in Qt, URL: `http://qt.nokia.com/doc/4.5/signalsandslots.html`, last retrieved October 15, 2009

3. User interface: *RoomRenderer*, *RoomWidget*

Room and *User* are defined in *ShapeTactilizer* and are used there and in the user interface part. *IO*, which provides static helper functions for file handling, is used in the same three classes. See the class diagram in Figure 5.3 and the collaboration diagram visualizing these three parts in Figure 5.6. Here follows a textual description of all structures and classes.

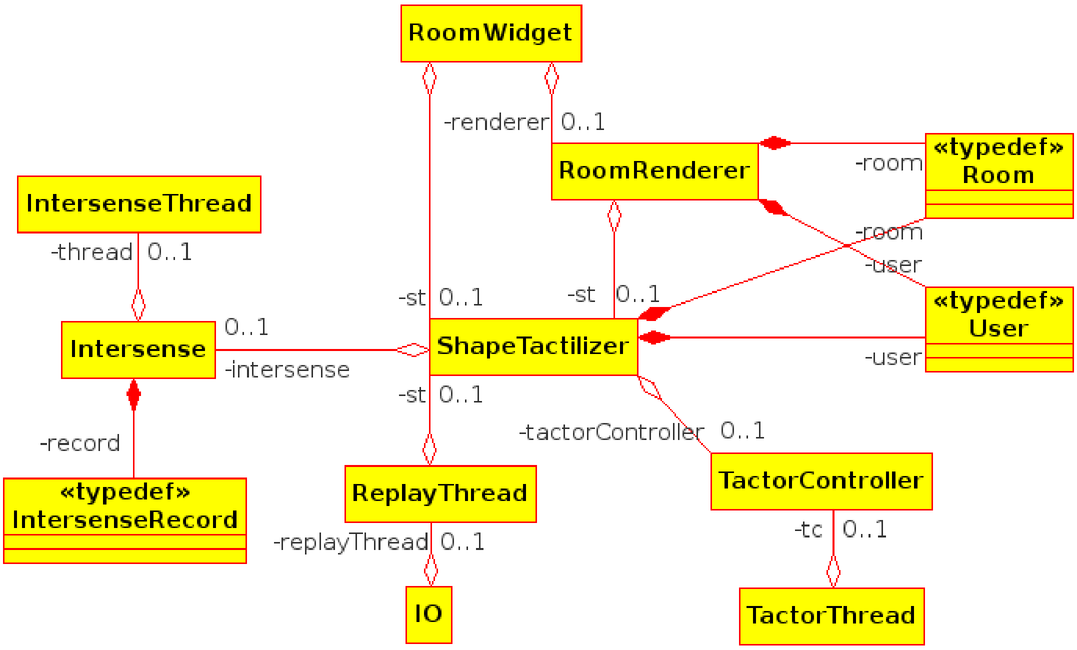

Figure 5.3: Class diagram

5.2.1 Overview of Structures

IntersenseRecord

IntersenseRecord holds one 6-DOF[9] record from InterSense which contains the coordinates and orientation in 3D-space. For identification purposes the number of the port where the tracker is connected to the InterSense base station is contained as well. It is used by *Intersense* and *IntersenseThread* to supply positional information to *ShapeTactilizer*.

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[9] Degrees of Freedom

Room

Room holds all the information that is required to represent a room and the available courses in this application. Courses as well as the number of the currently active course and the distance covered by the person are used for calculating the cues in *ShapeTactilizer*. All the other information: size, position of doors and windows, the area in which the user is allowed to move and the grid size have no effect on the cues but are used by *RoomRenderer* to display a visual representation of the experiment setup in *RoomWidget*.

User

User stores relevant information about a user: position, heading, walking speed, if the last waypoint of a course has been reached and the status of the tactors of the tactor belt. It is used to display a visual representation and the status of all the tactors in *RoomRenderer* and is constantly updated after a cue has been calculated in *ShapeTactilizer*.

5.2.2 Overview of Classes

Defines

Defines serves as a place for defining values for options that would be configurable in the GUI in software aimed at the end-user.

Intersense

Intersense emits a signal with a new *IntersenseRecord* every time it receives a signal from *IntersenseThread*. Since emitting a signal is basically a normal function call of all slots that are connected to this signal, execution of the line emitting the signal will take as long as all the function calls take. However, when the signal emitter and the connected slots live in different threads, a non-blocking queue is used and emitting a signal will only take as long as it takes to write to a queue. This is why reading *IntersenseRecords* from the server is done in *IntersenseThread*.

IntersenseThread

IntersenseThread holds the TCP/IP connection to the InterSense server and periodically retrieves position and orientation data. When a record has been retrieved successfully a signal containing the *IntersenseRecord* is emitted and processed by *Intersense*.

IO

IO provides static functions for all file handling in this program. Courses that are drawn in *RoomWidget* can be stored and loaded, the traces of test persons can be recorded and loaded.

ReplayThread

ReplayThread is used to replay recorded traces, simulating the behaviour of retrieving data from an InterSense server. It reads a *.trc*-file (see Chapter 5.2.3) with position and orientation data and forwards this to *ShapeTactilizer*. *RoomWidget* will show the user walking through the room and the tactor belt will emit cues as expected.

RoomRenderer

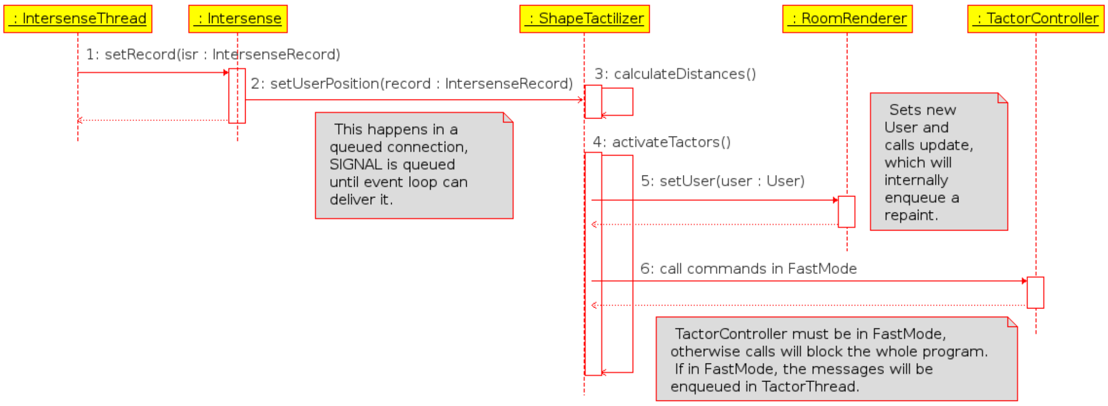
RoomRenderer, as the name suggests, renders a graphical 2D-representation of a room with its floor tiles, the active area that is covered by InterSense, the active course and the user with the tactor belt in a *QWidget*. Signals from *ShapeTactilizer* containing the updated *User* cause a repaint of the widget, however, repainting is capped at $25fps$ to avoid unnecessarily high CPU strain.

RoomWidget

RoomWidget is the main GUI widget and holds all widgets for interaction with the software as well as a *RoomRenderer*.

ShapeTactilizer

ShapeTactilizer is the core class of this software. Initialization of the connection to InterSense and the Tactor Control Unit is happening here. After that it is responsible for the ongoing process of using position data to calculate and send cues (see Figure 5.4): *IntersenseRecords*, *User* and *Room* are used to calculate the tactile cues which are then sent by calling the appropriate methods in *TactorController*. Figure 5.5 shows the different ways of how position information is supplied to ShapeTactilizer.



This happens in a queued connection, SIGNAL is queued until event loop can deliver it.

Sets new User and calls update, which will internally enqueue a repaint.

TactorController must be in FastMode, otherwise calls will block the whole program. If in FastMode, the messages will be enqueued in TactorThread.

Figure 5.4: **Sequence Diagram – Data Flow:** This diagram shows one iteration of the process of getting the user's position (1,2), calculating the vibro-tactile cue (3,4), updating the GUI so that it shows the currently activated tactors and the correct user position (5) and issuing the cue (6).

TactorController

TactorController is used to communicate with the Tactor Control Unit and provides methods for sending all the commands it supports. Typically after sending a command to the controller an answer will be read and the method will return after that. When time is critical and it is important to quickly send commands to the belt the *FastMode* suppresses reading answers from the belt, which makes calling methods for issuing commands return immediately and uses *TactorThread* to queue and send these commands in intervals of $50ms$.

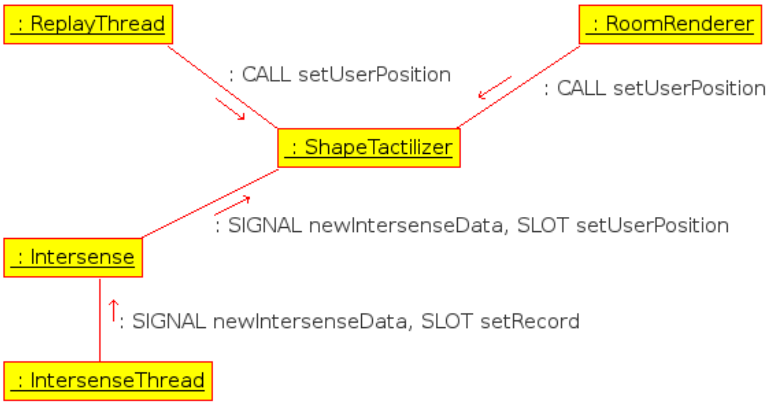


Figure 5.5: **Collaboration Diagram – User Position:** there are three ways how *ShapeTactilizer* can receive user position and orientation. The regular one is from InterSense, but also recorded traces may be played back by *ReplayThread* and mouse movements in *RoomRenderer* can be interpreted as movements of the user.

TactorThread

TactorThread is used when *TactorController* is in *FastMode*. Messages are queued and sent in intervals of $50ms$. A detailled description of this process is given in Chapter 5.2.4.

