Design and Development of a Visual Warning System for Worker Safety On Roadside Work zones

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Dedication

This thesis is dedicated to my family, my father Mohammad and my brother Amin without whose love, support and encouragement I could not even dream of the life I lead today and to the memory of my dearest late mother, Habibeh Sheikhnavehsi, who will always be my inspiration and my strength.

Abstract

Growing traffic on US roadways and heavy construction machinery on road construction sites pose a critical safety threat to construction workers. This writing summarizes the design and development of a worker safety system using Dedicated Short Range Communication (DSRC) to specifically address the workers' safety for the workers working around the heavy machinery. The proposed system has dual objectives. First objective is to improve workers' safety by providing visual guidance to the operators of the construction vehicles about the workers' presence in the vicinity. This visual guidance keeps the operators of the heavy machinery well informed about the whereabouts of the workers in close proximity while operating the heavy vehicle. The second objective of the proposed system is to improve the work-zone traffic mobility by dynamically posting suitable speed limits and other warning messages on the DSRC-equipped variable message signs (VMSs) depending on the workers' presence in an active work-zone to appropriately warn the drivers of the passing-by vehicles.

A prototype was developed and field tests were conducted to demonstrate and evaluate the performance of the proposed system. The evaluation test results show that the system can successfully identify the presence of workers around a construction vehicle on an Android tablet with acceptable distance (1.5 – 2 m) and direction (1-5 degrees) accuracies. Furthermore, the test results show that a DSRC equipped VMS can successfully post a suitable speed limit corresponding to the presence of workers in its vicinity.

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CHAPTER 1: INTRODUCTION

Vehicles present in and around a work-zone can pose a major safety risk to nearby workers. Each year over 20,000 workers are injured in work-zones. From 2004 to 2013 work-zone deaths have averaged 773 per year of which 15-20% are workers. This means that every year more than 100 worker fatalities occur at US road construction zones. The cause for nearly two-third of these fatal incidents is a worker being struck by a vehicle or being involved in a vehicle/mobile equipment collision. Most of these fatalities are due to run-overs/back-overs and 38% of these fatal incidents involve a heavy construction vehicle [*1*]. Figure 1.1 depicts the detailed causes of work-zone incidents; the aim of this research project is to reduce the safety risk imposed by some major causes such as back-overs and contact with equipment.

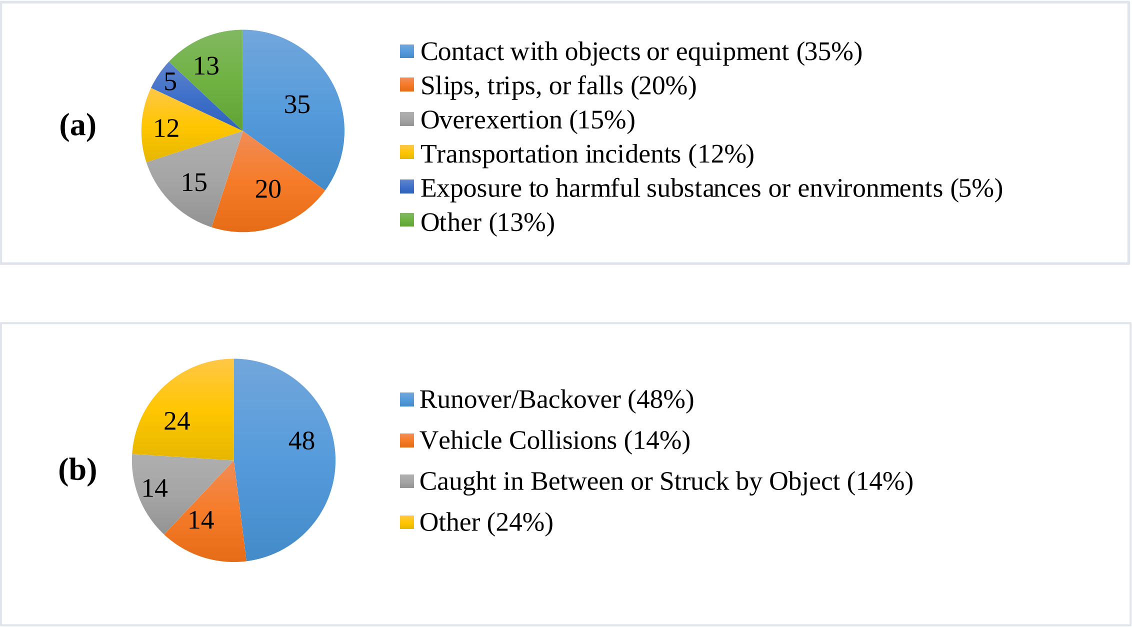

Figure 1.1(a) Work-zone injuries between 2003 and 2008 (b) Work-zone fatalities between 2004 and 2013

The main solution to make the work-zone roads safer has always been reducing the speed limit. Although strict enforcement of lower speed limits and traffic control regulations is necessary to make the road construction sites as safe as possible, lower speed limits alone cannot guarantee workers' safety since there are serious safety risks present from sources other than passing vehicles; in addition to this, lower speed limits decrease traffic mobility causing congestion at work-zone sites and increasing the potential for rear-end crashes *[3]*. This research projects aims to provide an automated way for posting the appropriate speed limits on work-zone roads to improve the traffic mobility without compromising worker safety.

