Curb-Ramp Design (CRD) and Inspection System (CIS)

FINAL REPORT

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Abstract

Inaccessible routes between locations can be a major barrier to participation for people with physical disabilities Even with regulations, inaccessible sidewalks continue to create problems for wheelchair users. Existing technologies do not offer a comprehensive solution to the measurement, data collection, and information storage and display of curb ramps and sidewalks. The University of Pittsburgh was tasked to build a device to help streamline curb-ramp measurements. Through design changes, focus groups and interviews with industry stakeholders, the Curb-Ramp Design (CRD) and Curb Inspection System (CIS) device was created. The CIS prototype is now completed and ready to help bridge the gap in curb-ramp inspection systems.

Keywords: Curb-Ramp Inspection, Wheelchairs, Mobility, Built Environment, Infrastructure, Human-Centered Design, Accessibility, Americans with Disabilities Act, ADA, Sensors, Software Development, Systems Engineering, Human Factors

Introduction:

Inaccessible routes between locations can be a major barrier to participation for people with physical disabilities. Public buildings (1), restaurants (1), food stores (2), businesses (3) and doctors' offices (4) are frequently found to be inaccessible, due in part to architectural obstacles such as the absence of suitable ramps. Slip-and-fall accidents involving stairs or ramps are a common cause of injury among wheelchair users (5,6). Inaccessible workplaces can be challenging for retaining employment (7). Wheelchair users frequently prioritize routes with smaller slopes and better surface conditions over shorter routes in order to facilitate travel (8). Curb-ramps are created to enable people with disabilities to safely travel from the sidewalk to the street, and vice-versa. Considering that, the physically and visually impaired rely most heavily on curb-ramps (9), almost all design best-practices are created with these user groups in mind (10).

Difficulties with Curb Ramp Assessment

Even with regulations, inaccessible sidewalks continue to create problems for wheelchair users. A survey in New York found that 80% of individuals in manual wheelchairs and 73% of individuals in motorized wheelchairs considered curb ramps to be a barrier to physical activity (15). Another study found 60% of wheelchair users needed to overcome a blocked curb ramp and 12% have been unable to overcome a blocked curb ramp during a 28-day period (16). Furthermore, the process of assessing curb ramps for Americans with Disabilities Act (ADA) compliance contains inefficiencies. The Department of Justice (DOJ) recommends that assessments of curb-ramps are completed in teams of three. One member of the team systematically reads the survey instructions aloud, a second member takes the curb ramp measurements and the third team member records notes and takes photographs of the measurements (14). The DOJ also recommends that measurements are taken using a tape measure, digital level, and digital camera. These methods are tedious, ergonomically inefficient, and time consuming.

Existing Technology for Curb Ramp Assessment

The use of data collection and archival software is recommended for curb ramp assessment, along with the presence of workers with adequate ADA training in the field; the integration of ADA standards into project planning and development; the use of user-friendly websites providing information about regulations, laws and procedures; and the prioritization of the improvement of locations with greater importance, use, and urgency of improvement (17). A number of software tools have been developed for general management and maintenance of sidewalks, including the evaluation of curb ramps for ADA compliance. StreetSaver is a tool for inventory and budget planning used for road and sidewalk maintenance and includes features for rating curb ramp ADA compliance and a geographic information system (GIS) for displaying information as a map (18). ArcGIS, a cloud-based GIS platform, also has features for keeping an inventory of curb ramps and their ADA compliance (19). The state of New Jersey created a free online calculator for determining whether a curb ramp was ADA compliant (21). The Public Rights of Way Assessment Process (PROWAP) is used for evaluating sidewalks and curb ramps

for ADA compliance (22). The system consists of a cart with an attached inclinometer for measuring grade and a wireless roll-a-wheel for measuring distance. Data is transmitted to and displayed on a laptop or tablet computer on the cart and can also be uploaded to a Geographical Information System (GIS) database.

Shortcomings of Existing Technology

Existing technologies do not offer a comprehensive solution to the measurement, data collection, and information storage and display of curb ramps and sidewalks. The existing software technologies, such as ArcGIS and StreetSaver, are useful for the management of curb ramp data and for displays on maps, but not helpful for measuring curb ramp dimensions and addressing the associated time and effort to input that measurement data into the software. Although PROWAP ameliorates this problem by integrating database software with a measurement tool, the system is bulky, requires an additional tool for measuring distances, and does not automatically upload information into the GIS database. Thus, there is an unmet need for a curb ramp assessment tool which successfully and seamlessly integrates length and grade measurements, and software for storage and mapping curb ramp inspection data.

Focus Group Methodology

Students from the University of Pittsburgh participated in a focus group to help better understand the usability of the CIS/CRD device. Each participant watched a short training video that demonstrated the logistics of the app and the CIS device. Each participant also measured five different curb-ramps in East Liberty, Pittsburgh PA, selected by PennDOT. Each curb-ramp was measured in two ways. First, it was measured in the traditional method with a digital level and measuring tape, along with subsequent recording into the PennDOT CS-4401 form. Second, it was measured with the CIS, using only the device for all forms of measurement. Each subject was responsible for conducting four measurements of each individual curb. This included two horizontal distance measurements and two grade measurements.

The final measurement taken for this focus group was time. Time was measured for both PennDOT method and CIS curb ramp measurements. For PennDOT time measurements, time was recorded when the participant began the manual measurement and after the measurement was written down and she/he verbally stated the measurement. For CIS time measurements, time was recorded after calibration of the device, when the participant pressed "Begin Measurement" on the CIS and ended when the participant pressed "End Measurement" on the CIS. Three other testing measurements were taken during the focus group: the CIS Task Assessment Sheet developed by the University of Pittsburgh Rehabilitation Science & Technology Department, the System Usability Scale (SUS), and the Rapid Entire Body Assessment (REBA). For more details on the methodology of the CIS Task Assessment Sheet, SUS and REBA see Appendix C.

FOCUS GROUP RESULTS

The focus group included three student volunteers from the University of Pittsburgh. All focus group participants have previous engineering experience, but varying demographics listed below in Table 1.

Table 1: Focus Group Demographics

	Gender	Height	Age	Education	Degree	App Use
Subject 1	M	5'9"	25-34	Master's Degree	Rehabilitation Tech.	1-3 hrs.
Subject 2	F	5'5"	18-24	Bachelor's Degree	Mech. Engineering	1-3 hrs.
Subject 3	M	5'9"	25-34	Bachelor's Degree	Mech. Engineering	1-3 hrs.

Curb-ramp grade measurements were variably accurate depending on the ramp type and the specific measurement. Horizontal distance measurements were also variably accurate, although to a lesser extent. In terms of time required for measurement, initial analysis shows that manual measurement is less time consuming than measurement with the CIS device. However, accounting for the number of people whose time is required to complete each task, a modified analysis shows that CIS measurement is, overall, more time efficient than manual measurement. We also analyzed the efficiency and accuracy of the CIS device by measuring the five selected curb ramps in terms of time (seconds), grade (percent) and horizontal distance (inches). Four measurements were selected, A, P, W, and C, out of the twelve total curb ramp measurements to save time. Each subject conducted three trials for the five curb ramps. All the subjects' data were averaged based on measurement for both CIS and Manual. Tables 1.1-1.5 were made for each curb, producing the Graphs 1.1-1.4 (Appendix D). All error bars were based on the PennDOT data within 5% error.

All participants scored at least 14 points out of 15 total points on the CIS task assessment sheet. The main area of concern is choosing the type of curb ramp being measured on the app and locating the correct ending position for the CIS at the end of the curb-ramp measurement. These areas of concern were addressed in the CIS redesign (see Design Results). The participants' SUS scores for the CIS device were 78, 92.5 and 75 out of a total 100 points, with an average score of 81.7. Based on these results, for this focus group, the CIS device is above average for participant usability. The REBA analysis was significantly higher for manual measurements (8.6 ± 0.6) than CIS measurements (2.6 ± 0.6). REBA scores were higher for manual measurement and indicated a high-risk task, whereas the scores were lower for measurement with the CIS device, indicating low risk (Appendix C).

DESIGN RESULTS

At the beginning of the project, the initial Scooter-based prototype (Appendix A) was evaluated and reviewed to assess its usability, durability, and integrity of data collection. Based on this assessment, areas of improvement were identified for further development throughout the project. In terms of usability, the size and shape of the initial prototype made it difficult to maneuver. In addition, volunteer prototype testers were frustrated with the first-generation user interface design. To improve the design, the overall size and length of the device was reduced, as well as the weight. The user interface was also made more intuitive, especially when entering measurements and navigating between options within the initial prototype Android mobile

application. Further, volunteers suggested that data collected should automatically be saved.

In terms of durability, the interconnections between components in the initial prototypes were identified to be potential failure areas. In particular, the 3D printed battery securement was fragile. Additionally, the steering column of the initial prototype was prone to considerable movement, which would introduce inconsistencies in measurement as well as put the tablet at risk of dropping. On top of this, the system needed to be better protected and resistant to wet conditions in the field. To improve the design, different materials were used on the next prototypes to increase strength and durability while keeping the weight low. There was also emphasis on the connection point between the handle and platform base, where most of the rotation occurs. The power supply was moved toward the handle, which is closer to the tablet computer. The sensors were kept as low to the ground as possible. In terms of integrity of data collection, the methods of data collection used by the initial prototype had faults. First, the encoder for horizontal distance encountered accuracy issues based on gear slippage. Second, grade from the accelerometer on the tablet was not sufficient. To improve data collection & ensure proper accuracy, a timing bolt instead of 3D printed gear was to be used for the encoder to measure horizontal distance, and an external accelerometer was to be used and located on the base of the platform to minimize potential for error and inconsistencies.

From these goals, a complete redesign of the CIS was completed. The prototype (Appendix B, Figure 3) was much lighter and smaller, and was now intended to be held in front of the user, much like a metal detector. Changes were also made to the tablet, and the software was migrated from Google Maps to ArcGIS. Other planned design changes were also completed, such as moving the battery, adding an external accelerometer, and using precision gears for measurement horizontal distances. The physical and software goals were outlined and completed to resolve the issues identified in the initial prototype (see Appendix B).

Based on this complete redesign, new prototypes were constructed, and then were evaluated for usability using the CIS Task Assessment Sheet and the System Usability Scale (SUS). The prototype was evaluated ergonomically, using the Rapid Entire Body Assessment (REBA). The results from these evaluations showed that the CIS prototype was above average in terms of participant usability and encompassed lower risk movements than manual curb ramp measurements (see Appendix C). Evaluators also provided feedback for the improvement of the prototype, which included suggestions like covering exposed electronics, modifying the handle grip, simplifying the user interface, including a more stable battery compartment, and providing a better explanation of the calibration procedure. These mechanical and software improvements were then incorporated into the overall design and built into the final prototypes (see Appendix D).

Discussion

Focus Group Feedback and Future Improvement Plans

From the focus group testing, there were many advantages of the CIS over manual measurement in terms of usability. The CIS was more comfortable to use, as it was no longer necessary to squat low to the ground to measure, which is consistent with the REBA

measurement results. In addition, using the CIS was less labor intensive and more time efficient than manual measurement. This is because the CIS offers a simpler workflow and does not require measurements to be written out with pen and paper. Electronic data collection allows for a smaller chance of losing paper data. Users also thought the CIS was intuitive and more precise for length measurement, as tape measure only gives length to 1/16th of an inch and may introduce variation based on how the user measures. In the CIS software application, users appreciated the layout and diagrams, as well as that the color of a measurement number which immediately indicates whether it complies with ADA standards.

Some disadvantages identified during the focus group testing were in the application user interface, sturdiness of the system, calibration procedures, ergonomics, and the cost. First, focus group members were concerned about the system cost compared to the inexpensive alternative of a measuring tape and level. Beyond this, some users were frustrated by the numerous and sometimes unclear steps in the application and expressed a desire for a more user-friendly interface with the ability to skip steps. Note that users were not provided enough time to fully grasp the functionality of the application. Further, users thought that entering information was unintuitive and that small, unresponsive buttons were an issue. Users also said that the screen was sometimes difficult to see as a result of glare from the sun.

In terms of the physical device, users said that exposed electronics would be a liability and should be covered. Further, they were concerned about the durability of the device and often were afraid to break the system. The users also said that the device felt rigid, bulky, and was difficult to transport. Some users suggested that more weight should be added to the base of the device to increase stability. Ergonomically, some users experienced tightness in the back and shoulders during use and suggested that a better handle is incorporated and that they be able to move in reference to the base plate. Focus group users expressed concern about the calibration of the device based on a bubble level at the baseplate of the device. Users said that this calibration method is subjective and that it may introduce more error into the system than necessary.

Changes requested by the focus group were related to the handle grip, electronic protection, application functionality and interface, screen glare, and calibration procedures. Improvements that users said were a high priority included the decreased weight for easier use and portability, a better application user interface, simpler and more effective calibration procedure, improved ergonomics, straps across the arm to make the device easier to hold, increased durability, and larger wheels with better grip. Users also requested a summary page in the application, such that data would be easier to view and interpret.

Some suggested improvements from the focus group were: more clear instructions in the application about how to use the CIS device, a simpler and more unified design, a swivel handle, and the ability to lock the device to stay in a straight line. In addition, a more stable battery compartment was suggested, as the current one often moved during use. Also, users would like to be able to track the completion status of ramps to determine which have been inspected and which still require inspection. Users also thought that the application may benefit from a step-by-step process layout, rather than requiring users to choose each measurement parameter themselves. Based on this feedback, we plan to make improvements to the application interface,

sensor calibration procedure, and mechanical elements like the handle, battery compartment, and baseplate.

Limitations

The CIS device contributed greatly to the purpose of the project. The user-friendly application system and lightweight model made the measurement process ergonomically easier for the subjects. With many positive aspects to the device, a few limitations are addressed and considered for the next redesign phase. Manual measurements conducted by the subjects were significantly different from PennDOT measurements. However, this may be a result of outdated measurements by PennDOT or inaccurate measurement by the test subjects. The test subjects were not professional contractors or surveyors with experience in ADA-compliant curb ramps, and this may explain why their measurements do not agree with those of professionals.

There were also several restrictions during the testing phase that affected the results. Lack of uniformity in the way curbs were measured introduced more human error, and this surely impacted the reliability of measurements. In addition, ramps undergo erosion and may wear over time as they are struck by vehicles, encounter frequent contact with shopping carts, disrupted by the growth of tree roots, and affected by other causes. PennDOT's measurements were conducted in 2008, which may have been ample time for impactful changes to occur to the curb ramp structure. Further, all measurements were taken by University of Pittsburgh students with little to no background in curb ramp construction. With very minimal knowledge in measuring curb ramps manually by traditional means, their measured data may differ from PennDOT data measured by official contractors for this reason. On a related note, there was a slow learning curve when using the CIS, and each user only used the device for a small amount of time; therefore, users were not entirely familiar with the device upon its use in the trial, and this could have impacted their measurement accuracy. On the application side, consistent calibration of the device was mandated by the protocol, and inaccurate or incorrect calibrations could have impacted individual measurements. Due to time constraints, users were only able to calibrate the device once before each measurement trial, which could have introduced variation into the data.

Implementation Plan

To implement the CIS/CRD system, the physical and software design should be considered in the overall context of PennDOT's internal curb ramp inspection process, as well as how this system interacts with contractors and curb ramp designers. The CIS prototype, as well as the accompanying tablet and microcontroller software, are fully functional and well-documented. These tools can be replicated and distributed to curb ramp inspectors with relative ease. The CIS prototype, however, was not entirely useful to the curb ramp designers we interviewed for their specific design process and is most valuable in the inspection phase. To address the design phase in the future, the CRD process architecture conceptualizes the operation of a curb ramp design tool and outlines the necessary steps and best path forward for its eventual creation (see Appendix G for details). Overall, the CIS prototypes and CRD process architecture are ready to begin their implementation into the curb ramp inspection and design process.

Conclusion

In summary, the development of the Curb Ramp Design (CRD) and Curb Ramp

Inspection system (CIS) from first generation prototype to a more robust and complete function and ergonomic system was successful based on the evaluations and interviews conducted. The CIS device has the potential to decrease the time required for curb ramp inspection measurements, as well as to streamline the curb ramp data collection, storage, and use over time. Through iterative design and consistent involvement of key stakeholders in the curb ramp design and inspection process, the curb ramp inspection system has potential to facilitate the increase in accessibility of the built environment through simplifying and curb ramp inspection process.

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Deliverable 1: Review of the Curb-Ramp Inspection System (CIS)

System Design Overview

      The CIS system is a combination of an Android based Nexus tablet, multiple sensors to measure distances, and an Arduino Uno microcontroller, mounted on a Micro Kickboard Compact commercially available 3-wheeled scooter (Figure 1). The ramp is measured by moving the scooter over various regions of the ramp, as identified by the CS-4401 form. The microcontroller controls the sensors as well as receives and transmits data to the Android application (Figures 2-4). The measurements taken by the individual will automatically appear within the Android application (Figures 5-7).
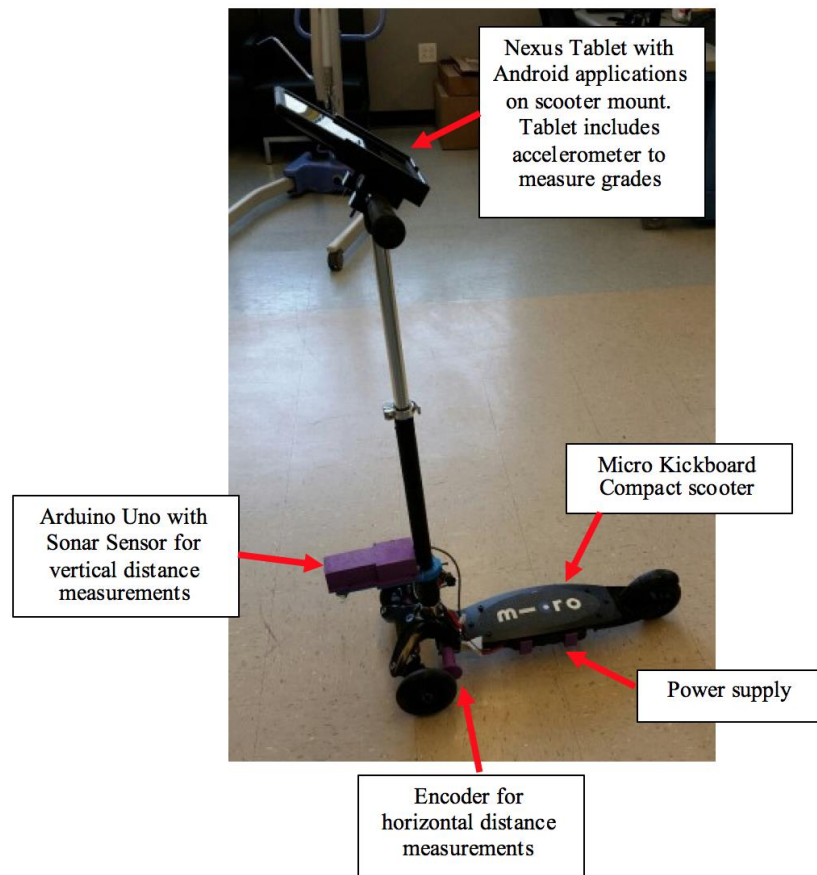

Figure 1: CIS System (CurbMET)

Figure 2: Sonar Sensor. This sensor measures vertical distances. To correctly measure curb height, the individual positions it over the road and takes the measurement. They then position it over the curb and take the measurement. The difference between the two measurements is automatically calculated and appears within the Android application.

Figure 3: Encoder. This sensor measures horizontal distances. When the scooter is pushed, an encoder measures the number of rotations of the wheel. The distance is automatically calculated based on the circumference of the wheel and appears within the Android application.

Figure 4: Accelerometer. This sensor measures change in grade. To correctly measure curb grade, the individual positions the scooter on a flat surface and takes a measurement. The individual then positions the scooter on the desired surface and the tablet's built in accelerometer records the angle.
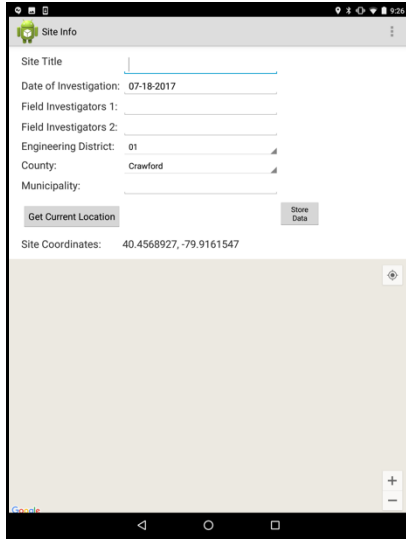
Figure 5: Site Information: This page of the application allows the user to input date, personnel, and location of the curb ramp inspection.
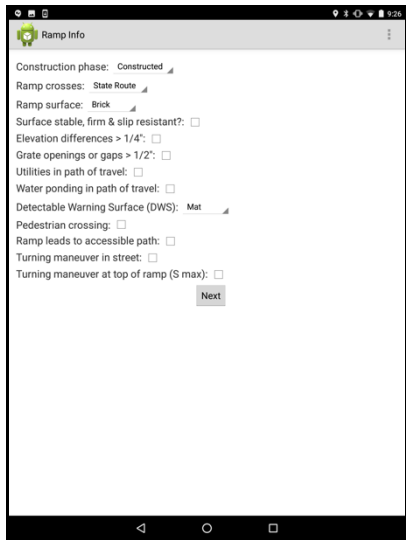

Figure 6: Ramp Information: This page of the application allows the user to input characteristics of the curb ramp being inspected.
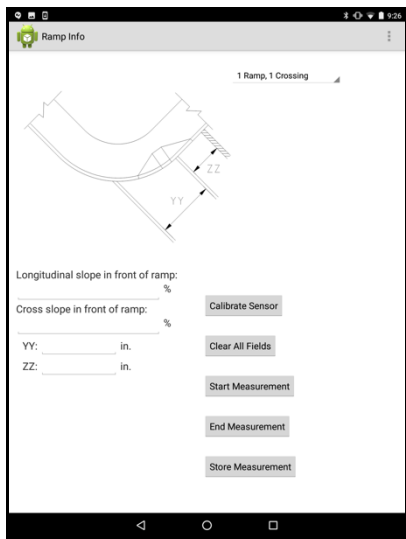

Figure 7: Ramp Measurements: This page of the application allows the user to select the type of curb ramp they are inspecting in the upper right-hand corner dropdown list. Additionally, it provides the user with the diagram of each curb ramp found in the CS-4401 form. The user can calibrate the sensors before taking measurements. Next, they can select the field ready to be measured and use the start and end measurements to complete the task. The store measurement button is used to save the measurements.

Methods

   The design of the existing university CIS system, a beta-level prototype, was reviewed for areas of improvement regarding the usability, durability, and data collection and integrity. The objective of the review was to identify the modifications necessary to adapt the system to PennDOT inspection requirements. To evaluate the system, five volunteers who had not previously used or worked with or on the scooter were trained on how to assess a curb ramp with both the scooter and by hand. After training, each volunteer was asked to assess a curb ramp close to our location using both methods. A coin flip determined whether the volunteer assessed the ramp with the scooter or by hand first. After the testing, the volunteer was asked to provide feedback related to the different categories based on the physical device and the mobile application. For usability, individuals were asked to focus on how easy it would be to learn and master using the CIS. Improvements were identified to simplify the completion of a curb ramp inspection. For durability, individuals were asked to identify potential failure areas related to the physical device as well as the application. Lastly, for data collection and integrity, individuals were asked to identify potential faults with the electronic functioning and accuracy in measurements.

Design Review Results

   The design review results are broken up into the three respective categories: usability, durability, and data collection and integrity. Each section first describes the findings of the review conducted and the issues which need to be addressed in order to adapt the system appropriately. A list of prioritized improvements follows the description of findings, to recommend how those issues can be addressed with design changes.

Usability

   With regards to the usability of the device itself, the size and shape of the device posed several maneuverability issues. Additionally, volunteers for testing identified the user interface as an area of frustration that would inhibit their ability to simply adopt the CIS into practice.

Improvements:
1. Reduce the over size, particularly length, of the device
   a. After user testing, it was stated that the device is difficult to maneuver and operate in smaller spaces and turns, forcing testers to pick up the scooter and reorient the device in that manner. This issue is caused by its length in combination with the fixed axle for the horizontal distance measurement sensor. A scooter was originally chosen as the base of the device assuming users would push and potentially ride the device during data collection, but during testing it was revealed that was not the ideal way to take measurements. The testers always walked behind the device or to the side trying to stabilize it during data collection. They believed it was too bulky and not the ideal configuration for its purpose.
2. Reduce the weight of the device
   a. The weight of the device was a limiting factor for testers because they have to constantly pick up the device. Over an extended period of time, the weight became frustrating, as well as a concern for transportation purposes.

b. The weight of the device should be kept under 5 pounds to ensure optimal usage.

3. Improve the user interface to make more intuitive for users
   a. It was noted that individuals had a difficult time switching between pages within the app (Figure 8).
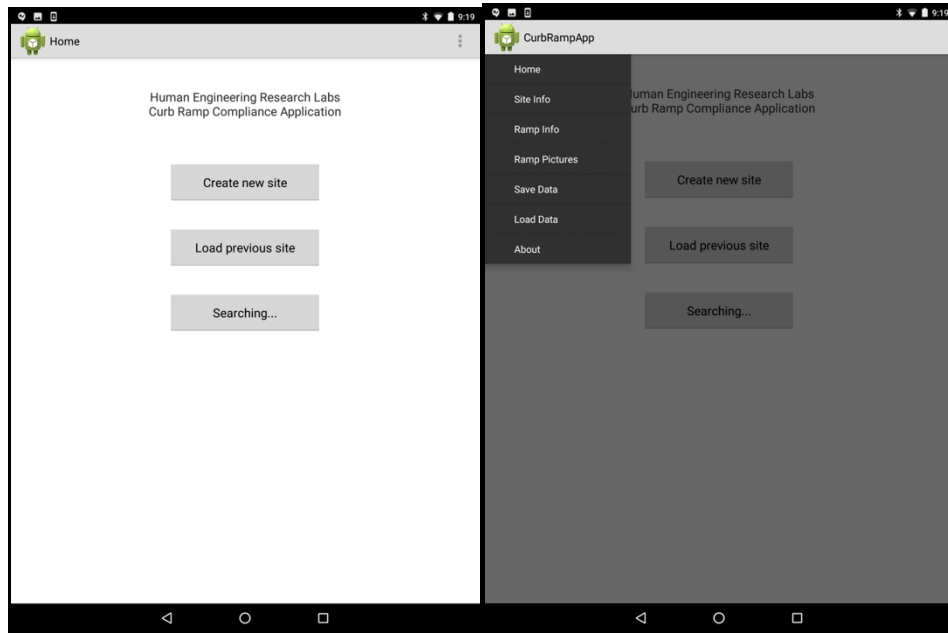
Figure 8: Navigation Bar: The user must swipe to the right in the upper left corner of the application to navigate between pages. This was difficult for users to figure out without instruction.

   b. Users often erased their previous measurements because the cursor does not automatically move between open fields.
   c. The keys and diagrams throughout the app do not move with the long list of required fields, therefore users could not constantly visualize the measurement they were taking (Figure 9).
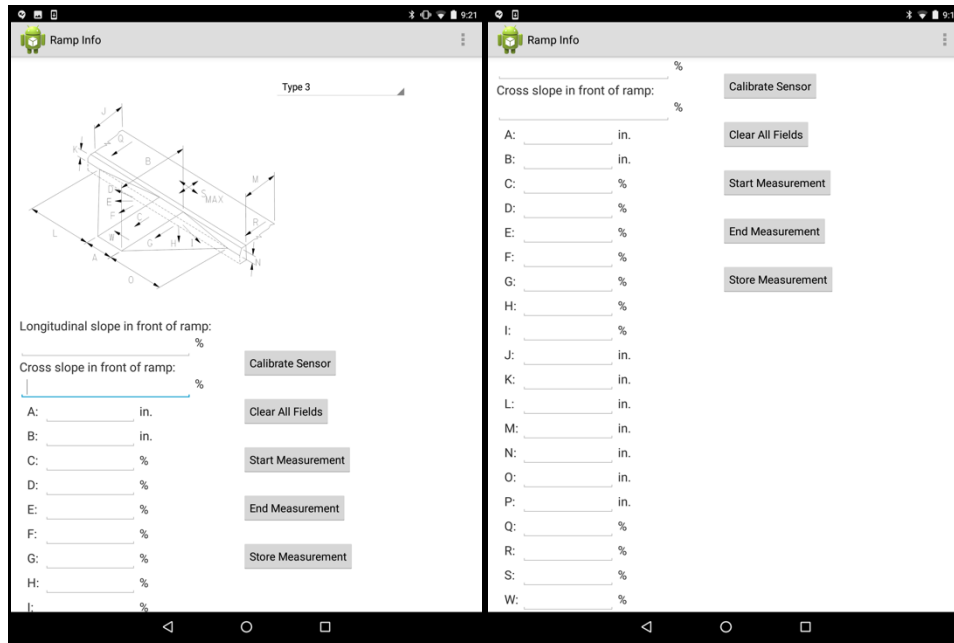
Figure 9: Curb Ramp Diagram: When the user moves down the list of measurements to take, they can no longer visualize the diagram above. There were questions and frustrations as to which measurement corresponded to the different areas of the curb ramp.

d.   Every time you click on a field, the keyboard would open, causing frustration while trying to take a measurement (Figure 10).

Figure 10: Keyboard: When a field was selected to begin a measurement, the keyboard would open, impeding the visibility of the fields on the screen.

e.   Users wanted a notification when all necessary fields have been completed.

4. Include visual cue when a measurement is being taken
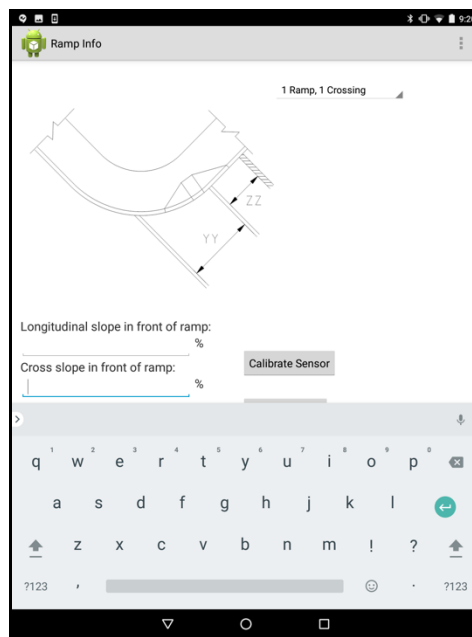   a. It was unclear when a measurement was being taken with the sensors, which made completion of curb ramp assessment take longer and with additional hesitation from the individual testing. Including a visual cue to inform users when measurements are being taken will help speed up the process.
5. Include a braking mechanism on the device
    a. There are no brakes on the system, which caused the device to roll when not being used if it was not secured. Users testing the device found that it was difficult to secure the device while working on the app simultaneously.
6. Automatically save collected data
    a. The app does not automatically save while an individual is working, so there was much concern for losing data along the way.
7. Include all necessary information from PennDOT curb ramp inspection form (CS-4401)
    a. App is currently missing:
        i. ECMS #
        ii. Alg Delta Grade #
        iii. Intersection ramp # of #
        iv. Pedestrian push buttons Y/N
        v. Status curb ramps
        vi. Archive ramp @ location #
        vii. Level of service

Durability

With the current prototype, the potential failure areas are due to inadequate interconnections between components. The 3D printed battery securement on the bottom of the scooter is breaking, which could cause the battery to disconnect during data collection. Additionally, there is considerable movement in the steering column, causing inconsistencies in measurements and a potential to drop the tablet. The attachment for the sonar sensor is loose, causing unwanted movement during measurements. The height and insecure method of attachment are failure risks during usage. The electronics and tablet need to be better protected or resistant to wet conditions in the field. Lastly, the use of rapid prototyping to produce several low-quality structural pieces of the device are potential failure areas.

Improvements:
1. Use appropriate materials for weight, type of usage, and usage conditions
    a. In order to ensure the strength and durability of the device, higher quality 3D printers or different materials should be used. We additionally are looking into using aluminum for parts that need to be lightweight and higher strength.
2. Ensure secure connection point between the handle and the base platform
    a. A majority of the weight of the device and rotational movement will occur between the handle and base platform. Designing a connection point that is stable, secure, and made of high-quality materials will help ensure lasting performance.

3. Use water resistant electronics where available

a. While the electronics will be protected by a cover on the device, using parts that are water resistant will help ensure they continue working properly and are not damaged.
4. Move power supply to more logical position on device
   a. Moving the power supply from underneath the device will help ensure there are no failures related to its method of securement.
5. Keep sensors on same surface as low to the ground as possible
   a. By keeping the electronics together and low to the ground, we can help prevent an area of failure.

Data Collection and Integrity
      With the current prototype, there are potential faults for all three methods of data collection. The encoder for horizontal distance measurement is not accurately taking measurements. The gears to track the distance are currently disengaging and skipping teeth causing the encoder to falsely read a measurement. The grade measurements are being taken by the accelerometer within the tablet, which is not consistent in its measurements nor accurate enough for this purpose. The movement of the steering column, where the tablet is mounted, also plays into the inconsistent grade measurements. Lastly, because the sonar sensor is mounted high along the steering column, it could be detecting other objects in its path while trying to measure curb heights. It is unclear what surfaces it is picking up.

Improvements:
1. Use a timing belt instead of 3D printed gears for the encoder
   a. Using a timing belt to track horizontal distance with the encoder will provide a better, slip proof method of measurement. The slots for the belt help prevent it from disengaging.
2. External accelerometer
   a. Using an external accelerometer will allow us higher accuracy of the measurements. Additionally, it will allow us to mount the accelerometer directly on the base platform, which places it parallel to the surface it is measuring.
3. New, repositioned sonar sensor
   a. By moving the sonar sensor closer to the ground, located on the base platform, we can minimize the potential for picking up external objects during data collection. Additionally, purchasing a more accurate sonar sensor will help the consistency of the measurements.

Appendix B

Task 2: Finalize Design Drawings for a Beta Prototype of the CIS
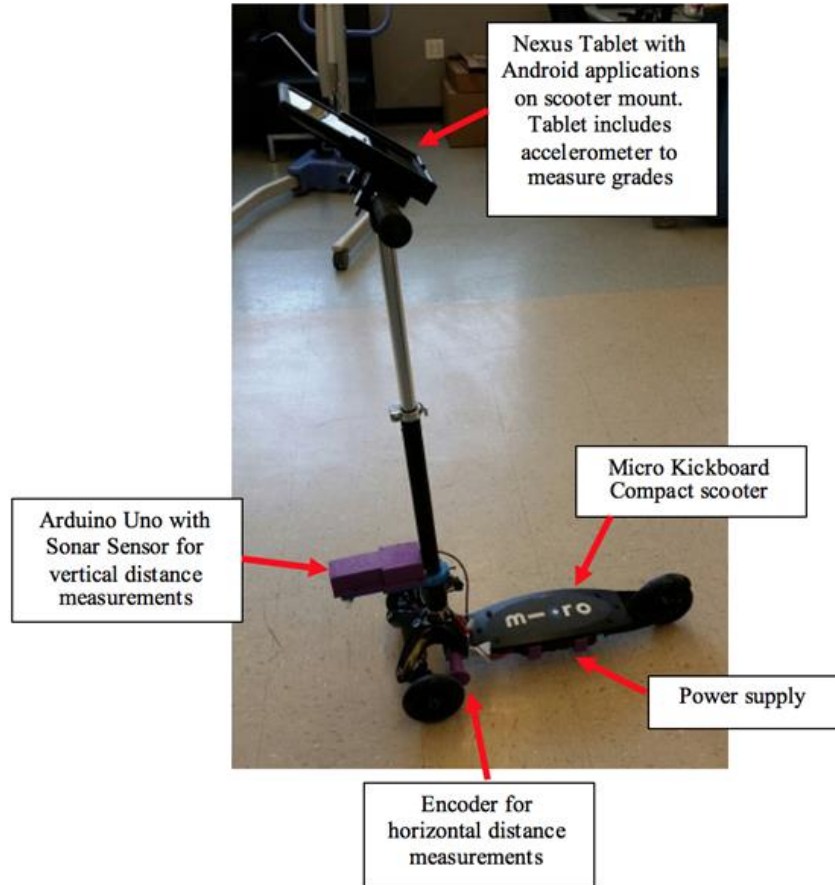


Figure 1: Previous version of the CIS.

