AN AUTOMATED SIDEWALK ASSESSMENT METHOD FOR THE AMERICANS WITH DISABILITIES ACT COMPLIANCE USING 3-D MOBILE LIDAR

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ABSTRACT

Sidewalk is an indispensable infrastructure for pedestrians, especially wheelchair users. Wheelchair users rely on quality sidewalks to facilitate safe and uninterrupted trips in their everyday lives. Transportation agencies are required to evaluate the regulatory compliance of the Americans with Disabilities Act (ADA), and are responsible for timely maintenance of inadequate sidewalks. However, these timely evaluation and maintenance activities are usually lacking due to the labor-intensive and cost-prohibitive data collection process in the current practice. There is an urgent need for an efficient and reliable sidewalk assessment method for the ADA compliance. This paper aims at addressing such a need by proposing an automated sidewalk assessment method using 3-D mobile light detection and ranging (LiDAR) and image processing. The presences of sidewalks and curb ramps are extracted first using video log image and LiDAR point cloud. Then, the corresponding key features regulated by the ADA, including sidewalk width, cross slope, grade, and curb ramp slope, are automatically measured. Comparing with the manual ground truth from field survey, the experimental tests conducted on Georgia Tech campus at Atlanta, Georgia show accurate measurement results of the key features for sidewalk and curb ramps. A case study is then conducted to demonstrate that the proposed method can support transportation agencies a convenient and cost-effective means for ADA compliance assessment by integrating the accurately extracted sidewalk location and measurement information.

Keywords: Sidewalk, ADA, Inventory, Compliance, Mobile LiDAR, Automation

INTRODUCTION

According to 2010 census in the United States (1), there are more than 3.6 million people with disabilities using wheelchair on a daily basis for mobility. These wheelchair users primarily rely on their local communities to engage in activities and participate in everyday life. Sidewalk, as one of the most indispensable infrastructures, connects different destinations and provides essential accessibility for wheelchair users in their communities. Although many sidewalks have been put in place to enable wheelchair users' accessibility and improve their mobility, many physical barriers have been unintentional created simultaneously by their inadequate construction and deteriorating condition.

In 1990, the Americans with Disabilities Act (ADA) develops a set of standards and guidelines for implementing the environmental facilitators with the intention of enabling the accessibility of "*the public street to people with disabilities with a continuous, unobstructed pedestrian circulation network to the maximum extent feasible*" (2). The Americans with Disabilities Act Application Guideline (ADAAG) specifies a series of key features for designing and constructing sidewalks that allows uninterrupted and safe trips for wheelchair users. Transportation agencies are required to assess the regulatory compliance of ADA and responsible for timely maintenance of inadequate sidewalks. However, it is usually impractical for transportation agencies to comprehensively carry out these activities timely due to the labor-intensive and cost-prohibitive nature of the manual data collection process in the current practices. Therefore, an efficient and effective sidewalk inventory and evaluation method is in most urgent need to fulfill the regulatory demand from ADA, and more importantly to create a barrier-free environment for wheelchair users.

With the recent advancement of remote sensing technologies, many mobile systems with high data acquisition frequency and measurement accuracy, e.g., mobile light detection and ranging (LiDAR) have become cost-friendly and commercially available. The outcome derived from these mobile systems has the potential to support the comprehensive inventory (3, 4) and condition information (5, 6, 7) of the existing infrastructure. This paper, for the first time, is aimed at developing an automated method to cost-effectively and reliably assess the sidewalks compliance of the ADA using 3-D mobile LiDAR and image processing. The presence of sidewalks and curb ramps are extracted first based on their unique characteristics captured by the mobile LiDAR and video log images. The corresponding key features regulated in the ADA including sidewalk width, sidewalk cross slope, sidewalk grade, and curb ramp slope, are then automatically measured based on their 3-D representation in LiDAR point cloud. Finally, a comprehensive sidewalk inventory data layer can be established to facilitate transportation agencies' assessment and maintenance need.

The organization of the paper is as follows. This section presents the background and need of this study. Section 2 presents a brief literature review of the current practices and methods for sidewalk inventory and condition evaluation. Section 3 presents the proposed method in details. Section 4 presents the experimental test on Georgia Tech campus in Atlanta, Georgia to evaluate the accuracy of proposed method. A case study is also presented to demonstrate capability of the proposed method in facilitating a convenient GIS-based sidewalk inventory system for transportation agencies. Finally, Section 5 summarizes this study's findings and recommends the directions for future research.

LITERATURE REVIEW

The impacts of sidewalks for pedestrian, especially wheelchair users, have been extensively studies in previous research. The primary focus of these studies depicts the significance of different environmental facilitators and barriers on the mobility of wheelchair users based on surveys, travel diary and walking audits (8). These studies confirm the criticality of sidewalk (9, 10, 11, 12) and endorse the need from transportation agencies for timely assessment and maintenance of sidewalks regulated by ADA.

ADAAG is developed to provide a set of standards for accessible design, covering both new construction and alternation of the existing infrastructure. ADAAG emphasizes the criticality of sidewalks for wheelchair users and people with other physical disadvantages, and recommends its quantitative measurements, including width, cross slope, grade, and curb ramp slope. To facilitate the implementation of the ADAAG, several transportation agencies have developed GIS-based sidewalk and curb ramp management systems using both manual method and automatic method. GPS and camera-equipped hand-held PDAs were developed to comprehensively inventory sidewalks and curb-ramps with the City of Tucson, Arizona (13) and City of Bellevue, Washington (14), respectively. The operation of these systems requires comprehensive visual inspection and full coverage of the sidewalk network using walking or bicycling audit, which are time-consuming and labor-intensive. More importantly, the detailed geometry information is either measured by hand or by visual estimation, which can be tedious and/or inaccurate. To achieve more accurate and comprehensive sidewalk geometry information in compliance with the ADA standards, both inertial profiler-based system and vision-based systems have been developed to measure slope-related measurements, e.g., sidewalk grade and cross slope and dimension-related measurement, e.g., sidewalk width, sidewalk length. A modified ultra-light, slow-speed inertial profiler (ULIP) mounted on a Segway Human Transporter is developed in the City of Bellevue, Washington (15, 16). The detailed sidewalk cross slope and grade is reported to be measured accurately with high resolution using the ULIP and spatially correlate to the pedestrian network for management. Another camera-based system with an automated sidewalk width measurement algorithm has also been developed (17).

