Automated Identification of Wheelchair Accessible Outdoor Pathways using Aerial Photogrammetry and Artificial Intelligence

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Abstract

Wheelchair users and other mobility-impaired individuals often face access barriers such as stairs, steep slopes, and narrow pathways when navigating outdoor spaces. Many of the existing accessibility maps and wayfinding applications source their data through inefficient methods such as manual surveys and crowd-sourcing. Consequently, they typically lack specific, accurate, and current accessibility information. This paper proposes the use of aerial photogrammetry, artificial intelligence, and geographic information system (GIS) analysis to automate the identification of wheelchair accessible outdoor pathways. This paper considers a case study of Carnegie Mellon University's campus and measures the degree of wheelchair accessibility using the 2010 Americans with Disabilities Act (ADA) standards for ramp slopes and walking surface width. The proposed methodology could be extended in future research to include other ADA standards such as surface quality and the presence of curb cuts. The wheelchair accessibility information provided by this methodology can be used by wheelchair users to identify accessible routes of travel and by facility managers and government agencies to survey and correct access barriers along pedestrian pathways.

Introduction

Navigation in outdoor spaces can be challenging for wheelchair users and other disabled individuals. Depending on the mobility device used, key barriers for mobility impaired individuals include path width, the presence of stairs and ramps, slope steepness, the presence of curb cuts, and surface quality (Beale et al. 2006).

The Americans with Disabilities Act (ADA) provides standards for accessible design which include guidelines for ramp slopes, path widths, and other key mobility-related barriers (U.S 2010). Although new buildings are required to be ADA compliant under Title III of the ADA, barrier removal for existing facilities is only required when the removal is "easily accomplishable and able to be carried out without much difficulty or expense" (U.S 1994). This means that not all outdoor pathways and building entrances are accessible. Thus, it is important for disabled individuals to have access to current, accurate, and specific information about which buildings and pathways are accessible for their disability type and individual needs.

Unfortunately, many maps and wayfinding applications do not provide sufficiently useful (i.e., specific in terms of location and type of barrier) or reliable (i.e., accurate and current) accessibility information (Prescott 2016). Wheelchair accessible navigation tools have typically collected accessibility information using manual data collection via crowd-sourcing or inspections by experts (e.g., Wheelmap; AccessAble; Wheeler et al.). These techniques are inefficient and often lead to incomplete data. For example, over 3 years after Wheelmap – one of the most popular online wheelchair accessibility mapping applications – first launched, 98.44% of the 421,666 entities identified in the United Kingdom were annotated as unknown for wheelchair accessible information (Ding 2017).

This paper will combine existing classification and GIS techniques in a novel way to provide a more automated method for mapping wheelchair accessibility of outdoor pathways. The scope of this paper is limited to two standards provided in the ADA Standards for Accessible Design (2010): ramp slopes (Section 405.2) and walking surface widths (Section 403.5.1). The methods used to detect ramp steepness will also detect obstacles such as benches, vehicles, and stairs. It is suggested that future research extends these methods to identify additional accessibility attributes such as sidewalk surface quality and the presence of curb cuts.

Case Study: Carnegie Mellon University Campus

This paper will explore a case study of 62 acres of Carnegie Mellon University's campus in Pittsburgh, Pennsylvania. As is common in many public spaces, there is currently very little information about wheelchair accessibility on Carnegie Mellon's campus. Publicly available campus maps[1] do not provide information about wheelchair accessible pathways, parking, or building entrances. According to Carnegie Mellon's Offices of Admissions, Marketing and Communications, and Disability Resources, the most recent wheelchair accessibility map of the University's campus was created in 2013. This map is outdated and inaccurate.

The scope of this case study will be limited to the outdoor

[1] https://www.cmu.edu/visit/maps-parking-transportation.html

pathways on the campus; wheelchair accessible navigation within buildings may be an interesting and useful extension for future research. The results of the case study are intended to be a proof of concept that aerial photogrammetry and artificial intelligence techniques could be applied to identify wheelchair accessible outdoor pathways in similar environments such as university campuses, parks, outdoor shopping centers, and other public spaces.

