Improving wheelchair route planning through instrumentation and navigation systems

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***Abstract*— Route planning is an important tool to reach points of interest. The current technology offers options for public transportation and pedestrians on the road and sidewalks, respectively. However, for people who use electric powered wheelchairs (EPW) as their primary means of mobility, the level of accessibility and EPW battery consumption are important during route planning. This paper introduces the concept of an accessible route navigation application to reduce EPW battery consumption. The application, called eNav, uses five layers of information including OpenStreetMaps (OSM), airborne laser scanner (ALS), Point-of-Interests (POIs), public transportation, and crowdsourcing. eNav collects these layers of information to provide the shortest, most accessible, and most comfortable routes that consume the least amount of EPW battery. Additionally, the paper presents the Mobility Enhancement roBot (MEBot), a legged-wheeled power wheelchair, to drive over architectural barriers and less accessible environments. The paper proposes the use of MEBot as a sixth layer of information to inform eNav and road authorities about sidewalk/route conditions, to improve road accessibility, and to provide an energy efficient route planning for non-MEBot users.**

***Clinical Relevance*— The eNav application offers the most energy efficient route to enhance EPW user's mobility.**

I. INTRODUCTION

Route planning applications allow people to navigate to points of interest (POI) by suggesting the shortest and easiest transit routes. These applications offer real-time public transportation departure and arrivals for pedestrians. While route mapping applications benefit pedestrians, the suggested routes are not necessarily accessible for people who use electric powered wheelchairs as primary means of mobility. Wheelchairs are important assistive devices, providing mobility and independence for people with spinal cord injuries and mobility impairments [1]. In 2014, the U. S. Census Bureau reported 5.5 million wheelchair users [2], increasing at a 5.2% growth rate per year [3]. However, wheelchairs are limited to driving in indoor environments and outdoor areas compliant with the American with Disabilities Act (ADA) guidelines [4]. Streets and sidewalks are constantly changing; therefore, it is difficult to maintain maps to suggest wheelchair users the most efficient and shortest accessible routes available. Driving in less accessible routes with environmental barriers can lead to wheelchair accidents [5-7], and these barriers can lead to social isolation [8, 9] and limit participation in the community [8-10].

Research studies proposed different methodologies for accessible route mapping which take into consideration sidewalk characteristics and user preferences. Kasemsuppakorn et al. [11] proposed the Absolute Restriction Method (ARM), a routing technique based on user preference. Results showed that users preferred personalized routes with better route quality than the shortest routes. Study [12] provides the most optimal routes using six sidewalk parameters: width, length, slope, surface type, surface conditions, and traffic. Neis et al [13] proposed a route planning method for wheelchair users based on individual requirements and geo-information made available by the Volunteered Geographic Information (VGI) [14] and retrieved from the OpenStreetMap (OSM) project. RouteCheckr presents a multimodal annotation prototype allowing users to add geographical data and share experience on travelled routes to recommend suitable routes [15]**.** mPass defined aPOIs (accessibility Points of Interest) based on six urban design requirements (gap, cross, obstruction, parking, surface, pathway) and classified in three reports (S-report by sensors, U-report by users, and A-report by building administrators) [16]. Lastly, Ferrari et al used a route planning method that weighs travel routes between accessible and non-accessible routes based on travel time and interchange differences [17].

A factor to be considered during accessibility route planning is the limited range of battery capacity in electric powered wheelchairs (EPW) which translates to 24,000-58,000 meters of travelled distance in ideal conditions (e.g. flat surfaces, moderate weather conditions, optimal batteries) [18]. To optimize the route planning for EPW users, it is necessary to consider the energy cost of travelled distance against battery consumption. This paper presents a route planning application, called eNav, to optimize EPW's energy consumption. Additionally, the paper introduces the use of a novel mobility enhancement robot wheelchair (MEBot), an instrumented power wheelchair with indoor and outdoor capabilities, to complement eNav benefits for real-time accessibility mapping and navigation improvement.