While the performance of these systems have been validated and well received by several local transportation agencies, there are still several challenges preventing these methods from large-scale practical applications, including: 1) The systems are designed to only extract individual sidewalk feature instead of the comprehensive information of the sidewalk; 2) the operation of these system require actual ride on the sidewalk surface at a relatively slow speed; 3) it is still challenging to accurately extract and measure some of the critical features, e.g. curb ramp slopes. This study, for the first time, aims at addressing these challenges by proposing an automatic method using 3-D mobile LiDAR and image processing as presented in the following sections.

PROPOSED METHOD

System and Data

The mobile system used in this study consists of four video cameras, two mobile LiDAR, and the global navigation satellite system (GNSS). The primary mobile LiDAR system (i.e. SICK LMS211-30106), a line-scanning laser device producing 15,000 laser points per second, is used in this study. As the vehicle moves in the longitudinal direction of the road, the scanning line of the LiDAR system is aligned horizontally long the ground. The scanning range is $\pm 50^\circ$ to the horizontal direction, which produces a 100° fan covering the road surface. Currently, the frequency of the LiDAR system is configured at 75 Hz and 200 points within each scan, while the LiDAR heading angle is configured at 20° to provide the coverage of the critical infrastructure of interest, e.g., sidewalks, curb ramps, etc. To integrate different features of sidewalks captured by

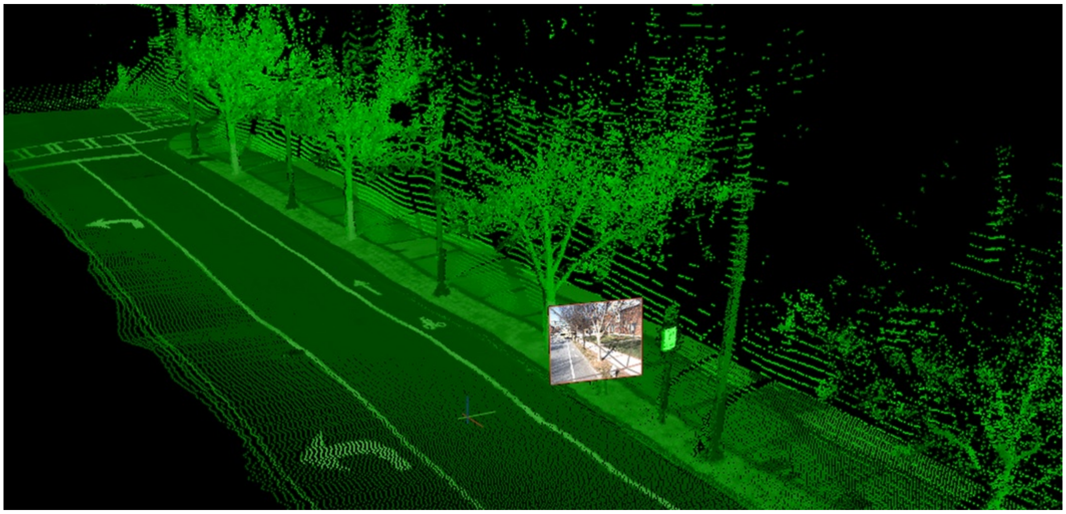


FIGURE 1 : An illustration of the acquired LiDAR point cloud and the synchronized video log image data

different sensors on the same location reference, the mobile LiDAR and the cameras are rigorously synchronized and registered. The registration is implemented using the rigid body transformation and the camera homography model (18). Figure 1 shows an illustration of the acquired point cloud data and one of the synchronized video log images with a resolution of $2,448 \times 2,048$.

Method Overview

The objective of the proposed method is to automatically identify the location of the sidewalks and curb ramps, and conduct the measurements for the corresponding key features, including width, grade, cross slope and curb ramp slopes. Figure 2 shows the overall flowchart of the proposed method. The sidewalks are extracted from LiDAR point cloud using a roadway cross section segmentation method. The curb ramp regions are extracted from video log images using a deformable part model (DPM). The key features of the extracted sidewalks and curb ramps are then measured based on their 3-D representation in LiDAR point cloud. Finally, the extracted sidewalks and curb ramps, and their corresponding measurements can be integrated in a sidewalk inventory system on a GIS platform.

Sidewalk Extraction

In this study, sidewalks are modeled as the parallel path built with uniform surface along the driveway on elevated curbs. Therefore, two unique characteristics are introduced to develop the sidewalk extraction method, including the lateral offset and the curb elevation height. LiDAR point cloud filtering based on the lateral offset and elevation offset is first applied to eliminate the LiDAR points that are irrelevant to sidewalks. The roadway cross section segmentation is then applied to partition each LiDAR scan into different segments based on the slope, the flatness and the elevation. Finally, the cross section segmentation results from consecutive LiDAR scans are connected to identify the sidewalk region.

