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Aid for the Blind to Facilitate the Learning Process of the Local Environment by the Use of Tactile Map

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1. Introduction

In this chapter we present one possibility of application of the path planning from mobile robotics of the local urban environment learning of a blind person.
The general problem of mobile robot navigation was summarized with three questions: "Where am I?", "Where am I going?", "How should I get there?" (Leonard & Durrant-Whyte, 1991). Almost identical questions were posed also in the textbook for teachers who are dealing with the blind and visually impaired (Zovko, 1994). Not surprisingly, similar to a mobile robot, in the everyday manoeuvring in the local environment the blind are forced to resolve problems of localization, orientation, navigation and moving around. Like a mobile robot, also the blind rely on *relative measurement* (e.g. "there are five steps from the house door to the street level") or *absolute measurement* (e.g. "the second crossing from the house is marked by a beeper"); that is, they rely on the sense of touch (how many steps or stairs they have already made) and hearing (sounds from the surroundings - natural and artificial markers).
Therefore, the applicability of the results from mobile robotics research seems natural also for the blind. Indeed, applications of the obstacles avoidance, localization, sensor fusion and path finding have found their use in the development for the blind. The range of equipment so far developed is from complex machines to specialized devices. The examples of the former are motorized wheelchairs, e.g. *RoTA (Robotics Travel Aid)*, which are well equipped with vision, sonar, and tactile sensors. They also posses a map database system (Mori & Kotani, 1998) that is capable of guiding the blind along the road or sidewalk. However, although these wheelchairs, in fact mobile robots, are theoretically capable of guiding the blind, they are still too heavy, too big (and too expensive) to be widely accepted by the blind (let us only imagine all the raised surfaces, like stairs and sidewalks). More convenient are other devices. The portable device *NavBelt*, for example, consists of a belt with an array of eight ultrasonic sensors and a small computer worn as a backpack. After gathering the information from the sonars, the computer applies the unique obstacle avoidance algorithms and relays the data about the surrounding to the blind via stereophonic headphones (Shoval et al., 2000). Yet another device from the Mobile Robotics Laboratory, University of Michigan, is the *GuideCane*, a kind of robotic guide-dog. The blind, setting the desired direction, holds a special white cane tipped with a small mobile robot that is capable of

sensing and avoiding obstacles. After avoiding an obstacle, the mobile robot proceeds following the given direction. The blind follows the trajectory of the robot in a similar way a trailer follows a truck (Shoval et al., 2000; Ulrich & Borenstein, 2001).
Generally speaking, the main advantage that mobile robotics can offer the blind is *obstacle avoidance*, which means sensing the obstacles and planning the path around them, with respect to *conventional electronic travel aids* for the blind whose capabilities are limited to *obstacles detection*. By the name of conventional electronic travel aids one most frequently recalls (Zovko, 1998):

- The *Pathsounder,* one of the earliest ultrasonic "go-no-go" device, which informs the blind about the obstacles in the surrounding by tactile vibrations (Russel, 1965),
- The *C5 Laser Cane*, a cane equipped with three laser detectors, capable of detecting the obstacles in three directions: UP, FORWARD, and DOWN (Benjamin et al., 1973),
- The *Sonicguide*, a binaural ultrasonic aid attached to the spectacles, which encodes the distance to an object into the low frequency tone, separately for the left/right side in front of the blind, each information channel leading to left/right ear (Kay, 1974),
- The *Mowat Sensor*, an ultrasonic hand-held device that informs the blind person of the distance to the object by tactile vibrations, whose frequency is inversely proportional to the distance (Pressey, 1977).

