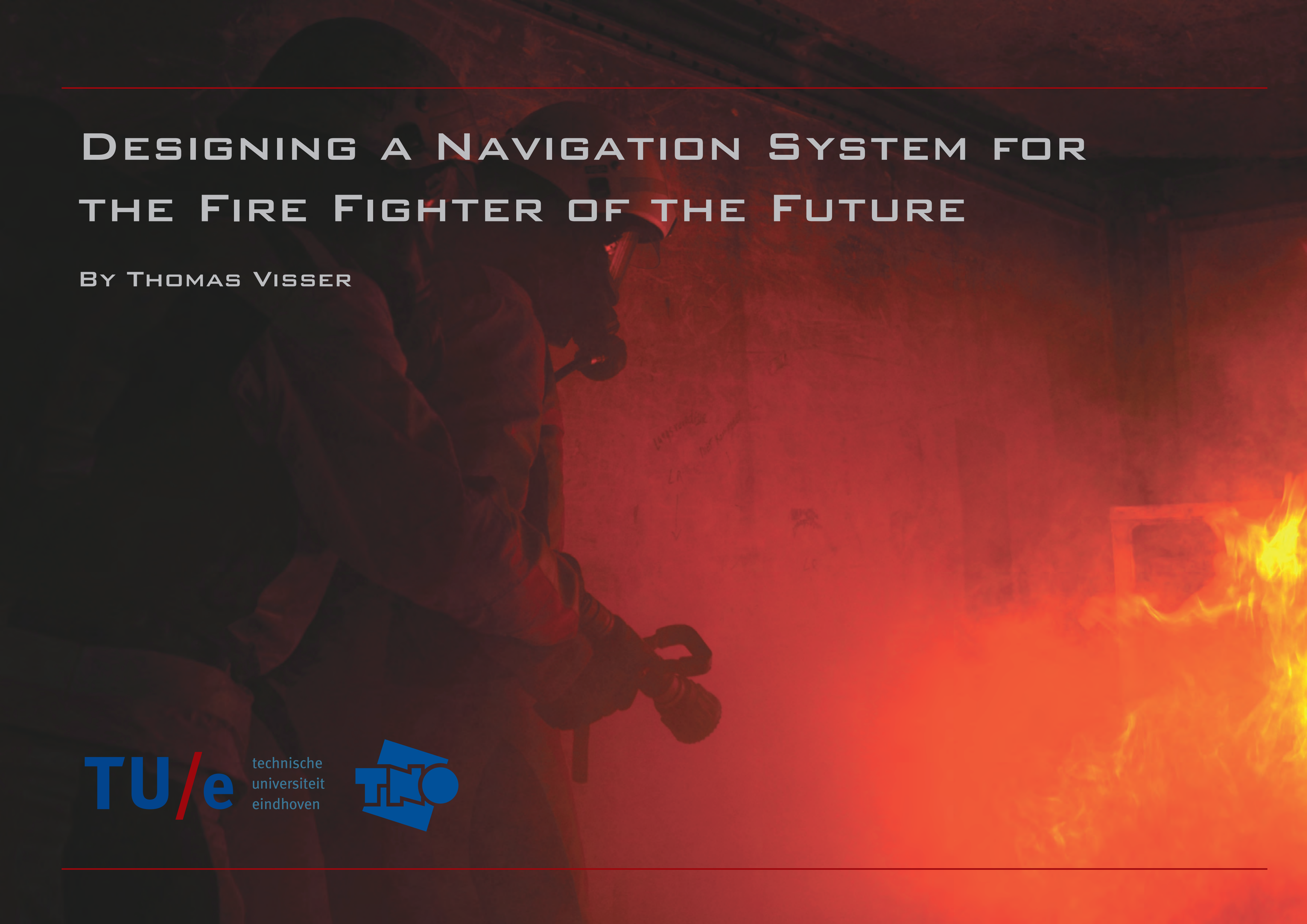

Designing a Navigation System for the Fire Fighter of the Future

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1 Dr.ir. J.W. (Joep) Frens was replaced by Dr.ir. C.C.M. (Caroline) Hummels at the graduation presentation on the 27th of August.

Abstract

This report describes the development of an indoor navigation system for fire fighters.
Fire fighters are encountered with hazardous situations as part of their daily job routine. One of the main dangers is losing orientation when working in a complex structure. Some products have been designed to prevent this from happening, but these are either inconvenient in use, or they are considered just not helpful. The aim of this project is to design a system that can help disoriented fire fighters to evacuate in an efficient and effective way.
In an idea generation session, multiple ideas were created to solve small parts of the problem. These small solutions were then merged into three different concepts. Each concept was based on a theme: aware-, integrated- and automatic-navigation.
These concepts were discussed in a user focus group session. This first session was not as effective as planned, because the participants (all were fire fighters) had difficulty in imagining what innovation could mean for them. Not as much feedback was collected as was planned for.
Nevertheless the concept was developed further on basis of the received feedback. Parallel to this, a new strategy was developed for a second user focus group session. In this session, the users were confronted with all kinds of state-of-the-art (and imaginary) technology. Next, they were asked to create their own ideal fire fighting scenario. This resulted in a list of abstract values that was later used to evaluate the developed concept. In this setup, the participants had less difficulty in imagining the future and they gave useful feedback.
The feedback on the concept was used to develop the design into a final version. The interaction scenario was designed, based on the user feedback and on studies found in literature. An exploration on technological feasibility was done to determine whether it would be possible at all to eventually build a fully working system.
In the final design, the fire fighter places beacons on his way into the complex structure. At every corner he takes, he places a beacon on the wall or floor. When evacuating, a radar-belt (integrated in the breathing apparatus-belt) detects the beacons that the fireman had placed in advance. A belt, equipped with vibration motors around the waist and integrated in the jacket, points the fireman in the right direction by vibrating in the direction of the token towards the exit.
To demonstrate this navigation experience, a prototype was built. With this prototype, one can detect and navigate towards a beacon that is placed in a space, based on tactile signals.

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0.1 Client description

"TNO Defense, Security and Safety provides innovative contributions to the advance of comprehensive security and is a strategic partner of the Dutch Ministry of Defense to build up the defense knowledge-base. We employ our acquired knowledge for and together with contractors. In the area of Security and Safety, the emphasis lies on combating crime, calamity and terrorism."
(www.tno.nl, July 2007)

At this moment, TNO runs two research/innovation programs on fire fighting. Both programs are initiated by The Ministry of Internal Affairs and Kingdom Relations (Dutch: Ministerie van Binnenlandse Zaken en Koninkrijksrelaties), which is a client of TNO. The first program is called the Fireman Modernization Program *(FMP)* . This project focuses on modernizing the equipment and clothing of the fire fighter. The second program is Effectief en Veilig Ingrijpen, or *EVI* (English: Effective and Safe Intervention).
The project described in this report is done within the *FMP*, with strong links to parts of the EVI program. The report therefore is delivered to The Ministry of Internal Affairs and Kingdom Relations. This project should demonstrate what technological innovation could mean for fire fighting.

0.2 Project goals

To answer to the demand of the Ministry of Internal Affairs, TNO determined the goal as following:

Design a product-system combination that enables fire fighters to evacuate efficiently out of *complex structures*[1] from the moment they get disoriented.

This incorporates the following sub-goals:

- The interference of the system with the regular activities of fire fighters, in such situations, should be minimized.
- The project should demonstrate a system concept that is based both on scientific data (not necessarily generated within the project) and user input.
- The technological and interaction feasibility of the concept should be shown.
- The project does not involve a performance test of the designed system.

Within the project some goals were refined and extended with the following:

- The tactile modality has been shown to work conveniently for navigation goals (Visser and Heus, 2005; Bosman et al., 2003). When where interference of the navigation feedback is not desired this convenience is also confirmed.(Erp 2007). Therefore, tactile interaction will be considered as a modality with high potential.
- The designed interaction scenario focuses on operation of one team or one fire fighter. Within the scenario, room should be kept for eventual extension of the scenario with multiple team operation. This extension is not included in this project.
- The technology, which could be used in a final, fully operational system will be specified as part of an exploration on technological feasibility.
- An experience-prototype is developed to demonstrate the look-and-feel of the user-system interaction.

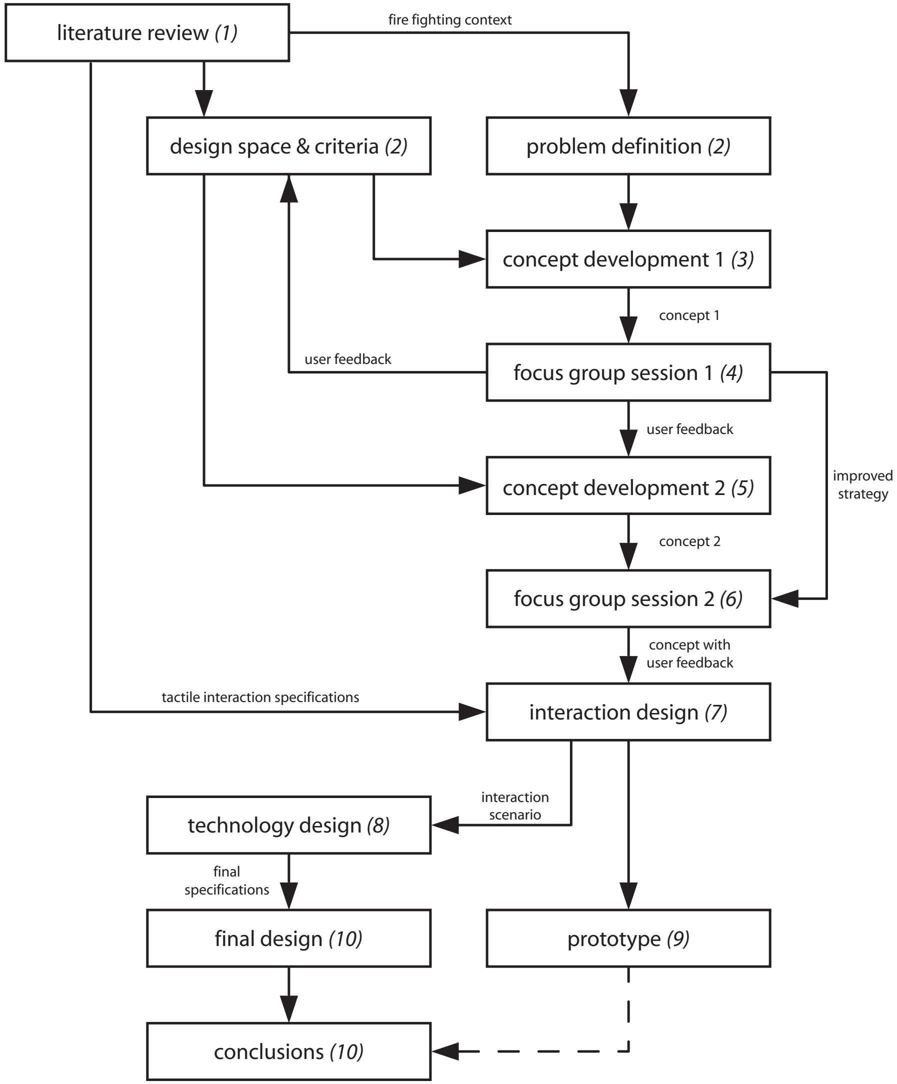
1 These are structures that induce a significantly larger risk of disorientation in a fire fighting situation (NIBRA, 2004). See Appendix A for more information.

0.3 Overview of the report

The organization of this report is chronological, as much as possible, and follows the design process that aims to design a navigation system for the fire fighter of the future.
The first two chapters serve as the basis for the design and development later in the project. The report starts with an overview of issues considered relevant as background knowledge. Chapter 1 describes procedures in fire fighting, as well as issues on trust, existing technologies and solutions for the disorientation problem. In chapter 2, the design space is defined and the criteria are set and explained.
The next four chapters describe the concept design process in which users are involved in focus group sessions. Chapter 3 describes an idea generation session, which was followed by the design of three concepts. These concepts were evaluated in a user focus group session, as described in chapter 4. Chapter 5 describes how the feedback from the focus group session was used to revise and develop one concept out of the three earlier concepts. Chapter 6 describes the second user focus group session. A revised methodology is worked out, which was designed to enable the participants to think in more innovative and radical themes.
The three following chapters describe the efforts to come to a final design. Chapter 7 describes the interaction design. Both the interaction scenario of the system and the development of the stimuli for the final system are worked out. Chapter 8 explores the technological feasibility, when design is to become a commercial product. Two technological concepts are explored and a choice for one of those is described. Chapter 9 describes the efforts to explore the conceptual and interaction feasibility. In the project this was done by the building of an experience-prototype.
Finally, chapter 10 describes the final design and scenario. In this chapter, also the conclusions of the project, and the recommendations for continuation are given.

When reading the report, please note the following:

- Whenever *he*, *him*, *his* or *fireman* is mentioned, it may also be substituted by *she*, *her*, *hers* or *firewoman*.
- Whenever TNO is mentioned, it must be interpreted as the core area TNO Defense, Safety and Security, unless mentioned otherwise.
- When a ● appears in the margin, the word or phrase in *itallic* is explained in the list of definitions in *Appendix A*.
- Whenever notion is made of *disorientation*, this should be read as spatial disorientation (also see *Appendix A*).
- Whenever notion is made of a '*tactile*' interface, this has to be read as '*vibro-tactile*'. Other tactile interfaces are temperature-tactile and pressure-tactile.



***Project process**: This flowchart describes the chronological process of the project, in relation to the chapters in the report (numbers between brackets).*

1. Introduction

In the process of achieving the project goals several issues were considered relevant to include in a preliminary literature study. First, the project context is explained by a description of how fire fighters do their job. After that, several navigation principles and technologies are presented. Also, existing solutions are described.

1.1 Fire fighting as a job

- Organization
- Fire fighting action
- Disorientation

1.2 Trust, navigation principles and existing technologies

- Trust
- Navigation
- Positioning
- Existing products and technologies

1.3 Conclusion

1.1 Fire fighting as a job

In the Netherlands there are around 5000 full time fire fighters. Their work is supported by almost 22.000 volunteers who also had proper fire fighting training (CBS, 2005).
Fire departments throughout the Netherlands are responsible for fighting fires, but also for technical assistance (e.g. at car crashes), diving tasks (e.g. for police cases), safeguarding events and fire prevention. Although their job is named after it, fighting fires is not the activity the firemen spend most of their time on. Only a few percent of their time is spent in the heat of the battle (Bos et al., 2001).
However, fighting fires is the most risky part and the most physically and mentally exhausting part of the job of a fireman. This is indicated by the large amount of accidents and casualties caused in this part of the job (Ministerie van Binnenlandse Zaken, 1999). This risk is even increased when the fire fighting is to be done inside complex structures, due to more complex escape routes and increasing time-to-exit.

Organization

A regular fire department[1] has at least the following personnel and material stand-by:

- 1 fire truck
- 1 *fire chief*
- 5 firemen, of which 1 driver

This is the minimum occupation for a department in a small village. Larger towns have at least the double amount of trucks/personnel. A larger department would also have a *fire officer* standing by, to coordinate the process in case of a larger fire. Whenever there is a need for more than one fire truck and its crew, a fire officer will be present.
Each fire department is responsible for its own equipment. It takes care of selection, purchase and maintenance of the clothing, technology and vehicles. This means that the decision of which equipment to use is not decided on a national level, but it is a matter of choice of the regional fire departments and their budgets. In the Netherlands, procedures are nationally standardized while equipment is not.

Fire fighting action

In a recent study by Mol and Moonen (2006) the official procedures of the Dutch fire fighting departments are evaluated. This study describes every procedure belonging to the tasks of the fire departments (from diving to rescuing and fire extinguishing). For this report, only a description of the procedure relevant to the project context will be described: the fire fighting in a complex structure. This procedure is described from the moment an emergency call comes in, to the point were the location of the incident area has to be cleaned up. This process consists of five phases.

1. **Incoming call**. A centralized call center warns the fire department closest to the fire incident. Immediately one fire truck with the complete 6-man crew drives out.
2. **The drive**. During the drive towards the incident location the fire chief receives all available information from the call center about the incident, e.g. location of water supply, amount of casualties, possible chemical or explosion hazards and size of the fire.
3. **Scouting**. The driver and two other firemen prepare the water supply. The fire chief explores the situation and prepares a first reconnaissance with the two remaining firemen.
4. **Repressive activities**. This includes the two main activities of rescuing casualties and extinguishing the fire, the first of the two receiving the highest priority. This phase will be explained in more detail later on in this chapter.
5. **After care**. After the fire is out and the casualties are taken care of by the medical personnel, the fire chief formally hands over the command to the police force. Often, the fire department is involved in cleaning the place.

For this project, the fourth phase is most important. The other phases are involved when it is about wearing and storing the system. In phase 4, the firemen are involved in these specific activities:

- **Reconnaissance**. in order to find possible casualties, the firemen scout the building following strict procedures of movement. Also, reconnaissance is performed to estimate the nature and development of the fire.
- **Rescue**. Whenever a casualty is found, he is immediately evacuated by two firemen.
- **Extinguish**. If a fire is found, two firemen 'cover' the fire by guarding it with a water hose. By applying this tactic, the other firemen can continue further into the building, without a risk of their way out to become blocked.

During this phase, the firemen are in continuous contact with each other over a radio network.

1 Special departments are e.g. Schiphol or DSM.

Disorientation

Fire fighters in practice rely on the procedures that they have trained. A part of these procedures is designed to prevent fire fighters from losing orientation in complex structures. For fire fighters in the Netherlands, these procedures are very strict, and if these are followed correctly, a fireman should not be able lose orientation.
Because of this reason, no procedures have been designed for what the fire fighter should do if he, or a colleague, loses orientation. Tragically enough, fire fighters sometimes do get disoriented and if this happens they are often confronted with injuries or death (Ministerie van Binnenlandse Zaken, 1999).

1.2 Trust, navigation principles and existing technologies

The complete reviews of the literature and technologies can be found in *Appendix B*. This chapter will summarize the most important findings.

Trust

According to Deutsch (1960) the need for trust arises under specific contextual parameters:

- There is an unambiguous course of action in the future
- The outcome depends on the behavior of another party
- The strength of the harmful event is greater than the beneficial event

Trust can be seen as a mental mechanism that helps to reduce the complexity and uncertainty in a situation, in order to facilitate and stimulate the development or the maintenance of relationships under risky conditions (Luhmann, 1988).
According to Rempel et al. (1985), trust in personal relationships is composed of several components: Predictability, Dependability and Faith. Egger (2003) adds that reputation can also be a significant factor when it comes to judge whether one should trust another party. Individuals strive to have a good reputation in order to gain trust from other parties.
An aspect of trust, which is beyond the scope of inter-personal relationships, is whether the user can actively manipulate the system and intervene in the process or not (Egger, 2003). It is possible that a user is willing to take more risk, if errors can be corrected.
Although no research on trust was found for the fire fighting domain, a speculation can be made on the role of trust in developing fire fighting equipment. Most important is that fire fighters have to be convinced that the new equipment is a useful and operates flawless.
For a design project in fire fighting, this study was concluded with the following:

1. Risk and stakes are higher than in regular product design domains
2. Trust is fragile. It takes time to build and it is easily destroyed
3. Trust can be created on a social level, only if the product/system operates flawlessly
4. Trust might be increased by leaving some tasks to the fireman instead of to the system

1-3 address issues that fall beyond the scope of this project, because no testable prototype is delivered. Future user tests should however address these issues. Nr. 4 can be addressed in the design of the concept.

Navigation

Navigation is about the planning and traveling through an environment towards a specific destination within that environment. Human and many other organisms have developed

a sophisticated behavior which helps to update position, orientation and course time. This behavior is formed by 3 different mechanisms. These mechanisms are based on perception of position, velocity and acceleration (Loomis et al. 1999). Humans use a combination of these mechanisms or methods. Possibly, in different specific activities or environmental conditions, one mechanism can be more dominant than another, due to the availability of information cues.
On a cognitive level, cognitive mapping is the ability to describe the knowledge of a spatial layout (Sholl 1987; Golledge 1999). It allows humans to construct an image of a certain space from memory of personal experience and integration of external information such as route indications and maps. The cognitive mapping increases cognitive load. Because maximum cognitive load is lower in stressful situations, the cognitive load induced by the designed system should be minimized to maximize the room for cognitive mapping.

Positioning

There are three positioning technologies which are relevant in the context of this project.

- **GPS**. The Global Positioning System is the best known most applied method for determining the position of an object. A GPS chip can obtain its exact position on the earth surface. The signals transmitted by the GPS are however not strong enough to be received in an indoor environment.
- **Ultrasound**. Ultrasound signals can also be used to determine position using *trilateration*. This technology is especially useful in environments where distances are small (<100m). Physical obstructions do however significantly decrease accuracy and reliability, as identified by Dijk (2004). Also, time-of-flight of acoustic signals is dependant on the air temperature, which is relevant in fire-fighting situations.
- **Radar technology**. At the Integrated Systems department of TNO Defense, Safety and Security, research and development performed on radar positioning systems for fire fighting[1]. A fireman is equipped with a radar reflector. By placing two powerful radar antennae outside the building, the position of the radar reflector can be determined. At this point, however, the radar is only strong enough to penetrate a structure a few meters. Radar waves are naturally obstructed by metal within a structure and water.

