A FRAMEWORK FOR IMPROVED SAFETY AND ACCESSIBILITY THROUGH PEDESTRIAN GUIDANCE AND NAVIGATION

FINAL PROJECT REPORT

by

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16. Abstract

With the changes in America's demographics comes a need to provide improved accommodation of individuals with reduced capabilities. To date, our research has focused upon assistive pedestrian signal technologies for pedestrians with impaired vision. Such individuals must learn to cross complex intersections safely using a range of sensory inputs, including auditory cues from traffic surge and beaconing systems. Unfortunately, reduced vehicle noise, particularly for hybrid or electric vehicles, combined with increases in background sound levels, reduces the effectiveness of this approach. Furthermore, once the signal changes and the pedestrian starts to cross, there is very little communication with the pedestrian other than the possibility of active beaconing. The traffic controller has no way of knowing how far pedestrians have progressed and whether they are still in the crosswalk. This project is proposing the integration of commercial technologies commonly found in smartphones and other mobile electronics into a framework that will provide for pedestrian tracking and navigation. Such capability would allow the pedestrian signal device to take corrective action, such as providing navigational corrections or extending the walk signal (in extreme circumstances). With a "technology-neutral" framework (using a device other than a smartphone), this pedestrian support can be expanded to other avenues, such as railway crossings, bus terminals, and airports.

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Executive Summary

With changes in America's demographics, there will be a need to provide improved accommodation of individuals with reduced capabilities. In particular, pedestrians with impaired vision must learn to cross complex intersections using a range of sensory inputs, including auditory cues from traffic surge and beaconing systems. Unfortunately, reduced vehicle noise combined with increases in background sound levels has begun to reduce the effectiveness of this approach. There is also very little communication between the pedestrian and traffic controller resulting in no indication of the pedestrian's progression while crossing. This project worked to develop a framework that would allow pedestrian guidance and navigation with the use of a Smartphone or other mobile electronic. In an effort to provide more dynamic, real-time intersection data for the visually impaired, we worked to close the loop of control at the intersection by making the traffic controller aware of pedestrians in the vicinity.

The current project showed that we could not rely upon just one device to determine the location of a pedestrian with the accuracy needed. Instead, a fusion system needs to be developed so that multiple signals can aid in the precise location of a pedestrian within a 1.8 m wide crosswalk. An additional project will further explore the best system to use for accurate and fast data transfer between the pedestrian and the signal device.

Chapter 1 Introduction

With the changes in America's demographics comes a need to provide improved accommodation of individuals with reduced capabilities. To date, our research has focused upon assistive pedestrian signal technologies for pedestrians with impaired vision. Such individuals must learn to cross complex intersections safely using a range of sensory inputs, including auditory cues from traffic surge and beaconing systems. Unfortunately, reduced vehicle noise, particularly for hybrid or electric vehicles, combined with increases in background sound levels, reduces the effectiveness of this approach.

Furthermore, once the signal changes and the pedestrian starts to cross, there is very little communication with the pedestrian other than the possibility of active beaconing. The traffic controller has no way of knowing how far pedestrians have progressed and whether they are still in the crosswalk. This research sought to integrate commercial technologies commonly found in Smartphones and other mobile electronics into a framework that will provide for pedestrian tracking and navigation. Such capability would allow the pedestrian signal device to take corrective action, such as providing navigational corrections or extending the walk signal. With a "technology-neutral" framework (using a device other than a Smartphone), this pedestrian support can be expanded to other avenues, such as railway crossings, bus terminals, and airports. The immediate goals of the research were:

1. Develop a system framework for pedestrian location and navigation that can easily be integrated into existing infrastructure;
2. Develop and demonstrate a prototype system that is compatible with existing intersections;

3. Take the prototype to stakeholders to obtain reports of evaluations and assessments of the product; and
4. Hold training/education sessions for users to help further develop the device.

Due to unforeseen complications in the framework development, goals three and four were not able to be achieved. In addition, goal two was only partially developed and not fully tested with existing intersections as we had planned. However, there is a continuing project in the coming year that hopes to address these goals after a suitable framework is fully developed. We feel that it is most important to have a fully working framework than to rush into implementation and have the interface fail.