5.2.3 File Formats

.trc – Traces of Participants

The file begins with the string “trace” followed by the interval of retrieving records from InterSense in milliseconds in the next line. The consecutive lines are either recordings of the user position and heading in degrees ($0^o - 360^o$) from InterSense or a notification that a waypoint has been reached, where the coordinates of the waypoint are logged along with the unix timestamp of when this has happened. The timestamp is required for evaluation of the time it takes a participant to walk from one waypoint to the next, because calculating it from the number of records and the interval is not exact due to the concurrent nature of the operating system and the program itself.

```
trace
```

```
<int intervalInMs>
{<int userX>,<int userY> <float userHeading>}
{<int waypointX>,<int waypointY>:waypoint reached <long unixTime>}
```

Example file:

```
trace
25
356,56 12.002
360,60:waypoint reached 1241613650
361,60 13.834
364,62 14.231
```

.pol – Courses

Courses are built up from coordinates that must be visited one after another by the user. Several courses can be specified in one file by separating them with a dash.

```
polygons
{{<int x>,<int y>}
-}
```

Example file with two short courses consisting of four waypoints each:

```
polygons
120,60
223,170
296,302
402,409
-
120,60
270,58
416,94
566,89
-
```

5.2.4 Communication with the Tactor Control Unit (TCU)

Commands to the TCU are sent via serial connection over bluetooth. The software already expects an alredy established serial connection at `/dev/rfcomm0`, this location can of course be changed in *Defines*. Under Linux it is sufficient to adapt the config file `rfcomm.conf` by adding the MAC-address of the TCU, which can be discovered with `hcitool scan`, and then calling `rfcomm connect 0` to open the connection. The minimal `rfcomm.conf` could look like follows:

```
rfcomm0 {
    bind no; #do not bind during system startup
    device 00:0B:CE:01:C5:C7; #serial nr: F2M46
}
```

For conducting the experiments it was very important for the system to react as fast as possible. The way how the belt was intended to be used by the manufacturer is to send a command to the belt and then to read its answer, telling if the command was successful or not. After implementing this behaviour it was clear that reading the response after sending each command consumes too much time. Experiments revealed that it is safe to send commands to the controller in intervals of $50ms$. If they are sent faster, the internal buffer of the device will be overwritten before the command has been executed, resulting in no action at all. Another discovery was that after successfully sending many commands the device suddenly stopped working and required to be turned on and off again. This was caused by an overflow of the device's response buffer which must be cleared before it grows bigger than 4096 bytes. Since the length of each answer is known it is possible to indirectly monitor the buffer size and read all the responses at once before the critical size is reached. Reading all the responses at once takes about 1 or 2 seconds.

In the first series of experiments the behaviour of the response buffer was not yet discovered, so after some experiments the tactor belt started working and the affected experiments had to be repeated. Also for unknown reasons the first experiments to determine the interval of sending commands to the TCU yielded a value of $180ms$ which was used throughout the first series of experiments (1-3).

5.2.5 Threads and Concurrency

Three different threads apart from the main thread are used, their relationship is explained in the following list and in Figure 5.6.

- *TactorThread*: a thread with a command-queue sends commands from its queue every $50ms$. If it sends the last item of the queue it requests a new command from *ShapeTactilizer*.
- Position data is set in *ShapeTactilizer* by either *IntersenseThread*, *ReplayThread* or by *RoomRenderer* in the main thread.
- As soon as *TactorThread* notifies *ShapeTactilizer* about its empty queue, a cue is calculated based on the current (cached) position and orientation of the user, the position of the next waypoint and the selected type of cue. Then the necessary commands are enqueued in *TactorThread*. This is necessary as the number of commands per cue is varying, even if the same type of cue is used it may happen that e.g. only the position but not the frequency of the vibration has to change, therefore only one command is necessary.

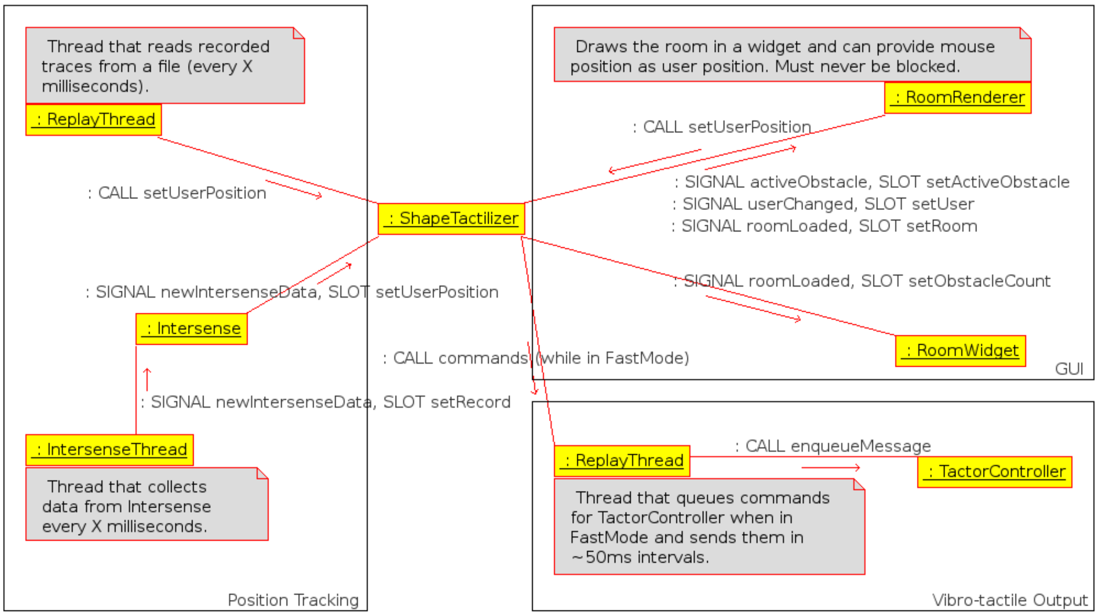
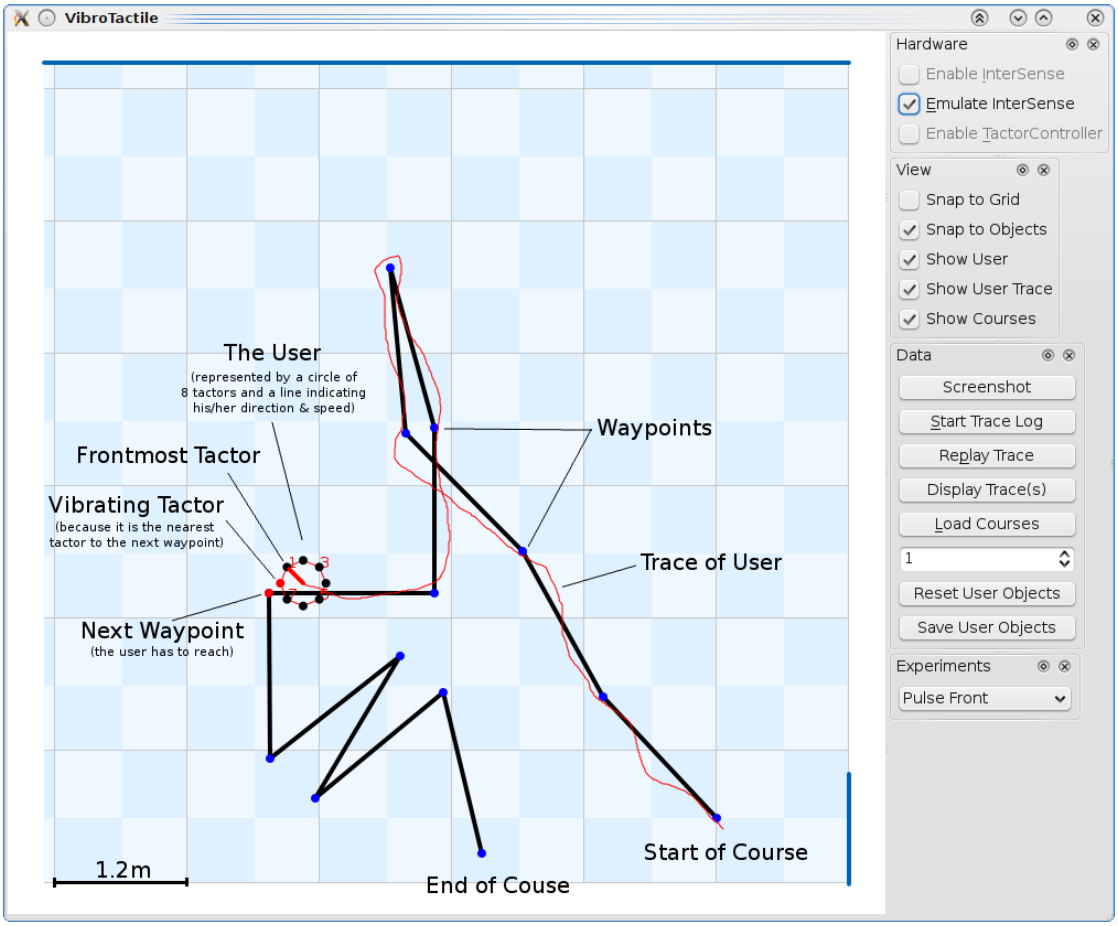


Figure 5.6: **Collaboration Diagram – Threads:** The use of threads guarantees that (i) fetching position information from InterSense or a trace and (ii) sending commands to the Tactor Control Unit do not interfere with or block each other and the GUI.

5.2.6 GUI

Its main purpose is to allow an easy setup and visual debugging of an experiment. In addition recorded traces can be replayed or just displayed which is helpful during analyzation. For setting up an experiment first a *.pol* with courses must be loaded, then a course and a cue are selected and recording of the user's movement in a `.trc` is started. While conducting the experiment one can easily follow the user on his path, see a trace of where he already went, which tactor is currently vibrating and if tracking works properly. This use-case was documented in the screenshot in Figure 5.7. For the analyzis later on it can be helpful to display several overlaid traces or to replay a trace again.

Additional features include the ability to quickly activate or deactivate retrieving data from InterSense, emulate a user by moving the mouse and sending commands to the tactor belt. It is also possible to construct and save courses as `.pol`.



Hardware

☐ Enable InterSense
☑ Emulate InterSense
☐ Enable TactorController

View

☐ Snap to Grid
☑ Snap to Objects
☑ Show User
☑ Show User Trace
☑ Show Courses

Data

1

Experiments

Pulse Front

Figure 5.7: Annotated screenshot of the software while emulating tracking of the user with the mouse. The area covered with the checkerboard pattern represents our laboratory, which is 7.45m by 7.3m in size. InterSense and the TCU were not available while making the screenshot and are therefore greyed out.

Chapter 6

First Series of Experiments – Encoding Distance in Frequency and Intensity

Through the course of this thesis 7 experiments split into two series have been conducted, the first three experiments belonging to series one, the other four belonging to the second series. In all experiments participants were able to complete the test courses, even though they took place in a quite small room and directions changed often and sharply. Still, different cues and other factors lead to different results, all of which will be discussed in this and the next chapter. As already stated in Chapter 1, the first series of experiments was designed to prove or refute the following two hypotheses.