There have been a considerable amount of studies and research projects with the purpose of enhancing traffic safety, the following section will introduce some of these research projects, specifically those that can be of value for work-zone safety solutions and have been useful in the developing the approach of this research project.

1.1 Prior Art

Many studies and research work have been done to improve traffic safety and mobility by proposing new technologies and systems e.g., *[4-6]*. One important step to avoid accidents involving pedestrians is to correctly detect and estimate the pedestrians' position. *[4]* discusses the problems and possible solutions for currently used Pedestrian Protection Systems, by pointing out that due to the varying appearance of pedestrians (e.g., different clothes, changing size, aspect ratio, and dynamic shape) and the unstructured environment, it is difficult to achieve the desired robustness for this kind of systems; This work also proposes to make changes in the processing procedure that is done on the images to improve the performance of such systems. In *[5]*, the paper introduces a novel pedestrian detection system for low-speed driving scenarios, capable of detecting pedestrians in a 360-degree fashion around the vehicle using multiple cameras mounted on the vehicle.

Another important topic in the smart safety/assistance systems research field is how to issue and communicate warning messages such as lane change and departure warnings to the drivers. As an example of such studies, *[6]* discusses that even though many safety countermeasures are implemented in work-zone to reduce forward collision in work-zones, due to complexity of such accident scenarios, traditional countermeasures often fail to prevent accidents. In such cases, intelligent transport system (ITS)-based warning systems can be applied to guide the drivers about the upcoming condition on work-zone roads. In this study, a smart-phone based warning system using ITS applications was designed in an effort to reduce forward collisions in advance warning areas in work-zones.

Dedicated short range communication (DSRC)-based traffic information systems for work-zones have also been developed to estimate work-zone travel parameters such as travel time and starting location of congestion, with the purpose of relaying this information to the vehicles approaching the work-zone [*7-8*]. These studies aim to reduce accident risks and increase traffic mobility by providing the drivers with useful information about the situation of the road ahead. In a recent work, an intelligent awareness system has been designed to estimate the trajectory of the oncoming work-zone traffic and evaluate the risk level that it imposes, using a global positioning system (GPS)-based solution [*9*].

1.2 Research project Approach

In most of the research work done on driver assistance systems including the above mentioned approaches and solutions, the emphasis is on preventing accidents caused by passing-by vehicles by providing situational awareness to the drivers of those vehicles so that they would be more cautious when travelling through active work-zones. However, a very little portion of these solutions target to provide situational awareness to the operators of the heavy construction vehicles which are present in active work-zones. These construction vehicles can potentially cause harm not only to the workers present in the work-zone but also to the vehicles passing by. In this work we focus on preventing the work-zone accidents such as workers being backed over by dump trucks or workers being struck by the mobile construction equipment by bringing situational awareness to the operators of the construction vehicles.

We have designed a safety/warning system that uses GPS to determine the relative positions of the workers around a heavy construction vehicle and proactively provide constant visual situational awareness about the proximity of the workers to the construction vehicle operator.

In our approach each worker will be required to wear a device containing a GPS receiver to determine his or her position as well as a DSRC device to communicate this location information to the construction vehicle which is also equipped with a DSRC device and a GPS receiver. The relative positions of the workers with respect to the construction vehicle is then estimated at the construction vehicle, and visually presented to the construction vehicle operator using a monitor screen. This mechanism will keep the construction vehicle operator continually aware of the presence and movement of the workers in vicinity while operating/moving the construction vehicle.

Furthermore, our designed system addresses the issue of traffic mobility by posting a variable speed limit for the passing by traffic using DSRC-equipped variable message signs (VMSs). Currently, on many work-zones, static work-zone signs are used to alert drivers about workers' presence or if dynamic signs (e.g., VMSs) are used, the display message needs to be changed manually. Although this can be done remotely, manual input needs to be provided to post suitable warning message about workers' presence or to post lower speed limits on the sign. On the contrary, our system can auto-detect presence of the workers and can post a different speed limit on the DSRC-equipped VMS depending on whether the workers are present in the work-zone or not. This can be especially useful for longer work-zones spanning over many miles where some parts of the work-zone may be active with workers present on that specific section, while some are inactive. The DSRC-equipped VMSs can caution drivers of workers' presence as well as post lower speed limits on active parts of the work-zone while regular speed limits can be posted on the inactive sections of the longer work-zones, improving overall traffic mobility.

In the proposed system, we are suggesting to use DSRC to communicate location information from workers to the construction vehicle as well as to the VMS whereas another wireless communication technology could have been used for the same purpose.