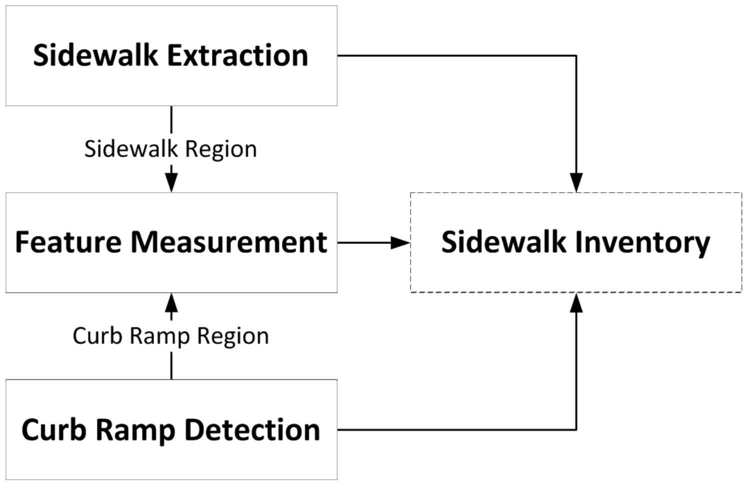


FIGURE 2 : The flowchart of the proposed method

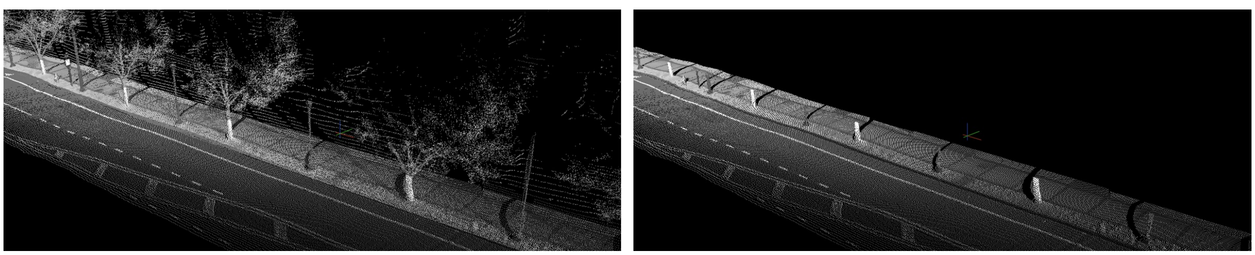


FIGURE 3 : The LiDAR point cloud before and after filtering (Left-Before; Right-After)

LiDAR Point Cloud Filtering

The objective of the LiDAR point cloud filtering is to significantly reduce the LiDAR points that are not associated with sidewalks. Two geometrical constraints are applied in the filtering scheme, including the lateral offset and the elevation offset. The lateral offset is computed as the absolute distance between the LiDAR point and the vehicle trajectory in the normal direction of the trajectory in the x, y-plane. As the sidewalks is built adjacent and parallel to the driveway, the LiDAR points with lateral offsets beyond a certain threshold is no longer considered associated with sidewalks. The elevation offset is computed as the elevation difference between the LIDAR points and the elevation of the vehicle ground trajectory (the trajectory of vehicle projected on the ground) in the z direction. As the sidewalks are built on a slight elevated curbs, the LiDAR points with an elevation beyond a certain threshold is no longer considered associated with sidewalks. Figure 3 shows the LiDAR point cloud after the filtering. It can observed that majority of the interfering points are dramatically reduced, whereas the drive way and the sidewalks regions are well preserved. The thresholds for the lateral and elevation offsets can be empirically defined by transportation agencies according to their data collection routing plan. Typically, a 7.3m (24ft.) lateral offset and a 0.6m (2ft.) elevation offset serve a good balance between reliability and efficiency.

Cross Section Segmentation

The objective of the roadway cross section segmentation is to partition the LiDAR points based on the elevation difference along the cross section. Figure 4 shows an illustration of an ideal roadway

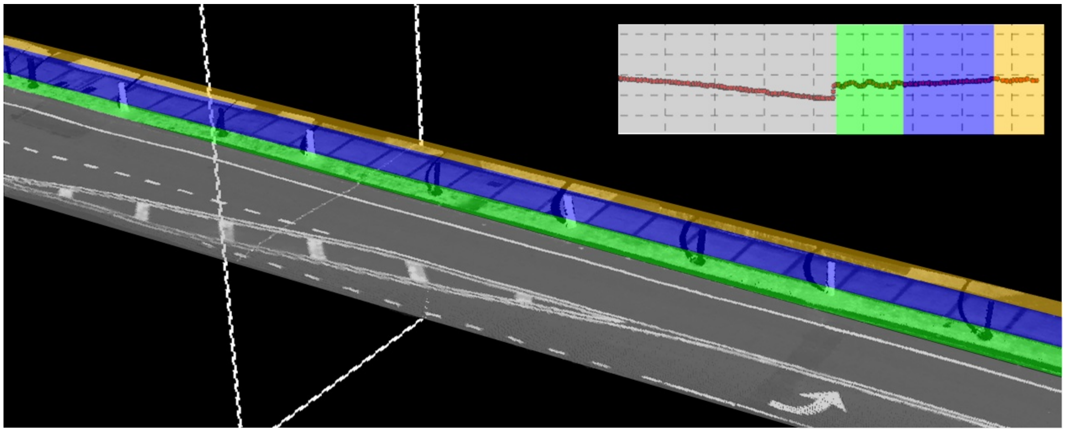


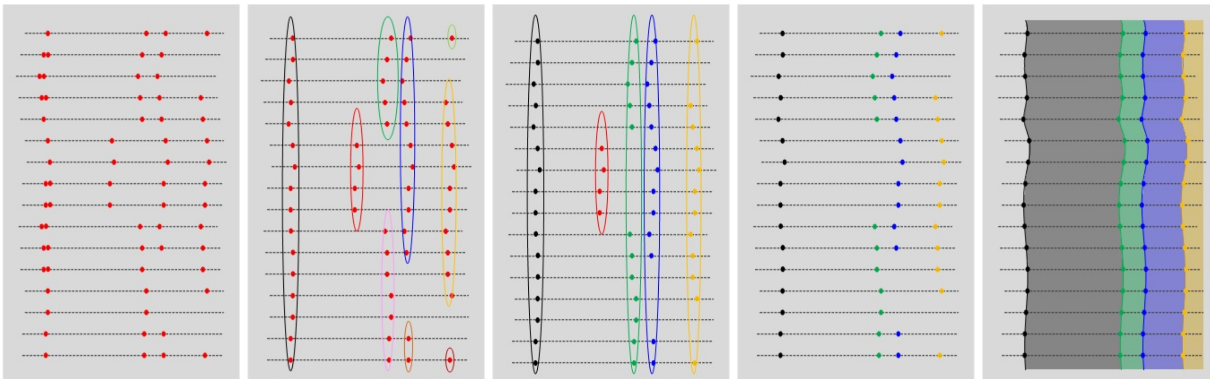
FIGURE 4 : An illustration of an ideal road cross section captured by LiDAR point cloud