6.1 Hypotheses

I Encoding of distance information into vibro-tactile messages will allow persons to find waypoints faster and more exact when compared to a simple baseline cue due to more situation awareness.

II A navigation performance degradation is expected when removing the auditory sensory channel as information carrier (blanking the noise caused by the vibration elements). This is motivated from earlier work, e. g. [6, p. 225], where it has been found that the noise generated by vibration elements provided an additional information source.

6.2 Experimental Design

6.2.1 Vibro-tactile Stimulation

The following parameters were used in the experiments which are described in more detail in Section 6.2.4 below. Frequency range and amplitude both encode the same information in order to make the cues more distinctive than when only using one parameter.

1. *Tactor Position:* As in [18] and [22] we use the tactor position around the belly to hint the direction in which the user has to go. The number of tactors was chosen to be 8 since it offers about the same performance as 12 tactors but with a lower error rate (see Section 3.2).
2. *Frequency Range:* We used frequency variation in the range from 200 to $300Hz$, since it is known to be perceived best by the Pacinian Corpuscles (PC) (see for instance Cholewiak et al. [14] or Riener [6], p. 115f). Initial studies conducted on higher and lower frequencies confirmed that using frequencies below approximately $150Hz$ or above $350Hz$ are difficult to perceive and thus should not be used in tactile cues.
3. *Amplitude/Intensity Variation:* For notifications using different vibration intensities the full range offered by the tactor system has been utilized. The overall range encompasses $24dB$, fragmented into 256 intensity levels. The linear mapping between distance and corresponding intensity level results in a logarithmic sensation.

6.2.2 Route Design

For each of the three experiments a different course, as exemplarily shown in Figure 6.1, was defined. The illustration shows a top view of our laboratory room with a tile size of 60 by $60cm$ (tiles of the checker-board pattern) and an overall room size of 730 by $745cm$. The light-shaded area was accessible for test participants (and limited by the coverage area of the InterSense tracking system[1]).

To guarantee comparability between the different courses they have been designed according to the following properties, equal for any experiment.

---

[1] The routes for all the experiments have been defined with respect to fit into the InterSense coverage area.

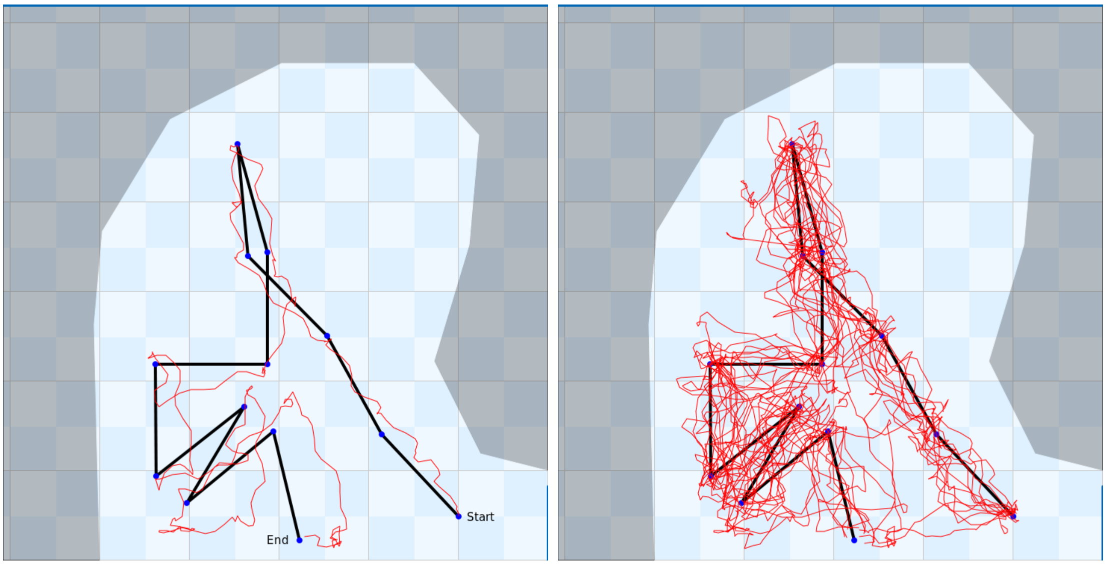


Figure 6.1: The left image shows the test course from experiment 1 (combination of thick, straight lines) with the overlayed trace of one test participant (thin solid line). Overlayed traces of all test persons on the same track indicate a rather good navigation precision, however, with several outliers (right image).

1. *Entire walking distance:* 18.0m
2. *Waypoints:* 13
3. *Distance between waypoints:* 1.50m
4. *Track sections:*
   (a) A nearly straight part consisting of 3 track sections (defined by 4 points), +15° and −15° angles.
   (b) One 170° U-turn.
   (c) Two consecutive angles of 90° each.
   (d) A zig-zag path, +160° and −160° angles.
   (e) The four remaining angles were 16°, 40°, 117°, and 127°.

6.2.3 Test Persons

Experiments were conducted with 10 male volunteers, aged between 23 and 32 years with an average age of 26 years, sized between 174 and 194cm with an average height of

182.1cm, weighted from 65 to 104kg with an average weight of 79.8kg, and with abdominal girths around the navel from 75 to 100cm with an average of 86.2cm. Three of the participants were staff members, the remaining seven were computer science students.

It has been evidenced that there is a strong gender dependent difference in reaction speed and navigation precision (e. g. in Kosinski [34], Dane and Erzurumluoglu [35], Der and Deary [36], Surnina and Lebedeva [37]), thus only male persons were allowed to take part in the experiments.

6.2.4 Definition of Experiments

Before conducting the actual experiments test participants had to perform a short familiarization experiment. It consisted of five waypoints and should help participants to get used to the system and the notification behavior of the tactor belt, particularly to the distance encoding scheme and its varying parameters vibration amplitude and frequency. They received no prior instructions on how the systems worked or that distance was coded into vibrations. The only information they got was that (*i*) they had to walk along a route with several waypoints and (*ii*) a simultaneous on-off-pattern of all vibration elements for one second means that a waypoint has been reached.

Experiment 1: Fixed Frequency and Intensity with Auditory Masking (Baseline)

The results of this most trivial test case conducted at first for all test attendees were used as baseline for further investigations. The distance and direction mapping for this experiment was as follows: the two vibro-tactile elements on the waist belt closest to the destination (waypoint) were activated with the highest possible vibration amplitude and a fixed frequency of 250Hz, thus there was no notification about the actual distance to the next waypoint. If a participant was more than 1.9m away from the next point of interest (POI), the tactor element with shortest distance to this POI was activated in a 180ms pulse, 180ms pause pattern. Distances between waypoints were always 1.5m, so this should signal that the user was far off track.

Reaching a waypoint: If a POI was reached, all tactor elements were activated in a 100ms pulse - 100ms pause pattern for 1 second, to clearly notify the walking person about its arrival at a waypoint. Immediately after this notification pattern the direction to the next waypoint was delivered. The covered path as well as the time required for approaching each waypoint were recorded and later used as reference values to evaluate the performance of the other two experiments featuring varying vibration frequency and intensity.

Masking vibration noise: For the purpose of auditory masking of the noise generated by vibrating tactors, a harmonic title of drone music [38] was played at a certain volume so that the person could no longer hear the vibration source. This was done to avoid multimodal feedback and to (dis)prove Hypothesis II.

Experiment 2: Varying Frequency and Intensity without Auditory Masking (FreqInt)

In this test case the distance of the test person to the next waypoint was encoded using vibration frequency and amplitude variation as follows. If a participant enters a freely configurable area around a point of interest (in all of the presented and discussed test sets a circle with a radius of $1.9m$ has been utilized) the parameters described in the paragraph “Vibro-tactile Stimulation” above were linearily mapped to the distance by increasing both frequency and amplitude with decreasing distance to the waypoint. Beyond the defined area directional notifications were given as described in the baseline test above. Figure 6.2 illustrates the use of varying frequency and intensity.

Experiment 3: Varying Frequency and Intensity with Auditory Masking (FreqInt)

This experiment was similar to the previous one with the only difference that auditory vibration information was masked with music as described and used in the first experiment.

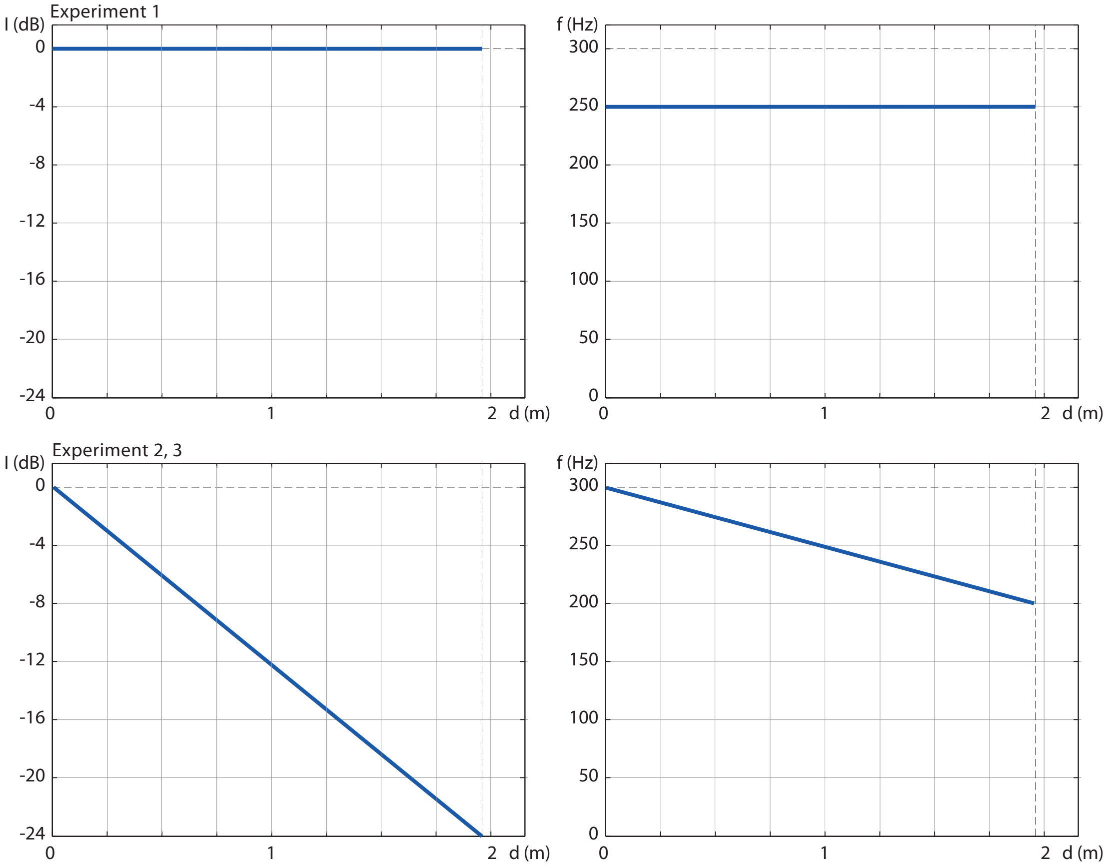


Figure 6.2: Encoding schemes for the three experiments. Constant vibration intensity (peak value, $0dB$ attenuation) and frequency ($250Hz$) have been used in experiment 1, for the experiments 2, 3 a variation of vibration intensity ($0dB$ to $-24dB$ attenuation) and frequency ($300Hz$ to $200Hz$) depending on the distance ($0.0m$ to $1.9m$) have been utilized.