This choice is based upon future potential growth of market penetration of DSRC technology among passing-by vehicles, in which case the proposed warning/safety system can be expanded to the DSRC-equipped passing-by vehicles, enhancing the workers' safety system's capability to provide the construction vehicle operator with visual proximity information of the passing-by DSRC-equipped vehicles in addition to the nearby workers. Furthermore, DSRC offers high security and unaffected performance in severe weather conditions *[2]*.

The rest of this writing is organized as follows. The next chapter describes the architecture and the objectives of the proposed system as well as its principle of operation followed by system development details in Chapter 3 and the field test results and discussion in Chapter 4. The conclusions are given in Chapter 5.

CHAPTER 2: SYSTEM DESIGN

2.1 System objectives and architecture

The conceptual architecture of the proposed visual warning safety system is shown in Figure 2.1. The system has two objectives; first to provide visual guidance to the construction vehicle operator about the presence of the workers in its close proximity via a monitor screen, and second to alert the passing traffic to active work-zones and post variable speed limits depending on the workers' presence in the field.

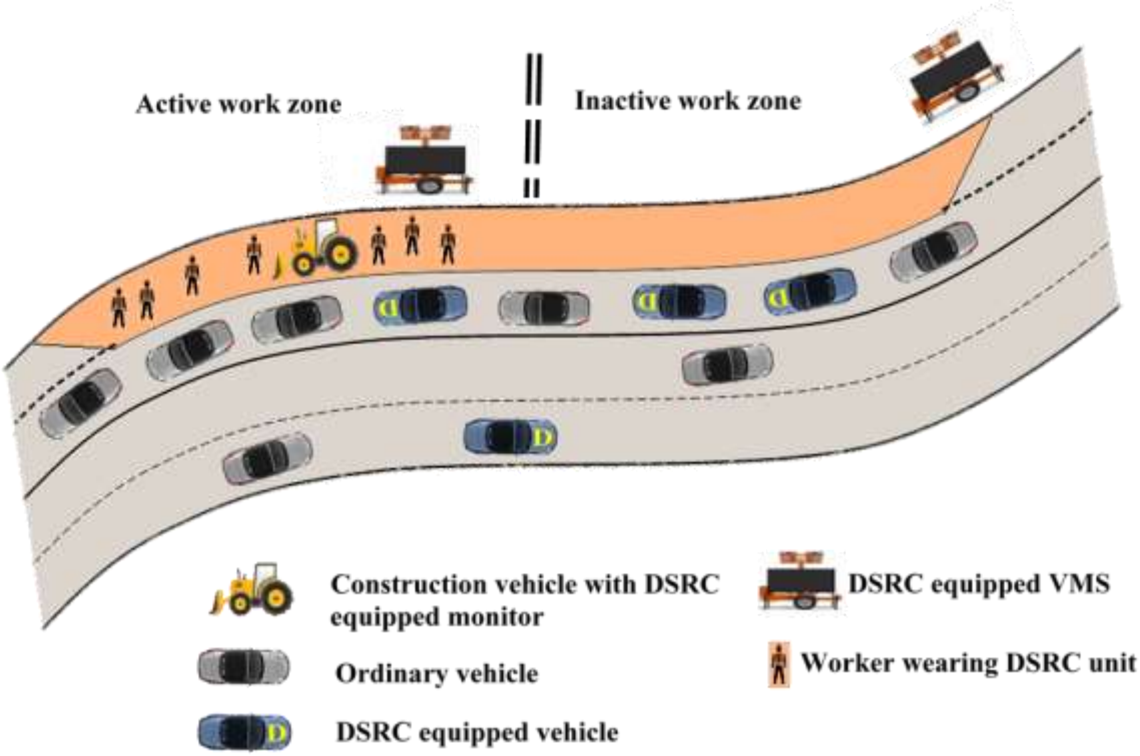

Figure 2.1 Conceptual architecture diagram of the proposed system.

The proposed system requires each worker to wear a miniaturized DSRC device embedded in their safety vest, which will constantly broadcast that worker's GPS location to the DSRC device installed on a nearby construction vehicle or a nearby DSRC-equipped VMS. The DSRC unit on the construction vehicle is connected to a monitor screen that will show the real time positions of the workers to the vehicle operator to warn him/her if a worker is dangerously close. At the current stage of the research project which is to demonstrate proof of the concept, only visual warning is provided but the system can be equipped to support sound alerts as well. The system also helps improve traffic mobility by dynamically changing the work-zone speed limit posted on the VMS depending upon if the VMS's DSRC unit can detect at least one worker present within its direct wireless access range. To achieve the above mentioned objectives, the proposed system will need to have three critical components: DSRC-based wearable safety device, construction vehicle with onboard DSRC device and monitor and finally DSRC-equipped VMS. All of these components will be described in more detail in the following chapter. This chapter of the writing discusses the principle of operation and design challenges of the proposed system.