In order to detect the obstacles, the majority of previously mentioned devices demand from the user to actively scan the environment. Another problem with the acoustic feedback devices is the interference with the sounds from the surroundings, which obstruct the blind's essential ability to orientate. In order to improve independence of the blind via active sensing, perhaps it is now time to upgrade this kind of devices with obstacle avoidance software systems from mobile robotics.
But there is yet another field of application of mobile robotics: the learning process, a sensitive and demanding process, which both the blind by birth and the acquired blind must undergo. Somewhere at the end of this learning process, there is a task where the blind must build in mind their own representation of local urban environment. This is but one of the indispensable conditions not being dependent on the help from others, that is to be able to go to school or to a job alone, to feel secure and autonomous, to take part in the social life, shortly, to be an active member of the society.

2. Spatial representation of the environment

In order to be autonomous in the local urban environment, for the blind, being able to build in mind their *own representation of this environment* is of the greatest importance. It means that a blind person relates all the possible markers he/she can sense (e.g. noises, smells) with spatial representation of the environment.
The results of working with sighted adults proved that the learning method when a sighted person is using a map or panoramic verbal description resulted in better coordinated spatial schemas, than the one when the space is learned through direct interaction with the environment or from a sequential verbal description (Thorndyke & Hayes-Roth, 1982). One may speculate that the more structure is 'revealed' by the learning method, the more structural spatial representation the learners are to be able to build.
As for the blind, on the other hand, the studies have pointed out that, in order to acquire, code, store and recover spatial information (e.g. Passini & Proulx, 1988; Spencer et al. 1989), they can make use of certain perceptual cues (landmarks in mobile robotics). Using those

alternative strategies, the blind are able to organize the spatial information in a way that is *functionally equivalent* to that of the sighted people. However, with respect to the sighted, they do need a prolonged period of time and bigger cognitive effort.
The research with the blind has shown that tactile maps may represent useful means of providing the blind with complex spatial information about the environment (Ungar et al. 1993; 1995). To compare the effectiveness of different methods for introducing the blind to the spatial layout of urban environments, Espinosa et al. carried out two experiments. In the first, the blind learned a complex and long route through the city by direct experience, by a combination of direct experience and a tactile map, or by a combination of direct experience and a verbal description of the area. Participants who used tactile maps demonstrated significantly better spatial knowledge compared to those from the other two groups. In the second experiment, participants learned a similar route using either a tactile map or direct experience only. No significant difference in spatial knowledge was found between the two groups. The researchers concluded that the combination of direct experience and tactile maps should be employed by the orientation and mobility instructors; however, even when direct experience is impossible, an isolated use of tactile map can represent adequate means of familiarizing the blind with the environment (Espinosa et al., 1998).

3. Tactile maps

A tactile map is a relief map, a plastic foil, imprinted vacuumly on a metal mould with a 3D representation of an urban environment. In comparison with normal city map, a tactile map, normally of the A3 format size, contains considerably fewer information. It is also enlarged: it encompasses smaller city area than the ordinary city map. The surface of the tactile map is normally divided into levels (Fig.1), each being a millimetre or so raised over the lower one: the streets are in the lowest level, forming the channels, ground and houses are in the intermediate level, while special objects like churches or other objects of importance are represented by the highest level.

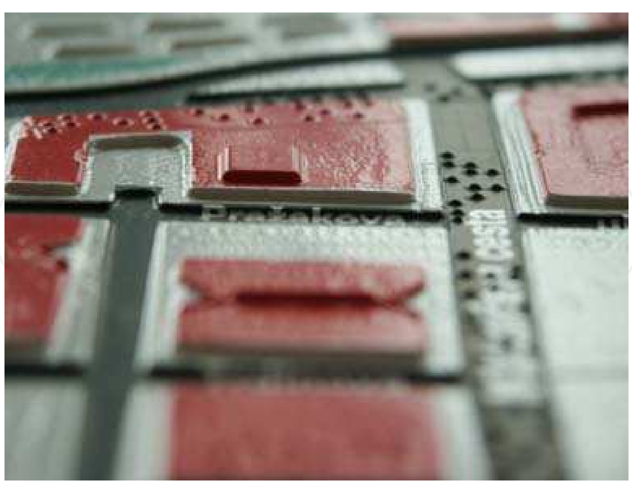


Fig. 1. Relief structure (layers) of the tactile map.