Guiding

When focusing on tactile interfaces for navigation and orientation, literature can be found within several user domains, e.g. visually impaired, car drivers, foot soldiers and pilots. Below, a short description is provided of the most interesting examples:

- **Get Me Out**. Visser & Heus (2005) have investigated a waypoint-navigation method for a fire fighting context. They have designed a concept for placing waypoints within an unknown hazardous environment. (*Image 1.1*)
- **Personal Tactile Navigator** (PeTaNa). Erp et al. (2005) and Duistermaat et al. (2006) have tested a tactile belt and compared the system to GPS- and map-navigation in their studies (*Image 1.2*). The PeTaNa has eight *tactors*, each covering a 45° angle. The system is more efficient than the existing navigation methods (GPS or map) in an outdoor environment. The results of these studies also suggest that the system improves *situational awareness* due to a smaller cognitive load. Erp et al. (2005) also performed performance tests on the PeTaNa system in helicopters and small boats. They have suggested that the system also performs well in highly vibrating direct environments.

***Image 1.1**: Get Me Out performance tests*

***Image 1.2**: PeTaNa tactor-belt*

***Image 1.3**: Tactile vest*

1 No formal documentation is available at this time; the research has not been published yet. Information is based on interviews with engineers working within the department of Integrated Systems and on a demonstration that was given in May, 2007.

- **Tactile Vest**. At TNO, research on tactile perception and interaction is performed by using a tactile vest (*Image 1.3*). Erp et al. (2007). In these experiments, the tactile vest and the stimuli it provides improve reaction times and improve situational awareness.
- **Fire Eye.** Wilson et al., (2005) have implemented a *heads-up-display (HUD)* in a firefighting helmet. The display works, technically, but the authors do not discuss information display or information acquisition.

Existing products and technologies

Several products and systems aim to prevent disorientation or to rescue in case of a disoriented fire fighter. Systems like the radar transponder are more supportive and might provide a technological infrastructure for this project.

- **High-pressure hose**. The high pressure water hose is not designed as an orientation/navigation tool. It is however often used as such. The hose is connected to the water reservoir in the fire truck. If possible, firemen enter a structure with a hose and use it as a protection against fire and as a marker for their route. (*Image 1.4*)
- **Refinder**. This is a so called line-system (*Image 1.5*). Firemen attach a thin rope to their body using a separate belt and they walk into the building, putting the rope on the route they walk. The method is effective, but it takes time to prepare and to deploy the system (>4 minutes). Also, the lines can obstruct firemen, or may be hard to find when lying on the ground. A line-system would only be used if the hose is not available due to e.g. remoteness of the fire truck. The experiences are that it works, but it is a hassle to find the lines when inside a building, and to properly use the lines[2].
- **Radar Transponder**. The Integrated Systems department of TNO has developed a radar transponder (*Image 1.6*). This is a device that powerfully reflects radar signals. Besides reflecting the signal it can also incorporate a unique code with the reflected signal. The transponder can operate on a small battery for at least three years. The transponder uses a patch-antenna; this is an antenna that is situated in a square flat surface and typically is 62mm x 62mm in size for a 2,4GHz radar system. The transponders are used in the radar-positioning technology described earlier.

Image 1.4: *High pressure hose*

Image 1.5: *Refinder attached to body*

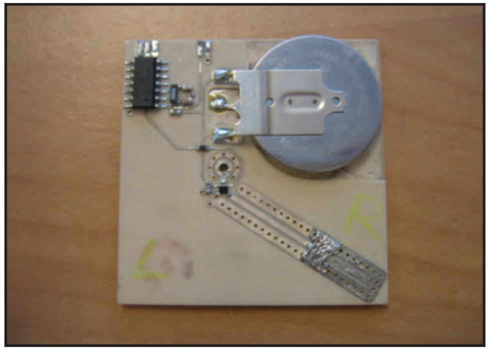


Image 1.6: *Transponder patch (62mm x 62mm)*

2 Several firemen of the departments of Amsterdam, Schiphol and Utrecht were informally interviewed about the line systems.

1.3 Conclusion

Disorientation is a serious problem. This can be concluded from literature, as well as from the fact that there are serious attempts from industry and academia to find solutions or work-arounds for it. However, the solutions that are on the market take too much time to install, are dependant on external resources or are considered inconvenient in use by the fire fighters. Advanced technologies have not yet been introduced in the problem domain. This could be because the technology is not considered reliable, or because of unfamiliarity with the potential of existing orientation and navigation technologies.
The specifications of radar technology, as reviewed up to this point, seem most promising for an indoor navigation solution. However, no radar technology has been developed for this problem so far.

2. Problem Definition & Criteria

As a result of the contextual study in the previous chapter, this chapter defines the challenge of this project. First, the problem is defined in specific terms. Following that, the design space is explored and defined by describing the external and project factors. Finally, a set of criteria is given with which a final design should comply.

2.1 Problem Definition

2.2 Design Space

- External factors
- Project factors

2.3 Design Criteria

- Fixed criteria
- Variable criteria
- Wishes

2.1 Problem definition

In the current way of working, all fire fighters are evacuated to a meeting point in a case of disorientation. Firemen, who are in the building and cannot find the exit, stay where they are. The fire chief maintains radio contact with these firemen. Subsequently, a rescue team is sent in. This procedure is time consuming and it does not solve the problem per se. There is a possibility that the disoriented fire fighter perishes due to an empty oxygen reserve, before the rescue team finds him.

The challenge is to design a system that can help fire fighters to maintain orientation and to help them in case of disorientation. The system should make entering and evacuating safer and more efficient.

2.2 Design Space

The context in which the solution to the earlier defined problem is to be realized is called the design space. This space defines both the design freedom and the constraints. It is defined first by external factors, which are not set by the designer, but by the natural context of the problem (such as laws of nature or the nature of the user task). Second, the design space is refined by project factors. These are issues determined by the project designer, client or stakeholders. Project factors are a combination of assumptions and preliminary project decisions. The relevant factors for this project are described below.

External factors

Time	In the most frequent scenario, where fire fighters have to rescue people from a burning structure, time is a critical factor. This has to do with the fact that casualties have to rely on fresh air in the building and can only do a few minutes without, before they perish.
Indoor environment	In the context of the project problem, fire fighters will always be indoors. They can be separated from their colleagues by walls and/or floors.
Unknown areas	It has been suggested (Visser, 2005) that people will not create 2D maps of every existing building or other objects, let alone making them 3D and keeping them up to date. Therefore it has to be assumed that the area of operation is known only on a superficial level; details are not available most of the time.
Thermal and Chemical	Fire fighters will always operate in hazardous environments. This is due to the nature of the task of extinguishing a fire, or rescuing people trapped in an object that is on fire. Smoke and flammable or explosive gasses are natural by-products.
Physical labor	The suit of a fire fighter, his breathing apparatus and extra gear altogether weigh 20-25 kg. They have to work in extreme temperatures while doing heavy work such as breaching doors or carrying casualties. It is therefore inevitable that they have to deal with heavy physical work.

Project factors

Stand alone	The innovation should be stand alone, not relying on any technology or physical infrastructure already used in fire fighting. Also, it should not rely on the infrastructure of a structure (e.g. built in beacons) or devices (e.g. radar- or GPS-technology) that have to be set up outside the complex structure. The system is installed and operated by the fire fighters that enter the structure. In this way, the system can be deployed anywhere, at any time.
Procedures	In order to let the use of the newly designed system easily flow into the daily practice of the fire fighters, it is important that it interferes with the existing procedures as little as possible.
Modalities	The tactile modality has been shown to work conveniently for navigation goals. To increase redundancy in the signal, a multimodal interaction language will be considered (adding sound or visual information).
Equipment	As a result of the previous issue, the innovation will be based on and added to the current modern equipment the fire fighters are using.

2.3 Design Criteria

The criteria for the design of the navigation system are divided in three categories: fixed criteria, variable criteria and wishes. Fixed criteria are those to which a possible solution should fully comply. Variable criteria are those to which a possible solution has to comply as much as possible. Wishes are not necessary criteria, but can increase the attractiveness of a solution in the final decision.

Fixed Criteria

Stand Alone	The system should be independent of other technologies or equipment.
Modalities	The stimuli provided by the system for the user are tactile. Other modalities may be added.
Indoors	The system should work in an indoor environment. Structures can be concrete, metal, wood, etc.

Variable Criteria

Time	Deploying the system should take as little time as possible. It should at least take less time than existing systems and products.
Mental load	Using the system should be intuitive to support operation in highly stressful situations. It should minimize sensory and cognitive load.
Procedures	Existing procedures should be influenced as little as possible by the use of the system.

Wishes

The following criteria were considered important but not primarily decisive for the concept choices which were to be made.

Physical load	The system should be as light as possible and it should not obstruct the movements of fire fighters.
Heat and chemicals	The system should be resistant to high temperatures, to smoke and other gasses.
Technology frame	Technology that is used in the system is available within the coming 5 years.

3. Concept Design 1

The first idea generation session was adapted to the domain of fire fighting, where constraints are high and the design freedom seems minimal. An adapted version of the *Methodic Design-method* (Siers, 2004) was used. After the generating ideas, three concepts were formed.
Each concept is a collage of ideas that would fit together in a scenario. Following that, a short review of the three concepts is done to identify the strong and weak aspects of each concept.

3.1 Idea generation
- Scenario steps
- Idea generation session

3.2 Concept development
- Aware navigation
- Integrated navigation
- Automatic navigation
- Ideas that were not included

3.3 Evaluation of concepts

3.1 Idea generation

The Methodic Design method is a brainstorm-type of idea generation. It is composed of two main activities. First, the design problem is split up in several sub problems. Second, ideas are generated to solve the sub problems individually. This method is often used in highly technical projects (e.g. mechanical engineering). The similarity between those projects and this project is that the constraints of the problem context are high and a lot of factors are predetermined by that context.
This method is system oriented while the design problem is more user oriented. For this reason, the method was adapted to transform the method from a system oriented, to a more user oriented method. This was done by defining sub-steps in the scenario instead of defining sub-problems.

Scenario steps

Based on the scenario explained in chapter 1.1 the following steps were defined as a starting-point for the idea generation session.

1. **Navigation principle**: what technology can be used? What components are needed?
2. **Wearing**: how will the fire fighter carry the system into the building? Will he put it on, or is it integrated in the equipment?
3. **Deploying and activating**: will the system be activated manually or automatically and how? Or is the system 'always-on'?
4. Searching movements: what will the movements be? Does the user make extra movements? Does he hold a device or is the technology integrated in e.g. clothing?
5. **Display**: what senses does the user use? Will the commander receive signals? When in a team, will both fire fighters in a team receive the signals?

Idea generation session

Three students of the Industrial Design master-course participated in the idea session. These students were assumed to be acquainted with idea-generation sessions as well as being aware of state-of-the-art technologies. Therefore, they would be able to make this session as effective as possible.
A fifteen-minute introduction was given on fire fighting, including the introduction of this report. This was done to familiarize the participants with the constraints of the project.
After the introduction, a brainstorm of approximately fifteen minutes was held per scenario-step. The results were summarized and reviewed with the group afterwards.
The complete list of ideas, which was the result of the idea generation session can be found in *Appendix E*.

3.2 Concept development

A selection of the ideas would be evaluated in a focus group session. In order to effectively do this, three concepts were formed out of the generated ideas. The concepts were formed such that each concept covers the full scenario, from entering to evacuating from the structure. The three concepts are composed of individual ideas that are grouped. Each of the three groups of ideas has a general theme of how the concept deals with the design problem. The three themes are Aware-, Integrated-, and Automatic-navigation.

Aware Navigation

(*Image 3.1*) The fire fighter actively places beacons. He has to activate the beacons by hand when put down. When disoriented, the fire fighter slowly waves his flashlight around. This flashlight contains a radar that will detect the closest beacon, in the direction of the exit. When detected, the flashlight/radar vibrates. Aware Navigation combines the following ideas:

- *Waypoint* navigation
- Bag with beacons
- Actively activated
- Searchlight movement
- Tactile on search device

Integrated Navigation

(*Image 3.2*) A computer is attached to the air-bottle of the breathing apparatus. This computer also contains accelerometers and gyroscopes that enable the system to determine the route walked by the fire fighter. In an 'always-on' configuration, a projection of an arrow indicates the way back, following the route as walked when going in. Integrated Navigation combines the following ideas:

- *Inertia* tracking
- Attached to breathing apparatus and integrated in used equipment
- Automatic and always-on
- Walking and turning movements
- Heads-up-Display interface

Automatic Navigation

(*Image 3.3*) The system, attached to the air-bottle, automatically drops beacons. When disoriented, the fire fighter activates the system. A tactor-belt directs him towards the exit by vibrating at the direction of the exit route, taking the body center as a reference point. On top of that, every beacon generates a tone of sound. The lowest tone is at the exit, the highest being the utmost inside. By using natural hearing and using both ears, the fire fighter can determine the direction of the exit. Automatic Navigation combines the following ideas:

- Waypoint navigation
- Attached to breathing apparatus and attached to clothing
- Semi-automatic
- Walking and turning movements; head moving for listening
- Tactile integrated in clothing

To evaluate the individual ideas of which the concepts are composed, the concepts will be evaluated with fire fighters in a user focus group setup. Note that the concepts are built up out of as many different ideas as possible, instead of aiming for one 'killer concept'. This was done to be able to evaluate the ideas in a scenario context. It is therefore not probable that the final concept will be exactly one of these three concepts. The final concept is more likely to be an integrated solution of the most positively evaluated aspects of these three concepts.

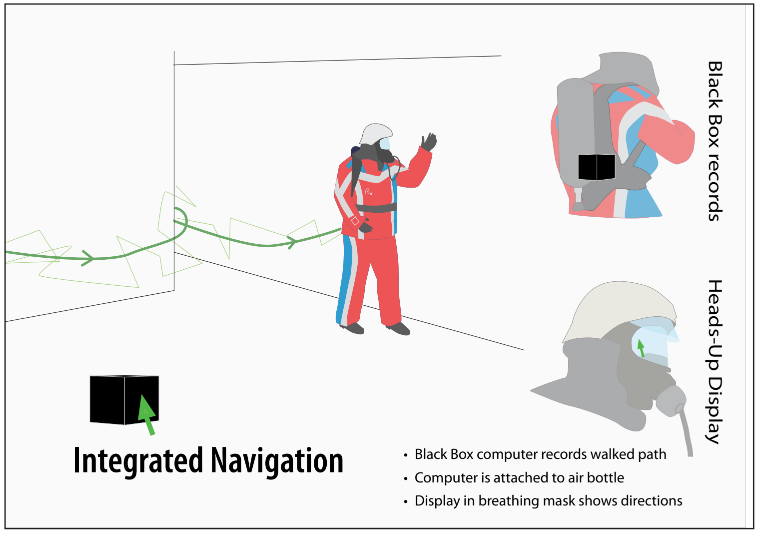


***Image 3.2**: Integrated Navigation scenario*

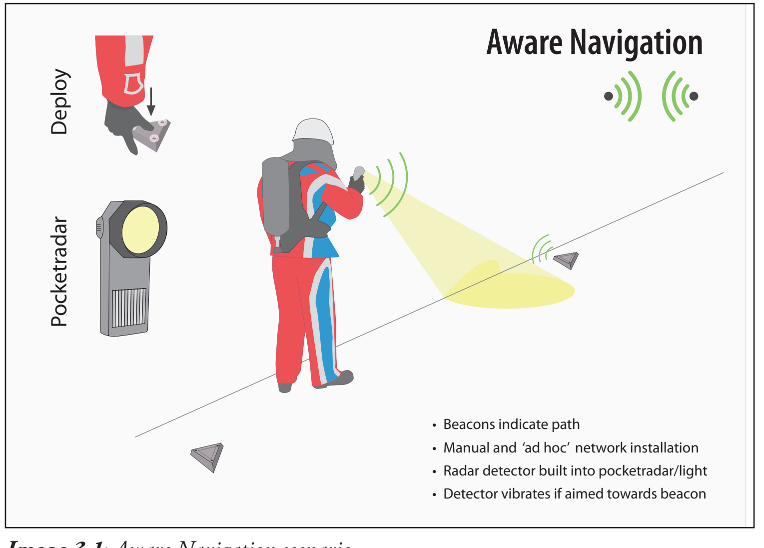


***Image 3.1**: Aware Navigation scenario*

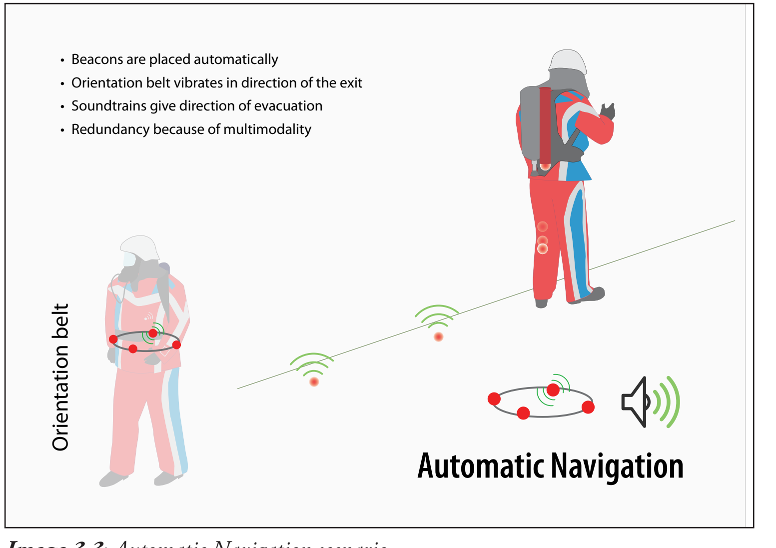


***Image 3.3**: Automatic Navigation scenario*

3.3 Concept evaluation

The concepts were shortly evaluated. This was done together with two Industrial Design master course students. The concepts are evaluated on the fixed and variable criteria defined in chapter 2.3. As a point of reference, the most common existing system is also included in the evaluation, as can be seen in *Table 3.1*.

Criteria	Aware Navigation	Integrated Navigation	Automatic Navigation	Refinder
Stand alone	√	√	√	√
Modalities	√	X	√	√
Indoors	√	√	√	√
Time	+	++	++	– –
Mental load	+	+	o	–
Procedures	o	++	+	–

***Table 3.1**: Concept evaluation*

For the fixed criteria, either a √ or X is given, meaning 'fulfilled' and 'not fulfilled' repsectively. For the variable criteria, scores range from -- to ++.
Most important in this evaluation are the very-low and very-high scores. Because each concept is built up out of several different ideas, the total score of a concept is not the most relevant.
Conclusions that can be drawn from this evaluation are the following:

- Designed concepts fulfill the fixed criteria, but one. Integrated navigation does not comply with the tactile modality demand, because it is based on a heads-up-display. This specific part of the concept is therefore not strong.
- Designed concepts are faster in application than the existing system.
- Including sound as a modality demands higher mental load, but still less than using an existing system.

Note that the evaluation was based on speculation. The focus group session should add to this and in the best case, confirm the results of this evaluation.

4. Focus Group 1

A user focus group session was held with fire fighters to obtain feedback on the created concepts. This chapter describes the goals and method that was used. The firefighters were invited to describe how they would use each of the concepts in a real fire fighting situation.
Their comments and feedback on the concepts are presented and conclusions are drawn from this. Finally, recommendations are given both for the development of the concepts, as well as for the setup of a next focus group session.

4.1 Introduction

To get user input on the ideas that have been generated, a focus group session was organized. Focus group meetings can be very efficient when well prepared and well mediated (Langford and McDonagh, 2003). Fire fighters are used to working in teams, they are enthusiastic about their job and they like to talk about it. Therefore, a focus group session is a user analysis setup that is more suitable than interview or questionnaire setups.
In this session it was also key to let the firemen have confidence in the development within this project. Following the conclusions from chapter 1.2 on Trust and Confidence, this could help the acceptance of the designed system by the firemen.
The goal was to collect feedback on the individual ideas for development of the project concept. A secondary goal is to get the group interested for the project. This would help to set up future focus group sessions.

4.2 Method

The session was held at the main fire station of the Utrecht fire brigade. Five fire fighters and two mediators were present during the session. The mediators guided the participants through the evaluation process. One mediator made notes and the session was also recorded by video camera. The second mediator facilitated the discussion by asking questions and explanations.

Group composition: 3 Fire officers and 2 fire chiefs. All of the participants had more than five years experience in fire fighting.