cross section captured by LiDAR point cloud. The ideal roadway cross section comprises of four zones, including driveway zone (gray), planter zone (green), pedestrian zone (blue), and frontage zone (yellow). The driveway and pedestrian zones are paved surfaces to facilitate motorized vehicle and pedestrian's trip respectively, where the planter and frontage zone are typically non-paved surfaces for vegetation. To capture the characteristics in each zone, the generalized 1-D edge detection method (19, 20) is introduced to identify the breakpoint of elevation, slope and surface homogeneity.

Cross Section Segmentation Connection

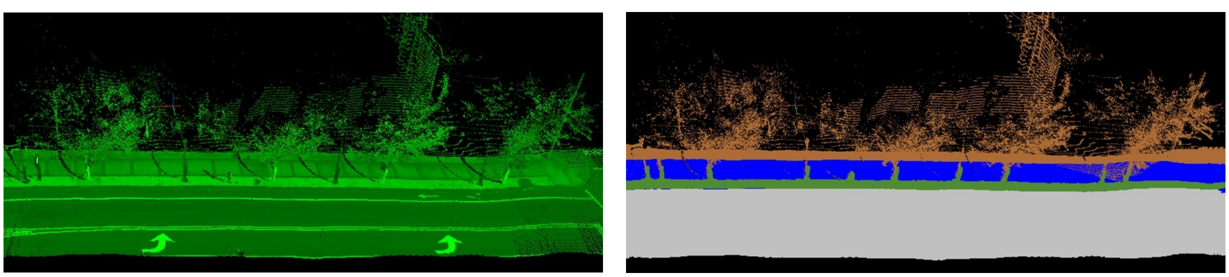
The segmentation results from the previous step are likely to be discontinuous due to the presence of parked vehicle, interruption of the sidewalk (e.g., intersection) or other interfering object (e.g., tree trunk, fire hydrant, etc.). A segmentation connection method is introduced to adjust the segmentation results and to link the segmentation results from consecutive scans into a continuous boundary (21). Figure 5(a) illustrates the original segmentation results in consecutive scans, where the dash lines represent the laser scans and red dots represent the raw segmentation results. The segmentations results will be clustered longitudinally based on the k-nearest neighbor (k-NN) method (22). Figure 5(b) illustrates the clustered results, where different circles represent the label of the clusters. The spatial relationship in longitudinal direction is then measured to further merge the clusters that are along the same trace in the longitudinal direction as shown in Figure 5(c). The spatial relationship in transverse direction is measured to remove the collinear segments with shorter length. Figure 5(d) illustrate the results after the removal of the red cluster. A B-spline algorithm (23) is then introduced to smoothly connect different segmentation points. Figure 5(e) illustrates the final results of the final segmentation results, where different colors represent the corresponding zones of driveway (gray), planter (green), pedestrian (blue), and frontage (yellow).

Figure 6 compares the original LiDAR point cloud and the processed LiDAR point cloud with extracted sidewalk regions. Similar algorithms, such as the laser line striping and tracking algorithm by Aufrere et al. 2003, have been developed; they can also be introduced in this study. However, significant amount of hardware modification may be required. More importantly, the proposed cross section segmentation connection method can more effectively minimize the impact of interruption of the LiDAR points on the sidewalk extraction, e.g., stalled cars, roadside plantations, pedestrians, etc.



(a) (b) (c) (d) (e)

FIGURE 5 : The process of the cross section segmentation connection method



(a) (b)