In this level there could be special map marks, or short texts in Braille letters; the signs are now more or less in accordance with the standards, which have been established recently. For the sake of clearness for the sighted people, tactile maps are coloured. The tactile maps used in this work were supplied by Geodesic Institute of Slovenia (Rener, 1993).

Practice guidelines for the design, production and presentation of tactile maps are available on the web (Gardiner & Perkins, 2002).

4. Tactile map monitoring system (TMMS)

We propose to extend the conventional use of the tactile maps by a system consisting of camera and the computer, named TMMS. TMMS consists of a camera connected to a computer. The camera is placed about 50 cm above the tactile map, whose field of vision encompasses a bit larger area than tactile map alone. This vision system tracks the movements of the user's forefinger while sliding all over the tactile map. In fact, it tracks only the special magenta marker, placed for the sake of quick recognition on the nail of the forefinger (Fig. 2).

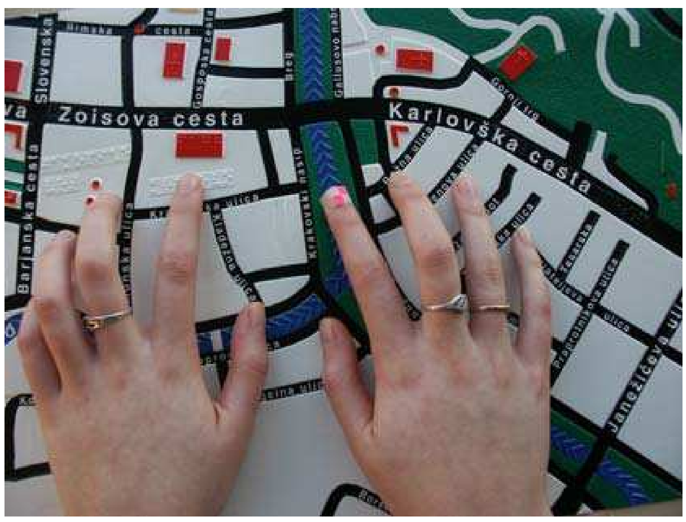


Fig. 2. The tip of the forefinger is tracked.

Although the user obviously uses all his fingers, it is only the position of the tip of his forefinger which the system regards as the *user's current position*, $P_t = (x_t, y_t)$ on the tactile map.
The TMMS expects the tactile map is always laid in front of the user like a map (north-south).

4.1 Tactile map description graph (TMDG)

The functionality of the TMMS is realised through the employment of a special data structure, *tactile map description graph* (TMDG), a graph where all the objects from the tactile map (e.g. houses, monuments, parks) are connected in a special way. This is the source of all the information the monitoring system is able to produce to the blind. While the user is sliding along the streets, rivers, etc., on the tactile map, the monitoring system should be able to localize his position P (the *current user's position* in the TMDG) to supply him with the name of the street, river, building, or other relevant information, regardless of which specific area of the (for example) building is he currently pointing at. To capture the structure of the objects on tactile map, we use Generalized Voronoi Diagram (GVD).

4.2 Generalized Voronoi Diagram of the tactile map

Tactile map $\boldsymbol{T}$, formally a set of planar points, could be partitioned into set of objects $\boldsymbol{O}$

$$\boldsymbol{O} = o_1 \cup o_2 \cup \ldots \cup o_n \quad \text{for } i = 1 \ldots n$$

and the so called *free space* $\boldsymbol{F}$

$$\boldsymbol{T} = \boldsymbol{F} \cup \boldsymbol{O}$$

Sets of objects normally represents buildings, parts of parks, but also parts of rivers (e.g. from one bridge to another). The free space represents what is left, the surface you can move along, the streets, squares, etc. The objects from $\boldsymbol{T}$ are of course non-everlapping. Let $d_E(p, o_i)$ denote the minimum Euclidean distance from a point p to a point in o_i.

