A confidence-based approach for the assessment of accessibility of pedestrian network for manual wheelchair users

Amin Gharebaghi[1,2], Mir-Abolfazl Mostafavi[1,2], Geoffrey Edwards[1,2], Patrick Fougeyrollas[2], Patrick Morales-Coayla[1], François Routhier[2], Jean Leblond[2] and Luc Noreau[2]

1. Center for Research in Geomatics, Université Laval, Quebec, Canada, {amin.gharebaghi.1, patrick.morales-coayla.1}@ulaval.ca, {mir-abolfazl.mostafavi, geoffrey.edwards}@scg.ulaval.ca

2. Center for Interdisciplinary Research in Rehabilitation and Social Integration, Université Laval, Quebec, Canada{Patrick.Fougeyrollas, Jean.Leblond}@cirris.ulaval.ca, {Francois.Routhier, Luc.Noreau} @rea.ulaval.ca

Abstract: An obvious way to assist people with disabilities in their efforts to move around in urban areas is to offer information regarding accessible path segments that take into account their specific needs. Providing safe navigation in urban areas for people with disabilities can substantially enhance their opportunities for full social participation and the exercise of their basic rights. In order to offer these people information on accessible paths, we need to assess the accessibility of pedestrian networks. Accessibility is the result of interactions between the individual and the environment. These interactions need to be more carefully considered when we evaluate accessibility for persons with disabilities. This paper proposes a new approach for assessing accessibility, based on user confidence while moving around in urban space. For validation purposes, the proposed approach is applied in the Saint-Roch area of Quebec City using confidence information from 127 manual wheelchair users. The results are presented and discussed and further research perspectives are proposed.

Keywords: Accessibility, pedestrian networks, confidence, wheelchair user, modeling, dynamic segmentation

1. Introduction

Ensuring full social participation of people with disabilities is a challenging issue. This is because the special needs of these people are often not taken into consideration in the development of cities, public places, new technologies and services. People with disabilities who cannot move about autonomously can not carry out their daily activities such as going to work and school, shopping, or participating in community and family life. The needs for better participation in social activities by people with disabilities are usually referred to as "hidden demands" (Marston & Golledge, 2002). These are activities that people with disabilities are unable to carry out despite their desire to do so. According to a Canadian survey on disability (CSD, 2012), pain, motor disability[1] and lack of adapted services, are the most common causes for social exclusion among Canadian adults. Indeed, mobility problems constitute 7% of the aforementioned disability issues (CSD, 2012). Providing people with disabilities with assistive technologies to improve their mobility will help to increase their effective participation in society. To address this issue, the research reported here aimed to develop a new approach for evaluating the accessibility of pedestrian networks for people with motor disabilities. Since mobility is a result of interactions between humans and their environment (Gharebaghi and Mostafavi, 2016), our approach was to focus on human capabilities and their confidence levels across a range of environmental interactions during displacements.

Several studies have attempted to address this issue by modeling the interactions between humans and the environment. For example, Warren (1984) analyzed the dynamics of an human-environment system using Gibson's affordance theory (Gibson, 1977). He showed, for example, that stair climbing is made possible by the interaction

[1] Disabilities related to the movement and maintenance of body position (Fougeyrollas, 1998).

between leg length and stair height. Jonietz et al. (2013) modeled the suitability of urban networks in relation to different types of agents, with and without motor disability. In similar research, Matthews et al. (2003) and Beale et al. (2006) developed a GIS-based system for modeling access for wheelchair users in urban areas. Kasemsuppakorn and Karimi (2009) developed a personalized routing model for wheelchair users focusing on user priorities and sidewalk properties. Jonietz et al. (2013) and Jonietz and Timpf (2013) proposed a framework for modeling spatial-suitability of pedestrian networks based on affordance theory[2]. This framework sought to assess suitability determined by characteristics of agents, environments, and actions. Tajgardoon and Karimi (2015) proposed an approach based on a weighted linear model for different characteristics of sidewalk segments to evaluate the accessibility of sidewalks for persons with disabilities. Although all of these studies proposed valuable methods to model the human-environment interactions, a) they did not fully consider the individual's capabilities for implementation of their approaches, b) their validation are not generally supported by human involvement and finally c) each of them identified and employed their own set of properties describing pedestrian networks. However, it does not appear that they fully took into account users' perception of these properties. As a result, the users' requirements are not fully met.