FIGURE 6 : An illustration of the sidewalk extraction results

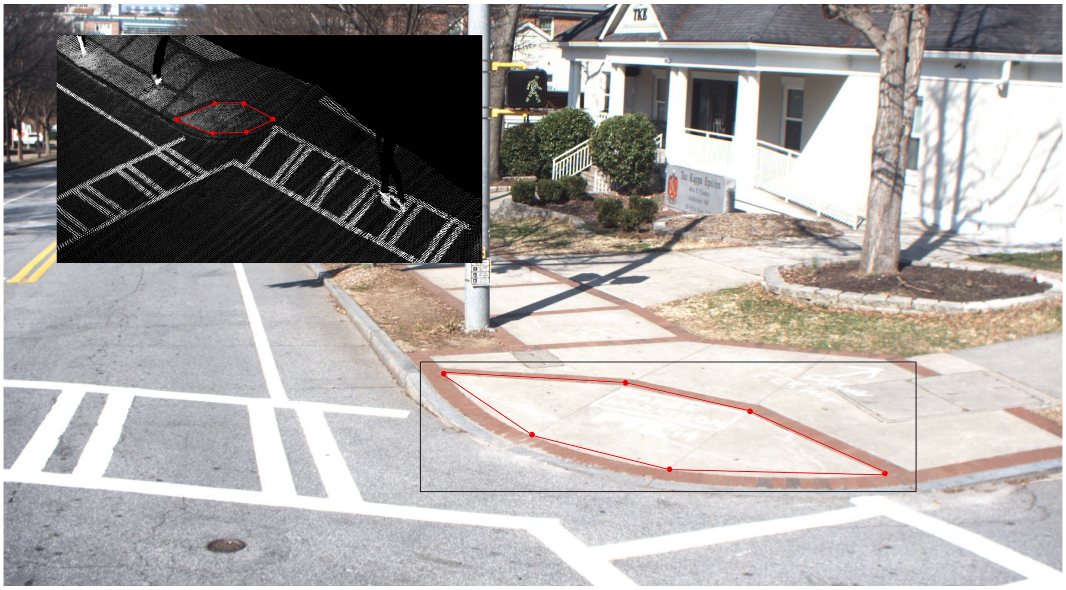


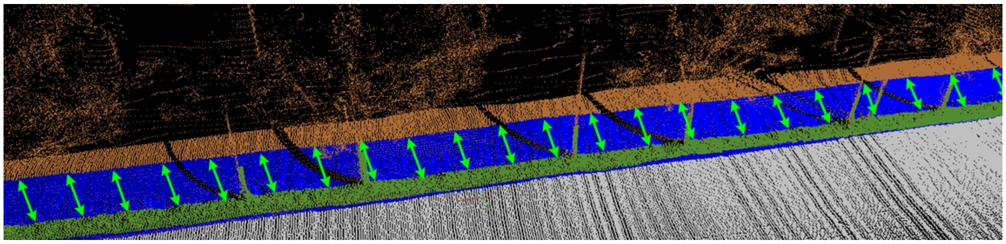
FIGURE 7 : An illustration of the detected curb ramp in video log image and the corresponding LiDAR point cloud

CURB RAMP DETECTION

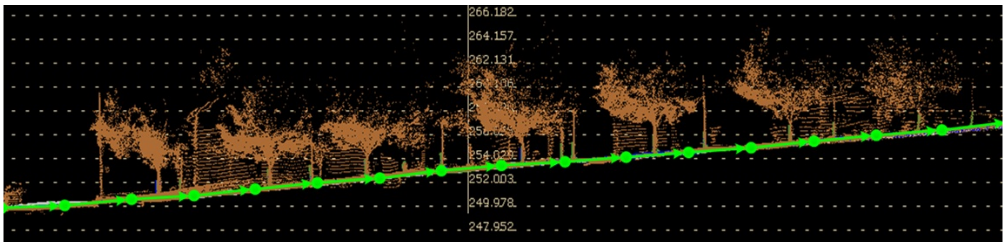
Although curb ramps have unique features, such as the shoulder ramp, the center ramp patch with truncated dome bumps etc., their diverse appearances and designs make it challenging to implement a fully automated curb ramp extraction method. Therefore, this study introduces a semi-automatic approach, including an existing automatic curb ramp detection algorithm and an interactive tool. The DPM-based curb ramp detection algorithm by Hara et al. 2014 is first introduced to identify and locate all the curb ramp candidates using video log images. An extensive training set containing different outlooks of curb ramps are prepared to minimize the false negatives, including various types of curb cuts, landing islands with and without domes and strips, etc. A manual review of the candidates using an interactive tool (26) is then conducted to remove false positives. The interactive tool also provides a convenient function to digitize the accurate vertex positions for the detected curb ramps. Figure 7 shows an illustration of the detected curb ramp. The black and red bounding boxes represent the automatic detected and the manual adjusted results respectively. As the mobile LiDAR and the cameras are rigorously synchronized and registered, the vertices of a curb ramp extracted from the video log image can be accurately projected to the LiDAR point cloud as shown in the top-left of Figure 7.

SIDEWALK AND CURB RAMP FEATURE MEASUREMENT

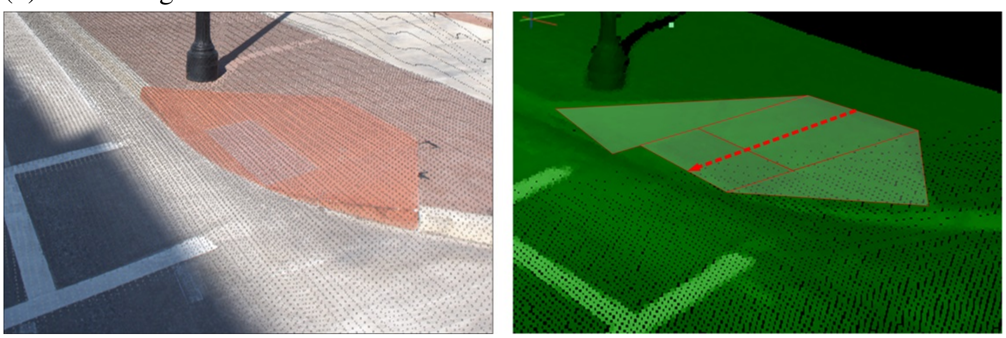
The critical geometry features of sidewalks and curb ramps are mandated in the ADAAG to enable a safe and obstruction-free facility for pedestrians, in particular wheelchair users, including sidewalk width, sidewalk cross slope, sidewalk grade, and curb ramp slope. Therefore, these features are measured in this study to represent the condition of the sidewalk and the curb ramp. As the identification sidewalk derived from the previous step is represented by 3-D polygons, the geometry of the polygon can be automatically measured using the method developed by Tsai et al. (5), including the sidewalk width, cross slope and grade. Figure 8(a-b) shows illustrations of how these values are measured. The resolutions of the measurements are determined by the resolution of the



(a) Sidewalk width measurement



(b) Sidewalk grade measurement



(c) Curb ramp slope measurement

FIGURE 8 : Illustrations of the measurement for different ADA-mandated infrastructures

LiDAR point cloud. In this study, the sidewalk width is measured at a 1m (3ft.) interval, whereas the sidewalk grade is measured at a 3m (10ft.) interval. Curb ramp slope can also be automatically measured based on the extracted region from the previous step. Depending on the different design of ramps, different slope measures can be conducted, including the approaching slope, flare slope, landing slope, and main ramp slope. The main ramp slope is the focus of this study. Figure 8(c) shows an illustration of how the main ramp is measured.