6.3 Evaluations

6.3.1 Notification Latency

Latency in our context is defined as the time from the moment a person arrives at a specific location in the room to the moment when the tactor belt emits the vibro-tactile cue based upon this position.

The time lag from InterSense was $200ms$ because on average position updates were available only every $400ms$. So on average when querying position information from InterSense it was already $200ms$ old. Communication with the belt added another delay, it took around $180ms$ to send one command to the tactor controller.

For the first experiment only one command was required for changing tactile cues, the time lag was therefore $200ms + 180ms = 380ms$. However, for the second and third experiment three commands were needed, the latency rose to $200ms + 3 \times 180ms = 740ms$.

6.3.2 Interviews and Observations

In general, the reaction from test attendees on the experiments and the vibro-tactile navigation was quite positive. Even though 73% of the participating persons had no experience with this kind of notification, they stated that (*i*) the belt-type navigation system was intuitively usable for navigation and (*ii*) they could imagine being guided by such a system in their daily routine. More specifically, following conclusions can be drawn from observations and interviews following the user tests.

1. *Latency:* Some of the test candidates quickly learnt how to compensate the indicated time lag. They seldomly turned around their own axis, but tended to step sidewards and backwards. 55% (6) of the test candidates explicitly complained about the latency of the system and that this made it particularly difficult to navigate efficiently when being close to a waypoint.
2. *Tactor placement:* The sensed vibration intensity for three test participants was maximum for the frontmost tactors, two persons had problems in feeling vibrations there. One person felt that the tactors placed left/right on his sides provides best vibration feedback. 45% (5) complained about a generally low vibration intensity

on the back. Even if Cholewiak et al. [14] stated that belly and back are two anatomical reference points where vibrations are sensed better than on the sides, this did not hold true in our experimental setup, presumably caused by the fact that the tactor elements on the back were only pressed against the skin with low force. This suggests that adjusting the belt is crucial for good results.

3. *Masking vibration noise:* A piece of music delivered via headphones was used to mask the vibration noise in two of the three experiments. This was regarded as a good option by four participants (36%) – they stated that the masking helped them to focus their attention on the vibro-tactile sensations. One person missed the noise and felt less capable of precise navigation, the other six participants felt indifferent to the music.
4. *Vibration amplitude:* 73% (8) of the test persons noted that in some cases the vibration signal was not strong enough, which was obviously caused by the applied distance encoding scheme used in experiments two and three. 64% (7) of the participants perceived the changed distance coding scheme between the first and the other two experiments, and furthermore found the distance dependent variation of frequency and intensity a useful addition to the first experiment.

6.3.3 Walking Traces

All participants successfully navigated the courses in all three experiments. The only briefing carried out just before the experiments was a short training course with only 5 waypoints for the participants to get familiar with the system. In the course of the experiments three "walking anomalies" recurred again and again, namely (*i*) extensive zig-zaging when approaching a waypoint, and then passing by, (*ii*) revolving around the waypoint, and (*iii*) making a fast beeline to a waypoint, missing it, and coming back again, see Figure 6.3 (from left to right). Figure 6.1 shows traces of a complete route.

6.4 Conclusions and Motivation for Further Research

Hypothesis I – probably disproved: Both the boxplots in Figure 6.4 and Table 6.1 show that the performances of the second and third experiment were significantly worse compared to that of the first one. This result holds true for the number of occured anomalies as indicated in the righthand plot of Figure 6.4. The number of anomalies

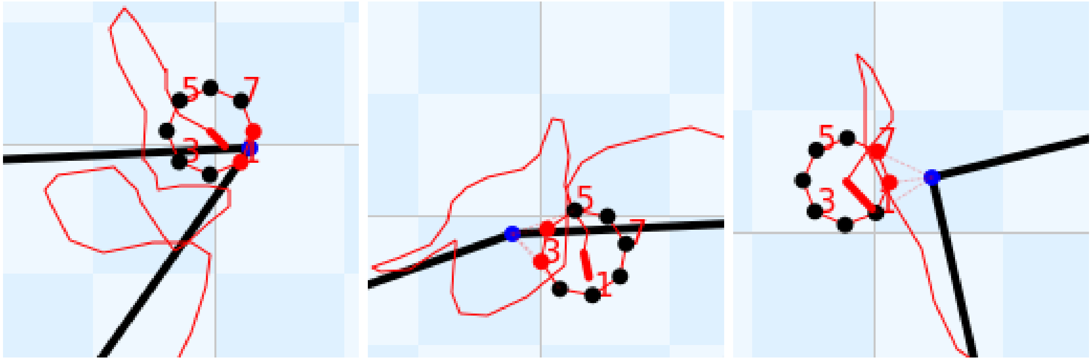


Figure 6.3: Walking anomalies (from left to right): zigzaging before, revolving around, and passing by a waypoint. The eight dots arranged in a circle represent the user wearing a waist belt with its eight tactors, the thick line from the center of the circle to tactor 1 shows the user's heading, the two long thick lines are a small part of the course the user has to walk, their intersection is the waypoint that must currently be reached.

	Walking Time (sec)			Walking Distance (cm)			Nr. of Anomalies		
Experiment	1	2	3	1	2	3	1	2	3
Min. (x_{min})	6.33	8.38	8.48	190.56	257.88	223.16	0.00	2.00	1.00
Median ($\tilde{x}$)	8.03	11.03	10.46	248.39	352.97	291.00	2.00	5.00	4.00
Mean ($\overline{x}$)	8.82	11.49	10.65	256.33	337.99	313.08	2.20	4.60	4.00
SD (σ_x)	1.79	2.16	1.66	34.97	62.04	60.31	1.93	1.78	1.70
Max. (x_{max})	11.61	15.88	13.89	324.26	428.91	408.09	6.00	7.00	7.00

Table 6.1: Statistical evaluation of the first three experiments: walking distance is on average 27.64% (20.23%) higher for the second (third) experiment compared to the first one. This relationship holds true for the walking time and the counted anomalies ($p<0.05$).

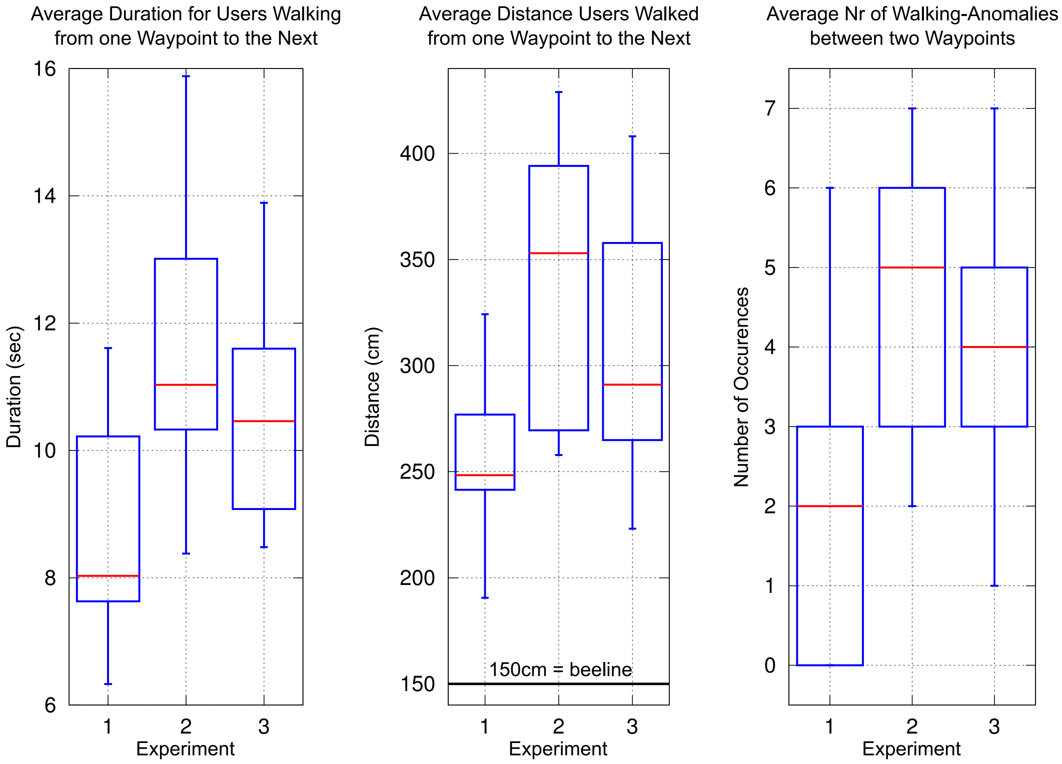


Figure 6.4: Boxplots for the first three experiments indicating the average walking time, walking distance and number of anomalies per user (from left to right).

was significantly lower for the first experiment (e.g. on average 2.18 compared to 4.73 for the second experiment), the result for the third experiment is slightly better than for experiment two.

Unfortunately results of the three experiments can not be compared directly because of the influence of latency – for experiments 2 and 3 it was $740ms$ whereas it was only $380ms$ for experiment 1. During planning the first three experiments latency was not considered, the performance degradation could be caused by either higher latency or the distance encoding scheme or both.

73% (8) of the test persons noted that sometimes vibrations were very difficult to sense. From combining these statements with our observations while conducting the experiments it became clear that the occurence of this problem correlated with high waypoint distances and therefore low vibration amplitudes during experiment 2 and 3. Therefore, distance encoding caused at least parts of the degradation, but the differences in latency are a highly probable cause as well. The rising number of anomalies near waypoints, where vibration intensity was nearly the same for all three experiments suggests negative influence of higher latency. In short, performance degradation was most probably caused by both latency and distance encoding, but the respective influence of each of them can not be inferred.