Related Work

Wheelmap[2] is an online application that crowd-sources information about the wheelchair accessibility of various entities such as restaurants, hotels, and transportation. Each location can be labeled as fully, partially, or not at all accessible for wheelchair users. There are some limitations to this application. First, the crowd sourcing approach has led to large gaps in the data; three years after Wheelmap launched, 98.44% of entities in the UK were annotated as unknown (Ding 2017). In addition, the simple labeling system may not provide sufficiently useful information about the type and location of barriers. For example, it is unclear which rooms or entrances are inaccessible in a building labeled "partially wheelchair accessible."

In contrast to the simple labeling system used by Wheelmap, AccessAble[3] is an application based in the UK and Ireland which provides accessibility information for various needs. AccessAble uses 33 accessibility symbols to label entities and provides detailed access guides with images of the entity. An access guide for a cafe may include information about the height of the lowest table, availability of braille menus, layout of the bathrooms, etc., which allows users to identify whether a location is accessible for their personal needs. The information for the access guides is collected by expert surveyors, which is time and labor intensive. Although this application provides useful and accurate accessibility information, it is not easily scalable and it may be difficult to keep it up-to-date.

Wheelmap and AccessAble both focus on the accessibility of specific entities. Access Map[4] is an application focused on the accessibility of pedestrian pathways in the Seattle area. Access Map provides customized navigation; users can select the maximum uphill and downhill steepness and whether to avoid raised curbs on their route. The application color codes the sidewalks by steepness and codes crosswalks by the presence of curb cuts. The data used in the application was collected from the city of Seattle's Department of Transportation and, since the format of this data is not standardized across departments, the Access Map interface is not easily translatable to other cities (Capsi 2017).

Scalability is a concern in all of the applications discussed thus far. Artificial intelligence methods could help reduce the time and labor required to collect the accessibility information provided in these applications. For example, Mapillary[5] uses computer vision to recognize over 40 object types (e.g., crosswalks, traffic signs) in crowd-sourced street-level images. Although it does not currently provide navigation for wheelchair users, the data collected by Mapillary could potentially be used in an accessibility wayfinding application (Capsi 2017).

The goal of this paper is to begin to address the issues of usefulness, reliability, and scalability that arise in the existing solutions. A useful and reliable solution would provide users with accurate, current, and specific information about the location and type of accessibility barriers in an outdoor space. A scalable solution would collect complete data in a repeatable and time efficient manner. Not only would this make it feasible to identify wheelchair accessible paths for a large number of outdoor spaces, but would also allow entities to quickly and easily update the accessibility information when changes occur (e.g., new construction).

Methods

Data Collection

The area of interest was flown using a DJI Mavic 2 Air small unmanned aircraft system (sUAS) and video was captured at 4k resolution. The flight was conducted at 320 feet, with a second pass over the most critical areas (i.e., the main academic buildings on Carnegie Mellon's campus) at approximately 165 feet. The flight pattern was arranged in a double grid with the intention of achieving 65% side overlap. A total of 28 minutes of video was recorded.

From this video, 1 of every 100 frames was extracted as an image, and these frames were used as input to the photogrammetry process. The images were processed using Pix4DMapper (version 4.6.4) to produce a 3-dimensional model in both point cloud and triangle mesh formats, digital terrain model which provides elevation for ground surfaces and man-made objects such as benches, and a correctly scaled and geo-referenced orthomosaic. The entire model was correctly oriented using Google Elevation Service. This methodology was chosen over satellite imagery and LiDAR because neither of those sources provide adequate resolution to identify stairs and ramp slopes at the level necessary for this project.

