Technical Correspondence

An Assistive Navigation Framework for the Visually Impaired

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***Abstract*—This paper provides a framework for context-aware navigation services for vision impaired people. Integrating advanced intelligence into navigation requires knowledge of the semantic properties of the objects around the user's environment. This interaction is required to enhance communication about objects and places to improve travel decisions. Our intelligent system is a human-in-the-loop cyber-physical system that interprets ubiquitous semantic entities by interacting with the physical world and the cyber domain, viz., 1) visual cues and distance sensing of material objects as line-of-sight interaction to interpret location-context information, and 2) data (tweets) from social media as event-based interaction to interpret situational vibes. The case study elaborates our proposed localization methods (viz., topological, landmark, metric, crowdsourced, and sound localization) for applications in way finding, way confirmation, user tracking, socialization, and situation alerts. Our pilot evaluation provides a proof of concept for an assistive navigation system.**

***Index Terms*—Cyber-physical system, navigation, situation awareness, visually impaired.**

I. Introduction

Ambient intelligence is an information paradigm in which people are empowered through a digital environment that is "aware" of their presence and context and is sensitive, adaptive, and responsive to their needs [1]. Indoor location identification is a useful component in ambient assisted living (AAL) applications, allowing tracking, monitoring, and providing fine-grained location-based services for the elderly [2]. For independent travel, sighted people can perceive their surrounding environment, orient themselves in a physical space, and navigate from place to place with ease. However, it is challenging for visually impaired people to interact and access unfamiliar environments even with the help of electronic travel aids [3] and vision techniques [4] because these conventional assistive devices address the obstacle avoidance problem only. They do not provide visually impaired people with a global perception of the surrounding environment and nearby events and an intelligent way-finding capability. Thus, AAL applications may support the travel of visually impaired people.

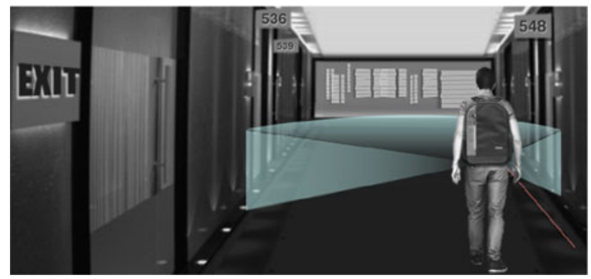

Fig. 1. Visual cues (exit and door number) and distance sensing of objects as line-of-sight interaction for context awareness.

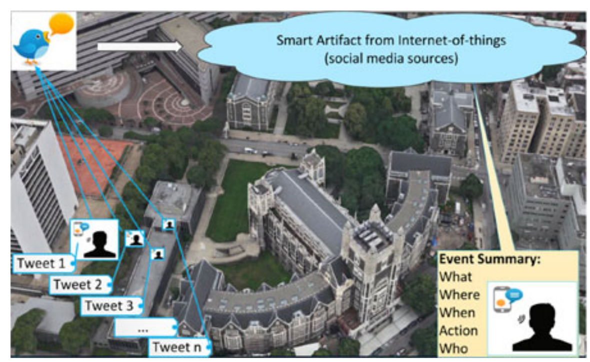

Fig. 2. Events from digital objects (tweets posted by people) as event-based interaction for situational vibes awareness.

We are developing an assistive navigation system that will tackle the blind mobility problem by integrating real-time localization technologies based on wearable sensors with event-based artifacts interpreted from social media networks. Fig. 1 shows the visually impaired user's line-of-sight interaction in the physical world. Integrating wearable sensors, such as cameras, proximity sensors, accelerometers, and gyroscopes, can enhance the environment at the proximity level through location awareness (e.g., obstacle avoidance and scene understanding capabilities). Fig. 2 shows the user's interaction with the cyber domain, which enables the discovery of special events (e.g., social gatherings, detours, and hazards) and provides a vibe of the nearby environment through text-to-speech feedback. *"Vibe"* is defined as a feel of the user's vicinity that represents a current state that is frequently updated by social media messages sent by humans acting as sensors, termed as *"social sensors."* Social media networks, such as Twitter, Facebook, and RSS, are examples of social sensors that enhance the global perception of the surrounding environment from situational vibes through event summary.

