Original article

Navigation and space perception assistance for the visually impaired: The NAVIG project

Assistance à la navigation et à la perception de l'espace pour les déficients visuels : le projet NAVIG

S. Kammoun [a], G. Parseihian [c], O. Gutierrez [a], A. Brilhault [a,b], A. Serpa [a], M. Raynal [a], B. Oriola [a], M.J.-M. Macé [a], M. Auvray [c], M. Denis [c], S.J. Thorpe [b], P. Truillet [a], B.F.G. Katz [c], C. Jouffrais [a,*]

[a] *CNRS, UMR 5505, équipe ELIPSE, IRIT, université Toulouse-3 Paul-Sabatier, 118, route de Narbonne, 31062 Toulouse cedex 9, France*
[b] *CerCo, CNRS, université Toulouse-3 Paul-Sabatier, 31062 Toulouse cedex 9, France*
[c] *LIMSI-CNRS, université Paris Sud, 91403 Orsay, France*

Abstract

Navigation, especially in unknown areas, remains a major problem for the visually impaired (VI). Over the past 50 years, a number of electronic travel aids (ETAs) have been developed with the aim of improving the mobility of the VI. Despite the efforts, these systems are rarely used. Although the explanation is likely to be incomplete, it is possible to identify three important factors: (1) positioning accuracy provided by these devices is not sufficient to guide a VI pedestrian, (2) these systems are based on Geographical Information Systems not adapted to pedestrian mobility, and (3) the guidance methods should be adapted to the task of pedestrian navigation. The NAVIG project aims to answer all these limitations through a participatory design framework with the VI and orientation and mobility instructors. The NAVIG device aims to complement conventional mobility aids (i.e. white cane and guide dog), while also adding unique features to localize specific objects in the environment, restore some visuomotor abilities, and assist navigation.

Résumé

La navigation, notamment dans des endroits inconnus, reste un problème majeur pour les déficients visuels. Durant les 50 dernières années, plusieurs dispositifs électroniques d'aide à la mobilité et à l'orientation ont vu le jour avec comme objectif d'améliorer l'autonomie des déficients visuels au cours de leurs déplacements. Malgré les efforts fournis, ces systèmes sont très peu utilisés. Bien que le constat soit probablement incomplet, il est possible d'identifier trois facteurs importants : (1) la précision du positionnement fourni par ces dispositifs est insuffisante pour guider un piéton déficient visuel ; (2) ces dispositifs reposent sur des systèmes d'information géographique non adaptés au déplacement des piétons ; (3) les méthodes de guidage proposées sont souvent sommaires et devraient être adaptées à la tâche de navigation piétonne. Le projet NAVIG a pour objectif de répondre à toutes ces limitations à travers un cadre de conception participative avec les déficients visuels et les formateurs en orientation et mobilité. Le dispositif conçu vient en complément des techniques classiques d'aide à la mobilité (i.e. la canne blanche et le chien guide) et ajoute des fonctions uniques permettant de détecter des objets dans l'environnement, restaurer des capacités visuomotrices et assister la navigation.

* Corresponding author.
  E-mail addresses: kammoun@irit.fr (S. Kammoun), gaetan.parseihian@limsi.fr (G. Parseihian), gutierrez@irit.fr (O. Gutierrez), adrien.brilhault@cerco.ups-tls.fr (A. Brilhault), serpa@irit.fr (A. Serpa), raynal@irit.fr (M. Raynal), oriola@irit.fr (B. Oriola), mace@irit.fr (M.J.-M. Macé), malika.auray@limsi.fr (M. Auvray), michel.denis@limsi.fr (M. Denis), simon.j.thorpe@cerco.ups-tls.fr (S.J. Thorpe), truillet@irit.fr (P. Truillet), brian.f.g.katz@limsi.fr (B.F.G. Katz), jouffrais@irit.fr (C. Jouffrais).

