"Personal Radar": A Self-governed Support System to Enhance Environmental Perception

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“Personal Radar”: A Self-governed Support System to Enhance Environmental Perception

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In this work we propose a wearable solution for boundary detection (using ultrasonic range finders) and notification (via tactile actuators) under conditions of poor visibility. “*Personal Radar*” is not ’yet another’ belt-like tactile feedback system used for walking navigation, the unique feature of our obstacle scanning and notification solution is, that it is self-contained and fully self-governed. User studies have confirmed that using “*Personal Radar*” can increase safety in close proximity to unseen obstacles by reducing the movement speed in that region. To compensate for this speed reduction, studies demonstrated a speed up in walking pace in regions distant to obstacles as compared to subjects moving sightlessly and without technology assistance. Finally, evaluation revealed that learning increases utilization performance of the system significantly.

Ultrasonic sensing, Tactile feedback, Boundary detection, Collision avoidance, Wearable route guidance, Spatial perception.

1. WEARABLE ROUTE GUIDANCE SUPPORT

The “*Personal Radar*” sensing system proposed in this work aims at supporting indoor (and outdoor) movements under conditions of poor visibility. Such a situation might arise from environmental issues caused by emergencies (such as smoke or power outage) or being caused by bad visual faculty (visual impairments, blindness). The approach is, in general, not new – quite a few solutions have been presented to assist walking under poor visibility conditions or for the blind. However, common to the existing approaches is that they are working very well in certain, restricted situations or environments, but are lacking major drawbacks on universal use (e. g., GPS is not working indoor, WiFi based approaches are only poor or not at all usable outdoors, infrared technique is susceptible to sunlight, laser technology consumes lots of energy, etc.). While the group of blind or visually impaired people (such as persons with amblyopia[1]) have been using supporting systems such as a walking cane, guide dog or technical devices for environmental scanning (e. g., the *Sonic Guide* (Goldstein & Wiener 1981)) for a long time, solutions to assist sighted persons in situations of limited vision (e. g., fire fighters equipped with a breathing protection system rescuing people from a burning house) are rather rare.

[1] amblyopia (WHO ICD-10, H53.0, `apps.who.int/classifications/icd10/`) is a brain based vision deficiency in the otherwise physically normal eye(ball); according to Webber & Wood (2005), 1-5% of the population are affected by this disorder.

1.1. History in environmental scanning

The aim of this work is not to develop yet another assistive technology for the blind, however, the sensing part (i. e., obstacle/target detection) in scenarios of poor visibility is not different from systems helping people with impairments and thus, can be learned and adapted from the numerous solutions on the market. Hersh (2008), Moore (1995), Benjamin (1974), Bolgiano & Meeks (1967) and diverse Internet sources provide an overview and a description of commercial mobility aids for the blind. All the subsequently mentioned systems are designed as hand held (partly integrated in the walking cane) or wrist worn devices and offer similar functionality. They sense the path ahead in the range of about $0.8m$ to $4.0m$ using ultrasonic technology (*Polaron*, *Pathsounder*, *Mowat Sensor* (The Blind Association 2012), (AbleData 2007), *Haptic Torch* room scanner (Spiers & Harwin 2004)), laser beams (*Lasercane* (AbleData 2007)), or infrared sensors (*Haptic Radar* (Wolfe, Kluender, Levi, Bartoshuk, Herz, Klatzky, Lederman & Merfeld 2008)). The before mentioned *Sonic Guide*, one of the first commercially available electronic mobility aid (Pugh 1971), is also based on ultrasonic sensors. Different to the proposed system, all these ’basic’ devices uses only a single or very few sensors to probe

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upcoming paths. Recently, systems with extended and more complex sensor technology have been emerging. Sethu, Kamath & Sudhin (2008), for example, proposed a obstacle warning system for the blind equipped with range finders mounted on different heights, Bousbia-Salah & Fezari (2006) proposed a assistive technology using a combination of ultrasonic sensor and accelerometer for obstacle detection while on the move, and the *Sonic Pathfinder* (an extension of *Sonic Guide*) is worn as a headband and integrates filtering mechanisms to scale the detection range and provide more reliable data (Cassinelli, Reynolds & Ishikawa 2006). Systems based on multiple ultrasonic sensors have had a long tradition for environmental perception in the robotics domain. Parameters such as the optimum fragmentation of space into different distance regions, quantity and placement of sensors, update intervals, acceptable movement speed, troubleshooting (e. g., on reflexions) can be learned from related works in this discipline, e. g., (Kim, Seo, Jang & Sim 2007) or (Liu, Zhu, Jin, Feng & Gong 2004). One example taking this line is the *NavBelt* obstacle avoidance system (Shoval, Borenstein & Koren 1998). Originally developed for mobile robots, the underlying technology was adapted by *NavBelt* (eight ultrasonic sensors on a waistband) and used for environmental scanning on human persons.