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To develop this approach, we collaborated with visually impaired communities in New York City to solicit their input and conduct usability studies. Visually impaired people require assistive technology that can provide spatial position and orientation information, obstacle avoidance in dynamic environments, real-time warnings about dangerous situations, alerts of events of interest, and intelligent way-finding capabilities. Unfortunately, such technology does not exist. Hence, leveraging results from computer vision, robotics, the Internet of Things (IoT), and nonvisual user interfaces, we are developing an assistive navigation system based on simultaneous localization and mapping (SLAM) technology [5] with the fusion of social sensors and wearable sensors, and interaction with the environment to improve the navigation of visually impaired people.

The AAL group at DIEEI in Catania, Italy has developed a cognitive system to provide visually impaired people with an awareness of their surroundings. A sensing module with inertial and ultrasound sensors is hosted on the user for localization. In addition, sensor network nodes are preinstalled in the user environment to represent the contents of the environment for interaction [6], [7]. These conventional AAL environments usually support the inhabitants at the cost of installation of additional sensors or infrastructure modifications in the physical environment. Moreover, the physical sensors preinstalled in the environment have limited coverage. Our proposed technology does not require physical sensors installed in the environment but takes advantage of human-centric computing with the fusion of social networks and wearable sensors.

An accessible global positioning system (GPS) provides turn-by-turn directions for visually impaired people in outdoor navigation [8]. However, the main drawback of GPS-based navigation is that it may fail to operate in urban areas with tall buildings due to signal reflections or inside buildings where the GPS signal is not available.

Researchers have applied SLAM technology in assistive navigation for visually impaired people [9]–[11]. However, they did not consider how to detect features and how to correct GPS errors. For example, in [10], the indoor map is assumed to be known *a priori*, and the user acts as a sensor to detect the intersections of hallways and open doors.

Considering the cyber domain, certain devices use the IoT to discover location awareness from the social media and provide alerts of disaster events [12]. Crosswalk assistance for visually impaired people is provided based on location-specific resources from the IoT by using cloud computing-based navigation [13]. The PULSE system discovers and speaks the text tweets when users approach the physical location where a tweet was composed [14]. However, these technologies do not accommodate the visually impaired perception and are not integrated into a navigation framework.

Our prior work addresses semantic navigation [15], visual odometry (VO) and mapping [16], floor plan digitization [17], crowdsourced situation awareness [18], and context recognition [19]–[22]. This paper addresses the operational concepts and architecture of our intelligent assistive navigation system. It also presents a proof-of-concept prototype evaluation.

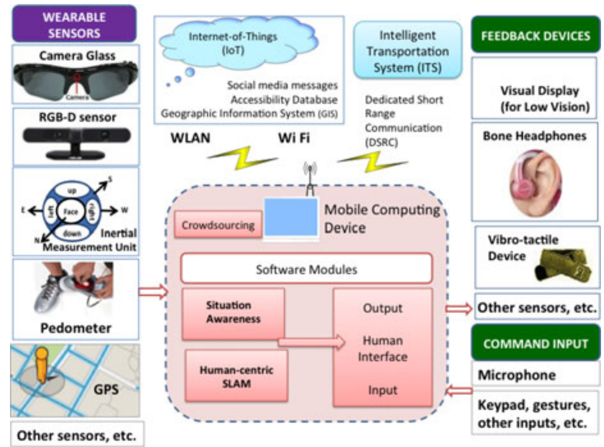

Fig. 3. System architecture of the proposed framework.

