SWAN 2.0: Research and Development on a New System for Wearable Audio Navigation

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A System for Wearable Audio Navigation (SWAN) has been developed that aids a user in navigation, orientation, and situation awareness. SWAN provides support to persons with temporary or permanent visual impairment. SWAN has undergone many iterations, with the common requirement for mobility via wearable computing platforms, spatialized audio output, and robust position/orientation tracking of the user.

Keywords: wayfinding; mobility aid; blind and vision impaired; auditory display

Introduction

There is an urgent need for wayfinding and navigation aids for the visually impaired. This need applies to individuals who have suffered physical vision loss (e.g., full or partial blindness) as well as those affected by temporary vision impairment such as firefighters in a smoke-filled building. For a person with vision loss, the two fundamental tasks of navigating through a space and knowing what is around can be challenging. Thus, it is important to develop a system that communicates a range of information about the environment in a non-visual manner, to allow a person greater knowledge, connection to, and more effective navigation through the space. Audition is the obvious choice for display modalities, due to the excellent human ability to localize the source of environmental sounds.

There are approximately 32 million adults in the United States (representing about 13% of adults) who report having trouble seeing, or who are totally blind (Blewett et al., 2019), over 500,000 children with vision difficulty in the U.S. (ACS, 2019), and perhaps shocking to note, "at least 2.2 billion people have a vision impairment" globally (World Report on Vision, 2019; emphasis in original). Many can remain very productive even with diminished eyesight, so long as they are able to get to and from work, and move about the office building safely and effectively. Spatial orientation is the major mobility problem encountered by all individuals with profound vision loss (LaGrow & Weessies, 1994; Blasch, Wiener, & Welsh, 1997), but is especially difficult for people whose onset of vision loss occurs later in life (Blasch, et al., 1997; Levy & Gordon, 1988).

Wayfinding (the ability to find one's way to a destination) depends on the ability to remain oriented in the environment in terms of the current location, heading, and direction of a destination. Even experienced blind pedestrians exhibit movement error large enough to occasionally veer into a wall or into a parallel street when crossing an intersection (Guth & LaDuke, 1995). These problems persist when the person is indoors. While there has historically been a lot of research in the area of electronic travel aids for obstacle avoidance, there has not been comparable research and development of wayfinding devices that keep one apprised of location and heading (Blasch, et al., 1997).

In addition to visually impaired workers, there are many situations where sighted individuals cannot use vision for navigation. For example, a firefighter in a smoke-filled building may not be able to rely on vision, and any resulting disorientation can have serious consequences. Sonification of navigation data can help these individuals find their way, while being constantly aware of their surroundings.

Previous Work

Historically, the primary presentation modality of existing path planning auditory displays has been synthesized speech that is used to speak instructions to the user. The early Personal Guidance System (PGS) (Loomis, Golledge, Klatzky, Speigle, & Tietz, 1994; Loomis, Klatzky, & Golledge, 2001; Loomis, Golledge, & Klatzky, 2001) was typical of that class of devices used primarily for research: the computer created words that seem to come from the same place as the object or feature to which they refer via virtual speech beacons. "Doorway here" would sound as if it came from the real doorway. Other examples have included the Mobility of Blind and Elderly People Interacting with Computers (MoBIC) system (Strothotte et al., 1996), and the Drishti system (Helal, Moore, & Ramachandran, 2001; Moore, 2002).

There have been two notable commercially available navigation systems for the visually impaired. One is the Humanware Trekker1 and the other is the Sendero BrailleNote GPS. Both support basic navigation tasks via speech presentation and are intended as supplements to a user's existing obstacle avoidance techniques.

There are several drawbacks to using speech sounds in this way. Speech beacons are harder to localize in a virtual environment than non-speech beacons (Tran, Letowski, & Abouchacra, 2000). Users also give speech beacons low ratings for quality and acceptance (Tran et al., 2000). The speech-based interface cannot display a large amount of information, as two or more speech beacons presented simultaneously are difficult to track (e.g., Mowbray, 1953). It is also difficult to use a speech-based interface for navigation and carry on a conversation at the same time (see, e.g., Wickens, 1992; Walker & Lindsay, 2006). Further, spoken messages in such a system are each generally more than a second long, so the system is often talking. For occasional spoken directions (e.g., "Turn left"), this is not a major issue. However, if the system is simultaneously presenting other sounds representing the upcoming curb cut, a low hanging branch, etc., the inherent inefficiency of speech can result in a cluttered listening environment. Research has also shown that using non-speech cues leads to better performance than speech cues in situations where there is a significant cognitive load such as simultaneous tasks (Klatzky, Marston, Giudice, Golledge, & Loomis, 2006). One possible alternative may be spearcons (Walker, et al., 2013), compressed speech stimuli that have shown superior performance to artificial speech, auditory icons (Marila, 2002) and earcons (Brewster, Wright, & Edwards, 2003); see, also, Dingler, Lindsay, and Walker (2008).