2.2 System Design Challenge and Principle of Operation

We have chosen to use GPS receivers to acquire the position information that is needed in this research project. Using GPS receivers along with infrared light laser sensors and video cameras are the most common ways to locate static or dynamic objects in driver assistance systems. We chose to use GPS over the other methods since GPS is not dependent on the line of sight whereas video cameras and infrared sensors will not be able to detect workers if there are equipment or other obstructions in their direct line of sight to the worker. Also the processing power needed for analyzing this data is considerably more than what is needed for GPS data, which makes using GPS a faster and more economically feasible choice.

A crucial issue with using GPS receivers for safety applications is that the position accuracy of consumer-grade available GPS receivers is not high enough. Absolute position error of ordinary GPS technology is around 5 m [*10*-*12*] which is too high to provide accurate visual guidance. There are some specially designed GPS receivers e.g., differential GPS receivers, which can provide very high position accuracy, with less than 1 m error [*11*-*12*]. However, such devices are costly. In this research project, each worker needs to have a WSD with a GPS receiver so using expensive GPS receivers will make the WSD cost-prohibitive. Therefore, in this research project we have used regular GPS receivers to achieve acceptable relative position accuracy based on the differential GPS principle.

The differential GPS principle is used in differential GPS (DGPS) receivers, which are very accurate but expensive. In the DGPS method, there are fixed ground-based reference stations for which the GPS coordinates are known. The GPS data acquired from the satellite signals is compared to this set of known location data and the amount of error in the GPS reading is determined. The corresponding correction is then transmitted via RF communication (other types of transmission are also available) to the nearby DGPS receivers to correct their GPS readings before final positions of the receivers are calculated. This improves accuracy because the biggest part of GPS error is due to atmospheric disturbances and remains the same over a large geographical area for DGPS receivers to use the same correction as the ground-based stations [*11*-*14*].

In this research project, we have chosen to use a similar approach. When two separate GPS receivers of the same kind are used, to determine the distance between them the same principle of cancellation of common error is applicable and the relative distance error is reduced significantly as compared to absolute position error, which is conceptually shown in Figure 2.2(a). The error in the absolute position (bigger circle) of each receiver is in the range of 4-5 m but the error in the relative distance becomes much smaller (the small circle) as shown in Figure 2.2(a). The residual error in the relative distance measurement depends on the inherent GPS receiver error and in some cases multipath interference, if present. To further examine this hypothesis, we measured the distance between two different GPS receivers in many orientations and compared that to the calculated distance acquired from their GPS locations as shown in Figure 2.2(b). Although, each time, the absolute position error was much bigger, the relative distance error was less than 2 m suggesting that ordinary GPS receivers can be used in the proposed system.

In the case of this research project, since a bigger part of GPS error remains the same over a large area, the GPS receivers of the worker and the construction vehicle will have a similar atmospheric error. We show the construction vehicle operator the relative GPS locations of the workers with respect to the location of the construction vehicle (as opposed to absolute locations of the workers) which essentially eliminates the larger portion of common GPS error.

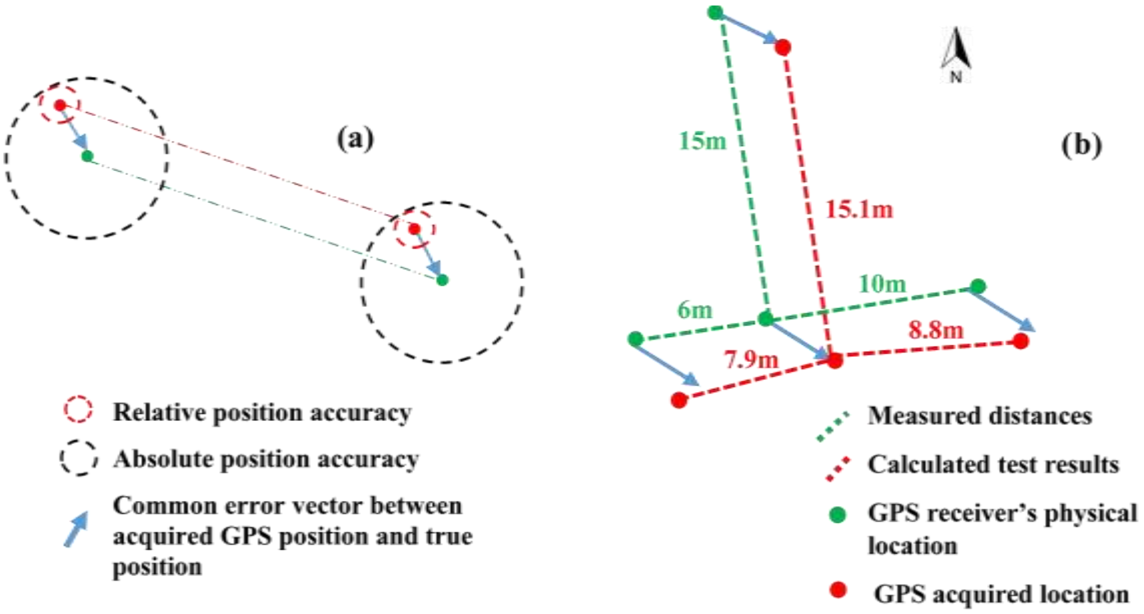

Figure 2.2 Conceptual diagram to show (a) absolute and relative position errors, and (b) measured test results.