User Testing

Five volunteers who had never used or worked with the CIS were trained to assess curb-ramps by hand and using the CIS. The users next measured a curb-ramp using both methods, then provided feedback regarding the CIS's usability, durability, and data collection and integrity. Users commented about the heavy weight and poor maneuverability of the device. The length and fixed directional wheels forced users to repeatedly pick up and reorient the device, especially when in tight spaces. Repeatedly picking up the scooter was also tiring due to its weight. Users also reported difficulties with the Android app's user interface. Navigating between pages was unintuitive. Users sometimes erased their measurements by accident. Figure 2 shows a screenshot of the page used while taking curb-ramp dimensions. Taking measurements required users to scroll through a long list of fields, thus placing the diagram of the curb-ramp off-screen, making it difficult to visualize the measurement they were taking. An on-screen keyboard opened

when switching between measurement fields, which frustrated users. Users also requested some indication of when measurements were being taken, a notification for when all necessary fields were complete, and that the data be saved automatically.
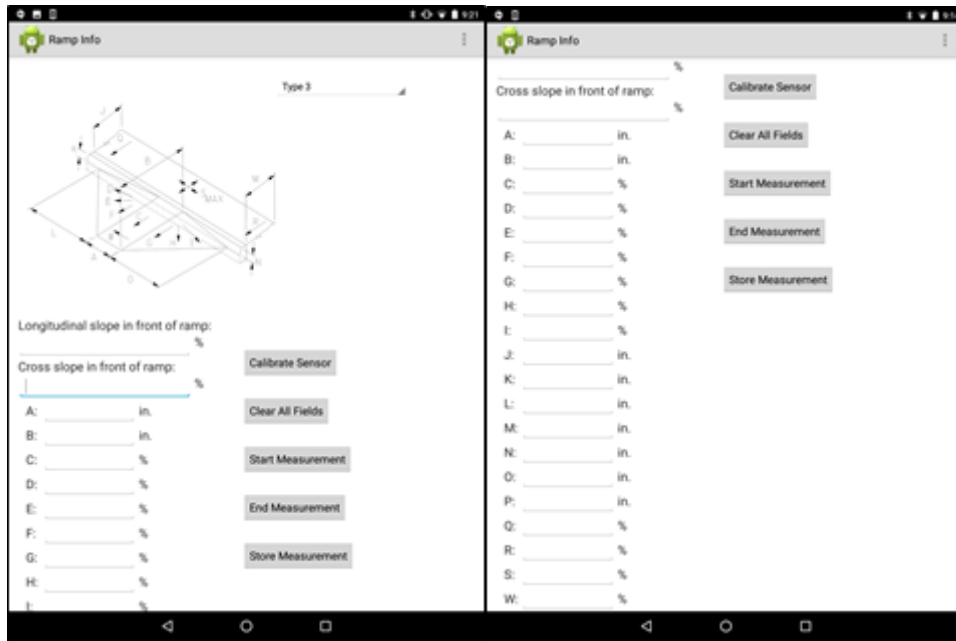
Figure 2: Screenshot of user interface used for taking measurements. Each field represents a dime on a curb-ramp. The user must click on a field, then click 'Start Measurement' and 'End Measure measure the dimension. A diagram of a curb-ramp with labeled dimensions is provided, but the lo of fields required the user to scroll down so that the diagram was out of site, making it difficult to which field corresponded to a dimension on the curb-ramp.

The device's durability was also problematic. The 3D printed securement attaching the battery to the underside of the scooter was prone to breaking. The sonar attachment was also loose, leading to unwanted movements while taking height measurements. Movements in the steering column led to inconsistencies in measurements and increased the risk of dropping the tablet. The unprotected tablet and electronics were also vulnerable to water damage.

There were several potential causes of measurement inaccuracy. The gears connecting the motion of the wheels to the encoder were prone to skipping, leading to incorrect horizontal distance measurements. The accelerometers used for measuring grade were stored in the tablet, which was mounted at the top of the steering column. As a result, wobble and differences in the angle between the curb and the base of the scooter were amplified up the steering column, leading to inaccurate grade measurements. Furthermore, the sonar was mounted high along the steering column, which made it unclear as to whether the sonar was measuring the distance to the intended surface.

Figure 3: Fully assembled CIS

Design Changes

Substantial modifications to the overall structure of the CIS (Figure 3) were made to reduce the size and weight (see Mechanical Design and Functionality section for more details). The CIS is now intended to be held in front of the user like a metal detector. Instead of a metal scooter, the base is composed of a thin sheet of ABS plastic. The steering column is a light-weight aluminum rod with an adjustable length and is attached to the base plate by a hinge, thus allowing for greater flexibility, maneuverability, and accommodation of a variety of user preferences.

The Android Tablet has been replaced with an iPad Mini, and ArcGIS is being used instead of Google maps to store and retrieve location data. Instead of a scrolling through a long list of fields, users now touch an icon on the diagram of the curb ramp to take and display measurements (see Software Design and System Integration section for more details about the iPad software). The iPad is attached to the steering column by an adjustable arm, allowing the user to adjust the iPad display to their preferred location and angle.

To reduce durability problems, the battery has been moved and is now integrated into a protective case surrounding the iPad. The microcontroller and all sensors are attached to the base and do not protrude out. The sonar distance sensor is now attached to the base and is much closer to the ground, making it harder to accidentally measure the distance to the wrong surface, as well as reducing measurement inconsistencies introduced by attaching the sonar to a loose steering column. To reduce the problem of gears skipping, gears will now be purchased and have a higher degree of manufacturing precision than the 3D-printed gears used in the previous prototype. The accelerometer is now external to the iPad and is attached to the base, eliminating the problem of wobble being amplified along the steering column.

Design Criteria

Electronics			
Criterion	**Units**	**Target Spec**	**Current Spec**
Battery life	hr.	> 8.0	10.8
Encoder distance measurement accuracy	in	< ⅛	< 1/16
Sonar distance measurement accuracy	in	< 1/8	1/8
Accelerometer angle measurement accuracy	degrees	< .1	.1

App Software Requirements	
Section	**Requirement**
Map View	• The map view must default such that the user's current location is at the center. • The user must be able to filter the features on display by curb ramp type, ADA compliance, status, and date last modified. • A map legend must be available to the user.
Map Features	• Curb ramp can be created at location tapped on the in-app map. • User can delete a feature from the map in the app. • The user can select an existing curb ramp to edit attributes. • All existing attributes will be viewable for the selected curb ramp. • The app must provide options for controlling when slope and distance measurements are started and stopped. • The app must allow the user to repeat a measurement if desired.
Bluetooth Services	• The app must allow the user to connect to any CurbMET device in the vicinity. • Bluetooth services will be enabled such that the app can receive slope and distance measurements from the CurbMET device.
Camera Services	• The user must be able to take pictures within the app and save them for a specified curb ramp. • The user must be able to upload existing pictures to the app and save them for a specified curb ramp. • The user must be able to remove and/or replace pictures associated with a curb ramp.
Cloud Services	• If there is a cellular connection, then curb ramp data must be retrieved and uploaded to the ArcGIS CurbMET database at specified points within the app.
Non-Functional Requirements	• Maps and their data must only be visible to users that have viewing permissions.

Hardware			
Criterion	**Units**	**Target Spec**	**Current Spec**
Total Weight	lbf	< 6	5.59

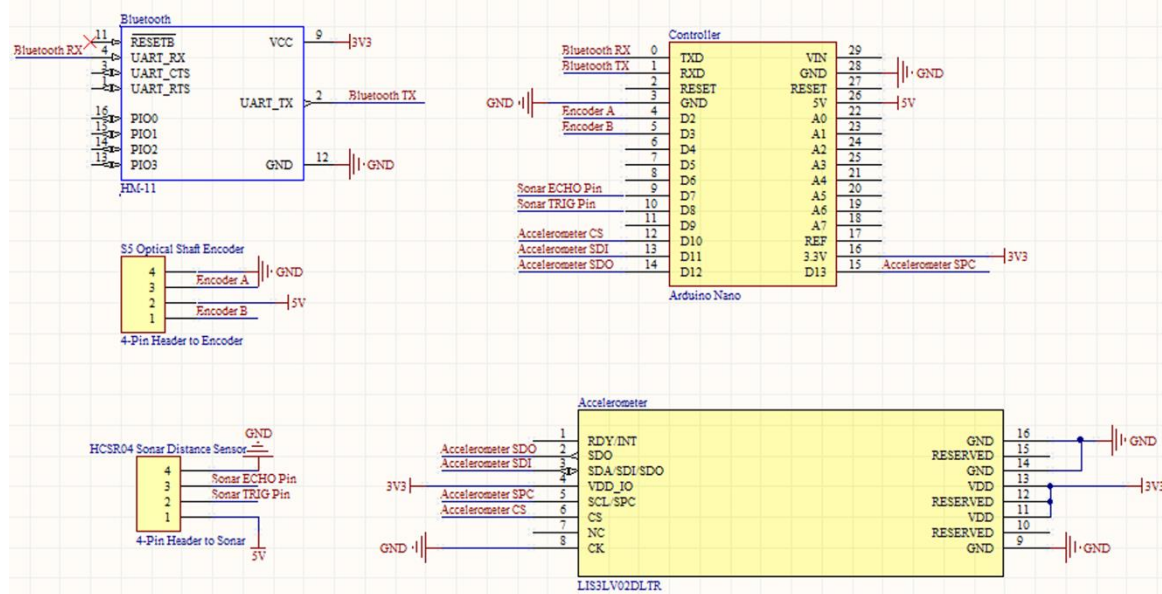| Overall Length (measured from end of grip to front wheel when handle at 50-degree angle to ground)	in	Adjustable from 51 - 59	Adjustable from 51 - 57

CIRCUIT DESIGN AND FUNCTIONALITY

Circuit Overview

General Features

The CIS hardware consists of an HM-11 Bluetooth module, LIS3LV02DLTR accelerometer, Arduino Nano microcontroller S5 optical encoder and HC-SR04 Sonar distance sensor (Figure 4a). The user controls the circuit by touching icons on the iPad app (see section App Developer Guide for further details). The app transmits the information to a microcontroller via Bluetooth. The Arduino then directs the appropriate sensor to take a measurement, which the Arduino processes and returns to the app via Bluetooth. The Arduino, Bluetooth module and accelerometer are soldered directly to a single PCB board (Figure 4b). The sonar and encoder are located elsewhere on the base plate and connect to the Arduino via wires which insert into two 4-pin headers soldered to the PCB board.

Power Supply

The power source of the circuit is stored in a Mophie Space Pack - a protective case surrounding the iPad mini which contains a built-in 5V 8,000 mAh battery, which can charge the iPad while simultaneously powering the rest of the circuit via a USB running from the battery down the CIS handle and into the Arduino (B&H, "Mophie Space Pack with External Battery & 32GB Storage for iPad mini (Black)"). The CIS has a battery life of at least 10.8 hours of continuous use.

Figure 4a (top): Schematic of CIS circuit. **Figure 4b (bottom):** PCB board (encircled in red) is attached to CIS base plate. Arduino unit is visible on top of base plate. Hex standoffs are placed between the PCB and base plate to prevent the board from resting on the pins of electronic components, which could otherwise damage the pins.

Arduino Nano Microcontroller

The circuit is controlled by an Arduino Nano, which activates and deactivates sensors, records their readings, performs noise filtering, accepts commands sent from the iPad via Bluetooth and returns data to be displayed. When the user decides to begin taking a measurement, the user touches an icon on the app, which causes the iPad to send a string to the Arduino indicating which sensor needs to be activated, thus causing the Arduino to begin reading from the appropriate sensor. When the measurement is complete, the user touches a different icon, causing the iPad to send a string indicating the end of the measurement, thus causing the Arduino to stop reading from the sensor and send the average of the measurement samples back to the iPad via Bluetooth.The Arduino also serves as a power source for the sensors. The Arduino is powered from the space pack through its USB port, and powers the rest of the circuit through its 5V and 3.3V power pins.

Approximate Rolling Average

Filtering of the sonar and accelerometer measurements is done using an approximate rolling average (also known as a modified moving average). Equation 1 displays the rolling average after i samples $\underline{s}_i$:

$$\underline{s}_i = ((i - 1) \times \underline{s}_{i-1} + s_i)/i \qquad\qquad (1)$$

Where $\underline{s}_{i-1}$ is the previous average value and s_i is the newest sample. This calculation is preferable to a simple moving average (where the average of some number of the most recent previous values is taken) for two reasons. The first benefit is that a simple moving average requires the storage of a number of previous values, while an approximate rolling average stores only the previous value of the rolling average $\underline{s}_{i-1}$ and the number of samples taken i. This reduces the required memory and reduces the likelihood of integer overflow errors that can occur when taking the sum of a large number of values. The second benefit is that the user does not need to wait for any set period of time to take a certain number of samples. A simple moving average requires a set number of samples to be taken, and if measurement stops before this

number of samples is taken, the remaining samples will default to 0, causing the calculated average to be erroneously small. The approximate moving average will return a reasonable value after even a single sample (although it is still preferable to take more), thus avoiding errors due to stopping measurement after an insufficient period of time.

HM-11 Bluetooth Module

The HM-11 Bluetooth module is used for Bluetooth 4.0 communication between the Arduino and the iPad. The HM-11 advertises a connection, which the iPad app discovers and connects to when the app starts up. Bluetooth data is relayed to and from the Arduino via serial communication (see section Software Design - Bluetooth Connection for further details).

Sonar Distance Sensor

Figure 5: HC-SR04 ultrasonic ranging module used for measuring vertical distances (RobotShop, "HC-SR04 Ultrasonic Range Finder").

Vertical distances are measured using an HC-SR04 Ultrasonic Ranging Module (Figure 5). The HC-SR04 uses sonar to measure the distance from itself to the nearest solid surface in front of it. The sensor has a range of 2 - 400 cm and an accuracy of 3 mm (ELECFreaks, "Ultrasonic Ranging Module HC - SR04"). Applying a pulse of high (5V) voltage to the 'Trig' pin activates the sensor to emit a burst of ultrasound, and the 'Echo' pin becomes set to high voltage. Once the burst of ultrasound bounces off the nearest surface and returns to the sensor, the 'Echo' pin returns to low (0V) voltage. The Arduino detects whether the 'Echo' pin is high or low and records the time t for pin to return to low voltage. Distance d is determined using equation 2:

$$d = t \times v/2 \tag{2}$$

Where v is the speed of sound in dry air at room temperature. $t \times v$ returns the total distance traveled by the ultrasonic pulse, which is then divided by two to account for the fact that the pulse travels the same distance twice (once traveling from the sensor to the surface, then again when returning to the sensor).

The sonar is mounted at the front of the CIS base plate (Figure 6a). To take a measurement of vertical distance (such as the height of a curb), the user places the base plate on the higher of two surfaces such that the sonar is directly above the higher surface, then touches an icon on the app, which directs the sonar to measure the distance from the sonar to the higher surface (Figure 6b). After, the user moves the base plate such that the base plate is still resting on the higher surface, but the sonar is directly above the lower of the two surfaces (Figure 6c). The user then touches an icon which directs the sonar to measure the distance between itself and the lower surface. The height will be equal to the difference between the two measurements.

Figure 6a (top): Sonar (encircled in red) is mounted at the front of the base plate. **Figure 6b (bottom left):** First, the distance between the sonar and the higher surface is measured while the CIS is resting on the higher surface. **Figure 6c (bottom left):** After the first measurement, the CIS is moved so that the sonar is above the lower surface and the distance between the sonar and the lower surface is measured. The height of the curb is equal to the difference between the two measurements.

Accelerometer

Grade will be measured using a LIS3LV02DLTR accelerometer. The LIS3LV02DLTR has a resolution of .001 g (ST, "MEMS inertial sensor"), which will allow for grade measurements with an average accuracy within 0.1 degrees when used to measure angles under 5.0 degrees (although the exact accuracy will be dependent on the angle). The accelerometer will continuously measure and transmit the acceleration in the x, y and z direction to the Arduino as 16-bit binary numbers representing accelerations between 2.0 and -2.0 g. When the accelerometer is stationary, these measurements will indicate the components of the force of gravity in the x, y

and z directions (x, y and z, respectively), which can be used to measure the angle A in degrees according to equation 3:

$$A = C * tan^{-1}(\sqrt{x^2 + y^2}/z) \hspace{3cm} (3)$$

Where tan^{-1} is the inverse tangent, and C is an experimentally determined constant used to calibrate the accelerometer. The angle is next converted from degrees to percent grade PG using equation 4:

$$PG = 100 \times tan^{-1}(A) \hspace{3cm} (4)$$

Where $tan^{-1}()$ is the inverse tangent.

The accelerometer is soldered to the PCB board, which is attached to the CIS base plate. To measure grade, the CIS is placed on the surface, and an icon on the app is touched which causes the CIS to continuously take angle measurements until the user touches a different icon, which causes the CIS to stop taking angle measurements, and display the approximate rolling average of the angle measurements (see section Circuit Design and Functionality - Approximate Rolling Average for a description of the approximate rolling average).

Encoder

Horizontal distances such as the length of a curb are measured using the S5 Optical Shaft Encoder (specifically the S5-360-250-NE-S-B model). The A and B pins of the encoder switch between high (5V) and low (0V) voltage as the encoder shaft rotates. Each pin can switch from high to low and back (clicks) 360 times per full revolution of the encoder shaft (US Digital, "S5 Optical Shaft Encoder"), giving the CIS a resolution of .05 in (see section Mechanical Design and Functionality - Encoder Gears for further details). The switch from high to low voltage between the two channels is slightly offset (90 degrees out of phase), so that whether channel A leads B or B leads A can be used to determine whether the shaft is rotating in a clockwise or counter-clockwise motion.

To make horizontal measurements, the user touches an icon on the app which causes the CIS to begin counting encoder clicks. When the user touches another button, the Arduino uses the total encoder clicks to calculate the distance traveled.

SOFTWARE DESIGN- ArcGIS

Introduction

This section describes the steps taken to design and publish a custom hosted feature service that stores curb ramp data. By interacting with a map representation of these data, users with the correct permissions can view features, edit attributes, and add attachments to the cloud dataset through ArcMAP for Desktop, ArcGIS online, or the CurbMET App. Feature and layer design was based on the June 2017 version of PennDOT's CS-4401 Curb Ramp Inspection form.

Brief explanations of GIS-specific terminology are given to orient a general audience; however,

for those seeking a deeper understanding of the concepts introduced, ESRI publishes free online guides and tutorials for all the software mentioned in this section.

ArcMAP

ArcMAP 10.4.1 for Desktop with an advanced license was used to generate the framework for the hosted feature service that the CurbMET app accesses and updates. A curb ramp feature class was designed based on the June 2017 version of PennDOT's CS-4401 Curb Ramp Inspection Form. The feature class served as a template for subclasses that are separated by curb ramp type (Type 1, Type 2, etc.). Feature layers were created from the subclasses and added to a map, which was published to ArcGIS Online as a hosted feature service. This section presents descriptions of the elements listed above and the steps taken to connect them together.

Curb Ramp Feature Class

"Feature classes are homogeneous collections of common features, each having the same spatial representation, such as points, lines, or polygons, and a common set of attribute columns, for example, a line feature class for representing road centerlines."

The curb ramp feature class contains all possible fields that a curb ramp could have. Subclasses were created for each curb ramp type and added to a geodatabase.

Domains

Domains were used to limit the number of valid values for attributes and correspond with drop-down menus on the CS-4401.

Fields

Each feature has a set of non-spatial information called attributes linked to it (Esri, "Attribute | Definition"). The feature class fields define the set of attributes associated with the curb ramp.

Feature Layers

"A feature layer is a grouping of similar geographic features, for example, buildings, parcels, cities, roads, and earthquake epicenters. Features can be points, lines, or polygons (areas). Feature layers are most appropriate for visualizing data on top of your basemaps. You can set properties for feature layers—such as style, transparency, visible range, refresh interval, and labels—that control how the layer appears in the map. Using a feature layer, you can view, edit, analyze, and execute queries against features and their attributes (Esri, "Feature Layers")."

To aid querying and display, feature layers are separated by type. The following feature layers were created for CurbMET - Type 1, Type 1A, Type 2, Type 4, Type 4A, Type 5, Type 6, Blended Transition, Type A Median, Type B Median, and Other. All feature layers have the same fields except for numbered dimensions (A, B, C, etc.). Only the required numbered dimensions for the ramp type are available for each layer.

In addition, all layers have two sublayers - Complete and Incomplete. Features in the incomplete

layers do not have all required fields filled and are displayed with a colored "X" symbol. On the other hand, "complete" features do not have any blank required fields and are displayed with a colored circle symbol. The color is determined by the parent layer. Features are automatically added to these sub-layers based on their "All Required Fields Filled" attribute.

CurbMET Map

Although each of the components listed above - feature classes and layers - are saved in separate files, they are brought together in the CurbMet Map.mxd file, an ArcGIS ArcMAP document. Layers from the catalog are added to the map. From here, features can be added to a layer in the map if desired; they will be saved in the layer's attribute table. Feature layers can also be queried using the "Select Layer by Attribute" Tool. For more information on the query tool, see http://pro.arcgis.com/en/pro-app/tool-reference/data-management/select-layer-by-attribute.htm.

After logging into an ArcGIS account with publishing permissions, the map was published as a service named "Curbmet_Map" to ArcGIS Online. It has 100000 maximum records. Feature access is enabled with a REST URL; cCreate, delete, query, sync, and update operations are enabled.

ArcGIS Online

A web map named "CurbMET_Map" was created on ArcGIS Online, and the published feature service was added to it. The map's service URL is used to access it through an ArcGIS Portal Item within the app.

App Developer Guide

Introduction

This section is a developer's guide for those who seek to understand or modify the structure of the CurbMET iOS app source code. To accomplish this goal, lists of dependencies, class diagrams, user experience flow charts, and an appendix of all app views are included.

A basic knowledge of Apple's XCode integrated development environment (IDE) and Swift programming language is assumed.

Dependencies and 3rd Party Acknowledgements

App Build Information

Deployment Target: iOS 10.0
Base SDK: Latest iOS (iOS 11.1)
Devices: Universal (iPhone and iPad)
Swift Language Version: Swift 3.2

Apple Libraries and Frameworks

Name	Version	Documentation	Application in CurbMET App
Core Bluetooth	Swift 3.1	Apple Developer Documentation	The Core Bluetooth framework provides the classes needed for your apps to communicate Bluetooth low energy devices, which the CurbMET CIS uses to facilitate communication between the measuring device and the iOS app.
UIKit	Swift 3.1	Apple Developer Documentation	Paraphrased from Apple's Developer Documentation - Window and view architecture (view controllers, labels, table views, etc.) - Event handling infrastructure for delivering Multitouch and other types of input to your app "Main run loop needed to manage interactions among the user, the system, and the app."
Foundation	Swift 3.1	Apple Developer Documentation	"Access essential data types, collections, and operating-system services to define the base layer of functionality for your app."

CocoaPods and 3rd Party Libraries

Using Cocoapods

"CocoaPods is a dependency manager for Swift and Objective-C Cocoa projects. It has over 40 thousand libraries and is used in over 2.9 million apps (CocoaPods Dev Team, CocoaPods.org)." Pods are added to the XCode project by creating a editing the project's Podfile. Detailed instructions for installing pods can be viewed on the Cocoapods website. Pods can only be referenced when working from the <Project Name>.xcodeworkspace file.

Cocoapods works by creating or updating a workspace and adding the Cocoapods static library project to the workspace if needed. Next, it adds libPods.a and an Xcode configuration file to the project. Once the app's target configurations are changed to be based on CocoaPods's, a build phase is added to copy resources from your pods to the app bundle (CocoaPods Dev Team, "Adding Pods to an Xcode Project").

Pods Used in CurbMET

Note: Although some libraries are written in Objective-C, all can be easily used in Swift.

Name	Language	Versio	Documentation	Application in CurbMET App

		n		
ArcGIS	Swift	100.1.1	ArcGIS Runtime SDK for iOS	Provides viewing and editing access to the CurbMET ArcGIS hosted feature service. Provides login API for ArcGIS online accounts.
SVProgressHUD	Objective-C	2.2.2	GitHub Page	Displays progress, error and success messages.
RxSwift	Swift	3.0	RxSwift Cocoapods Page	Provides fundamental functional reactive programming classes, such as observables.
RxCocoa	Swift	3.0	RxCocoa Cocoapods Page	Extends Apple's Cocoa and CocoaTouch frameworks to take advantage of RxSwift.
MMDrawerController	Swift	0.6.0	Github Page	Easily create and interact with side menus.
Eureka	Swift 3	3.1.0	Github Page	Create dynamic forms, which are used to populate content in settings page and some side menus.

Third Party Images and Icons

Ramp images were copied from PennDOT's CS-4401 form.
All other images not listed in the table below were created by Zoe Toigo.

Name	Source	Filename in App
Bluetooth icon	Made by Minh Hoang from www.flaticon.com	Bluetooth.png
Legend icon	Made by Pavel Kozlov from www.flaticon.com	legend.png
Menu icon	Made by Smashicons from www.flaticon.com	menu.png
Edit icon	Made by Smashicons from www.flaticon.com	edit.png
Filter icon	Made by Smashicons from www.flaticon.com	filter.png
Map icon	Made by Iconnice from www.flaticon.com	map.png

Photo album icon	Made by Smartline from www.flaticon.com	photoAlbum.png
Re-center crosshair icon	Made by Freepik from www.flaticon.com	crosshair.png
Question icon	Made by Linh Pham from www.flaticon.com	question.png

App Architecture

Theoretical Introduction

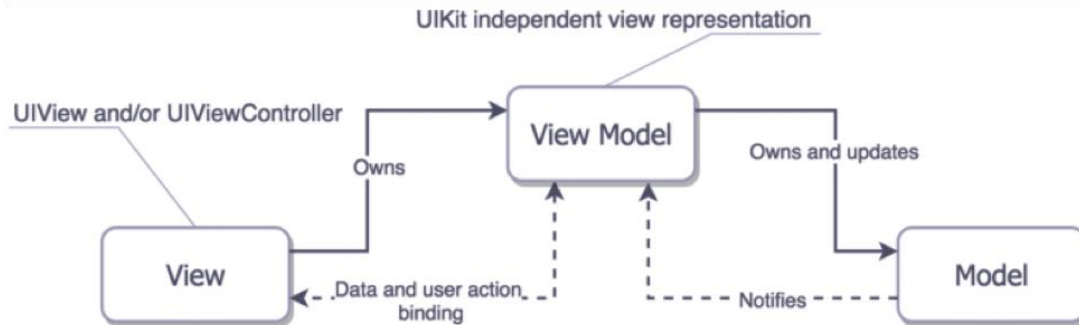"Software architecture encompasses the set of significant decisions about the organization of a software system including the selection of the structural elements and their interfaces by which the system is composed; behavior as specified in collaboration among those elements; composition of these structural and behavioral elements into larger subsystems; and an architectural style that guides this organization. Software architecture also involves functionality, usability, resilience, performance, reuse, comprehensibility, economic and technology constraints, tradeoffs and aesthetic concerns (Shaw and Garlan 1996)."

It is necessary to organize code such that there is a clear structure for creating objects and relations between them. Otherwise, what often results is spaghetti code. By using a standard app architecture, it becomes easier to find specific sections of code, test, and initiate changes that do not require modification in other documents.

MVVM - Model, View, View Model

MVVM is a popular app architecture which separates components that make up a storyboard into three separate categories of files:
1. Models - contains data and/or accesses from databases or online services. For example, AuthorizationAccessProvider.swift is a model that accesses OAuth authorization services, which enables logging in using ArcGIS accounts. There is typically one model per view model, and it is instantiated as a singleton within the view model. See "Table of Models, View, and View Models in CurbMET" on page 25. Never import UIKit into the model file; it should only be used for views and view models.
2. Views - a UIViewController class, which contains UIViews (buttons, text fields, labels, UITableViews, etc.). All code within the View should be directly dealing with user interaction, such as taps on the screen. Any other code, such as data manipulation or modifying the visual appearance of the view, should be moved to a different file.
3. View Models - a struct with properties and functions that handles presentation logic. Properties such as color and size live in the view model. Like the model, there is a one-to-one relationship between a view model and a view. The view model is instantiated as a singleton within its corresponding view. Don't import UIKit, and don't directly reference the view controller.

Figure 7: MVVM Component Interactions (Orlov).

MVVM has the following guidelines:
- Models do not talk to anybody.
- View models only talk to models.
- View controllers cannot talk to models directly; they only interact with view models and views.
- Views only talk to the view controllers, notifying them of interaction events.

Functional Reactive Programming

Reactive programming is based on the idea of asynchronous data streams. It is powerful because any data type can be turned into a stream of ongoing events ordered in time - values of properties that change over time, sequences of inputs, etc. We can subscribe to these streams, and asynchronously react to them when one of three things happen: a new value is emitted, an error occurs, or the stream is completed (Staltz).

For example, in the CurbMET app, we fetch image attachments that are associated with a given feature located in an online hosted feature table. As the attachments are fetched, they are added to a stream, which we display on the screen. Reactive programming is useful here because it enables us to deal individually with each emitted attachment, as opposed to waiting until all of the attachments are successfully retrieved. Depending on the number of attachments, this process could take more than a few seconds, and users do not like to be stuck watching a loading symbol.

Functional reactive programming brings in toolboxes that allow us to manipulate these streams by merging, mapping, or filtering. In this app, RxSwift and RxCocoa provide this additional capability. "RxSwift is a framework for interacting with the Swift programming language, while RxCocoa is a framework that helps make Cocoa APIs used in iOS and OS X easier to use with reactive techniques (Shapiro)." Marble diagrams are used to illustrate the functions at your disposal by displaying the input and output streams parallel to each other ("Observable").

Reactive programming has many benefits
- "Reactive streams allow you to write modular code by standardizing the method of communication between components. The reactive data flow allows for a loose coupling between these components, too (Lew)."

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- "Reactive programming raises the level of abstraction of your code, so you can focus on the interdependence of events that define the business logic, rather than having to constantly fiddle with a large amount of implementation details. Code in RP will likely be more concise (Staltz)."
- "Reactive programming enables us to create a highly-interactive experience that responds in real time (Staltz)."

Binding the View and the View Model

Because the view owns the view model, it is very easy for the view to change properties in and call methods from the view model. The same can be said for the view model's relationship with the model.

The example below shows the beginning of a simple login page.

SampleLoginViewController.swift

```swift
import Foundation
import UIKit
class SampleViewController: UIViewController {
        private let viewModel = SampleLoginViewModel()
    @IBOutlet loginButton: UIButton
        @IBOutlet usernameField: UITextfield
        @IBOutlet passwordField: UITextField

        override func viewDidLoad() { }

    @IBAction func loginTapped(_ sender: UIButton) {
        viewModel.login(usernameField.text, passwordField.text)
    }
}
```

SampleLoginViewModel.swift

```swift
import Foundation

class SampleLoginViewModel {
        private let authorizer = LoginModel()

        init() { }

        func login(_ username: String, _ password: String {
                authorizer.login(username, password)
        }
}
```

When the user taps the login however, it is much more complicated to notify the view of changes in the view model because MVVM forbids creating any references to the view in the view model. Swift standard libraries provide a few options for creating asynchronous subscriptions, including Key Value Observing (KVO), using "didSet," and callbacks. However, these strategies are verbose and can become hard to maintain as the number of observers increases. Thus, RxObservables are used in the app to bind the view and the view model.

For example, we want to display an error message when the username and password are incorrect. The login model, which performs all authorization functions, has a public observable named authStatus, which emits a stream of login validation statuses.

SampleLoginModel.swift

```
import Foundation
import RxSwift
import ArcGIS
class SampleLoginModel {
    //For brevity, this example does not include all properties
    // and methods that are needed to implement login validation
    // using AGSPortal.
        ...
        var authStatus: Observable<AGSLoadStatus>
        ...
}
```

Using the code below, which is added to SampleLoginViewModel.swift, the view model subscribes to authStatus, and when a new item is emitted from the stream, determines the correct message to display. The message is stored in the validationMessage variable, which is a RxSwift Variable<string>.

```
var validationMessage: Variable<String>
init() {
        authStatus.
                .subscribe(onNext: { newStatus in
                        validationMessage.value = getValidationMessage(newStatus)
                }).disposed(by: disposeBag)
}
private func getValidationMessage (_ status: AGSLoadStatus) {
        ...
        return message
}
```

Finally, the view binds validationMessage to the SampleViewController's validationLabel. As a result, whenever the portal's load status changes in SampleLoginModel, the view controller

automatically responds based on the type of status.

```
@IBOutlet validationLabel: UILabel
viewDidLoad() {
        viewModel.validationMessage.asObservable.bind(to:self.validationLabel).disposed(by:
disposeBag)
}
```

Why not MVC?

Figure 8: Model View Controller Diagram (Orlov).

Those with previous iOS app development experience have probably seen MVC, not only because it is promoted by Apple, but also because it is one of the most commonly used design patterns ("Model-View-Controller").

However, iOS uses a combined-roles variation of View and Controller, in which these two layers are tightly coupled together into a "View Controller." Because the view controller is responsible for responding to user interaction and manipulating the view, it is easy to bloat the view controller with UI logic. And as the number of views increases, so does the amount of business logic in the view controller. Eventually, the view controller becomes hard to read and impossible to reuse (Schmidt and Morrison).

Thus, MVVM was chosen to help alleviate these issues.
Table of Models, Views, and View Models in CurbMET
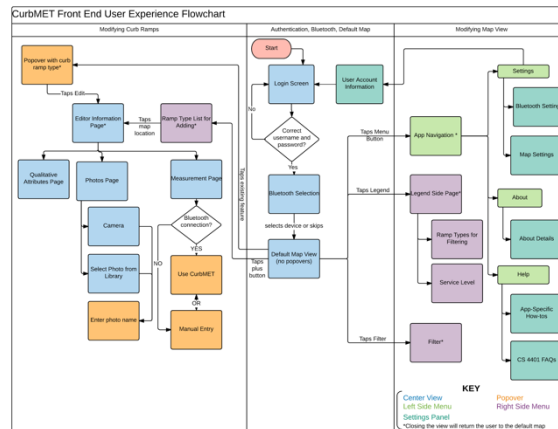Note: All files are Swift files. The .swift filename extension was removed for readability.

Function	View	View Model	Model
Logging Into App	LoginViewController	LoginViewModel	AuthorizatonAccessProvider
Bluetooth Connection	ScannerViewController	ScannerViewModel	BluetoothSerial
	SideMenuViewController		

	LegendTableViewController	LegendViewModel	
Filtering Map Display	RampTypeSelectionTableViewController	RampCarouselViewModel	
	FilterMenuTableviewController		
	MultipleSelectionTableViewController		
	AddFeatureTabBarController		
Accessing and Editing ArcGIS Hosted Map	MapViewController	MapViewModel	
	RampTypeViewController		
	EditorViewController	FormCellTypes EditorForm	FormItem
	QualitativeAttributesController		
	RampMeasurementViewController	MeasurementViewModel	
	MeasurementButton	MeasurementDataItem	MeasurementDataSource
	LegendTableViewController	LegendViewModel	
	AttributeMeasurementPopoverVC	AttributeMeasurementPopoverViewModel	
	AttachmentsViewController	AttachmentsViewModel	AttachmentsDataAccessProvider
App Settings	SettingsMasterViewController		
	SettingsDetailViewController	SettingsFormFactory	

User Experience Flowchart

Figure 9: User experience flowchart shows the steps that a user can use to access views in the app.

Major App Functions

Logging in and Authorization

The first screen that appears upon app launch is the login page. Because ArcGIS viewing and editing permissions are required for the app's core features - interacting with curb-ramp features on a map - the client and developer determined that login solely via ArcGIS online accounts would be most appropriate for the application. It should be noted that authentication requires an internet connection. Credentials required are a username and password, which are entered using an in-app keyboard. Currently, credentials cannot be saved between app launches.

Available login functionality is shown in the use case diagram below. All of the CurbMET app actions are accessible in the same view. The ArcGIS Online sign-in webpage will open in the device's Safari app.

Figure 10: Login use case diagram for the device's app.

Regarding the code for logging in, the ArcGIS iOS SDK provides several classes for implementing authentication.

AGSPortal

The fundamental class for authentication is the AGSPortal. "AGSPortal is an object that represents a view for a user (anonymous or not) into a portal. www.ArcGIS.com is an example of a portal...AGSPortal is the main class and the entry point into the API to work with portals and organization subscriptions. It implements all the operations to interface with the backend ArcGIS Portal REST API."

"Portals allow users and organizations to publish and share content over the web. Portals include "Users (AGSPortalUser), Groups (AGSPortalGroup) and Content (AGSPortalItem)."

Users
- Signs in to the portal and create and share content which is organized into Items.
- Can be part of an organization, but this is optional.
- Can create and join groups.
- Can share items with groups.
- "A user of the Portal (and of the REST API) sees the view off the Portal that applies to their organization subscription. This view includes users, groups and items that belong to the organization and have been shared with them. This view may also include users, groups and items that are external to the organization and have been shared with the user."