1.2. Notifications about distance/orientation

Information about the distance and orientation to targets/obstacles or boundaries ahead is most commonly provided using the visual and/or auditory channels. However, and in particular for the fire fighter application scenario, visual feedback is not at all applicable because of smoke-filled rooms or darkness due to power loss. For that reason, numerous solutions targeting the audible sense, for example the *NavBelt* (Shoval et al. 1998) which relays the processed information to a user via stereophonic headphones (binaural feedback) or the system proposed by Bousbia-Salah & Fezari (2006) which uses synthetic speech output for notification of close-by obstacles, have been presented. However, a binaural display is, as for instance shown by Shoval et al. (1998), also not very well suited for presenting directional distance information and in addition takes quite long to learn and correctly interpret the signals. On the other side, Wilson, Walker, Lindsay, Cambias & Dellaert (2007) showed that a audio-only navigation system can work for pedestrian navigation by using a process of non-speech sonification. But even if navigation would be possible, such a system might not be usable in the outlined emergency situation for several reasons. The action forces have to continuously communicate with each other using a headset/intercom and the team leader heading a group of action forces has to communicate with several policy makers via the audio channel, needs to update with the control center, and examine environmental noise. In contrast, there is evidence that only a few overlayed audio sources can be distinguished from each other and that auditory/verbal feedback has a very limited bandwidth (Wolfe et al. 2008).

1.2.1. Vibrotactile distance information

Haptics has been shown to complement vision and hearing, offering the potential to deliver additional information in a effective way (Franz 2010). Vibrotactile feedback has been previously used in information systems operating hands-, ears- and eyes-free, but often only in a binary manner, e. g, to gain a user's attention. Referring back to para. 1.1, user feedback in most of the listed devices is provided with vibrations using a single actuator (placed on the cane and stimulating the index finger) or a motorized disc with a raised bump (as in Spiers & Harwin (2004)), and potentially facilitated by audio signals. In such a configuration, obstacle detection is basically only supported in a straight line (no lateral information) and distance estimation is also not possible or only in a very limited way. But even these simple devices/settings demonstrated high confidence of users in non-contact navigation. For more complex feedback systems distinguishing multiple levels of distance and orientation, several systems have demonstrated the suitability of tactile messaging, mostly with actuators integrated into a belt. Tsukada & Yasumrua (2004), for example, presented a navigation belt using vibrotactile stimuli for directional guidance. Distance was represented as pulse-pause time variation and orientation by activating one out of four tactors. Evaluation confirmed that environmental perception using tactile signals was better in the stationary case as compared to its application while on the move. Furthermore, they found out that tactile pulses shorter than $500ms$ were hard to detect in the dynamic setting while it did not caused problems in the static case. In (Riener, Straub & Ferscha 2009), the authors experimented with different tactile distance information encoding schemes on a waist belt with 8 actuators and with both intensity and frequency variation. Examination with regard to stimulation intensity showed that vibrations below a certain intensity level were hard to correctly assign, even if strong enough to be clearly perceived by the subjects. In addition, the evaluation in a route guidance scenario revealed that distance encoding into vibrotactile messages did not improve the time required to reach a way point. Erp (2007) experimented with tactile displays to provide navigational information as well. In one specific setting the author evaluated the performance of distance information encoding via vibrotactile feedback and did also found no significance in walking speed variation for different encoding schemes. Asif, Heuten & Boll (2010) explored the distance information encoding theme in a vehicular setting using a belt interface to provide effective route navigation information. Their results showed that a tactile spatial display helps drivers to successfully navigate in an urban environment. Further studies on distance/direction encoding for a turn-by-turn car navigation system were conducted by Boll, Asif & Heuten (2011), who demonstrated that the cognitive load of the tactile navigation system is not higher than with a classical car navigation system. Elliott, van Erp, Redden & Duistermaat (2010) used a tactile display consisting of eight vibrating elements mounted on a waistband for GPS based route guidance in an outdoor environment. They concluded that tactile navigation displays can outperform visual displays, at least under conditions of high cognitive and visual workload. Applications beyond the abdomen and hip area were shown by Sethu et al. (2008) or Yoon, Jeong & Yu (2009). The former provided vibrotactile feedback with high operation accuracy at the kneecap and the hand, (Yoon et al. 2009) displayed information about obstacles on the subject's palm using a 3 by 3 array of tactile actuators.

1.3. Implications and own contribution

Directional distance information transmitted to a subject via vibrotactile signals was until now most likely used for navigational tasks and often in combination with GPS positioning, e. g., to inform a person about the distance to the next way point or point of interest. What has –to the best of our knowledge– not been investigated so far is the potential of added tactile information on the '*safety*' of walking in hazardous areas and the achievable performance improvement in following a path or crossing a room as compared to feeling the way sightlessly. The attribute '*safety*' and its linkage to tactile notifications in the course of this work is understood as to influence the walking speed of subjects to move faster in safe areas and to throttle pace in danger zones. To optimize the parameter settings for the prototype described later, findings such as type, number, and placement of sensors, stimulation intensity/frequency/patterns, delays in signal processing and human perception, etc. that have been learned from the related work review were thoroughly considered while developing and optimizing the "*Personal Radar*" sensing system.

