Bulletin of Electrical Engineering and Informatics
Vol. 10, No. 3, June 2021, pp. 1747~1758
ISSN: 2302-9285, DOI: 10.11591/eei.v10i3.3055

Methodologies and evaluation of electronic travel aids for the visually impaired people: a review

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Article Info

Article history:

Received Sep 29, 2020
Revised Feb 17, 2021
Accepted May 4, 2021

Keywords:

Autonomous mobile robot
Electronic travel aids
LiDAR point cloud

ABSTRACT

Technological advancements have widely contributed to navigation aids. However, their large-scale adaptation for navigation solutions for visually impaired people haven't been realized yet. Less participation of the visually impaired subject produces a designer-oriented navigation system which overshadows consumer necessity. The outcome results in trust and safety issues, hindering the navigation aids from really contribute to the safety of the targeted end user. This study categorizes electronic travel aids (ETAs) based on experimental evaluations, highlights the designer-centred development of navigation aids with insufficient participation of the visual impaired community. First the research breaks down the methodologies to achieve navigation, followed by categorization of the test and experimentation done to evaluate the systems and ranks it by maturity order. From 70 selected research articles, 51.4% accounts for simulation evaluation, 24.3% involve blindfolded-sighted humans, 22.9% involve visually impaired people and only 1.4% makes it into production and commercialization. Our systematic review offers a bird's eye view on ETA development and evaluation and contributes to construction of navigational aids which really impact the target group of visually impaired people.

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1. INTRODUCTION

For visually impaired people, the most common navigation aid is white canes. While this gives an excellent solution for a near ground obstacle, obstacles which are lower than ground or higher than knee level remain undetected. Difficult circumstances such as crowd disasters [1], road holes and hanging tree branches might also cause problems to blind people. Therefore, researchers are keen to explore scientific advancements which could help the visually impaired community with self-navigating. Mobility aids for visually impaired people known as electronic travel aids (ETAs) are equipped with measurement systems to detect objects and avoid collision [2]. Some of the objectives and challenges of ETA includes detection of obstacle, information on the travel surface, location of landmarks, identification information, self-familiarization and mapping of the surrounding [3]. Through solid ETA construction, the visually impaired people can be more self-independent, less likely to be involved in accidents, improve their reachability and finally improve the living lifestyle. The objective would be to enable the visually impaired people to travel in a safe and secure condition.

A. Types of electronic aids

Figure 1 shows the types of ETAs that have been proposed by different researchers. Categorically, ETAs can be grouped into robotic navigation aids (RNA), smartphone-based systems and wearable attachments. RNA is a type of machinery that carries itself [4]. Usually in the form of wheeled robot, it possesses simpler mechanical and dynamics requirements [5]. An active RNA moves on its own, decreasing the burden and preventing the user from exhaustion. Another type of assistive system for the visually impaired is smartphone-based, with image and video processing capability. Wearable attachment systems come in various designs, targeting different body parts for device fitting. Eyeglass, headgear which connected with EEG (electro encephalography) [6]-[8] are some examples of wearable attachment used for navigation.There are pros and cons of each type of ETA. There are pros and cons of each type of ETA. Therefore, it is important to highlight the advantages and disadvantages of different types of ETAs as shown in Table 1.

