2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

# Sensor-Guided Jogging for Visually Impaired*

C. Ramer, C. Ziegler, S. Reitelshöfer and J. Franke

*Abstract*— **This paper introduces an approach for enabling visually impaired and blind people to practice jogging activities by 3D environment perception for course detection and collision avoidance, as well as feedback generation in an intuitive manner. Besides a system concept, first prototypic realizations, that confirm the general feasibility, are presented for this domain, which has not been addressed by research until now.**

## I. Introduction

According to the World Health Organization (WHO) there were more than 161 million people worldwide with visual impairment, including 37 million blinds, in 2002, a growth by 80 percent compared to the year 1990 [1]. Even though visual impairment particularly occurs in the least developed regions [1], there is also a huge number in industrialized countries. While in many countries the number of visually impaired and blinds is not counted officially, experts estimate it for example in Germany to around 1.2 million in 2002 [1].

The definitions of visual impairment and blindness are not consistent worldwide. The WHO subsumes "blindness" and "low vision" under the term "visual impairment" [2]. The denotation "essentially visually impaired" according to German law is equivalent to the WHO category two and denotes a maximum residual vision of ten percent. The German "profoundly visually impaired" for a residual vision of five percent or less is already assigned to the term "blindness" by the WHO [3]. The approach presented in this paper is aimed at all people who cannot capture the necessary ambient information on their own to follow specified paths without additional aid when moving faster than going respectively walking. This means that for example people with residual vision, who can distinguish between brighter and darker areas but are not able to detect contours, are also included.

Traditional aids, as the white cane or guide dogs, which are commonly used for navigation, are not sufficient for faster movements. Currently a visually impaired can only conduct jogging activities by the help of an accompanying person, to whom he or she is connected by a short commonly held ribbon or who informs about the terrain - incline, decline and obstacles - and transmits navigation instructions by audio commands [4]. An entirely self-determined training, independent from time schedules and the availability of a guide, is therefore not possible. Additionally, the dependence on others and the missing possibility to conduct sports on their own could be felt very restricting by the affected people.

The fact that there is a huge number of visually impaired together with the popularity of jogging - according to a survey in 2009 51 percent of the Germans conducted this sport from sometimes up to four times a week [5] - lead to the development of the sensor-guided jogging approach, which is presented in the following. First of all a classification of the jogging navigation system in relation to similar existing approaches is made. In section three the jogging navigation concept and first prototypic realizations are explained in detail. Finally a short conclusion and future work are presented.

## II. Navigation Systems for Visually Impaired

Electronic navigation aids for visually impaired have been developed for some decades and can be divided into the three categories "vision enhancement", "vision replacement" and "vision substitution" [6]. Vision enhancement systems use the input of a camera for displaying the processed information on a head-mounted display as in virtual reality systems, while visual replacement refers to directly transmitting information to the visual cortex, the brain or the optic nerve of humans [6]. The approach that is used in our system corresponds to the vision substitution category, where information is gained as in vision enhancement devices, but the output is provided in a nonvisual manner, for example tactually or audibly [6]. Vision substitution systems can be further classified into "Electronic Travel Aids" (ETAs), "Electronic Orientation Aids" (EOAs) and "Position Locator Devices" (PLDs) [6] although this exact classification is not always applicable to all solutions.

### A. Electronic Orientation and Position Locator Devices

Position Locator Devices (PLDs) are understood in [6] as devices for providing coarse information about the current position, for example by the Global Positioning System (GPS) or other Global Navigation Satellite Systems (GNSS). Current examples for this category are the "NAV4Blind" initiative for enabling a satellite based navigation system for blind users with an accuracy of 0.3 - 0.5 meter [7] or the related "HaptiMap" project, that has the goal to develop haptic, auditory and visual navigation interfaces for available maps, which can also be used by visually impaired [8].

Other electronic aids which deliver global and/or local orientation information for users with visual impairment are devices that allow for example the perception of landmarks like street corners or pedestrian crossings, as described in [9], or indoor positioning as presented in [10].

*Research supported by the Bavarian Ministry of Economic Affairs and Media, Energy and Technology in the framework of the Embedded Systems Initiative (ESI) application center.