1.3.1. Tactile guidance

To assess the potential tactile add-on holds, we have developed a self-contained personal sensing system for boundary detection and collision avoidance built-up from and unifying the following main components:

1. **Ultrasonic sensors** mounted on a flexible belt and allowing for obstacle detection in a range of about 3 meters and at an angle of beam of 180 degrees in front of a person ("obstacles" of interest for this work are walls, objects, and persons in the range of view of at least one of the ultrasonic sensors),
2. **Tactile actuators** ("vibration elements") integrated into a waist belt and notifying the bearer with directional feedback about close-by obstacles/targets or boundaries in the walking direction, and
3. **Microcontroller board and software framework** to (a) manage the cycle time of the sensor array, (b) preprocess sensor readings, (c) condition data from the sensors, (d) compose tactile patterns, and (e) drive tactile actuators in order to provide sensible feedback to the user.

1.3.2. Research hypothesis

We propose a self-governed, wearable obstacle detection and collision avoidance system based on ultrasonic range sensors and vibrotactile feedback. The device is designed to detect and inform about obstacles in the vicinity and should help people with temporary loss of vision such as firefighters in a smoke-filled environment to avoid moving toward obstacles or boundaries, thus to safely pass by. We explicitly distinguish this work from assistance system for individuals who have suffered physical vision loss. To assess its potential, this paper covers the following research question.

(H.i) The vibrotactile *radar* **affects walking speed** as the bearer is coming closer to the obstacle.

(a) To enhance safety in close distance to boundaries/obstacles, sightless subjects equipped with the "*Personal Radar*" system reduce their walking speed as compared to movements without (tactile) assistance.

(b) The overall walking speed with "*Personal Radar*" is not slower as to movements without system (this means that –for compensational reason– walking at distance is accelerated).

(c) Learning improves the walking performance of subjects using "*Personal Radar*".

1.4. Outline

The rest of the paper is structured as follows. Section 2 gives detailed insight into system design, subdivided into ultrasonic sensing system, data processing unit and system logic, and the vibrotactile feedback component. Section 3 is all about the user study, describing the aim of the experiment and the system configuration, and furthermore reports about experiment execution. After data conditioning and evaluation, Section 4 discusses the results obtained and relates it to the raised hypothesis. Section 5 finally concludes the paper and outlines possible future work.

Figure 1: *Microcontroller with diverse switches, light indicators and connectors for sensors, actuators (exterior view: left image; housing opened: second left image); ultrasonic sensor belt with five ultrasonic range finders and 180 degree angle of beam (detail: center image; entire sensing system: second right image); vibrotactile waist belt with 8 tactors equally distributed along the whole length (belt opened: right image).*

2. SYSTEM DESIGN

The proposed system consists of a sensing subsystem (worn above the work clothing) and a tactile feedback component (worn under the clothing), both implemented as independent waist belts. Each subsystem comes with its own control unit, the former responsible for sensor signal processing and tactile signal encoding, the second for electrical actuation to actually control the tactors. The battery powered system operates fully autonomously without any environmental information stored in maps or external position tracking technology involved, and thus, can operate self-governed even in unknown territory. The sensing part of the prototype weighs in total 450g (including wiring and control unit), the actuator unit just above 500g. The heaviest part of the system is currently the battery pack (4Ah@6V; 750g). In the end, the two belts should be integrated into the waistband of the work clothing of a fire fighter and a more powerful yet compact battery should bring the weight of the system down to about 1kg.

2.1. Environmental sensing

For obstacle or boundary detection in the vicinity of users, five ultrasonic range finders are positioned at a waist belt carried by the user and facing forward. Each of the sensors features an operation range of about 3.5m and an angle of beam of 40 degrees, the whole system reaches (with some overlap) around 180 degrees beam width. To ensure exact placement and orientation of the sensing subsystem for test subjects with different waist circumference, the sensors are mounted on a slidable mounting frame fixed at the belt (Figure 1). (Not only the sensors are slidable on the mounting frame, the frame itself can also be adjusted around the belt.) The mounting frame is made out of plastic material sheets connected with 145° steel angles with rivet joints. With regard to the spatial resolution the sensory array can detect objects such as persons, tables, chairs, corners, pipes, etc. According to our tests, objects in size of a beverage can are detectable over the full operation range but problematic is the detection of soft materials such as curtains. Based on the current setting (sensor at waist level) and the used type of sensors, steps on the ground can only be detected at distances $\approx 1.2m$ or further away and the same applies for objects hanging down from the ceiling. However, the (later) inclusion of a vertical array of sensors might be one innovation that would benefit fire fighters. The ultrasonic sensors are directly connected to the main controlling unit (MCU), responsible for both controlling the transmitters and gathering measurements from the receivers. Due to mutual interference of sender/receiver pairs (caused by overlapping in the angle of beam), each of the five units in the array may only be activated at a time, i. e., sensors have to switched on one after the next. To make measurements more stable against ultrasonic reflections, additionally a minimum pulse-pause time of 200μs is maintained between consecutive readings. We have experimentally determined this value in preliminary studies. Ultrasonic based sensor systems use time-to-flight measurements for estimating distance to an object – a single measurement takes up to 50ms. This parameter setting results finally in an update rate of the entire system of about 4Hz.