Planned duration: 90 minutes.

Procedure

1. An introduction into the project goals and the goals of the session was given to the participants. After that, the concepts were explained.
2. A combination of two focus group tools was used in the remainder of the session. A Visual Evaluation of Products or Systems, as described by Langford and McDonagh (2003) was used in combination with a Scenario-based Discussion, as described by Cooper and Baber (2003). These methods fit well with the available input (three visualized concepts) and the procedural way of thinking of firemen (Mol and Moonen, 2006).
3. The participants discussed every step of a normal fire fighting procedure: incoming call, the drive, reconnaissance, repressive activity and after care. At each of these steps, the question was posed on how the participants would normally act in the situation and how they would act using concept 1, 2 and 3 respectively; i.e. the concepts were discussed in parallel. The steps of the fire fighting procedure followed the sub-steps in the scenario as defined in 3.1 as much as possible.

4.3 Results

The feedback collected in the focus group session is summarized in *Table 4.1* per scenario sub-step, per concept.

	Navigation principle	Wearing	Deploying and activating	Searching movements	Display
Aware Navigation	seems logical, like bread-crumbs in a fairy tale	fire fighter might have too much on his body (referring to pouch, not flashlight)	interferes in regular procedure and might therefore cause dis-orientation.		probably a strong signal, but not hands-free difficult to imagine what it feels like
Automatic Navigation		tactile belt looks like a good idea. Must be felt to judge more clearly.	does not take time to install tokens		audio is not an applicable modal-ity: when dis-orientation occurs there is heavy radio traffic.
Integrated Navigation	cannot see or check what is really happening	possible extra weight	no time involved to install/activate	natural movements	hands-free is good

***Table 4.1**: Focus group session feedback*

Feedback was not collected for all aspects of the different concepts.
Due to sudden restricted availability of the participants, the session could only last for 50 minutes, instead of the planned 90 minutes.
The participants of the session also commented (without being asked) on the problem definition and the design approach and assumptions. The following comments were supported by at least 80% of the focus group:

- "If a fireman gets disoriented, he will fall back to fight-flee-freeze reaction. This means that he will not be able to think actively."
- "What is the role of the fire chief in the concepts?"
- "We already use the hose. We never enter without it. Why would we need a navigation system?"
- "We are always in a hurry. Even if we aren't, we feel and act like we are. We don't have time to deploy or install anything."

4.4 Conclusions and discussion

Not from every cell in the table a direct conclusion may be drawn, but it gives an impression of the fire fighter's opinions on the concepts. The following conclusions can be drawn:

- Time is critical, and considered so even when it is not really critical (e.g. no casualties are in a building).
- The interfaces that were hands-free were appreciated.
- Audio cannot be used as an interface modality, due to much noise on the job and increasing radio communication in case of disorientation.
- Tactile interfaces are difficult to imagine and the participants agreed they should feel it before they can judge the value of a tactile interface.
- When fire fighters get disoriented, they can panic. This results in basic behavior (fight-flee-freeze) and decision-making is hampered.

The participants of the session did not seem to find it easy, to stick to the scenario that they were supposed to follow. The group rather wanted to discuss the assumptions made in advance, before designing the concepts. This resulted in an incomplete matrix of feedback on the concepts, as can be seen in the results.
One reason for this could be that not enough time was scheduled for this meeting. As a result of other scheduled activities of the fire fighters, they only had 60 minutes available, of which 50 minutes could be effectively used. The complete session was planned to last for 90 minutes. It remains unclear whether these 40 minutes would have filled up all the gaps in the matrix, but the extra time could have helped to ask the remaining questions.
Another reason for the shift from concept-related feedback to general feedback on the design assumptions could be the mindset of the participants. Firemen are trained to work with very strict procedures and with a very specific set of equipment. This is because their lives depend on their behavior in extreme situations. For this reason, it could be that these people have difficulties to imagine what role new technologies can play in their job. This is concluded from the general reactions they gave (while not specifically asked for) during the session.

Recommendations

For the development of the project concept, the following conclusions can be drawn:

- The system should be hands-free when evacuating
- Audio interface should not be used.
- The interface should be intuitive, to support basic behavior.

For the next focus group session the setup has to be changed. The following conclusions can be drawn and have to be kept in mind for a next meeting with the focus group:

- 50 minutes is not long enough for a session. An estimate is that 120 minutes would give the mediator enough time to bring up a fully effective discussion.
- A strategy has to be made to loosen up the somewhat conservative mindset of the fire fighters. A suggestion could be to introduce the participants to existing state-of-the-art technologies used in other domains like e.g. the army or police forces. Also, embedding the presented ideas in a complete scenario, might make it easier for them to imagine a future scenario.
- An example of a tactile interface should be shown to the participants of the session. Preferably, they are also given the opportunity to try the interface.

5. Concept Design 2

This chapter first describes how the design space was adapted as a result of the feedback obtained in the focus group session. From the three concepts, a new concept was developed, based on the adapted design space. This concept is discussed and visualized.
In following the recommendations from the previous chapter, changes were be made on the presentation of the concept towards the users. Part of this change is the development of a complete future fire fighting scenario, in which the navigation system will fulfill its specific role. This is where the *Fire Intervention Team*-scenario is introduced at the end of the chapater.

5.1 Change in design space

As a result of both the focus group session and the evaluation in chapter 3.3, the design space was to be adapted. Several issues had come to light that demand an adapted view on the requirements for the final design.
These changes would not alter the external factors, because these are based on more fundamental issues (like laws of nature and nature of the problem). The following changes were made in the Project Factors:

Procedures. New procedures may be introduced, as long as supported by a realistic scenario, describing not only the design, but the complete scenario of operation. (*Although the firemen urged on more conservative innovation, it is well possible, and even probable, that the job of fire fighting is much different in five years from what it is now. Methods and equipment will change. Therefore, if a design is made for the current situation, the solution will be outdated and irrelevant before it reaches the market.*)

Equipment. The system may be based on current or future equipment of the firemen. (*To support a more future-oriented view on the design, not-yet-existing equipment may be involved in the complete scenario, to support the design*)

Modalities. The system should be based on tactile-interaction, possibly supported by a visual display. Audio, taste and smell cannot be used as senses within the interaction scenario. (*This was pointed out by the participants of the focus group*)

Future technology. To be able to create an innovative design, the technology for the system needs to be available within 10 years. (*see 'Procedures'*)

As a result of these changes, the variable criterion *Procedures* was regarded as a 'wish' from now on.

5.2 Concept development

One concept would be presented during a second focus group session. Therefore, the feedback from the first session and the criteria evaluation, together with the three created concepts were merged into one concept scenario. First the decision path will be described, followed by visual representation of the concept.

Decisions

On basis of careful analysis of the concept and the feedback of users, the following main decisions were made regarding the further development of the navigation system:

- Beacons will be the spatial identifiers of the system, i.e. they will be placed inside the structure by the fire fighter. Waypoint navigation was chosen over inertia tracking because of feasibility issues. Inertia tracking systems are either extremely expensive and heavy or very inaccurate[1]. Also, an advantage of the beacons might be that it makes the infrastructure of the system more visible.
- The fireman 'wears' the beacons on the sleeve of his jacket. This will allow quick access and no putting on of extra equipment is required. This principle came up as a new idea during this concept phase.
- Beacons are automatically activated when released from the jacket.
- When evacuating, the fireman is guided by a tactor-belt; the tactor in the direction of the exit-route vibrates. This interface received positive feedback in both focus group sessions. Letting the firemen experience the PeTaNa belt made them enthusiastic.
- The tactor-belt is not always-on, but has to be activated by the fireman by tapping a tactor twice. The detection system is however always on. It continuously monitors all beacons that are in sight.
- The detection of beacons is done by means of radar technology; using radar antennae aimed at different angles and by equipping the beacons with radar transponders, as described in chapter 1.2.5.
- Radar antennae are attached to helmet and oxygen bottle to cover all directions; the 4 antennae each cover an angle of 90°

1 This was indicated by two experts on Integrated Systems from TNO

Concept visualization

The images below show the concept as explained above. Clockwise, from top left: radar antennae with a 90° coverage; detection of beacon and activation of tactor-belt; possible placement of beacons; beacons equipped with LEDs for low-smoke situations. Reflectors are positioned such to reflect in all directions. (*Images 5.1 - 5.4*)

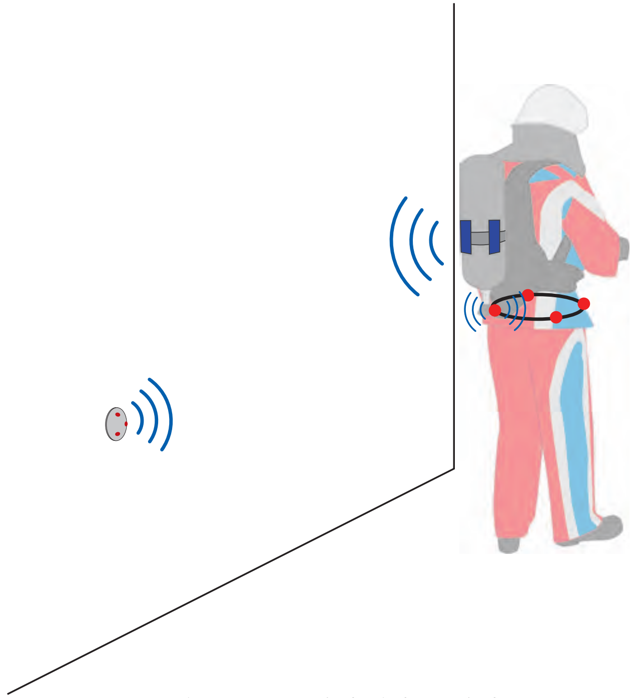


Image 5.3: *The antenna on the back detects the beacon on the wall. This triggers the rear tactor on the tactor-belt.*

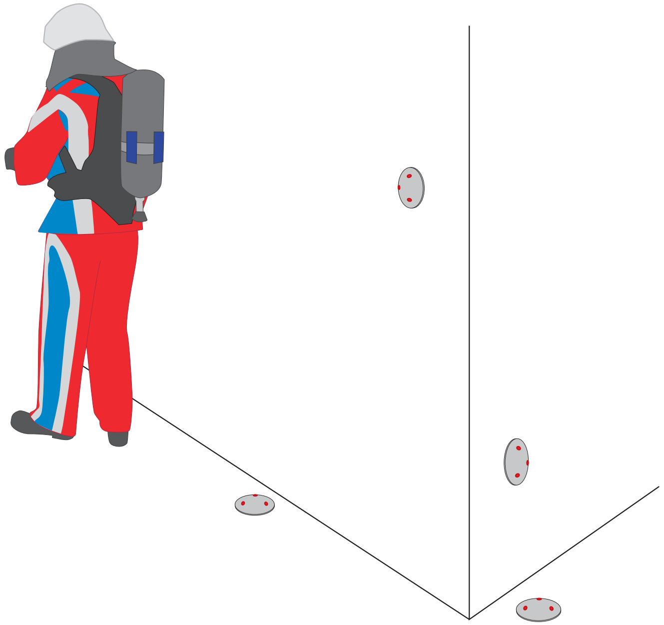


Image 5.1: *The fire fighter can place beacons on the floor an on the walls. The beacons are visible by the LEDs they carry.*

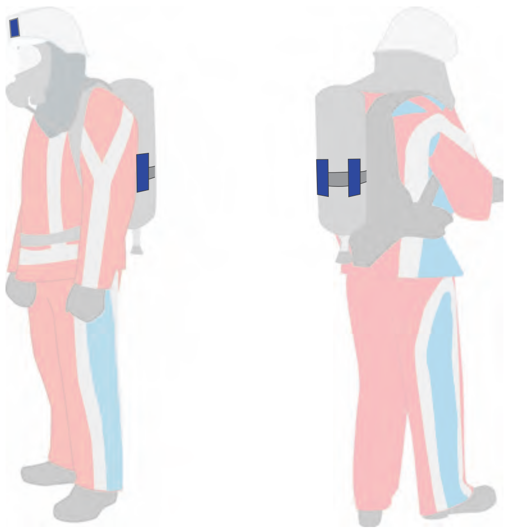


Image 5.2: *The fireman is equipped with radar antennae which enable him to detect the beacons he has placed. Note that the front tantenna is separated from the rear and side antennae.*

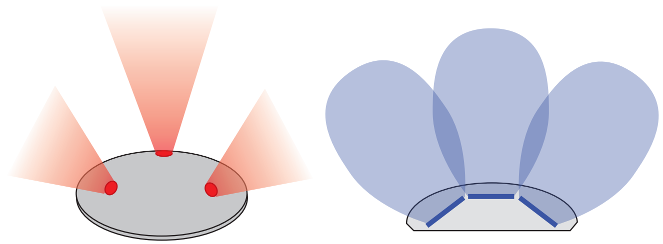


Image 5.4: *The beacons have LEDs for eye-visibility (red) and radar-transponders for radar-visibility (blue).*

5.3 Scenario development - *Fire Intervention Team*

To increase the effectiveness of a new focus group session, the developed concept is integrated in a full scenario. Such a scenario might help to let the participants understand the role of the presented innovation. It will prevent them from relating the presented concept to their current situation and procedures.
The following scenario is only loosely based on current procedures, but more on the procedures followed by police intervention teams or counter-terrorism units. The main differences with the current situation are higher speed, smaller teams and more energy in the movements (more aggressive).

1. Deployment by means of 4WD-vehicle or helicopter
2. The firemen enter the building alone or in a team of 2, depending on the layout of the building.
3. They carry breathing apparatus, a smart fire fighter suit[1] (containing a tactor-belt and thermo/heartbeat sensors for monitoring health status), compact fire extinguishers (such as oxygen-removing grenades and foam extinguishers) and beacons, attached to the sleeves of their suit.
4. The goals are rescuing casualties (1st priority) and localizing and, if possible, neutralizing fire (2nd priority).
5. The evacuation route is secured by placing radar beacons on every corner. The fireman has to place the beacons in a way that e.g. his radar system always has a line-of-sight[2] with each previous beacon. Beacons can be placed on the ground or on the wall, preferably at a height between 0 – 0,8m. Beacons have a sticky bottom surface, and are activated once pressed against a surface.
6. Take action (rescuing/localizing/neutralizing).
7. Activate navigation system.
8. The tactor-belt provides vibration-stimuli in the direction of the exit by following the beacons. In this way, the fire fighter can also walk sideways or backwards, without losing the signal.
9. Beacons are considered to be disposable and need not to be collected after action.

1 Within the EVI program of TNO, a smart suit is under development. This technology enhanced suit aims to monitor the physical status of the fire fighter.

2 In this case, a spatial relation between two objects is meant. In this relation one could virtually connect the two objects with a piece of rope in a straight line. This means that smoke or absence of light does not remove a line-of-sight relationship.

A trend towards this type of Fire Intervention Team (FIT) action has been identified in several fire fighter innovation panels in which I have participated[3]. This type of action is typified by the smaller size of the team, the used vehicle and the equipment. These are smaller and more specialized for fire intervention, compared to the current way of working of most Dutch fire departments. For this reason it was considered a valid direction for the concept and the procedures of the fire fighter of the future.

3 Parallel to this project, I was involved in two panel/presentation sessions on technological development within fire fighting. Both were organized by TNO in cooperation with the Ministry of Internal Affairs.

6. Focus Group 2

This chapter describes the second user focus group session. For this session a different strategy was developed to obtain feedback that would be better usable. The development of this new strategy is described. In the session, the participants eventually produced a list of abstract fire fighting values, which was then used to evaluate the concept that was developed in the previous chapter. Finally, this chapter presents the conclusions for the concept that could be drawn after the end of the session, in terms of strong and weak points.

6.1 Introduction

In the previous focus group session problems were encountered concerning the type of feedback that was collected. It was assumed that this type of feedback was due to the fact that the participants had a difficult time to imagine a future situation with the new product.
A lack of sufficient time to complete the planned session was another problem in the previous session. The conclusion was drawn that at least 2 hours are needed to run an effective session. This is also suggested by Langford & McDonagh (2003); results of the first session showed that no concessions should be made on this.
To avoid the problems encountered in the previous focus group session, a new strategy for the session was developed. This resulted in a thorough introduction (consisting of 3 parts) of 60 minutes, followed by a scenario-based-discussion combined with a why-why analysis. The why-why analysis, as described by Higgins (1994), digs deeper in the motives of the participants. It elaborates on the question why the participant would behave in the scenario the way he describes. The answers allow the moderator to bring more abstract values to the surface of the discussion.
The goal of this session was to generate abstract values of fire fighting that are supported by the focus group. Following, the developed concept are to be evaluated on these values. A secondary goal is to make the group feel confident with the development within the project.

***Image 6.1**: Participants of the second focus group*

6.2 Method

The session was held at the main fire station of the Utrecht fire brigade. Four fire fighters and one mediator were present during the session. The mediator guided the participants through the evaluation process. The session was recorded by a voice-recorder.

Group composition: 2 Fire officers and 2 fire chiefs. All of the participants had more than five years experience in fire fighting. One of the officers and both fire chiefs were also present during the previous session.

Planned duration: 120 minutes.

Procedure

1. Introduction and review of the observations made in the first focus group session.
2. An explanation was given to the participants about where this project wants to go in means of innovation value and in means of changes of procedures. The project ambitions were mapped in relation to other developments in fire fighting and by TNO. The aim was to let the participants imagine a future situation, without immediate rejection by any presumptions or prejudice (*Image 6.2*)
3. In a slide show, several high-tech products were shown. These varied from fire-extinguishing grenades to looking-through-wall-radar and tactile navigation. Some of the presented products did not exist and of some products the capabilities were exaggerated on purpose. A prototype of a navigation belt was shown and the participants were allowed to try this on. The participants were told that all of the products were on the market already. This tactic aimed to open up the minds of the participants for innovative technologies, partly by making them enthusiastic about the possibilities, and partly by telling them that fire fighting is 'behind on technology', aiming for a type of jealous reaction. A description of these technologies can be found in *Appendix F.*
4. A scenario-based discussion was held, combined with a why-why analysis. The group members were guided through every step of the procedure in a fire fighting situation in a complex structure (in this case a school building). At every step they were given multiple-choice options for a solution to a dilemma; e.g.: "Your teammate is delayed, but you know there is a casualty inside the building. Do you wait three minutes for your teammate, or do you go alone?" The group was invited to use any technology in their description. At each of the questions, a why-why analysis was done with the group to create a list of general values of fire fighting.

5. Concept presentation. The new concept with its scenario of use was explained to the group by showing the concept images from chapter 5.2.2. Each item of the list of values – created in step 4 – was discussed in relation to this new concept, asking the question “is this value supported by the concept, and how?” to the participants.

At the very end of the meeting, it was explained to the group that the technologies presented in part 3, were mostly non-existent. This was done to overcome unrealistic expectations of the participants towards technology in the future.

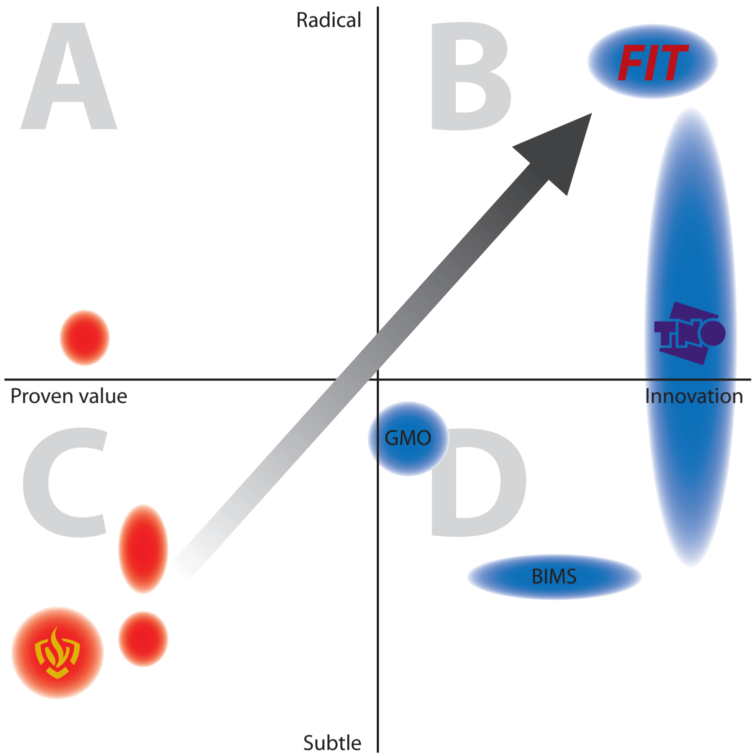


***Image 6.2**: Innogram. Shown to the focus group participants to clarify the position of the fire departments and TNO in relation to innovation and procedure changes. Red shows fire-fighting developments. Blue shows TNO aims and two fire fighting projects.*

6.3 Results

In the session, the participants were all actively and enthusiastically participating. They were impressed by the presented technologies and seemed eager to apply the technologies in the scenario that they would run through. In this session, the participants did not question the assumptions of the concept or the corresponding scenario.