C. Ramer, C. Ziegler, S. Reitelshöfer and J. Franke are with the Institute for Factory Automation and Production Systems (FAPS), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany (corresponding author to provide phone: +49-9131-85-27711; fax: +49-9131-302528; e-mail: ramer@faps.uni-erlangen.de).

*B. Electronic Travel Aids (ETAs)*

Existing electronic travel aids which use direct environment information for navigation are based on sonars, laser scanner and/or 2D or 3D cameras and realize feedback transmission to humans via sounds and/or haptic stimulation. Additionally, other sensors as inertial measurement units (IMUs), magnetic field sensors or GNSS integration could be enclosed. Beside the types of sensors used for environment perception and the implemented human-machine-interface, available solutions can be distinguished according their installation. There are for instance hand held or head, shoulder or belly mounted solutions. Available hand held systems which expand the ambient perception for white canes are for example the “Advanced Augmented White Cane” [11] or the purchasable “'K' Sonar Cane” [12]. Other commercially available hand held devices are the “Miniguide” [13] and the “Ultracane” [14]. The “Guidecane” system [15] can also be held like a white cane and changes its direction automatically in the presence of obstacles. There are also different approaches for wearable systems. In [16] a stereo vision based mapping of the 3D space onto a low-resolution 2D array of vibrators is described. The approach in [17] presents a portable sonar navigation system, which delivers information about the distance to nearest obstacles of the environment. “Navbelt” is another ultrasonic based system [18], that transmits information of the surroundings to stereophonic headphones. The “Virtual Acoustic Space” (VAS) device as well uses sound as feedback of the space information, collected by two microcameras [19]. In [20] a “Navigation assistance for visually impaired” (NAVI) is described which is also based on stereo vision.

*C. Classification of the Jogging System*

All systems, we evaluated during our research, focused on walking demands. Mostly no maximum or only slow velocities were specified. Our system mainly refers to local navigation based on current terrain information including possible obstacles on the path or track direction. Therefore it can be classified as an electronic travel aid (ETA) based on vision substitution. As a first test environment a standard running track in sports stadia was chosen, as it offers more structured, repeatable and known conditions than other scenarios. For this environment no global or relative position information related to some starting point is needed. As the system could be expanded to a future use in more general environments, additional position information based on GPS or landmark detection could be integrated to navigate the visually impaired on a pre-planned course.

## III. Jogging Navigation System

The sensor-guided jogging system presented in this paper aims at enabling visually impaired a self-determined and autonomous practicing of this sport by providing navigation instructions based on terrain information. In the next paragraph the system requirements are specified, which are used subsequently in the system concept.

*A. System Requirements*

The jogging system should be designed as a wearable assistive device in order to facilitate jogging movements. Hand held devices are not applicable. The user derived as well as special demands, based on the jogging, respectively running, application, are summarized in the following.

User based requirements

- small-sized and compact system design
- light-weight system
- simple and easy-to-use human-machine-interface including an intuitive navigation feedback
- pleasant wearing comfort
- adequate battery operation time
- embedded system with all processing power onboard
- preferably no motion restrictions by the use of the system
- cheap system

Safety requirements

- fast data processing with low latencies as the moving velocity is fast
- reliable system under existing conditions
- reasonable shock resistance
- indoor and outdoor usability, i.e. use under different weather conditions with sun, rain, humidity, low and high temperatures

*B. Jogging Navigation Concept*

The first task of the jogging assistive device is the detection of course limitations for returning feedback information to the athlete. The wearer of the system should be able to navigate on a pre-planned path. Initially only standard running tracks are considered as test environments, later an extension to other outdoor paths is desirable. Therefore as a first function a course detection component has to perceive and identify the boundaries, as the white lines, of a running track. The second function is the recognition of possible collision objects on the planned track to realize collision avoidance strategies, as slowing down or stopping the person for safety reasons. The third component has to transmit all output information, the navigation instructions, including next orientations, velocities and emergency stops, to the jogger in an intuitive way. An overview of the whole system concept is given in Fig. 1.