Before we proceed we give the definition of the *Generalized Voronoi diagram,* GVD, of the objects on a tactile map. Let the *generalized Voronoi cell* be defined as

$$V_i(o_i) = \left\{ p; p \in \boldsymbol{T} \ , d_E(p, o_i) \le d_E(p, o_j), \forall j \ne i \right\}$$

The collection of all Voronoi cells $\boldsymbol{V}_O(\boldsymbol{O}) = \left\{ V_i(o_i) \right\}$ is called a GVD generated by $\boldsymbol{O}$.

Voronoi edges and Voronoi points are defined in the same way as in the case of the ordinary Voronoi diagram. If freeform boundaries of objects in the tactile map were considered, this diagram is not easy to obtain. However, for the present purpose, it is sufficient to construct an approximated version of the generalized Voronoi diagram. Following the procedure proposed by Okabe (Okabe et al., 1992) we (a) approximate the boundary of each o_i by a finite set of points, (b) construct an ordinary Voronoi diagram based on these approximation points, and (c) delete from this ordinary Voronoi diagram all the edges which were generated by the approximated points belonging to the same boundary of o_i. So what we have previously called GVD was actually the *approximated* version of exact generalized Voronoi diagram.

4.3 An example: a detail from the tactile map

We shall illustrate the procedure of generating GVD on the detail from the tactile map of Ljubljana (Fig. 3). (Presently we may also observe the simplifications of the tactile map: several buildings are represented by a single object on a tactile map -all around the map-, some streets are left out completely -in the middle, on the left and the right bank of the river-, etc. On the other side, there are some additional information such as the arrows that indicate the flow of the river, descriptions in Braille letters etc. There also existxs some inherent disproportionality: narrow streets are relatively wider on the map, etc.)

At the beginning, following the procedure of constructing approximated GVD, we approximate the boundaries of each object o_i by a finite set of points. The approximated boundaries may be observed on Fig. 4, drawn by bold lines. (Notice that each object is presented by two borders, i.e. two bold lines; we will discuss the reason for that later.) Ordinary Voronoi diagram created by these approximated borders is drawn by light lines (Fig. 4a). Every light line segment on Fig. 4a consists of points, equally faraway to two neighboring approximation points which lie on the nearest boundary of some object o_i. Adjoining light line segments form a (convex) Voronoi cell of the ordinary Voronoi diagram. All the Voronoi points represent the complete tesselation of the tactile map. Each cell has the property that encloses the area which is nearer to some approximation point on the border of some object o_i than to any other approximation point.

a) b)

Fig. 3. The same detail of Ljubljana: a) the hybrid view supplied by Google, b) section from the tactile map

a) b)

Fig. 4. Construction of the GVD: a) ordinary Voronoi diagram (light lines), b) GVD (dotted lines)

If the user's current position P falls into that Voronoi cell, the corresponding part of the border may be readily identified (by that also the object the user is pointing at determined).

The third step of the construction of GVD instructs us to consider each edge in the ordinary Voronoi diagram and delete all those edges that were generated by the approximated points of the same border of the same object o_i. After this step only the edges generated by the borders of *different* objects are preserved in the diagram: these are the edges of the GVD. The preserved edges, hence GVD, are drawn with dotted line segments in Fig. 4b.

In the GVD, there are two types of edges: the ones that lie in the middle of the free space between two objects and the ones that pass right through the objects. The former capture the connectivity of the streets, the latter are merely information holders for buildings, rivers, parks, etc. It is clear now why every border of an object should consists of at least two parts: in this way the edges of the GVD 'enter' also the objects. Similar to an ordinary Voronoi diagram also the GVD represents the complete tessellation of the plane. It is a planar graph $GVD = \{E, V\}$ where the edges we have just described are connected at *Voronoi points*. Voronoi points, the vertices of GVD, are the positions of equal distance to at least three nearest objects in the tactile map.

