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Technical design of complex vision-tactile navigation system for using of blind persons navigation

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Abstract. This article presents the system used for navigation and orientation of blind persons in an unknown terrain. This system called 'Tactile Navigation System' constitutes a compensation instrument for blind persons. It is composed from three basic elements: a camera, a control unit and a tactile activator. The tactile navigation system converts the image from the camera to the tactile information and it transfers this information to the blind person. The blind person can recognize by vibration of the tactile activator placed on the antebrachium whether he comes on an impediment or if he can continue free walking. The main advantage of this system is the possibility of detecting any individual impediment earlier than using other common compensation tools, such as a simple blind stick, which is not a competitor with this device, but a helper. This way the system facilitates the orientation of a blind person an in an unknown terrain. The article describes in detail the overall composition and functionality of the system as well as the principle and function of its individual elements.

Key words: tactile systems, pattern processing, edge operator, blind persons, navigation, tactile activator.

INTRODUCTION

The need of navigation of blind persons is still a challenge. The white stick accompanies them for centuries, even in the electronic age. This article is a small contribution in this branch. The aim of the projected device is to enable the orientation of blind persons in the space. The design and the individual components have undergone some changes during the development, as the technology of individual elements developed. But the basic idea has not changed. The described tactile navigation system includes a camera, pattern processing system, a control unit, a tactile activator and a power supply, with detailed description of the edge detection system and the behaviour of tactile actuators. This navigation system has been designed basing on tactile perception of a picture from a camera. There are also other system using visuo-auditory based navigation (e.g. Auvray et al., 2007), however, we did not follow this way because the tactile sensing does not burden the audio sensing of the blind person and does not distract its attention this way.

MATERIALS AND METHODS

Overview of present systems

For the better awareness in this issue, we will present some already developed and experimentally verified navigation systems for blind persons.

One of the used systems is the Tyflosonar (2017), which represents a multi-functional electronic device. It uses ultrasound for the distance measurement. In addition to the obstacle detection it includes also a sound beacon and a sound indicator of light intensity. Additional functionalities are the obstacle distance measurement and the accumulator test. The blind person wears the device usually on the chest.

The navigation system Dinasys is intended for orientation of visually handicapped persons in an unfamiliar environment of buildings, corridors, closed outside areas or other closed rooms. This navigation system is not intended for orientation in streets or in open space. The navigation system consists of two components – a modified white stick and very strong permanent magnets. The magnets are put into or glued onto the ground to mark the proper path. The magnet can be placed under a carpet or embedded into soil up to 5 cm deep. There are also being developed another, particularly acoustic navigation systems by the company (Diansys, 2017).

Other system is called Tongue Display Unit (TDU, under the commertional name (Brainport®) (Kaczmarek, 2011). The TDU has been designed at the University of Madison. The system consists of a camera that scans the surroundings. The processed signal from the camera gets to a 12 x 12 matrix, which is located on an elastic foil. The foil is put on the tongue. The tactile cells of the tongue are stimulated by electrical impulses in individual points of the matrix. The letter T was tested in various positions. After a short practice, very good results in its recognition were achieved. The simultaneous brain examination has proved that while using the TDU, the picture processing centres of the brain are stimulated. It even holds true for persons that are blind from birth and that have never used the brain view centres.

An interesting solution of orientation of blind persons is called ActiveBelt (2017). The device is a vibration belt, which is equipped with eight vibration motors evenly placed at the belt´s perimeter. The belt is connected with a GPS module with a pre-set address. The direction of the motion towards an obstacle of the blind person is determinated by the vibrations of the corresponding vibration motor.

The last non-invasive system is a blind person camera. This camera has got no LCD but a Braille display (A camera For the Blind, 2017), which is capable to display the picture in 3D-mode. It enables the user to sense a picture by means of the touch. This way can the blind persons perceive their surroundings by means of visual information by way of the touch.

Recently, with the advance of the neurosurgery and the optical surgery, invasive solutions start to be implemented, e.g. an implant of the artificial retina or a picture taken by a camera, which is after modulation transmitted into the brain view centre. As the article is focused on non-invasive methods, further information of the invasive solutions can be found in Margalit et al. (2002) and Volf & Škeřík (2014). Psychological aspects of blind persons' perception and comparison of blind and blindfolded control groups are stated in Segond et al. (2013).