1. Introduction

Human navigation is a very complex process that mainly relies on vision. As such, for the majority of visually impaired (VI) people, walking in unknown places can be a very difficult task to perform. It is commonly accepted that the inability to move freely and independently can hinder the full integration of an individual into society [1]. In order to solve this problem, many research groups and companies have proposed devices dedicated to assisting navigational tasks. Electronic Travel Aids (ETAs) are designed to help the VI in detecting nearby obstacles, often based on ultrasonic or laser telemeters [2] or, more recently, on computer vision [3]. Electronic Orientation Aids (EOAs) are a second category of devices that provide the VI with some degree of situational awareness and guidance in unknown environments, dealing with more distant environments, aiding in a task sometimes called macronavigation. A review in 2009 of existing electronic mobility aids for the VI identified 146 devices, providing details on 21 commercially available systems that can be used without environmental adaptations [4]. The authors noted that many of the reviewed products are no longer available or are prototypes that are in development or failed to reach the market. Although future research should thoroughly investigate the reasons for the failure of products to come or to remain on the market, a few issues seem obvious: the lack of precision in the positioning component of EOAs, insufficient output interaction, and inadequacies between the system's functionality and the needs of the VI.

The NAVIG project (Navigation Assisted by embedded VIsion and GNSS, 2009–2012)[1] was created in an attempt to address some of these issues. The aim was to design and evaluate a powerful assistive device combining both micro- (sensing the immediate environment) and macronavigation (reaching a remote destination) functions. The micronavigation functions serve to restore a set of sensorymotor behaviors based on visual objects localization. The macronavigation functions provide the user with global orientation and navigation skills. This paper is an overview of the project that roughly describes the main work packages with their specific objectives, indicating pointers to detailed publications where additional details can be found.

2. Related work

The term 'navigation' defines the behavior of moving towards a destination, with all the motor, sensory, and cognitive processes that it implies. Downs and Stea [5] offer the following definition: "the process of solving one class of spatial problems, the movement of a person from one location on the earth's surface to another." They divided the process into four tasks:

- orienting oneself in the environment;
- choosing the route;
- keeping on track;
- recognizing that the destination has been reached.

Orientation and mobility are essential skills to the success of a navigation task. Mobility or micronavigation corresponds to obstacle avoidance in the immediate environment. Orientation or macronavigation is the ability to establish and maintain awareness of one's position in space relative to both landmarks in the surrounding environment and to the intended destination [6]. Obviously, both orientation and mobility (O&M) skills depend highly on vision. Several alternative projects have been carried out over the last four decades in order to develop aides for helping VI persons in navigation tasks.

The MoBIC project [7] (mobility for blind and elderly people interacting with computers) was presented as a set of tools designed to address journey preparation and outdoor navigation issues. It was made of two components:

- the MoPS pre-journey system allows travelers to plan a journey by accessing information about the environment around the itinerary. This is done on a personal computer with input/output interaction adapted to VI users (e.g. Braille display, synthetic speech);
- the MoODS outdoor system provides traveler's assistance during the journey.

The evaluations of the MoBIC system have shown that it is primarily limited by the lack of details in the GIS database and the necessity to combine data extracted from different sources.

A significant project in assisted navigation for the VI was conducted by Loomis, Golledge, and Klatzky over a period of twenty years. Their goal was the development of a personal guidance system (PGS) for the blind [8]. The PGS system included three modules:

- a module for determining the position and orientation of the traveler using a differential GPS (DGPS);
- a Geographical Information System (GIS) module;
- and the user interface. Several evaluations were conducted, demonstrating the effectiveness of such a device to help VI person to navigate.

They especially made important advances in the introduction of 3D sound based guidance interfaces [9]. Regarding outdoor positioning they suggested using DGPS. Differential GPS improves the accuracy of the GPS to about 10 cm in the best of cases. Unfortunately, it relies on a network of fixed, ground-based reference stations that are not publicly available everywhere. In addition, the receptor is cumbersome, expensive, heavy and hence not adapted to VI users' assistance.

The Drishti system, presented in 2001 by Helal et al. [10], is a pedestrian navigation system. It integrates a wearable computer with voice recognition and synthesis, wireless communication, a Geographic Information System (GIS) and a Global Positioning System (GPS). Drishti is designed to enhance the user's real world navigation experience. It augments the surrounding environment via a vocal interface that gives contextual information. Evaluations have demonstrated that GPS is not accurate enough to precisely locate a pedestrian. In order to improve positioning, the authors proposed to use dead reckoning techniques

---

based on a magnetic compass, the user's average travel speed and additional rules specified in the GIS database (e.g. map matching).