CHAPTER 3: SYSTEM DEVELOPMENT

This chapter of this writing discusses the details of system components as well as issues arisen in the course of prototype development and the proposed solutions.

As mentioned in the previous chapters, to achieve its objectives, the proposed system will need to have three critical components: DSRC-equipped wearable safety device, construction vehicle with onboard DSRC device and monitor, and DSRC-equipped VMS.

3.1 DSRC-equipped Wearable Safety Device

The WSD needs to be worn by each worker at all times for the successful deployment of the proposed safety warning system. For this purpose, WSD can be embedded in the worker’s vest or safety helmet, or can be designed as a wrist band. The preferred method is to embed WSD in the vest since the workers almost always wear the vest while in the field. The conceptual high level architectural design of the proposed WSD is shown in Figure 3.1. The WSD’s essential components are a GPS receiver and a DSRC radio to respectively obtain worker’s location and communicate it to the construction vehicle. Additionally, the WSD may also contain a ‘panic’ and a ‘caution’ trigger button.

The various components of the WSD except the GPS receiver antenna can be integrated in a small manageable device, which can be embedded in the vest as shown in the inset of Figure 3.1. The GPS receiver antenna is proposed to be located near the shoulder strap of the vest because GPS receiver works best in an open-to-sky scenario. We have worked with a DSRC device manufacturer, Savari Inc., to evaluate the feasibility and develop such a WSD based on the proposed design. According to our findings, it is feasible to develop a small WSD to be embedded in the worker’s vest. However, we have not yet actually developed such a device so regular vehicle DSRC units were used for the field tests which will be described later in the writing. The necessary factors that need to be considered for developing the WSD and the evaluation done by Savari Inc. about these factors are described in this section.

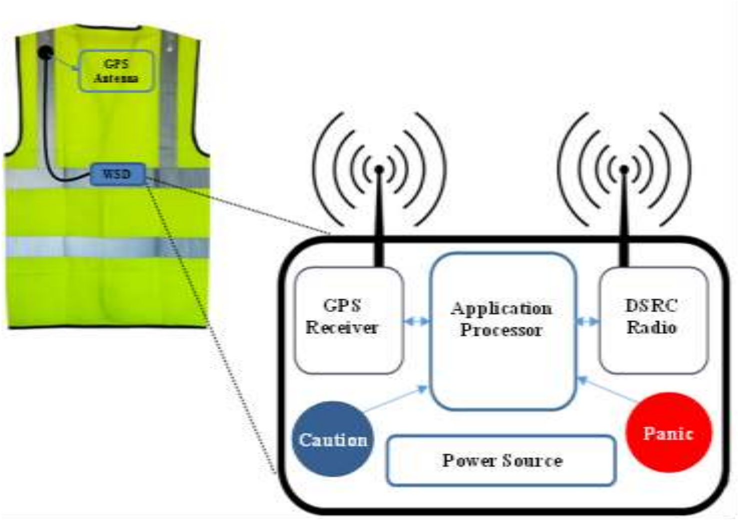

Figure 3.1 High level architectural design of the proposed WSD for worker. The inset shows the worker's vest with embedding locations of WSD and GPS antenna.

3.1.1 Main components of the WSD

GPS receiver: The purpose of GPS receiver is to acquire the location of the worker wearing the vest so that it can be transmitted via DSRC radio. The GPS receiver should be accurate enough so that the worker's location can be estimated near construction vehicles with necessary precision.

DSRC radio: The purpose of the DSRC radio is to send the information about worker's location to nearby DSRC receivers present in the construction vehicles. The DSRC radio only needs to function in transmitter mode to periodically transmit the safety message at reasonable time intervals; the safety message will contain the worker's position, the ID number of corresponding WSD and the optional panic or caution mode messages.

Application processer: The application processer will control and coordinate all the components and it will be programmed to control the overall functionality of the WSD. If all necessary functions can be achieved using a micro controller, then there won't be any need for a full Linux computing system as normally present in stand-alone DSRC devices e.g., Savari's Aftermarket Safety Device (ASD).

Power source: The power source should be a rechargeable battery which fulfils the power requirements of all the components of the WSD. It should have a minimum life of 12 hours to cover the whole work shift of the worker and it needs to be of minimum size and weight possible. To meet these goals different battery types will be considered for example a solar battery or a detachable rechargeable battery or a combination of both.

3.1.2 Major Design Considerations of the WSD

DSRC Message: A customized safety message can be designed for the use of WSD but since the privacy and security issues of such a message have not been studied and the WSD is not developed yet, we have used DSRC standard Basic Safety Message (BSM) in this research project. A point about using BSM as the safety message is that the ID number included in the pre-defined message format will change periodically per protocol to ensure protection of user privacy, however this does not contradict the goal of this research project. Although having a fixed ID number is useful to identify each single worker's location, it is not necessary since the worker's location will still be communicated to the nearby onboard DSRC units and will be displayed on the tablet screen, and the location of the worker can be determined.