4.4 From GVD to TMDG

Obviously, the GVD is the essential part of the TMDG, the latter being actually the extension of the 'geometrical' data associated with the edges and vertices of the GVD with the vital information for the blind. This additional specific information is organized into three levels: elementary, intermediate and detailed. During usage the TMMS reproduce the information to the blind aurally, through the synthetic or recorded speech, or, less conveniently, written on the Braille line.

The information associated with the edges are:

- elementary - the name of the street, river;
- intermediate - the names of the streets (bridges) at the forend and at the backend of the current edge;
- detailed - the description of the pavement along the street (sand, asphalt, etc.), special sounds/smells that may be heard/scented, the description of the possible dangers (small columns, parked cars, slippery terrain, crush, etc.), the distance to the both ends of the edge, the sample of the sound recorded at the very location, the important city sights, the important personal information, etc.

The information associated with the vertices are:

- elementary - the name of the crossing, bridge,
- intermediate - navigation data (which streets are in front, behind, on the left/right),
- detailed - the complete description of the crossing (traffic light?, the description of the crossing from a pedestrian's point of view, traffic aids for the blind?), the sample of the sound from the location, etc.

The reproducing level is determined by the user and may be changed at any time.

The GVD of the detail of the tactile map may be observed on Fig. 5a. The GVD consists of two types of the edges: the ones that 'capture' the free space between two different objects, let us call them *street egdes* (drawn by continious bold line segments), and the ones that *enter* the objects, *object edges* (dashed bold line segments). There are also two types of the vertices: the ones where the street edges join together, *street vertices*, and the ones where two street edges join with the object edge, *object vertices* (we put aside the fact that generally even more than just three edges may join at one vertex, since this situation may be avoided during drawing of the borders of objects). To the user, only street vertices are accessible, since it is there, where the stored information about the street crossings are reproduced. They are indicated by small circles on Fig. 5a. This small circles are neccessary also from practical reasons: noninterrupting reproduction of the information at some vertex would be difficult because of even small changes of P (due to small movements of a forefinger) unless some tolerance circle is introduced. Despite the distinction from the user's point of view, all the edges and vertices in GVD are equivalent, however when, for example, searching a path, only street edges are considered by the TMMS.

4.5 Correlation between P_t and P

In order to navigate in TMDG properly, when sliding over the objects of the tactile map, each pixel of the bitmap image of the tactile map should be in accordance with the appropriate position in TMDG. Generally, the position P_t has to be transformed into P by

$$P(x,y) = Tr(x_t, y_t) + Rot(x_t, y_t) + Scal(x_t, y_t).$$

The three transformations in the equation are translation, rotation and scaling of the user's forefinger position. The values needed for the transformations could be calculated from some calibrating process performed at the beginning of the usage of the tactile map. It may consist of touching the two prescribed objects in the (for example) lower left and the upper right corner of the tactile map. The existing objects of the tactile map, e.g. some monument, small building, a braille letter, or special marker could serve for this purpose.

5. Device - user interface

Normally, while listening to the aural information, supplied by TMMS, the user has both his palms resting or sliding over the tactile map. Yet the user also has to control TMMS by giving the commands. In this situation the TMMS is in the so called "Control mode", while, when activated at the level of operating system, it enters the "Setup mode" with the normal functionality of the keyboard. The set of active keys in "Control mode" is kept as simple as possible, nevertheless some input from the keyboard is still neccessary. Therefore, from time to time, the user has to displace his left hand (for right-hander) from the tactile map to the keyboard. The employed keys in "Control mode" are: SPACE-KEY (toggles among the operational modes, look below), PAGEUP/DOWN-KEY (rises or lowers the level of the reproduced information), ESCAPE-KEY (TMMS returns back to "Setup mode"), ENTER-KEY (TMMS stores the user's current position P in the TMDG), and UP/DOWN ARROW-KEY (scrolls up and down the list of predefined locations, objects on the tactile map).