More recently, another type of assistive devices based on remote guidance was proposed [11,12]. These devices are composed of two terminals; one for the blind user and one for a remote assistant connected via a GSM and Internet link. This connection is used for video and GPS data transmission, as well as duplex audio communication between the terminals. The GPS location of the blind traveler and real time video captured from the embedded camera are displayed on the operator's terminal. The operator can help the traveler to navigate to a destination and warn about obstacles. The evaluation of the remote assistance system presented in [11] has shown that the prototype frequently suffers from poor connection quality, e.g. the remote operator could not assist the blind user in critical tasks such as walking across a zebra crossing with no traffic lights.

In 2010, the NAVIG system was presented [13], with additional details in [14]. The specific objectives of the NAVIG project were multiple: analyzing the behavior and the needs of VI pedestrians during navigation tasks, improving global positioning to make it compatible with guidance for the VI, developing embedded vision for both micro- and macroguidance, designing non visual feedback output based on audio augmented reality and evaluating a functional prototype in challenging situations.

3. NAVIG project overview

3.1. Consortium

NAVIG brings together two research laboratories in computer science and information technology and one research laboratory in human perception. IRIT-Elipse, the project leader, is an interdisciplinary research group in Human Computer Interaction (HCI). The team is especially active in the field of assistive technology for the VI. LIMSI-Audio & Acoustic team is involved in acoustics, spatial hearing, and auditory augmented reality while the LIMSI-CPU team specialized in spatial cognition and perception. The Brain and Cognition Laboratory (CerCo) has worked for many years on human visual perception and modeling of human vision. The consortium also includes two companies active in the field of mobility aid for pedestrians, vehicles, and paratroopers (Navocap) and artificial embedded vision (SpikeNet Technology). The final partner is the Toulouse center for education of the VI (CESDV-IJA). The Grand Toulouse community supports the project, mainly by providing technical resources (e.g. GIS of Toulouse, FR).

3.2. Project management and communication

NAVIG is a project that includes an important set of actors in multiple remote locations. In addition, it is a "user-centered" project in which it is important to maintain a permanent connection between researchers and end users (i.e. participatory design, experimentations, and evaluations). Based on this observation, the project leader implemented a set of tools for coordination,

management support, communication between different actors, and project promotion.

For coordination and management, an intranet site was developed as a collaborative portal (e-groupware). This portal enables the exchange and archiving of all the project documents (contacts, calendar, text and multimedia files, etc.).

Regarding communication and promotion, implemented a public website (http://navig.irit.fr) was also created, receiving 127,223 visits over 3 years of existence. Finally, for improving the connection between end users and researchers involved in the project, several other communication elements were established:

- a private internet forum;
- several monthly live exchange sessions via Skype instant messaging software;
- an annual meeting and social event;
- a annual newsletter containing all the highlights and the status of the various aspects of the project.

3.3. Participatory design

Participatory design is an approach that can help in the design of usable systems. It is a process that starts with the analysis of users needs rather than with technology [15]. It also requires that designers evaluate physical devices, as well as communication and action modalities in order to examine how users employ them in their activities. The aim is to evaluate usability, effectiveness, efficiency of a device as well as user's satisfaction. It appears to be especially important when aiming to design for people with special needs.

3.3.1. Participants

In the NAVIG project, we have adopted a long-term user-centered design approach in collaboration with the Institute of Young Blinds (CESDV-IJA, Toulouse). A panel of 21 VI users has been involved during all design steps. These users have been selected using several criteria, including motivation to participate in the project, self-sufficiency in O&M, and some degree of practice with new technologies. The subjects in the panel were between 16 and 65 years old; eight females and 13 males. They were all legally blind: eight were blind from birth, seven before the age of five and six becoming blind later in life. They reside in the Toulouse region and declared being available for the whole project duration.

3.3.2. Analysis: user, task, context

The primary aim of the NAVIG system was to help VI people improving their daily autonomy and their ability to mentally represent their environment. The goal is thus to complement and go beyond what is possible with the use of traditional assistive devices (e.g., white cane or guide dog) and not to replace them. As an example, VI people use most of the time egocentric spatial representation strategies [16–18]. This involves that the various paths they know throughout their environment are well learned. However, the integration of these different paths into a global representation of the city, which is necessary for route variations, such as detours, shortcuts, and reorganizations

of the journey, requires a significant level of additional effort from the individual, more important than for sighted people. Thus, designing an assistive device for VI people requires taking into account the perceptual specificities of these individuals together with the problems they usually face, and the specific needs the device should respond to. In order to achieve these goals, the CESDV-IJA was actively involved in the ergonomic experiments and prototype evaluations ([14] for further details on the participatory design phases).