Organizations
- Used for managing who can create hosted services by uploading offline data.
- There can be multiple organizations in a portal.
- Includes users with roles of administrator, publisher, or information worker.

Groups
- Used for managing who can view and edit data that is already hosted online.
- Contains users. Users in the group can view items shared with the group.

Items
- Includes web maps, map services, applications, and data files
- Can be private, public, or shared with specific groups.

AGSAuthenticationManager

"This class allows you to manage authentication/security related events.

[The authentication manager] raises an AGSAuthenticationChallenge whenever an authentication or security issue is encountered anywhere in the API...It also maintains a cache (in memory) of credentials that have been previously used to satisfy authentication challenges. This allows credentials to be reused, where appropriate, and prevent unnecessary or duplicate challenges from being issued while accessing secure resources from the same security realm. Additionally, the cache can easily be persisted in the keychain so that if the app is restarted, the cache is automatically pre-populated with saved credentials and the user does not have to sign in again."

In CurbMET, custom UI responses to authentication challenges are enabled by setting the authentication manager's delegate is set to LoginViewController.

The application was also registered with ArcGIS, which created a client ID for OAuth 2.0 authentication. Because this client ID was provided to the authentication manager, the default challenge type to be created is OAuth.

In the app, an AGSPortal is instantiated using the URL www.arcgis.com. To attempt logging in, the portal's credentials property is set using the text entered in the textfields on the user interface.

Bluetooth Connection

In the CIS, the iPad is the Bluetooth Low Energy (BLE) central and the HM-11 Bluetooth Module is the only peripheral. After making the connection, the iPad is the server and the HM-11 is the client. The app is written such that it can only connect to one device at a time.

Establishing the Connection

This app uses a modified version of hoiberg's BluetoothSerial helper class to manage the Bluetooth connection (hoiberg). The software instantiates a global BluetoothSerial object called serial, which manages the Bluetooth connection for all of the app. A protocol/delegate pattern allows other files to respond to serial's events. lf a file in the app requires Bluetooth communication functionality, it simply adopts the Bluetooth protocol and sets serial's delegate equal to self.

The first view controller that calls for Bluetooth is the Scanner View Controller. The user is presented with a table of available devices to connect to. The Scanner View Model is a delegate of serial, and when serialDidDiscoverPeripheral() is called, it adds the detected peripheral to a Variable array of CBPeripherals. The view controller's UITableview is populated by the names of peripherals in the view model's array, and each time the the subscription detects an updated array, the view controller will refresh its UITableView. When the user taps a row in the tableview, the iPad will connect to the associated peripheral, and show the next view upon successful connection.

In the app, the Scanner View Controller is re-used in the settings section and the system status side panel. If the iPad is already connected to a device, its name will be displayed in the first section of the table, which is labeled "Currently Connected To."

The diagram on the next page is a high-level graphic representation of the functions used to discover and connect to a peripheral. It also illustrates the functions used to send and receive values, which is discussed in the next section of the document.

Figure 11: Functions used to discover, connect to, and communicate via Bluetooth.

Sending Values Between iPad and Circuit

Taking measurements with the CIS is the core of the app, and this function involves several subprocesses - creating a custom popover, validating the measurement, syncing with the ArcGIS feature service, and sending values between the circuit's microcontroller and the app. The focus of this section of the document is the flow of data between the circuit's microcontroller and the app.

Figure 12: Use cases for taking measurements using the CIS.

Each ramp type has its own scene in the XCode storyboard that is dedicated to taking measurements. Lettered buttons are layered on a diagram of the ramp. The letters, their associated measurements, and curb-ramp diagrams were copied from the June 2017 version of PennDOT's CS-4401 form. The layouts of these interactive pages are created in the XCode storyboard; the buttons are connected to the RampMeasurementViewController via IBOutlet actions. Because the same business logic is used regardless of curb-ramp type, the same view controller is used for all ramp measurement scenes.
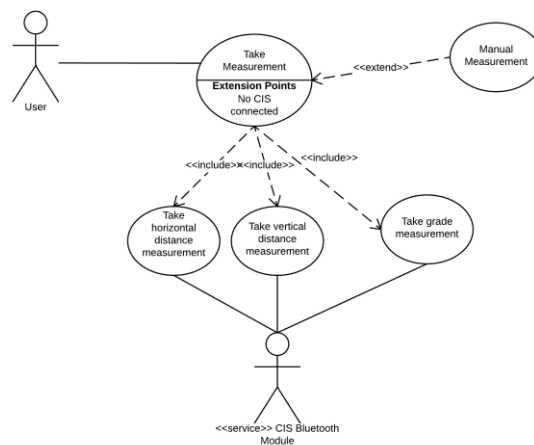
As shown in Figure 12, a measurement button passes the start/stop commands from the measurement popover to its data item, to the data item's Bluetooth handler. The Bluetooth handler sends the device to serial (a BluetoothSerial object). As a Bluetooth serial delegate, it waits for the "serialDidReceiveString" signal, and then uses the received value to set its private variable value received. The private property is exposed as an Observable, which the data item observes to set its private property "value". Finally, the measurement button observes "Value" - MeasurementDataItem's public measurement value - and uses the most recent string emitted from the stream to update its title, thus displaying the measured value to the user.

Accessing and Editing ArcGIS Hosted Map

Displaying the Map

To access the map, an AGSPortalItem is created using its item ID. If the user has logged in with valid credentials and the map is shared with the user's organization, then the portal will successfully load the item. If the user's credentials are correct but does not have viewing permissions, then a grey screen will appear. The map is assigned to the MapViewController's AGSMapView, which displays the interactive map to the viewer.

Whenever the map loads, it will center at the user's current location, with a zoom scale of 500. At this scale, sidewalks are clearly visible and minimal adjustment to the map's envelope should be required. The initial zoom scale can be changed in the app settings. Because the map and its data are hosted online, it will only function if the CIS is connected to the internet.

Adding Features

Once the user confirms his or her curb ramp type choice, a new instance of CurbRamp is assigned to the global curbRamp variable. At this point, the only information it contains is the curb ramp type and a readyToEdit boolean, which is set to true. This boolean confirms that the user chose a ramp type from the side panel immediately beforehand; otherwise, tapping the screen multiple times in succession would result in multiple features of the same type being created. When the user taps the map, the AGSGeoViewTouchDelegate determines the map location (an AGSPoint) that was touched. Using a series of functions from the MapViewModel, the view proceeds to determine whether or not a feature was touched at that location. If zero features are identified, the curbRamp variable is not nil, and readyToAdd is true, then curbRamp's create function (see "The CurbRamp Class" section) is called to add a new feature to the designated feature table.

Filtering the Map Display

ArcGIS feature tables can be queried using SQL expressions. The app builds a query parameter based on options selected from multiple choice menus and searches all of the map's tables for features that match the parameters.

The filter menu is displayed as a navigation controller assigned to MMDrawerController's right drawer container. When one of the filter categories is tapped (county, curb ramp type, etc.), the corresponding view controller of filter options is pushed onto the navigation controller stack. To send data between pushed view controller and the root view controller, a protocol was created. The top view controller is the delegating class, and the root is the delegate class. In each of the protocol functions that are implemented in the delegate class, an updateQueryParameters function is called. The where clause for the query is created by iterating through values stored in stacks. A LIKE expression is created using the stack values, and then the expression is appended to the existing where clause string. Next, each of the map's feature tables are queried using that expression. Any features that match the expression are selected on the map.

Displaying the Map Legend

The legend is a table view controller that toggles into view as a right-side menu using MMDrawerContainer. Each layer is a named section in the table, and its sublayers are rows in the section. The legend model contains an array of AGSLayerContent that stores the layers and sublayers found in the map's operational layers, and a dictionary of AGSLegendInfo that stores information such the layer's name and its symbol. These data structures are populated by recursively looping through the map's operational layers and their sublayers. The UITableView cells' text label and image view are set using the AGSLegendInfo dictionary. The AGSLayerContentArray determines the number of rows and sections in the table.

MECHANICAL DESIGN AND FUNCTIONALITY

Mechanical Design Overview- General Features

Figure 13: Fully assembled CIS

The new CIS is substantially smaller, lighter and more maneuverable than the previous prototype (Figure 13). All electronic components are housed on a ¼'' thick ABS plastic base plate. A handle is attached to the base plate by a hinge, allowing the user a high degree of maneuverability and flexibility (Figure 14). The base plate is meant to be kept flat on the ground while taking measurements but remains small and light so that steering or picking the CIS up will likely not tire the user. The total weight is 5.59 Lbs. (vs. 13.9 for the previous prototype).
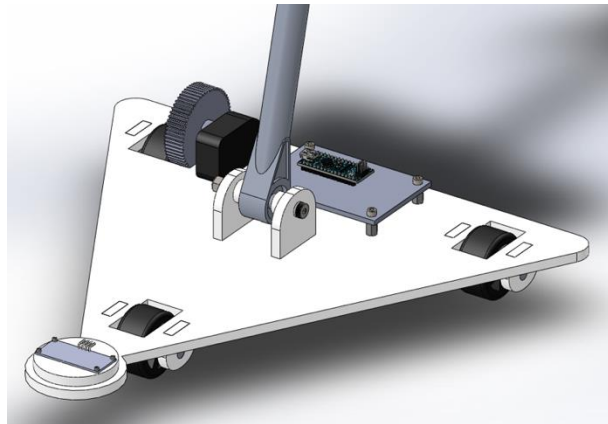

Figure 14: Base plate with handle and electronic components. The handle is attached to the base plate by a flexible hinge.

Use

The CIS is intended to be held in front of the user and rolled along the ground as would be done with a metal detector. The iPad is attached to the top of the handle on a stand and protected by a Mophie Space Pack (see section Circuit Design and Functionality - Power Supply for further details about the space pack). The iPad can be removed from the case and powered off its own battery or placed in the case and recharged during use.

Height dimensions are measured using the sonar in the front of the base plate (see Circuit Design and Functionality - Sonar Distance Sensor). Whereas the previous prototype of the CIS left the sonar unprotected from splash or from being side-swiped, the sonar now is protected from underneath by attaching the sonar to an ABS platform which elevates the sonar such that the speakers are not protruding downward, while still allowing a small slot through which the ultrasonic pulse can pass (Figure 15). Compared to the previous prototype, the sonar is also kept low to the ground to reduce the likelihood of accidentally detecting the wrong surface. Horizontal distances are measured using the encoder near the right wheel (see Circuit Design and Functionality - Encoder). Grade is measured using the accelerometer (see Circuit Design and Functionality - Accelerometer). Since the previous prototype, the accelerometer has been moved from the top of the steering rod to the base plate, which is comparatively sturdier and lower to the ground, thus allowing for more accurate and less noisy measurements of grade.
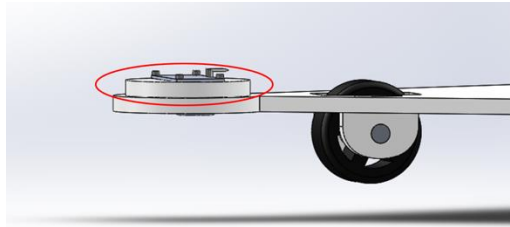
Figure 15: Sonar (encircled in red) is elevated from the rest of the base plate to prevent the speakers from protruding out from underneath the base plate, leaving them vulnerable to water and collisions.

Parts

Handle

A commercially available handle is used for the CIS handle, and features a grip, an arm bracket and an ergonomic shape (Figure 16). The iPad is held in an iShot Pro Adjustable Tablet Mount which clamps on to the top of the handle. The handle length can be adjusted between 46'' and 52'' using a push-button on the grip.

Figure 16: CIS handle. iPad is attached via a tripod clamped to the handle. Arm holder at the top of the handle helps to keep the CIS steady.

Base Plate

The base plate is made from flat ¼'' thick ABS plastic sheet (Figure 17a). The base plate is rigid so as to minimize measurement error due to flexing. Spaces in the base plate make room for wheels as well as ABS plastic slots by which the wheels are attached to the base plate (Figure 17b). There are also spaces for slots by which the handle can be attached. The base plate, slots, and sonar platform (see section Mechanical Design and Functionality - General Features for details about the sonar platform) can all be laser-cut cut from a single 24x24x¼'' sheet of ABS

plastic (Figure 17c). Slots are adhered to the base plate using epoxy. Hela-coils are inserted into the base plate into which the sonar and PCB board can be bolted (Figure 17d).
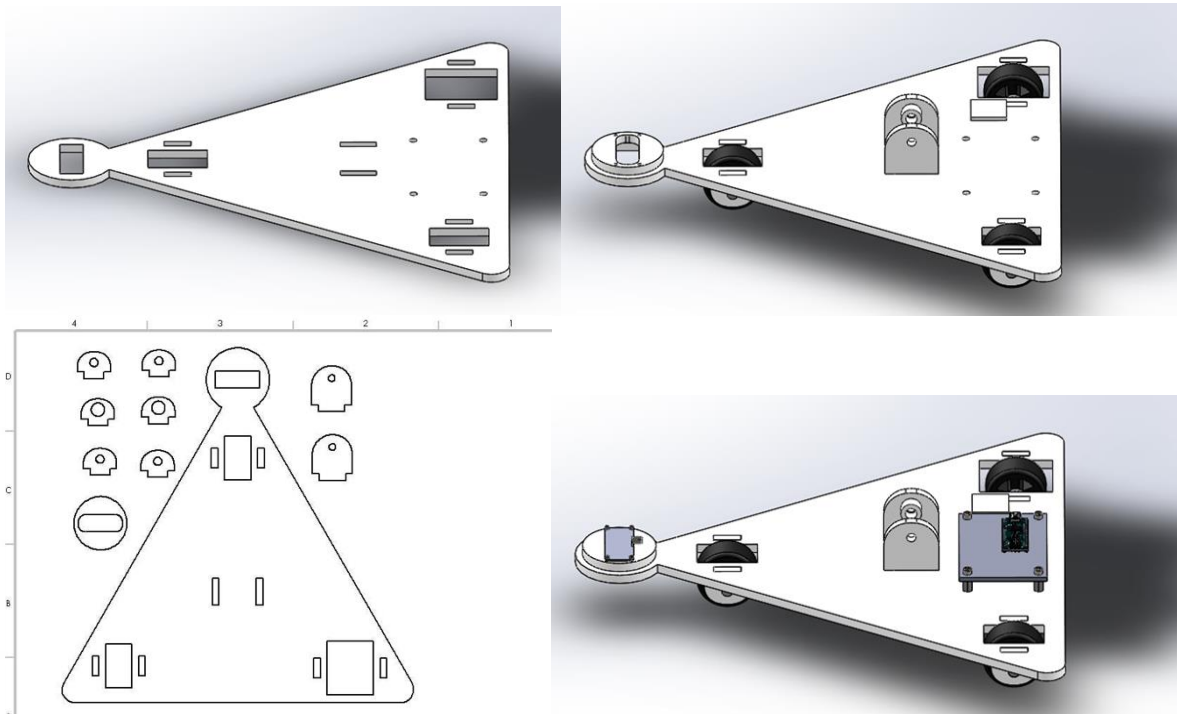
Figure 17a (top left): Base plate with no attachments. **Figure 17b (top right):** base plate with slots for wheels and handle as well as wheels attached. **Figure 17c (bottom left):** Base plate and related parts being prepared for laser-cutting by placing part profile on SolidWorks drawing. All ¼'' thick laser-cut parts can be cut from a single board. **Figure 17d (bottom right):** base plate with wheels, slots, sonar and PCB attached.

Encoder Gears
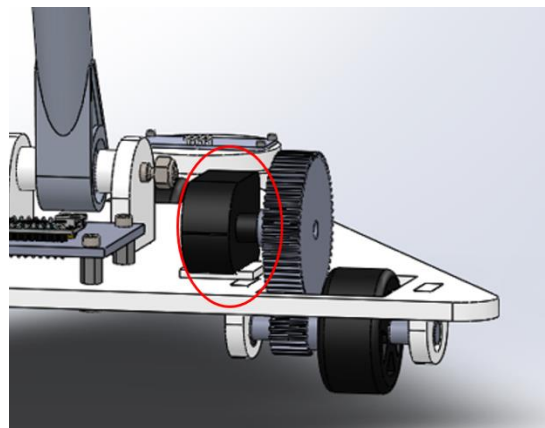
Figure 18: Encoder (encircled in red) coupled to wheel via two gears.

Horizontal distances are measured using an encoder coupled to a wheel of the CIS via two spur gears (Figure 18). The encoder is attached to a large gear of pitch radius r_{lg} which is meshed with a smaller gear of radius r_{sg} which connects to a wheel of radius r_w. As the CIS moves forward, the wheel rotates and drives the rotation of the encoder shaft. The rotation of the encoder is counted by the Arduino as "clicks" (see section Circuit Design and Functionality - Encoder for details). The rotation in radians of the encoder Θ_{enc}, large gear Θ_{lg}, small gear Θ_{sg} and wheel Θ_w are related by equation 5:

$$r_{lg}\Theta_{enc} = r_{lg}\Theta_{lg} = r_{sg}\Theta_{sg} = r_{sg}\Theta_w \qquad (5)$$

The relationship between wheel rotations and distance traveled d is given by equation 6:

$$d = r_w\Theta_w \qquad (6)$$

… which can be substituted into equation 5 to obtain the relationship between distance traveled and encoder rotation:

$$\Theta_{enc} = (r_{sg}d)/(r_{lg}r_w) \qquad (7)$$

Because the encoder has 360 clicks per rotation, the relationship between clicks and distance traveled can be determined:

$$clicks = (360 \times r_{sg}d)/(2\pi r_{lg}r_w) \qquad (8)$$

Using $r_{sg} = \frac{5}{32}$", $r_{lg} = \frac{1}{2}$" and $r_w = \frac{7}{8}$", it can be found that the CIS measures horizontal distance with a resolution of $\frac{1}{20}$".

CIS BILL OF MATERIALS

Part	#	Unit	Link to Manufacturer	Price per Unit ($)*
24x24x1/4" Sheet of ABS Plastic	1	1	McMaster-Carr	49.74
12x12x1/6" Sheet of ABS Plastic	1	1	McMaster-Carr	4.21
Bounty Hunter Tracker IV Top Rod	1	1	Bounty Hunter	18.95
Bounty Hunter Tracker IV Bottom Rod	1	1	Bounty Hunter	14.95
Bounty Hunter Tracker IV Arm Bracket	2	2	Bounty Hunter	3.70
Bounty Hunter Tracker IV grip	1	1	Bounty Hunter	3.90

1.65'' Diameter Plastic Wheels	3	Pack of 4	Inline Warehouse	10
5.16'' Diameter, 2'' Long Aluminum Rod	3	1 ft rod	Gamut	1.66
¼'' Long #6 Hex Standoffs	4	Pack of 10	Grainger	3.90
⅞'' Long #6 Socket Head Cap Screws	5	5	McMaster-Carr	2.72
#6 Hex Nut	4	1 Pack of 100	McMaster-Carr	1.24
0.565" OD Unthreaded Spacer	4	4	McMaster-Carr	4.91
¼'' Diameter, 2'' Long Shoulder Screw	1	1	McMaster-Carr	13.10
1-64 Thread Size, 1/8" Long Screw	4	1 Pack of 50	McMaster-Carr	5.25
10-24 Thread nylon insert lock nut	2	1 Pack of 100	McMaster-Carr	3.18
57155K378 Stainless Steel Ball Bearings	2	2	McMaster-Carr	6.43
iShot Pro Tablet Tripod Mount	1	1	iShot Products Inc	29.95
iShot Pro Pole Clamp Mount	1	1	iShot Products Inc	14.98
64-tooth, 2'' pitch diameter gear	1	1	N/A (3D Printed)	
20-tooth, 5/16'' pitch diameter gear	1	1	N/A (3D Printed)	
S5-360-250-NE-S-B Encoder	1	1	US Digital	70.65
LIS3LV02DLTR Accelerometer	1	1	Digikey	8.67
Arduino Nano	1	1	AliExpress	2.48
HM-11 Bluetooth Module	1	1	AliExpress	3.68
HC-SR04 Ultrasonic Ranging Module	1	1	Sparkfun	3.95
Mophie Space Pack	1	1	Mophie	199.95
iPad Mini	1	1	Apple Inc	399.00

2.4x3.53'' PCB Board	1	1	Advanced Circuits	370.07

* Cost of shipping and handling not included

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APPENDICES

Appendix A: App Screenshots

Login Page

Bluetooth Scanner
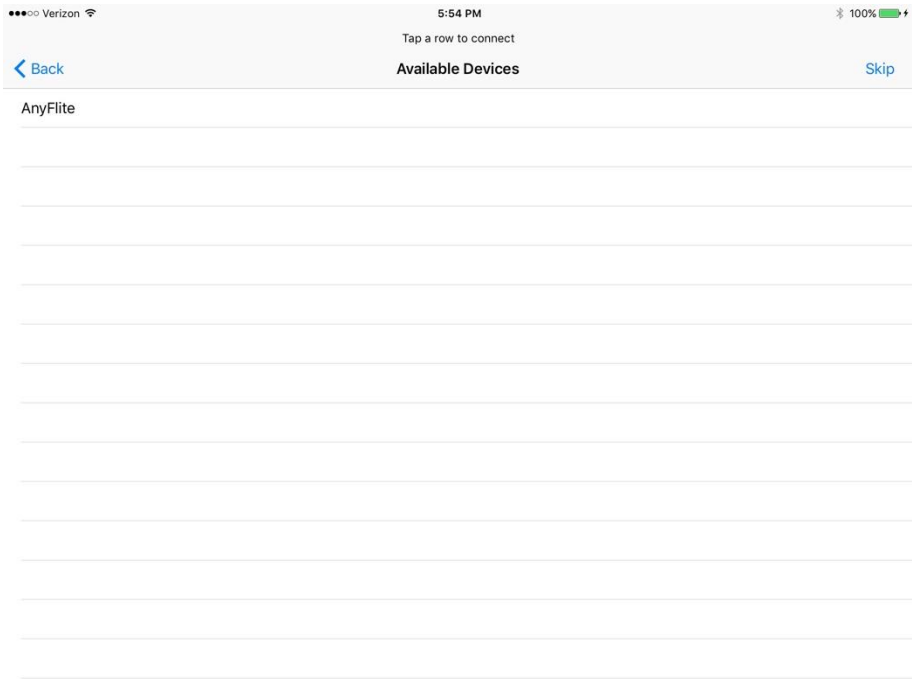
App Navigation Menu
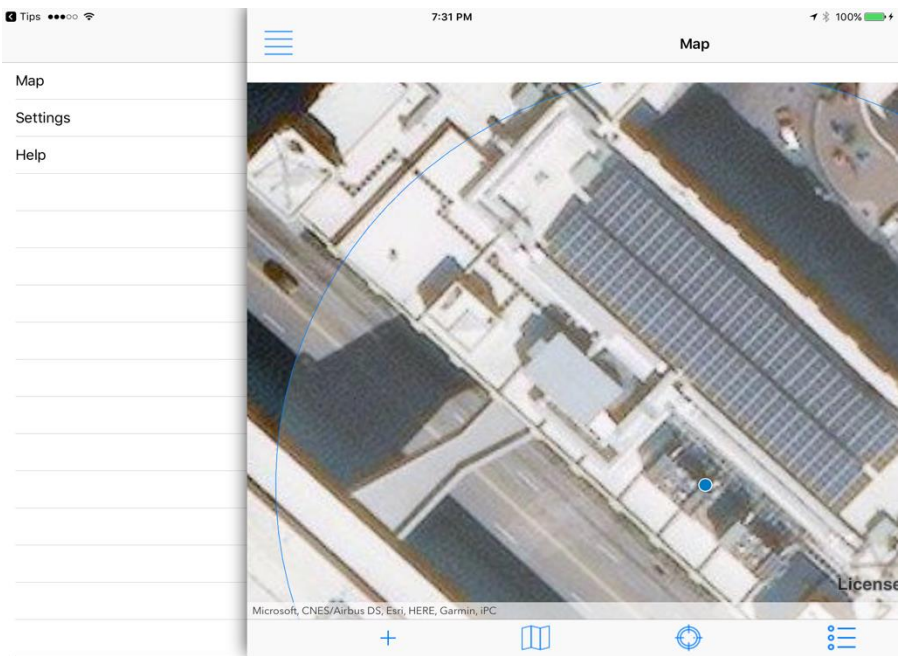
Map Landing Page
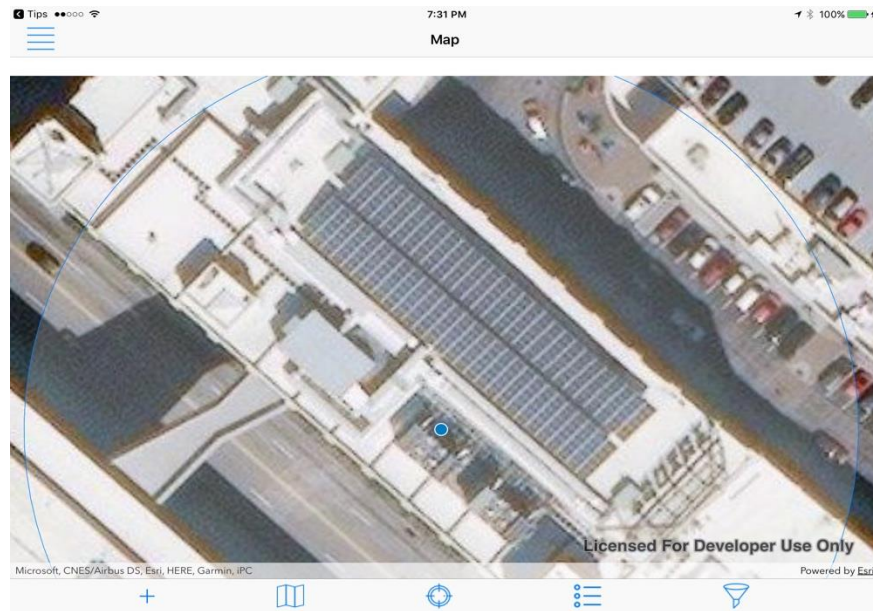
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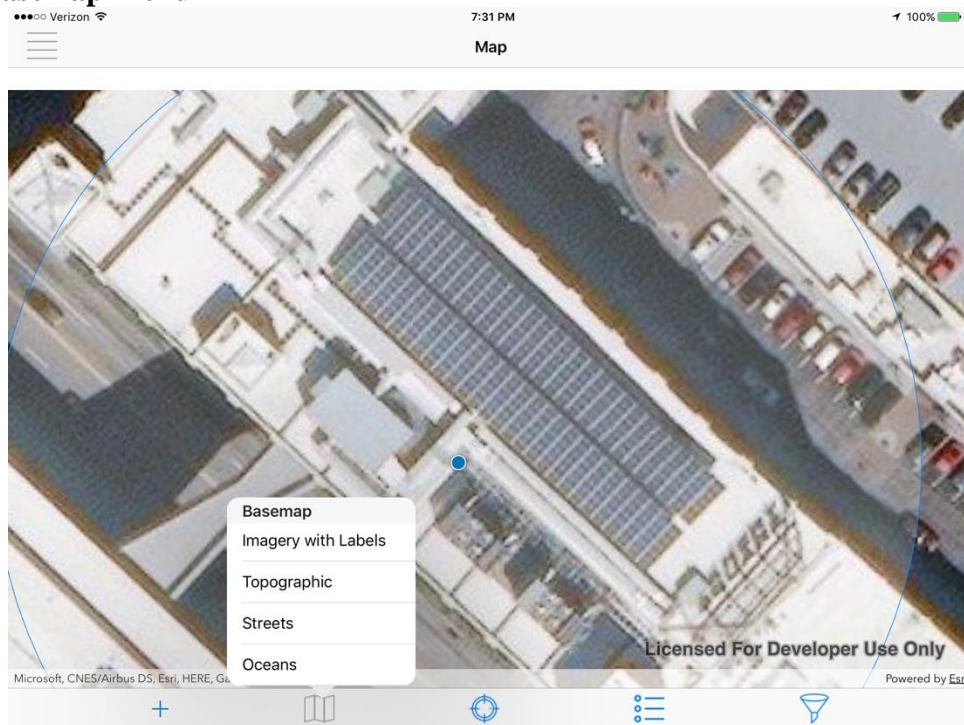
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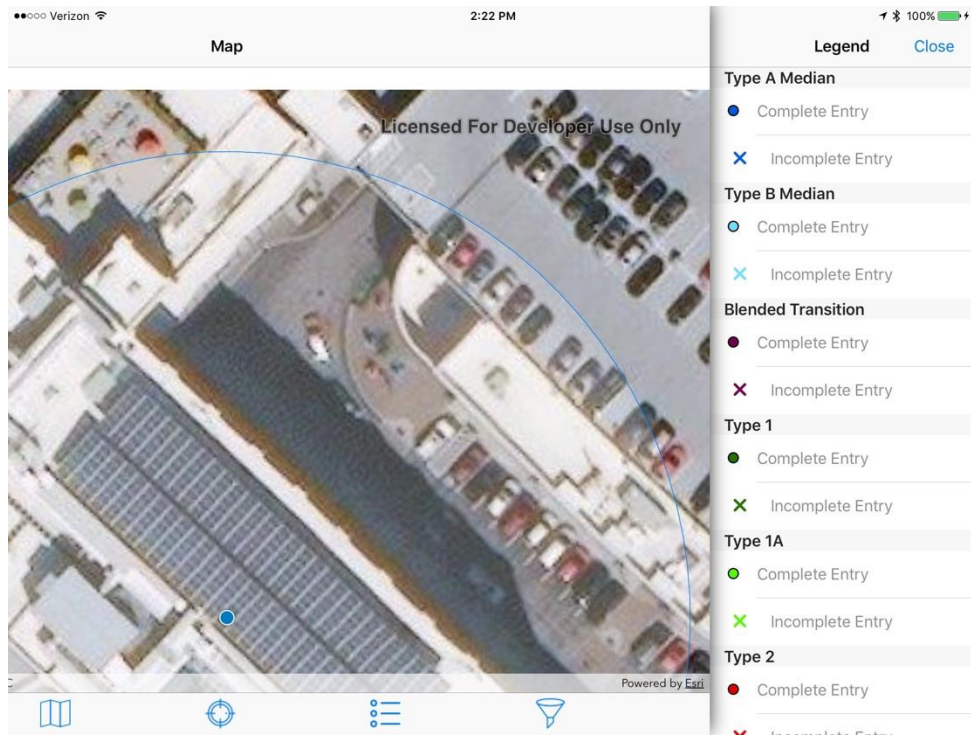
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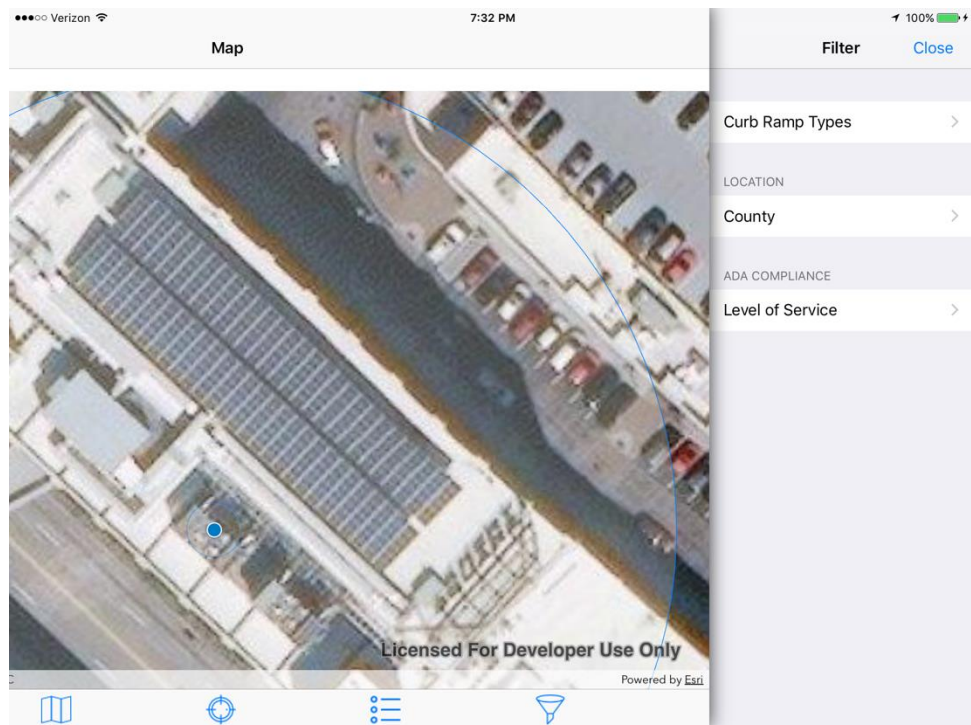
County List