We propose a new approach that considers the perception and capabilities of manual wheelchair users to evaluate the accessibility of pedestrian network for persons who use a manual wheelchair in their daily activities. We account for both actual and perceived capabilities of the users. User confidence is considered as a criterion to measure the user's perceived capabilities. The accessibility assessment process is undertaken in seven steps: 1) capturing the pedestrian network data, 2) partitioning the pedestrian networks into segments, 3) gathering the user profile information, 4) linking segment properties with the corresponding user confidences, 5) aggregating the confidence levels for each segment, 6) evaluating the accessibility level of each segment based on the total confidence, and finally, 7) visualizing the accessibility level of each segment on the pedestrian network map.

The remainder of this paper is organized as follows: In Section 2, we determine a specification for the database that will contain the information about the pedestrian network, identifying the most important environmental criteria in relation to the mobility of people with manual wheelchairs. In addition, we describe the segmentation process. Section 3 proposes the confidence-based framework to the assessment of the accessibility of the pedestrian networks for manual wheelchair users. Section 4 presents the results of the accessibility assessment for the Saint-Roch area of Quebec City for 127 individual. Finally, Section 5 presents conclusions and future work.

2. Pedestrian network database

One of the fundamental components of a navigation system is a geospatial database. A geospatial database provides the necessary information for performing navigation, mapping and routing functions. Nowadays road network databases are designed to serve divers navigation applications. However, these databases are not in general usable for navigation persons with disabilities. Pedestrian network databases require information about the environment in much greater detail such as obstacles on the sidewalks. In addition, to employ such databases for navigation by persons with different capabilities, these databases should be adapted to their needs. Therefore, a suitable database for navigation by persons with disabilities should have both information on user profiles including their capabilities as well as about the pedestrian network itself and its characteristics in relation to the mobility task.

A pedestrian network is one of the most important environmental entities in outdoor mobility that persons with disabilities interact with in their daily activities. It contains the geometric and topological relations between pedestrian path segments (Karimi and Kasemsuppakorn, 2013). Pedestrian networks are typically classified into sidewalks, crosswalks, footpaths, building entrances, trails, pedestrian bridges, and tunnels, each of these consisting of several segments. Two points, starting from one point and ending at another, define a segment. Each segment has properties that can be either permanent or temporal. The spatial database for enabling the mobility of people with disability should take into account both permanent and temporal properties (events) using appropriate algorithms

[2] The affordances of the environment are what it offers the animal, what it provides or furnishes, whether for good or ill (Gibson, 1977).

(see below for more details about these processes). To create these algorithms, first it is necessary to determine the most relevant entities of the pedestrian network that will affect the mobility of persons with motor disabilities. Following this, the segmentation of the network can be carried out based on the static and dynamic nature of those entities.

2.1 Determining the most important environmental criteria for enabling the mobility of persons with manual wheelchairs

As mentioned above, the variation of the characteristics of pedestrian networks or the presence of different obstacles on the pedestrian network may affect the network segmentation process. Furthermore, this set of characteristics may vary from one context to another. For example, while the quality of the pavement is likely to be of central importance for persons with motor disability, it may not be a significant factor for persons with hearing impairment. Therefore, to evaluate the accessibility of a segment for persons with disabilities, the main properties that affect their daily activities should be determined. So far, a number of studies have investigated these properties. For example, Matthews et al. (2003) used width, length, slope, sidewalk surface, steps, sidewalk conditions and sidewalk traffic. Kasemsuppakorn and Karimi (2009) considered slope, sidewalk width, steps, segment length, surface type, cracks, manhole covers, uneven surfaces, and sidewalk traffic. Although pertinent, there is no evidence that these properties were determined according a rigorous study involving the perception of people with disabilities or the experience of expert groups. To overcome the limitation of these works, we use properties that are identified in the Wheelchair Mobility Confidence Scale (WheelCon) (Rushton et al., 2011). This survey instrument is a questionnaire that was developed specifically for studying the mobility of wheelchair users. WheelCon is one of the most reliable approaches for evaluating capabilities of wheelchair users. The questionnaire includes 65 items, which were identified by a three round Delphi[3] survey among a panel of experts (43 experts), of which 30 percent were wheelchair users.