2.2. Vibrotactile user feedback

The vibrotactile feedback unit is assembled from eight high precision tactile actuators mounted on a belt which are driven by the tactor control unit (TCU)[2]. The actuators have a outer diameter of 30mm, a height of 7.8mm and a 7.5mm skin contactor with a maximal axial displacement of about 1mm. For exact positioning tactors are fixed on the belt with velcro patches. The tactor control unit is connected through a wired serial RS232 connection to the main controlling unit of the "*Personal Radar*" sensing system. According to Riener et al. (2009), a low time lag of the tactile feedback system can be maintained by reducing the communication effort with the tactor controller to a minimum, for example by using just a simple command (binary bit mask) for switching all the tactors on/off simultaneously. For data communication reasons the distance encoding strategy applied is not based on a variation of vibration strength (*intensity*), as for instance

[2]Engineering Acoustics, Inc., `http://www.atactech.com/PR_controllers.html`, retrieved June 25, 2012.

proposed by Riener & Ferscha (2008), but rather implemented as a distance dependent variation of activation frequency with a carrier frequency of 250Hz (documented for example by Wolfe et al. (2008) to gain very high perceptibility on the human skin) (Figure 2).

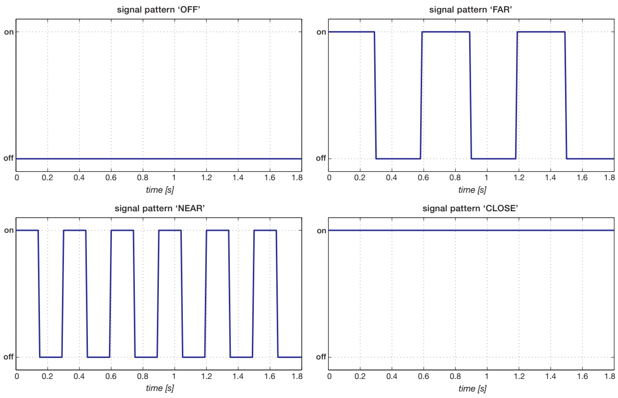

***Figure 2:** Signals used to drive the tactile actuators.*

The following mapping strategy was used for all the experiments conducted and described in this work (see also Table 1).

- **OFF** (*no tactile output*): Indicates that the user is distant to obstacles or boundaries. In the configuration evaluated within this work, 'distant' obstacles are greater than 2.0m away from any of the sensors.
- **FAR** (*slow pulsing*): This signal has sort of 'informative character' and should not yet influence the movement behavior of the user (i. e., indicating that an obstacle will be reached in some time).
- **NEAR** (*fast pulsing*): Fast pulsing should be interpreted as first stage of warning expressing that an obstacle will be reached in "short time" of walking. With this signal we want a subject to reduce his/her walking speed in order to warn the user not to move towards the detected obstacle/boundary.
- **CLOSE** (*continuous vibrotactile signal*): This strong and steady vibrotactile signal should be clearly noticed by any person, indicating imminent danger in the direction of walking. With the 'CLOSE' pattern we want to achieve that the user immediately stops to walk once observed and correctly interpreted the signal.

To get some idea of the speed that people typically move at in the conditions where the system will be used, prospective system dynamics was evaluated in preliminary studies. In designing the experiment we started with an upper limit of 1.3m/s, which has been determined by Murray, Drought & Kory (1964) as the average human walking speed under normal condition. However, as our subjects were blind(folded), we had to expect much lower movement speeds. In a pilot study we detected the average walking speed at about 0.8m/s in 'OFF' regions, further reduced to less than 0.4m/s when coming close to obstacles/boundaries. These results, which are supported by the work of Shoval et al. (1998), were used to define the final setting as shown in Figure 4. Maximum distance to walk is 6m which translates into ≈6$m \cdot$ 0.5m/s = 12 seconds of walking. The part interesting for the evaluation are the last 2 meters, which will be in accordance to a walking speed of ≈0.5m/s crossed in 4 seconds, resulting in about 4$s \cdot$ 4Hz = 16 data sets per trial.

Pattern	Linear mapping	Exponential mapping
OFF	$>$200cm	$>$200cm
FAR	130cm - 200cm	100cm - 200cm
NEAR	60cm - 130cm	60cm - 100cm
CLOSE	$<$60cm	$<$60cm

***Table 1:** Mapping of distance regions to vibrotactile signals for both the linear and exponential configurations.*

2.3. Main controlling unit

The core component of the main controlling unit (MCU) is a Arduino ATmega2560 based microcontroller board (clock speed 16MHz, 256k flash memory, 54 I/O's)[3] integrated into a plastic housing mounted on the sensor belt. Each of the five ultrasonic distance sensors[4] is connected to a single I/O pin on the microcontroller to trigger the measurements and read out sensor values. To initiate tactile feedback on one or more of the tactile actuators, connectivity with the tactor control unit (TCU) was established via a serial communication protocol using a standard RS232 serial connection (D-SUB9 connector, Figure 1). The USB connection to a host computer as outlined in Figure 3 serves two purposes, first to download sensor data gathered and stored during experimentation on the EEPROM, and second, to reprogram the Arduino microcontroller.

