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Safe Intersection Crossing for Pedestrians with Disabilities

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FINAL RESEARCH REPORT

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Safe Intersection Crossing for Pedestrians with Disabilities

Mobility21 Project # 40459.14.1080376
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Final Report

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1. Overview

In this report, we summarize work performed under Mobility21 Project #40459.14.1080376. The focus of this project has been on addressing some remaining obstacles to the general deployment of PedPal, a smartphone app that assists pedestrians with disabilities in safely crossing signalized intersections. Specifically, work has centered mainly on the design and development of two new capabilities: (1) an approach to localization that is accurate enough to enable detection of pedestrian arrival at a given corner of the intersection as well as active monitoring of progress during crossing, and (2) a scalable V2I/P2I communication infrastructure.

With regard to localization, work has focused on utilizing the increasing availability of ultra-wideband (UWB) sensors to overcome the inaccuracy of Bluetooth beacons positioned at intersection corners. Experiments have been performed to verify the accuracy of UWB devices in this context, extensions to the app have been implemented to allow receipt of distance data from UWB sensors positioned at the intersection, and algorithms have been developed for both reliable identification of intersection corners and for tracking of pedestrian progress through the intersection.

To achieve scalability of operations as the number of PedPal users traveling through a given traffic signal network increases, a hierarchical, cloud-based communication infrastructure has been designed for pushing information about specific intersections to PedPal users in their vicinity, and for mapping PedPal requests back to these intersections. Under this design, the signal network is partitioned regionally into clusters of intersections, and a separate cloud server is provided to service each cluster. A single root server is responsible for directing communications from various PedPal user processes to the appropriate regional server.

Finally, progress has also been made toward generalizing the PedPal app to accommodate complex signalized intersections where there are more than two timing phases; specifically those that additionally incorporate protected left turn phases and/or a separate "All Ped" crossing phase. An algorithm that generalizes the interpretation of MapData (MAP) and Signal Phase and Timing (SPaT) messages being broadcast from the intersection to address these more complex phasing alternatives has been developed.

In the sections below, we describe these accomplishments in more detail. In section 2 we first establish context by providing some background on the PedPal smartphone app and its initial development within the FHWA Accessible Transportation Technology Research Initiative (ATTRI) program. In Sections 3,4, and 5, we then summarize accomplishments made possible by enhanced localization ability, cloud-based communication infrastructure, and generalization of MAP, SPaT message interpretation respectively. In Section 6, we draw conclusions and summarize current research efforts aimed at expanding PedPal functionality to provide broader support for the "Complete Trip".

2. The PedPal Smartphone App

PedPal is a mobile smartphone app designed to assist pedestrians with disabilities in safely crossing signalized intersections. It was developed originally as part of the Federal Highway Administration's (FHWA's) Accessible Transportation Technology Research Initiative (ATTRI) program. [1,2] PedPal utilizes "connected vehicle" technology to interact directly with signalized intersections, and through integration with the Surtrac real-time adaptive traffic control system, it gives pedestrians the ability to actively influence traffic control decisions to enhance their safety and mobility. Most basically, PedPal communicates a pedestrian's crossing time requirements along with the desired crossing direction, ensuring that the pedestrian receives sufficient time to cross when the crossing signal is given while eliminating the need to locate and push a pedestrian call button at the corner to indicate presence. PedPal is also capable of dynamically extending the crossing time in circumstances where the user is moving slower than expected, and, if provided with pedestrian route information, PedPal can factor estimated pedestrian arrival times into the signal timing plans that are generated over time to streamline overall crossing time. PedPal currently runs on an iPhone and exploits the iPhone's native accessibility features (voiceover, haptic feedback, zoom, etc.) to provide a multi-modal user interface.

As part of original PedPal development effort, structured user field tests of the technology were carried out periodically at selected intersections in the Pittsburgh Surtrac deployment by members of the local disability community, including blind individuals, wheelchair users, elderly individuals, and hearing-impaired persons. In these tests, the user response has been overwhelmingly positive, and the feedback obtained has served to refine and improve the app's feature set and user interface. In addition, results have been produced that quantify the potential safety and mobility benefits over current intersection crossing practice. Full details of the user study conducted can be found in [1].