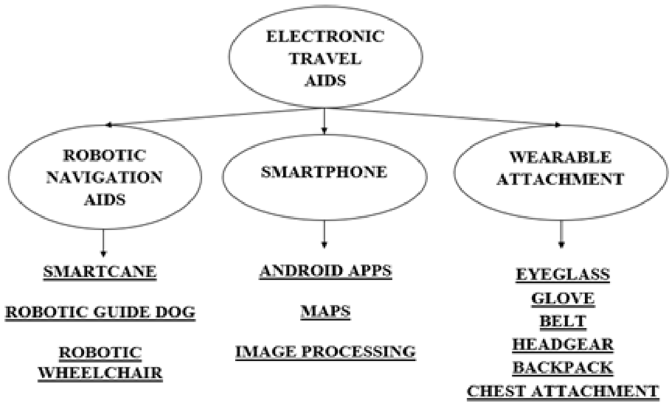

Figure 1. Type of ETAs

Table 1. Advantages and disadvantages of varying ETAs

Type of ETAs	Implementation	Advantages	Disadvantages	Ref
Robotic Navigation Aids	Smart cane	– Offers portability can be used as a normal white cane should the electronics cease to function.	– Needs to be compact and lightweight – Lacks obstacle information because of restricted sensing ability offers little information on wayfinding and navigation purposes as it requires bigger and bulkier hardware	[4] [9]
	Robotic guide dog/mobile robot	– The system gives room for larger hardware, as it does not require a user to carry it	– Complicated mechanicals while manoeuvring through stairs and terrain	[4]
	Robotic wheelchair	– Suitable for the elderly and people who have a physical limitation provides navigation and mobility assistance for elderly visually impaired who cannot walk on their own, multi-handicapped, or people who have more than one disabling condition	– Safety remains an issue as user mobility fully depends on the robotic wheelchair navigation, road-crossing and stair climbing are difficult circumstances where the reliability of the wheelchair is of extreme necessity	[9]
Smartphone-Based System	Android apps Maps Image Processing	– Mobility/portability – No load or invasive factor as the only device is the smartphone	– The system depends on sensors available on the smartphone. – May communicate with an outer sensor such as beacon or external server but then it limits the usage for indoor requires certain orientation for image processing or internet signal for online maps	[10]
Wearable attachment	Eyeglass Glove Belt Headgear Backpack	– Gives a natural appearance to the visually impaired user when navigating outdoors	– Too much attention is required, thus giving a cognitive load to the user these devices are intrusive as they cover ears and involve the use of hands users are burdened with the system's weight. – Requires a long period of training.	[4], [11]

As there are pros and cons of each types of ETA, it is up to the designer's approach to choose and build according to their set objectives and requirements. An RNA provides large room for designer's hardware compartment and could provide additional functionality, a smartphone-based system offers mobility and ease of usage for consumers and wearable attachment gives a more natural appearance for users of the visually impaired community.

To form a comprehensive review on ETAs, we investigate the fundamental aspect of ETA build with the methodologies to achieve navigation, and a common ground for ETA's evaluation. This review article investigates the contemporary and current designs of ETA's methodology of achieving navigation and its fraction leading to mobility, then evaluate and classifies the system into a more consumer-centered perspective rather than the commonly designer-oriented innovation, which in results provide in depth insight on how far does the advancement of ETA really impact the core-targeted consumer of the visually impaired community.The rest of the paper is organized as follows: Section 2 describes the work of ETAs on navigation, while section 3 discusses the test and experiment conducted for evaluation. Section 4 provides a discussion on difficulties and challenges faced in ETAs and finally, section 5 concludes the review article and makes recommendations for future researchers. Figure 2 shows the flow chart of the review article from the types of ETA, navigation modules, experiments conducted and finally classifications of the system.