While it is true that presenting a number of non-speech sounds around the user could also lead to a busy listening experience, the acoustic flexibility and brevity of non-speech sounds provides the designer with considerably more control. An immediately recognizable sound similar to knocking on a piece of wood could be an aesthetic and effective means of indicating the location of a door, without speaking "Door" aloud, especially if there are scores of doors present along the hallway of an office building or school. One final concern with spoken navigation commands that are not spatialized is that it simply takes many words to describe non-rectilinear movement:

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[1] http://www.humanware.com/en-usa/products/blindness/talking_gps

a 20-degree turn must be described as, “Veer to the left,” or “Turn a little bit to the left.” In our experience, simply walking toward a beacon sound is easier than translating “57 degrees” into a movement action. Thus, while speech-based navigation sounds have been useful in some cases, our design approach leaned more towards using non-speech sounds for most purposes.

SWAN 1.0 Implementation

The System for Wearable Audio Navigation (SWAN), originally described in 2007 (Wilson, Walker, Lindsay, Cambias, & Dellaert, 2007) and developed over the course of many years, addresses the limitations of previous speech-based navigation aids by using non-speech audio presentation of navigation information whenever possible. SWAN provides an auditory display that enhances the user’s ability to (1) keep track of her current location and heading as she moves about, (2) find her way around and through a variety of environments, (3) successfully find and follow a near optimal and safe walking path to her destination, and (4) be aware of salient features of her environment.

SWAN supports these goals through sophisticated position tracking technologies, sonification of navigation routes and environmental features, and implementation of a database of information relevant to the user’s navigation needs. SWAN allows users to record their movements or paths through the environment. These paths are used to create a personally relevant set of maps for the user. Additionally, the user can annotate the environment including locations, features, and obstacles. This could include, for example, a favorite coffee shop, a co-worker’s office, or a section of sidewalk prone to flooding after rain showers. The map can also be queried for directions to a particular location.

The Technology (woes) of SWAN 1.0

SWAN requirements include a portable computing device, an audio processor, audio output hardware, tactile input devices, and position/orientation tracking. The original SWAN 1.0 (Wilson, et al., 2007) involved a laptop computer, external sound board, and multiple GPS receivers, all of which had to be carried in a backpack. Users listened to the auditory user interface via bone conduction headphones (“bonephones”), which at the time were cutting edge technology (Walker & Stanley, 2005; Stanley, 2006).

The SWAN 1.0 system worked well as a research platform and proof of concept. Walker and colleagues describe a series of research projects and user tests that validated the concept and refined the user experience (Wilson et al., 2007; Walker & Stanley, 2005; Stanley, 2006; Dingler, et al., 2008; Palladino & Walker, 2008; Walker & Lindsay, 2003; 2004; 2006a; 2006b). However, the technology was simply not available at the time to make a viable commercial product. The mobile computing devices were insufficient for reasons of form factor, computing power, and battery life. Note that the now-ubiquitous smartphones were just emerging (the first iPhone went on sale in June, 2007,[2] the same year SWAN 1.0 was described).

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[2] https://en.wikipedia.org/wiki/History_of_the_iPhone

Tracking technology was crude, and even the useful global positioning system (GPS3) signals had challenges from intentional downgrades (so-called "Selective Availability"), and there were competing efforts and approaches to overcome these limitations (e.g., Differential GPS; Wide Area Augmentation System). Though the US government stopped degrading the GPS signal in the early 2000s, GPS remained too inaccurate for pedestrian applications, especially in urban settings where multipath reflections result in further accuracy decreases.

Indoor tracking was even more problematic, since GPS signals do not penetrate very far into buildings. Large-scale WIFI networks were not prevalent (universities were often the exception), and indoor localization was slow to develop (with efforts that included early versions of Ultra Wideband (UWB4), as well as TalkingLights5, TalkingSigns6, Bluetooth beacons, and other indoor tracking systems).

Thus, while the SWAN research supported the development of a system to help individuals with vision impairment move through their world, the engineering did not facilitate a solution. Even the advanced sensor fusion scheme called "MERGE" (Wilson et al., 2007) developed for SWAN 1.0 was not sufficient to provide a reliable location and pose in indoor or urban outdoor contexts.