Chapter 2 Literature Review

Inspired by the commercial success of the Advanced Accessible Pedestrian System (AAPS), a system designed to improve intersection safety by audibly indicating the status of the walk signal, we set out to make the intersection an even safer place for pedestrians in the intersection. In today's AAPS-equipped intersections, when a pedestrian presses the button to cross a street, an audible message instructs the pedestrian to wait if the walk sign is not on, or informs the pedestrian the walk sign is on. When informed the walk sign is on, the pedestrian embarks on their trek across the street. At this point, AAPS has no information about what the pedestrian is actually doing. Use of location information from sources such as Global Positioning Systems (GPS) and Bluetooth devices is a possibility to solve this problem, but they can be limited in their accuracy and information provided.

2.1 Evolution of AAPS

The first pedestrian buttons consisted of an open push contact where the pedestrians placed a call by pressing the button causing a circuit to be completed allowing electrical current to flow. This current flow was then detected by the traffic controller indicating that a pedestrian desired to cross at the intersection. However, there was no feedback to the pedestrian that the call had actually been placed. In 1990, the Americans with Disabilities Act (ADA) made it imperative that information concerning the state of the traffic signals be communicated through multiple human sensory modes such as auditory and vibra-tactile. In other words, there must be feedback to the pedestrian that a call was placed. The result was that the complexity of pedestrian call systems radically increased. Bidirectional communications between the traffic controller and the pedestrian call button is needed to make the state of the pedestrian WALK and wait signal available to be sensed by human touch or hearing.

To try and alleviate some of the complexity, the Smart Signals concept was first investigated in 2004 to generate a computer-based architecture of an enabling technology that supported advanced capability for traffic signals based on distributed control concepts[1]. Based upon the recommendations of traffic professionals, we turned our research focus on accessible pedestrian controls. There were five guiding objectives dictating our design decisions and methodology for the Smart Signals based accessible pedestrian system: (1) The resulting system had to maintain or improve the existing level of pedestrian safety at signalized intersections; (2) The system must be able to be integrated with existing traffic controllers in such a way that traffic controller operation was not compromised (3) The system must be able to use existing pedestrian signal infrastructures; (4) The system design must provide capability to address current and future pedestrian control needs; (5) The installation and maintenance of the system must be simple and low cost.

Since then, we have been improving upon the system and exploring the introduction of new technologies such as a second speaker, passive pedestrian detection, preemption warnings, and now pedestrian location.

The next step in the development was driven by Section 1A.13 in the 2009 Manual for Uniform Traffic Control Devices (MUTCD)[2]. The MUTCD defines an accessible pedestrian signal as being a device that communicates information about pedestrian signal timing in non-visual formats such as audible tones, speech messages, and/or vibrating surfaces. An accessible pedestrian signal detector is defined as a device designated to assist the pedestrian who has visual or physical disabilities in activating the pedestrian phase. The modern pedestrian station where an individual generates an action or places his or her self in a position to be detected is responsible for relaying the calls to the traffic controller as well as providing information concerning the state of the visual traffic and pedestrian signals. The need for Accessible Pedestrian System (APS) installations at intersections using fixed time controls are sometimes overlooked because a WALK phase is always included in the traffic control scheme. However, visually impaired pedestrians still would benefit from additional indications to assist them in crossing at signalized intersections.

The practice of using chirps and cuckoo audible tones to indicate that the WALK signal is active has recently fallen out of favor since the limited information provided by the two tones was easy to misinterpret due to non-uniform intersection geometries. The audio signals are also subject to distortion from surrounding mechanical barriers, such as buildings, landscaping, vehicles at the intersection, and even wild life. More recent APS systems provide verbal messages that are more descriptive and less ambiguous to indicate the state of the signal controls as well as the corresponding direction.

Regardless of physical capability, pedestrians are finding it more challenging to cross safely at signalized intersections. Traffic timing schemes are now tailored to accommodate the needs for efficient vehicle movements. Unconventional intersection geometries and roundabouts are becoming more common. Pedestrians with low vision now face a daunting task of learning and remembering the peculiarities of numerous intersections. If a system that would allow constant communication with the pedestrian were available, these individuals may have an easier and safer time crossing unfamiliar or complicated intersections.