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Search Menu

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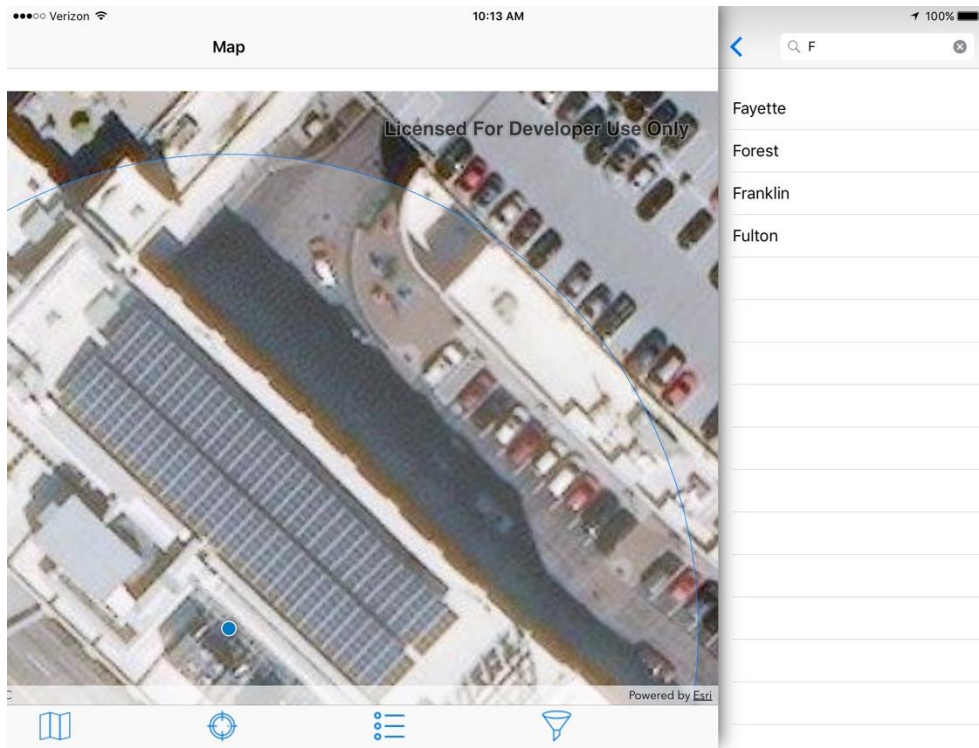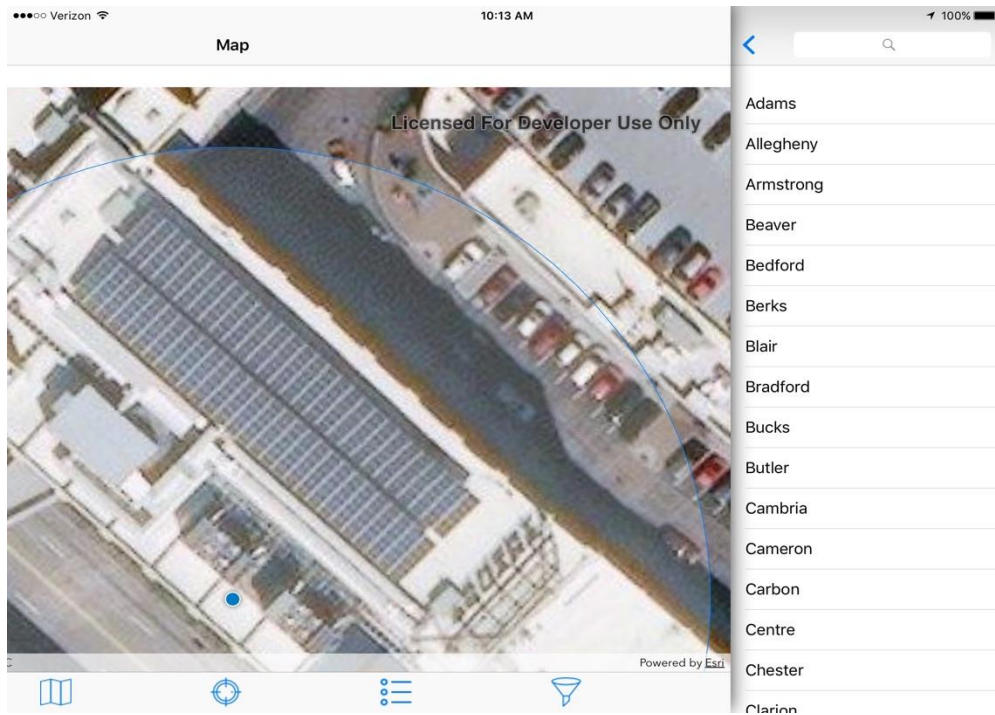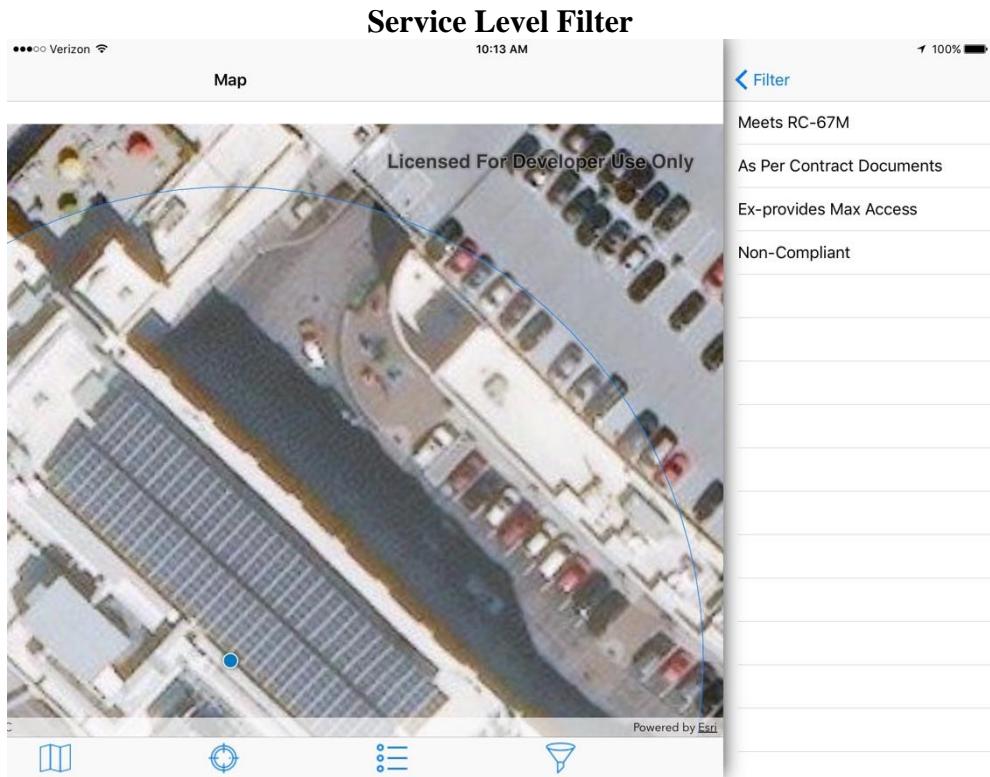
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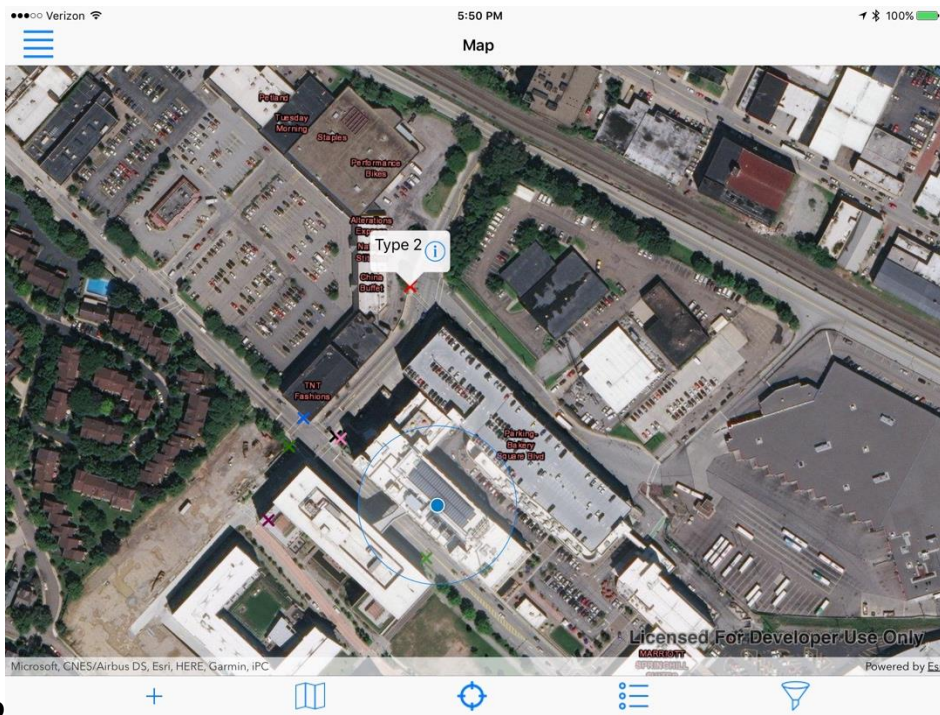
Map

<p align="center">**Editor Information**</p>

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| Editor Information |
| Ramp Measurements |
| Qualitative Attributes |
| Photos |

Editor Information   🗑

FIELD INVESTIGATOR 1   FIELD INVESTIGATOR 2

_____   _____

COUNTY NAME   COUNTY CODE

                                                      0

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Required field

MUNICIPALITY NAME   MUNICIPALITY CODE

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Required field   Required field

ENGINEERING DISTRICT CODE

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Page

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| Editor Information |
| Ramp Measurements |
| Qualitative Attributes |
| Photos |

Qualitative Attributes

Construction Phase   Ramp Crossses

| Constructed | Ex-Surveyed | Missing | | State Rte | Local Rd | Both |

Accessible Push Buttons   Status

| Yes | No | N/A | | Current | Achive |

Ramp Surface

| Brick | Concrete | Other |

Detectable Warning Surface   ⬤○

Pedestrian Crossing   ○⬤   Pedestrian Crossing Type   [ ]

Utilities in Path of Travel   ○⬤   Water Ponding in Path of Travel   ○⬤

Ramp at Stop or Yield Controlled Crosswalk   ○⬤   Ramp Leads to Accessible Path   ○⬤

Turning Maneuver in Street   ○⬤   Turning Maneuver at Top of Ramp (Smax)   ○⬤

Surface Stable, Firm, and Slip-Resistant   ○⬤   Service Level   [ ]

Taking Measurement with CIS
Popover appears when letter tapped.
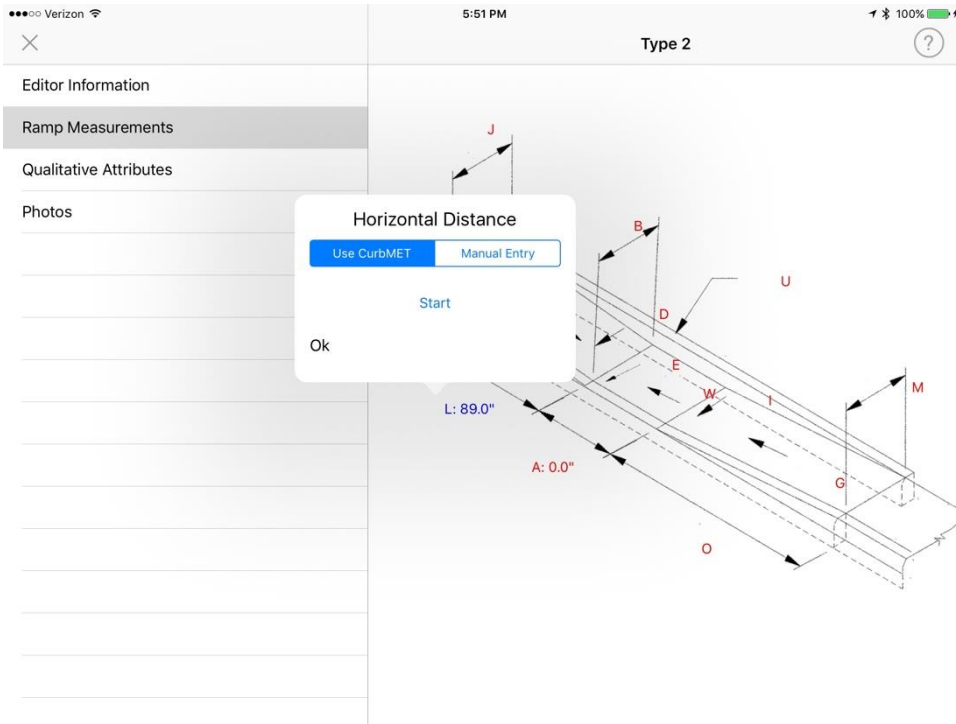
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Red letters are required and/or non- compliant.
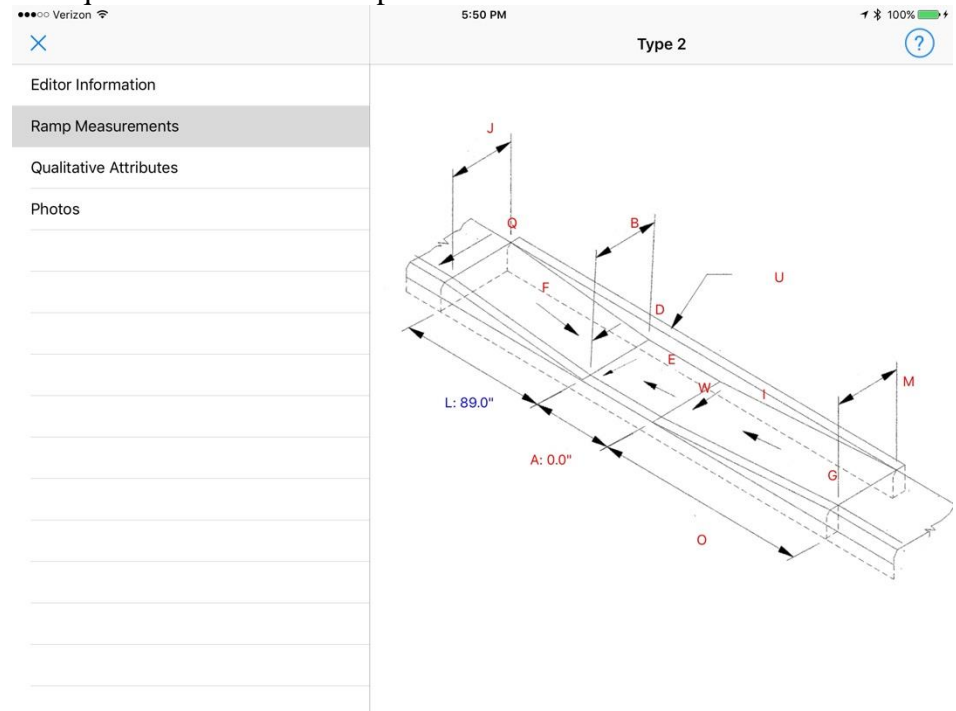
Photos Page

Appendix C

Task 3 Construct a Beta Prototype of the CIS and Perform Validity and Reliability Testing

INTRODUCTION
Inaccessible routes between locations can be a major barrier to participation for people with physical disabilities. Public buildings (1), restaurants (1), food stores (2), businesses (3) and doctor's offices (4) are frequently found to be inaccessible, due in part to architectural obstacles such as the absence of suitable ramps. Slip-and-fall accidents involving stairs or ramps are a common cause of injury among wheelchair users (5,6). Inaccessible workplaces can be challenging for retaining employment (7). Wheelchair users frequently prioritize routes with smaller slopes and better surface conditions over shorter routes in order to facilitate travel (8). Curb-ramps are created to enable people with disabilities to safely travel from the sidewalk to the street, and vice-versa. Considering that, the physically and visually impaired rely most heavily on curb-ramps (9), almost all design best-practices are created with these user groups in mind (10).

Task 2 Summary

The Task 2 summary reported detailed design modifications from Task 1 including revised drawings: SolidWorks mechanical drawings, electronics layout, and selected programming language (iOS using ARCGIS and SWIFT); and a bill of materials necessary for any changes. Task 2 compiles all the necessary pieces to explain the design, program, and electronics behind the CIS beta prototype. Using the finalized prototype, the Task 3 report details the validity and reliability testing of the CIS device.

Regulations on Curb Ramp Dimensions
The Americans with Disabilities Act of 1990 (ADA) was passed to protect the rights and ensure equal opportunity for those with mental or physical disabilities. Among the regulations in the ADA are standards for the dimensions of curb ramps. For example, a city curb ramp cannot have an incline exceeding 1:12 (4.8 degrees), must have a minimum width of 36 in (91 cm) across and cannot rise more than 30 in (76 cm) from the lower surface (11). In 1994, the United States Department of Agriculture (USDA) began requiring all cities to release a transition plan outlining the steps that the cities would take to make their facilities accessible to those with disabilities (12). As part of their transition plans, cities need to self-assess their roads and facilities to determine whether or not they comply with regulations. In 2006, the Department of Transportation (DOT) developed additional standards, such as the addition of detectable warning surfaces: a series of small domes built into ramps that would allow those with vision impairments to detect the boundary between the road and the sidewalk (13). In 2010, the Department of Justice (DOJ) released a new version of ADA standards for accessible design, which require curb ramps at newly constructed or altered streets, highways, and street-level pedestrian walkways to provide an accessible route for pedestrians at intersections (14).

Difficulties with Curb Ramp Assessment
Even with regulations, inaccessible sidewalks continue to create problems for wheelchair users.

A survey in New York found that 80% of individuals in manual wheelchairs and 73% of individuals in motorized wheelchairs considered curb ramps to be a barrier to physical activity (15). Another study found 60% of wheelchair users needed to overcome a blocked curb ramp and 12% have been unable to overcome a blocked curb ramp during a 28-day period (16). Furthermore, the process of assessing curb ramps for ADA compliance contains inefficiencies. The DOJ recommends that assessments of curb-ramps are completed in teams of three. One member of the team systematically reads the survey instructions aloud, a second member takes the curb ramp measurements and the third team member records notes and takes photographs of the measurements (14). The DOJ also recommends measurements are taken using a tape measure, digital level, and digital camera. These methods are tedious, ergonomically inefficient, and time consuming.

Existing Technology for Curb Ramp Assessment

The use of data collection and archival software is recommended for curb ramp assessment, along with the presence of workers with adequate ADA training in the field; the integration of ADA standards into project planning and development; the use of user-friendly websites providing information about regulations, laws and procedures; and the prioritization of the improvement of locations with greater importance, use, and urgency of improvement (17). A number of software tools have been developed for general management and maintenance of sidewalks, including the evaluation of curb ramps for ADA compliance. StreetSaver is a tool for inventory and budget planning used for road and sidewalk maintenance and includes features for rating curb ramp ADA compliance and a geographic information system (GIS) for displaying information as a map (18). ArcGIS, a cloud-based GIS platform, also has features for keeping an inventory of curb ramps and their ADA compliance (19). The state of New Jersey created a free online calculator for determining whether a curb ramp was ADA compliant (21). The PROWAP system is used for evaluating sidewalks and curb ramps for ADA compliance (22). The system consists of a cart with an attached inclinometer for measuring grade and a wireless roll-a-wheel for measuring distance. Data is transmitted to and displayed on a laptop or tablet computer on the cart and can also be uploaded to a Geographical Information System (GIS) database.

Shortcomings of Existing Technology

Existing technologies do not offer a comprehensive solution to the measurement, data collection, and information storage and display of curb ramps and sidewalks. The existing software technologies, such as ArcGIS and StreetSaver, are useful for the management of curb ramp data and for displays on maps, but other tools for measuring curb ramp dimensions and the associated time and effort to input that measurement data into the software. Although PROWAP ameliorates this problem by integrating database software with a measurement tool, the system is bulky, requires an additional tool for measuring distances, and does not automatically upload information into the GIS database. Thus, there is an unmet need for a curb ramp assessment tool which successfully and seamlessly integrates length and grade measurements, and software for storage and mapping curb ramp inspection data.

DESIGN

Current Beta Prototype Design

Pictured in Appendix A.1: Design Annotation, the current prototype design used for the reliability testing has a few mechanical improvements compared to the Task 2 version. The device lacked durability and stability hence the following changes. A plastic shroud is designed to cover the electronics on the device to prevent wear and tear, and water damage. A battery holder is added for convenience of wiring and turning on the device. The encoder is replaced with the same specifications, but the new version is easier to screw into the base plate of the device. All other changes were made to the base plates to create a sturdier and more concrete device for the user-testing phase.

RESEARCH STUDY

Methodology

Each focus group participant will complete the same tasks in the same order. Each task is explained in detail in subsequent sections of the document. All curb-ramp evaluations will be for the same curb-ramps, regardless of participant or measurement method. Before the curb-ramp measurements were taken, each participant was shown a short training video. In this video, a researcher demonstrates how to login to the app, how to connect to the CIS, how to navigate the map, how to add a curb-ramp, how to measure a curb-ramp with the CIS, and how to filter results. It is assumed that the same training video will be provided to all new users of the product when it becomes commercially available.

Three reliability and validity measurements were taken as part of the PennDOT CIS/CRD Focus Group. The first measurement participants were instructed to complete was manually measuring five different curb-ramps in East Liberty, Pittsburgh PA, selected by PennDOT, using the PennDOT method. The PennDOT method uses a digital level, measuring tape and the CS-4401 form to record each measurement. Each subject was responsible for measuring five different curbs, and four measurements for each curb. Two horizontal distance measurements: A and P, and two grade measurements C and W. While the focus group participant measured the curb-ramp another member of the research team recorded the measurement on the PennDOT CS-4401 form. The second measurement taken was measuring the same five curb ramps with the CIS device. For this task, the CIS records all curb-ramp measurements, so the participants were responsible for all aspects of the measuring process. The third measurement taken for this focus group was time. Time was measured for both manual and CIS curb ramp measurements. For manual time measurements, time was recorded when the participant began the manual measurement and after the measurement is written down and she/he verbally states the measurement. For CIS time measurements, time was recorded after calibration, when the participant pressed begin measurement on the CIS and ended when participant pressed end measurement on this CIS.Three other testing measurements were taken during the focus group: the CIS Task Assessment Sheet, the System Usability Scale (SUS), and the Rapid Entire Body Assessment (REBA).

Using the CIS Task Assessment Sheet

The CIS Task Assessment Sheet, created by the University of Pittsburgh research team, was used to assess the participants understanding of the CIS device. Participants were provided with open-ended tasks and minimal guidance at first. If needed, the researcher provided specific guidance after a predetermined amount of time has been spent attempting a task. Each step is associated with a point value of zero or one. One point is awarded for each step in the task that user completes successfully. If assistance is required for a step, or if the user fails to complete the step after assistance is provided, then the researcher will intervene and complete the necessary action. Zero points will be awarded. See Appendix B: Testing Protocol Tables, for all of the tasks the participant completed.

Using the System Usability Scale (SUS)

The SUS is a reliable measurement tool used to measure usability. The scale consists of 10 questions with five responses to each question that range from strongly agree to strongly disagree (15). The SUS was administered after the participant has had an opportunity to use the CIS

system. Focus group participants were asked to record their immediate response to each item, before group discussion. The scoring of the SUS yields a numerical representation of the overall usability. The SUS score was calculated by summing each individual question from 1-10, ranging from 1-5. For questions 1,3,5,7, and 9 the score contribution is the numerical value minus 1. For questions 2,4,6,8 and 10, the score contribution is 5 minus to scale position using only positive integers (15). After a final score is calculated, multiply the sum by 2.5 to obtain the overall SUS value. A SUS score of 68 or high is considered above average usability (16). For this focus group, the SUS score was calculated using the above-mentioned procedures.

Ergonomics Evaluation using the Rapid Entire Body Assessment (REBA)

The Rapid Entire Body Assessment (REBA) is a full-body posture evaluation that is used to identify design risks that could lead to musculoskeletal disorders. Each pose involved in a task can be quantitatively assessed by assigning scores based on the position of the wrists, forearms, elbows, shoulders, neck, trunk, back, legs and knees. Repeated small-range actions, prolonged static positions, grip, and load are also accounted for. Using a one-page worksheet with look-up tables, a final REBA score is assigned. Based on this score, the overall level of risk for the activity is determined. REBA scores are most relevant for postures that are the most difficult/awkward or posture sustained for the longest period of time (18). For this particular the study, the chosen postures to be evaluated are the trunk, upper arms, neck, lower arm, legs, and wrist. Traditional PennDOT measuring methods include bending over to take a curb-ramp measurement and holding a laptop or clipboard to enter data. The CIS measuring methods include holding the CIS with one hand and navigating through the app with another hand, extending one arm while walking with the CIS, bending down to put the CIS in a rest position. A photograph was taken of each participant during manual and CIS measurements of curb-ramp one, during horizontal distance measurement A. Using these photographs and a protractor, the REBA score was calculated by two members of the research team. See Appendix C below for more details.

RESULTS

Three students from the University of Pittsburgh participated in the focus group comparing CIS and manual measurements to PennDOT measurements. The average height for all three participants was 5 feet 7 inches, and an average age of 25 years. The participants had varying races, educations, and rural/urban locations, but all subjects have previous engineering experience and use apps 1 to 3 hours per day.

Quantitative data collected from this study includes curb-ramp measurements for grade and horizontal distance with both the CIS device and manual measurement, measurement time for manual measurements and CIS device measurements, the CIS Task Assessment Sheet, System Usability Scale (SUS), and the Rapid Entire Body Assessment (REBA).

CIS versus Manual Curb-Ramp Measurements

Grade measurements were variably accurate depending on the ramp and the specific type of measurement; for instance, P measurement for curb five was consistent between manual, CIS,

and PennDOT measurements, however, P measurement for curb two were noticeably different between the manual, CIS, and PennDOT measurements (Appendix D.2). Horizontal distance measurements were also variably accurate, although to a lesser extent; this accuracy also depended upon the ramp and type of ramp, with A measurements being generally closer to PennDOT measurements than W measurements (Appendix D.2). In terms of time required for measurement, initial analysis shows that manual measurement is less time consuming than CIS measurement (Appendix D.5). However, accounting for the number of people whose time is required to complete each task, a modified analysis shows that CIS measurement is, overall, more time efficient than manual measurement (Appendix D.6).

We investigated the efficiency and accuracy of the CIS device by measuring the five selected curb ramps in terms of time (seconds), grade (percent) and horizontal distance (inches). Four measurements were selected, A, P, W, and C, out of the twelve total curb ramp measurements to save time. Each subject conducted 3 trials for the 5 curb ramps. All the subject's data were averaged based on measurement for both CIS and Manual. Tables 1.1-1.5 were made for each curb, producing the Graphs 1.1-1.4 (Appendix D). All error bars were based on the PennDOT data within 5% error.

CIS Task Assessment Sheet

All participants scored at least 14 points out of 15 total points on the CIS task assessment sheet. The main area of concern is choosing the type of curb ramp being measured on the app and locating the correct ending position for the CIS at the end of the curb-ramp measurement. These areas of concern will be addressed in the CIS redesign.

System Usability Scale (SUS)

The participant's SUS scores for the CIS device were 78, 92.5 and 75 out of a total 100 points, with an average score of 81.7. Based on these results, for this focus group, the CIS device is above average for participant usability.

Rapid Entire Body Assessment REBA

For all subjects, the REBA analysis was significantly higher for manual measurements (8.6 ± 0.6) than CIS measurements (2.6 ± 0.6). REBA scores were higher for manual measurement and indicated a high-risk task, whereas the scores were lower for measurement with the CIS device, indicating low risk (Appendix C).

DISCUSSION

Focus Group Feedback and Future Improvement Plans

From the focus group testing, there were many advantages of the CIS over manual measurement in terms of usability. The CIS was more comfortable to use, as it was no longer necessary to squat low to the ground to measure, which is consistent with the REBA measurement results. In addition, using the CIS was less labor intensive and more time efficient than manual

measurement. This is because the CIS offers a simpler workflow, and also does not require measurements to be written out with pen and paper. Electronic data collection allows for a smaller chance of losing paper data. Users also thought the CIS was intuitive and more precise for length measurement, as tape measure only gives length to 1/16th of an inch and may introduce variation based on how the user measures. In the CIS software application, users appreciated the layout and diagrams, as well as that the color of a measurement number which immediately indicates whether it complies with ADA standards.

Some disadvantages identified during the focus group testing were in the application user interface, sturdiness of the system, calibration procedures, ergonomics, and the cost. First, focus group members were concerned about the system cost compared to the inexpensive alternative of a measuring tape and level. Beyond this, some users were frustrated by the numerous and sometimes unclear steps in the application and expressed a desire for a more user-friendly interface with the ability to skip steps. Note that users were not provided enough time to fully grasp the functionality of the application. Further, users thought that entering information was unintuitive and that small, unresponsive buttons were an issue. Users also said that the screen was sometimes difficult to see as a result of glare from the sun.

In terms of the physical device, users said that exposed electronics would be a liability and should be covered. Further, they were concerned about the durability of the device and often were afraid to break the system. The users also said that the device felt rigid, bulky, and was difficult to transport. Some users suggested that more weight should be added to the base of the device to increase stability. Ergonomically, some users experienced tightness in the back and shoulders during use and suggested that a better handle is incorporated and that they be able to move in reference to the base plate. In particular, focus group users expressed concern about the calibration of the device based on a bubble level at the baseplate of the device. Users said that this calibration method is subjective and that it may introduce more error into the system than necessary.

Changes requested by the focus group were related to the handle grip, electronic protection, application functionality and interface, screen glare, and calibration procedures. Improvements that users said were a high-priority included the decreased weight for easier use and portability, a better application user interface, simpler and more effective calibration procedure, improved ergonomics, straps across the arm to make the device easier to hold, increased durability, and larger wheels with better grip. Users also requested a summary page in the application, such that data would be easier to view and interpret.

Some suggested improvements from the focus group were more clear instructions in the application about how to use the CIS device, a simpler and more unified design, a swivel handle, and the ability to lock the device to stay in a straight line. In addition, a more stable battery compartment was suggested, as the current one often moved during use. Also, users would like to be able to track the completion status of ramps to determine which have been inspected and which still require inspection. Users also thought that the application may benefit from a step-by-step process layout, rather than requiring users to choose each measurement parameter themselves. Based on this feedback, we plan to make improvements to the application interface,

sensor calibration procedure, and mechanical elements like the handle, battery compartment, and baseplate.

Limitations

The CIS device contributed greatly to the purpose of the project. The user-friendly application system and lightweight model made the measurement process ergonomically easier for the subjects. With many positive aspects to the device, a few limitations are addressed and considered for the next redesign phase.

Manual measurements conducted by the subjects were significantly different from PennDOT measurements. However, this may be a result of outdated measurements by PennDOT or inaccurate measurement by the test subjects. The test subjects were not professional contractors or surveyors with experience in ADA-compliant curb ramps, and this may explain why their measurements do not agree with those of professionals.

There were also several restrictions during the testing phase that affected the results. Lack of uniformity in the manner in which curbs were measured introduced more human error, and this surely impacted the reliability of measurements. In addition, ramps undergo erosion and may wear over time as they are struck by vehicles, frequent contact with shopping carts, disrupted by the growth of tree roots, and affected by other causes. PennDOT's measurements were conducted in 2008, which may have been ample time for impactful changes to occur to the curb ramp structure. Further, all measurements were taken by University of Pittsburgh students with little to no background in curb ramp construction. With very minimal knowledge in measuring curb ramps manually by traditional means, their measured data may differ from PennDOT data measured by official contractors for this reason. On a related note, there was a slow learning curve when using the CIS, and each user only used the device for a small amount of time; therefore, users were not entirely familiar with the device upon its use in the trial, and this could have impacted their measurement accuracy. On the application side, consistent calibration of the device was mandated by the protocol, and inaccurate or incorrect calibrations could have impacted individual measurements. Due to time constraints, users were only able to calibrate the device once before each measurement trial, which could have introduced variation into the data.

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APPENDICES

Appendix A: Design Modifications

Appendix A.1: Device Annotation
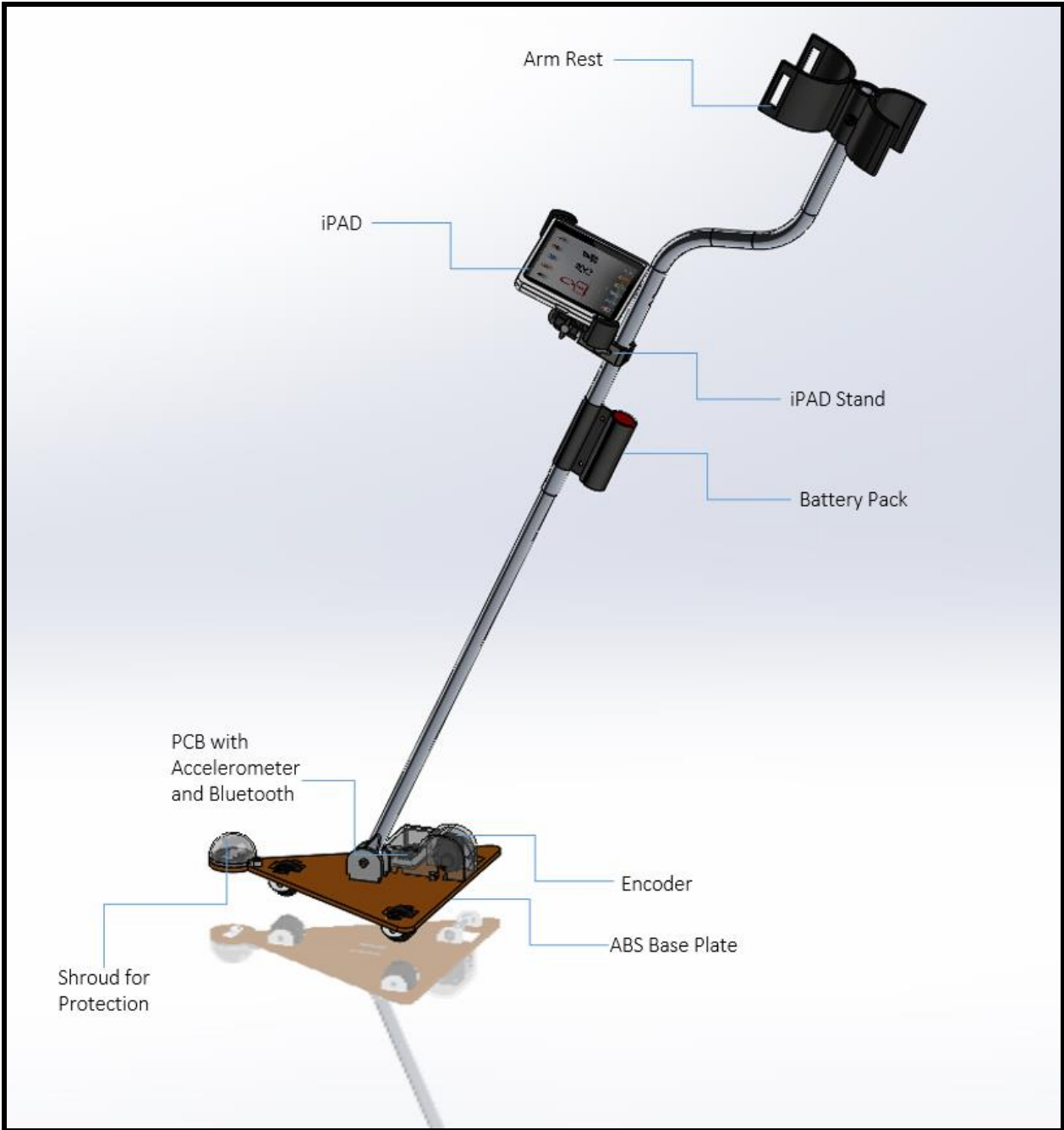
Appendix B: Testing Protocol Tables

Steps	Point Value (0 - 1)	Point Value Given
Log in to the app	0-1	
Connect to Bluetooth	0-1	
Tap plus sign (+) in bottom left hand screen to add a curb-ramp	0-1	
Choose curb-ramp type	0-1	
Zoom out to view full curb-ramp site location	0-1	
Tap curb-ramp location to add curb-ramp measurement	0-1	
Physically move the curb-ramp from normal starting position until bubble level is calibrated (bubble is in the center) and press calibrate	0-1	
Tap a letter to open measurement	0-1	
Choose moving when measuring a grade measurement	0-1	
Choose the correct starting point depending on measurement level (position is indicated on the app screen)	0-1	
Press start to begin the measurement	0-1	
Measure the curb-ramp distance required	0-1	
Locate the correct ending position	0-1	
Press stop to end the measurement	0-1	
Total	15	

Appendix C: REBA Assessment

Appendix C.1: REBA Score Table

Table 1.1: REBA SCORE

	CIS	Manual
Subject #1	3	9
Subject # 2	2	9
Subject #3	3	8

Appendix C.2: REBA Score Scale

Score	Level of MSD Risk
1	Negligible risk, no action required

2-3	Low risk, change may be needed
4-7	Medium risk, further investigation, change soon
8-10	High risk, investigate and implement change
11+	Very high risk implement change
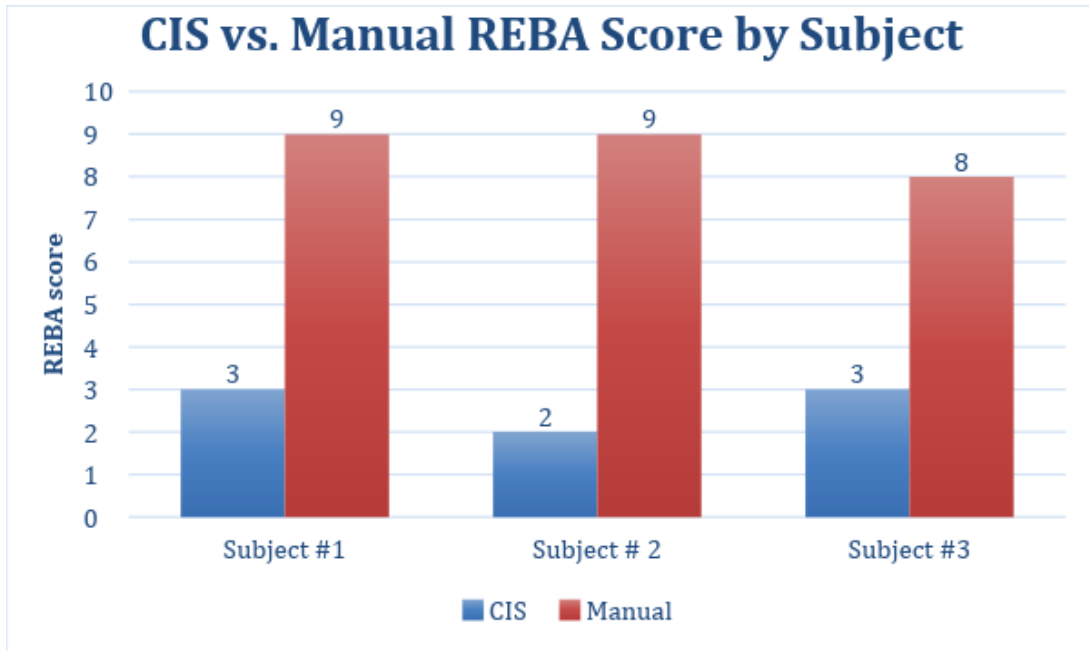
Appendix C.3: REBA Score Graph

Appendix D: Results Tables & Graphs

Appendix D.1: Raw Data Table of Measurements

Table 2.1: Raw Measurement Data of All Ramps for CIS & Manual							
User	Manual/CIS	Meas.	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
Subject 1	CIS	A	42.26	47.61	45.63	42.27	25.41
Subject 1	CIS	A	46.91	48.91	44.67	48.78	48.06
Subject 1	CIS	A	49.13	50.39	48.34	45.68	48.28
Subject 2	CIS	A	47.7	48.58	48.1	45.5	49.93
Subject 2	CIS	A	48.76	48.88	48.34	44.95	47.7
Subject 2	CIS	A	49.55	48.78	46.09	46.21	46.65
Subject 3	CIS	A	34.66	N/A	50.33	49.3	49.39
Subject 3	CIS	A	39.7	43.88	49.4	48.44	48.86
Subject 3	CIS	A	46.31	39.22	46.67	47.65	48.36
Subject 1	CIS	C	4.32	7.27	4.16	8.45	1.56
Subject 1	CIS	C	4.74	7.91	4.25	7.15	2.52
Subject 1	CIS	C	5.13	7.4	4.34	7.52	1.74
Subject 2	CIS	C	4.69	10.1	5.5	7.01	0.85

Subject 2	CIS	C	5.04	9.15	5.71	6.4	0.12
Subject 2	CIS	C	5.53	7.24	3.05	6.94	1.59
Subject 3	CIS	C	2.7	5.97	3.33	6.13	1.88
Subject 3	CIS	C	2.92	N/A	3.54	6.48	1.41
Subject 3	CIS	C	5.41	5.95	3.01	5.17	1.77
Subject 1	CIS	P	48.4	55.13	47.39	54.27	46.29
Subject 1	CIS	P	49.19	53.91	47.12	51.59	46.61
Subject 1	CIS	P	50.52	54.69	48.28	51.07	48.16
Subject 2	CIS	P	48.68	53.28	48.71	54.14	47.06
Subject 2	CIS	P	49.57	52.55	49.34	54.36	47.5
Subject 2	CIS	P	49.9	50.48	48.57	54.94	49.02
Subject 3	CIS	P	27.74	57.11	47.73	54.37	48.75
Subject 3	CIS	P	46.93	55.15	47.3	54.42	48.91
Subject 3	CIS	P	49.01	N/A	46.59	54.2	48.67
Subject 1	CIS	W	0.42	1.18	1.03	1.64	3.61
Subject 1	CIS	W	0.61	1.71	1.43	1.96	2.57
Subject 1	CIS	W	1.53	1.44	1.24	3.24	2.35
Subject 2	CIS	W	1.98	2.13	2.95	0.2	2.47
Subject 2	CIS	W	2.04	0.37	2.8	0.75	2.87

Subject 2	CIS	W	2.25	0.7	2.86	0.17	2.73
Subject 3	CIS	W	0.01	0	2.77	1.5	1.06
Subject 3	CIS	W	2.67	N/A	2.62	1.3	1.14
Subject 3	CIS	W	2.7	0.01	2.7	1.25	1.37
Subject 1	Manual	A	48.00	48.50	48.00	48.00	48.50
Subject 1	Manual	A	48.00	48.50	48.00	48.00	48.50
Subject 1	Manual	A	48.00	47.50	48.00	48.00	48.50
Subject 2	Manual	A	48.88	48.50	47.88	48.25	48.00
Subject 2	Manual	A	49.00	48.50	48.50	48.50	48.00
Subject 2	Manual	A	49.00	48.25	47.88	48.38	48.00
Subject 3	Manual	A	49.00	48.30	48.50	49.00	48.65
Subject 3	Manual	A	50.00	48.00	48.50	48.68	48.75
Subject 3	Manual	A	50.00	48.00	48.75	48.27	48.65
Subject 1	Manual	C	1.40	7.87	4.37	6.12	0.52
Subject 1	Manual	C	1.92	8.40	4.37	5.59	0.87
Subject 1	Manual	C	1.57	7.87	4.54	6.99	0.35
Subject 2	Manual	C	1.40	9.80	5.59	8.22	2.09
Subject 2	Manual	C	2.09	9.98	6.29	8.56	2.62
Subject 2	Manual	C	2.79	9.63	6.29	7.69	2.09

Subject 3	Manual	C	4.37	8.22	3.84	6.82	1.75
Subject 3	Manual	C	5.42	6.47	4.37	7.87	1.57
Subject 3	Manual	C	5.77	8.22	5.42	6.64	2.09
Subject 1	Manual	P	50.00	53.00	48.00	53.31	47.88
Subject 1	Manual	P	50.50	42.50	48.00	53.44	47.88
Subject 1	Manual	P	54.00	52.50	48.00	53.31	48.00
Subject 2	Manual	P	49.25	51.88	48.25	53.56	48.00
Subject 2	Manual	P	50.50	52.50	48.25	53.50	47.88
Subject 2	Manual	P	50.50	53.25	48.25	53.56	47.94
Subject 3	Manual	P	48.00	52.00	48.25	53.60	48.40
Subject 3	Manual	P	48.00	53.50	48.35	53.60	48.45
Subject 3	Manual	P	48.00	54.50	48.60	53.75	48.00
Subject 1	Manual	W	1.22	2.27	1.75	0.87	2.27
Subject 1	Manual	W	1.22	1.92	1.57	0.52	2.44
Subject 1	Manual	W	1.40	2.44	1.57	0.70	2.62
Subject 2	Manual	W	1.22	2.27	0.35	0.52	1.22
Subject 2	Manual	W	1.40	1.75	0.70	0.35	0.52
Subject 2	Manual	W	1.57	2.27	0.52	0.35	0.70
Subject 3	Manual	W	0.17	0.17	1.05	0.35	2.27

Subject 3	Manual	W	0.35	0.00	0.70	0.52	2.27
Subject 3	Manual	W	1.40	0.17	0.70	0.70	0.52

*All cells filled in red are data points that were not recorded and were left out in the data analysis.