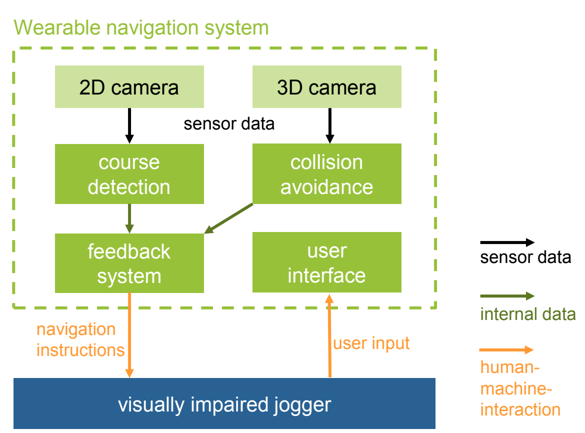


Figure 1. Concept of the functions of the jogging navigation system and the three main subsystems.

The three main modules have to be integrated functionally into a whole system structure for data exchange. First, different physical realizations are presented below. In the following sections the main subsystems are described in detail.

## C. Camera Based Course Detection

The course detection has to realize an online lane keeping of the jogger. For this reason a real-time computation of the current orientation of the person has to be determined in relation to the course boundaries to generate correction values. A perception of usual courses can only be done by the use of camera systems and image processing if no additional installations - as special transmitters which can be detected by other sensor types - shall be applied. In our approach we fix a camera at the body center of the jogger. In first tests we chose a chest position and used an adjustable GoPro belt, which is designed for the installation of action cameras. Fig. 2 shows the system setup, we used for a test series of the course detection with 20 probands.

Figure 2. Test setup of the course detection, worn by a test person, with the Asus camera, attached with a modified GoPro belt, the belt based feedback system and a laptop in a rucksack as processing unit.

As optical sensors the integrated camera of a Nexus 4 smartphone, different low-priced webcams and an Asus Xtion PRO LIVE camera were attached to the belt. The available GoPro connection enables the relatively easy application of other camera specific mounts, e.g. by the use of polymer based rapid-manufacturing technologies.

For detecting the boundaries of the jogging track, which are represented as edges, the well-known Canny algorithm according to [21] is used. On the resulting edges a probabilistic Hough transform algorithm, described in [22], is applied to generate line segments. As these algorithms not always provide the whole boundaries, they are concatenated to complete lines and prolonged to the picture bounds, which is illustrated in the left image of Fig. 3 for an indoor test course. In the next step the inner lines - as we conduct our first tests on a standard running track, at least four lines should be found - are calculated and assumed to be the actual guidance lines. The center of the picture is supposed to be in accordance with the bisector of the path if there is no lateral inclination of the person. Therefore the relative difference of the image center and the path bisector, reconstructed from the inner lines of the jogging track and normalized to the path width, is determined at the image bottom and saved for the last few frames. The calculated complete inner and outer boundary lines, composed of separate segments, are shown in the centered image of Fig. 3 as well as the image center for the indoor test route. The right picture in Fig. 3 shows the boundary lines, the bisector of the inner lines (in green), the image center (in red) and the current normalized difference value (in red) for a jogging navigation test on a real running track. The average difference of the last image frames is used for generating a feedback signal, a new orientation correction value, for the visually impaired jogger. For the first course detection and correction value generation tests, using a smartphone, an Android app was developed. Additionally different webcams and the Asus Xtion PRO LIVE together with a laptop were deployed on the basis of the Robot Operating System (ROS) for integrating different modules and realizing easy data exchange. In both applications the freely available computer vision library OpenCV (see [23]) is used for edge and line detection. During first tests different sounds served as feedback signal for a seeing person with covered eyes. The results showed that it is principally possible to follow a standard running track in this way, even though audio feedback alone is not the optimal solution, as it is not intuitive. The user has to learn in advance the right interpretation of the signal and must concentrate on the sound. Therefore the orientation feedback is transmitted via vibrotactile signals as described in paragraph E.

## D. 3D Camera Based Collision Avoidance

In addition to the course detection, possible obstacles on the jogging path have to be identified to realize collision avoidance strategies, as alerting and slowing down or stopping the visually impaired. 2D cameras, which deliver intensity values of the environment light, are well suited for boundary lines detection in daylight.