2.2 Accuracy of GPS and Bluetooth

Individuals use the GPS or even Bluetooth in their phone to determine their location, communicate with other devices, or map their path during a walk or run. When you are only trying to determine a total distance traveled or an approximate location while riding in a car, an accuracy of a few meters is fine. However, what if you were instead trying to cross an intersection without wandering into moving traffic? That could be an issue with current GPS and Bluetooth accuracies available for civilian use at an affordable cost.

Two studies at the University of New Mexico in 2009 and 2011[3,4] showed the accuracies of an iPhone and Android GPS were around 8 m and 5 to 8 m, respectively. These values were obtained using the assisted-GPS, which uses cell towers to aid in the positioning and reduces the time to initially locate the phone. If relying upon Wi-Fi or cell towers alone, the accuracies fall to 74 m and 600 m, respectively. Comparing these values to using a handheld device (3.5 m[6]) shows introducing a cell phone into the signal actually decreases the accuracy reading. A third party external GPS receiver can be used with a phone by connecting through Bluetooth that will improve the accuracy to 2.5 m. Although a fairly reasonable cost at $100[6], it is still not accurate enough to aid a pedestrian in crossing an intersection with a 1.8 m wide crosswalk. The military GPS service provides a more accurate GPS reading within 1 m and even centimeters[6]; however, this accuracy is obtained through augmentation systems currently available only for military use[7]. As with any GPS device, the accuracy of the signal also relies upon the environment. Interference from tall buildings, dense urban structures, and other conflicting signals can affect even the best GPS signal.

Chapter 3 Methods

Most of the time, the pedestrian is crossing the street within the bounds of the crosswalk, but it is trivial to envision a scenario in which this is not the case, such as a visually impaired pedestrian inadvertently wondering out of the crosswalk, or an elderly pedestrian falling while in the crosswalk. In such situations, the pedestrian is likely in a life-threatening situation and at the mercy of inattentive drivers. Ideally, a pedestrian-aware intersection could recognize this situation, and take measures to protect the pedestrian, (by putting the intersection into flash, for example, or turning all the lights red). Unfortunately, this is an impossible task for the current AAPS system today because it operates in what is called “open loop,” that is, the system has no information about the position or status of pedestrians or vehicles in the intersection. To further improve intersection safety, we must close this loop, and create an AAPS that is aware of the pedestrians it is protecting.

In an effort to make the intersection a safer place for the visually impaired, the elderly, and children, we have worked towards closing the loop of control in the intersection by making the traffic controller aware of pedestrians in its vicinity. This requires dynamic, real-time location estimation of pedestrians in need of assistance. To accomplish this, the research worked to engineer an architecture that uses innovative machine learning techniques to fuse together information derived from Smartphone sensors to produce a very accurate estimate the user's location.

The methodology for only goal one and part of goal two will be described, as that was the extent of the project due to complications listed earlier.

3.1 Goal 1: Develop a System Framework for Pedestrian Location and Navigation

To engineer the pedestrian-aware intersection, the first and most important requirement is to determine the physical location of the pedestrian the system is trying to protect. Because human lives may depend upon this protection, the mechanism to determine the location of the pedestrian must be extremely precise, with an estimation error less than a half meter. Secondly, the system must inform the pedestrian when they are on an unsafe trajectory or in an unsafe location and, if possible, guide the pedestrian back to safety or the system should put the intersection into a safe state if the pedestrian is unable to move. Finally, due to privacy concerns, AAPS must selectively track individuals; only those that desire or require the additional protection should be monitored. AAPS already has the foundation for this selection process: the extended button press. Currently, the extended button press, where a pedestrian presses the button and holds it down, indicates to the controller that there is a pedestrian that requires additional assistance. In future versions of AAPS, the extended press could serve as a sort of bonding mechanism between the controller and the pedestrian, enabling the controller to monitor and protect the individual.

The majority of the research and development conducted thus far has been focused on the first and most important requirement: estimating position of a pedestrian. Initially, GPS was considered as a potential option but was eliminated after brief experimentation demonstrated inadequate accuracy even under optimum conditions. Positional accuracy in typical conditions (such as an urban canyon or at an intersection) was much worse, on the order of five to six meters. Furthermore, we found significant variations between different models of GPS receivers, loosely correlated with cost; receivers costing tens of thousands of dollars are able to determine position to within about a meter but only after several minutes or offline data processing. As a result of these factors, we eliminated GPS as a stand-alone solution and investigated other alternatives.