Hypothesis II – disproved: Hypothesis II, which states that a test person will perform faster and/or better in experiment 2 than in experiment 3 by reason of multimodal instead of unimodal feedback, has to be rejected. Results even show that it is rather the other way round (see Table 6.1). All individual results, walking distance, duration required for completing the course and the number of anomalies are lower for the third experiment than for the second (however, statistically not significant). When interpreting this result the following facts must be considered.

1. In [6, p. 225] it has been found that the noise generated by vibration elements provides an additional information source.
2. 36% (4) of the test participants reported that using masking music during the experiment helped them to improve their concentration on the main task.
3. Even if different routes were used a learning effect between experiment 2 and 3 can not be ruled out, because the exact same notification cues were used for both experiments (first without (2) and then with masking music(3)) and no break was

taken inbetween. It is also possible that the high variance of walking duration and distance in experiment 2 was reduced by the learning effect in 3.

Ultimately we did not accept Hypothesis II, because even if a learning effect is advantageous for experiment 3, this advantage can not be big enough to revert a hypothetical significant advantage of bimodal feedback in experiment 2 to worse results than in 3. Also the result could be explained by the fact that the multimodal stimulation (vibration noise from a tactor element and the vibration itself) confuses and distracts test persons.

Further Research: Further research was motivated by different factors. First, we wanted to give a clear answer whether Hypothesis I can be accepted or not. Second, our distance encoding scheme was suspected to have a negative influence on performance. Also it was our declared goal to reach better performance than with baseline cues as in experiment 1 and we got positive verbal feedback from test persons with respect to the idea of distance depending encoding.

Chapter 7

Second Series of Experiments – Advanced Distance Encoding with Patterns

Hypothesis II was disproved in the first series, but results for Hypothesis I were not significant. The second series of experiments was initiated to clarify the interrelationship of performance degradation and (i) notification latency or (ii) distance depending variation of vibration intensity, in short, if Hypothesis I could be proven for experiments 2 and 3 and an experiment similar to experiment 1 but with higher latency. Also new distance encoding schemes have been developed in a repeated attempt to proof Hypothesis I.

7.1 Experimental Design

Basically the same setup as described in Section 6.2 also applies for the following experiments. The same room, room positioning system, tactor belt and placement of tactors have been used.

7.1.1 Vibro-tactile Stimulation

Experiment 4 required the same stimulation parameters as described in Section 6.2 to be comparable to the first series. For experiments 5 to 7 the following changes have been made to the cues, the rationale behind these changes being explained in the next paragraphs.

1. *Tactor Position:* Used as in the first series of experiments.

2. *Frequency Range:* The frequency range was altered so that cues at high distances to the waypoint used the ideal frequency for the human sensory system, which coincides with the resonant frequency of C2-tactors. The frequency range was therefore changed from $200 - 300Hz$ to $250 - 320Hz$.
3. *Amplitude/Intensity Variation:* In the first series of experiments test participants complained about problems sensing vibrations at high distances to the next waypoint. This problem occured due to the chosen distance encoding using varying frequency and vibration intensity which resulted in vibrations that were difficult to sense when the person was far away from the next waypoint. For a better noticeability of the cues the vibration intensity was always set to maximum.
4. *Vibration Pattern:* Constant vibration has the advantage that the effect of temporal summation which lowers the recognition threshold for up to one second [7] is exploited maximally. But after dropping vibration intensity as parameter for distance encoding in our cues, a new parameter had to be found. Introducing on/off patterns was motivated by two factors: first, patterns can easily be distinguished and it is even possible to put some effort in memorizing more patterns, which is not that easy with the ability to discriminate frequencies; second, we suspected constant vibration to cause a habituation effect after 2 to 3 seconds and believe that using patterns prevents that.

7.1.2 Problems with InterSense

InterSense behaved strangely while we planned the second series (see Chapter 5.1.1), in areas near the room's walls where tracking worked flawlessly before, the user position could not be tracked anymore. Even in the areas directly below InterSense's ultrasonic emittor stripes mounted on the ceiling it happened quite often that tracking was lost and participants were disoriented. Statistics for the occurences of this behaviour can be seen in Table 7.1. It is apparent that tracking was significantly worse for the second series, unfortunately this behavior came without us changing the system in any way and we were not able to fix it.

7.1.3 Route Design

As the problems with InterSense were identified before starting the second series, new and shorter routes that avoided the especially problematic areas near walls were designed.

Experiment	1	2	3	4	5	6	7
Segments * Participants	120	120	120	117	117	117	117
Discarded Segments (Nr.)	2	2	1	33	16	26	14
Discarded Segments (%)	1.67%	1.67%	0.83%	28.21%	13.68%	22.22%	11.97%

Table 7.1: Overview of the number of line segments (path between two waypoints) where participants were misguided due to wrong position information from InterSense. Data from these segments was not used in the evaluation of system performance.

For experiment 4 we used the same route as in experiment 1, for experiments 5 to 7 the new routes had the following properties.

1. *Entire walking distance:* $13.5m$
2. *Waypoints:* 10
3. *Distance between waypoints:* $3 \times 1m$, $3 \times 1.5m$, $3 \times 2m$
4. *Track sections:*
   (a) A nearly straight part consisting of 3 track sections (defined by 4 points), $+5°$ and $-13°$ angles.
   (b) One 175° U-turn.
   (c) Two consecutive angles of 90° each.
   (d) The three remaining angles were 33°, 50°, and 130°.

7.1.4 Test Persons

In experiment 4 all 10 test persons from the first three experiments participated, for experiments 5 to 7 we could motivate 2 more male students of computer science and a blind man in his late fourties, totalling to 13 participants.

7.1.5 Latency

Improvements in our software allowed for lower system latency. The average latency from InterSense was still $200ms$ but we could speed up communication with the tactor belt from $180ms$ to $50ms$ per command. The latency for experiments 5 to 7 was $200ms + 50ms = 250ms$.

An important point that we had in mind when designing on/off patterns was keeping them short. Using long patterns would have increased the system latency since when the user changes his direction shortly after the pattern starts, the cue is actually guiding the user into the wrong direction. Only the next cue that is based on current positional information will guide the user correctly, until he changes direction again. The time when a cue is already obsolete adds to the system latency, which we want to keep as low as possible.

7.1.6 Definition of Experiments 4–7

Experiment 4: Fixed Frequency and Intensity (Baseline)

To collect data that could be compared to experiments 2 and 3, this baseline experiment was designed to have a latency of $740ms$, otherwise it was identical to experiment 1 (see Section 6.2.4): all parameters of the vibro-tactile cues were static and even the test course was exactly the same. This allowed for determining the respective influence of latency and distance encoding.

Unfortunately an error in the software sometimes caused a pause of several seconds where no cues were emitted after the cue for reaching a waypoint. This negatively influenced results for the the walking time in this experiment only. Participants did not walk in a wrong direction when no cues were emitted, so there was no effect on walking distance.

Experiment 5: Fixed Frequency and Intensity (Baseline)

Since we could improve the overall latency of our software a new baseline experiment with $250ms$ latency for comparison with experiments 6 and 7 had to be conducted. It uses a different course and also a different cue for reaching a waypoint than the other baseline experiments.

Reaching a Waypoint: The pattern signalling that a waypoint has been reached was changed for experiments 5 to 7 and consisted of three short vibrations of all tactors, a short pause, and another three short vibrations with a total duration of $800ms$ as illustrated in Figure 7.1. The new cue was a little shorter but more intense than than the old one which consisted of a simple vibration for one second.

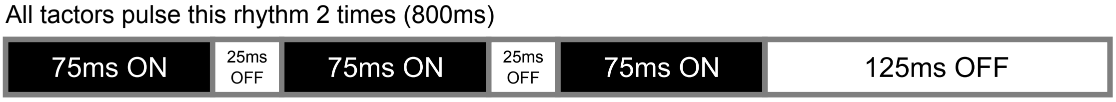


Figure 7.1: Vibration pattern triggered when reaching a waypoint

Experiment 6: Varying Frequency and Pattern (FreqPat)

In this experiment distance is encoded using both varying frequency and patterns. Frequency is $250Hz$ when the user is $1.9m$ away from the waypoint and $320Hz$ directly in front of it. The used pattern is the same for all eight tactors: $100ms$ vibration & $200ms$ no vibration at a distance of $1.9m$ and $200ms$ vibration & $100ms$ off at the waypoint. For all distances between $1.9m$ and $0m$ the durations will be linearly mapped, e.g. at $1.7m$ the on-phase will take about $110.5ms$. The topmost pattern in Figure 7.3 illustrates this behaviour.

Experiment 7: Varying Frequency and Pattern (FreqPatFront)

The distance encoding from the previous experiment was refined concerning the cue for the frontmost tactor. The motivation behind this is that most of the time people will walk in about the correct direction and if the resolution of cues in the front is higher than the 45^o provided by one cue per tactor this will hopefully lead to better results. As illustrated in Figure 7.2 the area where the front-most tactor vibrates in the previous experiments is divided into three zones: one where the persons walks really straight ahead with an error of only $\pm 6^o$, a second zone with a slightly bigger error of $\pm 6^o$ – $\pm 15^o$ and a third zone where the area for the adjacent tactor is nearly reached ($\pm 15^o$ – $\pm 22.5^o$). These three zones have three different cues as illustrated in Figure 7.3, in the first zone the cue will be sensed as a “double click”, which confirms that the current heading of the user is very exact. In the second zone the same cue as for all the other tactors will be used. In the third zone, when the user clearly deviates from the path, an additional correction cue on the adjacent tactor is added to the normal cue, which should signal a slight change in direction.

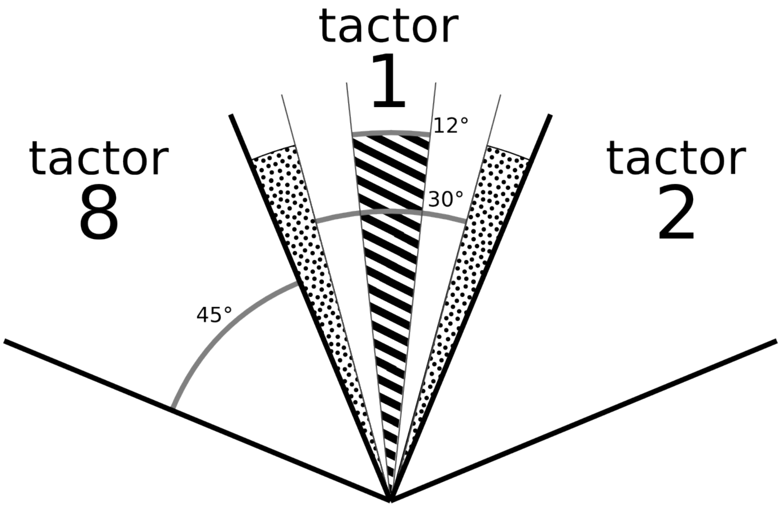


Figure 7.2: Angles where different notification cues are used for the frontmost tactor in experiment 7. The user can be imagined as standing in the middle of the pie-chart, his navel pointing to tactor 1, his back pointing to tactor 5. (Areas for tactors 3 to 7 are omitted to reduce the size of the illustration.)