Fig. 4. Visually impaired user testing our setup (the wearable sensors shown are (1) RGB-D sensor, (2) inertial measurement unit (IMU), and (3) vibro-tactile device).

II. System Overview

Fig. 3 illustrates the architecture of our proposed intelligent cyber-physical system that uses wearable sensors for assistive navigation based on SLAM, access to the internet through Wi-Fi communication, and interaction with an intelligent transportation system (ITS) through dedicated short range communication (DSRC). The physical system consists of wearable sensors (i.e., GPS, pedometer, camera, IMU, and RGB-D sensor), feedback devices (i.e., bone headphone and vibro-tactile device), and human interface hardware (e.g., voice input/output and touch pad). The mobile computing device is a wearable computer that has computational capability and a network connection, such as a tablet computer or smart phone. Through Wi-Fi communication, the system can access cyber resources, such as geographic information systems (GIS), transportation databases, and social media networks. Fig. 4 shows a visually impaired user testing our setup. The mobile computing device includes four software modules: the SLAM-based-assistive navigation module serves as the backbone, the situation awareness module executes computer vision algorithms for object detection and scene understanding, the crowdsourcing module runs algorithms for discovering situational vibes, and the human–computer interface module determines the display content, interacts with feedback devices, and accepts human commands.

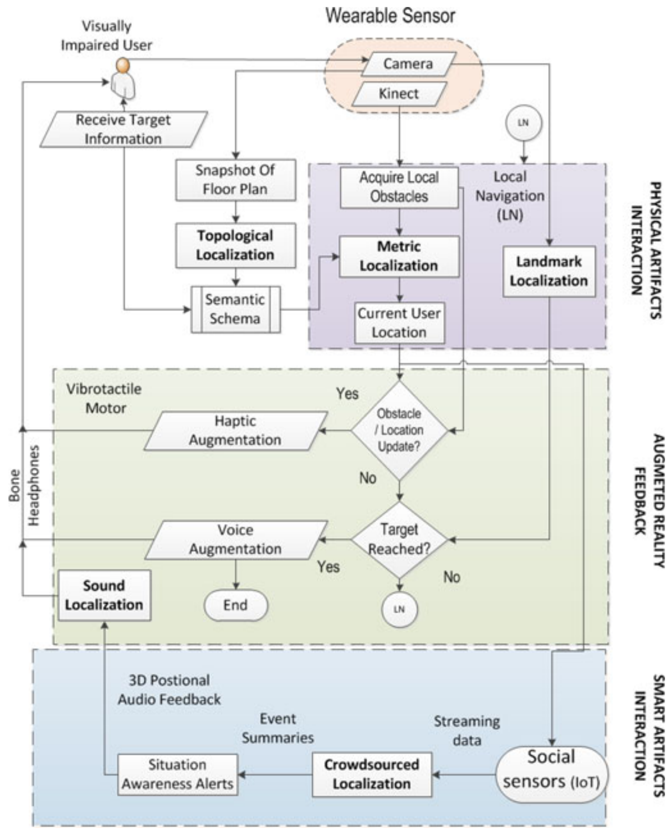

Fig. 5. Localization paradigm.

III. Assistive Navigation Framework

The proposed assistive navigation system in an ambient environment provides:

1) Line-of-sight interaction by using location-context awareness software with techniques for object detection and recognition, reading and recognition of text and signage, and detection, tracking, and representation of moving objects.
2) Event-based artifacts by using situational vibes from the IoT with crowdsourcing techniques for discovering live events that foster participation in social activities (e.g., engaging in a special event, such as gatherings) and provide warning of hazardous events.
3) A SLAM-based assistive navigation software to generate a map and plan a route, thus reducing the users' efforts in remembering landmarks and generating a global perception of the environment.
4) A nonvision user interface to convey map information, including auditory guidance and spatial updating of object location, orientation, and distance, for an automatic intelligent way-finding and navigation system to assist visually impaired people.