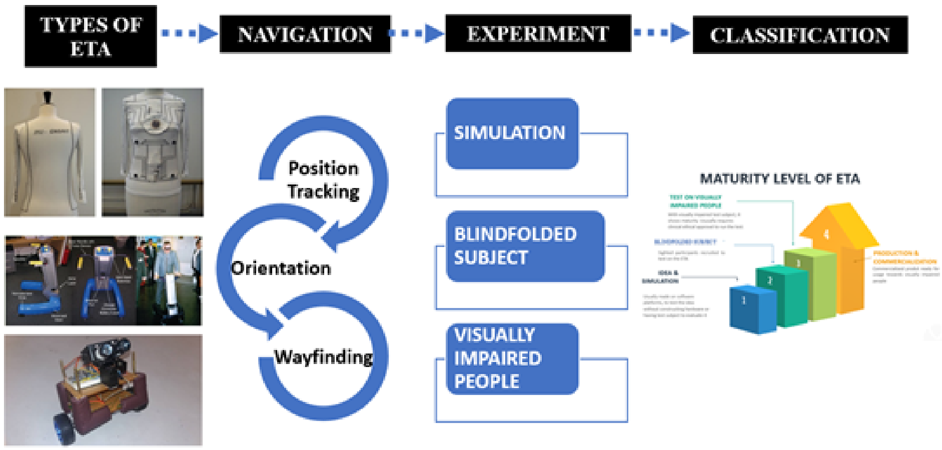

Figure 2. Flowchart of the review article

2. NAVIGATION

There are many integral functions which makes up an ETA. Human-machine interface, machine-human interface, object detection, object recognition, mapping, perception and control of locomotion are some of it just to name a few [3]. However, amongst all functionality, navigation remains as one of the most necessary and fundamental requirement of an ETA system for visual impairment [12].

Navigation is the process of updating one's position and orientation along with a preselected route leading to a destination [13]. Factors such as position tracking, wayfinding and orientation are integral aspects of navigation. The proposed taxonomy chart which classifies the navigation system is shown in Figure 3.

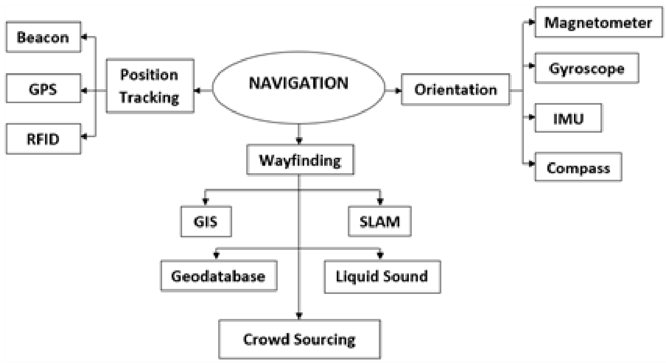

Figure 3. Taxonomy chart of a navigation system

2.1. Wayfinding

Wayfinding deals with the capability to select the correct route from a network of routes starting from an initial point to a destination [13]. It answers the question of "where do I go?" from the visually impaired person's point of view. Other than moving towards destination, wayfinding also includes the action of evacuation [14].

2.1.1. Crowd sourcing

One of the methods to achieve wayfinding is through crowdsourcing. An example of crowdsourcing is shown by in [15], where they designed a smartphone application to navigate from point A to B through reliable directions from the online community. A web app of Google App Engine is developed where a sighted user can log on and provide instructions.

2.1.2. Geodatabase

Geodatabase, which consists of paths designed for the pedestrian, land-use map, actual video recordings, filed survey and community reports are used in [1], [16], [17]. This key information is then accumulated and amalgamated to form a representation of crossings, sidewalk and real topology of a pedestrian network for users with visual disabilities.

2.1.3. Geographic information system

Geographic information system (GIS) with visual landmarks for GIS/vision based localization is discussed in [18]. A camera with a small portable computer such as a netbook is used as its hardware. Incorporation of GPS and GIS for determination of position and orientation for navigation of the visually impaired have also been done. Other implementations of GIS in wayfinding systems include [19], [20]. GIS system may face some difficulties as nature environmental conditions are extremely difficult to measure [21].

2.2. Orientation

Orientation is an ability to be aware of one's body position and heading in relation to surrounding objects, cardinal directions and one's location in the followed path [13]. Usually related to rotation of the person's body, it helps in making turns around a corner and keeping the body centre in the pathway. Different types of sensors used to accomplish orientation are discussed in this section.