Means of the information gain about the surroundings

As mentioned above, the described tactile navigation system is intended for the orienntation of blind persons in an unfamiliar or a partly familiar environment. A block diagram of the entire system is shown in Fig. 1.

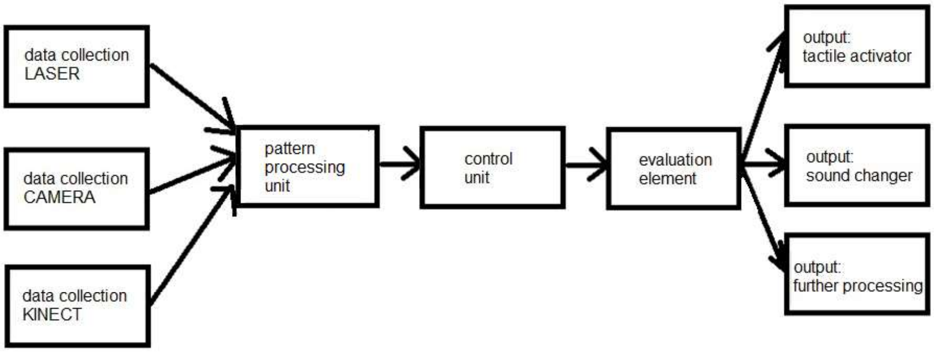

Figure 1. Block diagram of the tactile navigation system.

The tactile navigation system enables to collect information from various sources, not only from a camera or from a laser distance measuring system, but also from other supportive systems, e.g. the Kinect. The pattern processing unit processes signal from camera and reduces these data (by signal processor) to form, that can be processed by control unit. The control unit and the evaluation element process individual signals, convert them into requested form and transmit them to other components of the system, which mediate the information to the blind person by diverse ways. The system described in this article passes the information on via a tactile activator, which by means of vibrations of motors transfers this information through skin receptors at the forearm (Králíček, 2011; Silbernagl & Despopoulos, 2004; Volf et al., 2015).

Another way of use is a sound changer that should by means of speech synthesis speak the transmitted information, and so warn the blind person acoustically about the situation in front of it or in its surroundings. An alternative is use of acoustic signal with variable frequency. The designed tactile system is controlled by a microprocessor; it has to work with minimal energy in real time, so there are high demands on the simplicity of the recognition system.

A camera CMUcam3 (2017) was used to record the environment. The camera is placed on the head of the blind person and it records the area in the direction of the head´s turn, so the space of the view and the likely walk is scanned. According to the configuration of the processor, the camera can make a video record or individual snapshots by pre-set instructions that depend mainly on the recording and processing speed.

Individual pictures are passed on the control unit, which by means of SW detects edges and converts the resulting picture into information that can be transmitted to the blind person. The edge detection can be carried out by means of various software tools and methods; we have used the Hough Transformation. A closer description is in the part about the picture processing. To get the information about the obstacle distance, we need to use either two cameras or a rangefinder.

Other system that complexly solves the gaining of information about the environment is the game console Kinect by Microsoft. It combines a RGB camera, deep sensor, broad scale microphones and a separate control processor. Kinect can follow the motion in 3D mode, react to instructions and orders and it can even recognize a change of emotions or voice timbre. Today, there are being performed tests of a tactile navigation system that uses the sensor Kinect. The blind person will obtain exact information about the surroundings in that it can move safely.

Picture processing

A very important part of working with pictures and searching for specific objects is the pre-processing of the picture, further information can be found in Volf (1994), Šonka et al. (2014), Burger & Burge (2009) and Prajer (2009). The colour picture loaded by the camera is initially converted into a grey-scale and then its contrast is modified.

Based on neurophysiological and psychological research, it turns out that by image perception plays a very important role places with a significant change in brightness. These places are called edges. It is simply possible to prove the ability of the human brain to abstracted on the edge only the overall image perception – an example can be a drawing.

An edge in the image can be distinguished basing on pixel values, depending on the values of the surrounding pixels. This is caused by a sudden change in the value of the $f(x, y)$ image function. Changing the value of the function of the two variables can be quite easily determined using a partial derivative.