List of abstract values

The values that were distilled from the discussion in step 4 of the procedures are the following (in order of mentioning in the session):

- Personal safety and staying able to save oneself
- Evacuation securing and finding the way back
- Control of the situation
- Carry a casualty
- Arms against fire with foam, water, gas, etc.
- Speed and time

Concept evaluation

The following is a summary of the feedback given by the participants of the focus group.

Personal safety	• Increases the ability of a fireman to evacuate by himself • The chance of disorientation decreases • Fireman becomes more self sufficient • Entering structure alone (instead of in teams of two) becomes realistic
Evacuation	• Is supported by the system • Is improved by the system • Is physically made easier by hands-free operation and intuitive interaction of the tactor-belt
Control	• By introducing the system in the procedures, fire fighters hand over part of control to a computer system • Fire fighters liked the fact that they can place the beacons themselves and be in control of the waypoints in that way

Carry a casualty	• Possible in the presented scenario • Good thing that the evacuation system works hands free and without having to look in a certain direction
Arms	• Relating to the presented novel methods of extinguishing, the concept seems feasible • When using a hose, the system should navigate to the hose and follow it • When operating alone, a powerful extinguisher should support the fireman
Speed	• By not having to watch a screen interface, evacuation times will probably not increase • Uncertain whether evacuation times could decrease; a person will probably always be careful when visual is bad and the situation is hazardous.

Other observations

Some comments made by the participants, throughout the session

"We don't worry about form too much… it will become cool when it works and it is professional. If it is cool, it is beautiful."

An officer, answering the question "what about the shape and beauty of the products you use, how important is it?"

"Even in thick smoke, we analyze every grey-color change we see. The smallest change in gradient can tell a lot about the development of the situation"

Mentioned when discussing why the participants rather use something they feel, instead of something they have to look at.

"I can see this happening… 4 firemen in a truck, alternative extinguisher [e.g. grenade], tactor-belt, beacon here, beacon there… rescue the poor people and get outside before even the police arrives. And I want sunglasses with that product of yours… sunglasses and some chewing gum…"

By one participant, at the very end of the session.

6.4 Conclusions and discussion

From the evaluation, the following conclusions can be drawn about the concept. Conclusions are clustered in three different topics.

Strong points

- Personal safety – system increases the safety and the ability of a fire fighter to save himself.
- Evacuation – is improved by providing intuitive tactile and hands-free guidance.
- Casualty evacuation – is made easier by using the concept due to hands-free and intuitive operation.

Threat(s)

- Control – it is unknown whether situational awareness decreases due to a system that takes over the mapping of the evacuation route. This could become a problem. However, the participants liked the fact that they 'intervene' in the working of the system by having the power of placing the beacons themselves. This advantage seemed to overrule the disadvantage of the extra time this would take. Also, it confirms the advantage of waypoint navigation over inertia tracking. This conclusion confirms the fourth recommendation on trust given in chapter 1.2.

Average, or not known issues

- Arms – using the concept in the presented scenario implicitly demands development and innovation in the area of alternative extinguishers.
- Speed – the assumption, made by the participants, is made that the system will not slow the fireman down. However, due to natural care fire fighters take in their job, it will probably not significantly increase their evacuation speed (not counting a casualty-carrying situation.

As for the threats for the success of the concept, the control-issue has been identified in the literature study in chapter 1.2 as well. To gain trust from the users, the system should work without failure. Only then, gradually, faith will turn into trust, into confidence. This evolution in acceptance of a certain amount of control by the system has also taken place, years ago, when e.g. the breathing apparatus or the radio communication were introduced. Concerning the scenario on FIT-operation, the fire fighters were relatively positive. The participants showed interest and belief in such a concept, but they indicated that more and especially, different equipment is needed to make such operations effective and efficient.
As a result of the session, the developed context scenario and the navigation concept are considered positive, realistic and valid. The feedback of the participants of the user focus group will be used to develop the technology and interaction designs in more detail.

7. Interaction Design

This chapter describes the design of the system from an interaction perspective. First, a review of literature on tactile displays is given. Following, a detailed scenario will be described to provide insight in the actions and feedback a fire fighter will be involved in when using the system. Finally, the design of the tactile stimuli is described, which will be given to the fire fighter by the tactor belt.

7.1 Tactile interaction

In the last decade, research is published on the use of tactile feedback for user tasks. This research area describes the use of tactors in 2D and 3D contexts, orientation and navigation tasks and different environments, like sailing, driving and walking. Since 1998, TNO Defense Safety and Security has been running an extensive research program on tactile displays, covering most of this research area. Therefore, some references will also be made to internal TNO reports.

Two parameters are used in waypoint navigation: distance to, and direction of the waypoint, relative to the navigator (Burnet & Porter, 2002). Technically, only direction information would be sufficient to reach a waypoint, but distance information might help to make the navigation more efficient. Veen et al. (2004) found that extensive distance coding (either absolute or relative to the complete distance) does not increase the speed in a walking-situation, in fact, opposite trends are observed. Their study does however suggest that an 'almost there'-signal is convenient for users in adapting their walking behavior. People are able to navigate accurately using a tactor-vest with 12 tactors, each covering a directional angle of 30° (Erp, 2007). A study by Duistermaat et al. (2006) shows that foot soldiers are able to conveniently navigate with a tactor-belt using only 8 tactors, each covering a 45° angle.

In these two studies the tactor-belt is fit around the torso with an elastic band, enabling a tight but comfortable fit. The tactors used in these experiments were made in-house and were comparable with the tactors that are embedded in modern mobile phones. In a study of Visser & Heus (2005) waypoint navigation was effectively studied using a small electromotor that was outbalanced using a few grams of tin.

Considering the coding scheme, most literature describes designs using a pulse system, varying the duration of a pulse and the pause between two pulses. Although it is also possible to vary in the intensity of the vibration, Bosman et al. (2003) found that varying in duration is better perceived than a change in intensity. Most studies on using tactors in 2D navigation, determine the coding scheme by doing a short pilot study. The variations are mostly in the frequency and length of the vibration pulses. When the study is on navigating over longer distances and in less extreme environments the frequency and length of the pulses is mostly lower and smaller.

The studied literature did not mention tactor-belts with a resolution as low as 4 tactors for the complete belt. Therefore, the effect and efficiency of such a system, as used in the concept for this project, is uncertain. The expectation is that a resolution of 4 tactor locations per belt will be sufficient to guide fire fighters, since they are not navigating through open field, such as in the studies of Veen et al. (2004) and Erp (2007), but through rooms and corridors.

Another uncertainty is whether the tactors can still be perceived when fire fighters are in a working situation, including physically exhausting work and both mental and physical stress. Literature is contradictory on this issue. There are suggestions that a vibrating environment (e.g. a helicopter) could influence perception of tactile stimuli (Castle and Dobbins, 2004). The opposite, however, was found by Erp et al. (2004). Both sources state that more research in this area is needed to understand the effect of external vibrations on the user perception of tactile displays. For this project, it means that eventually a full prototype should be built and tested with users performing fire fighter-like movements in both mental and physical discomfort. A test circuit setup, containing movements representative for fire fighting, can be found in the study done by Vrijkotte (2007).

7.2 Interaction scenario

In the interaction scenario, two phases can be distinguished. The first phase describes the behavior of the user and the system when the user is entering the complex structure and deploying the system. This phase is called Deployment.
The second phase describes the behavior of the system, towards the user when the user has activated the system for evacuation. In this phase, the system guides the user to the exit of the structure. This phase is called Evacuation.

Deployment

When the Fire Intervention Team gets in, they carry beacons with them on the outer sleeves of their fire resisting clothing. Each sleeve carries 5 beacons, without obstructing the fire fighter in his normal movements; three on the upper arm and 2 on the lower.
On every corner the fireman passes and turns on, he places a beacon, either on the ground or on the wall, using the sticky bottom of the beacon. The beacon is activated if it is removed from the sleeve.
Whenever the user is out of range from all beacons any more for two seconds, the tactor-belt will give the fire fighter an alert message which should intuitively be understood as "turn-around". The tactor-belt has to be activated in order to provide the fireman with information to guide him out of the building.

Evacuation

The system is turned into evacuation-mode by hitting the front- or one of the side tactors two times. By hitting one of those three tactors again two times, the system is turned back into deployment-mode.
When turned to evacuation-mode, the tactor belt will vibrate in the direction of the beacon that is closest to the exit. This is called an approaching-beacon-signal.
When the fireman is at a distance of less than 2 meters from the target beacon, the tactor-belt will give 2 pulses on all four tactors. At this point, the system will already detect the next beacon towards the exit and it will react to this next beacon from this point on. This process will be repeated until the fire fighter reaches the exit.
A step-by-step scenario of the system in evacuation-mode is shown in *Image 7.1*.

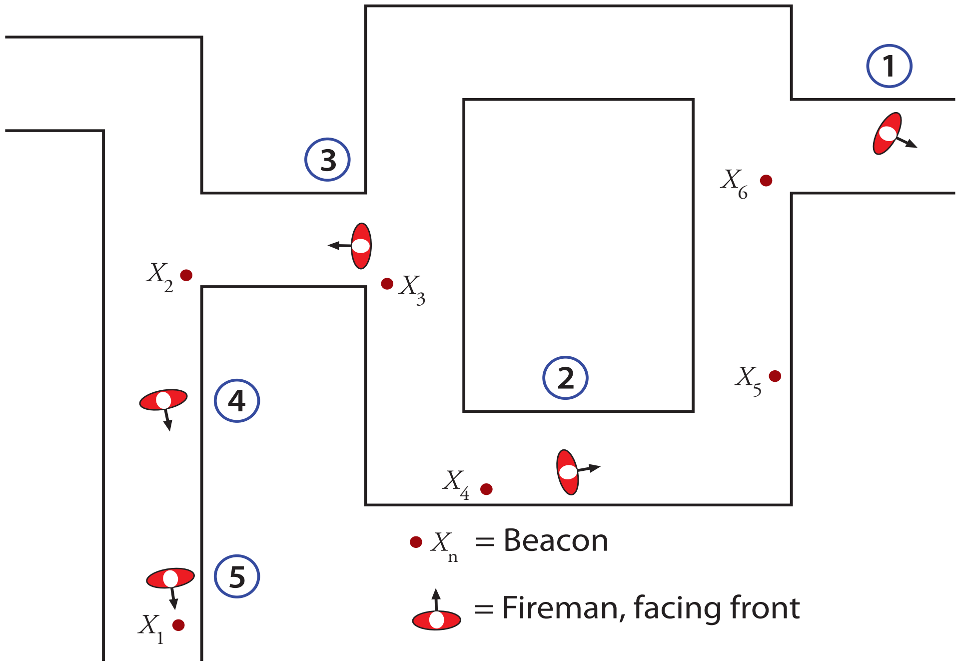


Image 7.1*: Interaction Scenario*

1: *Fireman turns system to evacuation-mode. X_6 was still in sight and is target. Right tactor activated.*

2: *System can be activated in the middle of a route. X_4 and X_5 are in sight. X_4 is the closest to the exit and becomes the target beacon. Rear tactor activated.*

3: *When a beacon is passed, all tactors are activated in two bursts. Subsequently the system reacts to the next beacon, in this case X_2.*

4: *When between two beacons, two short vibration bursts are provided every two seconds on the tactor in the direction of the beacon closest towards the exit; in this case beacon X_1 triggers the front tactor.*

5: *If the fireman arrives at a beacon within an area with a diameter of 2 meters, two short bursts are provided on all four tactors.*

7.3 Stimuli design

Literature that was found on tactile interaction describes performance experiments on stimuli that were designed in detail. Because the aim of this project is not to design optimal tactile stimuli, but to design a navigation concept that can be assumed to work, the choice was made to use the findings in literature and adapt those stimuli where needed.

In the approach of a beacon, the fire fighter receives vibration stimuli on his tactor-belt in the direction of the beacon (*Image 7.1*). Studies found in literature have shown that introducing a type of distance coding in the stimuli provided to the user, does not give better results in efficiency or effectiveness (Veen et al. 2004). Therefore, it was decided to use a non-distance coding direction scheme, based on the scheme used in a study with foot soldiers (Duistermaat et al., 2006). In this project context however, the walking distances are shorter (maximum of around 200m opposed to >5km) and turns will have to be made more often. Therefore, a choice was made to increase the frequency of stimuli to 2 pulses per 2 seconds. This is the double amount of the scheme used in the study Duistermaat.

Approaching Beacon distance to target > 3m, tactor in direction of beacon is active:
200ms pulse – 100ms pause – 200ms pulse – 1500ms pause

Literature has suggested that it makes sense to provide stimuli when the user is close to a beacon (close, in this context, is interpreted as a distance of 3 meters between radar antenna and beacon[1]). Therefore this was also implemented in the language. A *stay alert* or *watch out* signal is usually coded as a pulse or series of pulses on all available tactors (Bosman et al., 2003) (*Image 7.2*). After this stimulus, the tactorbelt will navigate to the next beacon.

Arriving Beacon, distance to target < 3m, all 4 tactors are active:
200ms pulse – 100ms pause – 200ms pulse – 100ms pause – 200ms pulse – 1500ms pause

Whenever the radar system, carried by the fireman, does not detect any beacons it is will give a warning signal. This signal is given after 2 seconds of non-detection. Its design is based on the research done by Friederichs (2005) on navigation for motorcyclists. Friedrichs uses a circular movement on an 8-tactor-belt for displaying a U-turn. This starts at the rear-tactor and moves to the side, front, other side and back (*Image 7.3*) and is repeated every 1,5 seconds.

No Detection, tactor 3, 4, 1, 2, 3 are active subsequently followed by a pause:
200ms (3) – 200ms (4) –200ms (1) –200ms (2) –200ms (3) – 500ms pause

1 This is an estimate. User testing should determine whether the 3 meter distance is convenient or that it should be revised. This is outside the scope of this project.

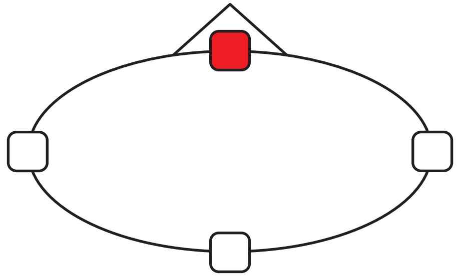
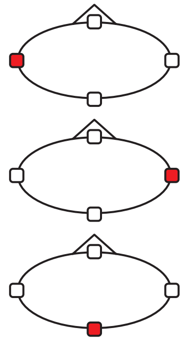



Image 7.1: *Approaching Beacon stimulus. In this case, the front tactor is active. Other configurations on the right.*

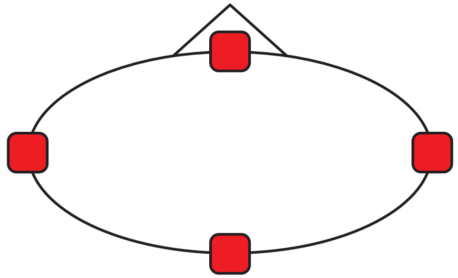


Image 7.2: *Arriving Beacon stimulus. All tactors active in three consecutive pulses*

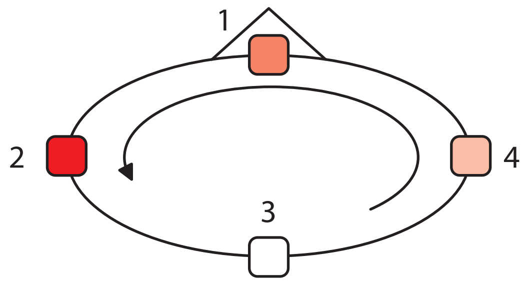


Image 7.3: *No Detection stimulus. A circular sequence of tactors, starting at rear, counter-clockwise.*

8. Technology

This chapter explores the technological feasibility of the designed system. First general radar principles are introduced. Two possible configurations for a radar antennae system are explained and explored. A description is given of how the choice is made. After this, the technology for the beacon is described. Finally, the system-software architecture is explained and final specifications are given.
The technology design that is described is a feasibility study that could serve as a brief for the design of a future prototype that could be used to test the system in a real-life situation. The development of such a prototype is however not included in the scope of this project.
Note that the source for the information on the specifications and properties of the radar systems and transponders was the department of Integrated Systems from TNO.

8.1 Body-radar

Radar is a system based on electromagnetic waves that enables the determination of the range and/or direction of objects. A transmitter emits radio waves, which are reflected by the object and detected by a receiver, which is typically in the same location as the transmitter. Although the radio signal returned is usually very weak, radio signals can easily be amplified.

The transponder-based radar system is based on the Frequency Modulated Continuous Wave (FMCW) principle, which enables accurate distance estimation. In FMCW, the broadcasted signal's frequency is modulated in a saw-tooth pattern (*Image 8.1*). The frequency of the reflected signal has a different frequency than the transmitted signal at any time; i.e. the reflected frequency was transmitted some time ago, described by Δt in the diagram. Δt can be used to determine the distance of the object that reflects the waves: $d = ½ c \Delta t$ (where c is the speed of light and d is the distance to the wave-reflecting object). This principle of measuring distance is more accurate than measuring time-of-flight of the RF signals.

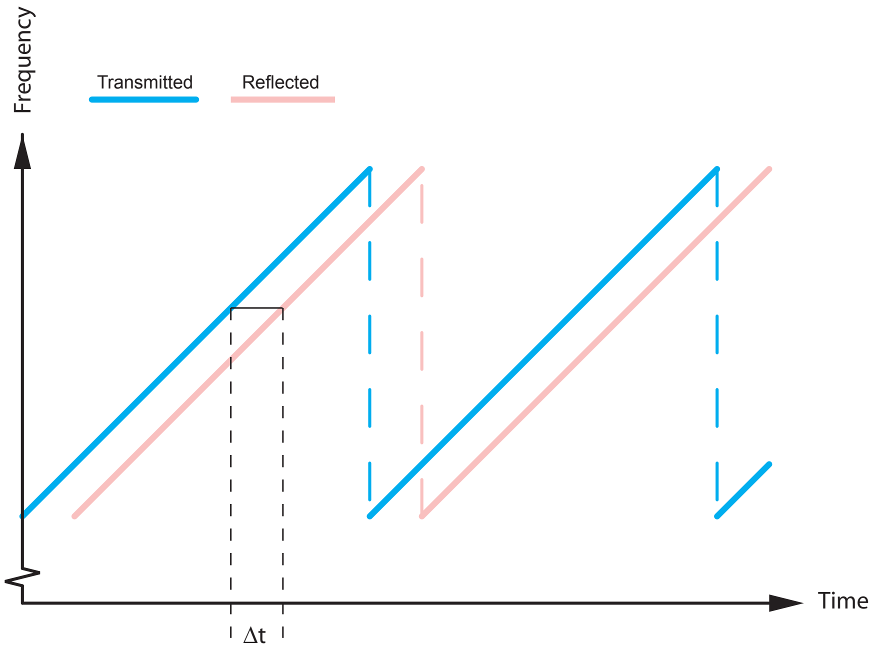


Image 8.1: *FMCW radar principle. The reflected signal is received after transmission with a time difference of Δt. Δt represents the distance to the object that reflected the signal.*

The radar system currently in development is based on 2,4GHz electro-magnetic waves. With the TNO prototype systems that have been built, an indoor range of >40m has been achieved.
It is also possible to use electro-magnetic waves on a higher frequency (5,5GHz). Using a radar system based on a higher frequency has several consequences. First, it would enable the system to have smaller antennae and more compact reflectors, as the size of the antennae that are used is relative to the wavelength. A higher frequency signal has a shorter wavelength. Second, higher frequency waves have lower signal strength at the same power supply. For the context of this project it would mean that the radar waves cannot penetrate walls. This is considered an advantage, because the system should only 'see' beacons that are in a line of sight. Despite the lower signal strength, indoor ranges of 25m are sill feasible. For this project, it would be optimal to use the 5,5 GHz frequency.

Two technology principles

For the body-radar, two different configurations were considered: phase-difference angle determination and a detection/no-detection principle.

The phase-difference principle measures the distance from a beacon to two antennae that are positioned next to each other (*Image 8.2*). The angle of the beacon relative to the position of two antennae (α) can be determined. This is accomplished by measuring the difference in phase of the reflected signal. This difference represents a difference in time-of-flight, and thus a difference in distance from antenna to object. From this difference, the angle α can be determined. Two antennae, as shown in the image, enable angle determination in a 2D space. To determine the location of an object in 3D, a third antenna is needed.