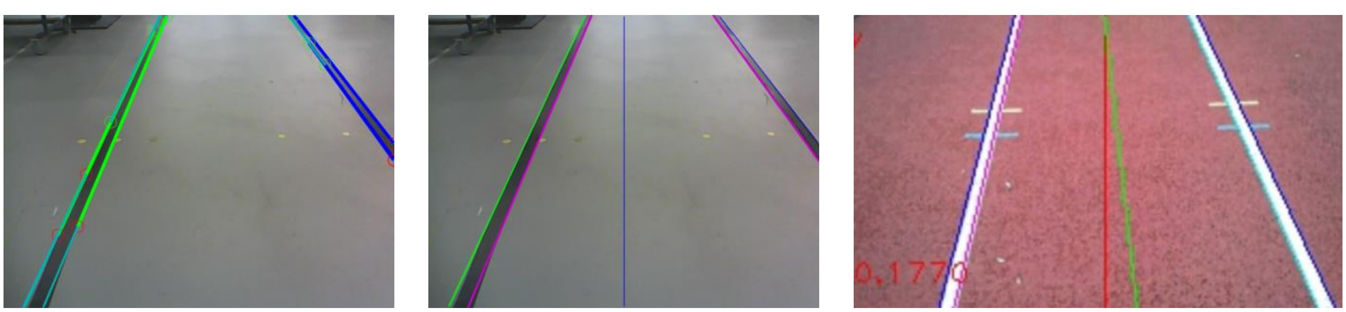

Figure 3. Course detection: In the left picture separate line segements (green and darker blue lines) of the whole course boundaries are recognized by the combination of the Canny and Hough algorithms on an indoor test track. These segments are aggregated to complete inner and outer lines in the second picture. The blue centered line denotes the bisector of the picture width. In the right picture on a second test route, a standard outdoor running track, the boundary lines recognition, together with their bisecting line (in green), are calculated. The relative difference of the current (green line) to the center position (red line) is shown at the picture bottom (red value), which is used for the orientation command in the feedback.

The perception of obstacles is very difficult based on gray level differences, which can represent real obstacles or shadows. Another principal possibility are ultrasonic sensors, that are used in existing ETAs as described in section two. They deliver the shortest distance to objects by the runtime of sound. Problems are multiple reflections and the one-dimensional measurement. During a jogging movement it would be complicated to distinguish between the actual ground and small obstacles lying on the path. 3D vision enables to differentiate between fore- and background much easier by generating a distance information to objects. Therefore our system is based on that principle. One possibility to get distance information by time of flight (ToF) measurements of light are laser scanners, that are already available in safe technology. Drawbacks are moving parts of the system and relatively long capture time for the 3D case or very high cost and high weight. Another option are stereo cameras, that are already used in present ETAs. Associated problems could be the dependence on textured surfaces to find corresponding pixels in different camera images and the fast sensor movement in the considered application. As from available cameras binocular stereo vision systems can be developed cheaply compared to other solutions, according to the special demands of the jogging scenario, this is one approach we are pursuing.