Change the function value is given by its gradient ∇, which is a vector variable that determines the direction of the greatest increment of the function in the given direction and the slope of this growth (gradient module). Pixels with a large gradient module are detected as edges. Gradient size $|\nabla f(x, y)|$ and its direction φ – represent the angle between the coordinate axis x and the radius vector to the point of coordinates [x, y]. This is for a continuous function given by the following Eqs (1), (2):

$$|\nabla f(x,y)| = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2} \tag{1}$$

$$\varphi = arg\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right) \tag{2}$$

The best of the edge detectors for our purpose appears to be the Canny edge detector, the today's advanced edge detector. It bases on the idea that the jumping edge (in 2D we can imagine it as a step) can be searched for by a filter. The design of this filter is conceived as a rotation variable. The detector is optimal for jump edges with respect to the three criteria (Šonka et al., 2014):

1. *The detection criterion* requires that significant edges are not overlooked and that multiple edges are not present on one edge.

2. *The localization criterion* requires that the difference between the actual and the found edge position is minimal.

3. *One response criterion* ensures that the detector does not respond multiple times to one edge of the image. This expectation is already partly secured by the first criterion. This requirement is especially focused on dull and non-smooth edges, which are not provided by the first requirement.

First, the edge detector was formulated for the 1D signal and the first two optimization criteria. Using the calculus of variations and symbolic derivation program, an explicit solution was found. After adding the *One response criterion*, it was necessary to look for the most appropriate filter response by numeric optimization. The resulting filter can be approximated by Gaussian filtration with an error of less than 20%. After generalizing into 2D, the edge is given by its position, orientation and size (it can be imagined as the height of the stairs). The edge thickness (magnitude of the intensity gradient *f*) is calculated according to the Eq. (3):

$$|G_n \cdot f| = |\nabla(G \cdot f)| \tag{3}$$

Since convolution and derivation are associative operations, we can first realize the convolution of the image *f* with Gaussian *G* in the Eq. (3) and then compute the directional second derivative using the estimation in the direction *n* according to Eq. (4):

$$n = \frac{\nabla(G \cdot f)}{|\nabla(G \cdot f)|} \tag{4}$$

The position of the edge (the local maximum of the convolution *f* with the operator G_n), depending on 2D Gaussian *G*, is obtained by substitution from the equation for its first derivative G'' (5):

$$G_n = \frac{\partial G}{\partial n} = n.\nabla G \quad => \quad \frac{\partial G_n}{\partial n} \cdot f = \frac{\partial^2 G}{\partial n^2} \cdot f = 0 \tag{5}$$

Image filtering is one part of the preparation of real-image scanning and its processing by a microprocessor or signal processor; here it is necessary to point out that today there are also CCD cameras with an inbuilt microprocessor allowing to filter directly and simplifying the device.

The distances of the obstacle could be determined using ‘higher’ image processing tasks. First, it is necessary to identify the object in the image and determine its dimensions. Then it is examined, based on its shape, how far it is from the observer. However, such real-time calculations are very hardware demanding. The simplier way to determine the distance is to use a laser or ultrasonic measuring device. The acquired distance information can be converted to a sound sensation – the closer the obstacle, the higher the frequency of signal intervals. It is not advisable to generate steady sound signals, because a blind person also uses hearing for the orientation in the space, and such steady signals could be rather confusing.

Tactile activator

There are demonstrated two possible tactile activator solutions to inform a blind person about the surroundings. The first one uses stimulation by alternating current and the second one bases on mechanical principle – transmission of information by vibration.

Due to the principle of irritation with AC electrical stimulation, the tip of the electric pulse must be able to transmit the electric impulses to the surface of the skin, which results in a number of requirements: the spikes must be rigid in order not to bend and their attachment in the matrix must be firm, to maintain their position. On the other hand, the entire matrix with spikes should be compliant to copy the shape of the surface of the human body where it is attached to adhere sufficiently to it. For the human body it were experimentally determined optimal values of frequencies around 200–250 Hz, voltage and the current must meet safety limits, voltage up to 12 V and current up to 3.5 mA.