The brainstorming sessions and discussions with VI users highlighted that an ideal system has to provide the best-suited level of audio guidance information: minimal without excess, presenting only what is necessary and sufficient to aid the user. In addition, the information provided should be highly efficient, minimally intrusive, and should be adaptable to the current conditions and individual user needs and preferences. These guidelines, which aim both at contributing to the construction of more reliable cognitive spatial representations and to a reduction in the level of anxiety during pedestrian journeys in unfamiliar environments have been taken into account in the design of the output interaction.

3.4. Embedded artificial vision

The vision module of the NAVIG system is designed to extract relevant visual information from the environment. The user is equipped with head-mounted stereoscopic cameras providing images of the surroundings. The images are processed in real-time by an object localization algorithm, based on pattern matching, called SpikeNet Vision (SpikeNet Technology, Inc.). The vision module includes two functions for object localization and user positioning, which both rely on the estimation of the distance between the target and the user by stereovision methods. In the object localization mode, the system looks for an object requested by the user (e.g. a mailbox), which is dynamically augmented with a virtual 3D sound. This function hence restores a functional visuomotor loop between the object and the user, and allows a VI user to move his body or his hand to targets of interest (Fig. 1) [19]. In the user-positioning mode, the system looks for geolocated landmarks tagged in the GIS. During the journey, according to the estimated location of the user, models corresponding to nearby targets are automatically loaded (e.g. signs, facades, logos, etc.). When detected, these visual landmarks (called visual reference points) are not rendered to the user but are used to refine the current GPS position (Fig. 2) [20]. This function can provide a position estimate relying exclusively on embedded vision. It can then be fused with GPS data to improve positioning; it can also be used in situations where the GPS positioning is faulty or absent.

3.5. Pedestrian positioning issues

3.5.1. Adapted geographical information system

The absence of pedestrian features in databases represents a major challenge to the effectiveness of Geographical Information System (GIS) based personal guidance system [21]. It is obvious that the presence of walking pathways (e.g. sidewalks

Fig. 1. Picture of a user with the NAVIG prototype. The camera view is shown in inset in the right corner. The user interacts with the system via voice recognition; in this case, he would like to grab his phone, the system then activates the search of the corresponding models. The phone is detected in the camera view (rectangle in the inset). A dynamic virtual sound indicating the object position is provided to the user.

and pedestrian crossing) would be valuable to guide VI users. So, one of the main problematic issues in the design of EOAs is that the map is optimized for car and not for pedestrian navigation. Even commercial navigation systems specifically developed for VI do still rely on map data optimized for car navigation. Several studies have been carried out to improve the accuracy of embedded maps designed to be used in EOA [7,8]. In the NAVIG project, two different classes of objects were added in the GIS:

- data used for more accurate navigation and space perception [14];
- data used for user positioning (visual reference points).

In addition to the GIS database, several improvements to the route selection procedure have been proposed [22].

3.5.2. GPS and IMU Pedestrian Positioning

GPS errors may be very important (e.g. frequently up to 50 meters in urban canyons). Dead reckoning methods based on Inertial Measurement Unit (IMU) have been used to increase the accuracy of positioning for vehicles or robots [23]. However, vehicle motion differs from pedestrian motion. Indeed, speed and trajectory of a vehicle show smooth and relatively slow variations. In addition, map matching methods constrain the position on the road, even when GPS signal is momentary lost. In the case of pedestrian navigation, it is much more complex. The accuracy required is higher (particularly for VI users), movement direction is less predictable, and movement speed is low. Dead reckoning may also be applied but rely on different methods and sensors. In the NAVIG prototype, we used an inertial motion tracker (three hip mounted gyroscopes and accelerometers) for body heading and a second one for head orientation. Based on these sensors, a relative positioning algorithm that can fuse these data with the global (GPS) and relative (detection of visual reference points) positioning was developed.

Fig. 2. Examples of geolocated visual landmarks (visual reference points) used for user-positioning. The rectangles indicate target detection in the camera view. Up left: shop sign, up right: facade, down left: road sign, and down right: mailbox.