6. Modes of operation

As already explained, the information for the blind is held in TMDG, in fact, in the edges and the vertices of the GVD. As the blind is sliding over the tactile map, the task of the TMMS is to *determine the corresponding edge* of TMDG. To do this, the Voronoi cells of the ordinary Voronoi diagram have to be searched to find the one which containes P and contributes a part of the edge in GVD. This is the central task of all the operational modes which are: Calibration, Exploration, Search and Navigation mode.

6.1 Calibration mode

Some technical aspects of the Calibration mode have already been described above, while the manipulating details will be omitted.

6.2 Exploration mode

The purpose of this mode is to enable the user to familiarize with the tactile map. The user only has to slide his/her fingers over the tactile map, and the TMMS reproduces the information about the objects the user is currently pointing at.
An example of such an exploration may be observed on Fig. 5b. The track of the movement of the user's forefinger is drawn by dashed bold line segments. For every position *P,* lying on this track, the TMMS determines a part of the corresponding edge in TMDG, aurally reproducing the available information at the selected level. The sections of the corresponding edges along the track of the user's forefinger, that are drawn by bold continuous line segments, are enumerated in increasing order. At the beginning (at the bottom, and in the middle) the Voronoi cell of the ordinary Voronoi diagram is determined in which the first *P* lies. When the corresponding object edge no.1 in TMDG is found its relevant information are aurally reproduced. As this edge also corresponds to all the successive points that are lying in the same object, the same information keeps on being reproduced every once in a while until the border of the object is reached. As the next point, representing the street, is already positioned in the channel of tactile map (the user has beforehand sensed the channel by his/her finger pad and is therefore expecting new information), the TMMS finds a new corresponding edge, no.2, which is the street edge. Following the channel of the street, he/she is continuing through the rest of the street (edge no. 2), until he/she reaches the junction of the street (a vertex in TMDG) with another. There is a continuous reproduction of the streets' and crossroads' names. Passing the junction, the user briefly follows the other street (street edge no. 3) while already exploring the next object (object edge no. 4), etc.

6.3 Search mode

The purpose of this mode is to help the user find the location of any desired object/location on the tactile map. The user scrolls through a list of objects/locations, that have been both predefined and added by the user him/herself, selecting one. Afterwards, while being instructed in which direction to move to find the desired object' location, he/she may slide over the tactile map in the arbitrary direction. The instructions are given by directions of eight point compass rose: N(orth), N(orth)E(ast), E(ast), etc. While advancing along the path, the appropriate information from the TMDG for the current position and a new direction are being aurally reproduced. The user may employ two strategies: he/she may either scan the area between him/herself and the selected object in order to gain the knowledge about its surroundings or approach the selected object by sliding a finger along the streets exclusively.
An example of such a search is given on Fig. 6a. The selected location is labelled by G and the user's starting position by S. The user's path (continuous bold line) reveals scanning at

the beginning and sticking to the streets when close to the goal. The directions given by the TMMS are written along the path.