As can be seen, some requirements are in direct contrast: the stiffness of the matrix and spikes can be met, but the positional stiffness of the spikes, to copy the shape of the human body is hard to match. A possible compromise is use of a thin fastening system and short spikes, which also lowers total activator height. Spikes are made from titanium, chirurgical steel, with combination with other conductive materials such as gilded tips. For our experimental use we created an array of 10 x 16 pin connectors with a 2.45 mm pitch embedded in silicone forming; see illustrative image in Fig. 2.

Another alternative is the use of cross-linked joints formed on thin printed circuit board, such as Teflon film with double-sided copper layer with the trade name Cuflex. This material is very flexible and replicates very well the shape of the arm.

The use of so-called ‘smart’ textiles is also very promising, a relatively new and progressive branch in the textile industry. Thin conductors forming points (conductive connections) or conductive paths (buses) are inserted into the outline of the fabric at selected locations. This way, it is possible to create e.g. a numeric keypad; or it is even possible to directly integrate circuits to the created busses or to connect the solar cells for the power supply.

In the other case, an activator with vibrating elements was used to transmit environmental information. The tactile activator is a box (see Fig. 3) that consists of 9 miniature electro motors, their control units and the control unit of the entire tactile navigation system. The signals from the camera or from the control unit of the system are brought by cable into the tactile activator and then are converted into information for the blind person by means of control units and a multiplexor. The information is created by an electro motor. The shaft of the motor is equipped with an eccentric mechanism that creates vibrations by its irregular shape after the spin-off of the motor. The electro motors are set into a 3 x 3 matrix, that will be extended to 5 x 5 matrix of motors in the future, in order to ensure the highest possible accuracy of the system. To transmit the vibration to the blind person, the electro motor is equipped with a small plastic plate that is placed in the opening of the plastic deck of the tactile activator. The electro motor is embedded in a rubber wrap in order to distinguish the vibration of the motor and not to influence other parts of the activator. Vibrating electro motors by the company Maxon (2017) were used, specifically the motor 30200 EC 10 lat, power 0.2 W.

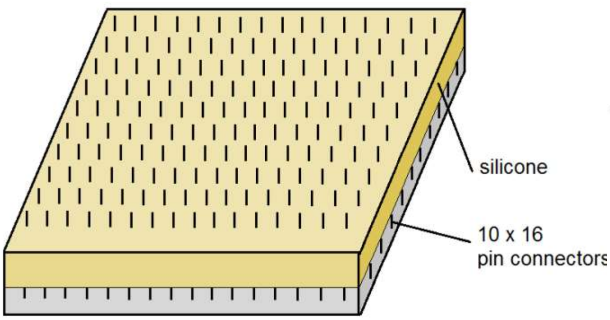

Figure 2. Pin connector matrix.

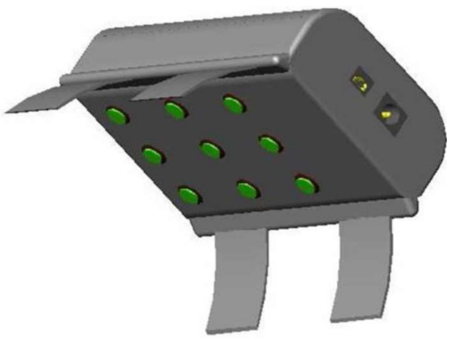

Figure 3. Tactile activator.

The activator itself is placed on the forearm and it is fixed by two belts that ensure its right position and that prevent shifting or slipping from this position. The belts are wide enough to minimize the pressure onto the arm and to ensure that the wearing will not be unpleasant.

By this prototype, the power supply of the entire system is realized by means of a battery that is placed in a bag at the waist. The entire system is designed to help with the orientation as much and to limit as little as possible. As the control unit the 1-Q-EC Amplifier DEC Module 24/2 was used. The unit is connected with the tactile activator with a 17-pin connector.

RESULTS AND DISCUSSION

Edge detection

In following we present the results of edge detection by using the Canny detector on two pictures. First Fig. 4 represents the scene from the interior, the second Fig. 5 the exterior scene; namely the entrance to Ládví metro line C in Prague. The interior was photographed from a distance of 1.8 m, exterior from a distance of 10 m.