One such alternative, indoor positioning systems (IPS), necessarily depend upon other techniques to locate a remote unit because GPS reception is non-existent. Many existing indoor positioning systems use signal integrity metrics derived from Bluetooth and Wireless Fidelity (Wi-Fi) communication links in an attempt to triangulate a remote device. The biggest challenge with these systems is the highly non-linear and environment dependent nature of radio frequency (RF) signal quality. Additionally, Bluetooth and Wi-Fi signal integrity metrics are not designed for determining distance; rather, they are intended to be used in determining if a transmitter is transmitting at adequate power levels, or a receiver has adequate sensitivity. For example the Bluetooth protocol specification mandates the use of one such metric, the Receive Signal Strength Indicator (RSSI) to dynamically negotiate optimum transmit power levels and receiver sensitivity in an effort to maintain a quality communication link. As a result, using such signal integrity metrics to determine distance between a remote unit and a base station often leads to error of the order of several meters, similar to GPS.

Concurrently exploring other alternatives, we researched dead-reckoning techniques. Dead-reckoning is the use of an inertial measurement unit (IMU) to calculate distance from a previously known position. Typically consisting of an accelerometer, compass, and a gyroscope, an IMU is very accurate when used to determine small changes in distance. Unfortunately, if an IMU is used exclusively over a long period of time or distance, the error accumulation (from the double integration of acceleration to determine distance) significantly degrades positional accuracy.

Ultimately, estimating position of a remote device or person with sub-meter accuracy is a very difficult problem and no single system (GPS, IPS, dead-reckoning) is presently known to have sufficient accuracy to reliably ensure the safety of disabled pedestrians. Consequently, our research focused on investigating the feasibility of combining information derived from each system, in real-time, in such a way that the resultant position estimation is more accurate than the sum of its parts. While this idea, called sensor fusion, is not new, surprisingly few systems demonstrate an effective implementation. Almost all examples of sensor fusion only combine GPS and an IMU, which is a fairly straightforward process. GPS is able to determine absolute position to within a few meters, and an IMU-based dead-reckoning system is able to determine differential position up to a few meters. Therefore, if we can correct the error introduced by GPS with an IMU-based system, and then correct the IMU-based system with an updated GPS position, we could potentially see a significant decrease in positional error. In fact, such a system is commonly employed in aircrafts and does improve positional accuracy. The algorithm used to "fuse" the GPS and IMU, is known as Kalman filtering: a two-step recursive process that uses statistical differences between the current measured values and the predicted values to form a weighted average which is then used to compensate for error in both sensors. Essentially, the Kalman filter is capable of mitigating the error from each sensor using other sensors in the system, but depends heavily upon the weights that are chosen for each sensor which indicate how "important" or "accurate" each sensor is.

With two sensors in the system, determining the importance of each sensor and measuring the error of each sensor is not a daunting task; with a GPS and an IMU, it makes sense when to rely on the IMU and when to rely on the GPS. For example, if the new GPS position indicates that the remote unit violated the laws of physics, we can disregard that position and rely on dead-reckoning techniques until the GPS position is more sensible. Conversely, sensible GPS position estimates can be used to compensate the error inherent to dead-reckoning systems. With more sensors, however, the problem becomes much more difficult. In our case, GPS and IPS both can both estimate an absolute position; so how much should we trust each estimate? When should we trust GPS over IPS or vice-versa? By how much and when should the IMU correct the error of IPS and GPS?

Asking such questions begins to reveal why sensor fusion is a difficult problem when employing conventional algorithmic and statistical models. Instead of taking an algorithmic approach, like a Kalman filter, we are developing a fundamentally different mechanism to combine sensory input modeled after the best example we have: the human brain. Human perception is a very effective implementation of sensor fusion. To illustrate this, envision what it would be like to perceive an object with only one sense (smell, for example). Chances are, you may not perceive it at all. If we add sound as another “sensor”, we can get much more information about the world. Adding more and more “sensors” (sight, touch, taste) allows us to perceive an additional dimension of the world. Applying the same logic to artificial sensors, it makes intuitive sense that the more sensors we have capable of determining distance or location in different (ideally orthogonal) ways, we should be able to combine these sensors in some way that reduces error.