EXPERIMENTAL TEST

A section of sidewalk on Ferst Dr. on Georgia Tech Campus was selected for conducting the experimental test, covering approximately two miles of sidewalk. This section of sidewalk connects the East and West campuses of Georgia Tech with high volume of pedestrian and vehicles traffic. In order to evaluate the performance of the proposed method, different sidewalk configurations and conditions are included, such as sidewalk with various slopes, grade, and widths, sidewalks with various surface types, etc. In addition, sidewalks besides mixed road with on-street parking and pedestrians are purposely included in this testing data set to reveal the performance of the proposed sidewalk extraction and curb ramp detection algorithms. The sidewalk extraction algorithm is evaluated based on the overlap of the extracted sidewalk with digitized ground truth. Out of the two miles sidewalk sections, more than 98.3% of sidewalks can be successfully identified with very limited false detection that is produced excessive obstructions by utility facilities and shuttle buses. Within the selected sidewalk section, all of the 25 curb ramps are successfully identified. The developed curb ramp detection method is robust to different curb ramps' outlooks, including various types of curb cuts, landing islands with and without domes and strips, etc. With the accurate extraction of sidewalk sections and detection of curb ramps, automatic measurements for different sidewalk features can be conducted subsequently. The following subsections present the performance of the measurement accuracy and a case study of a GIS-based sidewalk compliance system utilizing the derived sidewalk information.

Measurement Accuracy

To evaluate the measurement accuracy of the features of sidewalk and curb ramp using the proposed method, an experimental test was conducted on the selected sidewalk section. Sidewalk width, sidewalk cross slope, sidewalk grade and curb ramp slope along the sidewalks were manually measured using measuring tape and digital slope scale as ground truth. Twenty measurement locations along the sidewalk were randomly selected to conduct the sidewalk measurement (i.e., width, cross slope and grade), while a total of twenty curb ramps are also selected to conduct the curb ramp slope measurement. The sensing data was collected on the same sidewalk network and the key features were measured at the corresponding locations. Table 1 show the comparison between the ground truths (GT) and the results derived from the proposed method (PM). It can be observed that the measurements derived from the proposed method are close to the ground truth measured in field. The absolute error in the sidewalk width measurement is below 0.15m (0.5ft.) at all of the twenty locations. The primary reason that produces the width measurement difference is the accuracy of sidewalk extraction. The measurements of sidewalk cross slope and sidewalk grade are very close to the ground truths measured in field. Less than 0.2% of slope measurement errors are observed for at all of the twenty locations, which is consistent with the previous result reported by Tsai et al. (5). The measurements of curb ramp slope yield to a slightly larger error but is still well controlled within an absolute difference of 0.5% comparing with the ground truth. These errors are primarily attributed to the accuracy of the extracted curb ramp region. More manual review and revision of the curb ramp extraction using the interaction tool is expected to produce a better accuracy.

Case Study

According to the ADAAG and the Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way (PROWAG), several critical geometries are defined: 1) the sidewalk width should not be reduced below 1.2m (4 ft.); 2) the cross slope of the sidewalk should not exceed 2%; 3) the grade of the sidewalk should not exceed 5%; and 4) the curb ramp slope should not exceed 8.3%. Using the proposed method, the locations where these critical geometry requirements are not met can be immediately identified by querying the corresponding measurement. Figure 9 shows the identified locations where wheelchair users may have challenges to complete uninterrupted and safe trips.

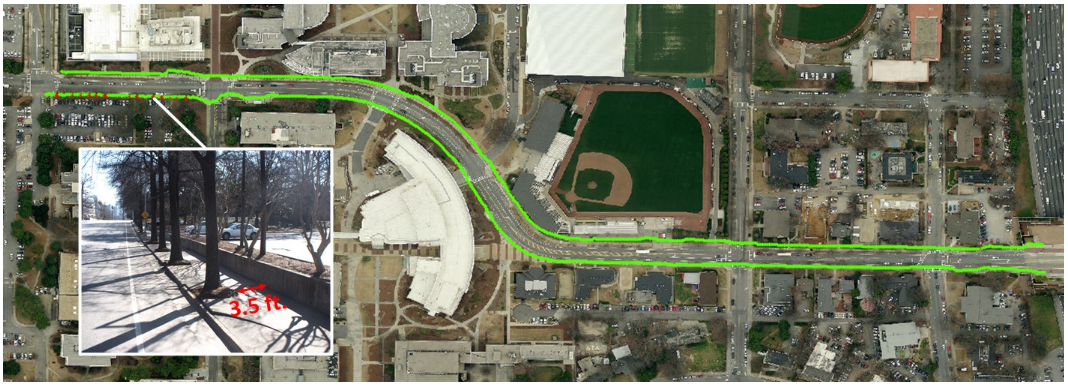
Figure 9(a) shows the locations where the sidewalk does not have adequate width, which will potentially prevent the wheelchair users from passing through. By querying the original video log images, it is observed that the tree trunks are blocking about half of the sidewalks in the identified locations. Figure 9(b) shows the location where the sidewalk has a cross slope that is greater than

TABLE 1 : Measurement results for the key features of sidewalks and curb ramp features