In robotics, localization is referred to as an estimation of the robot's location in its environment. The localization paradigm of our assistive navigation system in Fig. 5 illustrates several real-time localization technologies to estimate the location of the user.

1) Topological Localization

This is a technique used to determine location by recognizing a unique place-specific feature based on appearance (e.g., D-shaped feature in a floor plan is an entry point to a room) and its adjacency relationship in a layout map. We introduce a method called *floor-plan digitization*, which digitizes the snapshot of a floor plan posted on a wall inside a building. This method uses the room numbers and other features recognized in the floor plan to infer the waypoints to each room [17], [20]. A global plan or *semantic schema* is designed by using the waypoints to explore the shortest path based on semantic path planning through an adjacency matrix-based depth-first search.

2) Landmark Localization

This technique is used to determine location (without odometry) by recognizing the current view of the user based on visual landmarks captured with a camera. The visual landmarks in the immediate vicinity of the user are extracted using optical character recognition algorithms [19], [21], [22]. The user's location specified by the landmarks are compared with the salient features (e.g., room numbers) on the digitized floor map to confirm the correct travel direction of the user even if the user gets lost.

3) Metric Localization

This is a technique used to determine location by computing the relative pose between the current and the previous pose of the user based on odometry metrics. We estimate the user location by using a real-time fast VO and mapping approach for RGB-D cameras [16]. The accumulative errors in VO are corrected by taking advantage of the floor plan, which is regarded as the absolute ground truth. Then, a location update feedback is rendered to the augmented reality (AR) module to direct the user toward the correct travel direction by using voice or haptic augmentation.

4) Crowdsourced Localization

This refers to observer's ability to be aware of an event situation (situational vibe) that is crowdsourced from the IoT. Our system acquires social media messages to gauge the relevant aspects of the event and create alerts [18], [23]. By using a faceted summarization algorithm, we capture the parameters required for querying and reasoning about an event of interest from the IoT, such as what, where, who, when, severity, and action. We augment our system with streaming data from the cyber domain to provide situational awareness by summarizing the events around the user.

5) Sound Localization

This refers to a listener's ability to identify the location of an event in terms of direction and distance to the sound feedback. We project the events containing location tags with reference to the user's location in 3-D space to make the user interact with the evolving real-time events from Twitter [18]. Socialization events are triggered with a low-frequency sound whose amplitude increases when the distance to the event location becomes lesser and vice versa. Detailed event descriptions are available for users who are interested to know more about the event. Disaster events usually do not contain orientation and distance information; thus, they are triggered with an audio alert of high amplitude and high frequency to provide warning to the user.

IV. Operational Modes

The operational modes provide a system-level solution for assistive navigation for visually impaired people in indoor and outdoor environments.

A. Indoor mode

The indoor mode addresses the needs of users in attending events, such as a class/lecture or meeting, or otherwise being inside office buildings that are structured environments. Here, corridors constrain the motion and provide clues to a computer vision system for object recognition and to users for navigation. When a user accesses an unfamiliar building, the challenges include how to figure out the floor layout of the building, locate the elevator, avoid fixed obstacles, and find the correct office room or lecture hall. If the building has installed accessible AAL devices for visually impaired persons (e.g., an accessible route-planning kiosk near the entrance of the building with a chime beacon to indicate its location, braille instruction or other accessible signage), users may navigate the building relatively easily. However, most buildings lack those accessible features. The proposed system provides an infrastructure-free solution by using computer vision techniques to detect objects (e.g., doors), recognize text and signage, and gradually build up a navigation map (using SLAM) to help users reach their destination through effective guidance and feedback.

B. Outdoor Mode

In the outdoor mode, the major challenge is to ensure the safety of the traveler, especially at intersections, with audible tones and verbal messages. The system is able to use GPS signals to obtain a rough indication of the traveler's location, plan a route, and interact with ITS (if available) through wireless communication to initiate requests to cross intersections and broadcast the requests to approaching cars to ensure safety. However, the GPS signal may not be reliable or may fail to operate in urban areas with tall buildings. The system is able to detect landmarks and perform localization correction against landmarks to compensate for GPS errors. After several iterations, a personalized navigation map annotated with detailed accessible features will be built and offered to accessibility databases to benefit other travelers.