Imitating the example we have, the human brain, we choose to create an artificial neural network (ANN) that takes as inputs the sensory information from an IMU, GPS, and Bluetooth signal integrity, and combines the information in such a way that results in the continuous optimum weighting of each sensor in the system at any given time. If, instead of interpreting this as an equation to be solved, we interpret it as a pattern to be matched, then we can exploit the excellent pattern-matching ability of ANNs in fusing the sensory input.

ANNs excel at pattern-matching problems when used appropriately and trained correctly, but do come with their set of challenges. An adequate topology (how the neurons are connected) is essential for a successful realization, along with an appropriate number of neurons and a suitable neuron activation function for the problem. Conventional ANN designs typically use guess-and-check methods for these parameters, which obviously can take a very long time with no guarantee of ever arriving at a solution. Once again, our design deviates from convention and employs evolutionary methods to evolve the topology, weights, interconnect, and the activation functions of each neuron in the neural network. In an effort to maximize computational efficiency and to minimize the time required to evaluate the neural network, we used technique called Cartesian Genetic Programming (CGP) which has been shown to be one of the fastest and most efficient methods to evolve an ANN.

3.2 Goal 2: Develop and Demonstrate a Prototype System

In parallel to the development of the Neuroevolutionary algorithm for sensor fusion, we developed the necessary firmware to collect the data that would be used to evolve the neural network. The initial test setup was kept to the simplest case of a single remote unit and a single base station. The remote unit, a PIC32MX7cK development board equipped with an accelometer, compass, and a RFCOMM Bluetooth module simply collected data from the accelometer and compass (forming a 6-axis IMU), and transmitted the information via Bluetooth link to a LM4F232 development board. The LM4F232 was responsible for receiving the IMU samples from the PIC32MX7cK via the Bluetooth link, capturing the signal integrity of the last transmission, and storing both the IMU samples, signal integrity measurements along with a timestamp to an SD card so the data could be analyzed later, and as training data for the evolution of the ANN.

While the details are omitted for the sake of brevity, both microcontrollers used FreeRTOS to manage various subcomponents within each microcontroller. Additional hardware was added the LM4F232 for the Bluetooth evaluation module (CC2564B, operating in the low-level HCI mode), and a free, open source Bluetooth stack called btStack was ported to the LM4F architecture. Employing advanced features of the low-level Bluetooth module, the CC2564B and modifying the open-source btStack enabled 4 dimensional quantifications of signal integrity: transmit power level (TXPL), two orthogonal RSSI measurements, and the Link Quality Indication (LQI).

We developed the firmware necessary for the initial experiments that will associate known distance with recorded signal integrity measurements, accelerometer and compass samples. Additionally, we have demonstrated the functionality (and efficiency) of applying Cartesian Genetic Programming to an ANN on test problems. Once we have collected sufficient data for the simplest case, we will use the data to evolve the ANN to predict linear distance, and demonstrate the effectiveness of using Neuroevolution based in Cartesian principles to solve the problem of sensor fusion. If successful, future research will use this architecture to close the loop in AAPS, and make the pedestrian-aware intersection a reality.

Chapter 4 Results

4.1 Goal 1: Develop a System Framework for Pedestrian Location and Navigation

To verify that the evolutionary method was training the ANN correctly, we used some simple expression regression problems, where an array of *n* inputs is mapped to *m* outputs via some arbitrary expression. Using these inputs and outputs as training data, the neural network would evolve to almost identically match the arbitrary expression. The time required to sufficiently reduce the error varied depending on the complexity of the mapping function, but given enough time and a big enough neural network with a sufficient number of training samples, the neuroevolutionary algorithm almost always ended up matching the test function.

Two different development boards were used to test some of the proposals. The Lidar and Radar ideas were judged to be infeasible given the resources available. One platform, the Cerebot 32MX7cK development board, was used to test an embedded GPS sensor, a Bluetooth transceiver, a MEMS accelerometer and a digital compass. Using FreeRTOS, the sensor data was logged to a USB flash drive (with FATfs as the file system and Microchip's USB stack) for later analysis. The other platform, TI's LM4F232 development board (equipped with a SD card, FATfs, and an analog accelometer) was equipped with a Bluetooth baseband module, TI's CC2564.