At the same time, to achieve the desired user experience in the field test, some amount of "Wizard of Oz" experimental assumptions were introduced. Specifically, automatic recognition of intersection corners by the app upon arrival was simulated by manually sending a signal to the app at the appropriate time, to overcome the inaccuracy of the smartphone's localization capability.

In this project, we proposed to undertake work to address these key remaining obstacles to deployment. First, we developed localization techniques that enable real-time monitoring of crossing progress and detection of veering outside of the crosswalk, building on our recent success in using Bluetooth Beacons positioned at intersection corners in conjunction with smartphone localization capabilities to do automated corner identification. Second, we generalized the current PedPal app, which was designed to operate at simple, 2-phase intersections (north-south and east-west), to handle complex intersections with multiple protected turning phases. Finally, with matching support from Rapid Flow Technologies Inc., the most likely PedPal deployment partner, we developed a fully scalable, cloud-based V2I and P2I infrastructure for deploying the enhanced PedPal mobile app. Field test experiments were conducted periodically to validate and refine each of these proposed capabilities. The technical scope of the proposed work is described in more detail below.

3. Corner Identification and Real-Time Tracking

To detect arrival at an intersection corner and to track pedestrian crossing progress through an intersection, the PedPal app needs the ability to accurately compute its current location. Unfortunately, however, early tests showed that the native localization capability provided by the smartphone itself (in this case an iPhone) did not provide sufficient accuracy to support these capabilities. To address this problem, it was decided that the most viable approach was to extend the infrastructure at the intersection, by adding stationary beacons (with precisely known locations) to each corner of a Surtrac-controlled intersection.

Initial experimentation centered around the placement and use of weather-resistant Bluetooth beacons. The Surtrac-controlled test intersection at Centre Avenue and Cypress Avenue in Pittsburgh's East End was equipped with four Estimote Bluetooth beacons (priced at approximately $35 each) and associated software was used to broadcast distance information to the PedPal app. The results obtained were mixed. Distance information received from the beacons was accurate enough for a proof of principle demonstration of the feasibility of recognizing corners, but it was equally clear that introduction of the beacons would not in and of itself be sufficient to enable an ability to reliably track pedestrian progress through the intersection, nor would it enable an ability to recognize when a PedPal user moved outside of the crosswalk. It was hypothesized that achievement of both of these latter capabilities would require real-time integration of Bluetooth beacon outputs with those produced by the phone's native sensors, along with additional signal filtering techniques to reduce uncertainty. One original goal of the project was to develop such an improved localization capability.

However, the recent emergence of Ultra Wide Band (UWB) communication devices provides the basis for realizing much higher-accuracy stationary beacons, and effectively eliminates the need for any additional sensor fusion and filtering techniques to achieve adequate localization capability. Take Apple's recently introduced AirTag sensors, for example, which are attached to objects and communicate via UWB to a user's phone for the purpose of retrieving them when they become misplaced. These devices are advertised as having localization accuracy on the order of a few centimeters, and our initial testing in noise free environments confirms this level of accuracy. Although this precision will no doubt degrade in situations where there is significant surrounding noise, but we would still expect one or two orders of magnitude improvement over Bluetooth beacon performance. UWB technology is also inexpensive and of similar physical size; an AirTag, for example, is priced at under $30 and is only slightly larger than a US Quarter.