Identifying Wheelchair Accessible Paths

This paper focuses on two standards provided in the ADA Standards for Accessible Design (2010): ramp slopes (Section 405.2) and walking surface widths (Section 403.5.1). According to ADA standards, a ramp is any area whose incline is greater than 1:20 (i.e., 5% incline), and the maximum steepness for a wheelchair accessible ramp is 1:12 (i.e., 8.33% incline) (U.S 2010). To be ADA compliant, the clearance width for a walking surface must be at least 36-inches (915 mm) (U.S 2010).

A trained Gradient Boosted Trees (GBT) model was used to identify the road surfaces. Building on previous work which used geometric features for point cloud classification (Hackel, Wegner, and Schindler 2016), this GBT model was trained on both geometric and color features (Becker et al. 2018). Gradient Boosted Trees models train an ensemble of

[2] https://wheelmap.org/

[3] https://www.accessable.co.uk/

[4] https://www.accessmap.io/

[5] https://www.mapillary.com/

Figure 1: The slope data for an area outside of Doherty Hall on Carnegie Mellon's Campus. The road surfaces were identified by the Gradient Boosted Trees model and classified as flat, accessible slopes, or inaccessible slopes using the digital terrain model. Key features that were identified include stairs, two wheelchair accessible ramps leading into the building, and an inaccessible ramp (i.e., ramp with incline greater than 8.33%).

decision trees using a greedy algorithm to iteratively minimize the loss function (Ke et al. 2017). The GBT model was selected over Random Forest models (which have been used extensively in point cloud classification) because it has been found to have higher accuracy with comparable computational complexities (Becker et al. 2018).

The GBT model incorrectly labeled some building roofs as road surfaces. Publicly available building footprints[6] were used to remove these areas from the pathways. In addition, the model is unable to identify pathways under building overhangs. The pathways under buildings were manually validated to be wheelchair accessible and added to the path raster.

The slope of each point was calculated from the digital terrain model using QGIS (version 3.16) The slopes were used to classify the identified road surfaces as flat (i.e., incline less than 5%), accessible ramps (i.e., incline between 5% and 8.33%), or inaccessible (i.e., incline greater than 8.33%). Since points at the edge of stairs have an incline greater than 8.33%, these areas were correctly identified as inaccessible.

To incorporate the ADA path width standards, the maximum slope within a 36-in diameter of each point was calculated. Any point which did not have at least 36-inches of clearance from inaccessible barriers was classified as inaccessible. After completing this process, any pathway of adjacent pixels that were classified as accessible meet both the slope and path width accessibility standards.

[6]https://data.wprdc.org/dataset/allegheny-county-building-footprint-locations1

Wheelchair Accessible Navigation

To implement a navigation algorithm, the path raster was thinned and converted to a line vector to create a network graph. Any region classified as inaccessible was excluded from the edges of the network graph. Building entrance locations and accessibility (e.g., presence of automatic door) were manually identified and added as a point vector layer in QGIS. Dijkstra's shortest path algorithm was used to find the least cost wheelchair accessible pathway between each building.

Results and Evaluation

Results of Case Study

This methodology was applied to a case study of 62 acres of Carnegie Mellon University's campus in Pittsburgh, PA. A user interface[7] was developed to provide accessible navigation information for wheelchair users in the Carnegie Mellon community and allow CMU administration to identify areas which could be changed to improve wheelchair accessibility on campus.

The implementation of this algorithm identified wheelchair accessible paths for 254 of the 300 possible building pairs considered in the case study. The 46 building pairs without wheelchair accessible outdoor paths were from Roberts Engineering Hall to all buildings and from Wean Hall to all buildings except Porter Hall. Field tests validated that there were no outdoor paths – wheelchair accessible or otherwise – to Roberts Engineering Hall due to a construction zone. The field tests did not identify any additional wheelchair accessible paths to Wean Hall.