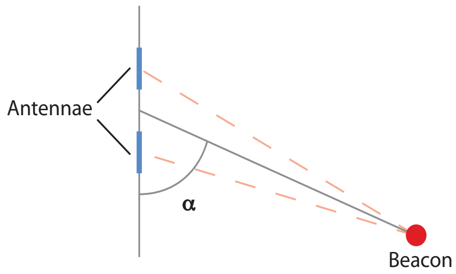


Image 8.2: *Phase-difference principle*

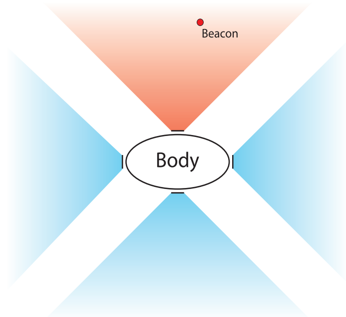


Image 8.3: *Detection/no-detection. The front antenna detects a beacon; the others do not detect anything.*

If this configuration were to be used, a logical position for the antennae would be on top of the helmet. This is because the antennae need to be at a fixed location and at a fixed distance from each other. Also, this location enables the antennae to have a clear view in all directions. Placing the body-radar in this location would however imply several additional technology issues.

- The body-radar should be connected to the tactor-belt by wire or wireless. The latter option implies that a power supply is needed on the helmet, thus increasing weight on the head.
- The received signals by the body-radar should be corrected for the difference in position of head and torso (where the tactor-belt is). Erp (2007) has found that people take the torso as a reference point. Therefore, the position of the head should be tracked. This can technically be done by a technology called MTi (xSens, Enschede, The Netherlands). However, this could possibly introduce extra noise and inaccuracy into the signal processing. Also, firemen would have to calibrate the head tracking system every time before using the system.

The detection/no-detection principle is a simpler configuration. Four antennae are placed around the waist, where each antenna is sensitive for radar signals received within an angle of 90˚. If a beacon is detected by an antenna, its direction is known – at an accuracy of 90˚– because the position of the receiving antenna on the body is known (*Image 8.3*).
The antennae could be integrated in the breathing apparatus-belt that is fixed around the waist when in action. Besides making it easy for the fireman to put the system on, it would also create a logical link between location of detection and location of tactile stimulus.
It must be mentioned that the accuracy of this principle is lower than the phase-difference angle determination. However, this not necessarily a decisive disadvantage for application in this project.

Choosing a configuration

In order to make a well considered decision on which configuration to use, not only the technological specifications should be reviewed. The position of the body of the fireman influences the effectiveness for each radar system in a different way. Therefore the spatial effects of movements and positions – typical for fire fighters – were explored.
The body positions that were considered in this exploration are based on a study by Vrijkotte (2007). In that study a standard set of stances, representative for fire fighting practice, was developed. In this project, a photograph was made of a human in each of these stances. These photographs were used as template to create more abstract body images, while maintaining the correct body proportions. Following, two versions of each stance were drawn, one depicting the body with a phase-difference determination system on the helmet, and one with a detection/non-detection system around the waist. (*Image 8.4*)
This exploration exposed several issues concerning the influence of body positions on the range of the radar system:

- The detection/non-detection system suffers from reduced range when in normal stance or in crouching position because the antennae are obstructed by the arms and knees respectively.
- In most stances, beacons that are close to the fireman will not be detected by the phase-difference configuration.

Below, a summary of the advantages and disadvantages of each principle is given.

Phase-difference determination	Detection/non-detection
+ good overall sight of radar antennae	+ location of antenna = location of stimulus
+ all detectors are in one location	+ simpler algorithm
- head-tracking sensor needed	+ can be integrated in breathing apparatus
- wiring and power supply needed to helmet	+ close-by beacons can be detected
- close-by beacons may remain undetected	- body positions may hinder radar signals

The main disadvantage of the detection/non-detection principle is the possible negative influence of body positions on the range of the system. But however not an elegant solution, the range can be increased by changing the position of the arms in the normal stance, as can be seen in *Image 8.4*. The crouching positions are not the most frequently taken in fire fighting practice. Placing the belt, which contains the antennae, higher on the torso might also solve part of this problem. Further user studies are needed to give confirmation on whether or not the positions influence the range of the system too much. These fall outside the scope of this project.
Considering the phase-difference configuration, the additional technology that is needed to develop an operational system could introduce additional error. The uncertainty about the precision of this configuration and the extra time calibration might take before action, are not in favor of this configuration
The detection/non-detection principle is considered the best option for the technological configuration. Weak points that were identified in the detection/non-detection principle are considered solvable with less effort than the phase-difference principle.

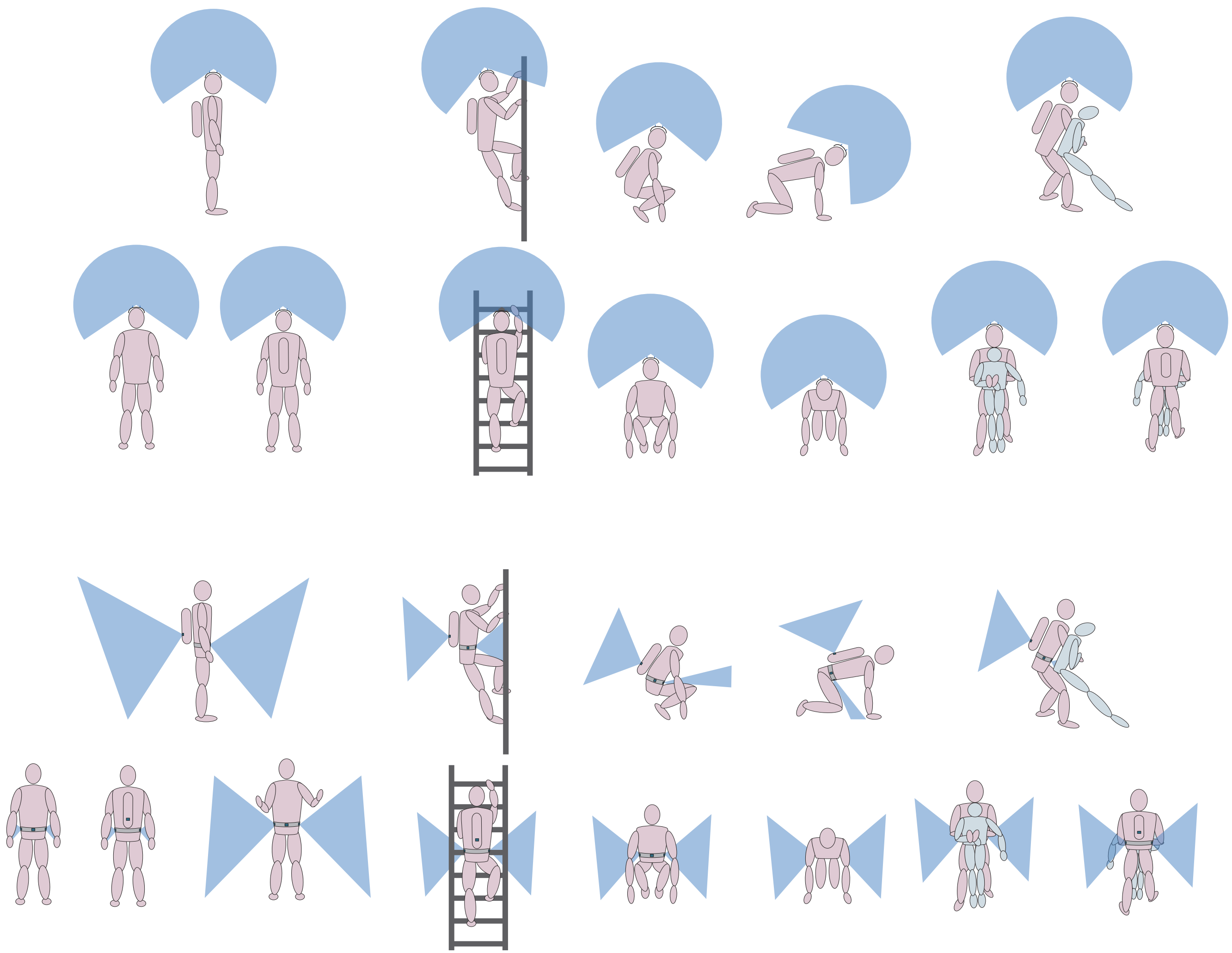


Image 8.4: *Fire fighting positions with two different radar principles. The top two rows show the phase-difference principle. The bottom two rows show the detection/no-detection principle. The angles at which the radar systems can detect beacons are shown in blue.*

8.2 Beacons

The technology inside the beacon is designed to reflect radar waves as effectively and as wide as possible. To do this, an adapted version of the radar transponder – introduced in chapter 1.2 – is proposed: a radar transponder with a monopole antenna. This monopole would replace the patch antenna in order to improve the angle in which radar waves are reflected, and to minimize the need for multiple antennae (and therefore minimize interference of radar signals) within a beacon. In this way, the beacon would have a larger angle of reflection (*Image 8.1*) while taking up little space.

The size of the antenna is determined by the wavelength (λ) of the radar-waves to be reflected. For a radar system on 5,5GHz frequency $\lambda \approx 56$ mm as can be derived from $\lambda = c / f$ (where c is the speed of light and f is the radar system frequency). The most powerful wave-reflection is obtained by using the following antenna dimensions[1]:

Height of the monopole: ¼ λ (≈ 14 mm)
Diameter of ground plane: ½ λ (≈ 28 mm)

The radar transponder is not only a powerful radar reflector; it can also reflect a unique transponder code to the radar system (the firemen in this case). This is done by breaking the ¼ λ antenna-connection intermittently, in a unique pattern for each beacon. Thus, every beacon reflects its unique code back to the radar system.
Because the monopole is a passive antenna, electrical energy is only needed to generate the code which is reflected. This electrical energy is provided by a small 3V battery, attached to the ground plane of the beacon.

***Image 8.5**: Patch vs. Monopole angle of reflection. Note that the antenna-patch has a much smaller reflection angle.*

1 This information was obtained from the TNO Integrated Systems department.

8.3 System architecture

The hardware components of the system that is used by the fireman consist of three entities: computer, radar-belt (input) and tactor-belt (output). When considering software, it is useful to split the functionality of the computer-entity into *System Controller* (the active system object) and a *Beacon List* (a database structure containing the beacon information). This virtual split creates clarity in terms of where data is stored and how it is manipulated.
This chapter describes the relation between the software entities and the actions they can perform.

The relation between the entities in is shown in the sequence-diagrams in *Images 8.6-8.8*. When looking at the diagrams, also note the following:

- When a new beacon is found by Beacon List, this can only be the result of the Fireman placing an activated beacon in the environment. Following to this action, the Radar will detect that beacon.
- Only the Fireman can change the system from deployment to evacuation mode. It is the only direct interaction the user has with the system. For this reason, the fireman is excluded from the diagrams.
- The System Controller will re-execute *updateStatus()* whenever a sequence is finished.

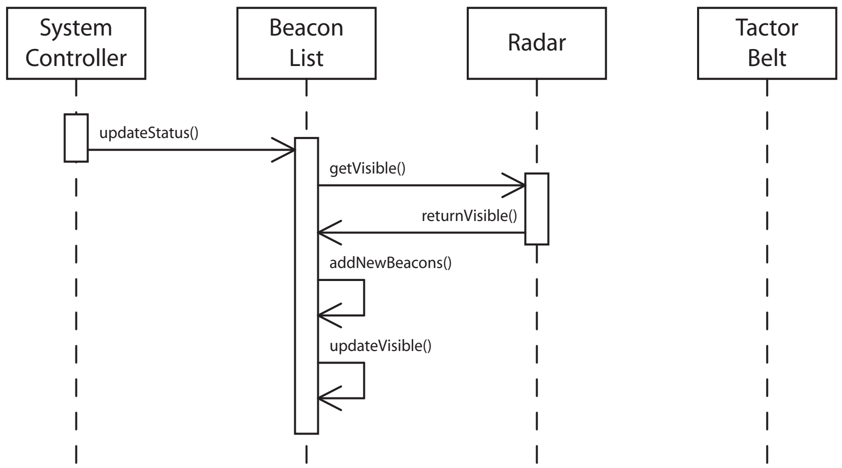


***Image 8.6**: Sequence Diagram of deployment mode. Note that the Tactor Belt is not involved when beacons are found. The system is designed to continuously monitor deployed and visible beacons. A newly deployed beacon will be returned as 'visible' by Radar, but it is not in the Beacon List yet. This discrepancy indicates that the 'unknown beacon' is recently deployed and will therefore be added at the end of Beacon List.*

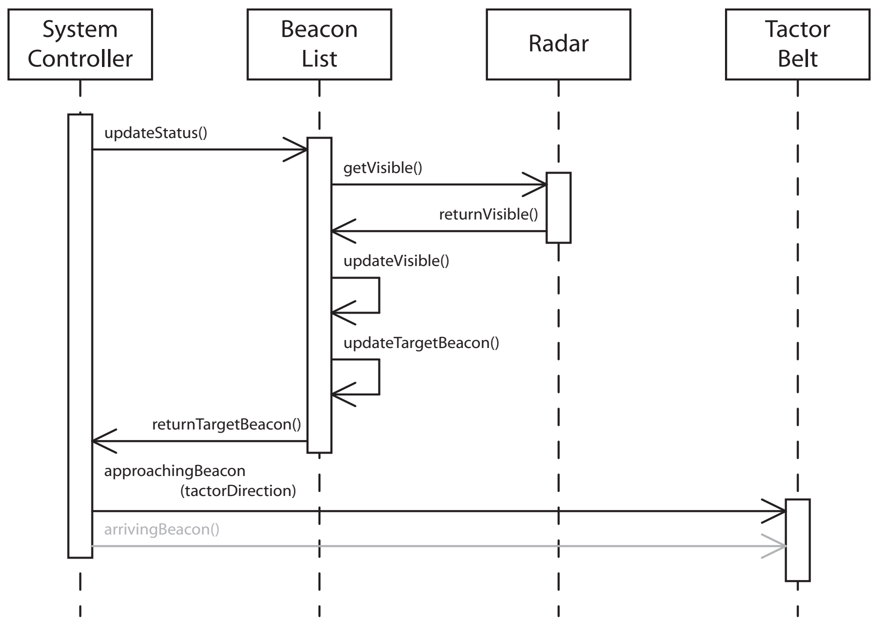


Image 8.7*: Sequence Diagram of evacuation mode. In evacuation mode, the system does not track newly deployed beacons, because the fireman will not deploy new beacons in this part of the procedure. Beacon List identifies targetBeacon. This will be used by System Controller to initiate the Tactor Belt. Depending on the distance to targetBeacon, it will trigger the approachingBeacon or arrivingBeacon signal.*

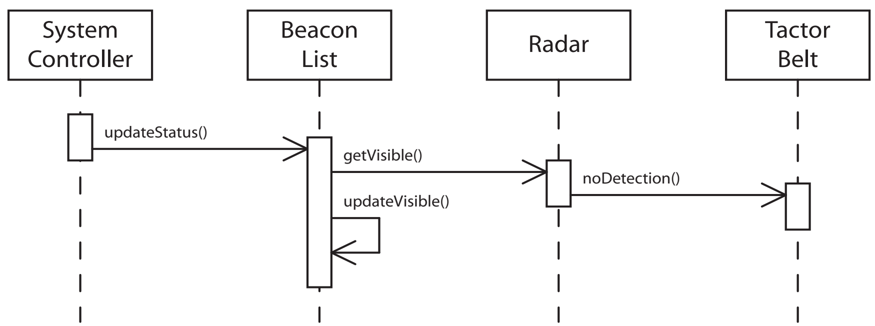


Image 8.8*: Sequence Diagram of no-detection signal. If no beacons are detected by Radar, Radar immediately issues Tactor Belt to execute a no-detection stimulus.*

The actions (methods) that can be performed by each of the entities are described in the table below. The Fireman entity cannot execute formal methods, because it is not a system entity.

Fireman	Can activate the system controller from *deployment* to *evacuation* mode. Can move around (this influences the values returned by the getVisible() method of Radar).	
System Controller	The system controller is the main system entity. All procedures are initiated by this entity.	
	Can update the status of the beacons.	*updateStatus()*
	Can turn system to *evacuation* mode.	*activateSystem()*
Beacon List	The Beacon List is a database that stores the status of all the beacons that are deployed. Newly detected beacons can be added to the list. The targetBeacon is always a visibleBeacon, and all visibleBeacons are all deployedBeacons by definition.	
	Contains list of all deployed beacons .	*deployedBeacons*
	Contains list of all visible beacons, including direction and distance.	*visibleBeacons*
	Contains the target beacon.	*targetBeacon*
	Can update deployed beacons.	*addNewBeacons()*
	Can update visible beacons.	*updateVisible()*
	Can update targetBeacon.	*updateTarget()*
Radar	Can return the codes of visible beacons and their distances.	*getVisible()*
Tactor Belt	Can give no-detection stimulus.	*noDetection()*
	Can give approaching-beacon stimulus.	*approachingBeacon(targetBeacon)*
	Can give arriving-beacon stimulus.	*arrivingBeacon()*

8.4 Final technology specification

The components described in this chapter are mapped on the body as can be seen in *Image 8.9*. Below, the components, sizes and power consumption/supply are given. The data is based on what can be realized with the current state-of-the-art technology. It is likely that the sizes and power consumption can be reduced with future technology developments.

Components

- Beacons (10 per user) equipped with a monopole antenna.
- Radar belt with 4 antennae positioned around the waist. Antennae transmit and receive at 5,5 GHz. The radar type is FMCW.
- Computer for processing radar signals and controling the tactor-belt.
- Tactor-belt with 4 tactors, corresponding to the antenna locations.

Sizes (mm)

Transponder antennae: in beacon	14 (height) x 28 (diameter)
Radar-belt antennae:	30 x 60 x 2 per antenna
Computer:	120 x 60 x 40 (2 year prognosis) 100 x 50 x 20 (5 year prognosis)
Battery:	100 x 50 x 20

Power consumption

Radar-belt antennae:	2 W
Computer:	3 W
Tactor-belt:	0,5 W (if all tactors are on simultaneously)
Battery :	8 W; 25Wh supply

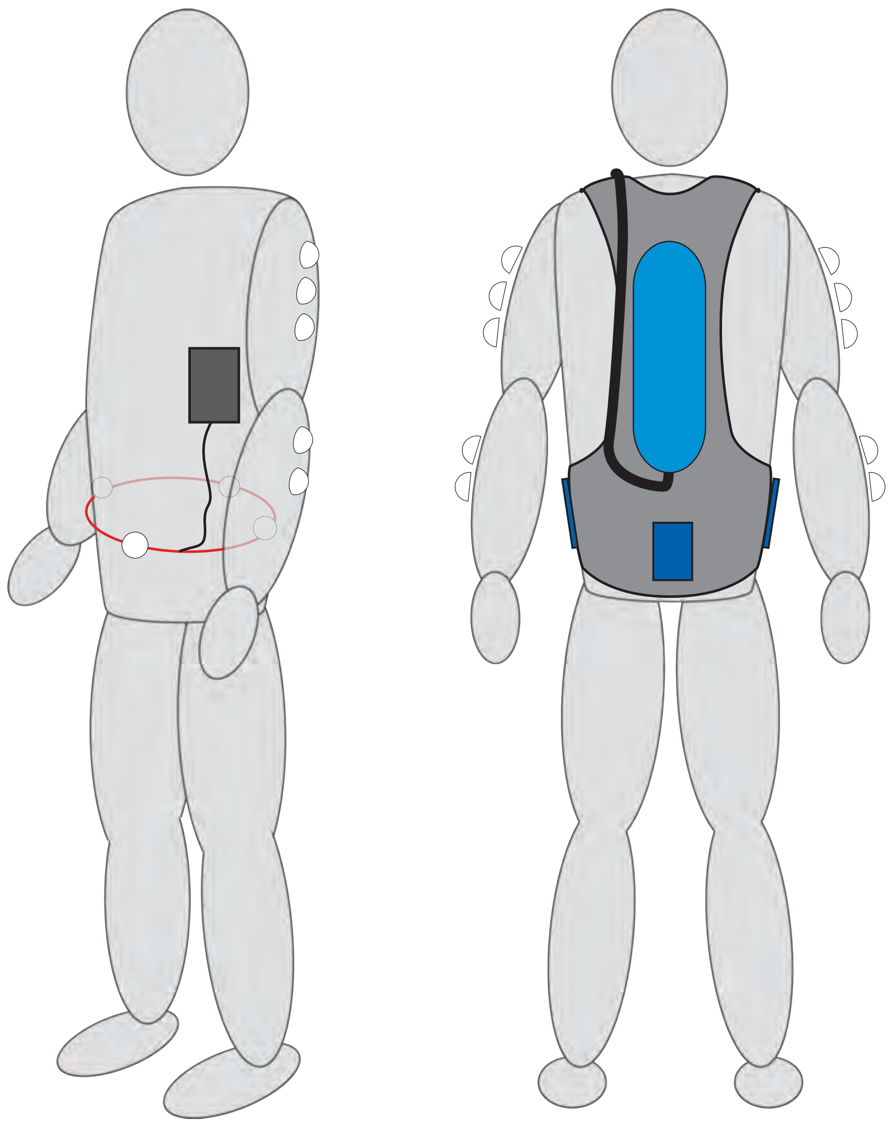


***Image 8.9**: The system components located on the human body. On the left, the inside, with tactor-belt and computer. On the right, the outside with the radar antennae (dark blue) integrated in the breathing apparatus belt. There are five beacons on each jacket sleeve. The sizes of the components are not to scale.*

9. Prototype

A prototype was built as a tool to demonstrate to users that they can use the designed navigation concept to locate and navigate towards a beacon that is positioned in a space.
This chapter describes the aims with which the prototype was built. Following that, a description is given of the technical properties of the prototype system.