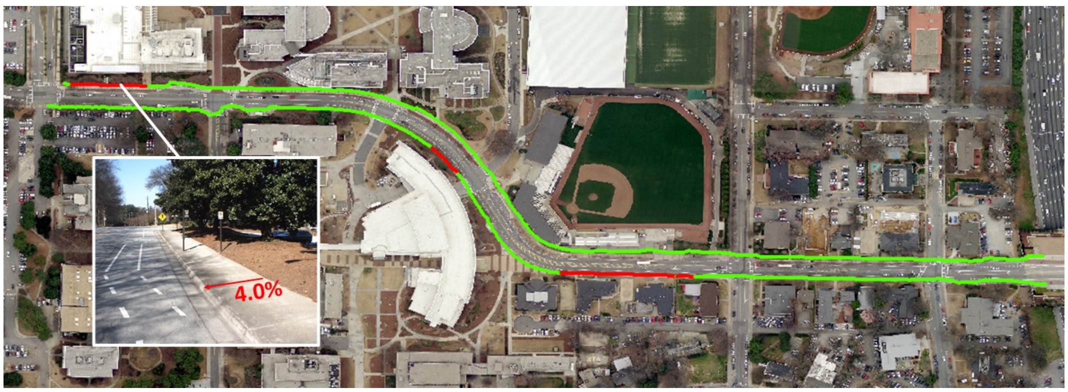
ID	Sidewalk Width			Sidewalk Cross Slope			Sidewalk Grade			Curb Ramp Slope		
	GT (m (ft.))	PM (m (ft.))	Err (m (ft.))	GT (%)	PM (%)	Err (%)	GT (%)	PM (%)	Err (%)	GT (%)	PM (%)	Err (%)
1	1.92 (6.30)	5.94 (1.81)	-0.36 (-0.11)	3.00%	2.90%	-0.10%	3.70%	3.80%	0.10%	8.80%	8.90%	0.10%
2	1.77 (5.81)	5.81 (1.77)	0.00 (0.00)	1.20%	1.30%	0.10%	1.50%	1.40%	-0.10%	4.70%	4.70%	0.00%
3	1.84 (6.04)	6.14 (1.87)	0.10 (0.03)	2.10%	2.20%	0.10%	1.20%	1.20%	0.00%	3.90%	4.20%	0.30%
4	1.97 (6.46)	6.96 (2.12)	0.50 (0.15)	0.20%	0.30%	0.10%	1.90%	2.00%	0.10%	6.40%	6.00%	-0.40%
5	2.32 (7.61)	7.74 (2.36)	0.13 (0.04)	1.00%	0.90%	-0.10%	2.40%	2.60%	0.20%	10.40%	9.90%	-0.50%
6	2.33 (7.64)	7.25 (2.21)	-0.39 (-0.12)	0.60%	0.60%	0.00%	3.20%	3.10%	-0.10%	3.50%	3.60%	0.10%
7	1.83 (6.00)	5.91 (1.80)	-0.09 (-0.03)	1.00%	1.00%	0.00%	3.30%	3.20%	-0.10%	11.80%	11.70%	-0.10%
8	1.77 (5.81)	5.51 (1.68)	-0.30 (-0.09)	1.60%	1.60%	0.00%	7.00%	7.00%	0.00%	10.40%	10.70%	0.30%
9	1.85 (6.07)	6.36 (1.94)	0.29 (0.09)	0.60%	0.70%	0.10%	4.10%	4.20%	0.10%	10.10%	10.40%	0.30%
10	1.31 (4.30)	4.30 (1.31)	0.00 (0.00)	0.50%	0.30%	-0.20%	5.90%	6.10%	0.20%	3.90%	4.10%	0.20%
11	1.27 (4.17)	3.94 (1.20)	-0.23 (-0.07)	2.80%	2.90%	0.10%	6.30%	6.30%	0.00%	3.40%	3.30%	-0.10%
12	1.19 (3.90)	3.54 (1.08)	-0.36 (-0.11)	3.20%	3.00%	-0.20%	6.60%	6.50%	-0.10%	2.10%	2.20%	0.10%
13	1.65 (5.41)	4.99 (1.52)	-0.42 (-0.13)	3.30%	3.40%	0.10%	5.10%	5.00%	-0.10%	9.10%	9.70%	0.60%
14	1.66 (5.45)	5.58 (1.70)	0.13 (0.04)	2.90%	2.80%	-0.10%	3.10%	3.20%	0.10%	5.30%	5.60%	0.30%
15	1.87 (6.14)	6.30 (1.92)	0.16 (0.05)	1.30%	1.40%	0.10%	3.40%	3.50%	0.10%	7.60%	7.40%	-0.20%
16	1.92 (6.30)	6.79 (2.07)	0.49 (0.15)	2.70%	2.60%	-0.10%	0.60%	0.70%	0.10%	7.80%	7.30%	-0.50%
17	1.92 (6.30)	6.53 (1.99)	0.23 (0.07)	2.60%	2.60%	0.00%	3.10%	2.90%	-0.20%	2.90%	3.00%	0.10%
18	1.11 (3.64)	3.77 (1.15)	0.13 (0.04)	4.70%	4.70%	0.00%	4.70%	4.60%	-0.10%	4.00%	4.30%	0.30%
19	1.15 (3.77)	3.31 (1.01)	-0.46 (-0.14)	3.70%	3.70%	0.00%	1.20%	1.10%	-0.10%	6.10%	5.70%	-0.40%
20	1.12 (3.67)	3.54 (1.08)	-0.13 (-0.04)	5.20%	5.20%	0.00%	1.00%	0.90%	-0.10%	9.70%	9.30%	-0.40%
			RMSE: 0.29			RMSE: 0.10%			RMSE: 0.11%			RMSE: 0.31%
			Stdev: 0.30			Stdev: 0.10%			Stdev: 0.13%			Stdev: 0.32%

2.0%, which will potentially introduce the rollover hazards for the wheelchair users. Figure 9(c) shows the locations where the sidewalk has a grade that is greater than 5%, which will potentially add downhill and uphill challenges for the wheelchair users. By querying the original LiDAR point cloud, it is observed that the pavement corresponding to the identified sidewalk sections exhibit more than 6.0% of downhill grade. Although the ADAAG does not mandate a maximum of 5.0% grade as long as the sidewalk has consistent grade with the pavement, the information provided in the proposed infrastructure layer can better inform the planners of the potential challenges that the wheelchair users may encounter. Figure 9(d) shows the locations where curb ramps slope exceed the required 8.3%, which will potentially create hazards of wheelchair users who easily flip backward or tip forward at the slope.