3.5.3. Data fusion for accurate pedestrian positioning

The fusion process relies on three phases: the pre-processing phase covers the signal processing of all the data inputs (filtering and noise reduction of the sensors). It also includes a walking model with speed and movement direction changes. The second step includes correction mechanisms that reduce random and systematic errors. The last step merges relative (vision based) and absolute (GPS based) positioning (Fig. 3). This powerful recursive algorithm gives a solution to the discrete-data linear filtering problem, without the need of a history of observations.
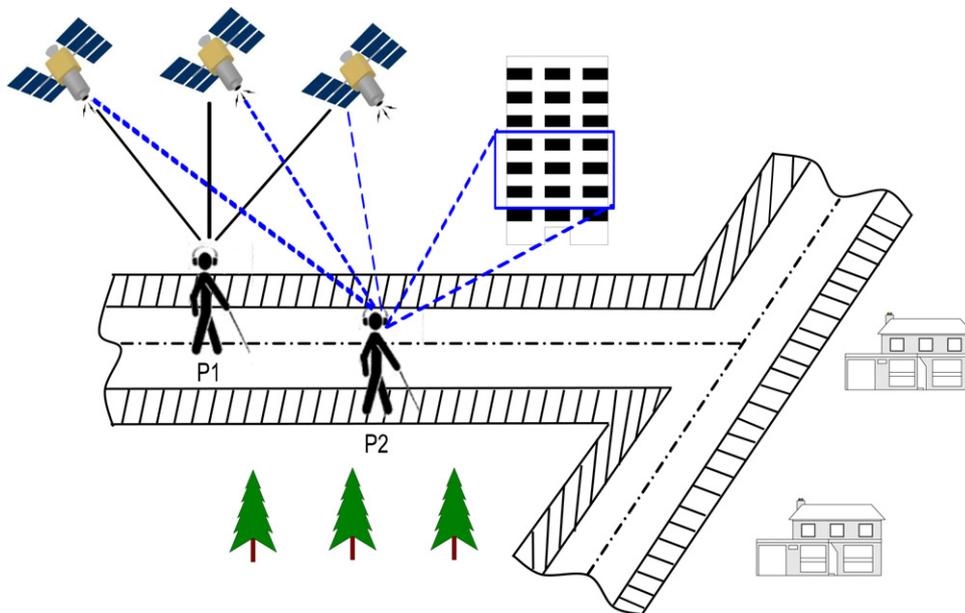

Fig. 3. Schematic principle of the regular (P1) and NAVIG (P2) positioning. User positioning P1 is the result of map matching GPS positioning with current commercial GIS. Using a Geographical Information System (GIS) including pedestrian areas and visual geolocated targets, the NAVIG positioning (P2) locates the user with a better precision, which is compatible with assisted navigation for the Blind.

Fig. 4. Left: the NAVIG Prototype including stereoscopic cameras, GPS, sensors, microphone, headphones, and a computer in a backpack. Right: blind user with the NAVIG prototype during a preliminary test.

3.6. Interaction

In order to design the user interface, we organized numerous brainstorming sessions with expert and novice users of EOAs (from the NAVIG panel). Our goal was to define the type and quantity of information required during a guided travel, as well as appropriate modalities that do not interfere with the learned O&M techniques and abilities. These sessions made clear that, during a navigation task, an EOA should provide two classes of information:

- direction instructions, i.e. turn-by-turn instructions;
- space-related information (landmarks for navigation, but also information about the surroundings, description of difficult points, etc.).

To display both of them, an adapted interface is required, which must rely on non-visual (e.g. auditory or somatosensory) modalities. Voice recognition has been chosen for input. A voice menu was implemented, which represents the different navigation possibilities mentioned during the brainstorming sessions. The usability of the proposed menu has been evaluated for a group of eight users [24].

The output interaction of the device is based on a 3D audio rendering engine. While locations of the user, the goals and potential obstacles, and determination of the proper trajectory to follow to attain the intended goals are fundamental properties of the system, this information is not useful if it cannot be exploited by the user. The NAVIG system proposes to make use of the human capacity for hearing and specifically spatial audition by presenting guidance and navigational information via binaural 3D audio scenes [25]. In contrast to traditional devices, which rely on turn by turn instructions, the NAVIG consortium is working towards providing spatial information to the user

concerning the trajectory, their position in it, and important landmarks. With the goal of providing the user with the information necessary to construct accurate cognitive maps of the environment, the users will become more confident in their displacement.

VI persons are already exploiting their sense of hearing beyond the capacities of most sighted people [26]. Using this same modality channel to provide additional and important information is novel, and the design of such information to minimize cognitive load and to maximize understanding is a key component of the system.