Another very promising possibility are 3D cameras, based on the time of flight or structured light principle, which became available in the last few years, as shown e.g. in [24]. Tab. 1 provides an overview of 3D cameras which were evaluated with respect to the requirements specified in paragraph A. One important characteristic regarding safety is the sensor range, as jogging or running people achieve velocities between 1.3 m/s (5 km/h) and 5.6 m/s (20 km/h). Supposing a reaction time of one second, a standard athlete with 10 km/h moves around 2.8 meter, excluding the processing time of the navigation system, until slowing down when he or she recognizes an obstacle. Except the newer Kinect, that was not available at that time, and the Asus Xtion PRO LIVE, all listed cameras were tested for maximum range under summer conditions outdoors against direct strong sunlight. These assumptions constitute special problems for 3D cameras, as too much sunlight can lead to oversaturation of the optical sensors or interference with the emitted infrared light signal. The tests showed that cameras with light emitting diodes (LEDs) as active illumination had inferior performance in comparison to those with laser light. The tested maximum achievable range with usable distance information can be found in the brackets value “(sun)” of column “range” in Tab. 1. The nominal range values are extracted as well as the other information from the camera data sheets. The older Kinect camera, that shares the same sensor with the Asus Xtion PRO LIVE, yields generally very good distance values indoors and outdoors if there is no strong sunlight. As a consumer product it is, as well as the Asus, very cheap. In our test environment with direct strong sunlight it mostly did not yield any usable distance value and is therefore not applicable under such conditions. The cameras’ field of view is also important to cover an ample area in front of the system user. Important features regarding the prior defined user requirements are weight, dimensions and costs. The best performance under environment conditions with strong sunlight was noticed for the heaviest-weight camera, the ifm 03D201, with distances up to five meter. The Fotonic 70E delivers a good range and disposes of medium weight but is relatively high-priced. Both Kinect versions deliver good outdoor range values without much sunlight with around 4.3 and 4.8 meter. The newer camera is bulkier but offers distance images with a higher effective resolution and lightly major range. Its performance under direct strong sunlight has not yet been tested. One special problem of the Blue Technix camera is that it becomes very hot after short usage. There are also other available ToF cameras, as the real.iZ from odos imaging or the CamBoard nano from PMDTechnologies, that were not tested more extensively for this application due to their high weight or short nominal range. The evaluation of commercially available 3D cameras showed that no present system meets all specified requirements perfectly. For this reason the light-weighted and low-priced Asus camera is chosen as obstacle detection sensor for first tests. It delivers depth and color information of the environment and can therefore also be used for course detection in a compact, integrated sensor system. As the deployed software algorithms are independent of the specific hardware, they can be easily ported to other cameras in the future.

TABLE I. COMPARISON OF CURRENTLY AVAILABLE 3D CAMERAS AS WEARABLE OBSTACLE PERCEPTION SENSORS DURING JOGGING

| ***3D camera system*** | ***Supplier*** | ***Functional principle*** | ***Weight [g]*** | ***Dimensions [mm]*** | ***Field of view (vertical x horizontal) [°]*** | ***Depth resolution [pixel]*** | ***Range [m] nominal (sun)*** | ***Cost (ca)*** |
|---|---|---|---|---|---|---|---|---|
| **Argos 3D P100** | Blue Technix | Time of Flight | 140 | 75 x 57 x 27 | 45 x 90 | 160 x 120 | 3 (3) | 850 EUR |
| **03D201** | ifm Electronics | Time of Flight | 1185 | 75 x 124 x 95 | 40 x 30 | 64 x 48 | 6.5 (4-5) | 850 EUR |
| **SwissRanger SR4000** | MESA | Time of Flight | 510 | 65 x 65 x 76 | 56 x 69 | 176 x 144 | 0.1-10 (3) | 5000 - 10000 USD |
| **70E** | Fotonic | Time of Flight | 800 | 80 x 80 x 86.3 | 53 x 70 | 160 x 120 | 0.1-7 (3-4) | 1500 - 2000 EUR |
| **Kinect** | Microsoft | Structured light | 560 | 283 x 58 x 38 | 43 x 57 | 640 x 480 (effective res. lower) | 0.8-4 (0) | 100 EUR |
| **Kinect 2** | Microsoft | Time of Flight | 680 | 250 x 58 x 67 | 60 x 70 | 512 x 424 | 0.8-4 (-) | 400 USD |
| **Xtion PRO LIVE** | ASUS | Structured light | 220 | 178 x 35 x 50 | 45 x 58 | 640 x 480 (effective res. lower) | 0.8-3.5 (-) | 150 EUR |