9.1 Aims

A prototype of the navigation system is built to demonstrate navigation-interaction properties of the concept. Haude & Hill (1997) have suggested that prototypes should be built for a clear goal. They identify three types of prototypes, each serving a different goal:

Role	Lets users experience the role an artifact could play in their lives
Look-and-Feel	Explores the concrete looks and interaction experience of an artifact
Implementation	Made to explore the technical feasibility and to see how a design can actually work

For this project, a *Look-and-Feel* prototype was built, which should demonstrate the concept of navigation with a tactor belt in combination with a movable beacon (that serves as a waypoint).
On a concrete level, the prototype should enable the user to do the following:

1. Feel tactile stimuli that are provided on a tactor belt. The tactor belt has tactors in four directions (front, back, left and right).
2. Identify the direction of a beacon that is placed within 8 meters of the user. The tactor-belt should provide stimuli, corresponding to the beacon direction.
3. Navigate towards the beacon while continuously receiving tactile feedback on the direction of the beacon.

Not included in the scope of this project are the navigation over a path, set out by multiple beacons. Related to this, the prototype does not provide different stimuli when a user comes in close range of a beacon.

9.2 Description

The prototype consists of four components: the tactor-belt, the beacon, the detectors and the microcontroller. Schemes of the electronics can be found in *Appendix G*.

Tactor-belt

The tactor-belt is a textile belt that can be attached inside the fire fighter jacket (*Image 9.1*). The final prototype is however not integrated in the jacket; this makes the connection with the detectors more convenient. Tactors are attached with Velcro-tape on the body-side of the belt. The tactors are controlled by the microcontroller. The tactor-belt has 4 tactors which are placed in the front, back and left and right sides.
The tactors that are used are of the type TTTD JHJ-3 (TNO Science and Industry, Eindhoven, The Netherlands) (*Image 9.2*). This tactor was chosen it was directly available and it is also used in the studies by Erp, which were described earlier.

Beacon and Detectors

For building the detection technology, the choice was made to use ultrasound technology. This technology is more easily build than a working radar system. This is mostly due to less complicated algorithms and filters. For the goals in this prototype, using ultrasound technology is sufficient.
The beacon continuously transmits 40kHz ultrasound waves. The detector will receive the ultrasound transmission when aimed towards the beacon. The principle is based on the natural angle of sensitivity of the ultrasound receivers that were used; in this case, receivers with a sensitivity angle of 85°. The transmitters transmit the waves at the same angle. For the transmission and reception, 400ST120 and 400SR120 (both Prowave, Taipei, Taiwan) components are used respectively. The beacon can be seen in *Image 9.3* and *9.4*.

***Image 9.1**: Tactor-belt prototype*

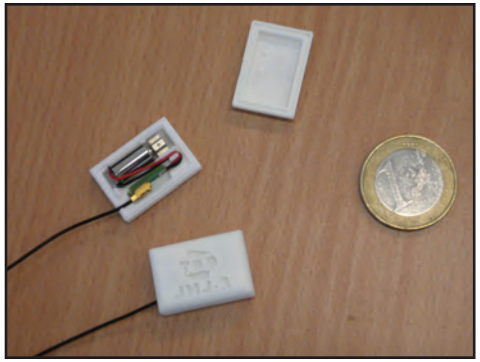


***Image 9.2**: Tactor of the TTD JHJ-3 type*

Image 9.3: *Beacon showing the transmitters.*

Image 9.4: *Opened beacon*

A preliminary identified problem was the possibility of reflections within a space (Dijk, 2004). This could bias the angle-detection, e.g. a receiver could a signal while the line-of-sight towards the transmitter is not within the sensitivity-angle. Pilot studies with the ultrasound transmitters and receivers have suggested however that such a problem was not to be expected with the use of this technology.

The signals that are received by the ultrasound receivers are amplified, filtered and slowed down by a counter. This slowing down is a proportional reduction of the received frequency; for every 256 periods of the ultrasound signal that come in, 1 period is sent to the microcontroller.
A total of three detectors are mounted at the outside of the tactor belt. This means that the prototype can only detect a beacon in three, instead of four directions. The reason for this is that earlier in the project, only 3 digital I/O ports on the microcontroller were available for detectors, because the other I/O ports were configured as output for the tactors (which were 8 at that time). Although in the current configuration, enough I/O ports are available for 4 detectors, the fourth detector could not be produced in this project any more. The three detectors are aimed in the following directions: the front, left and right.

Microcontroller

A microcontroller was used to process the received ultrasound signals and to activate the individual tactors. The microcontroller that was used in this project is an Arduino Mini[1] (Smart Projects, Chivasso, Italy) that uses an Atmel 164 processor (Atmel Corp., San Jose, USA). This microcontroller was chosen because of its accessible programming environment and the possibility to easily program the device from both Apple Macintosh and from a Windows platform. Moreover did I already have some experience in using the Arduino environment.
The digital I/O ports of the microcontroller are used to receive the data from the ultrasound receivers and to drive the tactor-belt. The software continuously monitors the frequency of the ultrasound signal that is received by the ultrasound receivers. The software, up to this point, can be found in *Appendix H*. Following, the software determines which of the three detectors receives the best signal and whether this best signal is good enough. If the 'best signal' is good enough, the microcontroller will activate the tactor that corresponds with the detecting ultrasound receiver. This tactor will then execute an 'approaching beacon' stimulus.

1 The Arduino microcontroller board was designed in a project by multiple universities. The controller is produced by Smart Projects and sold on the community website: http://www.arduino.cc

10. Final Design & Conclusions

This chapter will first describe the final designed system in its context by showing a scenario. Following, a short summary of the components will be given, which includes a more detailed description of the beacons. General conclusions are described and discussed. Finally, project specific recommendations are given to help the future development of this project.

10.1 Design
- Scenario
- Components

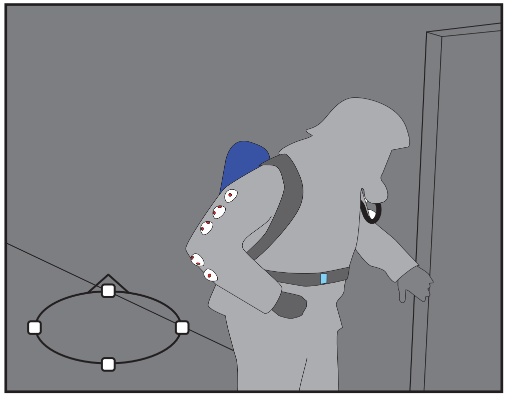
10.2 Conclusions and discussion
- Focus group user involvement
- Fire Intervention Team scenario
- Interaction design
- Technology

10.3 Recommendations
- User testing
- Scenario development

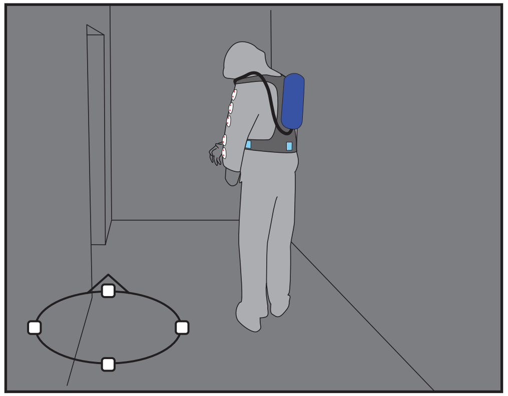
10.1 Design

Scenario

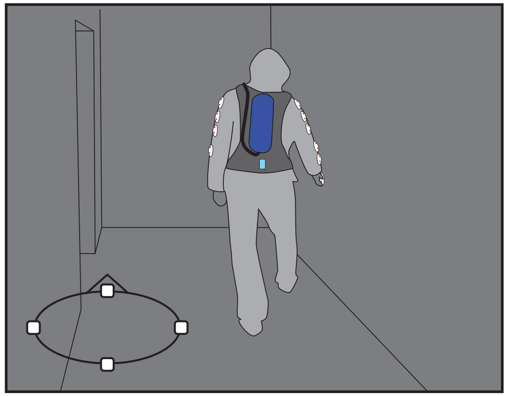
The following scenario shows the procedure in normal operation (1-10) and two special events (A-B). The behavior of the tactor-belt is included in the images. In every scenario step, active tactors are shown in red. Note that in the tactor-belt diagrams, the front of the tactor-belt is always at the top.



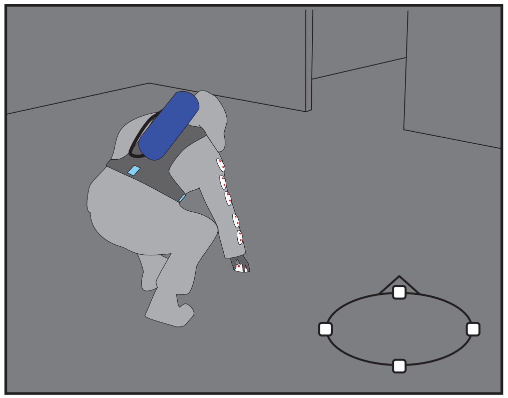
__1.__ Entering the building with beacons. (normally also with an alternative extinguisher)



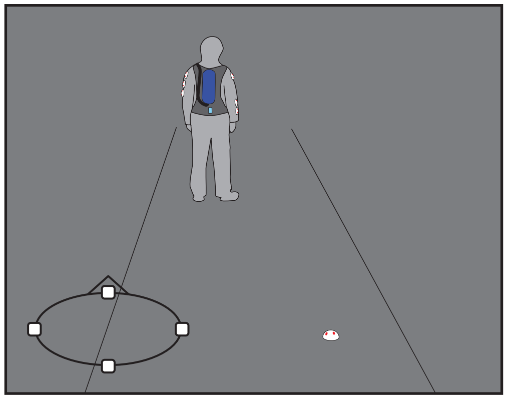
__2.__ Beacon is drawn from the sleeve and activated on release.



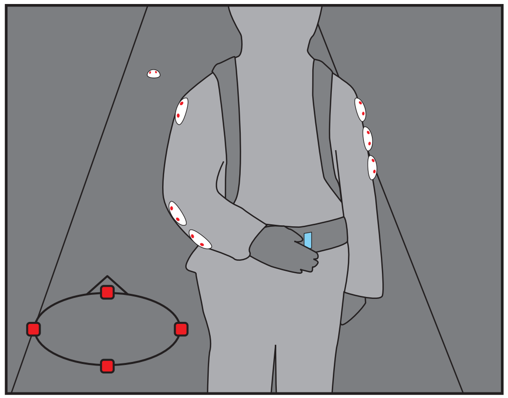
__3.__ The sticky bottom of the beacon enables it to stick on walls and floors.



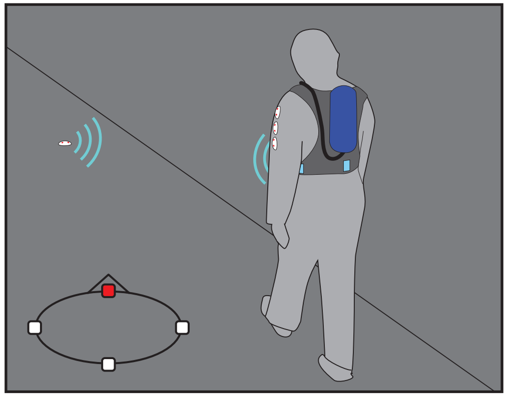
__4.__ Beacons can be placed in corridors or on floors of open spaces.



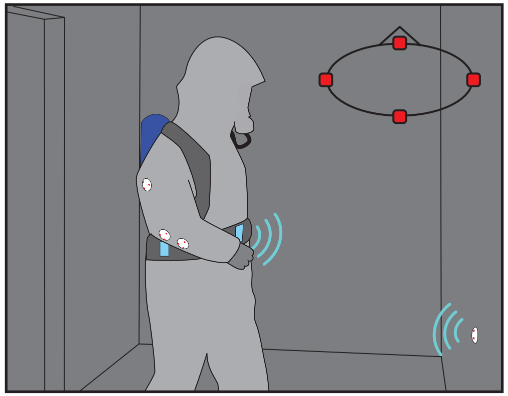
__5.__ Disorientation occurs, beacon is still 'in sight' of the radar system.



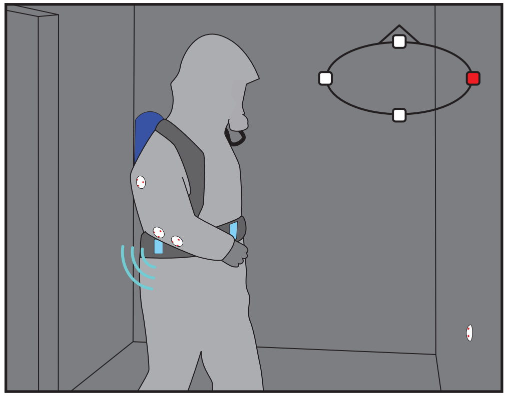
__6.__ Evacuation mode is turned on by hitting the front tactor twice. All tactors vibrate once to indicate activation.



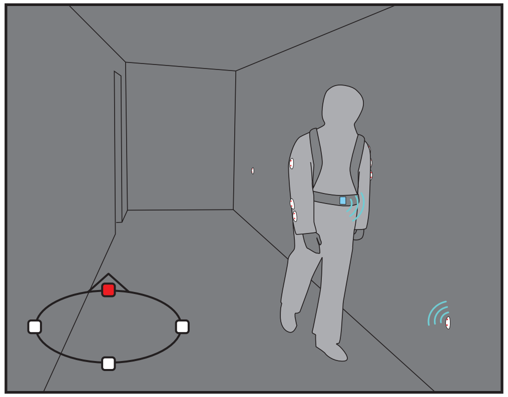
7. *The front tactor vibrates when walking towards the target beacon.*



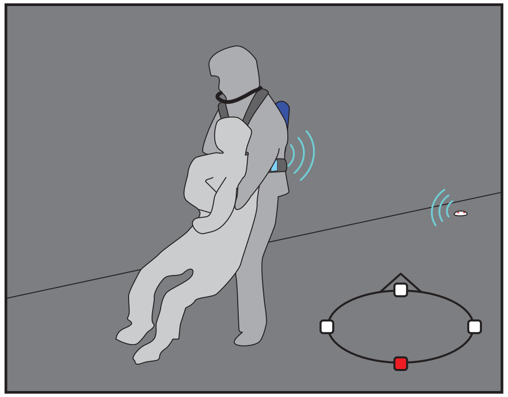
8. *When approaching a beacon close, all tactors vibrate at the same time...*



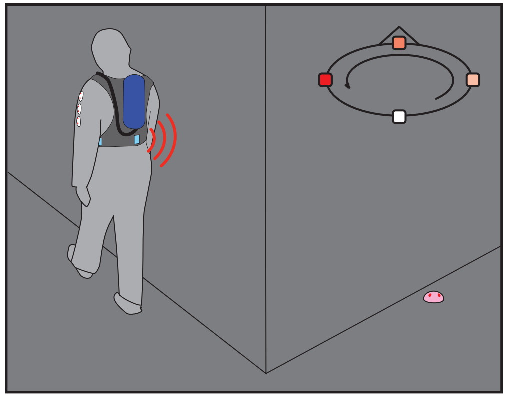
9. *...before navigating towards the next token on the right.*



10. *Beacon-by-beacon the fire fighter can navigate towards the exit.*



A. *If a casualty is to be carried, the fire fighter can navigate backwards.*



B. *The tactor-belt will give a turn-around signal if the last beacon is out-of-sight.*

Components

The system is composed of four components, of which parts also have been described earlier. Concerning the beacon, the designed interaction scenario demands specific functionality, such as stickyness and activation from sleeve. This chapter elaborates on how this could be done and some design suggestions are given.

- **Radar-belt**. Contains 4 antennae that are integrated in the breathing apparatus belt. As can be seen in the scenario images, the belt is placed higher to minimize radar wave obstruction.
- **Tactor-belt**. Is integrated in the jacket as can be seen in the prototype (*Image 9.1*).
- **Computer**. Is wired to the tactor-belt and placed in the inside pocket of the jacket. The computer has a wireless connection to the radar system which is outside of the jacket. Having a wireless connection prevents any unnecessary heat transfer, which would have been caused by making wired connections from outside to inside of the jacket.
- **Beacons**. All identical in design but reflecting a unique radar code. The beacon-shape is mainly determined by the monopole antenna which it carries. A beacon is 35mm in height and 60mm in diameter. Pulling the beacon from the sleeve removes a plastic release-part that disconnects the electronic circuit within the beacon, if in place. When released, the beacon its LEDs light up and the transponder will reflect radar waves with its unique code. Also, pulling the beacon from the sleeve will expose the glue on the bottom of the beacon, which enables the fire fighter to place it on walls. An exploded view of the beacon's interiors can be seen in *Image 10.1*.

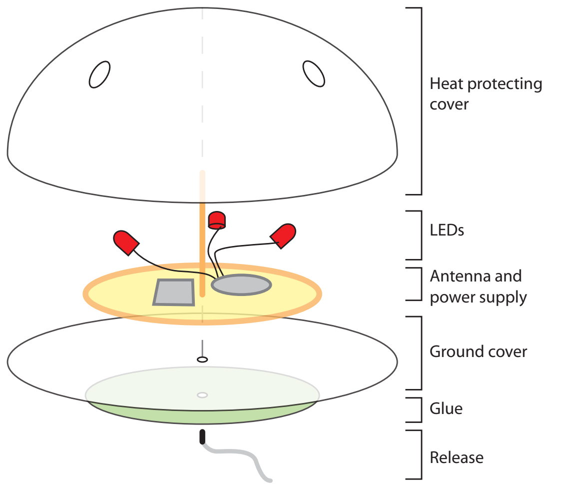


***Image 10.1**: Exploded view of beacon.*

10.2 Conclusions and discussion

The efforts in this project have lead to the following general conclusions:

- An effective method for involving user focus groups was developed. This was needed for the special user group this project deals with.
- A navigation concept and a corresponding interaction scenario have been developed. These were both based on a combination of user input - obtained in the focus group sessions - as well as on studies found in literature.
- An exploration was done on the technological feasibility of the concept. This has lead to the suggestion of a technology configuration that deals with core technology problems, as well as interaction issues.
- For the demonstration of the interaction experience a prototype was built. This prototype is designed to let people experience tactile navigation.
- A concept was developed of which technology, interaction and user issues have been explored up to a level that it merits the consideration of further development.

Focus groups user involvement

Users were involved in the design process from the beginning. They were allowed to inspire the developed concepts. Involving the users at an early stage resulted in enthusiasm and understanding for this project from their side. The users eventually provided useful feedback on the concepts as well as the design space and criteria. As a spin-off, the meetings between the Utrecht fire brigade and TNO have now been scheduled regularly; the fire brigade provides feedback and testing opportunities, and TNO shows new prototypes.
The project domain demanded a new approach towards the user, concerning the setup of the focus group sessions. In the first session, a more traditional approach was taken towards generating user feedback on concepts. Although based on recent examples of the integration of focus group techniques within a design process, the session did not provide the desired type of feedback; the users mainly discussed the assumptions on which the concepts were based rather than evaluating the practical implications of the concepts with their experience. A revised strategy, introducing a 'shock-effect' for modern technology and introducing a scenario of FITs, let the participants imagine future work scenarios. This approach might also be useful for using focus group sessions in a user centered design process for policemen, rescue workers, military and other extreme user groups. This focus group strategy was presented at the *CHI Nederland Conference '07* (Visser et al., 2007).

Fire Intervention Team-scenario

The development of the FIT-scenario has provided several results for the project and opportunities for the future. The scenario describes a way of working by elite fire fighters which is faster, is more aggressive and in which the firemen can operate independent from external help.
The scenario was used in the design process to generate a context for the navigation system that was to be designed. Especially in the focus group sessions it enabled the participants to see the system within a future context, instead of relating it to their current equipment and way of working.
For the future, the FIT-scenario could serve as a platform for innovation on fire fighting operation and equipment. Projects that are currently under development at TNO could be placed within the FIT-operation scenario. Examples of these projects are the following:

- Radar Uniform: a suit equipped with a radar that can look through walls.
- Fire Fighter monitoring: sensors integrated in the fire fighter suit to monitor heart rate, skin temperature and core temperature.
- Compact extinguishers: research into the feasibility of compact extinguishing methods.