Appendix D.2: Averaged Measurements Tables for Each Curb

Table 2.2: Averaged Subjects Data for Curb 1			
	CIS	Manual	PennDOT
A (in)	45.00	48.88	48.00
C (% or deg)	4.50	2.97	4.30
P (% or deg)	46.66	49.86	48.00
W (in)	1.58	1.11	1.60

Table 2.3: Averaged Subjects Data for Curb 2			
	CIS	Manual	PennDOT
A (in)	47.03	48.23	48.00
C (% or deg)	7.62	8.50	7.60
P (% or deg)	54.04	51.74	48.00
W (in)	0.94	1.47	1.30

Table 2.4: Averaged Subjects Data for Curb 4			
	CIS	Manual	PennDOT
A (in)	46.53	48.34	48.00
C (% or deg)	6.81	7.17	8.10
P (% or deg)	53.71	53.51	48.00
W (in)	1.33	0.54	0.4

Table 2.5: Averaged Subjects Data for Curb 3			
	CIS	Manual	PennDOT
A (in)	47.51	48.22	48.00
C (% or deg)	4.10	5.01	4.70
P (% or deg)	47.89	48.22	48.00
W (in)	2.27	0.99	1.30

Table 2.6: Averaged Subjects Data for Curb 5			
	CIS	Manual	PennDOT
A (in)	45.85	48.39	48.00
C (% or deg)	1.49	1.55	1.80
P (% or deg)	47.89	48.05	48.00
W (in)	2.24	1.65	1.60

Appendix D.3: Average Calculations for Curb 1

Average Formula: $\frac{1}{n}\sum_{i=1}^{n} \quad a_i = \frac{1}{n}(a_1 + a_2 + a_3 + \ldots)$

The example provided will be for Curb 1 horizontal distance and grade measurements using the CIS device. Using the data points highlighted in **yellow** in **Appendix D.1: Raw Data of Measurements Table** for CIS device (Ramp 1 Measurement A) the average is calculated:

Measurement A:

$$\frac{1}{n}\sum_{i=1}^{n} \quad a_i = \frac{1}{n}(a_1 + a_2 + a_3 + \ldots)$$

$$= \frac{1}{9}(42.26 + 46.91 + 49.13 + 47.70 + 48.76 + 49.55 + 34.66 + 39.70 + 46.31)$$

$= 45.00$ inches

Using the data points highlighted in **blue** in **Appendix D.1: Raw Data of Measurements Table** for CIS device (Ramp 1 Measurement C) the average is calculated:

Measurement C:

$$\frac{1}{n}\sum_{i=1}^{n} \quad a_i = \frac{1}{n}(a_1 + a_2 + a_3 + \ldots)$$

$$= \frac{1}{9}(4.32 + 4.74 + 5.13 + 4.69 + 5.04 + 5.53 + 2.70 + 2.92 + 5.41)$$

$= 4.50\%$

Using the data points highlighted in **purple** in **Appendix D.1: Raw Data of Measurements**

Table for CIS device (Ramp 1 Measurement P) the average is calculated:
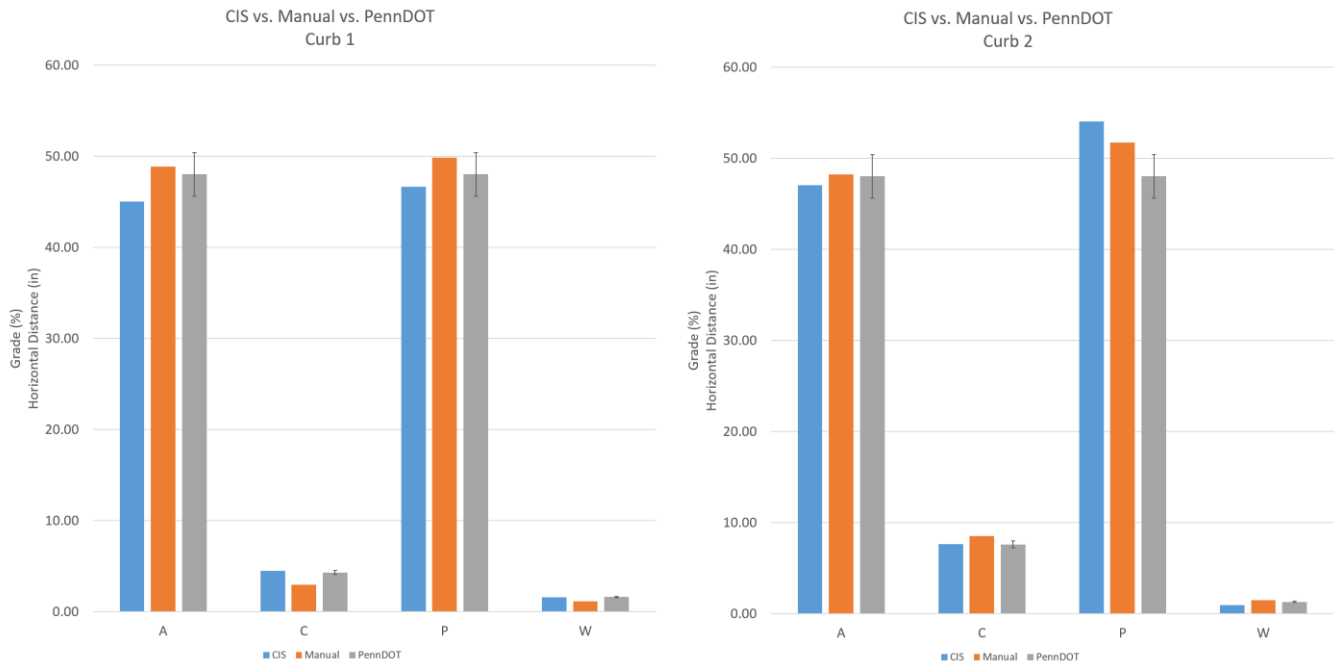
Measurement P:

$$\frac{1}{n}\sum_{i=1}^{n} a_i = \frac{1}{n}(a_1 + a_2 + a_3 + \ldots)$$

$$= \frac{1}{9}(48.40 + 49.19 + 50.52 + 48.68 + 49.57 + 49.90 + 27.74 + 46.93 + 49.01)$$

= 46.66 inches

Using the data points highlighted in **orange** in **Appendix D.1: Raw Data of Measurements Table** for CIS device (Ramp 1 Measurement W) the average is calculated:
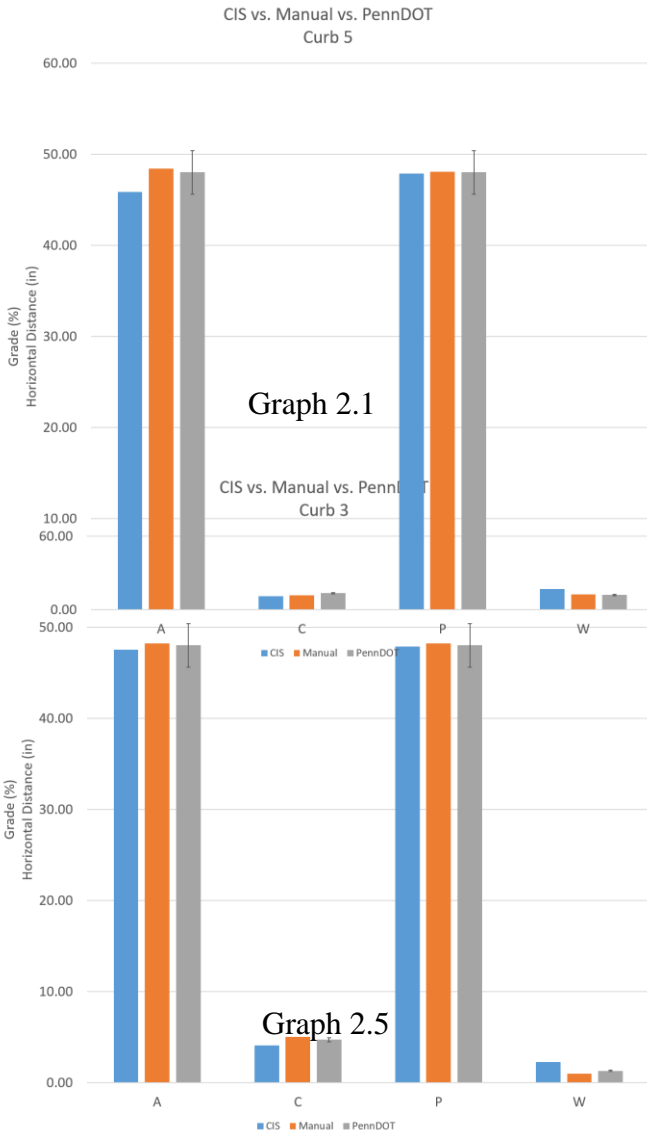
Measurement P:

$$\frac{1}{n}\sum_{i=1}^{n} a_i = \frac{1}{n}(a_1 + a_2 + a_3 + \ldots)$$

$$= \frac{1}{9}(0.42 + 0.61 + 1.53 + 1.98 + 2.04 + 2.25 + 0.01 + 2.67 + 2.70)$$

= 1.58%

Appendix D.4: Averaged Measurements Graphs for Each Curb

Appendix D.4: Averaged Measurements Graphs for Each Curb (continued)

Graph 2.1
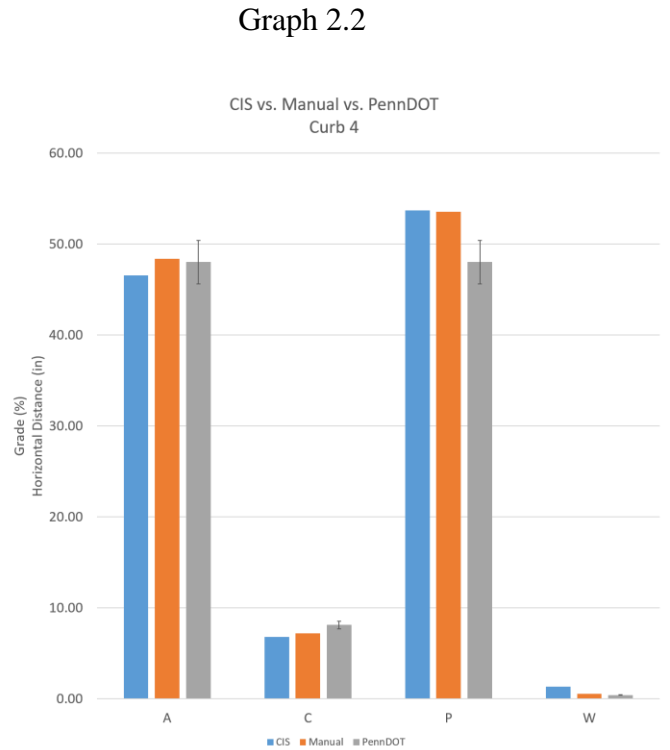
Graph 2.2

Graph 2.5

Graph 2.3

Graph 2.4

Appendix D.5: Averaged Time Measurements Table for Each Curb

During the user trials, one of the team members helped the subject note down the measurements on a document, a job normally done by another contractor. Therefore, the row "x2 Man Hours" counts for the doubled time that it would have taken if there was another subject present recording the manual data.

Table 3.1: Average Time Measurements for Each Ramp in Seconds

	Curb 1	Curb 2	Curb 3	Curb 4	Curb 5
CIS	89.33	64.00	77.25	77.11	70.38
Manual	80.88	69.44	57.33	68.78	54.11
x2 Man Hours	80.88	69.44	57.33	68.78	54.11

Appendix D.6: Averaged Time Measurements Graph for Each Curb
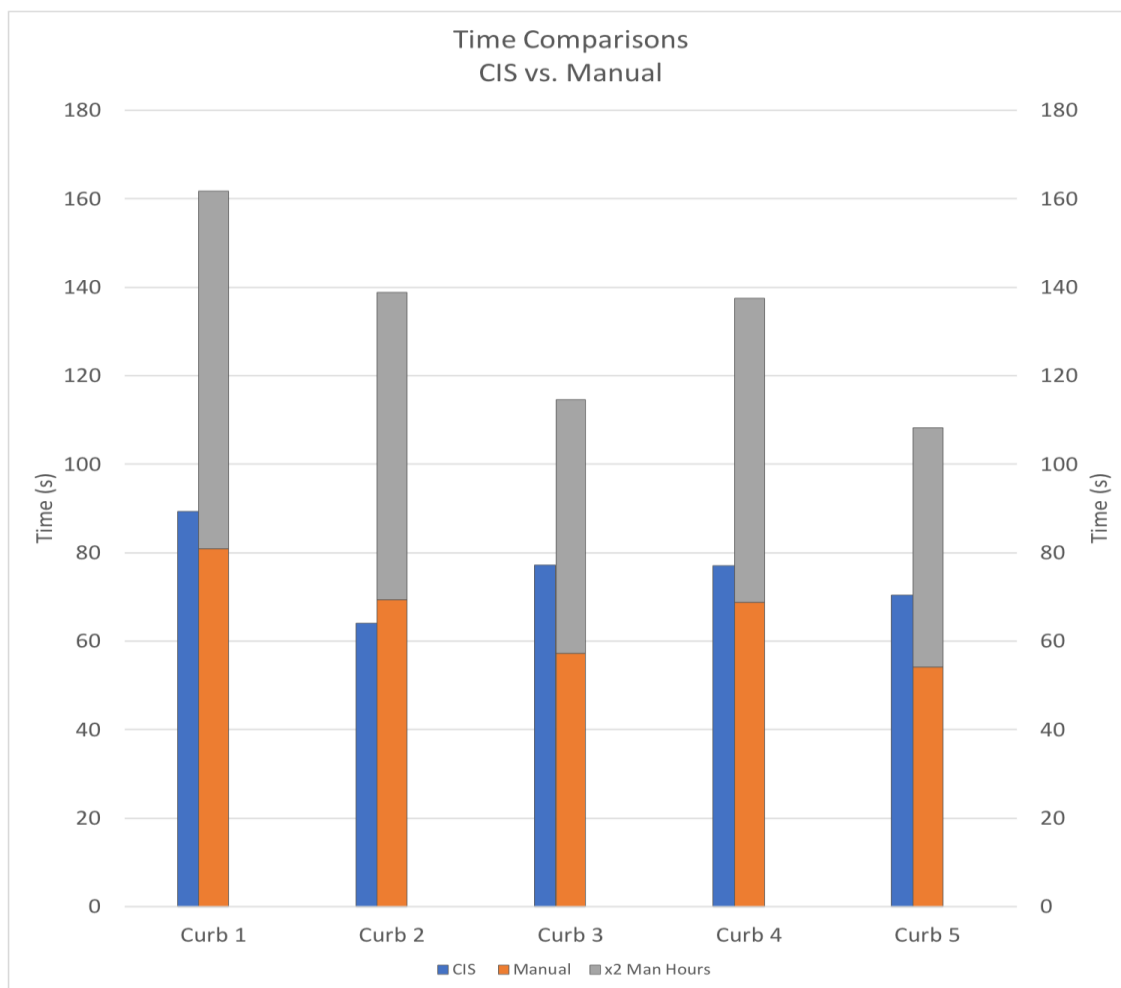
Graph 3.1

Appendix D

Task 4: Modify the CIS Design

Introduction

Deliverable

Design changes that are identified through the validity and reliability testing in Task 3 will be used to identify any final design changes necessary for the final CIS product. Few design changes are anticipated, though there may be usability or performance challenges that are identified after repeated testing by data collectors. Design drawings and the device will be modified to address those usability or performance challenges, and a fully operational CIS inspection tool with user manual will be delivered to PennDOT. A report describing the design modifications, a final set of design drawings, and a fully operational updated prototype of the CIS inspection tool with user manual.

Executive Summary

Mechanical

Focus group feedback guided mechanical design changes would make the CIS a more user-friendly and accurate tool. A complete set of drawings that reflect these changes are included in Appendix A. Focus group participants expressed concern with the sturdiness of the base, durability of the battery holder, a need for a shroud to protect the electronics, and a need to improve traction of the wheels to reduce the likelihood of slipping. Based on this feedback, we made the following changes:

1) To increase the sturdiness of the base, the base design which was previously a single layer of ABS plastic was changed to two pieces of 3/16" ABS with ⅛" high density fiberboard (HDF) placed in between. HDF, also known as hardboard, is primarily used for heavy duty construction work and provides stability for a long period of time. The layered base plate approach decreases the chances of breakage and increases stability during measurement.
2) To increase the durability of the battery holder, a silicone strap has been attached to the handle for easy removal and placement of the battery.
3) To prevent water or structural damage to the electronics on the CIS, a plastic shroud was created which can be easily removed or installed with bolts. The extruded tabs with hexagonal cuts allow for easy removal and avoid external items interfering with the device. Furthermore, a new angle bracket was created for the purpose of attaching the encoder to the base plate securely. The tabs inserted into the base plate have been increased by width and length to ensure stability. Lastly, a brand-new addition to the CIS is the timing belt system, which contains two gears with a timing belt to increase mechanical efficiency. The larger gear is attached to the encoder for measurement

of horizontal distances. Timing belts are known to have a longer lifetime and prevent easy breakage.

4) To address concern with the accuracy of measurement as a result of low contact of wheels to the ground. The wheel material was changed to rubber to increase traction with the pavement.

Software & Process

Task 6 interviews, as well as direct user testing, revealed a few key areas that the software usability could be improved. These improvements center around the need to calibrate the angle sensor, as well as the usability in direct sunlight. Based on this feedback, we made the following changes:

1) The previous calibration procedure required users to re-calibrate the accelerometer each time before performing a new grade measurement, setting a new zero point each time. Test users expressed frustration with the frequency and difficulty of calibration, especially because it was performed using a bubble level at the base of the device. In addition, interviewees from Task 6 expressed concerns that this calibration procedure may introduce more error into measurements, especially in mountainous areas where it may be difficult to find a level surface in the field to use for calibration. As a result, sensor calibration is now optional before each measurement if a user wishes to set a new zero baseline. The CIS device will be calibrated one time after it is built, and this percent grade calibration will be benchmarked against a NIST traceable digital level.

2) To address the concerns about user interface visibility in direct sunlight, mobile computing personnel at PennDOT were contacted to advise about how they solve this issue with existing mobile applications in the field. This outreach revealed that no solution exists for this problem at PennDOT other than avoiding direct sunlight. To help alleviate this issue, user interface elements were emboldened, and an anti-glare screen cover was applied to the tablet computer. Users may also wish to enable accessibility features on the iPad, such as increased contrast or color inversion if they feel that these features help increase visibility. The usefulness of these accessibility features was found to be subjective and overall not entirely effective. These changes helped marginally, but the most effective solution is still to avoid direct sunlight if possible.

1.0 User's Manual General Information

1.1 System Overview

The Curb Inspection System (CIS) is a device to quickly and efficiently evaluate curb-ramps for American Disabilities Act (ADA) standards. Initially a manual procedure, the device evaluates all measurements on the CS-4401 form and transfers that data using ARCGIS, a geographic information interface designed to keep track of the location of the ramps. An iOS app was developed to create a friendly user interface (Refer to Getting Started for more information).

1.2 Organization of the Manual

1.0 General Information: This section explains the basis of the device including its purpose, user background and its general features.

2.0 System Summary: This section provides a general overview of the system written in non-technical terminology. The summary should outline the uses of the system in supporting the activities of the user and staff.

3.0 Getting Started: This section provides a general walkthrough of the system from initiation through exit. The logical arrangement of the information shall enable the functional personnel to understand the sequence and flow of the system. Use screen prints to depict examples of text under each heading.

4.0 Using the System: This section provides a detailed description of the online system from initiation through exit, explaining in detail the characteristics of the required input and system-produced output.

5.0 Reporting: This section describes and depicts all standard reports that can be generated by the system or internal to the user.
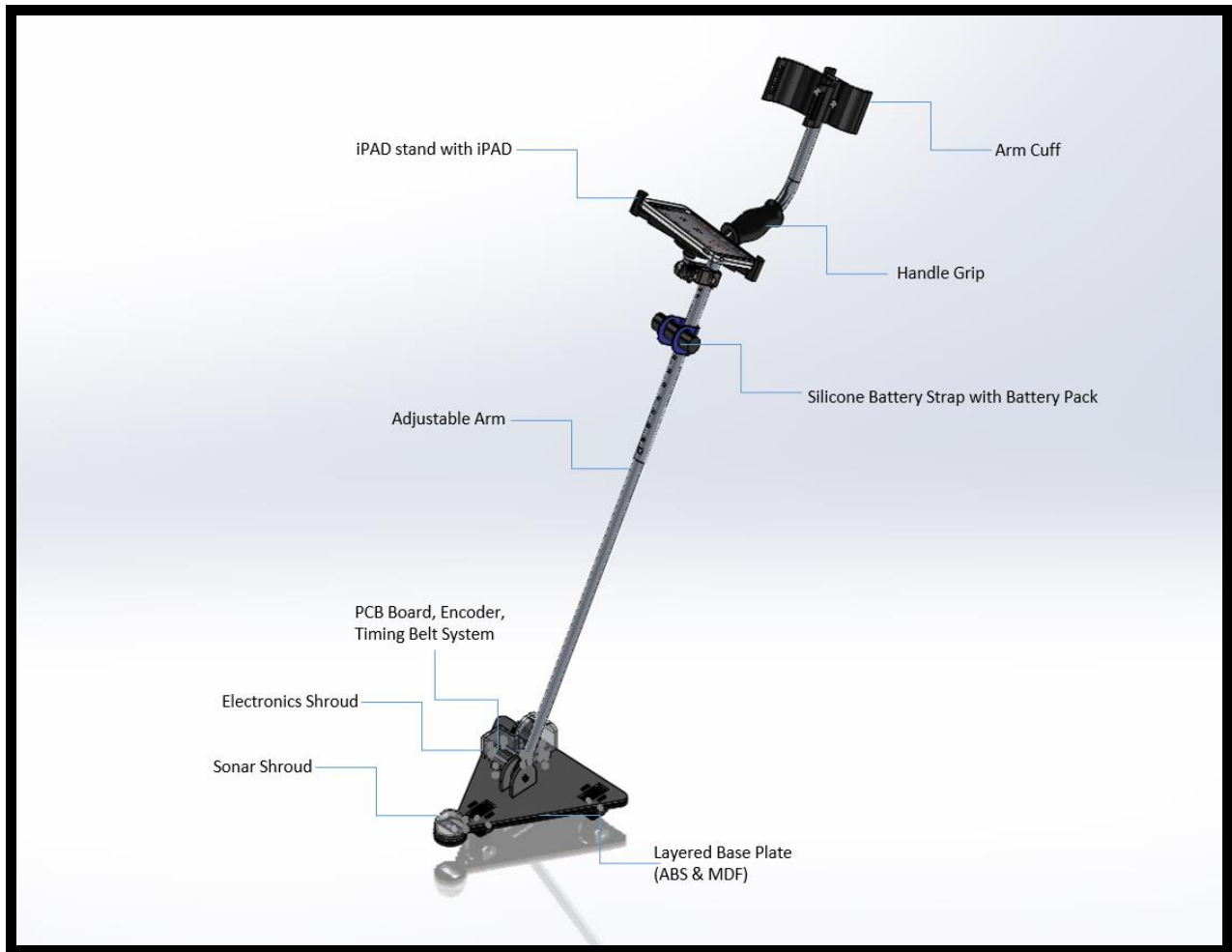
1.3 Acronyms and Abbreviations
- CIS: Curb Inspection System
- ADA: American Disabilities Act
- ArcGIS: Arc Geographic Information System

2.0 System Summary

2.1 System Configuration

System components are shown in the figure below.

2.2 Data Flows
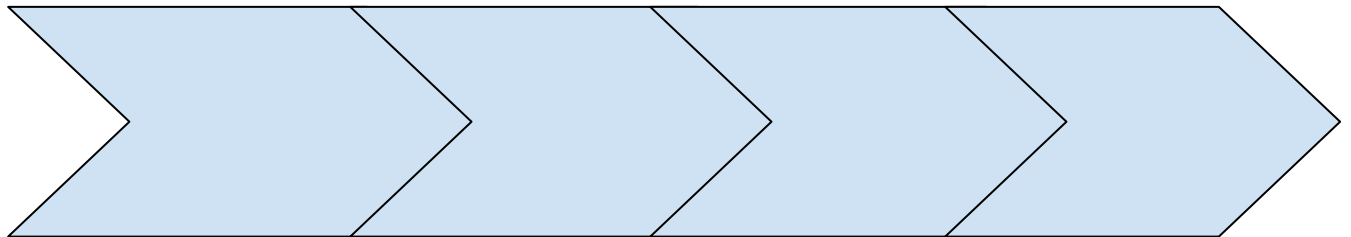
First, a user selects the curb ramp dimension that they wish to measure. Then, the user has the option to calibrate the sensors or to skip this process and start measuring. The user then measures the dimension, whether that be a distance or percent grade measurement. After measurement is complete, compliance with ADA regulations is indicated by the color of the measurement number. The measurement may be redone, or the user may move on to the next measurement. After measurement, the data is entered into an online ArcGIS database. This data may later be exported into CSV format to be analyzed in Excel. In the future, export into CS4401 format may be implemented.

3.0 Getting Started

Before using the device, the user must download the app, login, connect to Bluetooth, and calibrate the CIS device. In addition, the user must make sure all wires are connected, including the wires running from the electronics board to the encoder and battery pack. The following section will discuss each menu function in the application.

3.1 Logging On

The following images will show a step-by-step guide explaining how to use the app with the CIS device. Once the app has been downloaded and opened, a login screen will appear captured below.
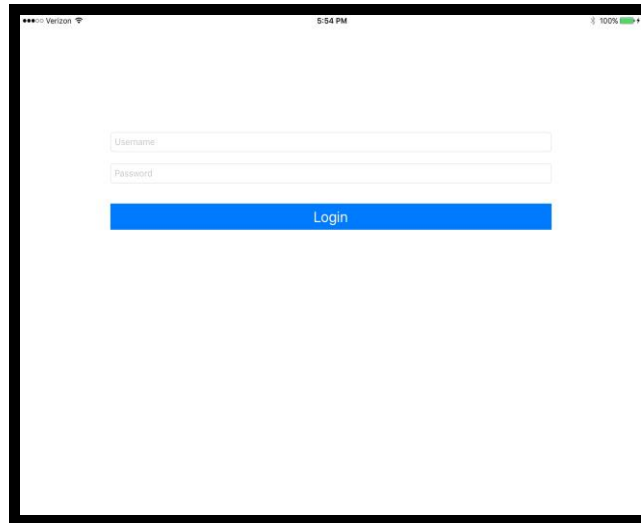
Once at this screen, the user should enter credentials and select **Login**.

3.2 Connecting to Bluetooth

After the user logs into the app, they will be redirected to this page to connect to Bluetooth. Click

on the available device to connect. If no devices show up, please do the following:
- Go to **Settings** on your phone
- Go to **Bluetooth**
- Make sure your **Bluetooth** is turned **ON**

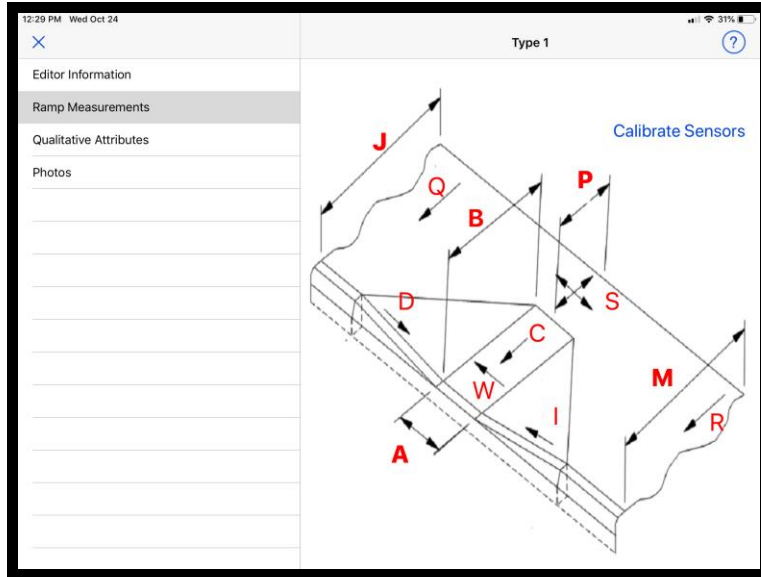If the user is unable to find a Bluetooth connection, try restarting the device.

3.3 System Menu

The following functions listed below will be explained in further detail on what it is used for. Please refer to the PennDOT CS-4401 form while going through the system menu.

3.3.1. Editor Information

The editor information menu contains text boxes similar to the CS-4401 form to help the user identify the ramp being measured. Boxes with "required field" or and "*" are mandatory.

Inputted information includes:
- Field Investigator(s) Name(s)
- County Name & Code
- Municipality Name & Code
- Engineering District Code

3.3.2. Ramp Measurements

Device calibration will be explained further in 4.0 Using the System section. This tab is used to take all measurements of the ramp which will be further explained on 4.1 How to Take a Measurement.

3.3.3. Qualitative Attributes

This tab includes additional questions found on the CS-4401 form. To save the information, click the correct choice.

3.3.4. Photos

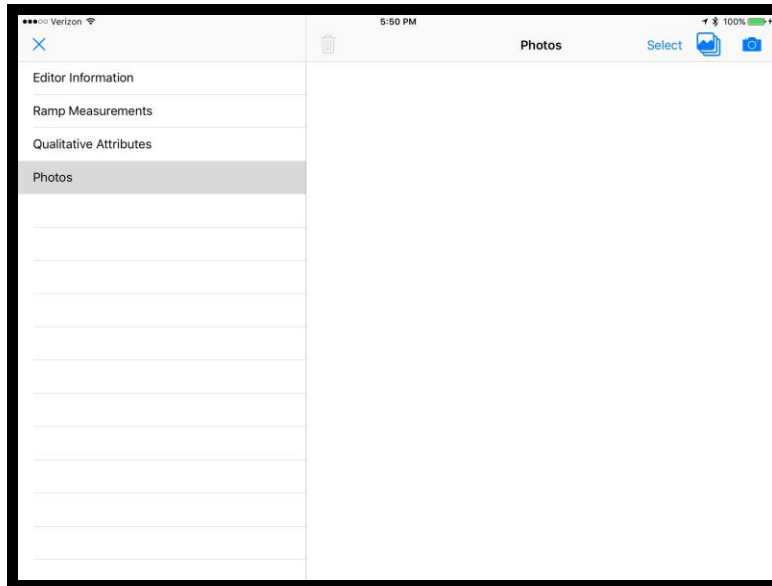The user is able to take picture of the curb-ramp using the iPad. The pictures can be uploaded onto the app for further use and easier identification.

3.4 Exit System

To exit the current data entry, click the "X" in the top left corner. Clicking "X" will redirect back to the map. Select the home button to exit the application.

4.0 Using the System

Please refer to the training video to follow along on how to use the CIS device. If unfamiliar with any of the menu functions, please refer to 3.3 System Menu.