Starting with the iPhone 12, all newer iPhone models come equipped with a UWB chip, and Apple IOS provides a standard API called "Nearby Interaction" for interacting with third-party UAB devices. Unfortunately, the AirTag device itself currently interacts with the iPhone through a separate, non-public interface, so it not possible for us to directly use AirTags as stationary corner beacons. But other third-party UWB devices do exist, and before long will be configured with power for mounting at the intersection to communicate distance information to apps such as PedPap through the Nearby Interaction API. So it is reasonable to assume UWB to be viable foundation for tracking pedestrian progress and detecting pedestrian movement outside of the crosswalk within PedPal. To provide a basis for validating this assumption and demonstrating these capabilities, we take advantage of the iPhone's capability to interact with other UWB equipped iPhones through the Nearby Interaction API, and place an iPhone at each corner to serve as a surrogate for the eventual (much cheaper) UWB stationary beacon.

With the above intersection infrastructure assumptions in place, solutions were developed for three separate detection problems: (1) corner detection, (2) pedestrian progress tracking, and (3) detection of pedestrian moving outside of the crosswalk. Let's consider each in turn.

3.1 Corner Detection

The problem of detecting corners is two-fold. First, as the PedPal user approaches an intersection, a mechanism is needed to recognize when the user is close enough for PedPal to communicate corner information and crossing options to the user. When communicating with the intersection via DSRC radios, PedPal may be simultaneously receiving MAP and SPaT information from multiple intersections, and the issue is one of determining which intersection is actually the next to be encountered. When using PedPal's current cloud-based service for communicating with intersections (see Section 4 below), which is the basic assumption moving forward, the issue is determining when the PedPal user is close enough to an intersection to start broadcasting MAP and SPaT messages. Once PedPal has confirmed arrival at an intersection corner to its user, the second task is to detect arrival at the destination corner at the completion of a street crossing, so that the PedPal app can change its visual/audio communication to its user from conveying the remaining time left to cross to indicating the new street-crossing state at the destination corner.

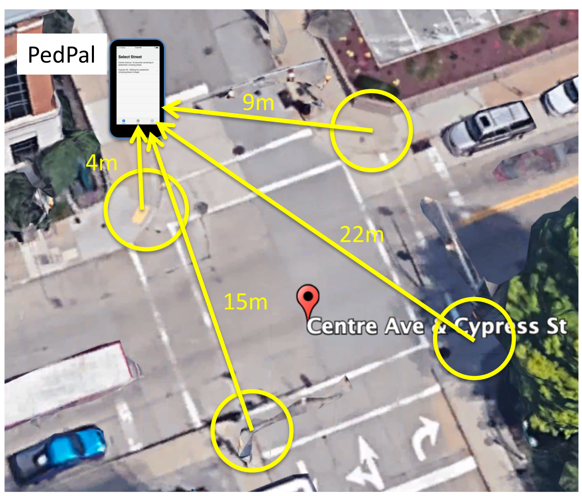

Figure 1: Detecting corners with PedPal. A circular geo-fence is associated with each intersection corner beacon. An approaching PedPal user receives distance readings from each corner beacon. When a reading within a geo-fence is observed, the corner is detected.

A simple geo-fencing approach is used to address both of these issues. As illustrated in Figure 1, we specify a circle of radius *r* meters around the known <latitude, longitude> pairs designating each corner of the intersection being approached. (These coordinates are known by each corner beacon, and are also encoded in the intersection's MAP message.) When PedPal receives a distance reading from a corner beacon that is inside of its geo-fence, then the cloud server is triggered to start broadcasting MAP, SPaT messages from the corresponding intersection. At this point, PedPal begins communicating crossing options to its user, and is poised to send a crossing request to the cloud server. Once the user submits the request and is subsequently informed that it is time to cross, the PedPal app shifts to advising the user on how much time remains to get across in the chosen direction. At this point, the destination corner is known, and when a distance reading to this corner is observed inside of its radius, the app announces arrival and displays potential crossing options from this corner. If the user instead chooses to leave the intersection after completing a cross, then detection of a distance reading from the corner beacon that places the app outside of the geo-fence will trigger a signal to the cloud server to cease broadcasting MAP and SPaT messages from this intersection to the app.