The interest for the FIT type of operation is growing. In meetings with fire fighters, the trend towards this way of operating was recognized. Fire fighting procedures at several military airfields in the Netherlands is already moving towards this operation scenario. For the domain of fire fighting, the FIT-scenario can therefore be seen as a strong concept which has the potential to serve as a strong basis for future research and development.

Interaction design

An interaction scenario was developed to help firemen evacuate more efficiently and more intuitively than the current ways of working. This scenario was based on literature on relevant interface designs, as well as on the results of both focus group sessions. On a high level, the interaction scenario is assumed to be more efficient and intuitive, but this has to be confirmed by elaborate user tests.
On a concrete level, an interaction language, by means of a tactor-belt is proposed. The stimuli that are applied are described in literature and therefore can be considered reasonably reliable, concerning the meaning and natural interpretation by the user. However, the physiological perception of the vibrations is still to be tested in future research.
In developing prototype, the choice was made to not do a 'Wizard of Oz' (or fake-interaction) demonstration, but to build a prototype that worked live. This has taken a considerable amount of time in building and calibrating the ultra sound technology. Creating a fake-interaction prototype would have saved time, but the question must be raised whether such a prototype would promise to be just as convincing.

Technology

The choice for the type of technology that was proposed is based on the results of user and interaction investigation. Because the arguments to support the final design are primarily user centered, it has a better chance of generating more trust/confidence in users.
The described radar technology has the potential to serve the final system on its orientation/navigation issues. The technology was determined and specified on a theoretical and abstract level. To realize a full prototype, the existing radar systems built within TNO Integrated Systems have to be further developed. Development in this area fits well within current radar- and fire fighting-programs running within the EVI program[1].

1 In this case, this would mean cooperation between TNO Human Factors (Soesterberg) and TNO Integrated Systems (The Hague).

10.3 Recommendations

Within the EVI program, this project could be further developed within the cluster of clothing and equipment. There is still a long way to go before this system could go in production. This chapter highlights the issues which should at least be included in the first next steps in the continuation of the project.

User testing

To validate the assumptions made after the second focus group, additional user studies on three different levels have to be performed. These are of perceptional, performance and behavioral (procedural) nature.

Perception The influence of increased mental, temperature and/or physical stress levels on the perception of the vibro-tactile stimuli have to be determined. Also, the perception of the vibro-tactile stimuli during extraordinary movements should be secured. This could be examined by using a test setup as used in the experiment of Vrijkotte (2007).

Performance Besides receiving the tactile signals, the users should also understand the meaning of the signals. Erp (2007) describes an experiment in which the performance in a driving task is examined while cognitive load is increased by a secondary task. Tactile stimuli seem to be effective and efficient under these circumstances, but a dedicated setup (different signals, different body positions) should be used in an experiment in the continuation of this project.

Procedures Because the introduction of the navigation system into fire fighting operations demands new procedures, these should be extensively tested and trained. This would also help to increase the trust of the fire fighters in the system.

Scenario development

To maintain and increase commitment from the fire fighting community, the FIT-scenario should be further developed. This would also stimulate the demand for the launch of new projects within this domain. The scenario should also be developed as a communication tool, such that it can be used to explain the project(s) to stakeholders. The approach within the second focus group session has shown that imagery and look-and-feel prototypes stimulate imagination and enthusiasm for the project cause.
Concerning the interaction scenario that was designed in this project, development is needed on the special events within a possible operation. The developed concept is based on the

operating of one team in a single level complex structure. During the design of the system, this type of operation was the basis. The further development should address spatial issues such as how to deal with stairs, doors, stair cases, etc. Also, The use of the system when operating with multiple teams is to be addressed.

Most important is that the design is developed together with fire fighters, as well as technology and psychology experts. The role of the industrial designer could be the integrator in that project.

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Appendix

A. List of Definitions

B. Trust and Confidence literature study

C. Overview of positioning, guiding and detecting principles

D. Overview of existing products and technologies

E. List of generated ideas

F. Description of envisioned technologies

G. Schemes of electronics for prototype

H. Software code for prototype

A. List of Definitions

Complex structure Structures like factories, office buildings, large public buildings and ships. These are structures that induce a significantly larger risk of disorientation in a fire fighting situation. According to the official current procedures, firemen should always take a hose or line-system with them when entering a complex structure. This is, however, not always done.

Disorientation confusion (usually transient) about where you are and how to proceed; uncertainty as to direction. Medical definitions describe three types of disorientation: spatial, time and identity. In this project, only spatial disorientation is considered.

EVI "Effectief en Veilig Ingrijpen" is a research program, run by TNO. The program has four main topics: Effectivity, Command Structure, Equipment and Clothing and Training and Cooperation. Within these topics several projects are run, such as the 'smart fire fighter suit' and the 'Looking Through Walls radar'.

Fire commander Highest rank in Dutch fire fighting. (Dutch: Commandant van Dienst) Will only be present at the site of an incident when there is a major disaster (e.g. an air crash).

Fire chief Leader of a fire fighter squad of six men, including the chief. (Dutch: Bevelvoerder)

Fire officer Leader of two to four squads. Directs the fire chiefs. (Dutch: Officier van Dienst, OvD)

Fireman Lowest rank in fire fighting. This is the most physical task due to the extinguishing, reconnaissance and rescuing tasks. (Dutch: manschap)

FMP "Firefighter Modernization Program" is a research program, run by TNO. This program deals with the implementation of the research and development delivered by the EVI-program. Although content-wise, the project described in this report it should belong within the EVI-program, it officially is run under the FMP program, because of budget reasons.

GPS Global Positioning System refers to a satellite-based radio positioning system that provides 24 hour three-dimensional position, velocity and time information to suitably equipped users anywhere on earth. Applications include hand-held telematics, fleet tracking and vehicle management systems: devices designed for automobiles providing drivers with personalized information, messaging, entertainment and location-specific travel and security services. GPS technology is used in a wide range of applications, including maritime, environmental, navigational, tracking and monitoring.

Heads-Up-Display HUD is a principle where visual information is presented to the user in his field of view. This implies that he does not need to look at a screen. The information can be presented on a head-mounted display or it can be projected on the visor of a helmet.

Inertia Tracking A method for collecting data on a path that has been followed by an object. The object is equipped with a compass or gyroscopes and with accelerometers. From this data, a covered path can be derived. Because a cumulative error is built up in this system (due to noise in the sensor data) this techonology is typically used to support GPS devices when the GPS device has lost satellite connection for a short time. Inertia tracking is too inaccurate to be used stand alone for extensive path tracking purposes such as in this project.

Look-and-Feel prototype One of three different approaches to prototyping, where the focus is on letting people experience what a certain product would feel and look like. This means visual appearance, as well as physical and audio interaction issues. The other two approches are Role- and Implementation-prototyping, where the focus is on user scenarios and technology respectively. (Haude & Hill, 1999)

PeTaNa The Personal Tactile Navigator (PeTaNa) was used by Duistermaat et al. (2006) to investigate tactile navigation in 2D. The navigator is a belt, equipped with eight tactors that can be individually controlled. In fact, it is a simplified version of the Tactile Vest.

Situational Awareness: The understanding of ones position relative to other objects. Two different types can be distinguished: macro and micro. Macro is the understanding of ones location on earth or on a map. Micro is the understanding of the local environment and the organization of its visual cues, like trees, rivers, houses, etc. (Duistermaat et al., 2006)

Tactile Vest: A vest with 64 tactors, positioned within the vest, all around the body. The vest is used as a platform for experiments in the domain of tactile interaction.

Tactor: A small vibration motor, serving as a vibro-tactile actuator. The ones used in this project are of the type TTTD JHJ-3, developed by TNO Science and Industry in Eindhoven (The Netherlands). These tactors were specifically developed for use under extreme movement and high G-load.

Trilateration: A method of determining the relative positions of objects using the geometry of triangles in a similar fashion as triangulation. Unlike triangulation, which uses angle measurements (together with at least one known distance) to calculate an objects location, trilateration uses the known locations of two or more reference points and the measured distance between the subject and each reference point. To accurately determine the position of the object on a 2D plane, at least three reference points are needed (e.g. GPS satellite).

Waypoint: Point in space that serves the purpose of navigation by acting as a point of reference. A waypoint has at least a known location, distance of angle towards the user.

B. Trust and Confidence literature study

According to Deutsch (1960) a need for trust arises under specific contextual parameters:

- There is an unambiguous course of action in the future
- The outcome depends on the behavior of another party
- The strength of the harmful event is greater than the beneficial event

Trust can be seen as a mental mechanism that helps to reduce the complexity and uncertainty in a situation, in order to facilitate and stimulate the development or the maintenance of relationships under risky conditions (Luhmann, 1988). Without risk, there seems to be no need for the trust-mechanism or confidence (Egger, 2003).
Arion et al. (1994) introduced the concept of the Faith-Trust-Confidence concept. They describe a continuum that can be split into three types of belief. If there is little or no evidence available on a certain situation, the actions of a user are based on faith. If there is more evidence, but the evidence is still incomplete, the actions can be described as being based on trust. If (almost) all evidence is available, users can be considered to have confidence in a certain situation.

Predictability, dependability and faith

According to Rempel et al. (1985), trust in personal relationships is composed of several components: Predictability, Dependability and Faith. The first component, Predictability, can be understood as general expectations towards the other party. These expectations are influenced and formed by the amount of time the two parties are involved in a relationship. The longer both parties are known to each other, the better one can predict the behavior of the other.
Dependability refers to the other party's moral integrity, reliability, honesty and concern with providing expected rewards. This component is clearly related to Predictability. However, Dependability is more related to the intrinsic behaviors of another party (why someone does something), where Predictability deals with the actions (what someone does).
The last component, Faith, refers to a pseudo-trust which is not based on past experience. No judgment can be made based on previous experiences of interaction with the other party. One can only hold beliefs about the other party. Faith is considered an emotional security that allows one to go beyond the known relationships. Rempel et al.'s (1985) makes no mention of a certain reputation or charisma in the Faith-component.
Egger (2003) states that reputation can also be a significant factor when it comes to judge whether one should trust another party. Individuals strive to have a good reputation in order to gain trust from other parties. Information obtained about another party's reputation is often ambiguous however, since it is out of the control of that party (e.g. consumer advice

websites). Also, people generally seek to confirm their theories about something or someone, instead of seeking to falsify those (Good, 1988). Therefore, reputation can be an important force in the trust mechanism: it makes the attention of people more selective, making them select those pieces of evidence that support their preliminary ideas about a relationship.

Trust in HCI and machines

Concerning trust in machines, three phases of trust/confidence can be considered:

1. Learning: system becomes more predictable for the user, due to an increasing experience of the user with the system.
2. Trust building: the user leans more about system behavior, reliability and the risks that are involved
3. Dependability: extensive interaction experience between user and system lets the user develop a reference (or mental) model

An aspect of trust, which is beyond the scope of inter-personal relationships, is whether the user can actively manipulate the system and intervene in the process or not (Egger, 2003).
If it is possible for a user to intervene in the process when the outcome of the machine is unfavorable, it will affect the trust a user has in that specific system. It is possible that that user is willing to take more risk, if errors can possibly be corrected.
Trust in machines can be split into two sub-categories: a social factor and a technology factor. The social factor is based on external information resources. E.g. the way other people judge the system or the way they react to the system can be used as a basis for building a certain amount of trust in the system. The technology factor is described by the objective knowledge of successes of the system. This objective knowledge describes the system reliability in terms of accuracy and effectiveness under specific conditions. This factor can ideally be calculated from the system description.
Fogg et al. (2002) describe in their work on the credibility of websites a similarity between trust and credibility, but they argue that they are not identical constructs. They argue that trustworthiness and expertise result in a certain credibility. This credibility can be divided in the following categories:

1. Presumed Credibility, based on general assumptions we hold about what certain [sites] should look like and contain in terms of information
2. Reputed Credibility, based on a third party reference
3. Surface Credibility, based on what can be found on simple inspection
4. Experienced Credibility, based on past experience with the site or company

Trust in products and technology

The concepts on trust mentioned above are all based on interpersonal interaction or human-website relationships. No literature could be found in the domain of human-product interaction. Therefore, in this chapter an attempt will be made to describe those aspects which are introduced when discussing human-product relationships.
The aesthetic quality of a product might have influence on the mood or emotions of a user (Botton 2006). Also, the interactions a user has with a product can be described in terms of aesthetics (Djajadiningrat et al. 2004) and can therefore influence user's ideas and emotions about the product. The effect of the aesthetic properties of products and systems on trust is very complicated and dependant on a lot of variables, such as previous personal experience and memories (Botton, 2006).
Also, the reputation of the manufacturing company might play a role in this case. In the previously described research, it was about the user and his trust in the medium (e.g. a website) provided by a company. However, when only products are involved, the interaction entity that the user has to trust is often the end product of the company. The reputation of such a company therefore will be interpreted differently by the user. The interaction entity is not a medium to communicate with a company, but the company's final deliverable.
Last, in this project's context, distributed knowledge and distributed cognition my affect users trust in a system. The bi-directional communication performance of the product/system could be important for how the user trusts the system.
An example of this is the previous system of radio-communication used by first-responders, where the users could only have one-at-a-time communication. Voice messages that were sent while the line was occupied were lost. In the dangerous situations where first-responders sometimes had to use the system, they rather relied on face-to-face communication. This took more time, but was far more effective and reliable in getting the message across. In an attempt to solve this problem, the current system (C2000) uses a store-and-forward principle: messages, if they cannot be delivered, will be stored and will be sent when target device is unoccupied.

Conclusion

The time for this small literature study was short in this project. This is a problem because there is no specific literature on human-product interaction in relation to the concepts of trust and confidence. Existing frameworks and models, which are applicable in other domains, have been described if considered relevant for the topic of this project. However, the relevance is not yet verified with fire fighters on an interview-basis. In order to generate scientifically valid data and conclusions, more research should be done in this area. It is possible that after this design project several issues around trust in products become clearer. For this project, it is most efficient to have regular discussions with users from the field to get an idea whether they would find the proposed design useful or not. Clear scenarios might help the user to understand the role of the product concerning distributed knowledge in action situations. Involving users from the target population might increase their trust in the final outcome of the design process. The exact role of the suggested human-product-trust issues is yet unknown however and in this project, theories can only be assumed to be correct or not.

This small review of literature gave some insight in issues concerning trust: why it exists, how it is built up and what it depends on. This general knowledge might help to understand process of the user accepting and using a product.

Application for fire fighting equipment

Even though there is no research in this domain, this chapter speculates on the role of trust in fire fighting equipment.
The training of fire fighters with new equipment is essential for building trust in working with the equipment. But before the real training, fire fighting experts have to be convinced that the new equipment is a useful addition to the existing equipment and that it works flawlessly.
The social factor of trust will be very important in fire fighting, since the users are generally well acquainted with each other and have to trust each other in dangerous situation. Since they trust each other, they will also respect and give high value to the opinion of colleagues. In order to make the opinions positive, first the product/system and its technology should work flawless.
The concept of intervention in operation was introduced. In a fire fighting case, this will not be applicable, since system/product failures should not emerge at all. If it does, future users will distrust the system and will not use it any more.
These speculations result in the following statements. In a fire fighting environment there are five important issues that make the design-domain different from a domain like consumer electronics:

1. Risk and stakes are much higher than in regular product design domains
2. Trust is fragile. It takes more time to build and it is easily destroyed
3. Trust can be created on a social level, only if the product/system operates flawless
4. Trust might be increased by leaving some tasks to the fireman instead of to the system

Additional sources

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C. Overview of positioning, guiding and detecting principles

Positioning

- GPS. The best known, and probably most applied method for determining the position of an object is using the Global Positioning System (GPS) satelites. A device on the earth surface, equipped with a GPS chip can obtain the exact position on the earth surface, with an accuracy of ± 1 meter. The chip measures the time it takes for a radiosignal to travel from the device to at least three different satelites (time-of-flight measurement). The satelites orbit in a fixed postion around the earth and thus by means of trilateration, using the 3 times-of-flight, the position of the chip on the earths surface can be determined. GPS is widely applied in cars, aircraft and in handheld devices. The signals transmitted by the GPS are however not strong enough for a system to be used in an indoor environment.
- Ultrasound. Ultrasound signals can also be used to determine position using trilateration. This technology is especially useful in environments where distances are small (<100m) due to the speed of sound, which is slower than those of radio signals and thus easier to measure with simple equipment. One of the main problems with ultrasound-positioning within a space are acoustic reflections of the signal, as identified by Dijk (2004). Inaccuracies are mainly due to obstacles that obstruct the signal, as well as irregular architectures of the space, making the prediction of reflections difficult. Accuracies between 1,2m (without blocking line-of-sight) and 3.2m (line-of-sight blocked) are found. Systems like MTi (xSens, Enschede, The Netherlands) can achieve much higher (few centimeters) accuracy, but only in a space of around 2m3 in volume. Another issue is that the time-of-flight of an acoustic signal is dependant on the temperature of the medium (air in most cases). This is relevant in fire-fighting situations.
- Radar technology. Within the Integrated Systems department of TNO Defense, Safety and Security, research and development is done on radar positioning systems for fire fighting. A fireman is equipped with a radar reflector. By placing two powerful radar antennae outside the building, the position of the radar reflector can be determined. This is done by comparing the angles of how the antennae are aimed, combined with the distance information that is obtained by the radar antennae. At this time, the developed antennae have just enough power to penetrate 10m into a building, only if no metal structures are present (radar signals are disturbed and blocked by metal). Estimates are that within 10 years, a penetration of 40m-60m can be obtained. The problem with metal will remain, since it is inherent to the electro-magnetic signal. Also, from a practical point of view, placing the powerful radars will demand coordination and a significant amount of time from the fire fighters.

Guiding and detecting

When focusing on tactile interfaces for navigation and orientation, literature can be found within several user domains, e.g. visually impaired, car drivers, foot soldiers and pilots. Below, a short description is provided of examples that were found.

- Tactile cane for the blind. Loomis et al. (2005) describe several studies of different tactile interfaces for visually impaired users. The interfaces vary from obstacle detection (e.g. a cane vibrating when pointed towards an obstacle) to providing navigation information by 'showing' the right direction. All interfaces are based on a cane-shaped object because visually impaired users are familiar with this form.
- Gentle Guide. Bosman et al. (2003) have studied stereo-tactile navigation. They have compared a system with one vibro-tactile wristband on each wrist of the user with a normal sign-posting way of navigating. Their system provided a vibration pulse on a wrist whenever the user should turn around a corner in that direction. The system was found to be more efficient and effective than the traditional signposting navigation. The authors also suggest (but did not test) that this system might reduce cognitive load during navigation.
- Get Me Out. Visser & Heus (2005) have investigated a waypoint-navigation method for a fire fighting context. They have designed a concept for placing waypoints within an unknown hazardous environment. They have measured the efficiency and effectiveness of the interaction concept which was designed to find the way back, using those waypoints. Their system was not significantly more efficient (faster) but it was more effective than the currently used method in fire fighting situations. Visser & Heus did however not compare their system to a procedure where e.g. a line-system or a hose is used to mark a route.
- Car seat navigation. Winsum et al., (1999) and Erp (2007) have implemented tactors in a matrix within a car seat, in order to compare a tactile road-guidance system with an audio (Martens) and visual (Erp) version of the guidance system. In both cases, the tactile system induced shorter reaction times and users indicated a lower cognitive effort. Erp (2007) also observed that multimodal system (both visual and tactile) induced even shorter reaction times than only visual or tactile stimuli, but the perceived cognitive load was higher (by user indication).
- Personal Tactile Navigator (PeTaNa). Erp et al. (2005) and Duistermaat et al. (2006) have tested a tactile belt and compared the system to GPS- and map-navigation in their studies. The PeTaNa has eight tactors each covering a 45° angle. The system proved to be more efficient than the existing methods (GPS and map). The results of these

studies also suggest that the system improves situational awareness <SYMBOL> due to a smaller cognitive load. Erp et al. (2005) also performed performance tests on the PeTaNa system in helicopters and small boats. They have suggested that the system also performs well in highly vibrating direct environments.

- Haptic Motorcycle Navigation. A tactile navigation belt was also designed by Friederichs (2005). Friederichs has translated the messages provided by a regular audio-visual navigation system to tactile stimuli, provided on a wireless tactor-belt. The language is an iconic language.
- Tactile Vest. At TNO, research on tactile perception and interaction is performed by using a tactile vest. Erp et al. (2007) give an overview of experiments to determine issues such as tactile resolution on the skin (how dense can tactile information be presented) and experiments which investigate the possibility of using tactile stimuli to improve 3D orientation. They also experiment with micro and macro gravity situations (i.e. in space and in jet fighter aircraft). In these experiments, the tactile vest and the stimuli it provides improve reaction times and improve situational awareness, concerning the position of the body or vehicle relative to its surroundings (space station or earth).
- Fire Eye. Wilson et al., (2005) have implemented a heads-up-display (HUD) in the helmet. Although this is not a tactile interface, it is interesting because it was specifically designed for fire fighting. A prototype display was made to be able to show information to firemen on the job. The display works, technically, but the authors do not discuss how the information should be displayed and how that information is to be obtained in a fire fighting situation.