The Asus Xtion PRO LIVE camera yields point clouds with a nominal resolution of 640 x 480 pixel. To fasten further calculations, in a first step the data size is reduced by applying voxel grid filtering according to [25]. Thereby a grid of equally sized cubes is laid over all 3D points, which are approximated by their centroid. In our application we choose a voxel size of 0.05 meter edge length. This has the advantage that all point areas possess the same density, which directly relates their number of points to their size. Additionally outliers are detected and removed by the statistical outlier removal filter, that determines erroneous pixels on the basis of their differing distance mean and standard deviation to neighboring pixels under the assumption of a Gaussian distribution (see [26]). In the next step object points are separated from ground points by applying the RANSAC (random sample consensus) algorithm described in [27] for ground plane segmentation based on calculations including the surface normal. This results in a ground and a second point cloud, which contains all possible obstacles. Subsequently the obstacle point cloud is divided into three horizontal regions, one central area for the actual jogging trail and one lateral on each side. The width of the central region can be chosen according to the running course, for the test track it is assigned to 1.5 meter. Additionally it would be possible to distinguish between different vertical regions to detect possible obstacles in the upper sector, e.g. low hanging tree branches, or objects on the ground and implement appropriate reaction strategies. For generating single objects, all points of the three horizontal regions are spatially decomposed by a kd-tree for finding the nearest neighbors and split into different clusters based on an Euclidean distance metric according to [28]. To avoid constructing too small objects, a minimum size of 30 points and a distance of 0.07 meter between different clusters is applied. All objects of significant size, which are detected in the central horizontal region, lead to an immediate stop of the jogger. Lateral obstacles can be tracked and classified as static or dynamic and can cause slowing down or also completely stopping the visually impaired if necessary. For implementing the object detection algorithms the Point Cloud Library (PCL) (see e.g. [29]), a free 3D point cloud processing library, in combination with ROS is used.

The obstacle detection has been tested in an indoor environment as stand-alone system, with the Asus camera attached to a test person by the modified GoPro belt. During walking and jogging different sized obstacles could be determined by the use of a desktop computer (dual core with 3.33 GHz, 4 GB RAM) with 8 frames per second, respectively 16 by a coarser resolution.

### *E. Feedback System*

The feedback information generated by the system, consisting of navigation instructions and collision warnings, has to be transmitted to the jogger in a simple and intuitive way. A vibrotactile feedback, that can be perceived without usage of the acuesthesia and therefore allowing e.g. conversing during jogging, and additionally audio warnings have been deployed. In order to meet the user requirements concerning pleasant wearing comfort and no mobility constraints, two main attachment principles are designed: a belt and a shoulder-breast based system. Fig. 4 shows the first prototypic realization of the belt based feedback system. The actual vibration is performed by small vibration motors, as they can be found in standard smartphones for vibration alarm. To ensure sufficient sensing resolution six motors are distributed over the waist width and sewed to a flexible standard running belt, which can be adjusted to the individual body size of the person.

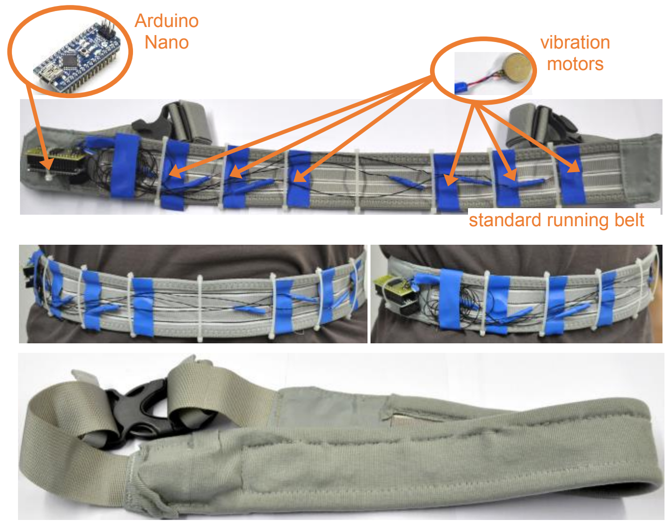


Figure 4. First prototpye of the belt feedback system, based on a standard running belt, six vibration motors and an Arduino Nano. The three pictures at the top show the motors only fixed by tape, in the subsequent version (image at the bottom) they are sewed into inlets by flexible fabric.

The small flat coin DC vibration motors (“VPM2” from Solarbotics) have a diameter of 0.012 meter and 0.0034 meter thickness and an operating voltage between 2.5 and 3.5 volts. With pulse width modulation (PWM) the rotation frequencies and thereby the intensities of the motors are controlled. An Arduino Nano board with an ATmega328 microcontroller serves as interface node to the course detection and collision avoidance modules to determine the applied voltage for each motor. For interfacing ROS with the Arduino board and passing ROS messages, rosserial is used. An electronic circuit with a 4096-step PWM module from Texas Instruments is applied, for being able to control up to 16 motors concurrently. The positions, number and frequencies of the vibrating motors transmit new orientation commands to the jogger. All motors vibrate if a possible collision object is detected on the track together with a planned acoustic warning. At the moment user tests are being conducted to get optimal parameters, as distinguishable vibration frequencies and maximum intensities, for enabling keeping track of the course.