Figure 4. Interior image.

Figure 5. Exterior image.

For filtering, a 5 point and 9 point Laplace operator, Robinson operator and Kirsch operator were used. Laplace operator is invariant respective to turn. It only indicates the size of the edge, not its direction. It represents a second derivative. Increasing the pixel weight of that closer to the representative point of the mask, it loses its invariance respective to rotation. Both Robinson and Kirsch operators approximate the first derivative; both are not directionally invariant. Robinson operator estimates the gradient for the neighborhood of 3 x 3. The x-axis and y-axis directions were used for image filtering, see expresions (6):

$$h_1 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ -1 & -1 & -1 \end{bmatrix} ;\ h_2 = \begin{bmatrix} 1 & 1 & 1 \\ -1 & -2 & 1 \\ -1 & -1 & 1 \end{bmatrix} ;\ h_3 = \begin{bmatrix} -1 & 1 & 1 \\ -1 & -2 & 1 \\ -1 & 1 & 1 \end{bmatrix} \qquad (6)$$

Figs 6 and 7 show the result of the operation using the Robinson operator, which achieves comparable results with Kirsch operator; Laplace operator has generated worse results.

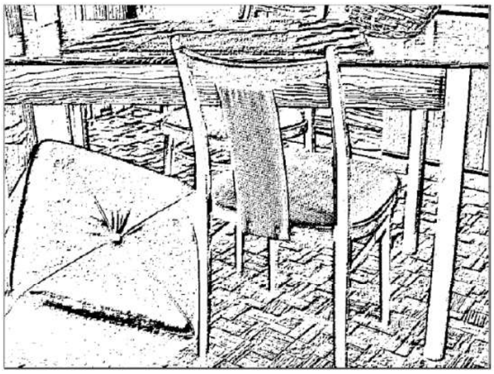

Figure 6. Results after using Robinson operator for interior scene.

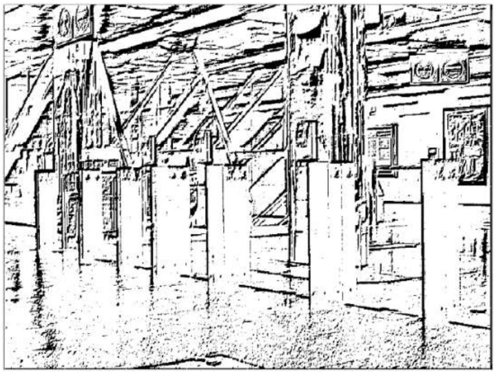

Figure 7. Results after using Robinson operator for exterior scene.

Tactile activator

During the realization and testing of pin connector matrix, it turned out that it is not advisable for the spikes to protrude too far from the silicone body. The touch experience was greater than the perception of electrical pulses. Pulses were tested with both constant voltage and superposed alternate component. By adding a conductive gel between the skin and the actuator, pulse perception improved.

It appeared that using dynamic irritation, by renewing pulses by rows with a certain period; it will be possible to achieve better results than with simple static irritation. Another possible modification to improve sensitivity is modifying the ground electrode: instead of existing antistatic bracelets, grounding electrodes may be placed just on the edges of the actuator, or grounding fibres may be inserted between the electrodes, which is exacting on the precise placement.

To address the spikes to the output of the multiplexer, it can be used the direct principle, i.e. to connect all the wires from the spikes (demanding on the number of M x N outputs), or the matrix selection principle addressing (M + N outputs only).

Finally, the spike resolution was tested on the actuator. First, the point on the left edge was switched and the distance to the next switched point gradually shortened. The smallest distance which can be distinguished with respect to the spike pitch of 2.54 mm is about its double, i.e. 5 mm. At less distances, perception was ambiguous.

Figure 8. Experimental door frame.