For convenient execution of user experiments and easy status checking, a number of external jacks, knobs and buttons, a multicolor LED, and a beeper are integrated into the front face of the housing (leftmost subimage in Figure 1). All these elements are only used for evaluation purposes and should not remain in the productive MCU (except potentially LED and beeper). The switch recognizable in the upper part of the housing is used to change the distance-tactile pattern mapping strategy (from linear

[3] Arduino Mega, URL: `http://www.arduino.cc/en/Main/ArduinoBoardMega`, retrieved June 28, 2012.
[4] Parallax PING))), URL: `www.parallax.com/Store`, retrieved June 26, 2012.

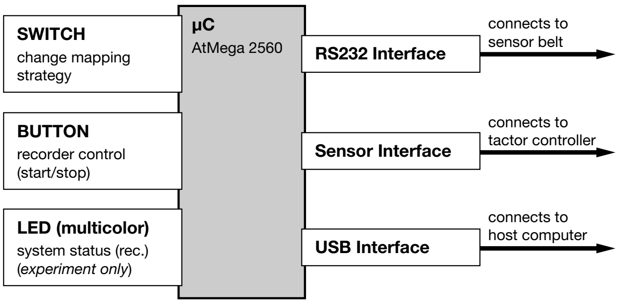

Figure 3: *The block diagram of the main controlling unit illustrates its autonomy.*

to exponential and vice versa) and the two push buttons on the right side are used for manually triggering diverse vibrotactile signals (used in the pre-experimental phase to allow subjects to get used to the different vibration signals). Another button starts/stops recording (data collection), a LED shows the current system status visually (green: system ready; changing to flashing red while collecting data), and a beeper is used for auditory delivery of status messages. The ultrasonic sensors are connected with the MCU via a pulse coded one wire interface and are consecutively triggered by the same to measure the time-of-flight of individual ultrasonic bursts. Ultrasonic sensing is performed all the time in the main loop of the software program and a smoothed value of the last three measurements is used for distance encoding and tactile signal selection. Generation of the vibrotactile feedback is driven by a timer interrupt service routine implemented on the microprocessor.

3. USER STUDIES

Most meaningful results –with regard to usability, system performance, convenience, etc.– would have been obtained by testing the "*Personal Radar*" system in a realistic emergency situation and with real action forces, e. g., fire fighters equipped with a breathing protection system. On the other side, however, operating and carrying a fire hose may well dramatically impede the operation of the equipment. To give an example, the sheer strength required to carry a hose may impair sensory detection and the physical nature of the fire fighter job may result in the disruption of the signals from the tactor belt and mean that messages are misread. For that reasons all the studies were conducted in the lab (Figure 4). Overall, n=12 voluntary male students in the age range 19-28 years with confirmed normal vision took part in the experiment. (Due to stack overflow problems on the microcontroller (μC) during data recording in the first session, four data sets had to be removed later.) It should be pointed out that not a single person was involved in any kind in the research of this study or had previous knowledge about the laboratory room (e. g., dimensional characteristics). Furthermore, all test subjects confirmed to not have used a body worn tactile assistance system before. To guarantee similar perception of tactile stimuli as much as possible, subjects were asked to take clothes such as jackets and pullovers off, and to wear only a light T-shirt during the experiment. While it is evidenced that the ability to perceive tactile stimuli varies between individuals, e. g., by Bikah, Hallbeck & Flowers (2008), sensitivity to the vibrations was not taken into consideration in our experiments. But as we only allowed males to participate in the study, the reported gender difference (Goff, Rosner, Detre & Kennard 1965) in tactile sensitivity (i. e., females are more sensitive to vibration than males) could be eliminated at least. Nevertheless, the set of equal preconditions and the usage of four very distinct feedback patterns should allow comparability of test results.

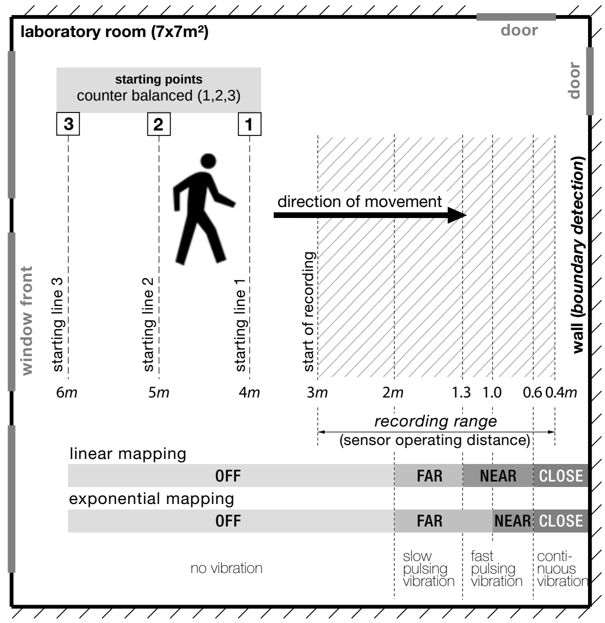

Figure 4: *Overview of the experimental setting. The lower part shows the mapping of proximity regions to corresponding vibration patterns.*