Here, we are specifically interested to the characteristics of the outdoor environment that affect the mobility of people with disabilities. For this reason, we have generated a short version of the main questionnaire that includes only items related to outdoor mobility tasks. A statistical process was used to analyze and sort out the items in terms of relevancy, correlation, and adaptation. The WheelCon questionnaire includes 65 items. Among them, 17 are especially relevant to this study. Data from 127 participants indicated that those selected items can effectively predict the 65-item WheelCon total score (SPSS 23; linear regression; adjusted R^2= 0.923; $p<.0001$). A principal component analysis on these 17 items identified two factors that catched respectively 65% and 9% of the total variance. The sampling adequacy was high (Kaiser-Meyer-Olkin index = 0.93). In order to further reduce the number of items of an abridged version of the WheelCon specific to our study, we iteratively removed one item at a time in order to check the impacts of this removal on the adjusted R^2 and KMO index. In order to preserve the most detailed information, we followed the strategy to remove first the item with the smallest variance. Optimally, this process identified a set of 12 items that has a minimal impact on the adjusted R^2 (0.888; $p<0.0001$) and the KMO index (0.92). These 12 items are similarly sensitive to two components that catched respectively 67% and 10% of the total variance. Figure 1 outlines this process.

As a result of the explained process, 12 items among the 65 original items of WheelCon were selected. These items are used to guide the segmentation of the pedestrian networks. They are classified into seven categories related to the segments that include slope, curb cut, surface quality, potholes, presence of snow on the segment, intersections with and without traffic lights, and sidewalk traffic. Among these properties, the slope, curb cut, and intersections are classified as permanent properties and surface quality, pothole, snow, and sidewalk traffic are classified as temporal properties. Different algorithms for the segmentation of the pedestrian network are proposed for each class of properties. These algorithms are described in the following section.

[3] The Delphi method is a structured communication technique or method, originally developed as a systematic, interactive forecasting method which relies on a panel of experts (https://en.wikipedia.org/wiki/Delphi_method).