V. Pilot Evaluation of the Navigation system

The wearable sensors used in this study include a head-mounted camera (Logitech C920 HD camera) for door number detection, an RGB-D sensor (ASUS Xtion PRO), and an IMU (Phidgets Spatial); the IMU is attached to the RGB-D sensor body with a slot, such that the unit is hooked on the waist belt for obstacle avoidance and human motion estimation. The feedback devices include a bone headphone for receiving verbal guidance without blocking hearing and a vibro-tactile belt for alerting the user of nearby obstacles. We use an HP laptop with micro-

Fig. 6. Floor-plan digitization.

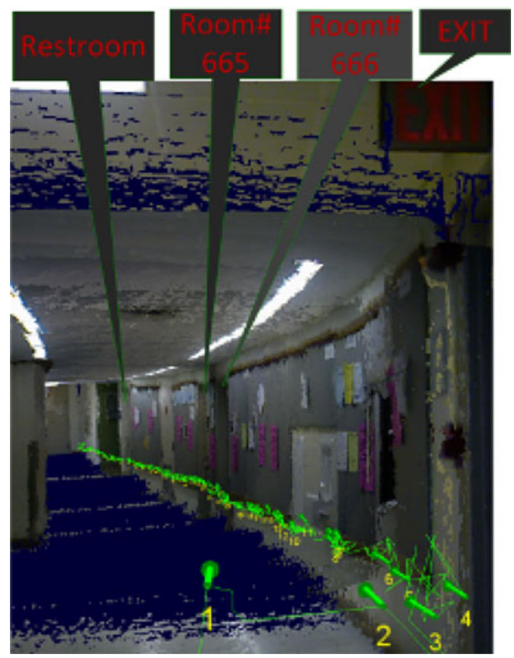

Fig. 7. Trajectory of the user on a 3-D map (green path with numbered step count) and its annotation provided by metric and landmark localization [15].

phone, placed in a backpack, as the mobile computing device. Through Wi-Fi communication, the system is able to access the Internet. The software is implemented under the robotics operating system [24] in Ubuntu. We use the CMU PocketSphinx speech recognition system [25] as the speech recognition tool and sound_play in the audio_common package [26] to deliver text-to-speech commands.

Consider a university scenario, where a visually impaired user joins the engineering program and stays two blocks away from the campus. We have developed a GPS-based outdoor navigation system [27] by using a smartphone, a bone-conducting headphone, and open source software. The user inputs the address to the system by speaking into a microphone through the PocketSphinx speech-2-text software. Once the destination address is obtained, the system will determine the user's current

Fig. 8. Trajectory taken by the user to the university campus (blue path) using our smart system.

position through a GPS receiver. Our system generates a pedestrian route based on route queries on the destination address by using the Geo-Coder-US module [28], OpenStreetMaps, and MoNav. The user hears the welcome message from our device to start travel and follows the 3-D sounds generated by the device. Near home, there is an intersection at 145th street (see Fig. 8). Whenever the user comes within 10 m of an intersection, the device plays a distinctive sound and alert: *"You are nearing an intersection; take a left turn"* and further provides turn-by-turn instructions toward the desired destination, as shown by the blue path. Finally, the user reaches the engineering building with the help of our device.