To evaluate the viability of this approach we conducted two experiments. Using three UWB-equipped iPhones as surrogates for eventual (cheaper) UWB sensors at each corner, we positioned them spatially into a NE, NW, and SE intersection configuration. A fourth iPhone was then used to host the PedPal app and communicate with the "beacons", and an intersection simulator was then connected to the app to provide signal phase and timing information. The PedPal app itself was instrumented to highlight the moment that PedPal detects that it is within *r* meters of a corner.

The first test was to simulate an initial approach to the NE corner of the intersection configuration, followed by a succession of 9 "virtual" street crossings (from one corner beacon to another). In all 10 instances, the approaching corner was correctly recognized by the PedPal app within 1 second of crossing into the geo-fence (where radius *r* was set to 2 meters).

As a second experiment, the accuracy of the distance reading received by a given corner beacon was measured at different distances. The results are shown in Table 1. It can be seen that accuracy tends to diminish slightly as the distance to the corner increases, but overall the accuracy remains strong. Although it is likely that detection accuracy will suffer somewhat in the midst of the interference present at an actual intersection, there is little doubt that this approach to corner detection will be effective.

PedPal Distance from corner	**Average Distance Reading**	**Variance**
1 meter	.91 meters	< 0.05 meters
4 meters	4.1 meters	< 0.25 meters
9.14 meters	9.45 meters	< 0.50 meters

Table 1: Accuracy of Distance Readings

3.2 Tracking Pedestrian Progress

Given the observed accuracy of UWB in detecting corners, the problem of real-time tracking of a PedPal user through the intersection also becomes feasible. The approach adopted is depicted in Figure 2. Since crossing intent has already been declared by the user, the PedPal app can localize its analysis to the distance readings received by the beacons located at the source and destination corners of the cross. At regular intervals (i.e., every *s* seconds), PedPal collects the latest distance readings received from these two beacons, and this information is combined with current phase duration countdown information (provided by the intersection's SPaT messages) and knowledge of the amount of crossing time that has already elapsed to determine a rate of progress, defined as the distance being traversed by the pedestrian per second. This rate of progress is then used to estimate the amount of time required for the pedestrian to complete the crossing, and compared with the amount of time left in the phase to determine whether the phase should be dynamically extended to accommodate a user that is moving slower than expected.

Several refinements of this basic strategy are currently being explored as a means of improving the accuracy of this rate of progress computation, including incorporation of a bias toward more recent distance-per-second calculations to account for circumstances where the user has unexpectedly stopped, slowed down dramatically, or has recently sped up. Once such refinements are in place we intend to analyze their respective advantages and disadvantages.

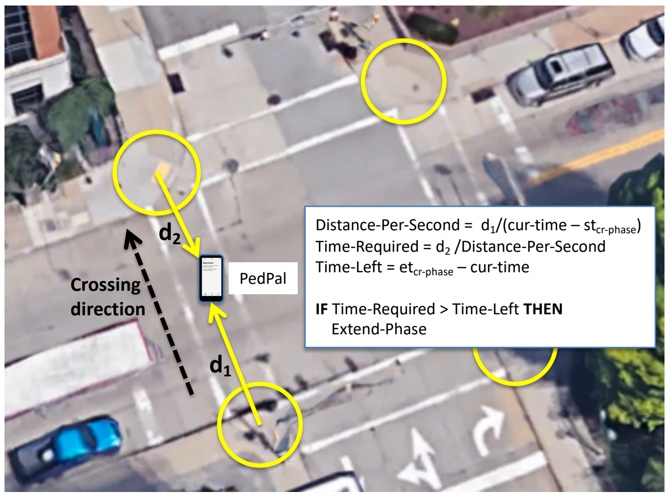

Figure 2: Tracking pedestrian progress

3.3 Detecting movement outside of the crosswalk

The use of UWB corner beacons also provides a reasonable basis for detecting when a PedPal user moves outside of the crosswalk while crossing a signalized intersection. In this case, a triangularization approach that integrates distance information from 3 or more corner beacons is used to determine the <latitude, longitude> location of the PedPal device (and by extension, its user) at any point during the crossing. Once this location has been estimated, it can be situated with respect to the intersection crosswalk that connects the source and destination corners of the cross, which is represented in the intersection's MAP message as a rectangle with 4 defining <lat, long> corner locations. If the PedPal device location is found to be outside of the rectangle, then the user is alerted. Currently a haptic signal is used, which is designed to indicate the recovery direction (left or right) to take back into the crosswalk. One direction of current research concerns how to indicate a more graceful recovery path that angles back toward the destination corner rather than moving directly left or right, and then having to change directions a second time.