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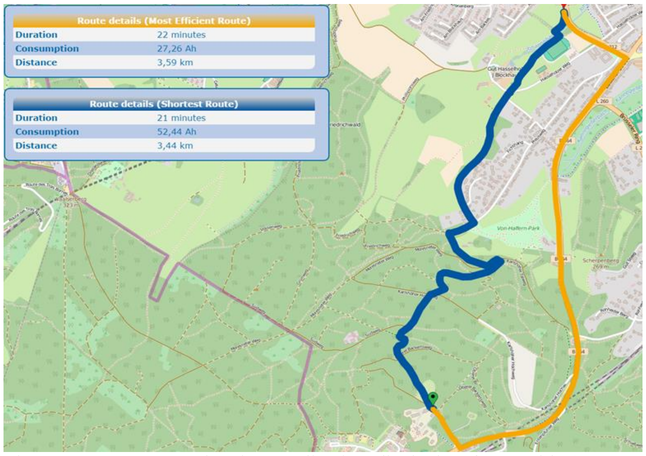

Route details (Most Efficient Route)	
Duration	22 minutes
Consumption	27,26 Ah
Distance	3,59 km

Route details (Shortest Route)	
Duration	21 minutes
Consumption	52,44 Ah
Distance	3,44 km

Figure 1: eNav route planning application displaying fastest (blue) vs most energy efficiency routes (Orange)

II. METHODOLOGY

A. *eNav*

eNav is a navigation application that allows wheelchair users to find an accessible route. Further, the application allows people who use EPWs to choose between the shortest route or the most energy efficient route for less EPW battery consumption [19]. The distance difference between both routes approximates under 200 meters; while the energy efficiency route can increase up to 20% in travelled distance and up to 50% in extreme cases. For example, Fig. 1 demonstrates a case where the route includes high slopes. In order to achieve significant energy savings, a short detour of approximately 100 meters longer is recommended to save up to 50% in battery consumption (Fig. 1).

In addition, the application provides the option to avoid less accessible surfaces, such as cobblestones, to improve the EPW user's comfort and safety. The eNav application implements the multimodal dynamic routing method which provides constant communication between the public transportation and eNav to inform wheelchair users about bus arrival/departure times and nearby bus stops in real-time.

B. *Navigation Algorithm Process*

The aforementioned tasks are performed through the use of highly detailed maps. These maps are obtained from five layers of information (Fig. 2). The first layer is the common street layout from which all the previously provided streets and barrier-free information is extracted. The basis for this information is the OpenStreetMap (OSM). OSM does not contain all environmental barriers; therefore, eNav uses crowdsourcing to complement this information. This is conducted semi-automatically through the analysis of the EPW user's driving behaviour. Alternatively, the user can manually register the barriers via the eNav application.

The second layer uses airborne laser scanning (ALS) to build a 3D-Map model. To build the 3D-map model, it is necessary to have detailed location coordinates and altitude point data of the route obtained via ALS and provided by the North-Rhein-Westfalen (NRW) state government of Germany. The model is important to improve EPW energy consumption which increases exponentially with respect to the angle of the slope. The ALS data have an accuracy of ± 20 cm. The third layer of information provides the surface information