3.1. Experimental design

All the user studies were designed and carried out as "blind walking situations" towards a boundary represented by a wall of our laboratory room (Figure 4). For this purpose, subjects were blindfolded with ski goggles with an opaque foil inlay. Before starting a test run, subjects were equipped with sensor/actuator belts and were shortly briefed about the aim of the experiment and the operational principles of sensor and actuator subsystems. Furthermore, they had the chance to get in touch with the "*Personal Radar*" system and to "play around" with the same, e. g., to try out the (three) different vibrotactile patterns later assigned to the different proximity regions. After this briefing session held in the coffee kitchen adjacent to the lab, subjects were blindfolded and brought into the laboratory room. The experimenter guided the test persons to the first starting point and executed the baseline test. For all the remaining test runs, subjects were brought back to the (varying) starting points on different ways to cover up the real room characteristics. Altogether ten runs with counterbalanced starting points were used per subject. As the sensing range of the ultrasonic range finders was technically limited to a maximum of about 3.0–3.5m, additionally different learning points between 4.0m and 6.0m (1.0m displacement each) were used to minimize as much as possible the chance of participants learning the room characteristics. To ensure that test participants did not run up against the boundary (wall) they were requested to stop approximately 40cm before the obstacle. For the cases involving tactile feedback this was achieved with the 'CLOSE' vibration pattern activated 60cm before the wall; for the baseline tests executed without tactile notifications a beeper integrated in the controller board was activated at the same distance (60cm) and used for informing test subjects to stop walking once perceived. Important to mention is that in the reference tests it was not possible for subjects at any point to estimate the remaining distance to the obstacle. To check the existence of a potential learning effect the first and very last (10th) trials were conducted as a baseline without tactile assistance. To assess the behavior of the tactile assistance system at a glance, in instantiations 2 to 9 of the experiment both the mapping strategy for tactile feedback (linear, exponential) as well as the starting points (4m, 5m, 6m) were counterbalanced.

4. RESULTS

The best outcome in the comparison of the two experimental conditions (with/without enabled tactile feedback) had been a improved internal representation of the vicinity with tactile assistance, discoverable by higher walking speed distant to obstacles and reduced walking speed when close to an obstacle or a boundary (i. e., more careful movement), with overall constant (or better shorter) time to reach the target. The evaluation of the user study with respect to the research hypothesis (and its two subdivisions) revealed results as follows.

4.1. Potential to assist safe walking

The average walking speed distant to obstacles is, as given in Table 2, higher in the test runs with tactile assistance as compared to the baseline experiments (subjects walked faster by 9.76$\%$ in 'OFF' and 11.40$\%$ in 'FAR' regions). Even more interesting is (in particular from a safety related point of view) the mean walking speed in close vicinity to obstacles, which is in the given cases 0.387m/s (no feedback, baseline) and 0.278m/s (tactile assistance) respectively. Subjects obviously perceived the 'CLOSE' information in tactile feedback and reduced their walking speed by 71.8$\%$ as compared to the baseline without assistance in order to not move toward the obstacle.

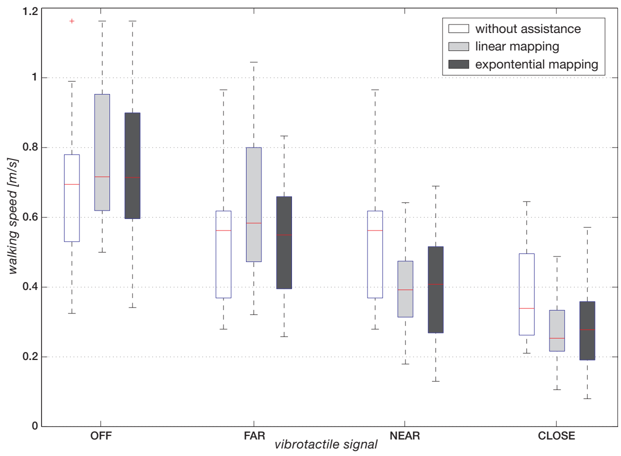

Figure 5: *Average walking speed for different settings and in different regions.*

To assess the potential of the interface with respect to the *safety* aspect, the movement behavior (i. e., walking speed) in the 'CLOSE' region was analyzed in detail for the two cases with and without (=baseline) tactile assistance (Figure 5). Sample X (n=16) corresponds to the determined walking speed in the 'CLOSE' region, sample Y (n=55) to the measured walking speed with tactile assistance in the same region. A Shapiro-Wilk test confirmed that the two samples are each drawn from a normally distributed population (w_x=0.936, p_x=0.304, w_{crit}(n=16,α=0.05)=0.887; 0.936$>$0.887; w_y=0.983, p_x=0.625, w_{crit}(n=55,α=0.05)=0.947; 0.983$>$0.947). The F-test is used to verify whether or not the mean values of the samples X, Y have the same standard deviation. According to the test results (F=1.864, p=0.098, F_{crit}(0.05, 15, 54)=1.856, 1.864$>$1.856) similar standard deviation could be confirmed.