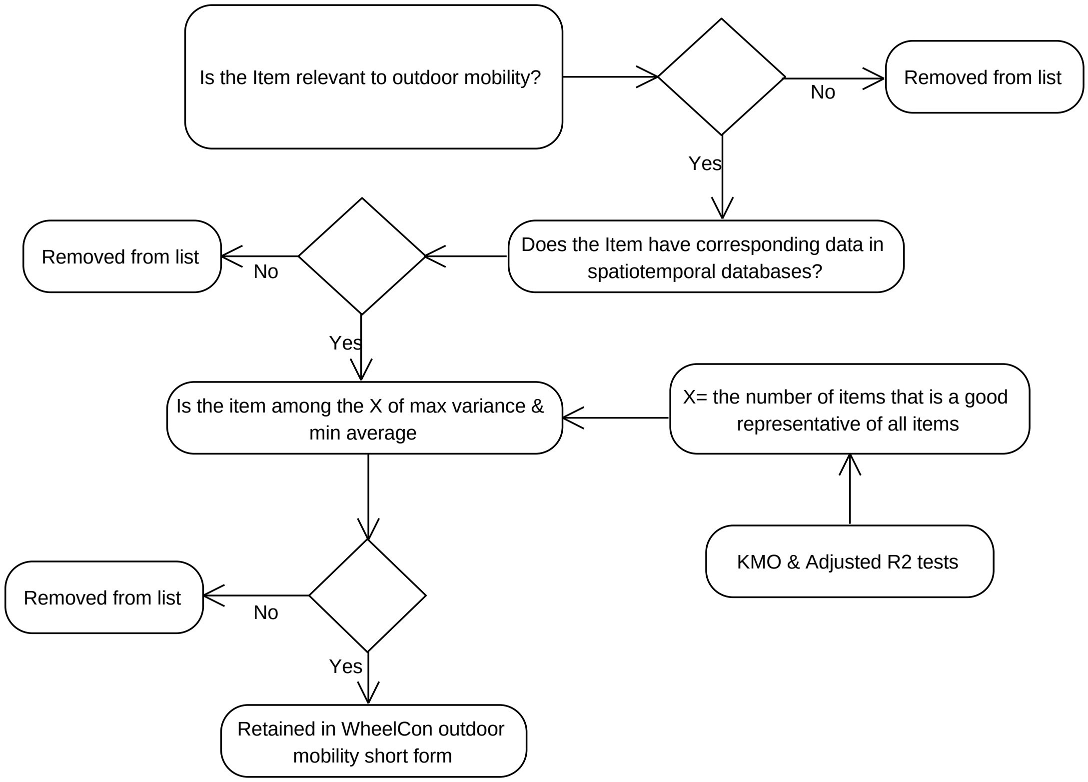

Fig.1. Selection of the most pertinent items for the mobility of manual wheelchair users from WheelCon questionnaire

2.2 Pedestrian network segmentation

The segmentation of the pedestrian network is the first step for its accessibility assessment and mapping . The segmentation should be carried out based on both the relevant properties of the network as described earlier and the user requirements. This process includes four steps: 1) extracting the centre lines of the network, 2) ensuring their connectivity and topological consistency, 3) carrying out the segmentation based on its permanent properties, and 4) and carrying out the segmentation based on the temporal properties. Figure 2_a shows the permanent segmentation in our research area considering slope changes of more than 5, as well as the presence of curb cuts. The process is extended to generate new segments based on temporal properties. Here we use a dynamic segmentation process (Weigang and Guiyan, 2009), which is a method for identifying segments with changing attributes in time. Instead of splitting segments whenever there is a change in attribute values, here we apply a linear reference system to indicate the start and end of a temporal property without splitting the segment (Cadkin, 2002). Figure 2_b shows an example resulting from this process. Once the segmentation of pedestrian network is carried out the accessibility of each segment can be assessed. The accessibility assessment process is explained in the following section.

a. Permanent segmentation **b.** Dynamic segmentation

Fig.2. Segmentation of the pedestrian network

3. Evaluating the accessibility of segments

In the context of urban mobility, accessibility is often defined by the ease of reaching a destination with respect to distance, time and cost constraints (Morris and Wigan, 1978). This definition was used at the basis of several statistical approaches to assess accessibility. In these approaches, count of accessible places, total distance, closest place, and absolute access are employed as the main criteria (Church and Marston, 2003). In each of these studies, accessibility is evaluated by measuring the cost value for each path. For example, in the case of automobile accessibility to a given location, although the cost is normally determined in terms of distance, it can be influenced by other factors such as surface type, speed limit and congestion (Beale et al., 2006; Martin et al., 2001; Lovett et al., 2002). For the mobility of a person, however, accessibility depends on the interactions between person and the environment. For example, a path can be accessible for some while it can be inaccessible for others. Therefore, the accessibility of each segment of a pedestrian network should be assessed considering not only the environmental factors but also the users' capabilities.

For evaluating the capability of a wheelchair user, approaches such as the Wheelchair Outcome Measure (WhOM) (Mortenson et al., 2007), the Wheelchair Skill Test (WST) (Kirby et al., 2002), and the Wheelchair Circuit (Kilkens et al., 2004) have been proposed. On the other hand, for evaluating the capability of a person, their confidence for performing a given task is a more reliable criterion than their skill alone (Rushton et al., 2011). A person might be able to perform a given task but not be confident enough to carry it out. In this research work, we employ user confidence to evaluate the accessibility of pedestrian segments. The accessibility of each segment is calculated by aggregating user confidence with respect to each attribute of the segment as follow.

$$A_{ijl} = \sum_{p=1}^{7} Con_{ijp} \qquad \textit{Equation 1}$$

Where, A_{ijl} is the index of accessibility of segment j for person i by travel type l; Con_{ijp} is the confidence level of the person i for the segment j in relation to the property p;

User confidence levels are evaluated based on the Wheelchair Mobility Confidence Scale (WheelCon) approach (Rushton et al., 2011). Each segment has more than one property, so it will take more than one confidence value. These confidence values are aggregated for each segment and a total confidence value for a given segment is assigned. Hence, the accessibility assessment process is completed in three steps: 1) Setting the user profile information that includes the user confidence level via the 12 questions of the WheelCon short-form questionnaire, 2) aggregating the confidence levels for each segment with respect to its properties, and 3) evaluating the accessibility level of each segment based on the total confidence.