There are many instances where textual verbal communication is optimal, such as indicating street names or landmarks. At the same time, a path is not a verbal object, but a spatial object, and the use of auditory trajectory rendering can be more informative and more intuitive than a list of verbal instructions. The ability to have a global sense of the trajectory is also highly desirable. In order to minimize the masking of real environmental sounds, tests are underway using bone conduction headphones and other acoustically transparent headphones for the sound rendering, including digital filters to optimize the quality of binaural rendering on these particular devices. Using a high performance 3D audio rendering engine [27], a particular sonification strategy has been developed for different objects and events. Through a newly developed concept of sonic morphology, termed *morphocons* (morphological earcons), different users can chose the type of sounds they prefer, while the basic syntax remains the same across individual sound palettes [14].

4. The NAVIG prototype, preliminary evaluations and future work

The first functional prototype (Fig. 4) operates on a laptop equipped with an Intel i7 QuadCore processor. The architecture
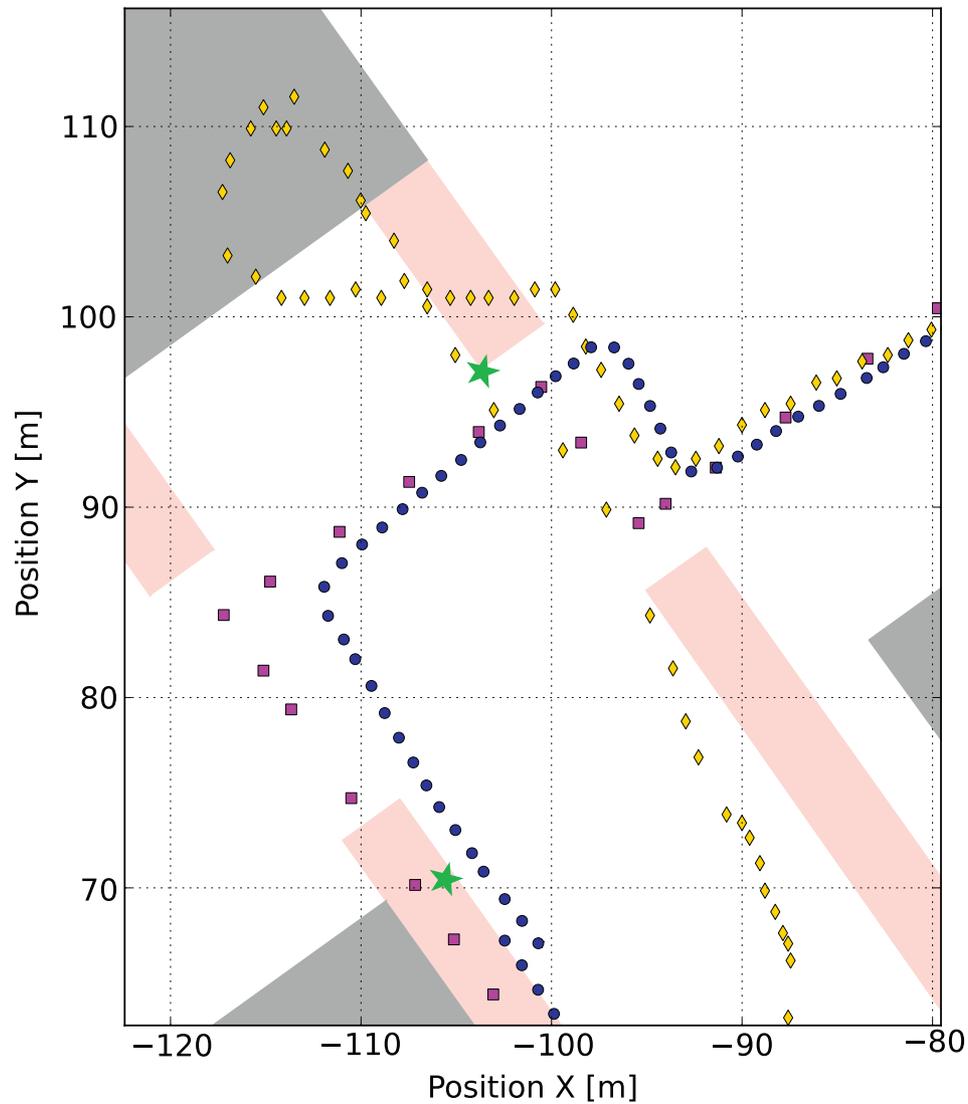
Fig. 5. Illustration of a real test realized in the Toulouse University campus. The squares indicate the travel that was really performed by the user. The diamonds indicate the positioning obtained with a commercial GPS. The dots indicate the positioning obtained with the NAVIG prototype. Visual Reference Points detected during the journey are indicated with stars.