With regard to the *safety* aspect we applied a Student's t-test with H_0 equal to "sample X has a larger mean than sample Y", i. e., higher average walking speed close to the boundary or a increased level of danger to collide. The weighted variance calculates to s^2=0.0155 and t=2.839, p=0.002966. t_{crit}(n=69, α=0.05)=1.995; from 2.839$>$1.995 it follows that H_0 can be accepted, confirming that there is significance that subjects walked in the baseline experiments faster when close to the boundary. From this result we can infer that the tactile assistance system implicitly increases safety when walking in close vicinity to a target/obstacle.

walking speed in m/s	OFF	FAR	NEAR	CLOSE
without assistance	0.693	0.526		0.387
with assistance	0.760	0.586	0.397	0.278
linear mapping	0.783	0.640	0.398	0.273
exponential mapping	0.736	0.532	0.396	0.283

***Table 2:** Walking speed of test subjects in different regions and with various feedback strategies.*

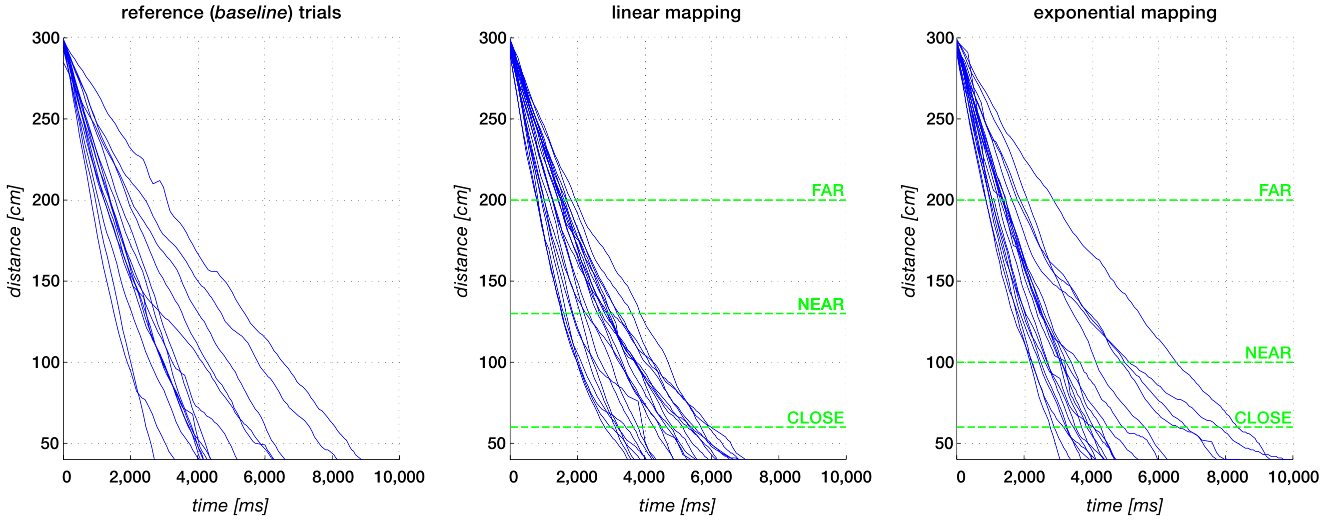

***Figure 6:** Walking trajectories for the reference (baseline) trials and the two series with tactile assistance.*

4.2. Improved overall walking performance

To prove the validity of H.*i* (b) the overall movement time of the initial reference series (i. e., first attempt of each user; sample X(n=8)) was compared to the movement time of the first series with tactile assistance (linear mapping, sample Y(n=8)), Figure 6. As normal distribution of the two series was confirmed by a Shapiro-Wilk test (w_x=0.746; p_x=0.00746; w_y=0.558; p_y=5.11e^{-5}; w_{crit}(n=8; α=0.05)=0.818), a one-sided t-test for paired samples was used for the evaluation. First, the variance heterogeneity was verified by a F-test (H_0: σ_x=σ_y; F=3.57, F_{crit}=4.284; F_{crit}>F $\Rightarrow$ H_0 can be accepted). Testing the samples X, Y against the null hypothesis "the average walking time with tactile assistance is lower or equal as compared to the baseline (without tactile assistance)", t_{xy}=-0.053; p=0.479 and relating this result to t_{crit}(n=10; α=0.975)=2.228, $|t_{xy}|>t_{critical}$ revealed significance for our initial assumption that test runs assisted by vibrotactile feedback resulted in lower (or at least equal) movement time as compared to the trials without tactile assistance.

4.3. Response to learning effects

To assess the stability of the tactile notification system against adaptation caused by learning (H.*i* (c)), the first and last test series (=the two baseline experiments) were tested against the null hypothesis H_0: $\overline{x}$=$\overline{y}$ or "the mean of the two control samples X, Y is equal, i. e., a learning effect cannot be detected" (alternative hypothesis H_1 "the mean of the two control samples is different"). Sample X (n=8) corresponds to the movement time of the initial baseline experiment, sample Y (n=8) corresponds to the walking time for the final baseline series. Before actually verifying H_0 the two samples are checked for uniform distribution using the Shapiro-Wilk test. From w_x=0.746, p_x=0.00746, w_{crit}(n=8, α=0.05)=0.818; 0.7464$\leq$0.818 it follows that sample X does not follow a normal distribution. w_y=0.909, p_x=0.3504, w_{crit}(n=8, α=0.05)=0.818; 0.9095>0.818 $\Rightarrow$ H_0 can be accepted, meaning that sample Y is normally distributed. As sample X does not come from a normally distributed population a t-test is not a valid measure, and the Wilcoxon signed-rank test is used instead of. w=min(w^+, w^-)=min(48,16)=16; w_{crit}(n=8, α=0.05)=3; w>w_{crit}?; 16>3 $\Rightarrow$ H_0 cannot be rejected at α=0.05, the alternative hypothesis H_1 ("different mean values $\overline{x}$, $\overline{y}$ or learning effect between the two baseline series") is significant.