Foot Print: The footprint of the WSD should be such that it can be embedded in the vest without the worker feeling any burden of its weight or size. The device should be as thin as possible since it will be easier to retrofit the WSD in the vest. Also size and weight profile should comply with any ANSI & AASHTO safety standards if required.

Antennas: The DSRC and GPS antennas should be integrated in WSD or the worker's vest in such a way that there is an efficient line of sight for these antennas to send and receive data.

3.1.3 Panic and Caution Mode Options

The vision behind panic and caution modes is that these can be activated by the worker under special event driven circumstances. Both options override the normal operation of the WSD and force the device to transmit event specific messages. The Panic mode can be activated by the worker when the worker has been involved in an accident or is in dire need of help. In this situation the WSD will sent out a 'Rescue call' message in addition to the usual transmitted message which contains the workers position. This message can trigger an audio alert onboard the construction vehicle and is transmitted more frequently than the usual safety message to ensure quick response from the emergency teams.

The Caution mode can be activated when the worker feels like he or she is working in a potentially dangerous situation and suspects that the DSRC message generated by his or her WSD may not reach to the construction vehicle. For example, if the worker is very close to the construction vehicle and is more likely to get harmed in a vehicle related accident, he or she can activate the caution mode to ensure that his presence is noticed by the construction vehicle operator. In the caution mode the safety message is transmitted with a higher frequency than the normal operation mode and the presence of the worker is shown to the construction vehicle by more prominent means. The flowchart shown in Figure 3.2 describes the software application that would be installed in WSD.