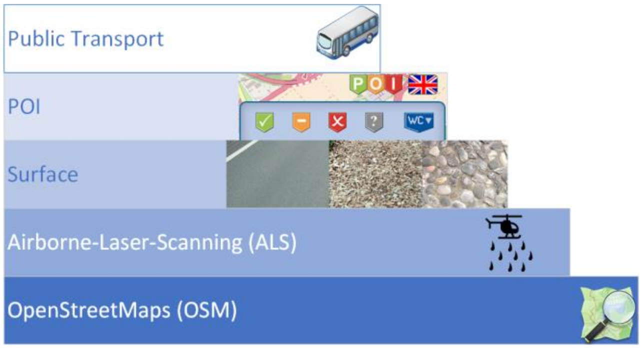

Figure 2. Five layers of information to reproduce eNav maps

obtained through crowdsourcing to offer a comfortable and safe route to EPW users. The concept is to use the z-axis acceleration (elevation) obtained from an Inertial Measurement Unit (IMU) sensor built on smartphones to detect the surface roughness and inclination. Duvall et al demonstrated that EPW users' satisfaction when driving over a surface decreased with an increase in the root mean square (rms) accelerations of the surface roughness [20]. For example, the wheelchair vibration on a cobblestone surface is higher than on an asphalt surface. The surface roughness can be complemented with the surface friction coefficient obtained by the current consumption in the drive wheels to improve the energy consumption model.

The integration of point-of-interests (POI) represents the fourth layer in the maps. POI is defined as a location or an attraction of interest for wheelchair users. The eNav system integrates the POI from wheelmap.org. This informs the user about different POIs and their indoor and outdoor accessibility. Lastly, the fifth layer of information integrates the public transport network in the eNav maps using a multi modal dynamic routing algorithm [19]. In multimodal routing, the algorithm finds the best possible route by combining different transportation modes (i.e. wheelchair route and/or desired bus in real-time). Study [21] provides further information about the eNav application, dynamic of contexts, data measurement and navigation simulation.

C. *eNav-MEBot Fusion*

Advances in sensing technology have enabled researchers to design novel robotic EPWs that enhance mobility and accessibility. The Mobility Enhancement roBotic (MEBot) wheelchair was developed to address the mobility limitations of EPW users when facing hazardous environments with architectural barriers [22]. MEBot offers six height-adjustable wheels to control its seat orientation and elevation. These features provide seat elevation for reaching, pressure relief, and eye-to-eye level conversation to improve the wheelchair user's activities of daily living. Additionally, MEBot provides advanced mobility applications such as a self-levelling seat application to prevent tips and falls while manoeuvring over uneven terrains [23] and a step climbing application to provide accessibility over architectural barriers [24]. Further, MEBot is composed of an array of sensors to detect obstacles ahead of time (proximity sensors), and to monitor the wheelchair speed (drive wheel encoders), terrain friction coefficient (drive wheels current consumption), terrain

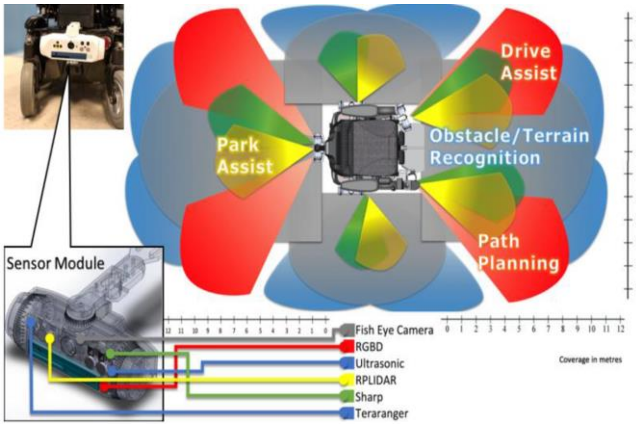

Figure 3. MEBot's sensor package

vibration (accelerometers), and seat and terrain angles (IMU sensor). A study suggested intelligent power wheelchairs would enhance social participation in a variety of important ways, thereby providing support for continued design and development of this assistive technology [25].

MEBot's sensor package is presented as a sixth layer of information to complement the energy consumption model and further expand the practicality of the eNav navigation application (Fig. 3). The use of sensors has demonstrated benefits for data logging to obtain in-depth information of environmental characteristics for crowdsourcing and improving route planning for wheelchair users. Routhier provided a scoping review in datalogger technology for wheelchairs in which sensors such as accelerometers, odometers, and outcomes related to kinematics (distance, speed, acceleration) were most common [26, 27]. Sinagra et al developed a Pathway Measurement Tool (PathMeT) to characterize pedestrian pathways [28] which records the surface roughness and submits its characteristics to a network for crowd-sourcing. Using the same principle, MEBot incorporates a sensor package including proximity and orientation sensors for obstacle detection, navigation, and tip/fall detection. This information can be used to characterize architectural barriers and update eNav maps for route planning with respect to the level of accessibility.