3.1 Aggregation of confidence levels

In order to assess the accessibility of each segment, the aggregation of confidence values related to properties of that segment is required. There are several methods that can be employed to aggregate these values such as weighted linear models and if-then rules approaches. Aggregation process is a very important step in the accessibility assessment approach. Weighted linear models might have some limitations in complex situations. For instance, in a scenario of mobility the user may a) move down from a standard curb, b) cross an intersection, and c) pass over a hole on the sidewalk. If the confidence level of the user with respect to each of these properties is at medium level, the aggregated confidence level might not be medium for this user. A weighted linear model would result a medium confidence level for this scenario, which does not reflect the reality.

Here we use If-then rules approaches, which provide more realistic values for aggregated confidence level. Fuzzy logic is a widely used if-then rule approach. Fuzzy logic is introduced by Zadeh et al. (1965) to model the vagueness that is associated with human cognitive processes. In recent years this approach has been widely used in many different applications including routing and transportation planning ((Kasemsuppakorn and Karimi 2009) and (Karimanzira et al. 2006)). To employ fuzzy logic, three steps must be followed: (1) build the rule set and define the membership functions (fuzzification), (2) make a fuzzy inference system (FIS) using if-then rules and (3) merge the outputs of the rules and ensure defuzzification of the results using a different set of membership functions to derive output variables (Mamdani and Assilian, 1975). The objective of the Fuzzification step is to transform the numerical confidence values to qualitative values (linguistic variables) by defining a membership function. For example, the values between 0-20 correspond to a very Low confidence. Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH) labels are defined for describing the confidence levels. Then the if-then rules are defined to aggregate the individual user confidences and, consequently, calculate the total confidence of the user for each segment. For example:

If (the confidence level of slope is low) & (the confidence level of poor surface is low)
Then (the total confidence level is very low)

Table 1 indicates the defined rules. Rules are stated as if aggregation would be applied on two components, in case that we have more than two parameter the result of first aggregation would be aggregated with the next parameter and this process is continued till the total confidence is obtained. Since these rules directly affect the result of the process, they need to be validated. In our research, an expert who is also a wheelchair user carries out the validation step. However, we understand that further investigation is needed for a more rigorous validation of these rules by participation of experts and wheelchair users.

Table 1. If-Then rules

Rule No.	Confidence Level		Agregated confidence	Rule No.	Confidence Level		Agregated confidence
	p	q			p	q	
1	V.L	V.L	V.L	9	L	V.H	L
2	V.L	L	V.L	10	M	M	L
3	V.L	M	V.L	11	M	H	M
4	V.L	H	V.L	12	M	V.H	M
5	V.L	V.H	V.L	13	H	H	M
6	L	L	V.L	14	H	V.H	H
7	L	M	V.L	15	V.H	V.H	V.H
8	L	H	L				

Once the aggregation of confidence levels is achieved and a unique confidence level is calculated for each segment, a numerical confidence value must be recovered. To address this issue, a defuzzification technique should be applied to produce exact numerical values from the fuzzy values, based on the defined membership functions and rules. The output values are utilized for determining the accessibility levels of pedestrian network segments in four categories of Not Accessible (NA), Low Accessible (LA), Accessible (A), and Very Accessible (VA).