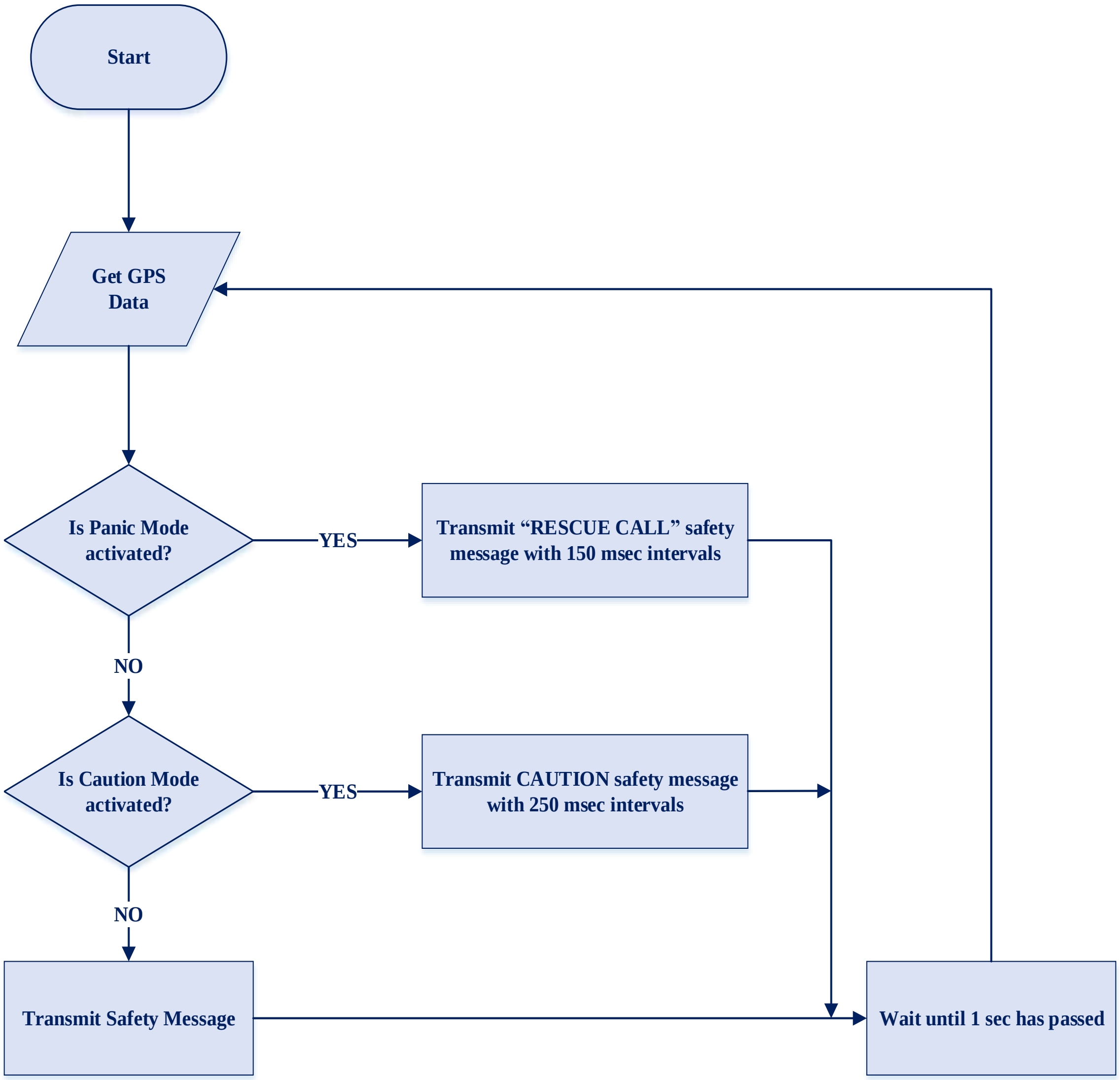

Figure 3.2 WSD software flowchart

3.1.4 Evaluation by Savari Inc.

Savari has recently built a small DSRC device with GPS receiver called Savari S55. The Savari S55 is shown in Figure 3.3 (specifications given in table 3.1). This device could potentially be used as the wearable safety DSRC device for the purpose intended in this research project.

Figure 3.3 Savari's MobiWAVE S55 unit

Table 3.1 Savari's MobiWAVE S55 unit specifications

Device	Power	Wireless	GPS	Ports	Antenna	Storage
Model #S55 DSRC Transceiver	12V DC 12" wire pair	1 25 dbm DSRC/Wi-Fi 2.4-2.4835 GHz 5.15-5.9 GHz, 10, 20 MHz channels, 802.11a/b/g/n	+/-2M Position Accuracy, 50% CEP	1 USB	Onboard Antenna External antenna for GPS optional	Up to 512MB internal

Currently, this device does not have the capability of 'Panic' and 'Caution' modes but these options can be added with a redesign and will require NRE work which will affect the cost. This is further discussed in the cost section below.

3.1.4.1 Foot Print

The S55's current dimensions are given in table 3.2:

Table 3.2 Savari's MobiWAVE S55 unit current dimensions

Length	100 mm
Width	60 mm
Height	25 mm
Weight	100 gms (without battery pack)

The current weight of the device is 100 grams. While the weight, length and width of the unit are reasonable to embed in the worker's vest, its height, at almost an inch is slightly too thick, meaning the vest will bulge out. With these dimensions, this device can still be embedded in the vest, but the worker will feel it protruding. However, this device can be substantially miniaturized and manufactured with the dimensions mentioned in table 3.3, which are more appropriate for the device to be embedded in the vest, either permanently or as a removable attachment to facilitate washing of the vest.

Table 3.3 Savari's MobiWAVE S55 WSD unit target dimensions

Length	140 mm
Width	100 mm
Height	~ 8 mm
Weight	150 grams (including battery pack)

It is important to note that this device will have a built-in battery of ~3000mAh capacity which will power the unit for around 10 hours or more, which is sufficient for an average work day at the construction site. These dimensions are ideal for usage in various conditions. Additional features such as IP68 compliance can also be added if needed.

3.1.4.2 Antennas

DSRC Antenna: Currently, the DSRC antenna is a small antenna which is present in the MobiWAVE box enclosure. Savari's vehicular and road side DSRC units use a 600mW 28dBm TX, -94dBm RX Sensitivity radio that has been proven to work in various line of sight scenarios at well over 300 m. The S55 will utilize a similar radio but will operate at reduced or optimized transmit levels according to the deployment scenario. The DSRC radios are in compliance with USDOT OBE transmission range requirements. Since the device is expected to be within a range of 20m from the heavy machinery, there will not be significant loss in signal strength even if the unit is not in direct line of sight.

GPS Antenna: Since GPS works best in an open-to-sky scenario, the GPS antenna will be located near the shoulder strap of the worker's vest as shown in Figure 3.4. The GPS antenna will be a puck antenna integrated into the vest as a permanent fitment. The cable for the antenna will be routed behind the reflective fabric to the MobiWAVE DSRC unit. The DSRC unit makes use of the GPS data strings to populate the DSRC message sets with location information.

Figure 3.4 WSD Unit layout

The GPS chip is built into the MobiWAVE DSRC unit. The GPS unit is similar to the unit used on other Savari DSRC units and has equivalent positioning performance. While there is no test document available for the S55 as of this writing, below chart indicates GPS performance of the same chipset on Savari S102 in a vehicle travelling at 20mph.