4.1 How to Take A Measurement

In order to add a ramp, the user must click on the "+" button located on the bottom left hand corner. Current location is indicated by a blue dot.
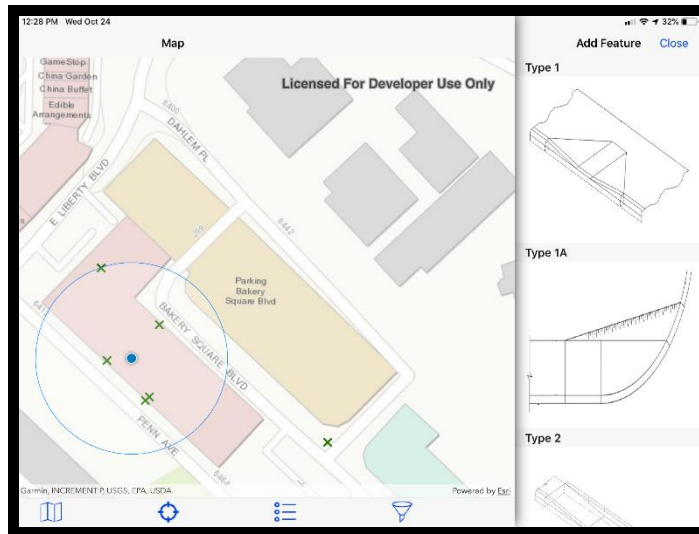
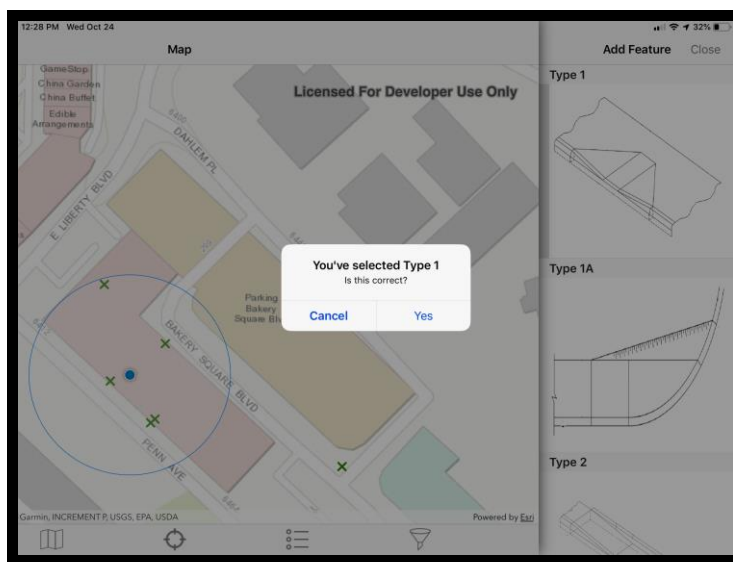A side bar will pop up with a list curb ramp types. Scroll up to see the list of all available curb ramps. To select a desired curb ramp type, click the picture.

Confirm your selection is correct by tapping yes on the pop-up message. Then tap the desired location of the ramp on the map for measurements. The user will be directed to the Editor Information tab. The User will input all necessary information and click on Ramp Measurements. Please follow the directions below to calibrate the system before usage.

4.1.1 How to Calibrate the CIS

Please refer to training video for additional information on calibration. Place the CIS device on a flat surface and make sure the bubble in the level located on the device is centered. Once satisfied with the level placement, press the **"Calibrate Sensors"** button located on the **"Ramp Measurements"** tap of the system menu. To redo the calibration, press the "Calibrate Sensors" button again.
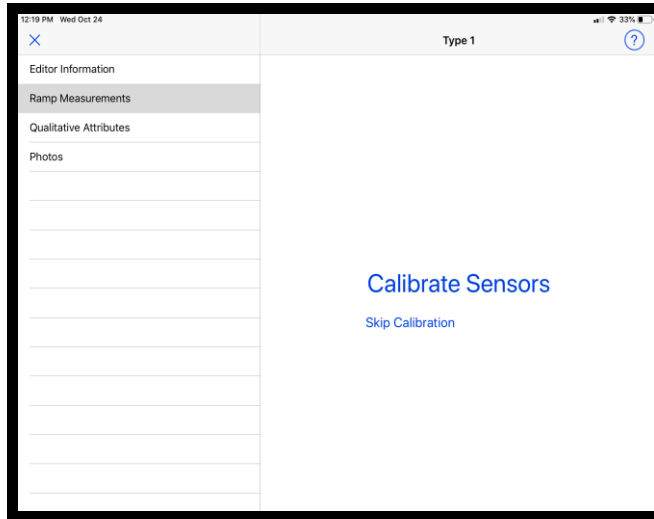
After calibration, stay on the Ramp Measurement tab to begin measurements.
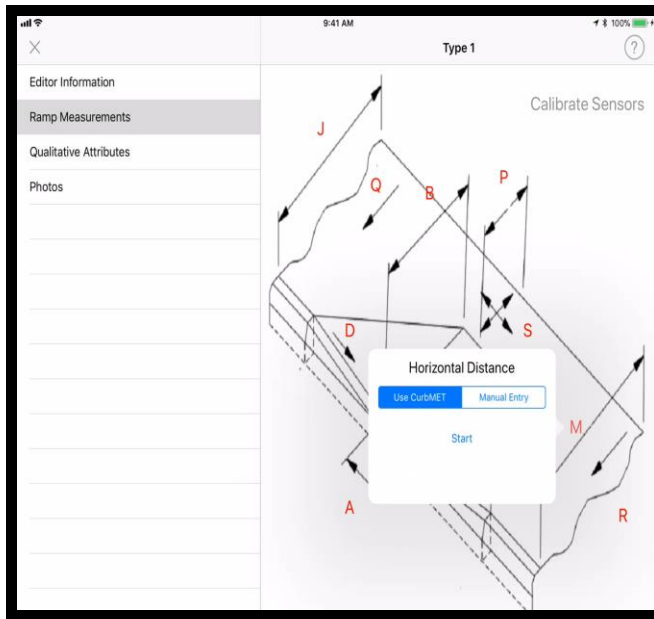
Select a curb ramp measurement letter. As shown above, the horizontal distance, measurement M, has been selected. Manually enter the curb ramp measurement or use the CIS device to obtain the measurement. Place the back wheels of the CIS device on the starting point, click start, and slowly push the device in a straight line to the other side till the front wheel reaches the end point, then press the stop button. If the measurement is unsatisfactory, the user may measure again. Otherwise, the application will tell the user whether the measurement is compliant with ADA regulations.
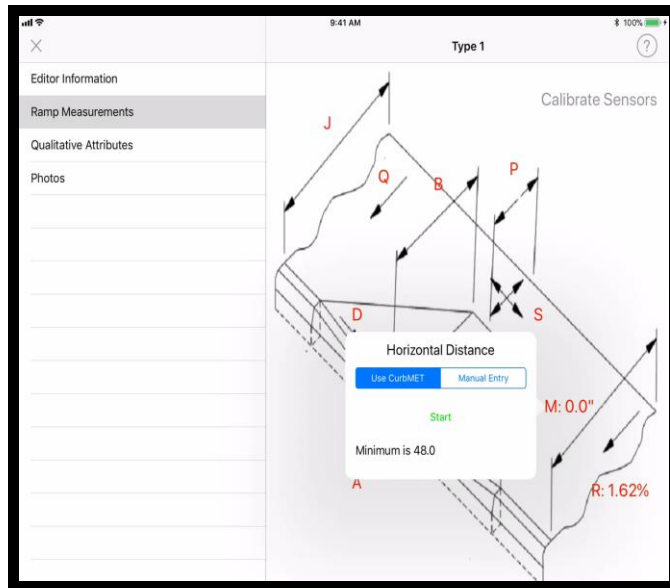
Measurements that have not been taken or are not compliant with be in red. Measurements that meet RC-67M will be automatically shown in blue.

4.1.2 Editing A Curb Ramp

To edit a pre-existing curb-ramp the user will click the "X" in the top left-hand corner which redirects them to the map. All pre-existing curb ramps have a blue "+" sign on the map.
Tap the ramp that needs to be modified and hit the "i" in the popup which will redirect the user to the system menu functions.
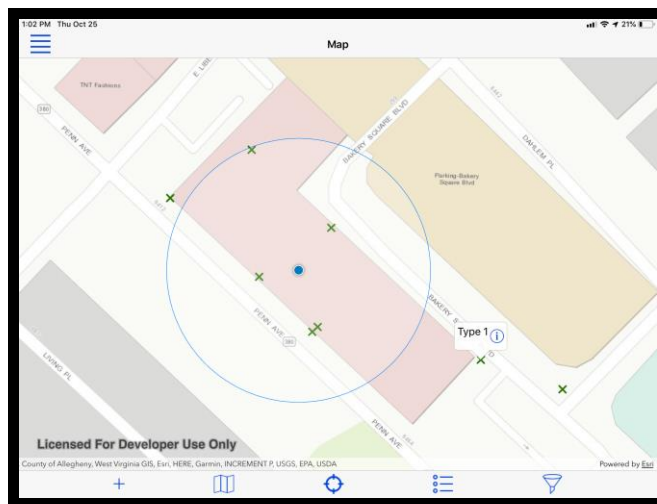
4.2 Caveats and Exceptions

To ensure the user is able to retrieve the data after measurements have been taken they must do the following:
  ● Data must be uploaded and retrieved in presence of wi-fi or cellular data

- Make sure all information inputted in Editor Information and Qualitative Attributes is correct

5.0 Reporting

This section describes and depicts all standard reports that can be generated by the system or internal to the user.

5.1 Report Capabilities

Users have the capability to convert the measured data into excel documents for further analyzing. All data taken or inputted by the user is represented on the excel sheet and is capable of modifying.

Appendix

Appendix A: Design Drawings PDF

Appendix B: Unchanged Circuit and Software Design

CIRCUIT DESIGN AND FUNCTIONALITY

Circuit Overview

General Features

The CIS hardware consists of an HM-11 Bluetooth module, LIS3LV02DLTR accelerometer, Arduino Nano microcontroller S5 optical encoder and HC-SR04 Sonar distance sensor (Figure 4a). The user controls the circuit by touching icons on the iPad app (see section *App Developer Guide* for further details). The app transmits the information to a microcontroller via Bluetooth. The Arduino then directs the appropriate sensor to take a measurement, which the Arduino processes and returns to the app via Bluetooth. The Arduino, Bluetooth module and accelerometer are soldered directly to a single PCB board (Figure 4b). The sonar and encoder are located elsewhere on the base plate and connect to the Arduino via wires which insert into two 4-pin headers soldered to the PCB board.

Power Supply

The power source of the circuit is stored in a Mophie Space Pack - a protective case surrounding the iPad mini which contains a built-in 5V 8,000 mAh battery, which can charge the iPad while simultaneously powering the rest of the circuit via a USB running from the battery down the CIS handle and into the Arduino (B&H, "Mophie Space Pack with External Battery & 32GB Storage for iPad mini (Black)"). The CIS has a battery life of at least 10.8 hours of continuous use.

Figure 4a (top): Schematic of CIS circuit. **Figure 4b (bottom):** PCB board (encircled in red) is attached to CIS base plate. Arduino unit is visible on top of base plate. Hex standoffs are placed between the PCB and base plate to prevent the board from resting on the pins of electronic components, which could otherwise damage the pins.

Arduino Nano Microcontroller

The circuit is controlled by an Arduino Nano, which activates and deactivates sensors, records their readings, performs noise filtering, accepts commands sent from the iPad via Bluetooth and returns data to be displayed. When the user decides to begin taking a measurement, the user touches an icon on the app, which causes the iPad to send a string to the Arduino indicating which sensor needs to be activated, thus causing the Arduino to begin reading from the appropriate sensor. When the measurement is complete, the user touches a different icon, causing the iPad to send a string indicating the end of the measurement, thus causing the Arduino to stop reading from the sensor and send the average of the measurement samples back to the iPad via Bluetooth.

The Arduino also serves as a power source for the sensors. The Arduino is powered from the space pack through its USB port, and powers the rest of the circuit through its 5V and 3.3V

power pins.

Approximate Rolling Average

Filtering of the sonar and accelerometer measurements is done using an approximate rolling average (also known as a modified moving average). Equation 1 displays the rolling average after i samples $\underline{s}_i$:

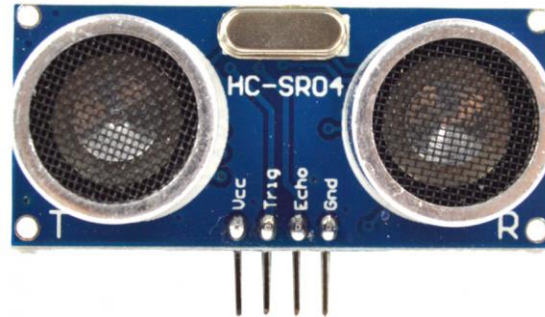$$\underline{s}_i = ((i - 1) \times \underline{s}_{i-1} + s_i)/i \tag{1}$$

Where $\underline{s}_{i-1}$ is the previous average value and s_i is the newest sample. This calculation is preferable to a simple moving average (where the average of some number of the most recent previous values is taken) for two reasons. The first benefit is that a simple moving average requires the storage of a number of previous values, while an approximate rolling average stores only the previous value of the rolling average $\underline{s}_{i-1}$ and the number of samples taken i. This reduces the required memory and reduces the likelihood of integer overflow errors that can occur when taking the sum of a large number of values. The second benefit is that the user does not need to wait for any set period of time to take a certain number of samples. A simple moving average requires a set number of samples to be taken, and if measurement stops before this number of samples is taken, the remaining samples will default to 0, causing the calculated average to be erroneously small. The approximate moving average will return a reasonable value after even a single sample (although it is still preferable to take more), thus avoiding errors due to stopping measurement after an insufficient period of time.

HM-11 Bluetooth Module

The HM-11 Bluetooth module is used for Bluetooth 4.0 communication between the Arduino and the iPad. The HM-11 advertises a connection, which the iPad app discovers and connects to when the app starts up. Bluetooth data is relayed to and from the Arduino via serial communication (see section *Software Design - Bluetooth Connection* for further details).

Sensors

Sonar Distance Sensor

Figure 5: HC-SR04 ultrasonic ranging module used for measuring vertical distances
(RobotShop, "HC-SR04 Ultrasonic Range Finder").

Vertical distances are measured using an HC-SR04 Ultrasonic Ranging Module (Figure 5). The HC-SR04 uses sonar to measure the distance from itself to the nearest solid surface in front of it. The sensor has a range of 2 - 400 cm and an accuracy of 3 mm (ELECFreaks, "Ultrasonic Ranging Module HC - SR04"). Applying a pulse of high (5V) voltage to the 'Trig' pin activates the sensor to emit a burst of ultrasound, and the 'Echo' pin becomes set to high voltage. Once the burst of ultrasound bounces off the nearest surface and returns to the sensor, the 'Echo' pin returns to low (0V) voltage. The Arduino detects whether the 'Echo' pin is high or low and records the time t for pin to return to low voltage. Distance d is determined using equation 2:

$$d = t \times v/2$$

(2)

Where v is the speed of sound in dry air at room temperature. $t \times v$ returns the total distance traveled by the ultrasonic pulse, which is then divided by two to account for the fact that the pulse travels the same distance twice (once traveling from the sensor to the surface, then again when returning to the sensor).

The sonar is mounted at the front of the CIS base plate (Figure 6a). To take a measurement of vertical distance (such as the height of a curb), the user places the base plate on the higher of two surfaces such that the sonar is directly above the higher surface, then touches an icon on the app, which directs the sonar to measure the distance from the sonar to the higher surface (Figure 6b). After, the user moves the base plate such that the base plate is still resting on the higher surface,

but the sonar is directly above the lower of the two surfaces (Figure 6c). The user then touches an icon which directs the sonar to measure the distance between itself and the lower surface. The height will be equal to the difference between the two measurements.

Figure 6a (top): Sonar (encircled in red) is mounted at the front of the base plate. **Figure 6b (bottom left):** First, the distance between the sonar and the higher surface is measured while the CIS is resting on the higher surface. **Figure 6c (bottom left):** After the first measurement, the CIS is moved so that the sonar is above the lower surface and the distance between the sonar and the lower surface is measured. The height of the curb is equal to the difference between the two measurements.

Accelerometer

Grade will be measured using a LIS3LV02DLTR accelerometer. The LIS3LV02DLTR has a resolution of .001 g (ST, "MEMS inertial sensor"), which will allow for grade measurements with an average accuracy within 0.1 degrees when used to measure angles under 5.0 degrees (although the exact accuracy will be dependent on the angle). The accelerometer will continuously measure and transmit the acceleration in the x, y and z direction to the Arduino as 16-bit binary numbers representing accelerations between 2.0 and -2.0 g. When the accelerometer is stationary, these measurements will indicate the components of the force of gravity in the x, y and z directions (x, y and z, respectively), which can be used to measure the angle A in degrees according to equation 3:

$$A = C * tan^{-1}(\sqrt{x^2 + y^2}/z) \qquad (3)$$

Where tan^{-1} is the inverse tangent, and *C* is an experimentally determined constant used to calibrate the accelerometer. The angle is next converted from degrees to percent grade *PG* using equation 4:

$$PG = 100 \times tan^{-1}(A)$$ (4)

Where $tan^{-1}()$ is the inverse tangent.

The accelerometer is soldered to the PCB board, which is attached to the CIS base plate. To measure grade, the CIS is placed on the surface, and an icon on the app is touched which causes the CIS to continuously take angle measurements until the user touches a different icon, which causes the CIS to stop taking angle measurements, and display the approximate rolling average of the angle measurements (see section *Circuit Design and Functionality - Approximate Rolling Average* for a description of the approximate rolling average).

Encoder

Horizontal distances such as the length of a curb are measured using the S5 Optical Shaft Encoder (specifically the S5-360-250-NE-S-B model). The A and B pins of the encoder switch between high (5V) and low (0V) voltage as the encoder shaft rotates. Each pin can switch from high to low and back (clicks) 360 times per full revolution of the encoder shaft (US Digital, "S5 Optical Shaft Encoder"), giving the CIS a resolution of .05 in (see section *Mechanical Design and Functionality - Encoder Gears* for further details). The switch from high to low voltage between the two channels is slightly offset (90 degrees out of phase), so that whether channel A leads B or B leads A can be used to determine whether the shaft is rotating in a clockwise or counter-clockwise motion.

To make horizontal measurements, the user touches an icon on the app which causes the CIS to begin counting encoder clicks. When the user touches another button, the Arduino uses the total encoder clicks to calculate the distance traveled.

SOFTWARE DESIGN

ArcGIS

Introduction

This section describes the steps taken to design and publish a custom hosted feature service that stores curb ramp data. By interacting with a map representation of these data, users with the correct permissions can view features, edit attributes, and add attachments to the cloud dataset through ArcMAP for Desktop, ArcGIS online, or the CurbMET App. Feature and layer design was based on the June 2017 version of PennDOT's CS-4401 Curb Ramp Inspection form.

Brief explanations of GIS-specific terminology are given to orient a general audience; however, for those seeking a deeper understanding of the concepts introduced, ESRI publishes free online guides and tutorials for all of the software mentioned in this section.

ArcMAP

ArcMAP 10.4.1 for Desktop with an advanced license was used to generate the framework for the hosted feature service that the CurbMET app accesses and updates. A curb ramp feature class was designed based on the June 2017 version of PennDOT's CS-4401 Curb Ramp Inspection Form. The feature class served as a template for subclasses that are separated by curb ramp type (Type 1, Type 2, etc.). Feature layers were created from the subclasses and added to a map, which was published to ArcGIS Online as a hosted feature service. This section presents descriptions of the elements listed above and the steps taken to connect them together.

Curb Ramp Feature Class

"Feature classes are homogeneous collections of common features, each having the same spatial representation, such as points, lines, or polygons, and a common set of attribute columns, for example, a line feature class for representing road centerlines."

The curb ramp feature class contains all possible fields that a curb ramp could have. Subclasses were created for each curb ramp type and added to a geodatabase.

Domains

Domains were used to limit the number of valid values for attributes, and correspond with drop-down menus on the CS-4401.

Fields

Each feature has a set of non-spatial information called attributes linked to it (Esri, "Attribute | Definition"). The feature class fields define the set of attributes associated with the curb ramp.

Feature Layers

"A feature layer is a grouping of similar geographic features, for example, buildings, parcels, cities, roads, and earthquake epicenters. Features can be points, lines, or polygons (areas). Feature layers are most appropriate for visualizing data on top of your basemaps. You can set properties for feature layers—such as style, transparency, visible range, refresh interval, and labels—that control how the layer appears in the map. Using a feature layer, you can view, edit, analyze, and execute queries against features and their attributes (Esri, "Feature Layers")."

To aid querying and display, feature layers are separated by type. The following feature layers were created for CurbMET - Type 1, Type 1A, Type 2, Type 4, Type 4A, Type 5, Type 6, Blended Transition, Type A Median, Type B Median, and Other. All feature layers have the same fields except for numbered dimensions (A, B, C, etc.). Only the required numbered dimensions for the ramp type are available for each layer.

In addition, all layers have two sublayers - Complete and Incomplete. Features in the incomplete layers do not have all required fields filled and are displayed with a colored "X" symbol. On the other hand, "complete" features do not have any blank required fields and are displayed with a colored circle symbol. The color is determined by the parent layer. Features are automatically added to these sub-layers based on their "All Required Fields Filled" attribute.

CurbMET Map

Although each of the components listed above - feature classes and layers - are saved in separate files, they are brought together in the CurbMET Map.mxd file, an ArcGIS ArcMAP document. Layers from the catalog are added to the map. From here, features can be added to a layer in the map if desired; they will be saved in the layer's attribute table. Feature layers can also be queried using the "Select Layer by Attribute" Tool. For more information on the query tool, see http://pro.arcgis.com/en/pro-app/tool-reference/data-management/select-layer-by-attribute.htm.

After logging into an ArcGIS account with publishing permissions, the map was published as a service named "Curbmet_Map" to ArcGIS Online. It has 100000 maximum records. Feature access is enabled with a REST URL; cCreate, delete, query, sync, and update operations are enabled.

ArcGIS Online

A web map named "CurbMET_Map" was created on ArcGIS Online, and the published feature service was added to it. The map's service url is used to access it through an ArcGIS Portal Item within the app.

App Developer Guide

Introduction

This section is a developer's guide for those who seek to understand or modify the structure of the CurbMET iOS app source code. To accomplish this goal, lists of dependencies, class diagrams, user experience flow charts, and an appendix of all app views are included.

A basic knowledge of Apple's XCode integrated development environment (IDE) and Swift programming language is assumed.

Dependencies and 3rd Party Acknowledgements

App Build Information

Deployment Target: iOS 10.0
Base SDK: Latest iOS (iOS 11.1)
Devices: Universal (iPhone and iPad)
Swift Language Version: Swift 3.2

Apple Libraries and Frameworks

Name	Version	Documentation	Application in CurbMET App
Core Bluetooth	Swift 3.1	Apple Developer Documentation	The Core Bluetooth framework provides the classes needed for your apps to communicate Bluetooth low energy devices, which the CurbMET CIS uses to facilitate communication between the measuring device and the iOS app.
UIKit	Swift 3.1	Apple Developer Documentation	Paraphrased from Apple's Developer Documentation ● Window and view architecture (view controllers, labels, table views, etc.) ● Event handling infrastructure for delivering Multitouch and other types of input to your app ● "Main run loop needed to manage interactions among the user, the system, and the app."
Foundation	Swift 3.1	Apple Developer	"Access essential data types, collections, and

		Documentation	operating-system services to define the base layer of functionality for your app."

CocoaPods and 3rd Party Libraries

Using Cocoapods

"CocoaPods is a dependency manager for Swift and Objective-C Cocoa projects. It has over 40 thousand libraries and is used in over 2.9 million apps (CocoaPods Dev Team, *CocoaPods.org*)." Pods are added to the XCode project by creating a editing the project's Podfile. Detailed instructions for installing pods can be viewed on the Cocoapods website. Pods can only be referenced when working from the <Project Name>.xcodeworkspace file.

Cocoapods works by creating or updating a workspace and adding the Cocoapods static library project to the workspace if needed. Next, it adds libPods.a and an Xcode configuration file to the project. Once the app's target configurations are changed to be based on CocoaPods's, a build phase is added to copy resources from your pods to the app bundle (CocoaPods Dev Team, "Adding Pods to an Xcode Project").

Pods Used in CurbMET

Note: Although some libraries are written in Objective-C, all can be easily used in Swift.

Name	Language	Version	Documentation	Application in CurbMET App
ArcGIS	Swift	100.1.1	ArcGIS Runtime SDK for iOS	Provides viewing and editing access to the CurbMET ArcGIS hosted feature service. Provides login API for ArcGIS online accounts.
SVProgressHUD	Objective-C	2.2.2	GitHub Page	Displays progress, error and success messages.
RxSwift	Swift	3.0	RxSwift Cocoapods Page	Provides fundamental functional reactive programming classes, such as observables.
RxCocoa	Swift	3.0	RxCocoa Cocoapods Page	Extends Apple's Cocoa and CocoaTouch frameworks to take advantage of RxSwift.
MMDrawerController	Swift	0.6.0	Github Page	Easily create and interact with side menus.

Eureka	Swift 3	3.1.0	Github Page	Create dynamic forms, which are used to populate content in settings page and some side menus.

Third Party Images and Icons

Ramp images were copied from PennDOT's CS-4401 form.
All other images not listed in the table below were created by Zoe Toigo.

Name	Source	Filename in App
Bluetooth icon	Made by Minh Hoang from www.flaticon.com	Bluetooth.png
Legend icon	Made by Pavel Kozlov from www.flaticon.com	legend.png
Menu icon	Made by Smashicons from www.flaticon.com	menu.png
Edit icon	Made by Smashicons from www.flaticon.com	edit.png
Filter icon	Made by Smashicons from www.flaticon.com	filter.png
Map icon	Made by Iconnice from www.flaticon.com	map.png
Photo album icon	Made by Smartline from www.flaticon.com	photoAlbum.png
Re-center crosshair icon	Made by Freepik from www.flaticon.com	crosshair.png
Question icon	Made by Linh Pham from www.flaticon.com	question.png

App Architecture

Theoretical Introduction

"Software architecture encompasses the set of significant decisions about the organization of a software system including the selection of the structural elements and their interfaces by which the system is composed; behavior as specified in collaboration among those elements; composition of these structural and behavioral elements into larger subsystems; and an architectural style that guides this organization. Software architecture also involves functionality, usability, resilience, performance, reuse, comprehensibility, economic and technology constraints, tradeoffs and aesthetic concerns (Shaw and Garlan 1996)."
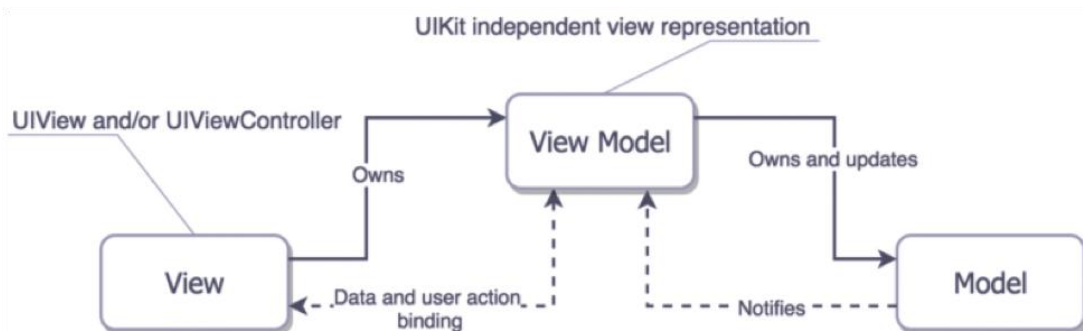
It is necessary to organize code such that there is a clear structure for creating objects and relations between them. Otherwise, what often results is spaghetti code. By using a standard app

architecture, it becomes easier to find specific sections of code, test, and initiate changes that do not require modification in other documents.

MVVM - Model, View, View Model

MVVM is a popular app architecture which separates components that make up a storyboard into three separate categories of files:

1. Models - contains data and/or accesses from databases or online services. For example, AuthorizationAccessProvider.swift is a model that accesses OAuth authorization services, which enables logging in using ArcGIS accounts. There is typically one model per view model, and it is instantiated as a singleton within the view model. See "Table of Models, View, and View Models in CurbMET" on page 25. Never import UIKit into the model file; it should only be used for views and view models.
2. Views - a UIViewController class, which contains UIViews (buttons, text fields, labels, UITableViews, etc.). All code within the View should be directly dealing with user interaction, such as taps on the screen. Any other code, such as data manipulation or modifying the visual appearance of the view, should be moved to a different file.
3. View Models - a struct with properties and functions that handles presentation logic. Properties such as color and size live in the view model. Like the model, there is a one-to-one relationship between a view model and a view. The view model is instantiated as a singleton within its corresponding view. Don't import UIKit, and don't directly reference the view controller.

Figure 7: MVVM Component Interactions (Orlov).

MVVM has the following guidelines :
- Models do not talk to anybody.
- View models only talk to models.
- View controllers cannot talk to models directly; they only interact with view models and views.
- Views only talk to the view controllers, notifying them of interaction events.

Functional Reactive Programming

Reactive programming is based on the idea of asynchronous data streams. It is powerful because any data type can be turned into a stream of ongoing events ordered in time - values of properties that change over time, sequences of inputs, etc. We can subscribe to these streams, and asynchronously react to them when one of three things happens: a new value is emitted, an error

occurs, or the stream is completed (Staltz).

For example, in the CurbMET app, we fetch image attachments that are associated with a given feature located in an online hosted feature table. As the attachments are fetched, they are added to a stream, which we display on the screen. Reactive programming is useful here because it enables us to deal individually with each emitted attachment, as opposed to waiting until all of the attachments are successfully retrieved. Depending on the number of attachments, this process could take more than a few seconds, and users do not like to be stuck watching a loading symbol.

Functional reactive programming brings in toolboxes that allow us to manipulate these streams by merging, mapping, or filtering. In this app, RxSwift and RxCocoa provide this additional capability. "RxSwift is a framework for interacting with the Swift programming language, while RxCocoa is a framework that helps make Cocoa APIs used in iOS and OS X easier to use with reactive techniques (Shapiro)." Marble diagrams are used to illustrate the functions at your disposal by displaying the input and output streams parallel to each other ("Observable").

Reactive programming has many benefits
- "Reactive streams allow you to write modular code by standardizing the method of communication between components. The reactive data flow allows for a loose coupling between these components, too (Lew)."
- "Reactive programming raises the level of abstraction of your code so you can focus on the interdependence of events that define the business logic, rather than having to constantly fiddle with a large amount of implementation details. Code in RP will likely be more concise (Staltz)."
- "Reactive programming enables us to create a highly-interactive experience that responds in real time (Staltz)."

Binding the View and the View Model

Becauses the view owns the view model, it is very easy for the view to change properties in and call methods from the view model. The same can be said for the view model's relationship with the model.

The example below shows the beginning of a simple login page.

SampleLoginViewController.swift

```
import Foundation
import UIKit
class SampleViewController: UIViewController {
        private let viewModel = SampleLoginViewModel()
    @IBOutlet loginButton: UIButton
        @IBOutlet usernameField: UITextfield
        @IBOutlet passwordField: UITextField

```

```
        override func viewDidLoad() { }

    @IBAction func loginTapped(_ sender: UIButton) {
        viewModel.login(usernameField.text, passwordField.text)
    }
}
```

SampleLoginViewModel.swift

```
import Foundation

class SampleLoginViewModel {
        private let authorizer = LoginModel()

        init() { }

        func login(_ username: String, _ password: String {
                authorizer.login(username, password)
        }
}
```

When the user taps the login however, it is much more complicated to notify the view of changes in the view model because MVVM forbids creating any references to the view in the view model. Swift standard libraries provide a few options for creating asynchronous subscriptions, including Key Value Observing (KVO), using "didSet," and callbacks. However, these strategies are verbose and can become hard to maintain as the number of observers increases. Thus, RxObservables are used in the app to bind the view and the view model.

For example, we want to display an error message when the username and password are incorrect. The login model, which performs all authorization functions, has a public observable named authStatus, which emits a stream of login validation statuses.

SampleLoginModel.swift

```
import Foundation
import RxSwift
import ArcGIS
class SampleLoginModel {
    //For brevity, this example does not include all properties
    // and methods that are needed to implement login validation
    // using AGSPortal.
        ...
        var authStatus: Observable<AGSLoadStatus>
        ...
```

```
}
```

Using the code below, which is added to SampleLoginViewModel.swift, the view model subscribes to authStatus, and when a new item is emitted from the stream, determines the correct message to display. The message is stored in the validationMessage variable, which is a RxSwift Variable<string>.

```
var validationMessage: Variable<String>
init() {
        authStatus.
                .subscribe(onNext: { newStatus in
                        validationMessage.value = getValidationMessage(newStatus)
                }).disposed(by: disposeBag)
}
private  func getValidationMessage (_ status: AGSLoadStatus) {
        ...
        return message
}
```

Finally, the view binds validationMessage to the SampleViewController's validationLabel. As a result, whenever the portal's load status changes in SampleLoginModel, the view controller automatically responds based on the type of status.

```
@IBOutlet validationLabel: UILabel
viewDidLoad() {
        viewModel.validationMessage.asObservable.bind(to:self.validationLabel).disposed(by:
disposeBag)
}
```

Why not MVC?

Figure 8: Model View Controller Diagram (Orlov).

Those with previous iOS app development experience have probably seen MVC, not only because it is promoted by Apple, but also because it is one of the most commonly used design patterns ("Model-View-Controller").

However, iOS uses a combined-roles variation of View and Controller, in which these two layers are tightly coupled together into a "View Controller." Because the view controller is responsible for responding to user interaction and manipulating the view, it is easy to bloat the view controller with UI logic. And as the number of views increases, so does the amount of business logic in the view controller. Eventually, the view controller becomes hard to read and impossible to reuse (Schmidt and Morrison).

Thus MVVM was chosen to help alleviate these issues.

Table of Models, Views, and View Models in CurbMET

Note: All files are Swift files. The .swift filename extension was removed for readability.

Function	View	View Model	Model
Logging Into App	LoginViewController	LoginViewModel	AuthorizatonAccess Provider
Bluetooth Connection	ScannerViewController	ScannerViewModel	BluetoothSerial
	SideMenuViewController		
	LegendTableViewController	LegendViewModel	
Filtering Map Display	RampTypeSelectionTableViewControll er	RampCarouselViewModel	
	FilterMenuTableviewController		
	MultipleSelectionTableViewController		
	AddFeatureTabBarController		
Accessing and Editing ArcGIS Hosted Map	MapViewController	MapViewModel	
	RampTypeViewController		
	EditorViewController	FormCellTypes EditorForm	FormItem
	QualitativeAttributesController		
	RampMeasurementViewController	MeasurementViewModel	
	MeasurementButton	MeasurementDataItem	MeasurementDataS ource
	LegendTableViewController	LegendViewModel	
	AttributeMeasurementPopoverVC	AttributeMeasurementPop overViewModel	

	AttachmentsViewController	AttachmentsViewModel	AttachmentsDataAccessProvider
App Settings	SettingsMasterViewController		
	SettingsDetailViewController	SettingsFormFactory	

User Experience Flowchart

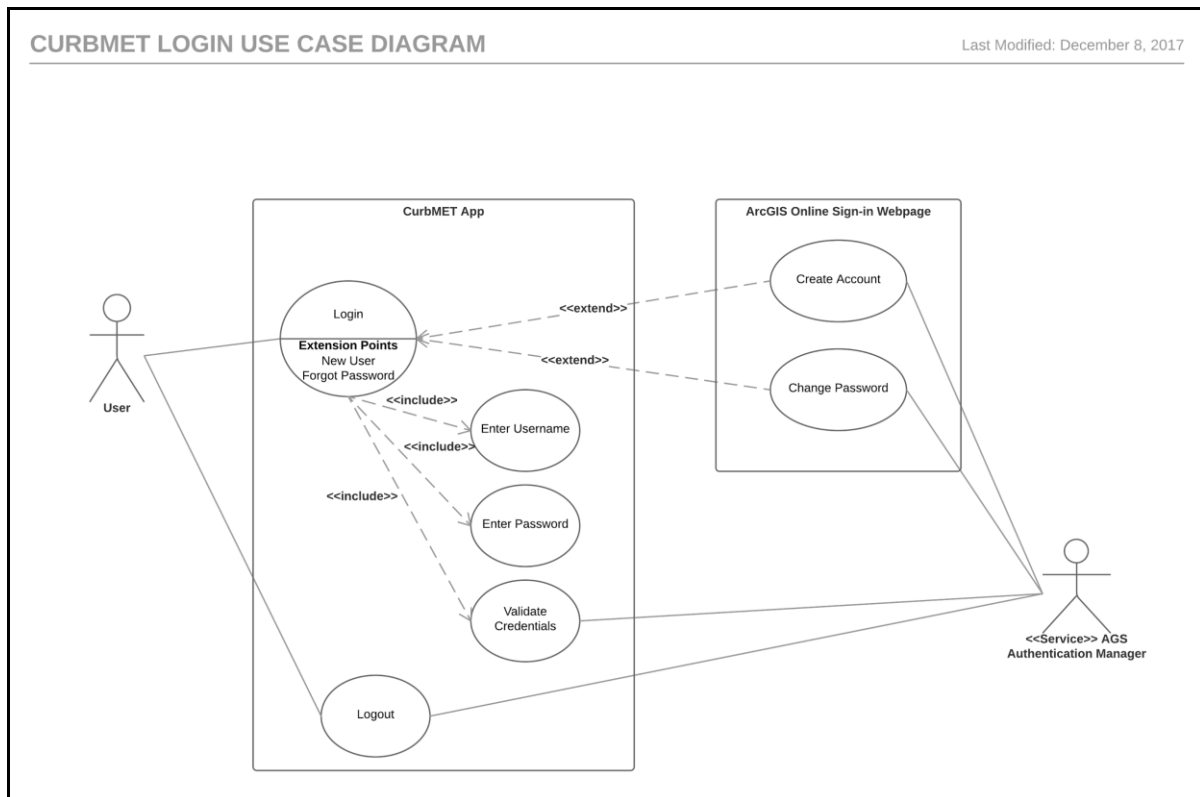**Figure 9**: User experience flowchart shows the steps that a user can use to access views in the app.