1) *MEBot as Barrier Detector*

MEBot provides the ability to climb over steps and architectural barriers, and the information collected during the step climbing process can alert other non-MEBot users about architectural barriers in the road and suggest alternative driving routes. This information is paired with global positioning system (GPS) data and transferred to the eNav server to recognize the architectural barriers at the location (Fig. 4). To validate the presence of an architectural barrier (i.e. steps), MEBot sends the required time to overcome a step (approximately 60 seconds) to the eNav server in addition to the obstacle (height/depth/width) dimensions detected by MEBot's sensor package. In the situation where there is a barrier-free route available or a ramp, this route will be preferred by MEBot due to the time efficiency and comfort to drive over the obstacle.

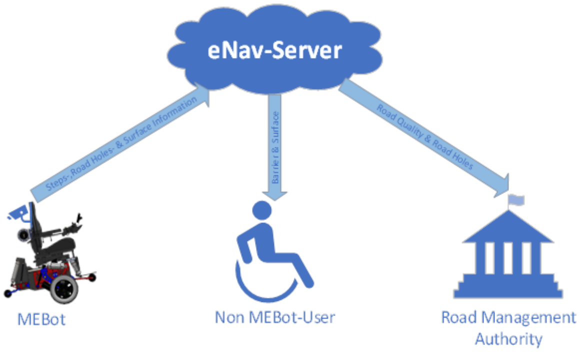

Figure 4. Use of MEBot's sensor package information to complement eNav maps

2) *MEBot as Uneven Surface Detector*

Uneven surfaces such as curb-ramps, steep slopes, and road-holes are identified with the help of the IMU sensor and MEBot's wheel movements to complement eNav's third layer of information. MEBot has the ability to maintain its seat levelled while driving over road-holes of 5.4 cm depth and surfaces of ±20° of inclination in the pitch and roll direction (Fig. 5). Simultaneously, the MEBot system creates a string of data that describes the characteristics (e.g. inclination and surface roughness) of the uneven surface. A camera attached behind MEBot provides a visualization of the surface. The system sends the data with the image of the surface and the respective GPS coordinates to the eNav server. Using this information, it is possible to analyze the data as hurdles or barriers. Then eNav warns the driver about the uneven surface or simply takes an alternative route avoiding the obstacle. At the same time the server can forward the geo-tagged information to the road management authorities maintain and improve pathways more effectively.

The Inertial Measurement Unit (IMU) of the self-levelling system can be used to detect the surface according to the same principle used in eNav on smartphones. However, the IMU sensor shows the advantage of being directly installed in MEBot which provides higher accuracy when

Figure 5. MEBot navigating over uneven terrains using passive suspension similar to EPWs (A) compared to MEBot using its self-levelling seat application for tip prevention (B). The MEBot's sensor package sends the location and surface angle to the eNav-Server (C).

compared with smartphone data. To prevent the disclosure of MEBot users' personal information, MEBot will be limited to sending unidentifiable personal information about the street and road holes.

III. CONCLUSIONS

The literature has shown route mapping apps can provide accessible routes; however, cities don't always maintain these routes in compliance with ADA guidelines and virtual maps are not updated with this information. The eNav navigation application integrates six layers of information to provide the most optimal routes in addition to offering less battery consumption. Along with these benefits, EPWs travel range is increased to reach 'the last mile' such as grocery shopping or visiting relatives' homes which enhances participation in the community.

Further, the MEBot wheelchair can detect and navigate over environmental barriers to prevent the risk of tips, which increases a user's independence. The eNav-MEBot fusion updates the eNav's virtual maps with these challenges to offer wheelchair accessible routes. Along with eNav, road management authorities will be informed to perform road maintenance that enhances the mobility and safety of wheelchair users.

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