[7]https://amylopata.github.io/

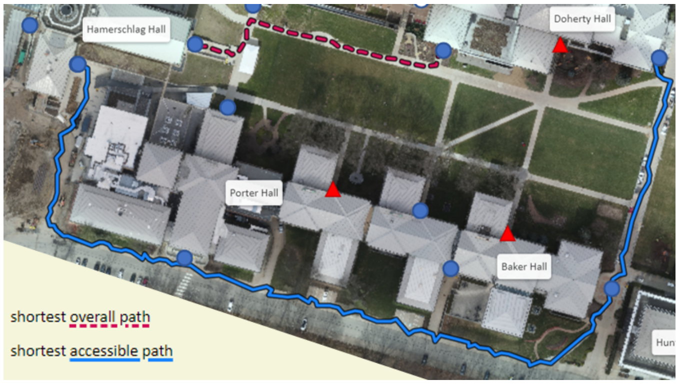

Figure 2: The shortest overall path (dashed red line) and shortest wheelchair accessible path (solid blue line) between Doherty Hall and Hamerschlag Hall (as identified by this algorithm). The shortest overall path is not wheelchair accessible because the ramps next to Doherty Hall are too steep (as noted in Figure 1) and there are stairs leading to the front entrance of Hamerschlag Hall.

At the time of the data collection in March 2021, a construction zone blocked the only wheelchair accessible path leading to the entrance of Hamerschlag Hall/Scott Hall. The algorithm failed to identify the fence surrounding the construction zone as a barrier (discussed further in ”Evaluation of Approach”) and therefore incorrectly classified the paths to the South-West entrance to Hamerschlag Hall/Scott Hall as wheelchair accessible (see Figure 2). Thus, of the buildings with at least one outdoor path between them, 22.8% did not have a wheelchair accessible outdoor path between them.

On average, the shortest wheelchair accessible path between two buildings was 1.46 times longer (in distance) than the shortest overall path between those same buildings. This is a factor that Carnegie Mellon administration could consider when creating university policies (e.g., the amount of time given between classes) because it indicates that it may take more time for wheelchair users to navigate between buildings compared to non-wheelchair users.

The results of this case study can be used to identify barriers which significantly contribute to inaccessibility on campus. For example, as noted in Figure 1, the bike ramps next to Doherty Hall and Wean Hall (in the area called ’The Mall’) are not wheelchair accessible according to the 2010 ADA standards for ramp slopes (Section 405.2). If these ramps were wheelchair accessible, there would be wheelchair accessible outdoor pathways to Wean Hall (20 additional building pairs) and the average distance disparity between the shortest overall path and shortest wheelchair accessible path would be reduced.

Evaluation of Approach

The case study of Carnegie Mellon University considered 62.22 acres of campus. The Gradient Boosted Trees model classified 19.93 acres of road surfaces. Of the area classified as road surfaces, 5.44 acres (27.29%) were building roofs and were removed using the building footprints. Pathways under building overhangs and other pedestrian pathways which were not identified as road surfaces by the GBT model were manually added. The final set of pathways contained 14.49 acres of road surfaces identified by the GBT model, 0.60 acres of manually identified pathways under building overhangs, and 1.24 acres of other manually identified pedestrian pathways. So, the GBT model identified 88.7% of the pedestrian pathways. This indicates that using the GBT model helps to resolve the issue of incomplete data collection which arises when relying on crowd-sourcing or expert surveyors (see ”Related Work”).

This case study required approximately 30 minutes of aerial video capture and approximately 5 hours of computer processing time. This, in combination with the completeness of the data collection, indicates that this approach is more scalable than other approaches (see ”Related Work”). In addition, it would not require much manual labor or time to re-run the data collection and analysis after construction or other changes to the campus. Thus, this approach can be used to provide current wheelchair accessibility information.