The next paragraphs describe the function of tactile activators; in Figs 8 and 9 is demonstrated the behaviour of the electro motors of the tactile activator while passaging through a door frame or through a narrowed space. The camera records the picture and converts it into data for the microprocessor. It calculates two vertical edges that don´t adjoin with each other, because their distance is sufficient. The data processing matrix evaluates the distance as high and passes the information on the specified control units that get going the electro motors at the sides of the activator. If the blind person approaches the frames, the picture will not change, so the same electro motors will be working. The transmitted information would change only by deviation of the camera´s direction. Red marked vibrating motors that warn the blind person about the door in front of it. Vibrating motors warn about an obstacle, non-vibrating motors guarantee a free pass. But the disadvantage of the 3 x 3 arrangement is clearly visible. With the 5 x 5 layout it would be possible to better specify the position of the door frame. However, since the primordial functionality of the system is tested, an actuator with lower resolution has been used. This is only capable to 'display' simple images, such as door frames or stairs. Complicated scenarios (such as in Figs 4–7) is not possible to process in this stage, it would be necessary to use an actuator with significantly more points; the scenes should demonstrate the capabilities of the edge detection. Real behaviour has been tested using following simple experimental scenes.

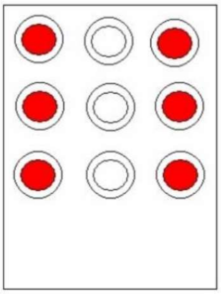

Figure 9. Visualization of the motors warning about the door.

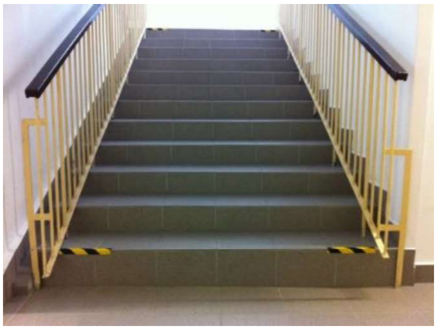

Figure 10. Experimental stairs.

While passing stairs (Fig. 10), the system detects a group of horizontal edges. The stairs are announced by vibrations for a specific time of the first row, then of the second and finally of the third, see Fig. 11. This way the blind person can be warned about rising stairs. Stairs represent a backward moving edge, that is indicated this way using the software to distinguish it from e.g. a fence, where all the actuator motors would be activated simultaneously. The electro motors continue working until the blind person is in the space in front of the stairs or until walking the stairs. As soon as the recorded space in front of the camera changes, the work of the electro motors changes correspondingly. While

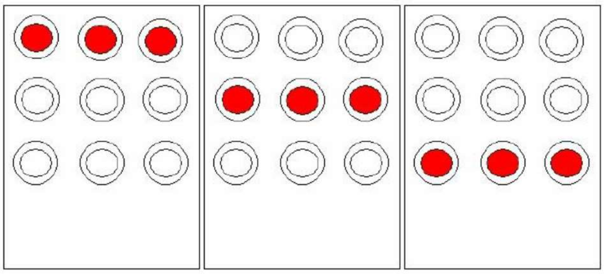

Figure 11. Visualization of the motors warning about the stairs.

going down the stairs, there is a problem with the appropriate detection of the edges; however, after their detection (i.e. falling stairs) the electro motors will work in a reversed order than by rising stairs to distinguish them.

CONCLUSIONS

The designed technical solution presents a contribution to the issue of the orientation of blind persons in a familiar and unfamiliar environment. The capabilities of various edge detection algorithms were tested; Robinson operator and Kirsch operator edge detection methods gave satisfactory results under both indoor and outdoor conditions. Further, two tactile activators were tested to enable the orientation in unknown space – a pin connector matrix and an array of 3 x 3 vibrating motors. The pin connector array sends small electrical impulses to the skin that warns the blind person about an obstacle. Better results were obtained using dynamic irritation by renewing pulses compared with static irritation, the resolution was limited to cca. 5 mm distance of corresponding pins. Next, the tactile activator with an array of 3 x 3 vibrating motors has been tested by detection of simple shapes, such as door frame of stairs. The detection and function of the activator is satisfactory, the main issue is the limited resolution of the 3x3 matrix; the resolution can be increased during the further research, to obtain more precise perception of the surroundings; however, even this simplified prototype demonstrated its designed capability. The system is designed for blind persons in the first way, but by its extension and by usage of additional supporting systems it can be used in every branch. The aim of the project is to design a functional system and to put it into practice in order to contribute to a simplification of the workflows. It can be also pointed out new possibilities of game consoles like the Kintec that can be used in support systems for disabled people.

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