4. Cases study

To illustrate the validity and utility of the proposed approach, the whole process of accessibility of the Saint-Roch area in Quebec City is assessed. To fulfill this assessment each user determines his/her confidence level by choosing a corresponding number from the rating scale from 0 to 100. The accessibility assessment process is visualized for two users. First, it is carried out for a 61-years-old female wheelchair user called user #1. In a second case, we suppose a user with mean confidence called user #2. The mean confidence value is obtained using information from 127 users to assess the average accessibility of the study area. The data on users confidences was obtained in collaboration with another team who has conducted a survey on manual wheelchair users skills. The mean confidence values for 12 properties for a given segment in sidewalk are provided in Table 2. In this example the mean values for the user #1 and user #2 are 17 and 52, respectively.

Table 2. Confidence values of manual wheelchair users for each parameter

No.	User confidence items	User #1	User #2
1	Can move your wheelchair up a standard height curb 15cm (6") without a curb cut?	15	22
2	Can move your wheelchair down a standard height curb 15cm (6") without a curb cut?	15	41
3	Can move your wheelchair across 3m (10ft) of flat, unpacked gravel?	15	51
4	Can move your wheelchair along a sidewalk with 5cm (2") of snow?	0	51
5	Can move your wheelchair through a pothole that is wider than your wheelchair and 5cm (2") deep?	10	54
6	Can move your wheelchair along a flat dirt path or trail with some tree roots and rocks?	25	59
7	Can move your wheelchair up a dry steep slope (> 5º incline)?	30	68
8	Can move your wheelchair along a paved sidewalk that is cracked and uneven?	40	70
9	Can cross a street with light traffic at a crosswalk with no traffic lights?	10	73
10	Can move your wheelchair through a crowd of people without hitting anyone?	10	73
11	Can move your wheelchair across 3m (10ft) of flat, freshly mowed, dry grass?	10	74
12	Can move your wheelchair to press the crosswalk button and cross the street before the traffic light changes?	10	75
-	Mean confidence	17	52

The accessibility assessment process started with the segmentation step based on the properties of each segment and related events observed in the environment. Then, the attributes of each segment for selected properties were stored in a spatio-temporal database. Next, the confidence value of the corresponding attributes for each user is imported into the database. The fuzzification, aggregation, and calculation of the total confidence for each segment are carried out for each user. Finally, the accessibility level for each segment in the study area is evaluated and visualized. Figure 3 shows the accessibility map for user#1 where "Not Accessible" segments are represented with red, "Low Accessible" segments are yellow, "Accessible" segments are green, and "Very Accessible" segments are dark green. As the accessibility map shows, there are a significant number of inaccessible segments for user#1. This process indicates that for this manual wheelchair user, 924 out of 2427 segments were not accessible. This represents 38% of the whole network. Most of the inaccessible segments were located in the intersections.

Fig.3. Accessibility map for user #1

The next map shown in Figure 4 is generated for the same area employing the mean confidence values for all 127 users. Since the average confidence level for all participants was significantly higher than the confidence level of user#1, the number of inaccessible segments is negligible. According to the statistical analysis, 62% of the St-Roch area's pedestrian network is very accessible, 25% is accessible, 12% is low accessible, and about 1% is not accessible. This map can be used by city authorities as a valuable decision making tool to locate the inaccessible and low Accessible segments and propose an accessibility improvement plan in the area.

Fig.4. Accessibility map for user #2

5. Conclusion and future work

In this paper, we proposed a novel method to assess the level of accessibility of a pedestrian network for manual wheelchair users for their mobility. First we presented a segmentation process for pedestrian network incorporating a range of segment properties and related events. The study also drew on the results of the WheelCon survey for assessing accessible paths based on users' perceptions and capabilities, to identify a set of 12 characteristics. A key contribution of the present paper was to propose a confidence-based approach for the assessment of the accessibility of pedestrian networks. To our knowledge, this is the first time that a confidence based approach is used to evaluate the accessibility in an urban area. To illustrate the utility of the proposed approach, we presented two scenarios using data from the Saint-Roch area in Quebec City. The results demonstrated different levels of accessibility for a specific user compared to an average manual wheelchair user. City authorities for further analysis and decision-making could use the resulting maps. Further investigation is needed for more rigorous validation of the if-then rules proposed here for aggregating confidence values in relation to different segment properties. We also plan to carry out further validation process with experts and wheelchair users in more realistic application scenarios.

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