Using a Cerebot 32MX7cK and a PmodGPS, we collected GPS data in ideal conditions, found an error radius of (at best) 3 meters. The length of time required to attain the first fix was on the order of 10 minutes in what should've been ideal conditions. For the Signal Integrity Trilateration, the Cerebox 32MX7cK was connected to a Bluetooth module, the PmodBT2 and tested. The PmodBT2 is a Bluetooth module that is designed to be as simple as possible (plug and play). It worked well and the development time was minimal, but only the RSSI was available. The LM4F232, connected to TI's CC2564 served as the other module. This particular module was only compliant up to the link-layer but provided multiple signal quality metrics (LQI, RSSI, BER, TPL). To establish a link with the other module, an open-source Bluetooth protocol stack called BTstack, was ported to the development board with the Bluetooth baseband controller, and modified so the signal integrity metrics were available at the application layer. Once both devices were communicating with each other, the signal integrity of the Bluetooth communication channel was recorded over a 70 foot linear path with measurements two foot intervals. Plotting each signal integrity metric (LQI, RSSI, TPL, and BER) against distance suggested a complex, non-linear, time-varying relationship between distance and signal integrity.

4.2 Goal 2: Develop and Demonstrate a Prototype System

There were no quantifiable and reportable results at this time. Another project will further explore an appropriate system to allow communication between the pedestrian and the AAPS.

Chapter 5 Discussion

Each method we experimented with had its advantages, but none were adequate on their own. Therefore, we explored the possibility of combining all of the methods in such a way that the real-time position estimate is more accurate than what could be attained by any one method alone. To do that, we created a sensor fusion with two sources of absolute location estimation: Bluetooth signal integrity and a GPS. We also used dead-reckoning as a relative location estimation. The idea was to combine a dead-reckoning system based off a 9-axis IMU with GPS so that we could use the absolute position of the GPS to “correct” the error from the IMU, and the IMU to reduce error in GPS position. This idea assumed our pedestrians obey the laws of physics, and our sensors were error-free. As a result, if the change in position from the GPS implies the pedestrian has moved 30 m in less than a second, we could be fairly sure the GPS signal was not valid and ignore it and rely on the position from the dead-reckoning system.

This method would take into account the measurements available from each sensor system and weight each measurement according to how error-free the signal is. If one measurement is error-free, then that measurement is used completely. However, the question is how to find these measurements. There are many ways to accomplish this, but the most common is the Kalman Filter and the extended Kalman filter. Unfortunately, the Kalman filter depends entirely on a very accurate model of the sensors (with accurate noise models), and the accuracy of the initial state. So, if the sensors are off on determining the correct position of the pedestrian waiting to cross the intersection, the measurements will be incorrect as they are crossing the street. This negates the whole purpose of the locator. Additionally, if the noise model (buildings in the area, interference from other signals, etc.) is inaccurate or does not adapt to the environment, the filter will once again most likely put the pedestrian in an unsafe situation. Therefore, we do not want to rely strictly on the filter or a signal input to locate and guide a pedestrian.

The next steps in another project will examine the use of ultra-wideband radio to locate pedestrians. Recently, there have been a number of new technologies developed specifically for "indoor GPS", driven by needs in several areas. These include first responders such as firefighters in a burning building, commercial applications inside of shopping malls, and informational assistance in public venues such as airports or museums. It is our belief that one or more of these technologies will allow a pedestrian with supplemental electronics (possibly integrated into a Smartphone) to place a call, have the traffic controller track their progress, and provide navigational feedback if needed.

Chapter 6 Conclusions and Recommendations

This project demonstrated the complexity and lack of accurate location systems for use in pedestrian location while in an intersection. The lack of accuracy and interference from environmental sources, such as buildings and other broadcasting signals, indicated that an accurate system should be comprised of multiple sensors and there most likely will need to be machine learning involved. As such, the next steps will be to examine other possible locator sensors (e.g., ultra-wideband radio) that could provide a shorter connection time resulting in more accurate results.

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