SWAN 2.0: A Tale of Stop and Go

A decade after work on SWAN had slowed down, we assessed that the technological landscape might have finally evolved to the point where a viable consumer-ready SWAN could be developed.

In terms of mobile computing power, a variety of smartphones and ultra-mobile PCs were becoming available with (relatively) substantial computing horsepower and memory, and running a range of more mainstream operating systems including iOS, Android, and Windows. Connectivity through Bluetooth was reaching higher throughput with lower latency, meaning fewer wires between system components. And smart phones were including built-in GPS and other sophisticated location services and motion sensors.

Mobile data streaming became reasonably useful and pervasive, including faster wireless services (4G then LTE, then the beginnings of 5G) and pervasive WIFI (e.g., the ubiquitous network of cable WIFI hotspots; open WIFI at places of business, etc.).

And, finally, it looked like tracking services, using a combination of GPS, WIFI, radio-frequency and time-of-flight tracking from cell towers, and other data sources would make a SWAN renaissance possible.

WirelessRERC and SWAN 2.0

The WirelessRERC supported a project to leverage the extensive work done on SWAN 1.0, and to produce a completely new mobile-phone-based version (SWAN 2.0) that

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[3] https://www.gps.gov/systems/gps/

[4] https://en.wikipedia.org/wiki/Ultra-wideband

[5] http://sciencenetlinks.com/science-news/science-updates/talking-lights/

[6] http://www.talkingsignsservices.com

could take advantage of the latest hardware, software, and tracking technologies.

SWAN 2.0 User Experience

Much of the SWAN 2.0 user experience leverages the approach from the SWAN 1.0 system. The primary design philosophy is the emphasis on non-speech auditory display. This approach draws from the foundation of Multiple Resource Theory (Wickens, 2002). The objective is to allow for efficient flow of information without overburdening the user's cognition or attention. Furthermore, the user needs to be able to hear and interpret environmental sounds in the presence of SWAN audio output. Given that speech processing is a low bandwidth capability for the user, non-speech audio proves to transmit information efficiently and allow the user to dedicate speech processing to external interactions like talking with others.

Path Sonification:

A naïve approach to indicating a path to a destination is to spatialize audio as if it is emitted from a real-world position. This position could be a waypoint along the path or the final destination. The problem with this approach is that the time when a new waypoint is introduced is (a) when the user is farthest away from the waypoint, and is (b) when the relative position information is most pertinent to the user. If conventional spatialization is used, the perceived loudness of the waypoint will be attenuated to a low volume initially and get louder as the user approaches. Initially perceiving a newly presented waypoint is more difficult for the user at an attenuated volume. This fact motivates an alternative solution. SWAN does not attenuate waypoint sonifications. Instead, a direction vector from the user towards the waypoint is determined (updated constantly as the user moves and rotates). A spatialized sonification is placed a fixed distance along this direction vector. Therefore, there is no variation in loudness. Unfortunately, without loudness attenuation there is no longer a cue for distance. Instead, SWAN maps distance (or, actually, proximity) to tempo. The waypoint audio is of short duration and is designed such that the user can effectively identify simulated direction cues such as Interaural Timing Difference (ITD) and Interaural Intensity Difference (IID). A submarine SONAR ping and guitar string plucks have both been identified as sounds that are effective for user orienting in SWAN. The short duration allows for repeating the sound at a varying tempo. The tempo of the repeated sounds is increased as the user gets closer to the waypoint. Upon successfully reaching the waypoint, the user is presented with a "success" sound, followed immediately by the waypoint sound playing from the direction of the next waypoint. This extends the critical listening period for the user to orient to the new direction of travel. One problem with simulating ITD and IID is that the user may perceive the sound as coming either from their front or their back. Therefore, an additional sonification strategy to identify front or back direction is useful. The method used in SWAN is a rising two-note ("bah-bing") sequence if the waypoint is currently in front of the user and a diminishing two-note sequence ("bing-bah") if the waypoint is behind the user.

Environment Features:

SWAN is built on a flexible audio system that can sonify a variety of environment features. Auditory icons, earcons, and spearcons have been employed. Features in the environment that are sonified are generally static (e.g., park benches, mailboxes) but may also include dynamic obstacles depending on sensing capabilities (e.g., a rolling cart in a hallway). Environment sonification may include potential obstacles that the user should be cautious around (e.g., stairwell entrance) or simply provide situation awareness and opportunities for community participation (e.g., entrance to a bakery).

Interactive Annotations:

The authors have previously explored social app features allowing users to contribute to the community of users via environment annotations. For instance, a user may discover a closed sidewalk, a low hanging branch, etc. The user could add an entry to the cloud to both remind themselves in the future and to provide support to other SWAN users. It is hoped that these features can be revisited as SWAN transitions to modern platforms.