is structured around a multi-agent framework based on the IVY middleware [28]. Within this architecture, agents are able to connect or disconnect dynamically to different data streams on the IVY bus. The "artificial vision" agent relies on the SNV algorithm (Spikenet Technology, Inc.). Video streams come from a BumbleBee stereoscopic camera (320 × 240 pixels at 48 Hz, Point Grey Research, Inc.) with an approximately 100° viewing angle. The "fusion" agent is based on the "vision agent" positioning data, an ANGEO GPS (NAVOCAP, Inc.), and two inertial motion trackers (Xsens, Xsens Technologies Inc., and Colibri, Trivisio Inc.). The interaction is based on acoustically transparent headphones and a microphone.

The combined positioning (vision, GPS, dead reckoning) was developed in two real environments (Toulouse University campus, and a district in the Toulouse center). Although systematic evaluation of the positioning is under way, Fig. 5 shows a typical example of the improvement observed during different travels

in the University of Toulouse. Another ongoing work is the evaluation of different Guidance methods. The Guidance process is decomposed in three important steps [21]:

- route selection procedure to compute the optimal itinerary;
- user tracking to estimate the location of the traveler;
- and the display of adapted instructions and selected surrounding elements.

All of these components were studied separately, but are now integrated in the prototype and will be evaluated in real conditions.

It is of interest that the NAVIG device can also assist in indoor navigation. With a map of the building including walking areas as well as models of stationary localized targets (visual reference points that may be signs or vending machines for example), NAVIG can compute an itinerary. Indoor guidance

could then rely on embedded vision only, or be completed with dead reckoning and/or indoor localization techniques (e.g. Wi-Fi triangulation).

In additon to navigation assistance, NAVIG includes a unique function for object localization and grasping (Section 3.4). Interestingly, this function may also serve to help user in the identification of objects sharing similar shape (jars, books, CDs. . .). A working prototype of this system has been tested on the issue of currency bill recognition. Experiments have demonstrated that the usability of the system was good enough for such a device to be used in daily situations [29].

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Acknowledgments

References

[1] Golledge RG, Klatzky RL, Loomis JM. Cognitive mapping and wayfinding by adults without vision. In: Portugali J, editor. The construction of cognitive maps. Springer Netherlands: Dordrecht; 1996. p. 215–46.

[2] Farcy R, Leroux R, Jucha A, Damaschini R, Grégoire C, Zogaghi A. Electronic travel aids and electronic orientation aids for blind people: technical, rehabilitation and everyday life points of view. In: Hersh MA, editor. Conference & Workshop on Assistive Technologies for People with Vision & Hearing Impairments Technology for Inclusion; 2006. p. 12.

[3] Ju JS, Ko E, Kim EY. EYECane: navigating with camera embedded white cane for visually impaired person. In: 11th international ACM SIGACCESS conference on Computers and accessibility. ACM; 2009. p. 237–8.

[4] Roentgen UR, Gelderblom GJ, Soede M, de Witte LP. Inventory of electronic mobility aids for persons with visual impairments: a literature review. J Vis Impairment Blindness 2008;102(11):702–24.

[5] Downs RM, Stea D. Maps in minds: reflections on cognitive mapping. New York: Harper & Row Publishers; 1977.

[6] Ross DA, Blasch BB. Development of a Wearable Computer Orientation System. Personal Ubiquitous Comput 2002;6(1):49–63.

[7] Petrie H, Johnson V, Strothotte T, Raab A, Fritz S, Michel R. MoBIC: designing a travel aid for blind and elderly people. J Navigation 1996;49(01):45–52.

[8] Loomis JM, Golledge RG, Klatzky RL, Speigle JM, Tietz J. Personal guidance system for the visually impaired. In: First annual ACM conference on Assistive technologies. New York, USA: ACM; 1994. p. 85–91.

[9] Loomis JM, Golledge RG, Klatzky RL. Navigation System for the Blind: Auditory Display Modes and Guidance. Presence: Teleoperators and Virtual Environments 1998;7(2):193–203.