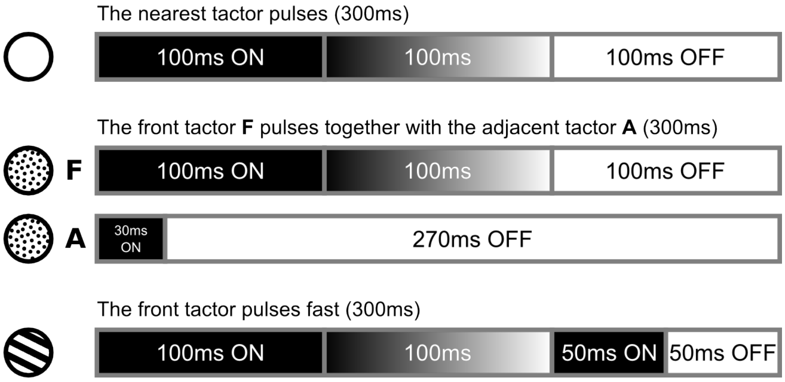


Figure 7.3: Vibration patterns of the cues used in experiments 6 (FreqPat – only the topmost pattern marked with the white circle) and 7 (FreqPatFront – all patterns). The fill-pattern of the circles corresponds to the areas where the cue will be used in Figure 7.2.

7.2 Overview of all Experiments

This section should give give an overview of the setup and results for all experiments before the final evaluation is done in the next section. Statistical evaluation for walking distance and duration can be found in Table 7.4, figures 7.4 and 7.5 are boxplots visualizing the same data.

Tactor Activation Methods: For different types of cues were used in all seven experiments. A quick overview of which type of cue is used in which experiment is given in tables 7.2 and 7.3.

- *Baseline:* fixed frequency and attenuation, constant vibration.
- *FreqInt:* frequency and intensity (attenuation) are linearly mapped to the distance to the next waypoint (when going towards a waypoint frequency gets higher and attenuation gets lower), constant vibration.
- *FreqPat:* frequency varying as in *FreqInt*, but the cue follows this pattern: vibrate $100 - 200ms$, pause: $200 - 100ms$. Duration of the vibration is gets longer, the pause shorter when walking towards a waypoint. Overall duration of a cue is always $300ms$.
- *FreqPatFront:* same as *FreqPat* but with three different vibration patterns for the frontmost tactor.

Experiment	1	2	3
TactorActivationMethod	Baseline	FreqInt	FreqInt
Freqency	$250Hz$	$200 - 300Hz$	$200 - 300Hz$
Attenuation	$-0dB$	$-24 - -0dB$	$-24 - -0dB$
Auditory Masking	yes	no	yes
Latency	$380ms$	$740ms$	$740ms$
Learning Effect	No	Marginal [a]	Yes [b]

[a] Second experiment in a row.

[b] The experiment directly before used exactly the same cues.

Table 7.2: Overview of all experiments from the first series (1-3).

Experiment	4	5	6	7
Tactor Activation Method	Baseline	Baseline	FreqPat	FreqPatFront
Freqency	$250hz$	$250Hz$	$250 - 320Hz$	$250 - 320Hz$
Attenuation	$-0dB$	$-0dB$	$-0dB$	$-0dB$
Auditory Masking	yes	yes	yes	yes
Latency	$740ms$	$250ms$	$250ms$	$250ms$
Learning Effect	No	Marginal [a]	Marginal [b]	Yes [c]

[a] Second experiment in a row with the same cues for participants of series 1 (10 out of 13 participants)

[b] Third experiment in a row for participants of series 1

[c] Fourth experiment in a row for participants of series 1 and the experiment directly before used similar cues.

Table 7.3: Overview of all experiments from the second series (4-7).

Experiment	1	2	3	4	5	6	7
Average Distance per Participant (cm)							
Min. (x_{min})	190.56	257.88	223.16	221.69	182.28	178.19	162.20
Median ($\widetilde{x}$)	248.39	352.97	291.00	276.60	202.18	220.57	194.39
Mean ($\overline{x}$)	256.33	337.99	313.08	289.88	218.93	243	209.18
SD (σ_x)	34.97	62.04	60.31	40.25	33.49	60.38	29.91
Max. (x_{max})	324.26	428.91	408.09	343.25	283.91	424.8	258.96
Average Duration per Participant (ms)							
Min. (x_{min})	6.33	8.38	8.48	7.63	4.63	5.71	5.78
Median ($\widetilde{x}$)	8.03	11.03	10.46	9.78	6.86	8.00	6.89
Mean ($\overline{x}$)	8.82	11.49	10.65	10.16	7.06	7.96	7.44
SD (σ_x)	1.79	2.16	1.66	1.83	1.10	1.21	1.14
Max. (x_{max})	11.61	15.88	13.89	12.91	8.5	10.33	9.29

Table 7.4: Statistical evaluation for all experiments. Both the numbers for distance and duration are the average for all route segments (path from one waypoint to the next) per participant.

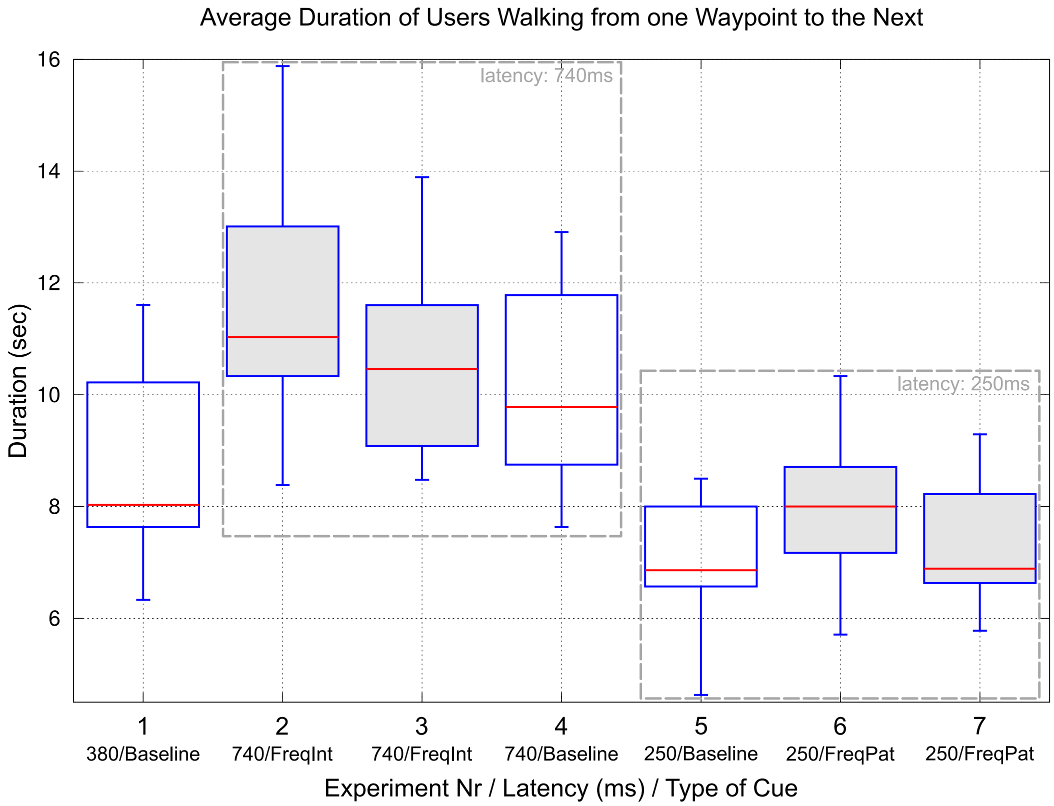


Figure 7.4: Boxplots of all experiments indicating the average walking time between two waypoints per user.

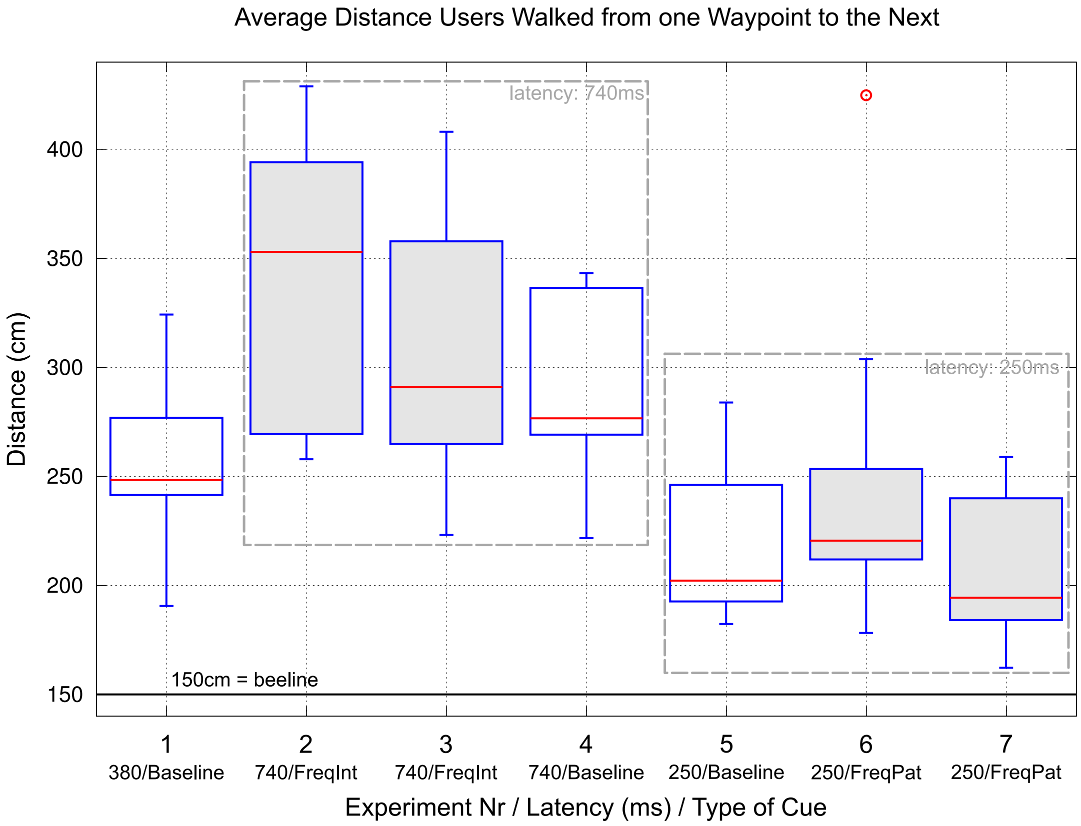


Figure 7.5: Boxplots of all experiments indicating the average walking distance between two waypoints per user.