5. DISCUSSION

By comparing the experimental results it can be observed that the walking speed in close vicinity to a boundary is actually lower in case of tactile assistance as compared to the baseline tests without feedback (Table 2). This supports our initial hypothesis that tactile feedback can help to increase safety when walking under poor visibility condition (demonstrated with blindfolded subjects) by reducing the probability of collisions (**H.i (a)**). Additionally, this can be considered as proof that subjects trusted the information they received from the "*Personal Radar*" assistance system. On the other side, however, it was expected that users of the tactile feedback system are moving with increased walking speed when distant to obstacles to compensate for the reduced speed when close to an obstacle (**H.i (b)**). Also this expectation (a summary of results is given in Table 2) could be proven with statistical analysis. For the long term, evaluation results satisfactorily showed that learning will increase utilization performance of the "*Personal Radar*" system significantly (**H.i (c)**).

In the final interview carried out right after the experiment, most of the test subjects confirmed the easy understandable mapping of the distance encoding scheme. Some of them explicitly mentioned the clearly perceivable tactile signal for the 'CLOSE' region. Furthermore, the following observations were made during the experiment or reported by the subjects.

1. Hands in the sensor field: Some of the data sets had to be refused as the hands of subjects partly covered the lateral ultrasonic range sensors, which invalidated gathered data from these sensors. This could be a true problem in a real application, for example with fire fighters carrying a fire hose or other equipment, however, was not a problem in the current study as feedback generation was primarily based on the data from the front-facing sensors.

2. Tactile distance encoding: Two subjects mentioned independently that they were not at all able to detect the tactile signal for 'NEAR' (in the exponential mapping). This probably could be explained by the fact that vibrational pulses shorter than 500ms are hard to perceive while in motion (Tsukada & Yasumrua 2004) (the pulse time used was actually only 300ms) and as the 'NEAR' pattern was only active in 40cm (between 100 and 60cm) which is less than one step for most of the persons.

6. CONCLUSIONS AND FURTHER WORK

In this work, we have proposed and tested the "*Personal Radar*" system, a fully autonomous operating tactile assistance system built-up from ultrasonic range sensors, tactile actuators, and a microcontroller to gather environmental data and trigger the tactors. The interface is aimed to improve spatial perception under poor visibility conditions for people with normal vision. User experiments (conducted with blindfolded subjects to reproduce a situation of visual blindness) confirmed that using such a system can increase safety in close proximity to obstacles by reducing the movement speed in comparison to walking under poor visibility condition without assistance. Experimental results brought up that subjects equipped with the "*Personal Radar*" system and moving in regions distant to boundaries walked faster as compared to blindfolded persons without feedback in the same area. To conclude, the determined average walking speed is similar for both settings (with and without tactile assistance), but is shifted from 'CLOSE' to 'FAR' regions when using the "*Personal Radar*" system, which is said to increase personal safety in close vicinity to obstacles.

In the meantime the experiment was repeated, testing the multi-directional capabilities of the system while walking blindfolded in a unknown maze (Figure 7). The evaluation results of this test will be published elsewhere. Next steps include the embedding of the

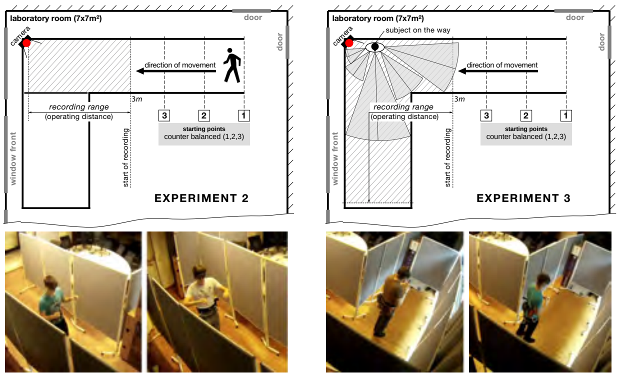

***Figure 7:** Overview of experimental series 2 (left) and 3 (right). The specific setting (distances, length) was assembled with chained paperboards.*

individual belt systems into a solution integrated into the clothes and with sensing/feedback parameters adjusted based on the previous gross findings. The system should be evaluated in the field (e. g., test course with fire fighters equipped with a breathing protection system and artificial smoke) and on a larger scale. Furthermore, the sensitivity of subjects to the vibrations and to hearing needs to be tested and it should be considered to use one or more control conditions in further tests.

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