2.2.1. Magnetometer

First, we examine the sensor of magnetometer which are used to estimate heading, measure roll and pitch angles [22]. Salonikidou *et al.* [23] proposed a system which makes use of a magnetometer for orientation purposes. It determines the heading angle with coordinates stored in GPS as a reference before giving direction command to the user.

2.2.3. Compass

A compass is another sensor that can enable orientation awareness. For instance, Skulimowski *et al.* [24] suggested the point of interest (PoI) explorer mobile application. Making use of an accelerometer and electronic compass within the smartphone, it calculates the angle and orientation of the user relative to the current position and gives direction to the target point. Nonetheless, the system does require a considerable amount of time for utilization, set to be 15 seconds for each complete scan.

2.2.4. Gyroscope/IMU

Zheng *et al.* [25] have estimated the orientation by making use of the gyroscope featured in a smartphone. By solely using a gyroscope, an accurate angle is achieved; with average error of 2.73 within 6% error rate. Correct altitude is tracked within a short period of 10s. Another sample of navigation assisted by IMU can be seen in [26], [27]. Other than wayfinding, gyroscope sensor is also associated with the ability of balancing and angle determination.

2.3. Position tracking

Position tracking or piloting is associated with sensing positional information and using it to determine one's location [28]. One can use an external map or cognitive map to locate oneself relative to the destination. Often referred to by the term localization, it answers the question of "where am I?" for the visually impaired. A well-known predicament, the localization cases are a necessity both within indoor and outdoor situations.

2.3.1. Beacon

First, we examine the use of a beacon to achieve position tracking. Cheragi *et al.* [29] proposed using low-cost, Bluetooth-based beacon for indoor localization named as GuideBeacon. The GuideBeacon implements received signal strength indicators (RSSI) to estimate user proximity from the sensor. In an experimental phase, the system showed reduced navigation time compared to cane users.

2.3.2. GPS

Global positioning system (GPS) is the most commonly used technique for outdoor localization [30]. Chaccour & Badr [31] have proposed a computer vision-based technique to guide the visually impaired on navigation aspects by making use of the GPS technology and Google maps.

2.3.3. RFID

Another method to accomplish position tracking is by using radio-frequency identification (RFID). Costa *et al.* [32] suggest RFID and computer vision for detection of landmarks placed on the ground. The hardware is equipped with a RFID reader connected via Bluetooth.

2.4. Discussion on navigation techniques

Table 2 shows summarizes the navigation techniques of ETAs development with criteria and references. Most commonly devices to achieve navigation purposes are GPS, off-the-shelf smartphone sensors and camera-based system. GPS can be used to attain both wayfinding and path tracking information [33]-[35]. IMU, gyroscope, compass and magnetometer are commonly found in smartphone devices [25], [24]. Camera based wayfinding techniques include SLAM [36], Microsoft Kinect [37]-[39], novel liquid sound navigation [40] and FL2-0352 camera [41]. Machine learning methods which are getting numerous attention for researchers nowadays [42], [43] such as particle swarm optimization (PSO) [44] have also been implemented for navigation purposes.

Table 2. Summary of navigation methods of ETAs development for visually impaired people