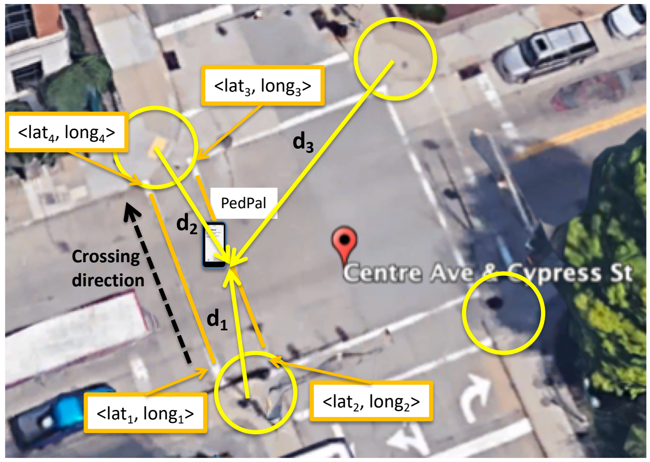

Figure 3: Detecting movement outside of the crosswalk

4.0 Scalable communication infrastructure

A second broad objective of the project has been to evolve PedPal's current cloud-based traveler-to-infrastructure (T2I) interface to Surtrac into a robust multi-user, network-wide communication infrastructure. Developed in Year 2 of the original FHWA ATTRI project to overcome the difficulties of working with Dedicated Short Range Communication (DSRC) radio technology, the principal focus was providing a mechanism to provide seamless support for the user field test experiments. Little attention was given to operational concerns such as multiple simultaneous users at an intersection and users moving through multiple intersections simultaneously throughout the signalized traffic network.

To address scalability issues we assume a hierarchical cloud server design. The root server acts as a message passing interface between individual PedPal users and the intersections that they are currently interacting with. The overall set of intersections in the network is partitioned geographically into n subnetworks, and management of information flows to and from intersections in each subnetwork is assigned to one of n regional cloud servers. Each regional cloud server maintains a list of all PedPal users that are currently active at one of its intersections, the state of their crossing requests, and the state of the signal groups at the intersections.

The diagram in Figure 4 shows the message flow within the overall system. When a given PedPal device detects that it is within the geo-fence that surrounds one of the corners of a given intersection, then the intersection will be triggered to start broadcasting the MAP and SPaT messages to the PedPal device, and the app will be able to start issuing crossing requests. The MAP message provides the geometry of the intersection, its streets, lanes, and crosswalks, and the correspondence between the lanes and the signal groups that control them. The SPaT message provides the current state of signal groups, i.e., the state (green, yellow, or red) of each of the signal groups and the amount of time each expects to remain in that state. Crossing requests to Surtrac are made through a Signal Request Message (SRM), which is relayed through the server to Surtrac. Surtrac responds to requests via a Signal Status Message (SSM), which is relayed through the server to the PedPal instance running on the device. PedPal monitors the SPaT information to tell the pedestrian when it is acceptable to cross and how much time remains to complete the cross. When the PedPal user has crossed the intersection and moves outside of the destination corner, then a signal is sent to the regional server to quit sending MAP/SPaT messages.