A field test of 15 randomly selected building pairs was used to evaluate the accuracy of the accessibility classifications. For each of the selected building pairs, non-disabled individuals walked the shortest wheelchair accessible path identified by the algorithm to manually validate the wheelchair accessibility of the paths. In the future, it would be important to seek input from wheelchair users to help identify additional considerations that are not currently

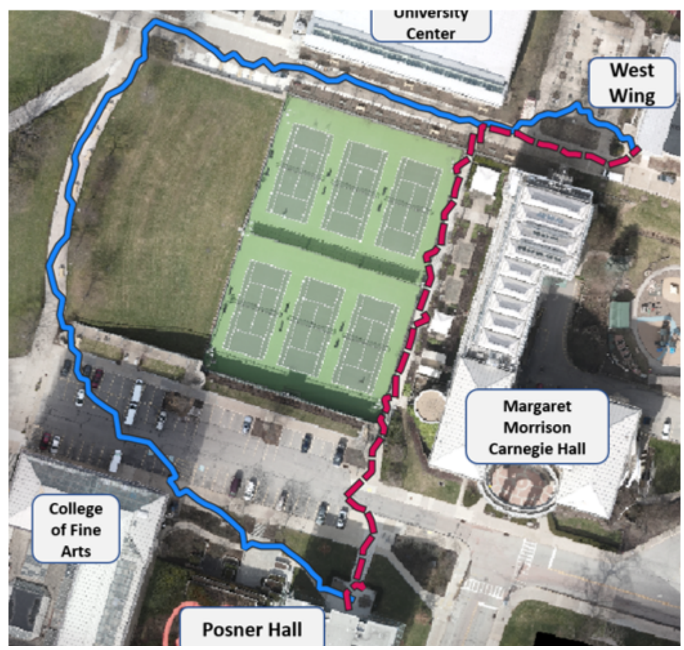

Figure 3: The shortest overall path (dashed red line) and shortest wheelchair accessible path (solid blue line) between West Wing and Posner Hall (as identified by this algorithm). The current algorithm does not consider the location of curb cuts when crossing the parking lot.

accounted for in the design of this approach. The field tests identified only two barriers which had not been identified by the algorithm. The first barrier was a raised curb when crossing a parking lot (see Figure 3). The ADA standards for curb cuts were out of scope for this project, so this omission was expected. The second barrier was a fence surrounding a construction zone. We hypothesize that the GBT model incorrectly classified the fence as a road surface because it was thin and similar in color to the sidewalk. Further investigation would be necessary to better understand this error.

As discussed above, the strengths of this approach include the completeness of data collection, scalability, accuracy, and ability to provide specific information about the location of barriers (see Figure 1). Some limitations of the approach include:

- The GBT road surface classification does not distinguish between sidewalks and roads;
- Requires manual identification of building entrances and pathways under building overhangs;
- Only considers two accessibility standards;
- Does not incorporate indoor navigation;
- Road surface classification and digital terrain model may be less accurate in areas with more trees and if snow covers the ground.

Many of these limitations could be addressed in future work (see "Conclusion and Discussion").

Conclusion and Discussion

This work is a proof of concept that artificial intelligence and aerial photogrammetry can be a scalable solution for providing complete, accurate, and specific wheelchair accessibility information for outdoor pedestrian pathways. The results of the case study will have an immediate social impact for wheelchair users in the Carnegie Mellon University community and Carnegie Mellon administration; it is the only comprehensive wheelchair accessibility campus map to be updated in the past 8 years.

Further research is necessary to evaluate the algorithm presented in this paper. The results should be replicated in other outdoor spaces such as public parks, university campuses, and outdoor shopping centers. Additionally, feedback from stakeholders such as wheelchair users and facility managers should be a priority.

As previously discussed, some limitations have already been identified. To address the accuracy of road surface identification and accessibility classifications, it may be useful to incorporate crowd-sourced validation in the user interface. This would provide users with higher confidence in the accuracy of the information presented. Once operational, this could be a mechanism to help facilities managers identify when and where to resurvey. The accuracy and completeness of the wheelchair accessibility information would also improve if future iterations of this work included additional ADA standards and navigation routes within buildings.

This paper has demonstrated a promising new approach for surveying outdoor areas for ADA accessibility and identified several areas for further investigation that could provide additional benefits to stakeholders.

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Data Availability

Data and scripts to replicate findings are available at https://github.com/amylopata/amylopata.github.io.

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