Category	Way finding	Orientation	Position Tracking
Sensors/Method	GPS &Crowd Sourcing	Magneto meter	Beacon & GPS
	GPS	Gyroscope	GPS
	GIS & Geodatabase	IMU	RFID
	GIS & GPS	Compass, Gyroscope	
	Camera [SLAM]		
	Camera [Liquid Sound]		
Hardware Spec	Smartphone sensors- camera, compass, GPS and accelerometer	Ultrasonic sensor (HC-SR04), (GPSUBLoX-NEO-6M-00) and (Honeywell HMC5883L) magnetometer	GPS, beacon
	Haptic device (SensAble Technologies, PHANToM OMNI), Laptop PC (Dell, Precision M6300) and a GPS receiver (GARMIN, eTrex Vista)	Mobile phone's gyroscope, microphone speaker	GPS, Cameras and IR sensor (SHARP GP2Y0A710K0F)
	Geodatabase from phone (Nokia 6120)	Stereoscopic camera, GPS & IMU	RFID and camera (Sony ICX084 CCD)
	Stereoscopic camera, GPS and IMU	Smartphone Android 4.2, accelerometer, compass	
	3D camera (SwissRanger SR4000)		
	Camera		
Device Feedback	Phone speaker	Audio speaker	Voice interface speaker
	Haptic device (SensAble Technologies, Phantom Omni)	Phone speaker	Audio speaker
	Phone speaker	Bone conduction headphones	Micro vibrator
	Headphones	Handsfree voice message	
	Tablet speaker (HP Stream 7)		
	Headphone (AKG K612 Pro)		
Test Subject	8 Blindfolded people	NA	2 Visually impaired people
	Blindfolded people	6 Blindfolded people	Simulation
	16 VIP	21 VIP	Simulation
	21 VIP	20 VIP	
	7 Blindfolded people		
	14 Blindfolded People		
Distance Travelled	NA	25 m to 30 m	2 Visually impaired people
	NA	NA	Simulation
	670 m	Within 110 m x 40 m	Simulation
	Within 110 m x 40 m	NA	
	45 m		
	NA		

Table 2. Summary of navigation methods of ETAs development for visually impaired people *(continue)*

Category	Way finding	Orientation	Position Tracking
Area	Indoor Outdoor Outdoor Indoor & outdoor Indoor Indoor	Outdoor Indoor & outdoor Indoor &outdoor Outdoor	Indoor & outdoor Indoor & outdoor Indoor & outdoor
Test Route	1 initial room 1 U-turn shaped hallway 1 destination room	7 location around campus	Straight path with 3 beacons along the way
	From starting point around a building to destination	Indoor; hanging TV & stone wall. Outdoor; glass wall	Object distance from 45cm to 325 cm
	12 segments 13 decision points 4 pedestrian crossings	Toulose University campus, and district in Toulose center	Set of different images were taken on UTAD campus
	Toulouse University campus, and district in Toulouse center 7 Points of Interest (PoI) 2 or 3 obstacles	Area with 100 Point of Interest, segmented into smaller section	
Evaluation Criteria	– Contact with wall – Completion time	Arrival to predetermined destination	– User location evaluation test – Calculate position of user
	Comparison between concave and convex haptic representation of the objects.	– Distance measurement accuracy – Wall detection accuracy	Object distance error percentage
	Error rate – Completion time – User evaluation on safety, efficiency & comfort	– User travel – Positioning from GPS – Positioning from the system	Trajectory tracking
	– User travel – Positioning from GPS – Positioning from the system	– Distance to POI – Direction of POI, with orientation relative to user and destination	
	– Reach to PoI – Reach to destination – Average time – Collisions with obstacle – No of subject leaving test area – Completion time		
Result	Time completion: 67.1 s	Correction from 224° degrees to 280° degrees	Accuracy: 90% Average distance error: 0.47m Distance error: 0.1m or 0.2m Low severity (neglected error) for the navigation system.
	Average contact: 0.25	Error rate: 6% Average angle error: 2.73°	Absolute error: 3.8% ~ 1.72%. Error minimal when the distance to the object is 3 m
	Based on user evaluation. Comfortability: 33% agreed Efficiency: 50% agreed Safety: 33% agreed	Better positioning given by the system compared to GPS and improved user navigation	The trajectory correction is computed, and output is given to blind target
	Better positioning given by the system compared to GPS only and improved user navigation	Time of application: 15 s System accuracy decrease with higher number of POI.	
	System identify PoI: 95% Percentage of users arrive at destination: 81% End Point Position Error Norm (EPEN): 0.29 m Percentage of completed scene: 76%		
Ref	[15], [16], [27], [36], [40], [45]	[24], [25], [27], [46]	[30], [32], [33]

3. TESTS AND EXPERIMENT

Test and experiment are done on ETAs to evaluate the system, acting as a benchmark for the prototype's real-life usage. We categorised test and experiments done on ETAs into 3 categories; simulation based, blindfolded-sighted people and visually impaired person.