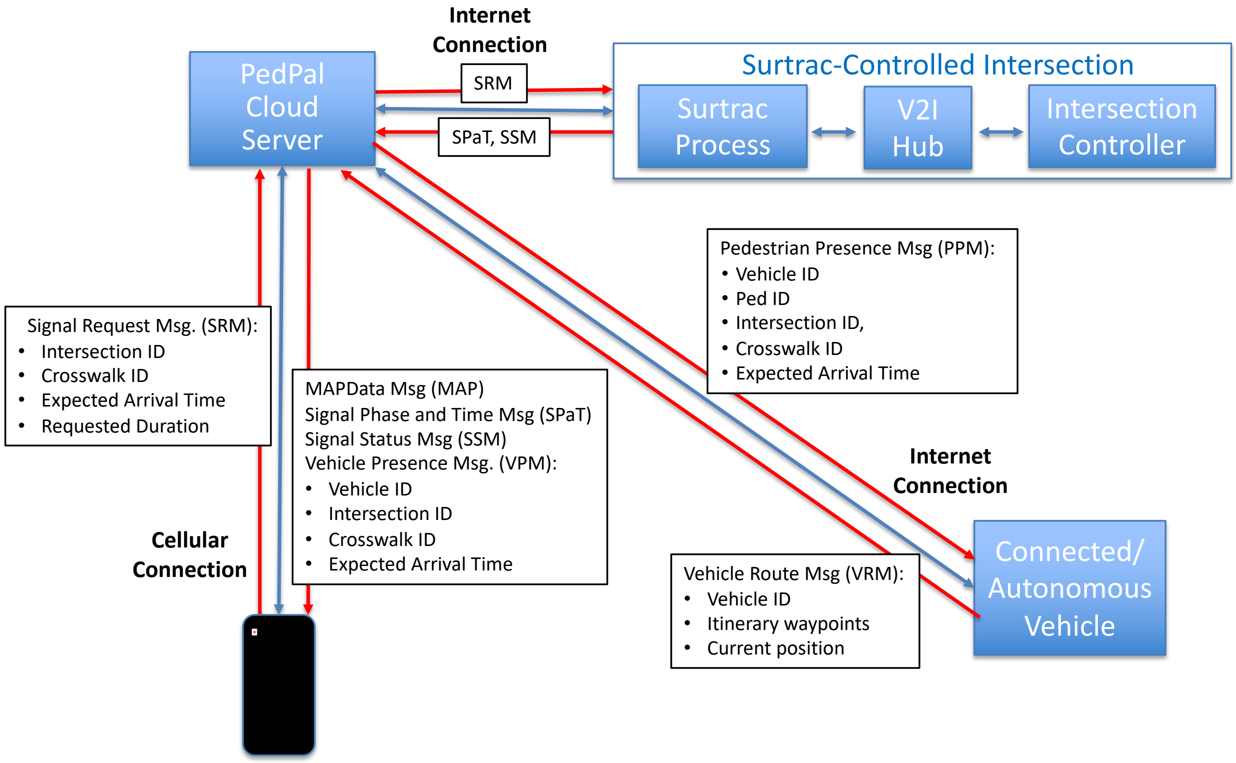

Figure 4: Message types and interactions between, PedPal device, the PedPal server , the Surtrac traffic signal system and external connected vehicles in the vicinity.

In addition to supporting the crossing capabilities of PedPal, the server coordinates crossing information between connected vehicles and pedestrians. Connected vehicles send a Vehicle Routing Messages (VRMs) to the server to provide their current and expected locations. The server compares the itineraries with the pedestrian crossing requests, resulting in notifications to both connected vehicles (via Pedestrian Presence Messages (PPM)) and pedestrians (via Vehicle Presence Messages (VPM)) that may come in close proximity to ensure extra caution.

5.0 Support for Complex Intersections

To signal to its user when it's time to cross and to indicate how much crossing time remains at any point, the PedPal app must know, for any given crosswalk, which signal groups to monitor in the SPaT messages being received. To simplify this requirement during original development of the PedPal app, the implementation assumed that all intersections would have only two crossing phases, a north/south crossing phase and an east/west crossing phase. In this section, we describe an extension to the standard MAP message that provides a basis for deriving this signal group information for more complex intersections with additional protected left turn phases and/or a separate "All Ped" phase, in addition to simpler 2-phase intersections.