The indoor scenario of attending a class in room #666 of the engineering building illustrates how the user accomplishes the travel task in an unfamiliar environment. If a sighted person identifies a floor plan posted on the building, then a snapshot of the floor plan can be acquired with the camera and provided to the visually impaired user. The system uses a heuristic method of extracting room numbers and door shapes (D-shaped feature) from the floor plan, which further acts as a parameter for defining an entry point to each room (see Fig. 6). Semantic schemas organize these semantic labels and generate a digitized global map based on [17], [20]. Thus, when the user commands the device: *"Go to room 666,"* our system provides the shortest route to reach the destination, including all landmarks within the intended route, based on semantic path planning that uses an adjacency matrix for a depth-first search. *Topological localization* provides the location-aware annotation to the user based on the digitized global map.

Landmark localization provides the context-aware annotation based on the optical character recognition algorithm [19], [21], [22]. Our system recognizes a visual semantic entity ("exit"), posted on the building (see Fig. 7) and announces: *"Turn to right and go straight ahead."* The RGB-D camera processes the environment around the user to identify any obstacles. If there is an obstacle in the proximity to the user along the intended travel route, haptic augmentation (vibro-tactile feedback) is provided so that the user can avoid the obstacle. *Metric localization* provides an accurate estimation of the user location by using a real-time fast VO and mapping approach for RGB-D cameras that is based on [16]. While walking straight along a corridor, the user senses a door by touching and commands the device with the keyword, *"door number detection."* Our system identifies the visual clue as room #666 and informs the user that the destination has been reached. The real path generated by a user in the travel direction toward room#666 at the sixth floor of the CCNY engineering building is shown in Fig. 7. The green trajectory is the path travelled by the user, and the number specified on the path is the step count of the user.

TABLE I
EXAMPLE OF TWEETS POSTED IN THE CAMPUS

Tweet 1	Calling all Freshers! meet and dine 6 P.M. Freshers' Party!...
Tweet 2	Come to Freshers' Party this evening at 18:00 in NAC
Tweet 3	Come to NAC cafeteria for "Freshers' Party!" on 27th Jan
Tweet 4	Wits freshers party today: enjoy the music and grab some coffee or sweets #witsfreshers
...	...
Tweet n	Freshers Party !! - 27th January 6 P.M.-10 P.M. at NAC. Free Tickets are available from Student Services

TABLE II
EXAMPLE OF FACETED SUMMARY

What	Freshers' Party
Where	NAC cafeteria
When	6 P.M., January 27th
Action	Free Tickets, music, coffee, sweets, dine, meet
Who	Freshers

To participate in any special events, the keyword *"discover events"* is applied. *Crowdsourced localization* provides event-based artifacts so that the user can become aware of an event's situation acquired from social media [18]. A special event that is of interest to the user is then discovered (e.g., Tweets on *"Freshers' party"* as shown in Table I; a summary of that party event is shown in Table II). The contextual information is extracted by using the IBM SystemT and Annotator Query Language. Our AR interface enhances the perception of the user by rendering the sound in the user's environment [18], [23]. *Sound localization* allows the user to identify the location of an event in terms of direction and distance by synthesizing a 3-D positional audio feedback of the tweets. It provides the user with a situational vibe and an intrinsic understanding of the environment by interpreting the social events through parameters such as what, where, who, when, severity, and action. Thus, our system integrates a localization paradigm so that the user is empowered through the cyber-physical system by being made aware of the environment for the purpose of independent travel.

VI. Conclusion

This paper presents a high-level overview of our assistive navigation framework with real-time localization technologies that interpret semantic entities from both the physical world and the cyber domain. We introduce the operational concept in developing such an intelligent system, which helps the user to travel independently. We also present a pilot evaluation to demonstrate the ability of our system in indoor and outdoor environments.

We have produced a working prototype but still face many challenges. When dealing with a large dataset from multiple sensors, it is challenging to allocate the computational resources and synchronize the image processing and other computations. When using a head-mounted camera carried by a visually impaired user, it is challenging to reduce the image blur caused by the up-and-down vibration of human walking steps. In outdoor navigation, it is important that the users have reliable access to the GPS, GIS database, and ITS, either through wireless or DSRCs. Other challenges include how to interface with ITS elements and how to create and manage the accessibility database.

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