Major App Functions

Logging In and Authorization

The first screen that appears upon app launch is the login page. Because ArcGIS viewing and editing permissions are required for the app's core features - interacting with curb-ramp features on a map - the client and developer determined that login solely via ArcGIS online accounts

would be most appropriate for the application. It should be noted that authentication requires an internet connection. Credentials required are a username and password, which are entered using an in-app keyboard. Currently, credentials cannot be saved between app launches.

Available login functionality is shown in the use case diagram below. All of the CurbMET app actions are accessible in the same view. The ArcGIS Online sign-in webpage will open in the device's Safari app.

Figure 10: Login use case diagram for the device's app.

Regarding the code for logging in, the ArcGIS iOS SDK provides several classes for implementing authentication.

AGSPortal

The fundamental class for authentication is the AGSPortal. "AGSPortal is an object that represents a view for a user (anonymous or not) into a portal. www.ArcGIS.com is an example of a portal...AGSPortal is the main class and the entry point into the API to work with portals and organization subscriptions. It implements all the operations to interface with the backend ArcGIS Portal REST API."

"Portals allow users and organizations to publish and share content over the web. Portals include "Users (AGSPortalUser), Groups (AGSPortalGroup) and Content (AGSPortalItem)."

Users

- Signs in to the portal and create and share content which is organized into Items.
- Can be part of an organization, but this is optional.
- Can create and join groups.
- Can share items with groups.
- "A user of the Portal (and of the REST API) sees the view off the Portal that applies to their organization subscription. This view includes users, groups and items that belong to the organization and have been shared with them. This view may also include users, groups and items that are external to the organization and have been shared with the user."

Organizations
- Used for managing who can create hosted services by uploading offline data.
- There can be multiple organizations in a portal.
- Includes users with roles of administrator, publisher, or information worker.

Groups
- Used for managing who can view and edit data that is already hosted online.
- Contains users. Users in the group can view items shared with the group.

Items
- Includes web maps, map services, applications, and data files
- Can be private, public, or shared with specific groups.

AGSAuthenticationManager

"This class allows you to manage authentication/security related events.

[The authentication manager] raises an AGSAuthenticationChallenge whenever an authentication or security issue is encountered anywhere in the API...It also maintains a cache (in memory) of credentials that have been previously used to satisfy authentication challenges. This allows credentials to be reused, where appropriate, and prevent unnecessary or duplicate challenges from being issued while accessing secure resources from the same security realm. Additionally, the cache can easily be persisted in the keychain so that if the app is restarted, the cache is automatically pre-populated with saved credentials and the user does not have to sign in again."

In CurbMET, custom UI responses to authentication challenges are enabled by setting the authentication manager's delegate is set to LoginViewController.

The application was also registered with ArcGIS, which created a client ID for OAuth 2.0 authentication. Because this client ID was provided to the authentication manager, the default challenge type to be created is OAuth.

In the app, an AGSPortal is instantiated using the URL www.arcgis.com. To attempt logging in, the portal's credentials property is set using the text entered in the textfields on the user interface.

Bluetooth Connection

In the CIS, the iPad is the Bluetooth Low Energy (BLE) central and the HM-11 Bluetooth Module is the only peripheral. After making the connection, the iPad is the server and the HM-

11 is the client. The app is written such that it can only connect to one device at a time.
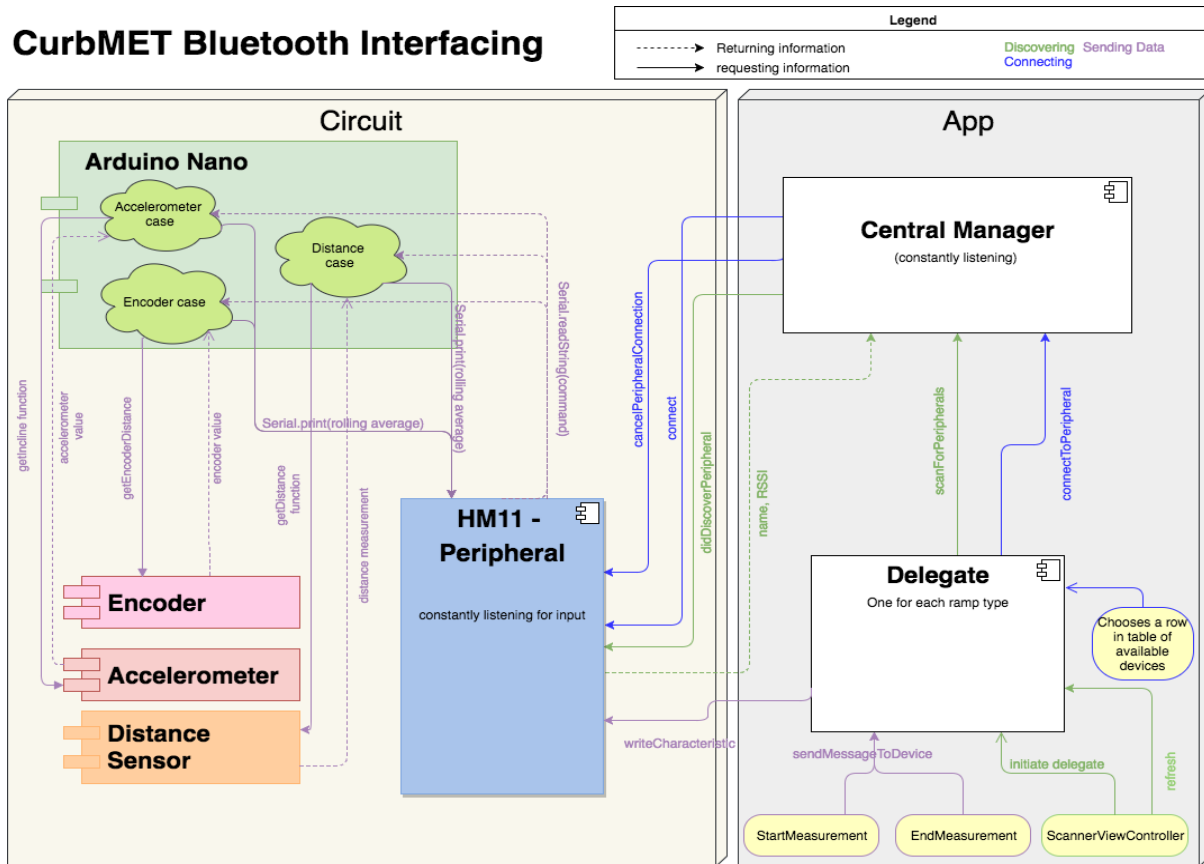
Establishing the Connection

This app uses a modified version of hoiberg's BluetoothSerial helper class to manage the Bluetooth connection (hoiberg). The software instantiates a global BluetoothSerial object called serial, which manages the Bluetooth connection for all of the app. A protocol/delegate pattern allows other files to respond to serial's events. If a file in the app requires Bluetooth communication functionality, it simply adopts the Bluetooth protocol and sets serial's delegate equal to self.

The first view controller that calls for Bluetooth is the Scanner View Controller. The user is presented with a table of available devices to connect to. The Scanner View Model is a delegate of serial, and when serialDidDiscoverPeripheral() is called, it adds the detected peripheral to a Variable array of CBPeripherals. The view controller's UITableview is populated by the names of peripherals in the view model's array, and each time the subscription detects an updated array, the view controller will refresh its UITableView. When the user taps a row in the tableview, the iPad will connect to the associated peripheral, and show the next view upon successful connection.

In the app, the Scanner View Controller is re-used in the settings section and the system status side panel. If the iPad is already connected to a device, its name will be displayed in the first section of the table, which is labeled "Currently Connected To."

The diagram on the next page is a high-level graphic representation of the functions used to discover and connect to a peripheral. It also illustrates the functions used to send and receive values, which is discussed in the next section of the document.

Figure 11: Functions used to discover, connect to, and communicate via Bluetooth.

Sending Values Between iPad and Circuit

Taking measurements with the CIS is the core of the app, and this function involves several subprocesses - creating a custom popover, validating the measurement, syncing with the ArcGIS feature service, and sending values between the circuit's microcontroller and the app. The focus of this section of the document is the flow of data between the circuit's microcontroller and the app.

Figure 12: Use cases for taking measurements using the CIS.

Each ramp type has its own scene in the XCode storyboard that is dedicated to taking measurements. Lettered buttons are layered on a diagram of the ramp. The letters, their associated measurements, and curb-ramp diagrams were copied from the June 2017 version of PennDOT's CS-4401 form. The layouts of these interactive pages are created in the XCode storyboard; the buttons are connected to the RampMeasurementViewController via IBOutlet actions. Because the same business logic is used regardless of curb-ramp type, the same view controller is used for all ramp measurement scenes.

As shown in Figure 12, a measurement button passes the start/stop commands from the measurement popover to its data item, to the data item's Bluetooth handler. The Bluetooth handler sends the device to serial (a BluetoothSerial object). As a Bluetooth serial delegate, it waits for the "serialDidReceiveString" signal, and then uses the received value to set its private variable value received. The private property is exposed as an Observable, which the data item observes to set its private property "value". Finally, the measurement button observes "Value" - MeasurementDataItem's public measurement value - and uses the most recent string emitted from the stream to update its title, thus displaying the measured value to the user.

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Accessing and Editing ArcGIS Hosted Map

Displaying the Map

To access the map, an AGSPortalItem is created using its item ID. If the user has logged in with valid credentials and the map is shared with the user's organization, then the portal will successfully load the item. If the user's credentials are correct but does not have viewing permissions, then a grey screen will appear. The map is assigned to the MapViewController's AGSMapView, which displays the interactive map to the viewer.

Whenever the map loads, it will center at the user's current location, with a zoom scale of 500. At this scale, sidewalks are clearly visible and minimal adjustment to the map's envelope should be required. The initial zoom scale can be changed in the app settings.

Because the map and its data are hosted online, it will only function if the CIS is connected to the internet.

Adding Features

Once the user confirms his or her curb ramp type choice, a new instance of CurbRamp is assigned to the global curbRamp variable. At this point, the only information it contains is the curb ramp type and a readyToEdit boolean, which is set to true. This boolean confirms that the user chose a ramp type from the side panel immediately beforehand; otherwise, tapping the screen multiple times in succession would result in multiple features of the same type being created. When the user taps the map, the AGSGeoViewTouchDelegate determines the map location (an AGSPoint) that was touched. Using a series of functions from the MapViewModel, the view proceeds to determine whether or not a feature was touched at that location. If zero features are identified, the curbRamp variable is not nil, and readyToAdd is true, then curbRamp's create function (see "The CurbRamp Class" section) is called to add a new feature to the designated feature table.

Filtering the Map Display

ArcGIS feature tables can be queried using SQL expressions. The app builds a query parameter based on options selected from multiple choice menus and searches all of the map's tables for features that match the parameters.

The filter menu is displayed as a navigation controller assigned to MMDrawerController's right drawer container. When one of the filter categories is tapped (county, curb ramp type, etc.), the corresponding view controller of filter options is pushed onto the navigation controller stack. To send data between pushed view controller and the root view controller, a protocol was created. The top view controller is the *delegating* class, and the root is the *delegate* class. In each of the protocol functions that are implemented in the delegate class, an updateQueryParameters

function is called.

The where clause for the query is created by iterating through values stored in stacks. A LIKE expression is created using the stack values, and then the expression is appended to the existing where clause string. Next, each of the map's feature tables are queried using that expression. Any features that match the expression are selected on the map.

Displaying the Map Legend

The legend is a table view controller that toggles into view as a right side menu using MMDrawerContainer. Each layer is a named section in the table, and its sublayers are rows in the section. The legend model contains an array of AGSLayerContent that stores the layers and sublayers found in the map's operational layers, and a dictionary of AGSLegendInfo that stores information such the layer's name and its symbol. These data structures are populated by recursively looping through the map's operational layers and their sublayers. The UITableView cells' text label and image view are set using the AGSLegendInfo dictionary. The AGSLayerContentArray determines the number of rows and sections in the table.

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Task 5 Perform a Literature Review Related to Curb-Ramp Design Methods

Abstract
This literature review synthesizes the design guidance available to curb-ramp designers who work to meet accessibility standards associated with the Americans with Disabilities Act (ADA). Challenges regarding the current design process are identified, as well as situations in which the University of Pittsburgh's curb-ramp inspection system could be beneficial.
Guideline documents are the primary source of material that describes the curb ramp design and consequently are the main source of material used in this review. Lists of best practices are described and case studies highlighted that demonstrate when accessible curb-ramps are technically infeasible. The literature indicates the need for a systematic approach to curb-ramp design, which will help reduce the learning curve for new designers as they develop engineering judgment through experience.

Introduction: Research Scope

Search Methods

Reports, classes, workshops, presentations, and design guidelines published by state departments of transportation regarding curb-ramp ADA compliance were the main source of information, with a focus on resources available through PennDOT. Published planning and design guides were reviewed on the FHWA website, as well as The US Access Board's Public Rights-of-Way Accessibility Guidelines (PROWAG).
Established databases were queried for articles related to curb-ramp design – Scopus, Compendex, TRID, World CAT, ProQuest, and Google Scholar. Of these databases, TRID yielded the highest number of related articles because it is focused on collecting transportation research.

Trends and Gaps in the Literature

Outside of PROWAG and the Americans with Disabilities Act Accessibility Guidelines (ADAAG), the most published design resources are "how to" documents created by state governments for their employees. Curb-ramp designs topics are not frequently mentioned in academic literature, such as dissertations, textbooks, or academic conferences abstracts. This could be because curb-ramps are a niche topic within an accessible design. Most curb-ramp designs and surveys are performed by private contractors who would not typically publicly release detailed descriptions of their design process. However, even if such literature were available, a standardized process would be difficult to create because curb-ramp sites have unique design constraints.

Furthermore, curb-ramp designs used by state departments of transportation and municipalities

can only be found on the respective department's website. A centralized analysis of curb-ramp designs in different states could not be found. Additionally, several states have created design guidelines that incorporate Public Rights of Way Accessibility Guidelines (PROWAG). For a broader study, a centralized record of which states adhere to PROWAG would be useful.

Overview of Curb-Ramp Regulations

Terms and Definitions

Alternate names for terms or abbreviations are listed in parentheses.
Curb-ramp (curb cut, curb-ramp): A short ramp cutting through a curb or built up to it (U.S. Access Board, 2011).
Cross slope: The slope that is perpendicular to the direction of travel (PennDOT, 2015).
Detectable Warning Surface (DWS): A standardized truncated dome grid surface built in or applied to the pedestrian access route to warn visually impaired people of hazards. The surface is placed where pedestrians will encounter the presence of hazards in the line of travel, such as the edge of roadway and railroads, indicating that they should stop and determine the nature of the hazard before proceeding further (PennDOT, 2015).
Engineering judgment: The evaluation of available pertinent information and the application of appropriate principles, standards, guidelines, and practices, for the purpose of deciding upon the applicability, design, operation, or installation of highway related facilities. Engineering judgment will be exercised by a licensed professional engineer, or by an individual working under the supervision of such engineer. Documentation of engineering judgment is not required but is desirable when providing access to the maximum extent feasible (PennDOT, 2015).
Longitudinal slope (running slope): The longitudinal slope is the slope parallel to the direction of travel.
Pedestrian Access Route (PAR): **A continuous and unobstructed path of travel provided for pedestrians with disabilities within or coinciding with a pedestrian circulation path. (U.S. Access Board, 2011)**
Turning areas: A 4 ft. x 4 ft. minimum level area of the walkway at the top or bottom of a ramp that allows wheeled users space to orient their direction before and after using a ramp. Also called pedestrian landings in the 2010 ADA Standards
Turning radius (minimum centerline turning radius): A circular arc formed by the turning path of the front outside tire of a vehicle (National Association of City Transport Officials, 2016).

The Americans with Disabilities Act (ADA) (1990): The Americans with Disabilities Act (42 U.S.C. 12101 et seq.) is a federal civil rights law that prohibits discrimination against individuals with disabilities. Title II of the Americans with Disabilities Act covers state and local governments.
ADA Accessibility Guidelines (ADAAG) (2004)
This document contains scoping and technical requirements for accessibility to buildings and facilities by individuals with disabilities under the ADA. These scoping and technical requirements are to be applied during the design, construction, and alteration of buildings and facilities. They are covered by Titles II and III of the ADA to the extent required by regulations issued by Federal agencies, including the Department of Justice and the Department of Transportation, under the ADA (U.S. Access Board, 2002).

ADA Standards for Accessible Design (2010)

Published by the Department of Justice, the ADA Standards for Accessible Design are comprised of the ADA and ADAAG. "The 2010 standards set minimum requirements – both scoping and technical – for newly designed and constructed or altered State and local government facilities, public accommodations, and commercial facilities to be readily accessible to and usable by individuals with disabilities (U.S. Department of Justice, 2010)."

Public Right-of-Way Accessibility Guidelines (PROWAG) (proposed in 2011)

PROWAG addresses various issues that are not on a site, such as access for blind pedestrians at street crossings, wheelchair access to on-street parking, and various constraints posed by space limitations, roadway design practices, slope, and terrain. The new guidelines cover pedestrian access to sidewalks and streets, including crosswalks, curb-ramps, street furnishings, pedestrian signals, parking, and other components of public rights-of-way (U.S. Access Board, 2011). In 2006, the U.S. Department of Transportation announced that PROWAG is the currently recommended best practices, and can be considered the state of the practice that could be followed for areas not fully addressed by the present ADAAG standards (Isler, 2006).

Who guides enforcement of ADA standards?

The Department of Justice (DOJ) is responsible for issuing regulations to implement Title II of the ADA, except for the public transportation aspects. The regulations issued by the Department of Justice include accessibility standards for the design, construction, and alteration of facilities (other than facilities used in the provision of public transportation covered by regulations issued by the Department of Transportation)((ODOT), 2016).

The Federal Highway Administration (FHWA)

Under DOJ regulations, the FHWA divisions must work with their state departments of transportation, metropolitan planning organizations, and local public agencies to ensure ADA and Section 504 requirements are incorporated in all program activities for all projects within the public right-of-way regardless of funding source. Program activities include project planning, design, construction, and maintenance (ODOT), 2016).

U.S. Access Board

The Access Board is an independent federal agency established by section 502 of the Rehabilitation Act (29 U.S.C. 792).1 The Access Board is responsible for developing accessibility guidelines for the design, construction, and alteration of facilities to ensure they are readily accessible to and usable by individuals with disabilities. When the Access Board's guidelines are adopted, with or without additions and modifications, as accessibility standards in regulations issued by other federal agencies implementing these laws, compliance with the accessibility standards is mandatory (U.S. Access Board, 2011).

The Curb-ramp Design Process

The decision to Add a Curb-Ramp

In the 1990 ADA Standards, the U.S. Department of Justice required that "Newly constructed or altered streets, roads, and highways must contain curb-ramps or other sloped areas at any intersection having curbs or other barriers to entry from a street level pedestrian walkway." In addition, "newly constructed or altered street level pedestrian walkways must contain curb-ramps

or other sloped areas at intersections to streets, roads, or highways." The decision of the case Kinney vs. Yerusalim in 1993 determined that resurfacing is considered an alteration. ((U.S. Department of Justice & Federal Highway Administration, 2013). The DOJ notes that new resurfacing technologies have prompted state and local governments to request additional guidance about which resurfacing technologies are considered alterations (U.S. Department of Justice & Federal Highway Administration, 2013). The DOJ/DOT responded with a joint technical memo clarifying what types of roadway surface treatments are considered alterations and which are considered maintenance.   However, the technical statements made in the document have been met with disagreement. Dr. DingXin Cheng, Ph.D., P.E., the director of the Pavement Preservation Center at California State University, Chico, stated that micro surfacing and cape seals are very similar to slurry seals and that they should all be classified as maintenance. However, the first two are considered alterations. FP2 Inc., a trade association supported by contractors, material suppliers, and equipment manufacturers, estimated the impact of these classifications. Making micro-surfacing and thin/ultra-thin overlays alterations instead of maintenance had significant impacts on state and local governments. They claimed that the increase required ADA upgrades that cost between 20% and 50% of state road maintenance budgets, which would decrease the total miles of road that can be adequately maintained.

All public agencies with more than 50 employees are required to have an ADA transition plan. The transition plan must identify obstacles in the public agency's facilities that limit the accessibility of its programs to individuals with disabilities and describe in detail the methods of that will be used to make the facilities accessible. A schedule for construction projects and the official responsible for the implementation of the plan must also be identified in the plan.

Topographic Survey

Detailed PennDOT requirements for preliminary surveys are presented in Publication 122M: Surveying and Mapping Manual (PennDOT, 2010). Collected information that directly affects curb-ramp design includes sidewalk width; sidewalk location with respect to the back face of curb; height and width of curb cross section; design turning radius and length of curve along the curb face; angle of street intersection(s); planned or existing location of signal and signal control devices; storm water inlets and public surface utilities; possible sight obstructions; street width, other physical obstructions such as buildings, bridges and walls; roadway grade; and parking spaces (AASHTO, 2011; PennDOT, 2015). PUB 122 refers to preliminary survey for design in general, not specifically survey for curb-ramp design. Topographic information is entered into the computer-aided-design software, which provides a 3-dimensional image for the designer (Mah, 2016).

Curb-ramp Location

Curb-ramps must be oriented in such a fashion that the grade break is perpendicular to the direction of travel. This can be accomplished by installing the curb-ramp perpendicular to the curb. This allows for a wheelchair to make contact with both wheels before experiencing a change in grade; however, this may cause the curb-ramp to not be aligned with crosswalk (see Figure 1). In this situation, the curb-ramp

may be installed in the same direction as the crosswalk and not perpendicular to the curb by providing a triangular landing. Curb-ramps aligned with the crosswalk are preferred.

Choose a Curb-Ramp Type

After the topographic survey is complete, designers typically choose a curb-ramp template provided by the appropriate state department of transportation and begin adding dimensions to the template. If none of the state's curb-ramp types can be used to build a compliant curb-ramp, an attempt is made to design a curb-ramp from scratch that meets ADA regulations. Where existing site constraints limit the ability to fully meet the latest standards, the improvements or upgrades must be done to provide access to the maximum extent feasible within the scope or limits of the designated project. PennDOT uses a Technically Infeasible form to document site constraints and design decisions.

General Design Guidelines

Curb-ramps are created to enable people with disabilities to safely travel from the sidewalk to the street, and vice-versa. Because individuals with mobility impairments (wheelchair users, the elderly, and users walking with crutches, etc.) are most affected by curb-ramps ((ODOT), 2016), almost all design best-practices are created with these user groups in mind (Beneficial Designs, Inc., Julie B. Kirschbaum, Peter W. Axelson, Patricia E. Longmuir, Kathleen M. Mispagel, Julie A. Stein, 2001).
Best Practices for Curb-ramp Design (copied from Designing Sidewalks and Trails for Access, Part II of II)

(Note: Some changes have been added that align with PROWAG, which was published after the text including this table. In 2006, the U.S. Department of Transportation announced that

| Best Practice	Rationale
Provide a level maneuvering area or landing at the top of the curb-ramp.	Landings are critical to allow wheelchair users space to maneuver on or off the ramp.
Clearly identify the boundary between the bottom of the curb-ramp and the street with a detectable warning.	Without a detectable warning, people with vision impairments may not be able to identify the boundary between the sidewalk and the street.
Place the curb-ramp within the marked crosswalk area.	Pedestrians outside of the marked crosswalk are less likely to be seen by drivers because they are not in an expected location
Avoid changes of grade that exceed 11% [PROWAG =13.3%] over a 610 mm interval.	Severe or sudden grade changes may not provide sufficient clearance for the frame of the wheelchair causing the user to tip forward or backward.
Design the ramp that does not require turning on the ramp surface.	Maneuvering on a steep grade can be very hazardous for people with mobility impairments.
[PROWAG: Always use detectable warning surfaces.]	Gradual slopes make it difficult for people with vision impairments to detect the presence of a curb-ramp.
Design the ramp with a grade of 7.1 ± 1.2 percent or less. [PennDOT asks its engineers to provide the flattest slope possible.]	Shallow grades are difficult for people with vision impairments to detect but steep grades are difficult for those using assistive devices for mobility.
Design the ramp and gutter with a cross slope of 2.0 percent.	Ramps should have a minimal cross slope to avoid wheelchairs from drifting off the ramp.
Provide adequate drainage to prevent the accumulation of water or debris on or near the ramp.	Water, ice, or debris accumulation will decrease the slip resistance of the curb-ramp surface.
Transitions from ramps to gutter and streets should be flush and free of level changes.	Maneuvering over any vertical rise such as lips and defects can cause wheelchair users to propel forward when wheels hit this barrier.
Align the curb-ramp with the crosswalk, so there is a straight path of travel from the top of the ramp to the center of the roadway to the curb-ramp on the other side.	Where curb-ramps can be ahead, people using wheelchairs often build up momentum in the crosswalk in order to get up the curb-ramp grade (i.e., they "take a run at it"). This alignment may be useful for people with vision impairments.
Provide clearly defined and easily identified edges of the ramp to contrast with the sidewalk.	Clearly defined edges assist users with vision impairments to identify the presence of the ramp when it is approached from the side.

PROWAG "is the currently recommended best practices, and can be considered the state of the practice that could be followed for areas not fully addressed by the present ADAAG standards

(Isler, 2006).")

Curb-Ramp Types in Designing Sidewalks and Trails for Access, Part II: Best Practices Design Guide

Designing Sidewalks and Trails for Access, Part II: Best Practices Design Guide, a recommended resource listed on the FHWA's Office of Planning, Environment, & Realty website, identifies the types of curb-ramps that can be installed.
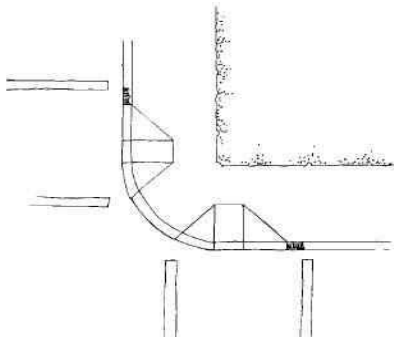
Perpendicular

Perpendicular curb-ramps are perpendicular to the curb. Generally, users will also be traveling perpendicular to vehicular traffic when they enter the street at the bottom of the ramp, which makes it easier for drivers to see the pedestrians as they cross the street. Perpendicular curb-ramps are best suited for tight radius corners; when this is the case, pedestrians have a straight path of travel aligned with the crosswalk. They are also at an expected location for blind pedestrians. Separate curb-ramps are preferred; however, installing two perpendicular curb-ramps at an intersection compared to a single diagonal curb-ramp requires a sidewalk corridor that is wide enough to contain both the curb-ramp and a 4'x4' level landing (Beneficial Designs, Inc., Julie B. Kirschbaum, Peter W. Axelson, Patricia E. Longmuir, Kathleen M. Mispagel, Julie A. Stein, 2001).
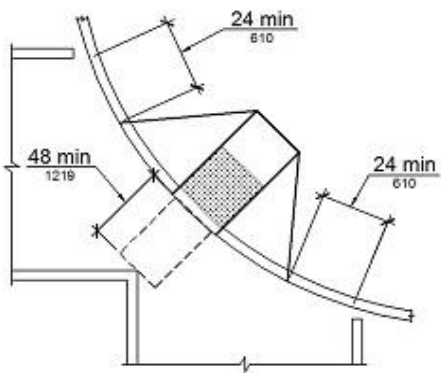
Diagonal

A diagonal curb-ramp is a single ramp which serves two directed of movement. Diagonal curb-ramps should be installed as a last resort option ((ODOT), 2016; INDOT, n.d.; Markesino & Barlow, 2007; PennDOT, 2015; U.S. Access Board, 2011). Pedestrians are put into an area of conflict with motorists who are traveling straight or turning. As a result, wheelchairs users must make an extra turn   and blind pedestrians might mistake a diagonal curb-ramp for a perpendicular one, thus traveling into the middle of intersections.

Parallel

Parallel curb-ramps are parallel to the vehicular path of travel on the adjacent street and to the user's path of travel on the sidewalk. They require minimal right-of-way, so they are ideal for narrow sidewalks. They can also be easily lengthened to compensate for steep terrains or high curbs. They also do not require any turning or maneuvering on the ramp itself and are clearly defined for people with visual impairments. However, they do require pedestrians to negotiate several slope changes in a short distance when 2 parallel ramps are used on the same corner. Engineering judgement should be used when designing.
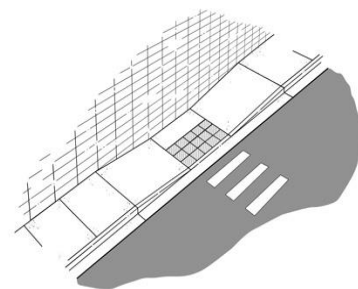
Combination
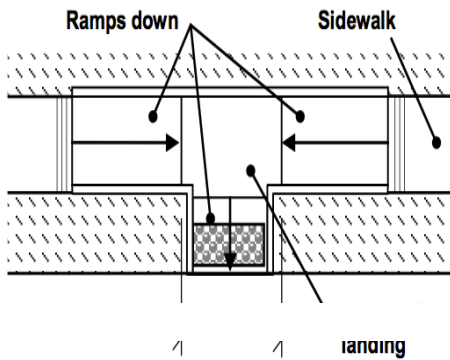
Combination curb-ramps are a combination of the perpendicular and parallel designs. These curb-ramps are excellent for improving access in challenging situations, such as a narrow sidewalk or steep grade. They provide the benefits of both the perpendicular and parallel curb-ramps, aligned with crosswalk and crossing direction, level maneuvering at the top and bottom of the ramps, and adequate drainage for water and debris. Combined curb ramps require more space than a parallel curb-ramp alone.

Blended Transitions

Blended Transitions gradually lower the level of the sidewalk, through an almost undetectable change in slope, to meet the grade of the street. By definition, blended transitions do not have slopes in excess of 5%. Depressed corners are often designed as an expanded diagonal curb-ramp that extends around the entire corner at the intersection. In addition, a decorative pattern is often used in downtown urban areas to visually blend the sidewalk and the street, giving the effect of one smooth pathway. As a result, it is much more difficult for visually impaired pedestrians to detect the boundary between the sidewalk and the street. Trucks and motorists may also try to make tighter turns by driving on the sidewalk, which is extremely dangerous for all pedestrians.

Design Challenges and Recommendations

The curb-ramp must be designed to meet the existing topographical and physical constraints, and the requirements for curb-ramp slope, cross slope, landings, and connection to the street. Altering one dimension to make it ADA compliant could cause another dimension to be out of spec, and not meet one or more given specifications.

The use of engineering judgment must be implemented when there are significant constraints that present design challenges. For instance, ramps that have 2 or 3 features slightly out of compliance may be a more favorable design compared to a design that only has one feature that is extremely out of compliance. Alternative designs can be modified and approved to create a more suitable design.

To improve engineering judgement the U.S. Access Board encourages engineers to seek opinions and recommendations from people with disabilities and to share ideas and solutions with industry peers. Staying open-minded to non-traditional solutions will better enable them to create a design that balances the needs of all users: people who use wheelchairs, people who have vision impairments, and other pedestrians, young and old. Documenting all analysis work, findings, and decisions will make it easier to switch between or combine ideas, as well as defend the final solution. "There will always be someone with a second opinion or a better design solution. However, if the scope of the project is clearly defined, research is adequate, and the method of selecting the preferred alternative is clearly documented, the solution can be adequately defended. It is the designer's responsibility to develop the expertise needed to evaluate potential alternatives before confirming an engineering solution (Markesino & Barlow, 2007)."

In the same publication referenced above - Accessible Public Rights-of-Way Planning and Designing for Alteration, the Access Board lists twenty-nine common problems and proposes accessible solutions. The case studies are divided into five categories: limited right of way, above-ground obstructions, push buttons are not accessible, excessive roadway slope, and underground obstacles. Twenty-five separate examples of curb-ramp designs for 10 foot and 30-foot radius returns are also included.

Design examples are a recurring theme throughout the literature reviewed. By learning from case studies, engineers expand their body of knowledge, making them better equipped to overcome real-world design challenges that they may not have personally encountered before.

Although the University of Pittsburgh's curb-ramp inspection system (CIS) may not have direct applications in the dimensional and location decisions that designers must make, the CIS has potential to increase the efficiency and accuracy of preliminary topographic surveying. This will be discussed with contractors during Task 6 of PITT WO-15.

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Appendix F

Task 6 Conduct a Needs Assessment for the Curb-Ramp Design Process

Introduction

Task 6 focuses on documenting the information gathered from interviews with curb-ramp design engineers and contractors. Several industry professionals were interviewed regarding their experiences and the following document is based on findings from their responses. These interviews focus on how useful the Curb Inspections System (CIS) device would be in the design process and post-construction evaluation. The interviews include the discussions of current curb ramp design, construction processes, and detail the hardships engineers and contractors encounter in the field. Lastly, the interviewees are asked about the role the CIS device may play in both the design process and post-construction process.

Background

When an alteration to the roadway is performed, such as resurfacing, the department identifies non-compliant existing ADA ramps and upgrades the existing ADA ramps to current standards. This process may be done through design in advance and included in the contract plans or incorporated in a design/build item. If the process is performed using a design/build item, the contractor hires an engineer to complete the surveying and design of the proposed ramps at the locations identified in the contract plans. The engineer then submits their designs to the department's ADA committee for review. The committee can either accept the proposed plans or make comments for revisions to the plans. If a plan cannot meet the current standards for any dimensions or grades, they need to submit a Technically Infeasible Form (TIF) outlining the reasons that a ramp cannot be built to the current standards. The ADA committee also reviews the TIFs and either recommends acceptance to the Assistant District Engineer – Design or makes comments as to required revisions. Once an approved design is achieved, the contractor can begin removal of the existing ramp and construction of the approved ramp. The Curb-ramp Inspection System then would be able to measure the final grades and distances in the as constructed ramp.

All alteration type projects must assess pedestrian needs and must improve, or upgrade altered existing facilities to the latest standards. Where existing site constraints limit the ability to fully meet the latest standards, the improvements or upgrades must be done to provide access to the maximum extent feasible within the scope or limits of the designated project. Therefore, existing ramps that do not meet current standards and a TIF has not been approved are identified as non-compliant. Ramps which are either: (1) able to be designed and constructed to current standard or (2) not fully able to meet current standards but are designed to the maximum extent feasible and have an approved TIF, are considered compliant.

Summary

These interviews reveal key information about the curb ramp design and inspection processes from the stakeholder and consumer point of view. Namely, these insights demonstrate

(1) the potential usefulness of the CIS in the design process, (2) the general consensus that the CIS will be applicable in the post-construction verification and inspection process, (3) the myriad challenges associated with the complex process of ADA-compliant curb ramp design, and (4) the various methods by which surveying is completed along with their respective advantages and disadvantages. Each of these insights relevant to CIS development and usefulness in the field are discussed in detail below.

The following questions were addressed in the interview to better understand the construction and reconstruction process for ADA-compliant curb-ramps; the context of each key insight is based on discussions generated by these questions:

- What are the steps involved in the process to design a curb ramp?
- What are some of the challenges you face at the curb ramp site?
- What are some of the challenges you face with data collection on curb-ramp measurements?
- What are some challenges you face with curb-ramp design?
- What is involved in surveying a site for building a curb-ramp?
- Which methods of surveying do you prefer and why?
- What is the process for curb-ramp reconstruction if needed?
- What tools and software do you currently use?
- In what ways can the CIS facilitate the design and evaluation process?
- Would a database of prior CIS inspection data be helpful long-term? How?

Based on the responses of the interviewees, these questions often led to varying levels of follow-up questions and discussions which also contributed to this report. In addition, interviewees often offered their own quantitative estimates of their personal experiences in their years of curb ramp design and contracting experience. These figures can be found in the appendices for each individual interview.