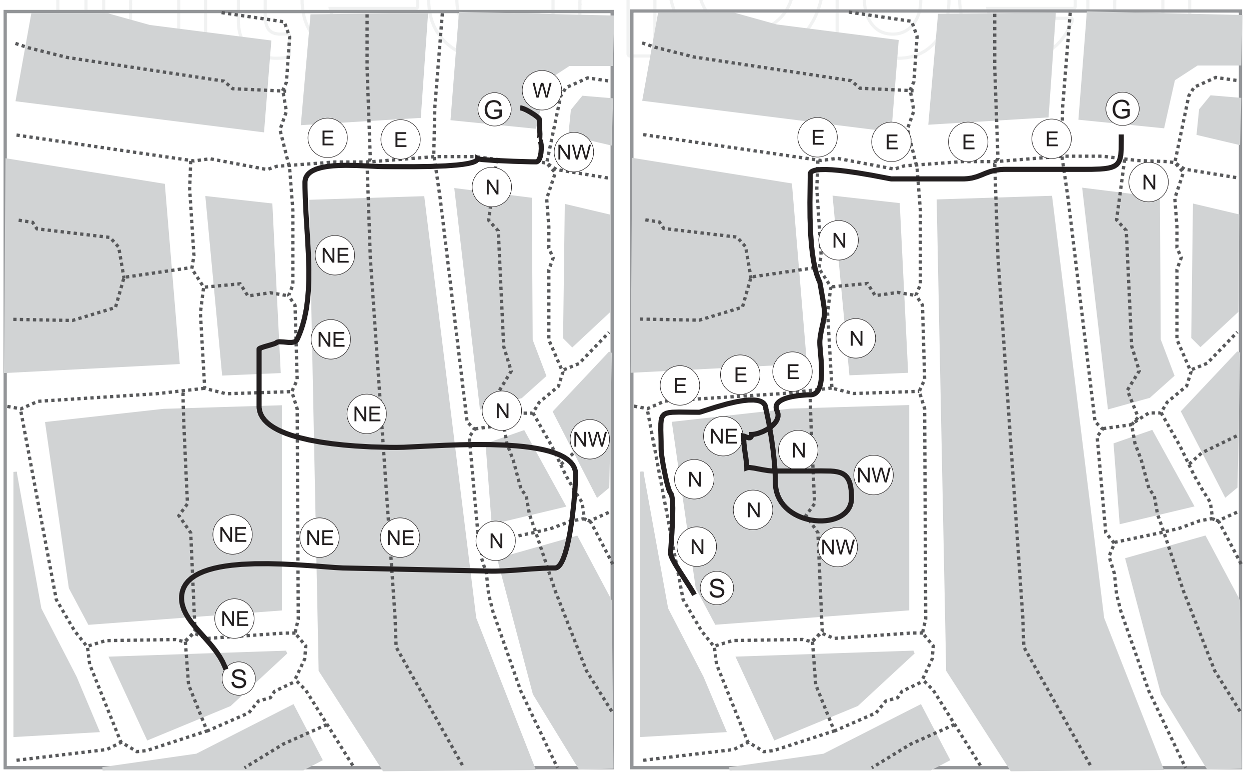
a) b)

Fig. 5. a) GVD of a tactile map detail: edges of the objects (bold dashed line segments) and egdes along the streets (bold continious line segments) b) Exploration mode example: the track of the user's forefinger (bold dashed lines), relevant segments of the edges in TMDG (bold continious line segments, enumerated along the movement), drawn over the objects and GVD (in light tones)

6.4 Navigation mode

This mode is dedicated to navigate the blind from one selected location S to the other G. This is the mode where the path from home to important everyday locations (e.g. school, bank, post office, shop, bus station, etc.) is thoroughly exercised. The TMMS determines the user's current position and instructs the user which way to take in order to move towards the goal location. Once again, the instructions are directions of eight point compass rose. As in the Search mode, the appropriate information associated with the current position in the TMDG is being reproduced aurally. In contrast to Search mode, there is also an aural reproduction of additional information whether the user's current position is *on* or *off* the proper path. The TMMS does not tolerate excursions off the proper path, so if it does happen, the user is instructed to return to the last valid position on the path.