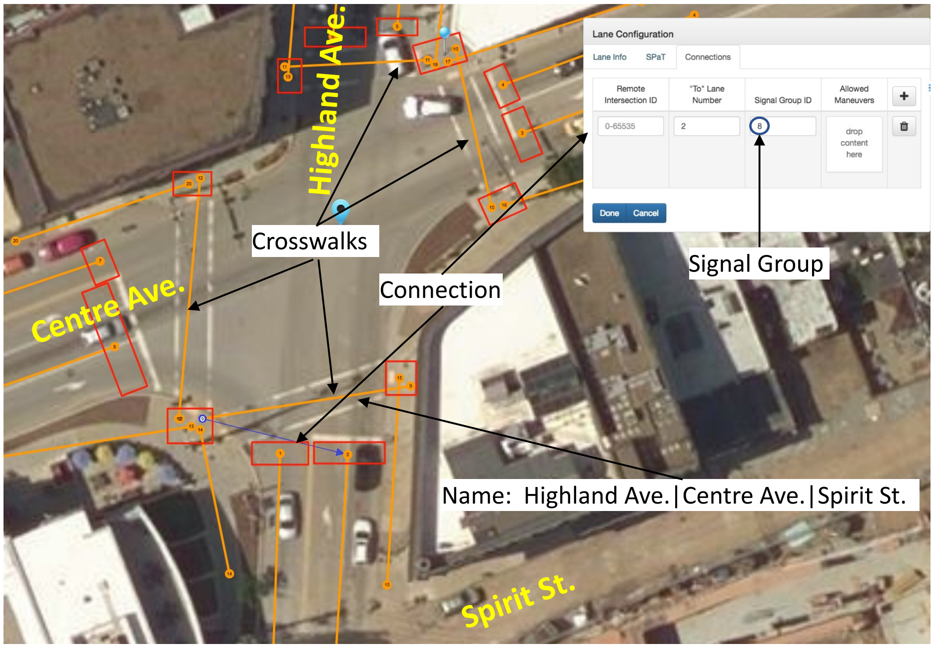

Figure 5: Crosswalk Connection Example

In specifying a MAP message, "connections" are defined to link the endpoints of various intersection crosswalks and lanes, and any given connection can be annotated with additional information. We take advantage of this construct to specify which signal groups need to be monitored to determine when and for how much longer a given crosswalk can be traversed. Specifically, the standard MAP message definition is extended to additionally include connections from each crosswalk to those lanes whose movements conflict and cannot be simultaneously active, and these new connections are annotated with the signal group that must be monitored.

Figure 5 shows a graphical representation of the extended MAP message for the intersection of Centre Ave. and Highland Ave. in the east end of Pittsburgh, PA. The southern east-west crosswalk, named *Highland Ave.|Centre Ave.|Spirit St.*, is represented as an orange line and has a connection (blue line) from its left start point to the top endpoint of the northbound lane (also represented in orange) on Highland Ave. The Lane Configuration dialog window shows the annotation associated with this connection, which designates signal group 8 as one that needs to be monitored. That is, this connector says that a pedestrian should not cross this crosswalk until signal group 8 is completed. Connections to other lanes can indicate additional signal groups that must also be monitored. For example, if this intersection also had separate, protected left phases, then the two northbound lanes on Highland would be instead modeled as separate lanes, with the connecter to the middle (left turn) lane indicating signal group 5, and the connector to the outer (northbound) lane indicating signal group 8 as before.

With these new connections in place, PedPal simply iterates over the "crosswalk-to-lane" connections associated with a given crosswalk to collect the set of signal groups that must be monitored.