The second feedback version, the shoulder-breast system, consists of a standard GoPro belt attached with eight vibration motors on different positions on the breast and back. This layout enables the possibility to additionally transfer information, as for instance just slowing down the visually impaired by two additional motors, when dynamic obstacles approach. Both systems are designed as test prototypes and will be evaluated for further optimizations. These layouts are selected as they offer a convenient wearability and a compact system design. Belts are usual solutions for attaching small bags or bottles during jogging or running. Therefore this position is not supposed to be regarded annoying by the user. Also the commercially available shoulder-breast camera mounting system is commonly employed. For this second feedback version molding of the electronic parts and of all motors in silicone for protective reasons is evaluated. The use of other options, as fingertip feedback systems, where the sensing resolution is very high, are not chosen as this possibility together with gloves could be felt unpleasant in summer. First tests showed the functional feasibility of both feedback versions.

To evaluate the course detection in combination with the first realized feedback system, a test series with 20 sighted people was conducted on a running track. Every test person had to walk and jog one lap with closed eyes and different feedback implementations. The feedback consisted one time of following the direction of vibration and the other time of following the opposite direction. The participants were able to follow the navigation commands given by the feedback, after a short instruction. No preference could be identified for one version. The probands tended to somewhat ignore the orientation correction signal when they thought being correctly on a straight route. Therefore the audio feedback could additionally inform about situations where stronger orientation changes are necessary, e.g. in curves or later at crossways.

## IV. Conclusion

In this paper the conceptual design and first prototypic implementations of a wearable jogging navigation system for visually impaired and blinds enabling jogging activities are presented. The different realized components - the course detection, the collision avoidance and the feedback modules - confirmed the principle feasibility of the concept. Future work addresses choosing optimal processing hardware, enabling course detection for more general tracks and improving the system according to user tests. Optimizations aim at ensuring reliable obstacle detection and avoidance and robust intuitive navigation feedback, as by accelerating the software algorithms and evaluating the use of special hardware as FPGAs (Field Programmable Gate Arrays). Beside the most important safety issues, also an easy to use human-machine-interface has to be developed and long-term-stability has to be reached to achieve user acceptance.

## References


[1] B. Bertram, "Blindheit und Sehbehinderung in Deutschland: Ursachen und Häufigkeit," Der Augenarzt, vol. 39, no. 6, 2005.

[2] "International statistical classification of diseases, injuries and causes of death, tenth revision," Geneva, 1993.

[3] Deutscher Blinden- und Sehbehindertenverband e.V. (DBSV), Definition Blindheit/Sehbehinderung. Available: http://www.dbsv.org/infothek/zahlen-und-fakten/ (2014, Feb. 11).

[4] H. Beier, "Sport und Spiele: für blinde und sehbehinderte Menschen," Munich, Nov. 2004.

[5] Deutsche Angestellten-Krankenkasse (DAK), Wie oft gehen Sie joggen? Available: http://de.statista.com/statistik/daten/studie/6583/umfrage/joggen-haeufigkeit-2009/ (2014, Feb. 11).

[6] D. Dakopoulos and N. G. Bourbakis, "Wearable Obstacle Avoidance Electronic Travel Aids for Blind: A Survey," Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on, vol. 40, no. 1, pp. 25–35, 2010.

[7] Kreis Soest, Initiative NAV4BLIND. Available: http://www.nav4blind.de/nav4blind/initiative/117060100000059328.php (2014, Feb. 11).

[8] C. Magnusson, HaptiMap project, FP7-ICT-224675. Available: http://www.haptimap.org/ (2014, Feb. 11).

[9] K. Koshi, H. Kani, and Y. Tadokoro, "Orientation aids for the blind using ultrasonic signpost system," in Engineering in Medicine and Biology, 21st Annual Conference and the 1999 Annual Fall Meeting of the Biomedical Engineering Society BMES/EMBS Conference, 1999, p. 587.