An example is given on Fig. 6b. At start point S, the user is instructed toward N(orth) and at the first encountered crossing, toward E(ast). The goal location is G, however, at the location where the user goes off the correct path, the goal location temporarily becomes the last valid location on the path. The advancement toward G is delayed until the valid location is resumed.



a) b)

Fig. 6. a) Search mode example: the track of the user's path from start position S to goal position G with the navigational instructions given along the path by TMMS b) Navigation mode example

6.5 Customizing the TMMS

Making a tactile map is not a trivial task and demands engagement of people of various professions. It is too expensive to be tailored for just one blind person. A blind person, on the other side, needs to learn about *his/her own* local environment. His/her tactile map shall include signs for *his/her* school, shop, bank, etc. Since it enables the user to store his own positions in the TMDG, which may be latter recalled and involved in the user's specific exercises of navigation, the TMMS in a way supports customization of the learning place. At those special locations on the tactile map, it would be useful to provide some tactile marks (drops of glue, stuck Braille letters). While in the "Control modes" only *the coordinates* of the user's own special positions may be stored, in the "Setup mode" also the associated information, to be reproduced later, may be added.

6.6 Other tactile teaching aids

Although only the tactile maps are treated in this work, any planar tactile aid may be used; e.g. the majority of the techniques for making tactile diagrams (Kermauner, 2009) produce aids suitable to be used in TMMS. For each aid, of course, its own description graph TMDG has to be made, which presently cannot be constructed by the instructors of the blind themselves. The independent production of new teaching aids at schools could be realized in the future.

6.7 Implementation

To construct the GVD from the tactile map, it is necessary to draw a boundary of each object from the tactile map. For the demonstrated example, this was achieved manually, although it seems possible that this process could be made automatic (after all, the mould of the tactile map is made on the CNC machine, which suggests that a suitable input for the calculation of the GVD could be obtained by the interpretation of the CNC program). Nevertheless, the information associated with the buildings and streets, held in the TMDG, should be added by hand.

The GVD was constructed by the use of the library of the data types and algorithms of combinatorial computing, LEDA (Mehlhorn & Näher, 1999); also all the searching in GVD, data structures definitions and manipulations were implemented in LEDA.

7. Conclusion

The research of mobile robotics has already made, and - as we may expect - is still to make even more important contribution also to developing machines, devices and aids for the blind. For example, the obstacle avoidance systems, originally developed for mobile robots, seem well suited to be incorporated into travel aids for the blind. Although most of today's dedicated mobile robots for the blind still seem too heavy, sophisticated and, first of all, too expensive, they may - as we believe - evolve into usable aids for the blind. But the mobile robotics could also participate in improving training of the blind.

The system we proposed in this work falls into this category. We further exploit the use of the tactile maps by associating the tactile information the blind gets from the tactile map with the information about the objects the blind person is pointing at. The position of the finger on the tactile map is associated with the corresponding description of the object in the information system. This description is presented to the blind aurally (the existing text-to-speech systems which involve synthetic speech have already been accepted by the blind).

The system works in three operational modes: exploration, search and navigation in which also the knowledge from the path planning is applied.

We believe the system could: (1) help the users to build in mind spatial representation of their local environment more quickly and accurately, which is essential for the blind in order to be more easily and quickly autonomous; (2) be applied whenever there is a need to associate the tactile information with aural explanation; and (3) allow for more independent learning and exercising.

8. Acknowledgements

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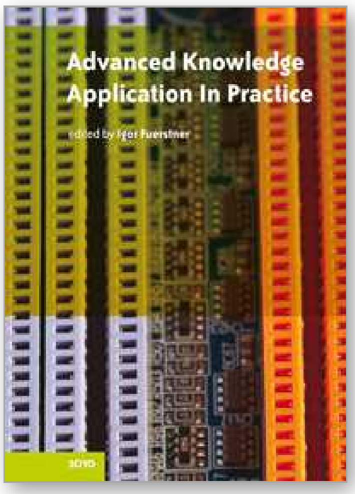

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The integration and interdependency of the world economy leads towards the creation of a global market that offers more opportunities, but is also more complex and competitive than ever before. Therefore widespread research activity is necessary if one is to remain successful on the market. This book is the result of research and development activities from a number of researchers worldwide, covering concrete fields of research.

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