6.0 Next Steps and Research Directions

The PedPal enhancements described in this report address key issues necessary for operational deployment of the smartphone app. The incorporation of UWB corner beacons at the intersection to overcome problems with the accuracy of smartphone localization has produced reliable capabilities for automatic corner detection (essential for a smooth user experience), for tracking user progress during street crossing and automatically extending the green time if necessary (to ensure safety if the user is moving slower than expected), and for detecting user movement outside of the crosswalk during crossing. Expansion of the PedPal cloud server infrastructure to support multiple users moving simultaneously through a network of signalized intersections satisfies another prerequisite requirement for general deployment. Finally, generalization of PedPal's algorithm for interpreting SPaT messages has extended its applicability to more complex intersections that involve protected left phases and/or and an "All Ped" phase.

We can identify a number of next steps with respect to transitioning the PedPal technology into operations, and enhancing its capabilities:

- One immediate next step is to design and carry out an extended set of user field tests to validate and refine new capabilities developed in this project. It is likely, for example, that our algorithms for tracking pedestrian progress when crossing the street, and detecting user movement outside of the crosswalk will benefit from subtle adjustments (e.g., incorporating some sort of distance bias to readings from different corners to improve accuracy). Likewise, experiments involving multiple simultaneous PedPal users are expected to improve overall system robustness (e.g., by identifying and mitigating potential race conditions).
- Another logical next step would be to develop the mechanics of making the PedPal app available to pedestrians with disabilities. One complication is the fact that PedPal sometimes causes Surtrac to set crossing phase durations that are contradictory to what Surtrac would have done on its own to minimize delay of all vehicles and travelers at or approaching the intersection. Although it makes sense to give this privilege to pedestrians with disabilities for safety purposes, it probably doesn't make sense to give this privilege to all pedestrians since it will lead to unnecessarily sub-optimal overall traffic flows. Hence, it may be necessary to acquire the app through some means of registration, rather than by straight download from the App Store.
- A third, slightly longer term next step aimed lessening the requirements for deploying PedPal would be to investigate development of a "PedPal lite" version of the app that eliminates the need to have Surtrac operating at the intersection. Instead, the PedPal-lite app would provide reduced functionality that can be achieved by integrating directly with the hardware controller running a conventional traffic signal control scheme at the intersection. For example, the app would provide the ability to communicate how much time its user needs to safely cross, based on knowledge of the user's average speed, but it would provide no ability to track user progress and dynamically extend the phase (since this requires a real-time smart signal system like Surtrac). Such an app could be deployed pervasively and immediately in any urban area. A proposal has been submitted to the Department of Transportation to develop and pilot test a PedPal lite app.

Looking further ahead, our current research is focused on expanding the scope of an app like PedPal to provide support for additional aspects of the "Complete Trip". Specifically, our objective is to create an expanded app that integrates solutions for:

- *Accessible route planning and navigation* – utilizing functionality from the smart phone app developed by pathVu, Inc., which utilizes previously collected data characterizing sidewalk conditions (referred to as pathVu's sidewalk database) to generate the most accessible routes for wheelchair users from specified origin and destination locations, and subsequently provides navigation instructions,
- *Safe intersection crossing*, building directly from the current PedPal smartphone app,
- *Coordination with Transit* - real-time coordination with approaching transit vehicles to streamline multi-modal pickup and drop off connections, and
- *Pedestrian to Vehicle (P2V) communication*, specifically to communicate pedestrian presence information to connected vehicles in the vicinity.

Motivated by a focus on wheelchair users, our target is to host the app on a hands-free wearable device, specifically an Apple watch, where user interaction is primarily speech driven. A companion part of the project if focused on providing autonomous wheelchair capabilities, including the ability to detect new obstacles and update the sidewalk data base, as well as allow the user to engage auto-pilot to navigate curb cuts or obstacles encountered along the way. We expect to have a prototype demonstration of this expanded app by June, 2022.

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[2] Vadakpat, G. S.F. Smith, Z.B. Rubinstein, and M. Bernardine Dias, "Technology to Make Signalized Intersections Safer for Pedestrians with Disabilities", *Public Roads*, 84(4): 17-21, Winter, 2021. (https://www.fhwa.dot.gov/publications/publicroads/21winter/index.cfm)