Additional Sources

Loomis, J.M., Marston, J.R., Golledge, R.G., & Klatzky, R.L. (2005) "Personal Guidance System for People with Visual Impairment: A Comparison of Spatial Displays for Route Guidance" in Journal of Visual Impairment and Blindness no. 4. pp. 219-232.

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D. Overview of existing products and technologies

Several products and systems aim to prevent disorientation or to rescue in case of a disoriented team member. Other systems, like SOWNet, the radar transponder and the Looking Through the Wall-radar are more supportive and might provide a technological infrastructure for this project.

- High-pressure hose. The high pressure water hose is not designed as an orientation/navigation tool. It is however often used as such. The hose is connected to the water reservoir in the fire truck. If possible, firemen enter a structure with a hose and use it as a marker for their route and it is a protection against fire.
- Refinder. This is one of the first products brought on the market to mark the walked route; it is a so called line-system. Firemen attach a thin rope to their body using a separate belt and they walk into the building, putting the rope on the route they walk. The end of the rope can be detached from equipment and attached to the structure or an object. It is possible to attach side-lines to the main line. The method is effective, but it takes much time to prepare and to structurally deploy the line system (>4 minutes). Also, the lines might obstruct firemen when in the air, or may be hard to find when lying on the ground. A line-system such as the Refinder or Haagse Lijn would only be used if the hose is not available due to e.g. remoteness of the fire truck.
- "Haagse Lijn". (translates to English as Line from The Hague) The fire department of The Hague in the Netherlands has developed this next generation of the Refinder. This line-system is more easily attached to the equipment (with a clip) and the line itself can show direction by means of knots. Although this system is more efficient than the Refinder, it still takes much time.
- Refra clips. To mark locations within a structure, the company EME prevent & rescue international (Helmond, The Netherlands) has developed PVC clips to attach to doors. These clips will prevent the door from shutting. Also, the location of the clip on the door can tell something about the situation behind that door if a certain location-language is used as provided on the EME website. Fire fighters indicated that they find the clips not convenient, for several reasons. The clips are not strong enough, they will not fit on every door and they become completely useless in a structure without doors. (*Image D.1*)
- Exit Tracker. The company Exit Technologies (Boulder, USA) has developed a tracking system, based on avalanche rescue detection methods. In the scenario using this product, each fireman carries a tracker. Whenever a fireman goes down, he can be located by other firemen who are using their tracker in search mode. The trackers show the distance to target, but the signal also penetrates walls. In this way, it is not the route

that is marked, but the absolute compass-direction and distance. To eventually find the downed fire fighter, a strict and time consuming search methodology has to be followed (grid-wise). Firemen have confirmed the problem this product tries to solve, but the solution is considered to complex for fire fighters to follow in a stressful situation. No tests on this have been performed however. (*Image D.2*)

- SOWNet. (SOWNet Technologies, Delft, The Netherlands) A spin-off company from TNO has developed a wireless sensor network technology, or Self Organizing Wireless Network (SOWNet). In example projects (which can be found on www.sownet.nl) the company has investigated possible applications in the military domain. The technology enables small physical wireless network nodes (golf ball-size) to ad-hoc create a wireless network. Sensors can be connected to those nodes and the data can be remotely collected, from e.g. outside the structure in which the nodes are placed. (*Image D.3*)
- Radar Transponder. The Integrated Systems department of TNO has developed a transponder. This is a device that powerfully reflects radar signals. Besides reflecting the signal it can also incorporate a unique code with the reflected signal, by varying on/off times. The transponder is about 3mm x 40mm x 40mm in size and can operate on a small battery for at least three years.
- Looking Through Walls radar (LTW). The same department has also developed a radar which can identify moving objects behind a wall. The device is twice the size of a laptop computer and weighs around 6 kilograms. The radar waves are naturally obstructed by any metal structures within the wall, and the technology can therefore only selectively be applied. (*Image D.4*)

Image D.1: *Refra Clips*

Image D.2: *Exit Tracker*

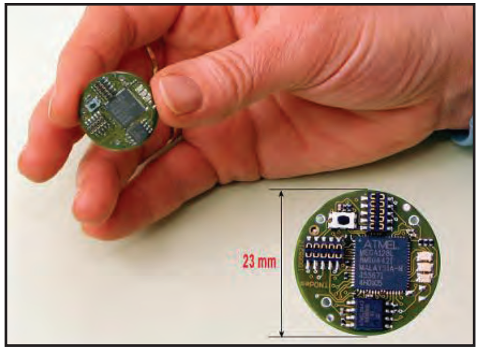

Image D.3: *SOWNet chip*

Image D.4: *Looking Through Walls radar*

E. List of generated ideas

Below, a short summary of the session results are given, per scenario step. This is the list that followed from the review at the end of the idea generation session.

Navigation principle

- **Waypoint navigation**. The fireman places or defines waypoints that form a simplified spatial description of the route that is followed.
- **Inertia tracking**. The route is tracked by sampling direction and velocity. A next point in 3D space is determined, relative to the previous recorded point.
- **Environment scanning**. By using radar technology, the direct environment of the fire fighter is scanned. By making a scan every x seconds, the system can determine the movement through the space.

Wearing

- **Bag with beacons**. Beacons are used to mark waypoints.
- **Attached to breathing apparatus**. The product is attached to the breathing apparatus in a fixed way. This means it is always there.
- **Attached externally to clothing**. It is carried as soon as the fireman puts on the suit.
- **Integrated in equipment that is already used**. E.g. flashlight, suit or oxygen-bottle.

Deploying and Activating

- **Actively activating**. By pressing a button or pulling a switch to turn the device on.
- **Always-on**. No activation needed.
- **Automatic**. When needed, the system automatically activates or deploys the system. Requires an intelligent system that detects disorientation.
- **Semi-automatic**. Used for deploying. The system automatically deploys and activates but the fireman can intervene in this system process. There is choice between aware and unaware deployment.
- **Proximity (de-)activation**. The system is 'always on' if the fireman is not close or very close, depending on the way the full system works. Distance to beacons is the activation parameter.

Searching movements

- **Waving**. Scanning the environment with the arm or hand as input for the system.
- **Walking**. Move the whole body into a direction (system relying on proximity).
- **Turning**. Measuring absolute direction (relative to earth's magnetic poles.
- **Moving head and looking**. Usable for systems relying on technology integrated in the helmet or breathing mask.
- **Listening** (moving head). Usable for e.g. directional or stereo sound.
- **Searchlight**. Form of waving the hand. Using the hand for both input and output by the device that is held in the hand.
- **Pointing**. Static way of scanning the direct environment by probing directions.

Display

- **Tactile on searching device**. E.g. a flashlight that detects waypoints and provides directional feedback by vibrating.
- **Tactile integrated in clothing**. Tactors in e.g. cuffs or belt of the jacket.
- **Heads Up Display**. A visual display by projection on the visor of the breathing apparatus.
- **Display on palm computer**. Adds an extra device to the equipment for e.g. displaying maps or positions of team members.
- **Stereo-sound made by beacons**. Beacons each producing an individual tone when activated. A sequence of sounds runs from inside (high tone) to the exit (low tone). By stereo sound, the fire fighter can determine where to go and what the direction of the exit is.
- **Sound of nearest beacon**. Based on proximity, only the nearest beacon produces a sound. From this, the fireman can determine the direction in which to walk.

F. Description of envisioned technologies

Cartridge foam extinguisher	This extinguisher supposedly was under extremely high pressure and therefore, firemen could take more with them without increasing volume. Also, the extinguisher could be recharged by inserting new foam-cartridges. This technology is non-existent. (*Image F.1*)
Extinguishing grenade	The firemen were told that the grenade, as shown in figure x.x, is a grenade that can be thrown in a room with a fire. The grenade would disperse the oxygen and thus extinguish the fire without liquids. This technology is non-existent. (*Image F.2*)
Get Me Out	This technology referred to the experiment done by Visser & Heus (2003) on tactile navigation for fire fighting. The performance test is done, but the technology is not commercial and was tested in a Wizard-of-Oz setup.
Looking Through the Wall radar	It was told to the firemen that this radar could identify signs of life behind a wall within 10 seconds. The technology can actually do that, but it needs a time of >60s, which is currently too slow to be effective.
PeTaNa	The firemen were told that this tactor-belt was used by US soldiers in Iraq in urban combat situations for waypoint navigation. The system could technically do that, but it is in prototype status at this point.
Transponder	This technology was explained without exaggerations or imaginations.

Image F.1: *Cartridge foam extinguisher*

Image F.2: *Extinguishing grenade*

G. Schemes of electronics for prototype

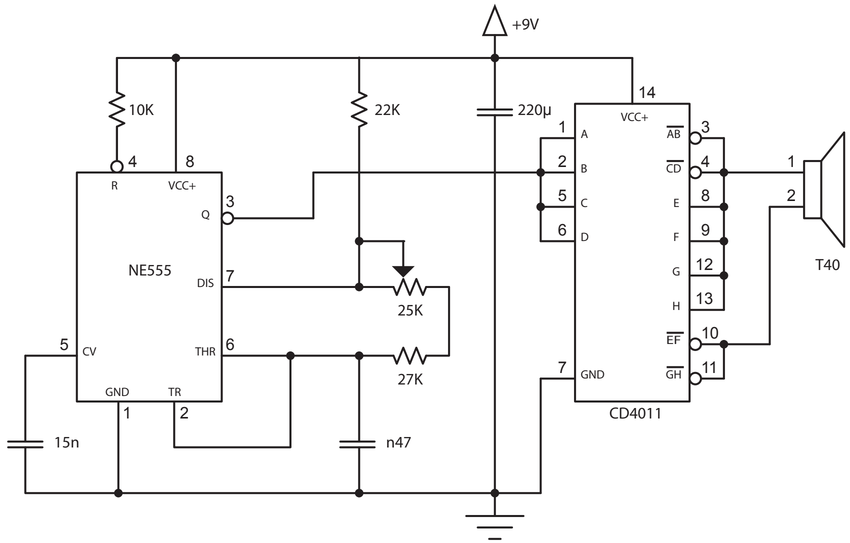

Image G.1: *Ultrasound transmitter. This autonomous transmitter circuit is driven by the oscillator (NE555). The generated block signal is sent to the NAND-gate (CD4011). This gate is organized in a pull-pull setup, which enables a voltage difference of 18V, by changing from -9V to +9V and vice versa. This maximizes the output of the ultrasonic transmitter (T40).*
Note: *The variable resistor (25kΩ) is used to tune the oscillation freqency exactly to the resonance freqency of the transmitter (39kHz > f > 41kHz)*

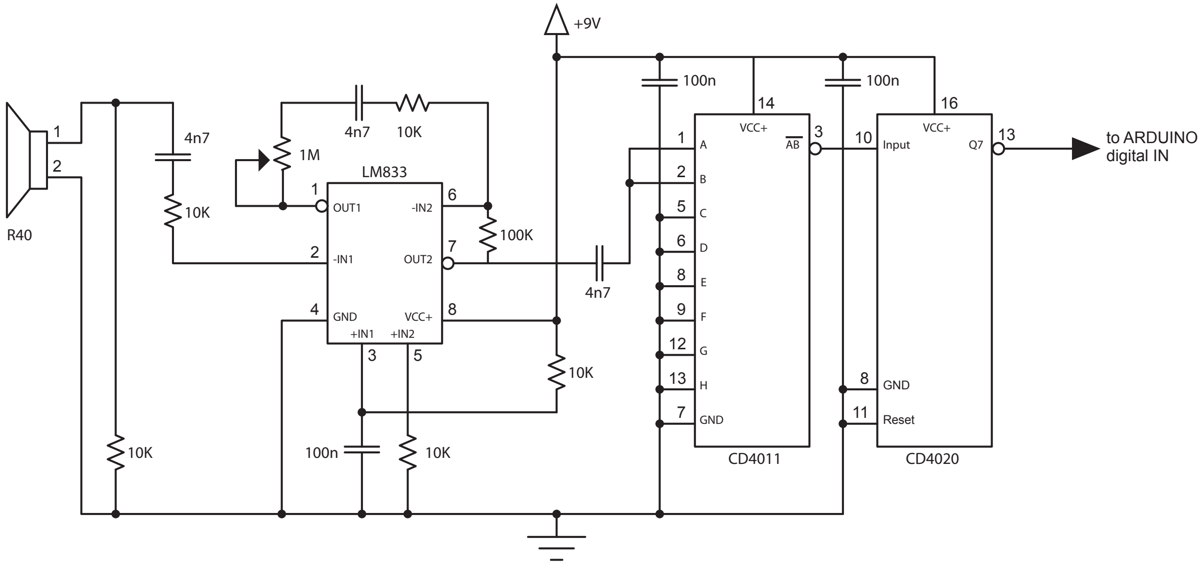

Image G.2: Ultrasound receiver. The incoming signal on the ultrasound receiver (R40) is amplified by the comparator. The amplification factor can be varied by tweaking the variable resistor (1MΩ). The output is sent to the counter (CD4020), which is used to reduce the frequency of the signal. This frequency reduction (factor 256) enables the Arduino microcontroller to read it.
***Note:** The NAND-gate (CD4011) is not necessary in this setup. It is there to stabilize a previous analog amplifier. It is rudimentary. In a next version, this component could be removed.*

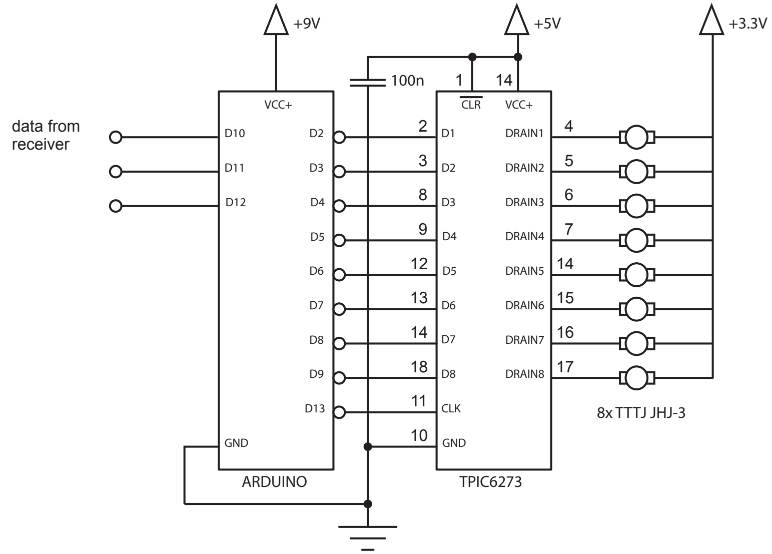

Image G.3: Tactor-belt driver. The Arduino microcontroller can set the driver inputs (D1-D8 on TPIC6273) to high. Whenever CLK changes from low to high, the corresponding drains are switched to ground, thus turning the corresponding tactors (TTJ JHJ-3) on or off.
***Note:** Three different power supplies are needed in this setup.*

H. Software

The software code described below contains the algorithm for interpreting the data that is provided by the ultrasound receivers (*Image G.2 and G.3*). At this point, the activation of the tactor belt is not yet included.

```
//*********************************************************************************
//  Variable definition
//*********************************************************************************

int ledPin = 13;                              // select the pin for the LED
int optimalCount = 51;                         // optimal loop count
int i=0;                                      // index for for.. loops
int val = 0;                                  // var to store the data from input pin
int pinIn[3] = { 10, 11, 12};                 // array of input pin nr’s
int pinOut[8] = { 2, 3, 4, 5, 6, 7, 8, 9, 13};// array of output pin nr’s
int LastState[3] = {0, 0, 0};                 // array of previous pin state from
last sample period
int EnableCount[3] = {0, 0, 0};        // array of Enable values for actiev high time
int EnableCountLow[3] = {0, 0, 0};     // array of Enable values for active low time
int ActiveTactors[2] = {0, 0, 13};      // array for active tactors + clk to driver.
unsigned long count[3] = {0, 0, 0};           // array of active high time per pin
unsigned long countlow[3] = {0, 0, 0};        // array of active low time per pin
unsigned long duration[3] = {0, 0, 0};        // array of duration per pin
unsigned long duration_period[3] = {0, 0, 0}; // array of duration_period per pin

//*********************************************************************************
//  Setup routine of device

//*********************************************************************************

void setup() {
  for (i = 0; i < 3; i++) {
    pinMode(pinIn[i], INPUT);                 // declare pin nr’s as input
  }
  for (i = 0; i < 8; i++) {
    pinMode(pinOut[i], OUTPUT);               // declare pin nr’s as output
  }
  Serial.begin(9600);                         // connect to the serial port
}

//*********************************************************************************
//  Count method of input pins
//*********************************************************************************

void Read_and_count_Pin (int pin_nr){
  val = digitalRead(pinIn[pin_nr]);
          // read the input pin

  if (!EnableCount[pin_nr]) EnableCountLow[pin_nr] = 0;
          // If not allowed to count, dont count low time as well
```

```
  if (val == 0) {
         // when value is low you may start counting on rising edge of signal

    EnableCount[pin_nr] = 1;
         // to ensure starting of count on upgoing signal after serial transmission

    if (LastState[pin_nr] == 1) duration[pin_nr] = count[pin_nr];
         // Falling edge of signal detection, write counted value in variable

    count[pin_nr] = 0;                      // reset counter
  }

  if (val == 1 && EnableCount[pin_nr] && EnableCountLow[pin_nr]){
         // when both Enablecount and Enablecount low are active and val == 1, you
            are sure a full period has been counted

    if (LastState[pin_nr] == 0) duration_period[pin_nr] = duration[pin_nr] +
countlow[pin_nr];
         // on rising edge write counted value into variable

    countlow[pin_nr] = 0;
         // reset count_low counter
  }

  if (duration[pin_nr] == 0 || duration_period[pin_nr] == 0) duration_period[pin_nr]
= 0;      // to prevent signal loss erroneous values

  if (countlow[pin_nr] > 1600  || count[pin_nr] > 1600) duration[pin_nr] = 0;
// time-out mechanism, change values if necessary

  if (val == 1 && EnableCount[pin_nr]) {
         // Count time signal is high

    count[pin_nr]++;
         // increase count on highvalue of pin

    if (LastState[pin_nr] == 0) count[pin_nr] = 0;
         // reset duration on signal change from 0 to 1

    EnableCountLow[pin_nr] = 1;
         // After high time measurment, count low time as well

  }

  if (val == 0 && EnableCountLow[pin_nr]) {
         // Count time signal is low

    countlow[pin_nr]++;
         // increase count on highvalue of pin

    if (LastState[pin_nr] == 1) countlow[pin_nr] = 0;
         // reset duration on signal change from 1 to 0
```

```
  }

  LastState[pin_nr] = val;
          // remember last pin status
}

//*************************************************************************************
//  Ultrasonic detection algorithm (declare over here)
//*************************************************************************************

void Ultrasonic_direction_finder (int pin_nr) {
    // To be created
    // Returns optimalDirection
}

//*************************************************************************************
//  Tactor activation algorithm (declare over here)
//*************************************************************************************

void ActivateTactors() {
    // To be created
    // Use optimalDirection to define which tactors are to be active
}

//*************************************************************************************
//  Main program
//*************************************************************************************

void loop () {

for (int counter = 0; counter < 10000; counter++) {         // for loop enables
// approx every second a serial transmission

for (i = 0; i < 3 ; i++) {
  Read_and_count_Pin(i);                            // Do actual counting of input pins
  Ultrasonic_direction_finder(i);                  // Save tactor with optimal signal
}

  ActivateTactors ()                               // ON tactors with optimal signal

delayMicroseconds(50);                           // pauses for 50 microseconds
}

//During serial transmission pins are not updated, LastState needs to be reset before
//new duration measurement

digitalWrite(ledPin, 1);          // blink during serial transmission

for (i = 0; i < 3 ; i++) {        // print all values of all inputs to RS232 port
  Serial.print("duration");
  Serial.print(i);
  Serial.print("\t");
  Serial.print(duration[i]);
  Serial.print("\t duration_period");
  Serial.print(i);
  Serial.print("\t");
  Serial.print(duration_period[i]);
  Serial.print("\t");
}

  Serial.println();
digitalWrite(ledPin, 0);         // blink during serial transmission


for (i = 0; i < 3 ; i++) {

  EnableCount[i] = !digitalRead(pinIn[i]); // If input = 0, counting is enabled, else
                                           // wait for signal to become zero.

}
} // end
```