Auditory Menus:

There are several ways to control the system (e.g., tell SWAN where you would like to go). One method is via a speech recognition/voice command interface. However, in practice, such an input method is neither reliable nor private enough to be seriously considered for continuous user input to a navigation system such as SWAN. Thus, we have also implemented a simple and effective audio menu system, to be used instead.

SWAN 2.0 Research and Evaluation

The program of research supporting SWAN 2.0 focused on: (a) the user interface; (b) prototyping and interface building; and (c) the indoor localization capabilities.

May (May, Sobel, Wilson, & Walker, 2019) conducted extensive research into the design of sounds for the SWAN 2.0 audio user interface (AUI), focusing in particular on the “last meter” of a path. That is, the earlier versions of the SWAN AUI focused on getting a user from start to finish along a path; the latest designs also feature the capability to help a user find an object at the destination. For example, consider a user who needs to get from her office to her laboratory, and then retrieve a notebook in the lab. That notebook might be on a counter, but it might also be on a shelf or in a cabinet above or below the counter height. Helping the user identify where, in vertical space, the object is located required an additional set of sounds. Variants of those sounds were designed and evaluated with participants in a real physical environment supported by a virtual scene constructed with the Unity VR toolkit. See (May, et al., 2019) and Figure 1 for more details on this aspect of the SWAN 2.0 AUI.

[insert Figure 1 about here]

The second line of research involved the tools and methods that could be used to lay out, prototype, evaluate and refine a complete sonic environment. That is, when determining the sounds that will be used to represent the many features and events in, say, an office building, it is necessary to have a prototyping environment that supports rapidly implementing sounds to try, allowing users to experience the spatially laid out sounds and (virtually) walk around in the space, and then port those sounds and design choices to the real-time run-time environment. May (May, Tomlinson, Ma, Roberts, & Walker, 2020) developed a VR system that allowed the sound designer to mock up and seek feedback on a sound design/layout, supporting rapid changes and on-the-fly revisions based on in-the-moment feedback from participants (see Figure 2).

[insert Figure 2 about here]

SWAN 2.0 Localization

The third major line of research supporting the development of SWAN 2.0 has been in indoor tracking. As discussed earlier, localizing the user, and in particular inside a building, has been a major hurdle for wayfinding systems, including SWAN. Very recent innovations in indoor location sensing have now made it possible, at least at the prototype stage, to identify where a person is located. The two main technologies include the Thales/Intersense IS-1500, and the Vortant smart pedometer.

The Intersense IS-1500[7] is a small sensor the size of a stick of chewing gum that includes a camera and an inertial sensing unit. The system can track indoors (or outdoors) using a combination of inertial motion sensing, visual point cloud sensing, and visual identification of pre-placed special images ("fiducials").

The Vortant[8] smart pedometer also uses inertial sensing to determine the distance and direction travelled by a pedestrian. The hope is that one or both of these technologies, in combination with WIFI, GPS (when available), and other localization methods can provide a robust and accurate position fix, thereby supporting the wayfinding functions of SWAN indoors, and in GPS-diminished outdoors locations.

The SWAN 2.0 team has been conducting research into the deployment, validation, calibration, and use of these technologies, as a foundation for our new system (see Figure 3). The technologies are still being refined, and we are coping with bugs and system incompatibilities. This tells us that (1) the location and tracking technologies are very promising; but (2) there remain technical challenges, still, before a full indoor wayfinding system such as SWAN 2.0 can be fielded.

[insert Figure 3 about here]

As we move past the various minor bugs, we have continued to implement the various sub-systems for the new SWAN, and to support integration and further testing we have implemented an indoor virtual test system (see Figure 4). This is similar to that developed by May (May, et al., 2020) but at a higher level of fidelity and with the various inputs and outputs included (or simulated, if necessary). This virtual environment allows us to test out path planning algorithms, obstacle avoidance, sound placement, and location tracking subsystems.

[insert Figure 4 about here]

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[7] https://www.intersense.com/is-1500

[8] https://www.vortant.com

One promising area of progress with SWAN 2.0 indoor tracking is that we are able to map floor plans in high fidelity given accurate floor plans. This allows tracking of navigable space with a navigation mesh (or NavMesh). The NavMesh provides a means of coordination of the static navigable space (walls, doorways, etc.) and temporary/dynamic obstacles detected by camera (rolling cart, people, etc.). In real time, the NavMesh data structure can be refined as obstacles are detected. A wayfinding path can then be automatically revised to go around the obstacle or take an alternative route if completely blocked.