3.1. Simulation

Initially, experiments to evaluate ETAs are done by simulation. One of the early simulation tests for visually impaired technology with stereo vision-based aid is presented in [47]. They tested the ground plane obstacle detection (GPOD) algorithm using a pair of cameras to simulate an image sequence of the real outdoor scene. Meanwhile, Karacs *et al.* [48] established a database for training and testing algorithms develop for bionic eyeglass; cell phone and camera-based image recognition system. A database of 200 videos with lengths of 10 to 90 seconds of indoor and outdoor recordings are taken from visually impaired persons. Nandini & Seeja [49] tested an algorithm for path planning within a supermarket environment with C++ simulation. A supermarket layout with numbered corners and section as point of interest (PoI) is mapped out on the system. Desired destination and current situation are given as the input from the user.

3.2. Blindfolded-sighted people

The second way of experiment is by having the ETA tested by blindfolded subjects. Several tests require the examinee to walk down a set of routes which resemble a real-life scenario, including walking within a pre-arranged pathway around indoor environment or outdoor surroundings. Table 3 shows some of the evaluation with a blindfolded examinee with varying numbers of the test subject, test route surroundings and evaluation criteria. The method of experiment using a blindfolded-sighted human subject can be considered as an intermediate technique in between simulation and using a real visually impaired people for testing. It is a more realistic way of experiment when compared to simulation-based testing but is less effective to really grasp the feeling and opinion of a visually impaired subject. In terms of difficulty, it is also in between simulation and using visually impaired as it involves human subject but depreciate of the necessity of the safety precautions and issues required of involving a real blind people subject.

Table 3. ETAs development tested by blindfolded sighted human subject

Ref	Distance	Indoor/Outdoor	Route/Obstacle	Evaluation criteria	Test Subject (blind-folded)
[50]	na	Indoor	4cycle around a trail	Time taken/No of contact on obstacle/Densities of vibration motor/No of vibration/Vibration motor allocation	49
[40]	na	Indoor	2or 3 obstacles	Collisions with obstacle/Number of leaving testing area/Completion time	14
[31]	na	Indoor	1 kitchen/1 living room/1 bedroom	Object search ability/Ability to provide path navigation	8
[15]	na	Indoor	1 initial room/1 U-turn shaped hallway/1 destination room	Contact with wall/Completion time	8
[51]	na	Indoor	4 doorways/4 hallways/2 downward stairways	Object recognition accuracy	7
[36]	45 m	Indoor	7 Points of Interest (PoI)	Reach to PoI/Reach to destination/Average time	7
[52]	na	Indoor & outdoor	*Indoor*; chairs and ventilators. *Outdoor*; bicycles, cars, bushes and pedestrians	Mental demand/Physical demand/Temporal demand/Performance/Effort/Frustration	6
[25]	na	Indoor & outdoor	*Indoor*; hanging TV & stone wall. *Outdoor*; glass wall	Distance measurement accuracy/Wall detection accuracy	6
[9]	20 m~40 m	Indoor	Looped trajectory	Final position error/Error reduction/Dead reckoning/Object recognition	5
[53]	32 m	Indoor	office room to a stair	Walking errors/Travelling time	4
[54]	10 m	Indoor	5 obstacles along the way	Travel speed/Cleared obstacle	3

3.3. Visually impaired person

The third method of evaluating ETA is by testing the device with visually impaired people. Having visually impaired as an experimental subject requires more safety measures and requirements. A clinical or ethical approval to run the test is compulsory before attempting to recruit a visually impaired person examinee. Table 4 shows the ETAs development which has been tested or evaluated by visually impaired people.