[10] T. Gallagher, E. Wise, L. Binghao, A. G. Dempster, C. Rizos, and E. Ramsey Stewart, "Indoor positioning system based on sensor fusion for the Blind and Visually Impaired," in Indoor Positioning and Indoor Navigation (IPIN), 2012 International Conference on, 2012, pp. 1–9.

[11] R. Pyun, K. Yeongmi, P. Wespe, R. Gassert, and S. Schneller, "Advanced Augmented White Cane with obstacle height and distance feedback," in Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on, 2013, pp. 1–6.

[12] Zabonne Ltd, A portable Electronic Travel Aid: The 'K' Sonar. Available: http://zabonne.co.nz/?action=product&id=10458&category=10049 (2014, Feb. 11).

[13] GDP Research, The Miniguide mobility aid. Available: http://www.gdp-research.com.au/minig_1.htm (2014, Feb. 11).

[14] Sound Foresight Technology Limited, Ultracane. Available: http://www.ultracane.com/ (2014, Feb. 11).

[15] I. Ulrich and J. Borenstein, "The GuideCane-applying mobile robot technologies to assist the visually impaired," Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, vol. 31, no. 2, pp. 131–136, 2001.

[16] N. Bourbakis, S. K. Makrogiannis, and D. Dakopoulos, "A System-Prototype Representing 3D Space via Alternative-Sensing for Visually Impaired Navigation," Sensors Journal, IEEE, vol. 13, no. 7, pp. 2535–2547, 2013.

[17] D. Aguerrevere, M. Choudhury, and A. Barreto, "Portable 3D Sound / Sonar Navigation System for Blind Individuals,"

[18] S. Shoval, J. Borenstein, and Y. Koren, "The NavBelt-a computerized travel aid for the blind based on mobile robotics technology," Biomedical Engineering, IEEE Transactions on, vol. 45, no. 11, pp. 1376–1386, 1998.

[19] González Mora, J. L, A. Rodríguez Hernández, E. Burunat, F. Martin, and M. A. Castellano, "Seeing the world by hearing: Virtual Acoustic Space (VAS) a new space perception system for blind people," in Information and Communication Technologies, 2006. ICTTA '06. 2nd, 2006, pp. 837–842.

[20] F. Wong, R. Nagarajan, and S. Yaacob, "Application of stereovision in a navigation aid for blind people," in Information, Communications and Signal Processing, 2003 and Fourth Pacific Rim Conference on Multimedia. Proceedings of the 2003 Joint Conference of the Fourth International Conference on, 2003, pp. 734–737.

[21] J. Canny, "A Computational Approach to Edge Detection," Pattern Analysis and Machine Intelligence, IEEE Transactions on, vol. PAMI-8, no. 6, pp. 679–698, 1986.

[22] J. Matas, C. Galambos, and J. Kittler, "Robust Detection of Lines Using the Progressive Probabilistic Hough Transform," Computer Vision and Image Understanding, vol. 78, no. 1, pp. 119–137, 2000.

[23] G. Bradski, "The OpenCV Library," Dr. Dobb's Journal of Software Tools, 2000.

[24] C. Ramer, S. Reitelshöfer, and J. Franke, "Automatisierte Pfadgenerierung und Kollisionsüberwachung für Sechsachs-Industrieroboter durch 3D-kameragestützte Umgebungserfassung," in Kongress Automation: Automation (in the) cloud, 2013.

[25] M. Munaro, F. Basso, and E. Menegatti, "Tracking people within groups with RGB-D data," in Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on, 2012, pp. 2101–2107.

[26] R. B. Rusu, Z.-C. Marton, N. Blodow, M. Dolha, and M. Beetz, "Towards 3D Point cloud based object maps for household environments," Robotics and Autonomous Systems, vol. 56, no. 11, pp. 927–941, 2008.

[27] M. A. Fischler and R. C. Bolles, "Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography," Communications of the ACM, vol. 24, no. 6, pp. 381–395, 1981.

[28] R. B. Rusu, "Semantic 3D Object Maps for Everyday Manipulation in Human Living Environments," Computer Science department, Technische Universitaet Muenchen, Germany, 2009.

[29] R. B. Rusu and S. Cousins, "3D is here: Point Cloud Library (PCL)," in Robotics and Automation (ICRA), 2011 IEEE International Conference on, 2011, pp. 1–4.