SWAN 2.0 Hardware

Identification of the SWAN 2.0 hardware is challenging given the rapidly evolving landscape of personal computing devices. In particular, augmented reality (AR) hardware is beginning to be commercialized with rumors of devices from major manufacturers. SWAN will certainly benefit from headphones with build-in inertial measurement units (IMUs). This feature will allow for head-tracking which benefits audio spatialization. Also, SWAN users will benefit from headsets (possibly in an eyeglasses formfactor) that provide camera systems for optical tracking, audio output (possibly via bone conduction), etc. Even if the user is unable to take advantage of AR visualizations in such AR glasses, the other I/O features could be very useful to the SWAN application.

In the absence of cutting-edge AR capabilities, a smart phone in a breast pocket with camera protruding such that it views the user's local environment could be a useful platform. Alternatively, a user could wear a phone case suspended by a lanyard around the neck. For this scenario, the smart phone provides local computing capability as well as I/O for the SWAN application. The smart phone approach does not place tracking capability on the user's head, but we have found that users can learn to localize audio based on torso orientation rather than turning the head.

SWAN 2.0 Future

One aspect of the emerging consumer AR product space is that visual display requires considerable computation and therefore power consumption. For this reason, it is desirable to minimize the use of visual capabilities only to important interactions and then go back to low power utilization. However, auditory display has much lower impact on power performance. For this reason, SWAN 2.0 and similar technologies have the potential to become a primary form of interaction for a broad range of AR users. SWAN could become much more than an accessibility-oriented platform and instead serve a contribution to Universal Design of AR technology.

Conclusion

Over many years we have developed a System for Wearable Audio Navigation (SWAN) with powerful localization capabilities, and a novel and effective auditory interface. SWAN aids a user in safe pedestrian navigation and includes the ability for the user to create and store personal pedestrian navigation paths. Emphasis is placed on the use of non-speech sounds through a process of sonification. SWAN serves as a foundation for research into a variety of aspects of psychoacoustics, human computer interaction, and novel tracking technology. SWAN 2.0 represents the potential for a state-of-the art commercializable system that can finally reach its potential to increase safety and independence for any who must navigate with vision impairment or blindness.

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Figure 1. VR testing environment for SWAN 2.0 user interface, focusing on the “last meter” vertical location of objects.

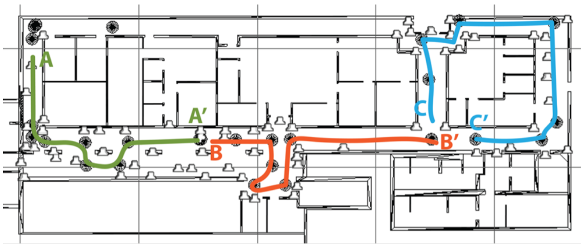

Figure 2. Tool developed to place sound sources in a (virtual) map of the real environment, for use in prototyping sound designs and layouts.

Figure 3. Indoor localization testing, using the mounted fiducials for the Intersense IS-1500 tracking system.

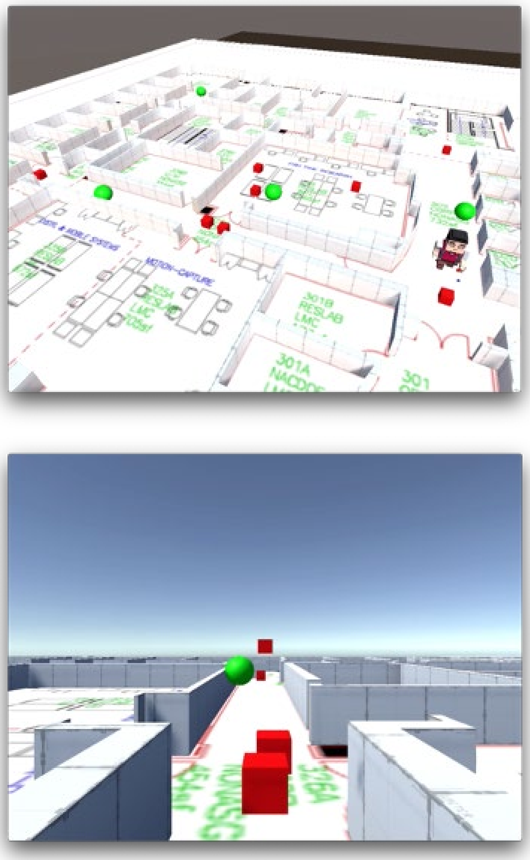

Figure 4. Design and prototyping tool (two views shown here) built in Unity for integrating real and simulated data sources, path planning, and auditory interface for the System for Wearable Auditory Navigation (SWAN 2.0).

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