7.3 Evaluations

7.3.1 Distance Encoding

With the enalysis of experiments 1 to 3 we could not make a clear statement regarding Hypothesis I in Chapter 6.4. When comparing experiment 1 to the other two both latency and distance encoding were different and the influence of each of them was unclear. However, with the results of the second series three comparisons, with two experiments each that only differn in distance encoding, can be done.

1. *Baseline vs. FreqInt:* Effects of using the simple distance encoding when comparing experiments 4 (baseline) and 3 (varying frequency and intensity): the mean of the duration was raised by 4.8% from $10.16ms$ to $10.65ms$ ($+0.49ms$), but this result was influenced by herein before mentioned bug, the mean for the walked distance by 8% from $289.88cm$ to $313.08cm$ ($+23.2cm$).
2. *Baseline vs. FreqPat:* Comparing experiments 5 (baseline) and 6 (varying frequency and pattern): the mean of the duration was raised by 12.78% from $7.06ms$ to $7.96ms$ ($+0.9ms$), the mean for the walked distance by 10.99% from $218.93cm$ to $243cm$ ($+24.07cm$).
3. *Baseline vs. FreqPatFront:* Comparing experiments 5 (baseline) and 7 (varying frequency and advanced pattern): the mean of the duration was raised by 5.36% from $7.06ms$ to $7.44ms$ ($+0.38ms$), the mean for the walked distance was *reduced* by 4.45% from $218.93cm$ to $209.18cm$ ($-9.75cm$).

Interestingly, the numbers suggest that FreqPat performs worse than FreqInt, which we strongly doubt. The quite low raise of only 4.8% in walking time between these two cases is mostly caused by the software bug that caused a pause until cues were emitted after reaching a waypoint. But also the increase in walking distance of 8% is lower than for Baseline vs. FreqPat, where the increase was around 11%. There are several reasons why the comparison of FreqInt with FreqPat and FreqPatFront may be flawed additionally: the influence of FreqInt was testet under a high-latency environment, whereas FreqPat and FreqPatFront under low latency. Also as noted before, during experiments 4 to 7, especially in experiment 4 (see Table 7.1), we experienced much more problems with InterSense and had to discard much data.

However, these results clearly show that FreqPatFront is the best encoding scheme as it is the only scheme that managed to reduce the walked distance, even if average walking duration was still higher than for the related baseline experiment. Results for FreqPat and FreqPatFront can be compared very well as they were conducted under the same conditions, only a slight learning effect from experiment 5 to 6 to 7 should be considered, but it is very improbable that the learning effect would have caused the significant difference in performance.

Hypothesis I - disproved: Unfortunately these final results still do not prove Hypothesis I. FreqPatFront may have yielded equal results as the baseline experiment, but the goal was to surpass it, therefore, Hypothesis I must be discarded. However, having the same performance with distance encoding and a baseline case motivates further research, as this means that a user already profits from the system: he will not lose speed or accuracy when using the system but gain situation awareness. Also the effect of distance encoding will most probably be positively influenced by a learning effect. Results may be different from ours when test persons learn to use the system for several hours and in such a case distance encoding provides more potential for learning than the simple baseline case.

7.3.2 Notification Latency

The negative effects of higher latency can be observed when comparing the different baseline experiments. To repeat its definition in the context of this work: latency is the time from the moment a person arrives at a specific location in the room to the moment when the tactor belt emits the vibro-tactile cue based upon this position.

1. *$380ms$ (exp1) vs. $740ms$ (exp4):* the mean of the duration was raised by 15.21% from $8.82ms$ to $10.16ms$ ($+1.34ms$), the mean for the walked distance by 13.09% from $256.33cm$ to $289.88cm$ ($+33.55cm$). Both experiments were the first in the respective series, so influnce of learning effects can be ruled out.
2. *$250ms$ (exp5) vs. $740ms$ (exp4):* the mean of the duration was raised by 43.88% from $7.06ms$ to $10.16ms$ ($+3.1ms$), the mean for the walked distance by 32.41% from $218.93cm$ to $289.88cm$ ($+70.95cm$). These numbers may have been influenced by the fact that the two experiments were conducted right after each other.

Even if herein before mentioned bug caused higher walking durations for experiment 4 the overall picture, which can be seen in the results for walking distance as it was not influenced by the bug, is clear: latency should by avoided at all costs. For a latency of

$740ms$ the walking distance was nearly twice as long as the ideal path. Of course the impact of latency is different for every use case: the distance between waypoints being a big factor. It could not be proven that a latency of $250ms$ already has no negative effect on performance in the experiments, but first it was not possible to further reduce latency and second it was not the goal of this work to analyze the effect of latency.

7.3.3 Interviews and Observations

General feedback from participants was even more positive than for the first series. An interesting point of criticism of two users was that they found the used distance encoding unintuitive and that they would use the encoding scheme the other way around: start with long $200ms$ pulses when far away from the waypoint and use short $100ms$ pulses when near the waypoint. Also a behaviour similar to a Geiger counter was suggested. This kind of cue could work if certain results from [18], where participants requested at least 4 seconds between pulses in an outdoor scenario with very long distances between waypoints, are taken into account. For an indoor scenario this maximum time between two cues must of course be smaller, therefore reducing the spectrum of possible variations. One user noted that for a real-world use he would not like to be constantly notified but only when e.g. a change of direction is imminent. This is a valid complaint, but the purpose of the experiments was not to create cues for a real-world system but to investigate parameters for vibro-tactile cues. A system for everyday use must of course be less verbose in order to be useful.

1. *Acceptance:* In comparison to the first series, acceptance of the system has improved: before, only 73% of the users said that the system was intuitive and that they could imagine using this kind of guidance. For the second series this percentage rose to 92%: all but one participants could imagine using such a guidance system for scenarios like (*i*) visiting a new city and using a map or visual GPS device in combination with a tactor belt, (*ii*) getting tactile directions and hints for upcoming events like "please take the next exit" in a car, or (*iii*) being warned of dangerous areas. Most users would like to use tactile feedback in combination with traditional methods of navigation because they want to know about their current location and surroundings and do not prefer to follow cues blindly. We expect this requirement to strongly depend on the users as well as the situation: tourists that visit a city want to learn to know it, a driver that has to just drive through it on the way may only be interested in directions. The one user who did

not like tactile guidance said that he felt overwhelmed by the vibration force and thought that the vibrations require too much attention.

However, most participants were either befriended with or colleagues of the author, which puts this good result into perspective. Two additional factors influencing this very good result for the acceptance rate should be taken into account. First, all participants work in the field of computer science, some even in pervasive computing, so they have a strong affinity to technology. Second, we asked them in the questionaire if they would consider using a miniaturized and well-integrated solution and not the prototype that does require wearing an obtrusive belt with a big controller box.

2. *Latency:* As the overall system latency was reduced to $250ms$ for experiments 5 to 7, it was no longer a flaw that was mentioned by the participants. When asked, 85% (11) of the users said that the reaction time of the system was sufficient, in comparison to 55% of the users complaining from their own in the first series. Therefore, we can accept a system latency in the magnitude of $250ms$ as a value that can be improved upon but that does not dramatically affect performance or acceptance.
3. *Situation Awareness:* The key benefit of using distance encoding is to provide situation awareness. In the first series overall performance was far from achieving this. In the second series 54% (7) of the participants said that they had at least a vague feeling of how far the next waypoint was still away. We did not investigate how a learning effect would have further improved the situation, but we could still prove that people profit from distance encoding.

From the Perspective of a Blind Man: The one blind person that took part in this research graduated and is still working at our university. He therefore knows the campus for nearly thirty years but still it was a challenge for him to walk to our laboratory. We had to describe the way in much detail because he has never been there before, a short excerpt looks like this: “after entering the building move slightly to the right, after about $2m$ ascend the stairs on the left. When the stairs end make a U-turn to the left and continue on them as you are now between two floors. After ascending the stairs make a u-turn to the right and walk straight ahead for about $5m$, there you will find the door to our department”. This demonstrates that even if a blind person knows a lot about a specific area, e.g. a campus, there are always places that are new for them and it will be difficult to find these places without assistance. Also open areas like a big entrance hall are problematic for blind people, they often tend to walk near walls because once they get lost they have no easy way to find out where the exit or their goal is located. A campus- or company-wide tactile navigation system could remedy these situations.

His reaction after participating in the second series was very positive, he was really excited about the possibilities such a system would provide. The system was very intuitive to use for him, he never missed a waypoint and was practically always on the right track. It was very easy for him to realize if he was going into the right direction, the waypoint-distance was not that clear but he was confident that he could learn to interpret the signals better. Varying frequency could not be heard with the test setup due to the masking music, he said that when these noises are not artificially blocked they would be a great second source of information. Limitations in relying on this are obvious though: the background of a normally busy bureau are enough to drown the tactor noises.

Chapter 8

Discussion and Outlook

8.1 Improvements to the Chosen Approach

Issues with Comparability: Comparability is essential for scientific research and hard to achieve. In retrospective experiments in this work should have been planned more thoroughly in this regard. Three different **latencies** are the most obvious factor making comparisons difficult. Due to them three baseline experiments had to be conducted, where one should have been sufficient. Also the **change of the frequency range** for experiment series 2 as explained in Chapter 7.1 should not have been done: first, it reduced reliable comparability between the first and the second series (which was not possible because of the different latency anyways) and second the frequency range was reduced from $100Hz$ to only $70Hz$, making it even more difficult to sense changes.

The **influence of the different courses** was not avoided completely. Even if their design tries to guarantee that they are equally difficult, their order should have been randomized per user. In the experiments 6 different courses were used (experiment 4 was a rerun of the first experiment with higher latency and they used the same courses), but for an experiment X all users had to walk the same course. To avoid an influence of the course the six individual courses must be assigned to the user's experiments randomly.