Table 4. ETAs evaluation test with the visually impaired people

Ref	Distance	Indoor/Outdoor	Route Surrounding	Evaluation criteria	Test Subject	
					V.I.P	Blindfolded
[55]	33.4 m	Outdoor	3 turning point/3 pedestrian overpasses/2 tress obstruction/2 parked motorcycle/1 side door/1 plant terrace/1 cardboard box	Finishing time/Collision frequency Most collided obstacle/Parts of the body in contact	15	5

Table 4. ETAs evaluation test with the visually impaired people *(continue)*

Ref	Distance	Indoor/Outdoor	Route Surrounding	Evaluation criteria	Test Subject	
					V.I.P	Blindfolded
[56]	1.2 m ~ 3.5 m	Indoor	3 persons in front of user to be recognized	Face recognition accuracy/User evaluation	5	9
[10]	5 m × 7 m	Indoor	4 room/1 entrance/1 exit	Exploration time/Navigate/Layout recognition & representation	5	20
[23]	10 m × 7 m	Indoor	3 obstacles along the way	Navigation time/User evaluation on familiarity	5	11
[57]	na	Indoor	Sunroom/smoking room/dining room/main entrance	Time completion/Force on handlebar/Number of collisions	2	-
[16]	670 m	Outdoor	12 segments/13 decision points/4 pedestrian crossings	Error rate/Completion time/User evaluation on safety, efficiency and comfort	16	-
[29]	50-300 steps	Indoor	beacon 7 to 0 situated on upper floor, northwest from entrance	Navigation time/Distance/User evaluation	7	1
[58]	4.6 miles	Outdoor	10 metro stations/2 different metro network lines	Choosing metro station/Changing between metro lines/Arrival to destination	10	-

4. DIFFICULTIES AND CHALLENGES IN ETAS BUILDUP

Figure 4 shows the maturity level inherent on the development of ETAs, categorically classified from simulation, tested on blindfolded subject, test on visually impaired. The final goal would be production and commercialization for end users. Table 5 shows the maturity level of ETAs development in selected reviewed research papers. Out of 70 related research articles only one exceptional product was successfully commercialized. The development of GUIDO, a smart walker for the blind [57] has seen success in preproduction unit sales to the U.S. Department of Veterans Affairs. There is an obvious trend of ETA constructions to be abbreviated the further they progress through the maturity stages. Therefore, it is of monumental importance to study the factors which hinder the progress of ETAs.

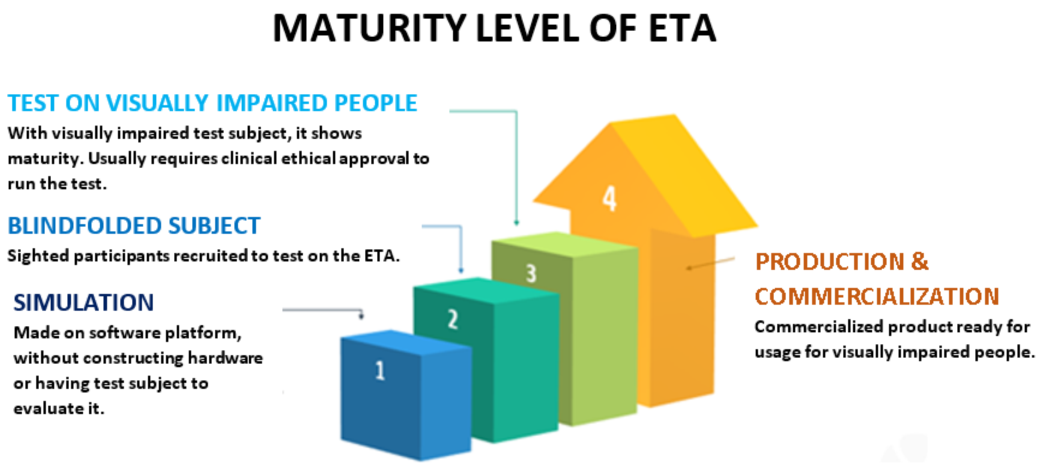

Figure 4. Maturity level of ETAs

Table 5. Maturity level of ETAs development

Maturity Level of ETA Development	No of research articles	Percentage % (out of 70 research articles)
Simulation	36	51.4 %
Blindfolded Subject	17	24.3 %
Visually Impaired Subject	16	22.9 %
Production & Commercialization	1	1.4 %