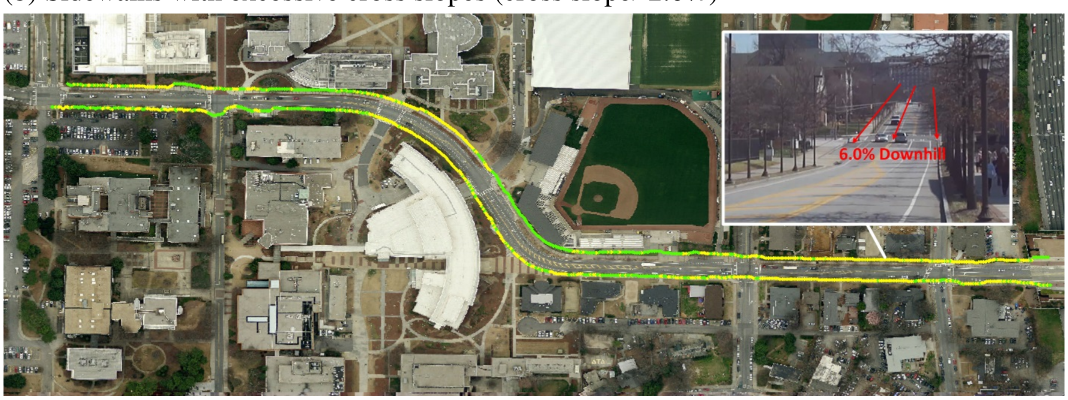
By integrating the extracted sidewalks, curb ramps and the corresponding measurements of their key features regulated by the ADA into a GIS-based sidewalk inventory, some of the critical locations that require timely maintenance and improvement can be immediately identified. For comparing purpose, the proposed method took less than an hour to complete a full-coverage assessment of the two-mile sidewalk section in this study thanks to the high speed data collection and effective processing, while the traditional field survey took more than three hours with only selected measuring locations. In addition, comparing with the existing automated methods, e.g., the ULIP-based method, the benefit of the proposed method is also significant. The ULIP-based method can only operate at slightly higher than walking speed (less than 10mph), while the proposed method can operate at posted speed (e.g., 30mph in this study, up to 60mph). This case study only presents a small-scale sidewalk network to demonstrate the capability of the proposed method. Transportation agencies that are maintaining a large-scale network could expect even more benefits from using the proposed method, in terms of productivity and reliability.



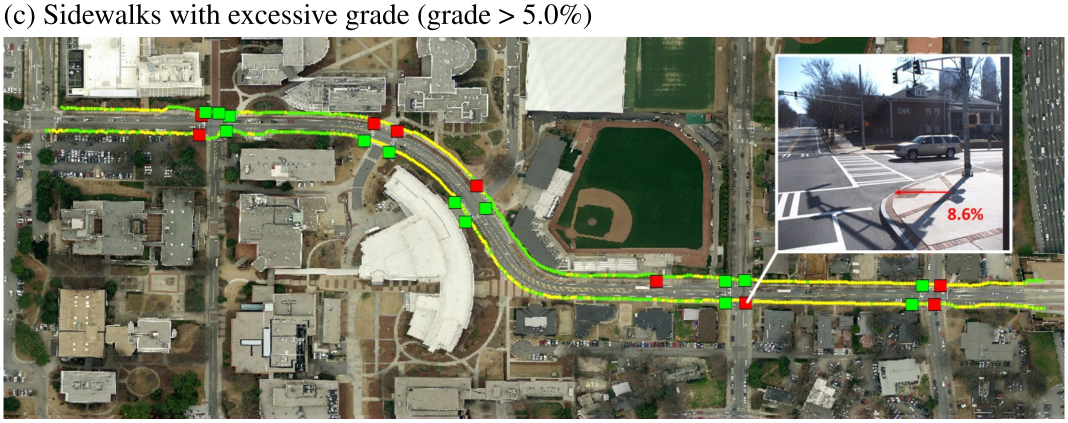
(a) Sidewalks with insufficient width (width<1.2m (4.0 ft.))



(b) Sidewalks with excessive cross slopes (cross slope>2.0%)



(c) Sidewalks with excessive grade (grade > 5.0%)



(d) Curb ramps with excessive slopes (cross slope > 8.3%)

FIGURE 9 : Identified locations for the inadequate sidewalks on Ferst Dr.

CONCLUSIONS AND RECOMMENDATIONS

Wheelchair users rely on quality sidewalks, one of the most indispensable infrastructures, to make essential trips to engage their everyday lives. The ADA specifically develops a series of key features for designing and constructing sidewalks that allows safe and uninterrupted trips for wheelchair users. Transportation agencies are required to assess the regulatory compliance of ADA and responsible for maintenance of inadequate sidewalks. However, lacking of cost-effective and reliable sidewalk evaluation methods, the assessment and maintenance of sidewalks in a timely manner is usually not achievable. To address this need, this paper proposes an automated sidewalk inventory method using 3-D mobile LiDAR and image processing. The location of sidewalks and the corresponding key features regulated in the ADA including width, cross slope, grade, and curb ramp slope, are automatically extracted and measured. The location and the key features can be integrated into a GIS-based sidewalk inventory system to facilitate transportation agencies' sidewalk assessment and maintenance needs in a timely manner. Experimental tests have been conducted on the Ferst Dr. in Atlanta, Georgia to evaluate the accuracy of the proposed method. The results show accurate measurements for all of the four tested features. Comparing with the ground truth established in field survey, the absolute error in the sidewalk width measurement is below 0.15m (0.5 ft.), while the absolute errors in the sidewalk cross slope and grade measurements are below 0.2%. The proposed method can also achieve an accurate measurement of curb ramp with an absolute error under 0.5%, which is a challenging task for other available methods. A case study has been conducted on a small-scale sidewalk network on Georgia Tech campus, Atlanta, Georgia to demonstrate the benefits of a GIS-based sidewalk inventory that integrates the extracted sidewalk information using the proposed method. Transportation agencies can cost-effectively identify some of the critical locations that require maintenance and improvement in a timely manner.

Further directions of this study includes: 1) A large-scale sidewalk network is recommended to be tested to further validate the proposed method; 2) New curb ramp extraction and measurement methods are recommended to be studied to further improve the accuracy of the proposed method. Other critical features of curb ramps, e.g., flare slopes, landing clearance, etc. are also recommended to be explored; 3) Automatic methods for extracting other sidewalk conditions, such as broken slabs, faulting, cracking, etc., are recommended for future study; 4) Development of a GIS-based sidewalk inventory application for sidewalk asset management. 5) Development of a GIS-based walkability application for public transportation, active transportation and urban planning study.

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