Learning effects between experiments were not avoided. Future experiments must try to either minimize lerarning effects e.g. by using long breaks between experiments, or to let the users learn the system for a sufficient period of time. The latter should avoid possible confusion due to a different cue and guarantee that users are familiar with the new cue.

Improvements for the Cues: After the first series it became apparent that variations in frequency and intensity are difficult to sense. An approach that we did not test is to increase frequency or intensity in **steps instead of a linear mapping**. Three different values representing either long, medium or short distance to the waypoint could be sufficient for situation awareness and may be easier to sense. The same concept could be applied to the patterns from the second series: instead of adjusting the length of vibration linearly, doing this in steps could improve perception of distance by avoiding change blindness. Additionally another parameter of the vibration patterns could be changed: the **duration**. In this work cues with a duration of $300ms$ were used to avoid the problem of a cue starting and immediately becoming obsolete because of a change in direction. If cues were longer, the potential of persons being able to differentiate between more cues would be higher, the amount of possible information that can be transmitted higher. For sudden changes in direction cues could just be stopped prematurely to still guarantee a fast response time.

8.2 Discussion of the Results

Overall, even the results for the worst performing experiment (experiment 2 with high latency and the initial distance encoding) are reasonable: all participants were able to navigate through all courses. When comparing the average walking distance between two waypoints, which should be near $150cm$ for a perfect outcome, was $209cm$ in the best experiment regarding walking distance (experiment 7 with low latency and advanced distance encoding) and $338cm$ in the worst. These findings suggest that even with the simplest cue and under poor circumstances it is possible to find waypoints solely with help of information perceived through the sense of touch. They can not be seen as evidence for "precise" route guiding because participants on average walked more than double of the direct line between waypoints, but it still is possible.

In contrast, the best results for advanced distance encoding were promising. Especially our one blind participant saw the system as an overall success. With only $192cm$ average walking distance for the last experiment he was amongst the best and his feedback was overwhelmingly positive.

Hypothesis 1 – Distance Encoding: The results do not directly motivate the encoding of distance information in vibro-tactile guidance cues. Nevertheless equal performance in comparison to baseline cues was reached. Therefore, it is no disadvantage to use it and at the same time performance has the potential to profit from a learning effect based on situation awareness. In addition, we still believe that distance information is important – especially for blind people who can not see their destinations. A possible alternative to our distance encoding could be special patterns that inform the participant regularly about his position.

Hypothesis 2 – Multimodality: This hypothesis could also not be proven, but results are influenced by a learning effect. A next step should be to repeat these experiments with low latency and measures to avoid a learning effect. These could be either a long break between the experiments or to let one half of the participants conduct the experiment with music and the other half the one without music first.

In future experiments all three combinations should be tested: *tactile only* (vibrations only, mask noises of tractors with music), *tactile and auditory* (feel vibrations and hear the noise of the tactors), *auditory only* (only hear the noise of the tactors, mask vibrations with layers of clothes).

8.3 Suggestions for a Real-World System

This work did not try to to cover everything that would be necessary for a complete guidance system (covered parts emphasized): (*i*) a map of the area, (*ii*) *position tracking*, (*iii*) an interface for the user to enter his destination, (*iv*) algorithms to calculate the best route to the destination and (*v*) *guidance cues.* When developing a tactile guidance system for application by the end-user new challenges arise. In the next paragraphs a few ideas and requirements are collected to give an impression of the complexity of such a system.

Depending on the distances between waypoints it is very likely that for a real world application it does not make sense to constantly send cues to the user. A system that is giving constant feedback will annoy her over time and lose one key advantage of the tactile sense: that it is not yet plagued with information overload.

Therefore, cues should only be provided when needed. In the case of our experiments this was all the time, because the courses changed directions quickly and participants seldomly walked into the exact direction of the next waypoint. For a real-world application this does not hold true, e.g. in the case of a person being guided through a city by foot it is clear that she should go straight ahead when no cues are sent. Most of the time the corridor of a street is guidance enough and the system is only required to emit cues when she approaches a crossing. For other use cases like a hiker in the mountains the density of cues will probably be higher.

For the scenario of guidance through a city by foot, it would make sense to notify the user $100m$ before a change in direction and then again when it is imminent. When she decides to take a look at a shop window the system must not repeat its cues, when she takes a detour the calculated route will be silently adapted. More detailed information would be required for blind people, it is not enough for them to know that they have to turn left or right, but it would also be helpful to be guided to cross-walks like in the work of Pressl and Wieser [30]. A great additional feature of a guidance system could be to notify the user of her points of interest, requiring even more cues.

8.4 Outlook

A study to investigate the difference between visual and vibro-tactile feedback for route guidance should be conducted, because it is not yet clear how well vibro-tactile cues perform in comparison to e.g. a handheld device that shows the user the way. All three permutations (*i*) tactile, (*ii*) visual and (*iii*) tactile and visual should be tested. Work related to this question was done by Riener [6], p. 204, who shows that reaction time for vibro-tactile stimuli outperforms both visual and in particular auditory cues. However, only four different cues (turn left/right, switch light on/off) were tested in an in-car scenario. Further work focusing on a route guidance scenario is necessary.

The learning effect regarding cues with distance encoding should also be examined in detail. It is likely that a learning effect is stronger for such cues than for simple ones only indicating the direction.

Steady progress is achieved in the field of haptics and tactile notification. An example for current research is the work by Armstrong and Dunne [39], who did preliminary investigations concerning the influences of galvanic skin response on the perception of electro-tactile stimulation. Future tactile displays may incorporate not only vibro-tactile but e.g. also thermal output.

Appendix A

Accepted Conference Submissions

Full Paper at the 4th European Conference on Smart Sensing and Context (EuroSSC 2009)

"Time-lag as Limiting Factor for Indoor Walking Navigation" [40]

Abstract: Several navigation situations can be imagined where visual cueing is not practical or unfeasible, and where the hands are required exclusively for a certain task. The utilization of the sense of touch, as relatively new notification modality, should provide sufficient possibilites to cope with this issue.

The focus in this research work is on two questions (*i*) how distance encoding schemas affect overall navigation speed (or in more detail to what level the time lag contributes to the navigation precision) and (*ii*) if, beside the vibro-tactile stimulation, the transmission of the noise generated by the individual vibration elements influences the speed and/or precision of route guiding. To deal with these questions we have defined and conducted three waypoint following experiments with two different tactor activation methods, one without and the other two with the distance encoded in the vibration patterns. Additionally, we did studies where we masked the noise of the vibration elements and compared the results against the general setting where masking was not applied.

Our results shows that notification latency led to an increasing number of walking anomalies and consequently affects the walking precision and time to a high degree. Furthermore, we could not find evidence that multimodal stimulation with both vibration force and vibration "noise" tends to result in an increased system performance compared to the system with unimodal feedback using vibrations only.

Poster/Demo at the 4th European Conference on Smart Sensing and Context (EuroSSC 2009)

"Route Guidance with a Vibro-tactile Waist Belt" [41]

With this poster/demo we won the best poster/demo award.

Abstract: Navigation in unfamiliar places is difficult, even if signposts are available they are located at fixed points, may be overseen when the area is crowded, and are impossible to use by blind people. Visual navigation devices make guidance information available at any place but are neither hands-free nor a solution for blind people. In order to tackle all of these problems, we experimented with vibro-tactile guidance cues.

First we created an indoor navigation system consisting of position tracking hardware and a vibro-tactile waist belt that guides a person from waypoint to waypoint of a predetermined course. For that we used the 6-DOF ultrasonic tracking system InterSense IS-900 and a waist belt composed of 8 C-2 tactor elements from Engineering Acoustics Inc. For the design of the vibro-tactile cues the following parameters have been used: (*i*) intensity (attenuation in dB), (*ii*) frequency, (*iii*) position (which tactor), (*iv*) vibro-tactile pattern. We started with a very simple notification pattern and then tried to improve walking speed and accuracy by adding distance information.

We showed that with a tracking system working at centimeter accuracy, vibro-tactile cues alone allow for precise walking with an estimated average distance to the test course of only $20cm$. Higher time-lag (around 750 vs $380ms$) lead to significantly worse results. Distance information did not yet lead to increases in precision, this may be due the subtle nature of the chosen encoding scheme. However, it is possible that after a longer learning period participants can estimate distance. More details about the experiment setup and the first part of the results can be found in [40][1].

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[1] Unfortunately we did not respect the fact that InterSense only delivers new values around every $400ms$ in our calculations there, so the estimations of time-lag in this paper are the correct ones.

Poster/Demo at the 13th International Symposium on Wearable Computing (ISWC'09)

"Tactograms for Vibro-tactile Route Guiding" [42]

Abstract: Research on vibro-tactile stimulation, particularly for application in navigational scenarios, has increased considerably in the last years. The bigger part of the reported work deals with outdoor navigation, mostly in combination with GPS position tracking. Outdoor route guiding operates sufficiently accurate even if the feedback is imprecise and the update rate is low or delayed, as the distances to walk between waypoints are great. With technology advances in both precise indoor position and orientation tracking and vibro-tactile feedback systems, directed and accurate indoor route guiding might come true. However, several problems have to be covered, for instance (i) the prevention or compensation of latency times or (ii) the definition of vibro-tactile notification patterns for precise route guiding.

In our studies, focused on precise and rapid haptic feedback for route guiding, we used the Intersense IS-900/Ubisense 7000 systems for person tracking on centimeter precision and a vibro-tactile waist belt composed of 8 C-2 tactor elements from EAI Technologies for providing navigational information to the wearer. Position and distance was encoded using combinations of (i) vibration intensity (attenuation in dB), (ii) vibration frequency, (iii) tactor position, and (iv) vibro-tactile pattern. First results showed that notification latency led to an increasing number of walking anomalies and consequently highly affects walking precision and speed. But in the case of ideal system parametrization (mainly determined by a low latency in the feedback loop), vibro-tactile cues alone allow for precise walking with an average failure of around $20cm$.

Poster at the 6th Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (MobiQuitous 2009)

Distance Encoding in Vibro-tactile Guidance Cues [43]

Abstract: To navigate in unfamiliar places is, for obvious reasons, particularly difficult for blind people. For this paper we used vibro-tactile guidance cues with the goal of allowing users to reach their destination with the most efficiency. Our hypothesis was that adding distance information should improve walking speed and accuracy, however, similar results were obtained with and without distance information.

Appendix B

Lists, Bibliography

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Bibliography

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