The first key factor which challenges the commercialization of ETAs is the market acceptance of new technology. Safety issues and concern remains an issue for the visually impaired community. However, with significant effort the sceptical mindset towards robotic machinery which hinders the progress of navigation technology can be eliminated. Researchers also claim that the user is not resistant towards adaptation of robotic technology if it can deliver benefits in their daily living [57].

The second obstruction to ETA's commercialization lies within the complex production and testing systems. Ethical approval, and recognition by clinical bodies and organizations are a must, such as the food and drug administration (FDA) in the United States. And in order to acquire clinical validity, large and well defined patient groups are needed as evidence of safety aspects of the development [59]. Therefore, more involvement and participation from each contributing party is necessary, including designers (engineers), authorities (doctors and clinicians) and the end users (visually impaired community).

The third factor are designed methodologies which lack user-centred philosophy and requirements. There are many cases where sophisticated innovations of the designer's concept overshadow consumer necessity. Therefore, an intensive effort must be made to see more collaboration between engineering designers, medical clinicians and visually impaired users to make the product more consumer-oriented and user-centred. There should also be a clear-cut objective which is to prioritize the needs of the visually impaired people at all costs.

5. CONCLUSION & FUTURE WORKS

This review paper has thoroughly discussed the fundamentals of ETA construction with the main objective of navigation and its components of wayfinding, orientation and position tracking. The evaluation stages of simulation, human subject tests and commercialization have been presented to assess the technology readiness level. This review article has presented the layout of advantages and disadvantages of each types of ETA, the methodologies of achieving the ETA's most fundamental functionality namely the process of navigation, capacity and capability of varieties of sensors to achieve fractions of navigation in orientation, wayfinding and position tracking, test and experiments done on evaluating the ETA's designed and finally classification of current ETA's level of maturity. We perceive that such purposefully set objectives could give future researchers a benchmark for experimentation, and act as a blueprint of future ETA evaluation. In a nutshell, the highlights of our review paper are:

- Breakdown of types of ETA and its advantages and disadvantages. The navigation techniques of ETA are then divided into position tracking, wayfinding and orientation methodology, with further study on its sensor's selection, and finally assessment on its capacity and capability of moving the visually impaired towards its destination.
- Results of ETA test and experiment, comparison on its level of readiness and overview of fraction of methods of evaluation; namely simulation, experiment done on sighted blindfolded subject and experiment done with real visually impaired subject.
- Classification of current ETA's development into levels of maturity, providing an eagle eye view of impacts of ETA towards the targeted subject of the visually impaired community as a whole.

For future work, it would be interesting to see further investigation done from experts of the medical field or clinicians to assess ETAs. This would open the doors to consumer-centred concepts and diminish designer-oriented designs that we have at the present time. The core ideas assimilated in this research could serve as a benchmark for future research projects relevant to ETA evaluation. Through this review, we perceived that the future developers would be encouraged to have a better communication with physicians and the medical side of the system's requirement, and to have a better understanding of the visually impaired people as the intended consumer of the developed product.

ACKNOWLEDGEMENTS

The research is funded by grant number SRCG20-046-0046 IoT-Based visually impaired community (VIC) Geospatial Tracking with Swarming RoVision (SR), UMP-IIUM-UiTM Sustainable Research Collaboration 2020 and IRAGS18-014-0015 from International Islamic University Malaysia (IIUM).

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