[10] Helal A, Moore SE, Ramachandran B. Drishti: an integrated navigation system for visually impaired and disabled. In: Fifth International Symposium on Wearable Computers. IEEE; 2001. p. 149–56.

[11] Baranski P, Polanczyk M, Strumillo P. A remote guidance system for the blind. In: International Conference on eHealth Networking Applications and Services Healthcom. IEEE; 2010. p. 386–90.

[12] Hunaiti Z, Garaj V, Balachandran W. A remote vision guidance system for visually impaired pedestrians. J Navigation 2006;59(03):497–504.

[13] Katz BFG, Truillet P, Thorpe SJ, Jouffrais C. NAVIG: Navigation assisted by artificial vision and GNSS. In: Workshop on Multimodal Location Based Techniques for Extreme Navigation. Helsinki, Finland: ACM; 2010. p. 1–4.

[14] Katz BFG, Dramas F, Parseihian G, Gutierrez O, Kammoun S, Brilhault A, et al. NAVIG: guidance system for the visually impaired using virtual augmented reality. Technology and Disability 2012 [in press].

[15] Norman DA. The invisible computer. Cambridge, Mass: MIT Press; 1998.

[16] Noordzij ML, Zuidhoek S, Postma A. The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. Cognition 2006;100(2):321–42.

[17] Afonso A, Blum A, Katz BFG, Tarroux P, Borst G, Denis M. Structural properties of spatial representations in blind people: scanning images constructed from haptic exploration or from locomotion in a 3-D audio virtual environment. Mem Cognit 2010;38(5):591–604.

[18] Gallay M, Denis M, Auvray M. Navigation assistance for blind pedestrians: guidelines for the design of devices and implications for spatial cognition. In: Tenbrink T, Wiener J, Claramunt C, editors. Representing space in cognition: Interrelations of behaviour, language, and formal models. Oxford: Oxford University Press; 2012 [in press].

[19] Dramas F, Thorpe S, Jouffrais C. Artificial vision for the blind: a bioinspired algorithm for objects and obstacles detection. Int J Image Graphics 2010;10(4):531–44.

[20] Brilhault A, Kammoun S, Gutierrez O, Truillet P, Jouffrais C. Fusion of artificial vision and GPS to improve blind pedestrian positioning. In: International Conference on New Technologies, Mobility and Security. IEEE; 2011. p. 1–5.

[21] Kammoun S, Macé MJM, Oriola B, Jouffrais C. Toward a better guidance in wearable electronic orientation aids. In: INTERACT'11-13th IFIP TC 13 international conference on Human-computer interaction. Lisboa, Portugal: Springer; 2011. p. 624–7.

[22] Kammoun S, Dramas F, Oriola B, Jouffrais C. Route selection algorithm for blind pedestrian. In: International Conference on Control Automation and Systems (ICCAS). IEEE; 2010. p. 2223–8.

[23] Borenstein J, Feng L. Gyrodometry: a new method for combining data from gyros, and odometry in mobile robots. In: International Conference on Robotics and Automation. 1996. p. 423–8.

[24] Kammoun S, Oriola B, Truillet P, Jouffrais C. Conception et évaluation d'un système de dialogue pour un dispositif de suppléance pour déficients visuels. In: Journées francophones Mobilité et Ubiquité. 2011. p. 34–7.

[25] Begault DR. 3-D sound for virtual reality and multimedia. Cambridge, Mass: Academic Press; 1994.

[26] Abel SM, Figueiredo JC, Consoli A, Birt CM, Papsin BC. The effect of blindness on horizontal plane sound source identification. Int J Audiol 2002;41(5):285–92.

[27] LIMSI Spatialisation Engine, InterDeposit Digital Number IDDN.FR. 001.340014.000.S.P. 2010.000.31235 (2010).

[28] Buisson M, Bustico A, Chatty S, Régis CF, Jestin Y, Maury S, et al. Ivy: un bus logiciel au service du développement de prototypes de systèmes interactifs. In: 14th French-speaking conference on Human computer interaction. ACM; 2002. p. 223–6.

[29] Parlouar R, Dramas F, Macé MJM, Jouffrais C. Assistive device for the blind based on object recognition. In: SIGACCESS conference on Computers and accessibility. New York, USA: ACM; 2009. p. 227–8.