Key CIS Improvement Suggestions

The first major concern interviewees expressed was how to calibrate the CIS device before each measurement to ensure grade accuracy. They also expressed how the CIS calibration could be particularly problematic in hilly or mountainous areas. A redesign similar to how transit tripods worked was discussed, but also a reworking on the CIS measurement calibration workflow was considered. There were also concerns about benchmarking to a bubble level at the base of the design; interviewees explained that precision and accuracy of the measurements with the encoder and accelerometer must be as good or better than measurements with a tape measure and level. Thus, the calibration process and workflow will be improved in the next design iteration. For potential usefulness in a design context, a non-contact measurement approach such as LIDAR was discussed, but this was deemed to be appropriate for a different tool or an iteration further in the future.

Perceived Value of CIS for Curb Ramp Inspection

All interviewees saw a considerable potential benefit of the CIS device as a verification and inspection tool, and each interviewee provided great feedback about their likes and dislikes of the device. Interviewees found the CIS useful in decreasing the time required to manually measure the ramps. Interviewees also appreciated how the data was automatically added to an online database, and that written measurement did not need to be recorded and later transcribed into Microsoft Excel. Participants were generally in agreement that $1,000 was on the higher end of what they are willing to pay, while some expressed, they may be interested in purchasing one or several devices.

Potential Design Phase Value

Interviewees were hesitant to identify the potential usefulness of the CIS in the design phase, but some indicated that the CIS may help prioritize curb ramps that are further out of compliance than others. Generally, the data that the CIS collects could be useful in the design phase if stored over time in a database. For instance, interviewees indicated that it would be highly desirable if all of the curb ramps in a particular area had their measurements from inspections accessible to curb ramp designers in a database. This historical inspection information would be largely more useful on an asset management level and help in the prioritization of ramp redesigns, rather than act as a source of survey data to guide the curb ramp design process.

The interviewees made clear that ADA-compliant curb ramp design, especially in reconstruction or rehabilitation projects, is often not straightforward. This led to many conversations about the importance of accurate, precise, and abundant survey data. In contrasting traditional surveying techniques versus more expensive and precise LIDAR methods, interviewees generally preferred LIDAR when possible, but emphasized that traditional survey is often still used. Some alternative methods of surveying were also discussed, such as the compilation of images by software into a 3D map. This photogrammetric approach to surveying could be accomplished through the use of the tablet computer (i.e. iPad) on the CIS in conjunction with software such as ContextCapture from Bentley Systems. This insight will be further investigated in future reports, including the process architecture development.

Conclusions

Based on these interviews, the CIS, in its existing form, does not provide significant value during the design stage of the curb ramp installation and inspection process. However, there is potential for CIS use in post construction and verification of curb ramp dimensions. In the future, a LIDAR-based measurement system and CAD tools would be useful additions to help to help streamline the design phase. Furthermore, a non-contact photographic measurement software could be used with the on-board tablet computer of the CIS to add value to the design phase by providing more accurate, precise, and useful survey data.

Appendices

Appendix A: Interview 1

Interviewee 1, a contractor thought that the CIS device would be very useful in design and post curb construction process. The interviewee is one of many companies that work with PennDOT to assess and build curb-ramps in the Pittsburgh area. With several years of experience with PennDOT and ramp construction, the interviewee pointed out the obstacles they face in order to build an ADA compliant ramp.

To begin, the interviewee explains the design and construction process that PennDOT goes through. The process of surveying begins, as design consultants are sent out by either construction companies or PennDOT themselves to assess the topography of the site. Within 50 feet of the site, shots are taken using a rover, transit or GPS system to develop designs and assess any uneven areas. Based on the measurements the consultants will create a design schematic on paper to submit to PennDOT for approval. According to the interviewee, although the process may seem easy there are some difficulties that they face.

The interviewee was asked to elaborate on the approximate breakdown of none, minor, and major changes needed for reconstruction. The interviewee noted that, in his experience, only 5-10% of ramp constructions are compliant with ADA standards upon completion; 50% need minor redesign changes and the remaining. 40% require major improvements which may include complete reconstruction. PennDOT does not cover all redesign and reconstruction costs, rather those changes will be covered by the design or construction company. To avoid any major reconstruction costs, carpenters are highly trained to make adjustments to ensure ramps are built within ADA standards with minimal error.

When asked whether the CIS would be useful for designing, the interviewee suggested the benefits of the device prior to demolition work and to check existing parameters. Checking the slopes of form work to see if they match with the designs was an additional need. In terms of positive attributes, the interviewee believed the device would be useful to speed up the process of measuring existing curb ramps. Additional capabilities that he suggested would be beneficial is measuring the area of the ramp, adding a lidar for an image of 3D topography and verifying form work of the site.

The interviewee found the device beneficial, but as noted above, suggested a few attributes that may heighten the value and usage of the device. Altogether, the feedback for the CIS was positive and would be very relevant to the design portion of curb-ramp construction.[1]

Appendix B: Interview 2

Interviewee 2, a design engineer, overall thought that the CIS device may decrease the time required for design by making the initial field work simpler but indicated that the larger benefits would be in the post-construction inspection process. More specifically, he explained that the CIS device would be helpful when examining existing curb ramps and measuring their slopes to determine whether a type of ramp may simply be specified for a contractor to build instead of

[1]Gesinski, Johnathan. Personal Interview. 26 July 2018.

requiring a full redesign. The interviewee also said that if data gathered via the CIS tool during inspections was stored in a database of historical curb ramps measurements, and their compliance inspection records existed with the long-term use of CIS, then this would aid with design in the future.

While describing the design process, the interviewee explained that accurate and precise surveying is key in designing an ADA-compliant curb ramp. The surveying group at his company uses a combination of 3D scanning with LIDAR and traditional survey tools like transits, levels, measuring wheels, and tape measures. He also said that, whenever possible, designers attempt to leave room for potential error in ramp construction. Based on his experience, it is not very common for errors in the initial construction of a curb ramp to deviate from the design and then require teardown. In addition, he indicated that, in his personal experience, over three-quarters of his curb ramp jobs were reconstruction or redesign of existing ramps rather than new construction because PennDOT is his main client.

In terms of feedback on the CIS prototype design, the interviewee expressed concern about the current in-application calibration procedure, which uses a bubble level on the base of the device. He explained that this calibration must be accurate and give consistent grade calculations with those of digital levels. Further, he suggested that a less frequent or more user-friendly calibration procedure be pursued. In the future, the interviewee said that a non-contact solution such as 3D scanning via LIDAR would be ideal.[2]

Appendix C: Interview 3

Interviewee 3, a designer and surveyor, thought that the CIS device would perform well when measuring sidewalks for design but may struggle where differently sloped streets meet one another. The scope of his work included surveying of the site and design, and then a contractor builds the curb ramp. He also appreciated that the CIS system automatically enters the record information into a database; they currently record measurements onto paper and then later transfer them to a computer, so this would save time and effort.

In describing his work in curb ramp design and surveying, the interviewee explained that four foot and two-foot levels are generally standard to use in measurement. However, he admitted that it is the choice of the surveyor of which size level to use to measure the dimensions of the built environment before the design phase and that this can impact measurement. He also went on to say that not everyone conducts these measurements appropriately. For surveying, his firm recently began using an expensive LIDAR scanner to 3D the curb before designing a ramp. He indicated that this was a state-of-the-art practice and that most firms still use traditional surveying methods. The interviewee also explained that adjustments that are required in the field, such as a result of sub-surface features, are generally reviewed by design engineers.

Speaking about the frequency of construction of non-compliant curb ramps, the interviewee said that ramps are often constructed as non-compliant even if they are designed as compliant. From his experience, this is most often a result of sub-surface features that must be worked around and

[2] Telega, Ed. Personal Interview. 9 August 2018.

cause the proper design to be technically infeasible. He also said that ramps that are designed as compliant but built non-compliant without a good reason occur, in his personal experience, around five percent of the time.

For feedback on the CIS device prototype, the interviewee said that the existing calibration procedure may pose challenges in hilly or mountainous areas. To improve, he suggested that calibration either be conducted only periodically or be simplified to a system similar to how transit tripod systems are leveled in surveying. He also indicated that contractors may be interested in this tool, but their interest would depend upon price because our tool is competing with inexpensive and ubiquitous tools like digital levels and tape measures.

Appendix D: Interview 4

Interviewees feedback on the CIS device and information regarding the curb ramp design process was gathered in interviews with two project managers as well as a principal at the firm. Their firm engages in full-service transportation engineering, which includes the replacement and reconstruction of curb ramps. On these projects, they also inspect curb ramps during the construction process. The clients for these projects are generally PennDOT and individual municipalities, as well as others.

In speaking about his role as a project manager, the interviewee indicated that his role varies between projects between design, survey, and inspection. He generally works to design roadways, for instance around the construction of a new convenience store or shopping center. Along with this construction, he noted aspects like consideration of traffic signals and ADA-compliant curb ramps come hand in hand.

When asked about the biggest challenges in the curb ramp design process, the interviewee emphasized that the lack of accurate survey information posed the greatest difficulty. Because ADA requirements are so stringent and precise, small variances can result in non-compliance. As a result, lack of quality survey data presents a challenge to designers to design a curb ramp that will fit the field conditions while remaining ADA compliant. For instance, the interviewee explained that he often works with PECO and that they use LIDAR to obtain survey data. He acknowledged that this LIDAR data was more accurate, provided many more data points, and was relatively quick and easy. One downside of LIDAR that the interviewee noted was the requirement for substantial computing power. This limitation is a reason that other tools may be used to survey the built environment, such as traditional levels and measurement wheels.

Giving their thoughts about the instructional CIS YouTube video, all three interviewees were impressed with the tool and agreed that the system had incredible value in the curb ramp inspection process. They explained that that existing workflow for curb ramp measurement uses a level and measurement wheel to obtain data about the curb ramp and this information is then recorded with pen and paper, while later the information is input into Microsoft Excel. On the design side, the interviewees did not see as much potential value. They noted that existing curb ramps are sometimes measured in the design process, but not often; it is more important to them to measure the other conditions of the built environment that will impact design.

Speaking about the iOS application accompanying the CIS device, the interviewees thought that it was helpful that a CS 4401 form may be automatically populated with the relevant data after measurement in the future. Further, they described the application as user friendly and explained that it would be especially helpful for people who are not very knowledgeable about ADA ramp inspection. When asked whether they would already have iPads for the application, they noted that their company would likely need to supply the iPads and that PennDOT reimburses monthly data usage in their firm.

Currently, their 300 inspectors are equipped with a smart level and tape measure that, combined, costs less than $175. The CIS is expected to be in the range of $1000 plus the cost of an iPad. When speaking with the interviewee, he mentioned the price point is a concern.

Detailing more of the nuances of curb ramp design, the interviewees described their use of Bentley MicroStation software, and how most curb ramps, in reality, are hybrids of a few "styles" of the ramp, and that it must be labeled whichever is closest. In addition, they emphasized that the curb ramp design has some human elements that would be difficult to automate; human judgement and reviewer preference often comes into play. The interviewee estimated that design and revision, in his experience, take about 10-12 hours per ramp overall, but that this varies with differences in the surrounding built environment and the complications it may pose.

On the topic of surveying techniques, the interviewees were asked whether they preferred LIDAR or more traditional survey techniques. They explained that LIDAR requires almost no interpolation between points and that this leads to less time required for design and less opportunity for error; a software called "TruView" is used to visualize the LIDAR data. Further, the cost of LIDAR versus traditional surveying varies between companies-- they indicated that LIDAR prices are decreasing, and traditional survey prices are increasing. However, one challenge with LIDAR is potential interference by obstacles or other light, so the scans may sometimes need to be conducted at night. Further, their firm often receives survey data from other parties, so they do not always get to choose which method is used. Despite this, whenever they do their own projects or can choose the survey method, they usually request a LIDAR scan. Sometimes the survey has already been completed by the time they are brought onto a project, in which case they must work with the data they are given.

On a final note, the interviewees again explained that the design of curb ramps has many human elements to it, but that they agreed that the inspection could use some automation and streamlining, such as with the CIS and accompanying iOS application.[3]

Appendix E: Interview 5

Feedback and information about the curb ramp design process were received from two interviewees at Bentley Systems: a product manager and an engagement manager. The product manager explained that he has fifteen years of experience in road and bridge design, in both engineering and sales roles. He originally worked for Bentley as an application engineer, and then worked at Hewitt Construction before returning to Bentley in his role as a senior product

[3]Stanton, Sean; Duong, Tuan; Dougherty, Anthony. Personal Interview. 20 September 2018

manager. Commenting about the measurements of the CIS, he was concerned about precision and accuracy, as the tolerances for inspections are very small.When asked whether the CIS would be useful in the design and surveying process, the interviewees said that it may help with planning and identifying problem areas before construction, as well as prioritize ramps that should be replaced soon and that may be further from compliance. Overall, though, they believed the CIS was more useful in an inspection and validation role. In addition, they liked that the CIS workflow was simple and streamlined and appreciated that data was stored in a GIS database.

On the economics of the CIS device, the interviewees indicated that the customer would likely be municipalities and cities because they are generally impacted the most by this issue. They also explained that this may vary by state. For instance, he described that California has many state roads that go through cities, but Nebraska has state roads that stop at city borders and then the city maintains roads from there on. When a price point of around $1000 was suggested, they were both unsure, as they mostly deal with the sales of software products. Both interviewees agreed that LIDAR was extraordinarily useful in surveying; if, for instance, they are redesigning an intersection, they would likely bring LIDAR to survey all the ramp areas. They explained that LIDAR is expensive and sometimes difficult to perform. For instance, one may have to shut down an intersection to ensure that all sides can be scanned and that nothing is in the way. As a result, the traditional survey is still often done.

In terms of other surveying technologies, the interviewees discussed 3D surface mapping via photos with a software called Context Capture. The software can create a mesh to use in CAD and help to visualize an intersection. One advantage over LIDAR is the ease of use because LIDAR is difficult to set up. On the topic of curb ramp design, the interviewees explained that it is often difficult to design a ramp because of the many interdependencies and relationships between dimensions within a design. They went on to say that, in their personal experiences, only about one in ten ramps are standard and that there is almost always something in the way or the grades do not work out. This process is much easier in new road design because the designer has more control.[4]

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[4]Johnson, Corey; Bacheson, Ed. Personal Interview. 21 September 2018.

Task 7: Process Architecture Development

Introduction

 Based on the interviews conducted as a part of the needs assessment of the curb-ramp design process in Task 6, a process architecture describing a curb ramp design tool was developed to show how a computer program could generate a curb ramp design from 3-D physical site data. The attached process flow is a roadmap of how a tool would take into account the requirements that a designer needs to evaluate in the selection of a ramp type, alignment within an intersection, and the minimum requirements for slopes and distances, and ultimately design a ramp that is compliant to the maximum extent feasible. This design data may then be extracted and inserted into a TIF for ramps which did not meet the criteria.

Process Architecture

 See PDF for the full Process Architecture flowchart. The flow chart is organized such that each row corresponds to a number, and an adjacent block is given a letter.

Discussion

 First, a 3-D model of the built environment is created (**1**). The resolution, precision, and accuracy of this 3-D model will vary based on measurement and processing methods; details regarding this are covered at length in Appendix A. This 3-D model is then exported in through the CADD program in either .DWG or .DXF file type (**2**). From this exported 3-D CADD data, mathematical spatial analysis is conducted to determine the physical site parameters (**3**). These parameters include:
  - Intersection type (i.e. the number of roads, intersection angles, traffic flow)
  - Sidewalk width
  - Sidewalk location with respect to the back face of curb
  - Height and width of curb cross section
  - Design turning radius and length of the curve along the curb face
  - Angle of street intersection(s)
  - Planned or existing location of signal and signal control devices
  - Storm water inlets and public surface utilities
  - Possible sight obstructions
  - Street width
  - Other physical obstructions such as buildings, bridges, and walls
  - Roadway grade
  - Parking spaces
  - Right of way lines

Then, a programmed best practices curb ramp type ruleset is applied to the above analyzed output parameters. The programmed ruleset selects the applicable possible curb ramp types, and breaks down as follows:

 Type 1

- Ideal for locations where the existing sidewalk is wide
- Well suited for tight-radius corners
- The drawback is the width of the relatively wider sidewalk needed to install this type

Type 2
- Useful on narrow sidewalks
- Drawbacks are a flat slope at the depressed curb, and that pedestrians must traverse the curb ramp regardless of wanting to cross the street
- Typically used in situations where non-walk areas are not present

Type 4 & 4A
- Similar to type 1
- Provide flares that may be installed where utilities limit installation of flatter slopes
- Typically used in situations where non-walk areas are present

Type 6
- Works well with narrower sidewalks
- Ideal in residential areas where a green/planted strip separates the sidewalk from the curb
- Requires more space
- Drawbacks are that pedestrians must traverse the ramp when continuing to walk on the sidewalk, and additional form work to construct
- Typically used in situations where non-walk areas are present

Blended Transition
- Useful where narrow (4-5') sidewalk is at back of curb
- Less desirable for individuals with visual impairments
- Locating 4'x 4' turning area is preferred behind the curb

Diagonal
- Serves two directions of motion, but avoid if possible
- Used only sparingly in areas with moderate-to-high vehicular and pedestrian traffic values
- Avoid for large radius corner curbs
- Less satisfactory for people with visual disabilities
- Locating 4'x 4' turning area is preferred behind the curb

Applying the above best practices curb ramp type ruleset narrows down the set of possible curb ramp for the given site conditions (**4 & 4A**).

From analyzed physical site parameters & eligible curb ramp types determined by the best practice ruleset, a design is generated that most closely adheres to the various grades and distances outlined by PennDOT's requirements and recommendations, which are as follows:

Requirements, Minimums, & Maximums

- 2.00% maximum longitudinal and cross slope
- Minimum 4'-0" x 4'-0" level landing beyond the curb face where turning movements occur in the street
- Ramp length not required to exceed 15 ft.
- Minimum width of a curb ramp is 48 in. exclusive of flared side slopes
- Sidewalks constructed at a longitudinal slope not to exceed 5.00%. For roadway profile slopes that exceed 5.00%, construct parallel sidewalks adjacent to the roadway at a longitudinal slope not to exceed roadway profile slope.
- The counter slope of the gutter or road at the foot of a curb ramp, landing or blended transition is not to exceed 5.00% maximum slope
- Grade difference between roadway slope and curb ramp slope not to exceed 13.33%, where grade difference exceeds 13.33%, provide a 24" transition strip across the DWS surface so that the grade difference is not exceeded. Transition strip not to exceed 5.00%.
- Cross slope rate of change should not exceed 3.00% per 1'-0" when transitioning to roadway profile
- Level landings (2.00% maximum longitudinal and cross slope) are required where pedestrians perform turning maneuvers.
- 4'-0" landings permit 10.00% max flare slopes, and less than 4'-0" landings require 8.33% flare slopes.
- Roadway surface shall be flush with the depressed curb
- Maximum curb ramp slope is 8.33%
- Curb ramp opening width at least 48 in.
- Pedestrian access route around corners should be assessed

Recommendations
- Curb ramp and flare slopes constructed with the flattest slope possible
- Diagonal curb ramps avoided when possible
- Smooth transitions from ramp to gutter with no level changes between ramp and street

- Pedestrian movement restriction should be avoided
- Curb ramps should be aligned with crosswalks
- Grade breaks are perpendicular to the direction of travel
- DWS should be located in accordance with RC-67M
- Need for curbing should be assessed and a type should be determined

From this, the set of possible ramp designs is output with accompanying CADD drawings & data (**5**). At this point, the curb ramp designer asserts engineering judgement and chooses the most suitable ramp design for the given site conditions (**6**).

This chosen ramp design is then evaluated for technical feasibility based on the PennDOT design requirements outlined above as well as whether any additional site constraints are present (**7**). Possible site constraints that could cause technical infeasibility include:

- Violating any of the PennDOT requirements, minimums, & maximums
- Roadway Profile Slope

- Limited Right-of-Way
- Existing utilities
- Existing buildings, walls, or vaults
- Environmental Impacts
- Historical Impacts
- Safety Hazards

If the chosen curb ramp design is determined to be technically infeasible, a TIF is generated in CSV format for input to Excel, and then the final CADD drawings are exported (**7A**).

If the chosen curb ramp design is determined to be technically feasible, then no TIF is generated and the final CADD drawings are exported (**8**).

Potential Methods of Implementation

CADD files which are generated from survey data may be exported as .DWG or .DXF file types. These file types may be analyzed and modified computationally through the open-source Software Development Kits (SKDs) published and maintained by the Open Design Appliance (ODA). For analogous tools developed with these protocols, see their member showcase5. For more information about the creation of CADD files of the built environment from survey data and the benefits and detriments to each method, see Appendix A.

Conclusion

The process architecture developed presents a blueprint for the means by which a curb ramp design tool may be created, in which the tool outputs a designed ramp that is compliant to the maximum extent feasible along with data about the new ramp. This includes a description of the necessary physical site parameters to determine through spatial mathematical analysis, the various heuristics and guidelines for choosing the most appropriate curb ramp type, the requirements, and recommendations outlined by PennDOT for curb ramp designs, as well as potential site parameters that may cause technical infeasibility. Open-source development resources for creating software that analyzes 3-D CADD data, such as the provided by the Open Design Alliance, provide a potential platform for the development of such a tool.

PennDOT Sources

PennDOT Pedestrian Facilities Pocket Guide
Chapter 6 Pedestrian Facilities and the Americans with Disabilities Act
RC-67M Curb Ramps and Sidewalks

Appendix A: Curb Ramp Design Process Flow
Based on the interviews conducted as a part of the needs assessment of the curb-ramp design process in Task 6, the CIS tool provided only minor benefits in the curb-ramp design phase in its current form. From the discussions in these interviews and additional research into the steps required to install or repair ADA-compliant curb ramps from start to finish, a process flow was

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5 https://www.opendesign.com/member-showcase

developed to outline the major data inputs, required decisions, potential bottlenecks, as well as strengths and weaknesses of different aspects of the ADA-curb ramp process. In addition, this process flow demonstrates the places where the CIS tool may provide additional value in both the data-gathering and surveying steps as well as in the decision making on an asset-management scale.

The process flow developed overviews each step to go from the requirement of a curb ramp to the successful installation or repair of an ADA-compliant curb ramp with the proper inspection forms submitted. The majority of the information in this report comes directly from the interviews conducted with curb ramp designers who are familiar with this process. Some key insights include (1) the importance of precise, accurate, and detailed survey data in the curb ramp design phase, (2) the potential for use of the CIS tool in the surveying phase and as helpful in a higher-level asset management capacity, and (3) the visual understanding of where delays may occur in the process of installing or repairing an ADA-compliant curb ramp.

Appendix A1: High-Level Process Flow
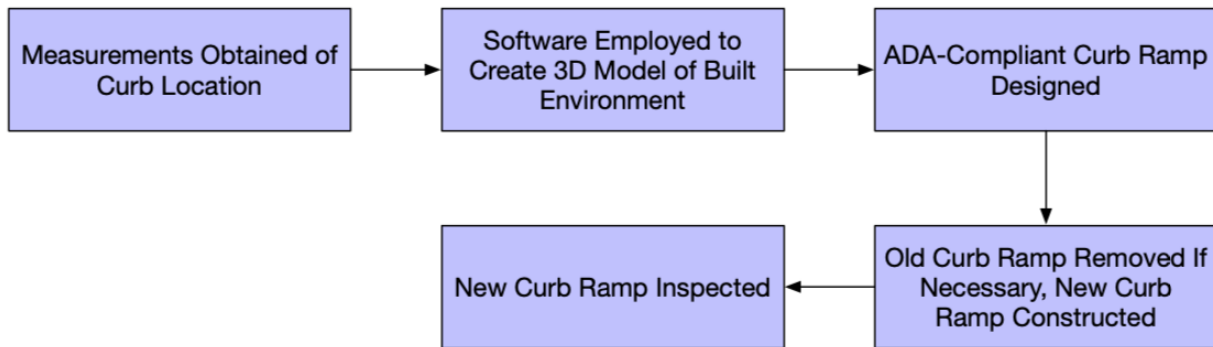
This higher-level process flow helps to summarize the general steps of installing or repairing a curb ramp. First, measurements are obtained from the site where the curb ramp is installed. From this measurement data, software is used to create a 3D model of the site, and then an ADA-compliant curb ramp is designed using this model. A contractor then constructs the designed ramp, and later this ramp is inspected to assess compliance with ADA regulations. This general understanding is helpful when viewing the detailed processes flow because of the many contingencies and potentials for errors and delays that come with each step. For instance, the choice of survey measurement method or technical infeasibility of a curb ramp pose challenges and decisions to make; these are covered below in the detailed process flow.

Appendix A2: Detailed Process Flow

See PDF for the full Process Flow flowchart. The flow chart is organized such that each row corresponds to a letter and each block in a row is assigned a number. For instance, the first decision block "Survey Method?" is assigned the alphanumeric code "A1". For a simpler discussion of the process flow, each aspect will be referred to as its alphanumeric code in the rest of the report.

**Appendix A3: Detailed Process Flow Discussion**

Starting from A1, the method of surveying measurement must be chosen. This can be either

traditional surveying with levels and measurement wheels, non-contact photographic measurement, or non-contact LIDAR6 measurement (B1-3). Each method has distinct strength and weaknesses, which are explored later in this report. Based on the type of survey conducted, this data is processed via software (C1-3) that creates a 3D model of the built environment surveyed (D1).

Using this 3D model, an ADA curb ramp can be designed to fit the conditions of the site (E1). If the site design features do not comply with established ADA criteria and standards (F1 answered no) then the design plans and a Technically Infeasible Form (TIF) identifying the reasons that those requirements cannot be met must be submitted to the ADA committee (F2). If the design and TIF are accepted (G2 answered yes), then the design is given to a contractor to attempt to build the new curb ramp as designed (I1). If the TIF is not accepted, then it must be modified based on comments and revisions and resubmitted (I2) If the site possesses design features that preclude a ramp design that meets established criteria and standards (F1 answered yes), then the design may be submitted to the PennDOT ADA 7 (G1). If the committee does not approve the design, then it must be modified based on comments and suggested revisions (H1). If it is approved, then a contractor may remove the ramp if one exists and then build the newly designed ramp (I1). If a contractor discovers the design is not technically feasible, for instance, due to an unknown subsurface feature such as a pipe, then a TIF form must be submitted (F2) and accepted (G2). If the contractor installs the ramp as designed and approved, then it can be inspected (K2). If the inspection shows the curb ramp does not comply with ADA regulations and it does not have an accepted TIF, then the non-compliant ramp must be torn down (K1) and then rebuilt (I1). If the ramp is compliant or aligns with its accepted TIF, then a CS-4401 form is completed and uploaded to a database (L1) and the process is complete.

This detailed outline shows that there are many different contingencies and places for the process to be derailed. It also demonstrates that there are a few choices that curb ramp designers must make that guide their design; namely, this includes the selection of the type of survey data. Below, the advantages and disadvantages of different types of survey measurement are discussed. In addition, the current and potential future role of the CIS tool in each step of this process flow is discussed below.

Strengths and Weaknesses of Different Survey Data Sources
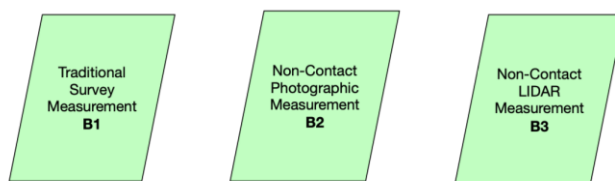
All interviewees from Task 6 emphasized the great importance of high-quality survey data in the

6 LIDAR is a surveying method that measures distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor.
7 Some Districts do not require review of ramp designs which meet established parameters. However, many designers/contractors prefer the committee to review the design to confirm that the ramp is compliant within established parameters.

curb ramp design phase. These interviewees summarized the various types of survey data commonly used to create a 3D Computer-Aided Design (CAD) model of the built environment such that a ramp may be best designed to suit the needs of a particular site. In general, the interviewees from Task 6 indicated that they preferred a non-contact surveying method such as LIDAR. However, they explained that LIDAR is often expensive, cumbersome, and requires specialized computing power to process the data. Another disadvantage to LIDAR systems is that they require a clear line of sight to the curb ramp, which means that obstructions (i.e. cars, pedestrians) must be accounted for. Some curb-ramp designers interviewed suggested that, if given the opportunity to select their survey data, that they would choose LIDAR for its high precision, accuracy, and resolution of the 3D CAD model that it creates.

Despite this, often the surveying has already been completed, and traditional surveying measurement with levels and measurement wheels is still the most common method according to the interviewees. Based on this, the traditional survey is advantageous because it is easier to complete and is generally less expensive. Curb ramp designers said that traditional survey data requires more interpolation in CAD modeling and therefore gives them a lower-quality model of the built environment. This can impact the probability of successful construction of the designed curb ramp. In addition, human error places a larger role in the collection of traditional survey data versus computation methods such as LIDAR.

In addition, one curb ramp designer suggested the use of non-contact photogrammetry methods, in which photographs are taken of the built environment at regular intervals and processed to computationally produce a 3D CAD model of the built environment. This method, although less common among our interviewees, is a promising survey data source. Photogrammetry, or surveying and measuring with the use of photography, combines the higher accuracy and precision as well as non-contact advantages of LIDAR with the lower cost and ease-of-use of traditional survey methods. Examples of software packages that enable this type of surveying include ContextCapture from Bentley Systems. Software such as ContextCapture can be used along with photographs from either a standalone camera or mobile phone/tablet camera to produce a detailed 3D model of the built environment.
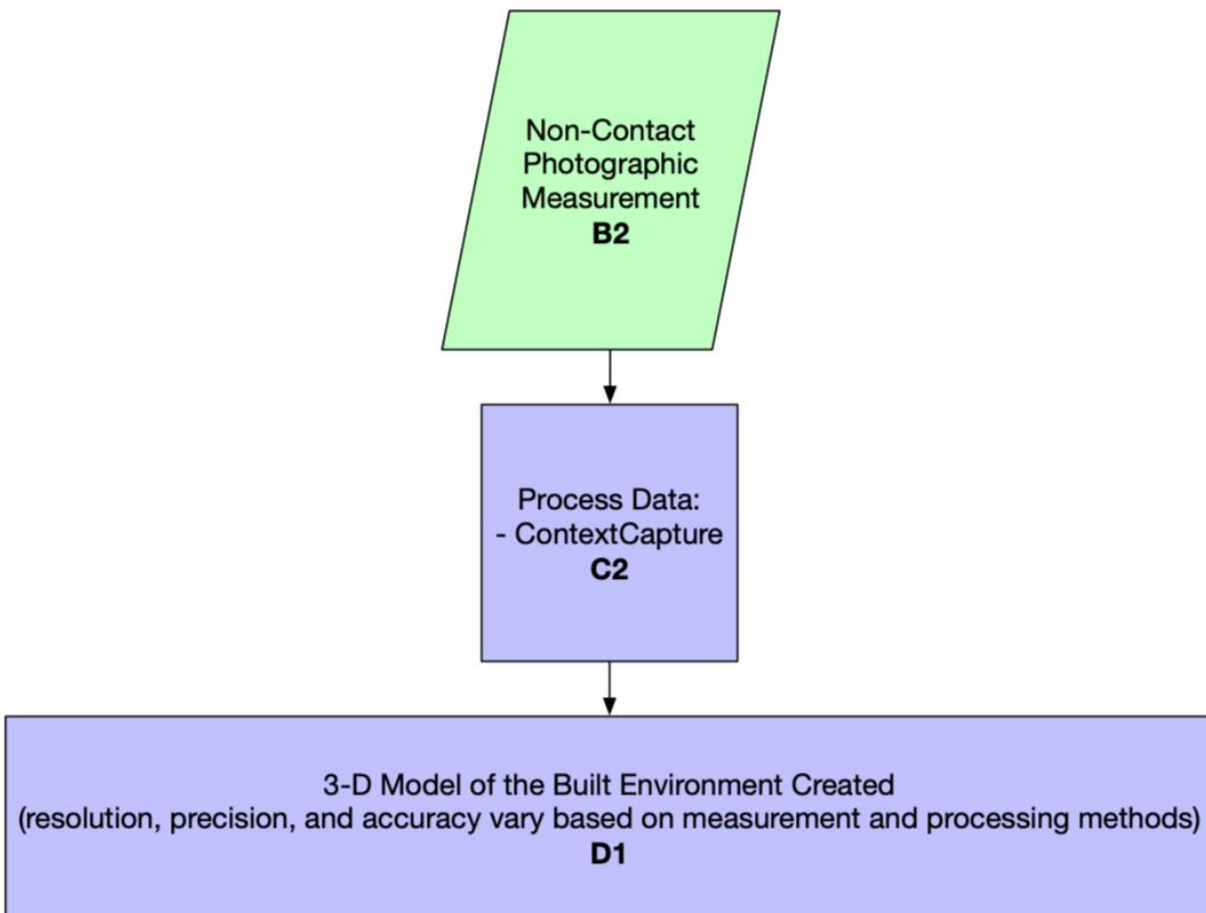
Role of CIS Tool

The CIS tool has a few key areas in which it can provide value to the curb ramp process. These areas include (1) curb ramp inspection, (2) asset management decision making based on historical CIS data, and (3) the potential for photogrammetry via the CIS tablet computer.
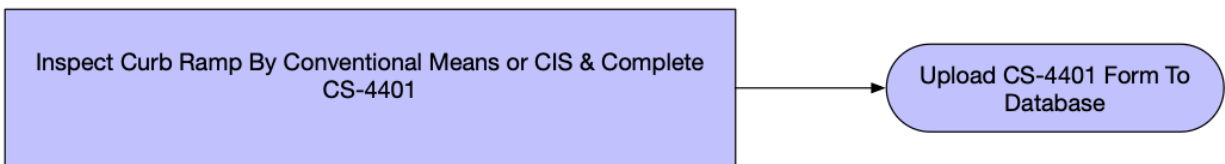
In curb ramp inspection, the value of the CIS tool is apparent. In step K1 of the process flow, the curb ramp inspection occurs, and may either be completed by traditional methods

(levels and measure wheels) or via the CIS tool.   Beyond the established benefits of the CIS tool in inspection, using the CIS can seamlessly upload curb ramp data to a database. This data, over time, could be accumulated to form a large set of data regarding the measurements of curb ramps within a city or municipality. Based on initial conversations with interviewees from Task 6, this historical CIS data could be useful on a larger scale when deciding which curb ramps to replace and rebuild first. Therefore, the CIS tool may prove useful in the asset management of curb ramps and the prioritization of ramps which are the farthest from ADA-compliance and which pose the most risk.

Non-Contact Photographic Measurement
B2

Process Data:
- ContextCapture
C2

3-D Model of the Built Environment Created
(resolution, precision, and accuracy vary based on measurement and processing methods)
D1

In addition to the inspection and potential helpfulness in asset management of the CIS tool, there may also be potential for usefulness in the surveying phase. Non-contact measurement of the built environment via photogrammetry (step B2 above) is possible using the camera which is part of the mobile tablet computer (iPad Mini) attached to the CIS device.

In investigating the potential for the CIS tablet computer in photogrammetric surveying, ContextCapture Mobile as well as the ContextCapture Cloud Processing Service from Bentley Systems, were found as examples of software that could enable the CIS tablet computer to collect this kind of survey data. There are also tutorials from Bentley Systems in which this sort of data is used to model and then redesign an ADA-compliant curb ramp. Non-contact survey measurement via photographs is an interesting manner in which the CIS tool may prove to be useful in the curb ramp design phase, and this application should be explored more thoroughly in

the future to increase the usefulness of the CIS tool for curb ramp designers.

Appendix A4: Detailed Curb Ramp Design Process Flow Conclusions

The process flow developed from the interviewee information as well as additional research demonstrates the areas in which the CIS tool may provide value in its current state, as well as areas for future development of the CIS. In particular, the use of the CIS tablet computer to conduct photogrammetric surveying may greatly increase its usefulness in the design stages. Further, the continued collection of CIS data over time may provide value on a larger scale in prioritizing certain redesigns or repairs over others. In addition, the outlined process flow shows the many different decision points and ways in which the curb ramp installation or repair process may be delayed. Overall, this process flow visually demonstrates the information gathered from interviewees in Task 6 and provides insight into the role of the CIS in each stage of the process.

Appendix A5: Interviewee Sources

- Gesinski, Johnathan. Personal Interview. 26 July 2018.
- Telega, Ed. Personal Interview. 9 August 2018.
- Langan, David. Personal Interview. 15 August 2018.
- Stanton, Sean; Duong, Tuan; Dougherty, Anthony. Personal Interview. 20 September 2018
- Johnson, Corey; Bacheson, Ed. Personal Interview. 21 September 2018.

Appendix A6: Detailed Process Architecture Flow Chart

See next page

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