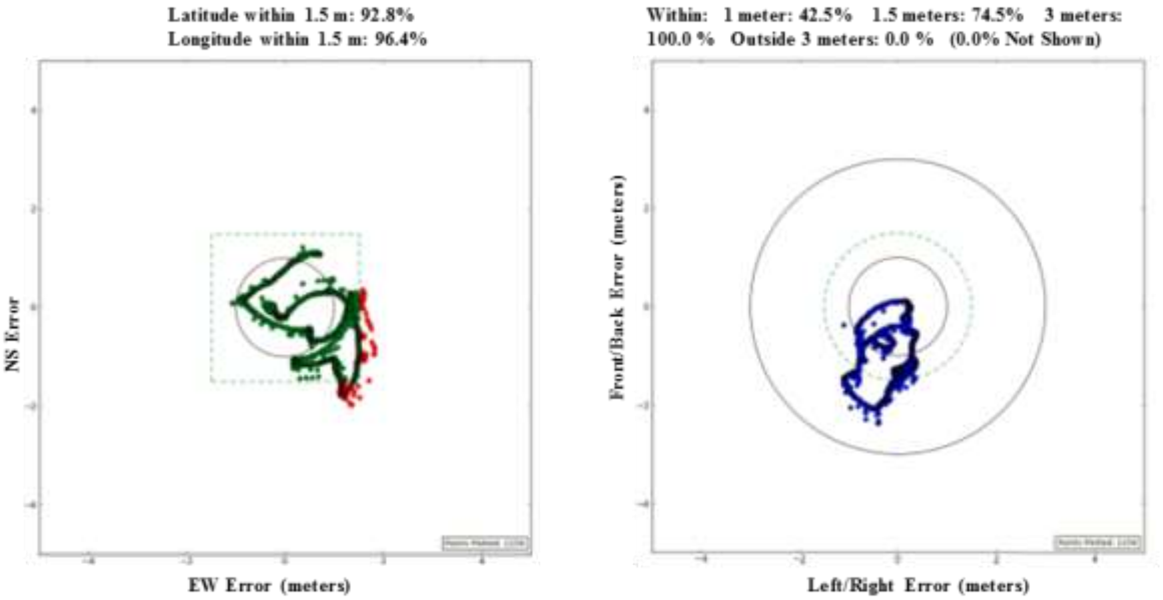

Figure 3.5 Savari DSRC device GPS receiver performance evaluation

It can be seen from Figure 3.5 that the unit is capable of positional accuracy within 1.5m more than 90% of the time. This degree of accuracy is sufficient for the intended application. More results can be provided on request.

3.1.4.1 Cost

The cost of the current Savari S55 MobiWAVE unit will vary depending upon the quantity as per table 3.4 below:

Table 3.4 Savari's MobiWAVE S55 WSD unit cost

<100 units	$ 475 per unit
100 -1000 units	$ 350 per unit
1001 – 10000 units	$ 250 per unit
>10000 units	$ 150 per unit

This cost does not include the cost of the battery which will need to be purchased separately for the current unit. Also, the cost will change if 'Panic' and 'Caution' modes are added, and also if the dimensions are modified.

The cost structure for the development of such a device with the modified dimensions including the capability to have two configurable hardware buttons and a built-in battery, is as follows (table 3.5):

Table 3.5 WSD customization cost

Feature	NRE Cost
Revised packaging	$ 340,000
IP 68 Compliance	$ 10,000

The NRE cost includes:

1. Device requirements gathering.
2. Custom fabrication of hardware.
3. Application customization.

3.2 Onboard DSRC device and Monitor for Construction vehicle

On a construction vehicle, there needs to be a monitor screen through which the visual information will be communicated to the operator of the construction vehicle, and a DSRC device which can receive location information from nearby workers and process it before displaying on the monitor screen. In the developed prototype system, we have used a regular vehicle DSRC unit as the onboard unit for construction vehicle and an Android-based tablet to provide visual alerts about the presence of the workers (shown in Figure 3.6).

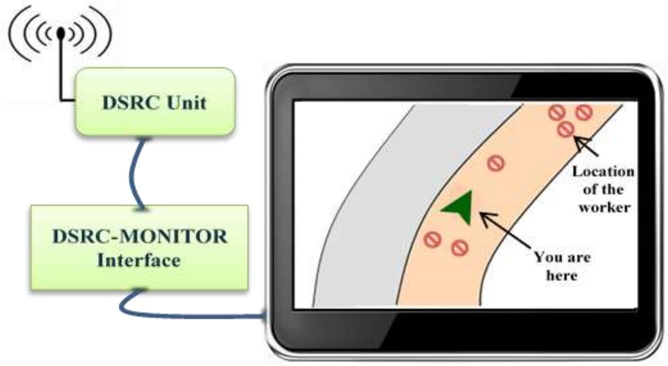

Figure 3.6 Conceptual DSRC-Monitor interface

Although this research project is primarily focused on providing visual guidance to the construction vehicle operator, to provide a less distracting warning method for the situations where fast reactions are essential, a sound alert can be added to the system to warn the operators when a worker has crossed into an area dangerously close to the construction vehicle. Geo-fencing can be used to set up a danger buffer zone around the construction vehicle.

3.2.1 DSRC device’s software application

As shown in the flowchart in Figure 3.7 the Onboard DSRC device continuously scans for messages sent from the WSD devices in the vicinity and upon reception of such messages it extracts the location information of the worker, at the same time the software would acquire the GPS data of the device itself and it bundles the GPS locations of the worker and the device and communicates this information package to the tablet via Wi-Fi (UDP) link.

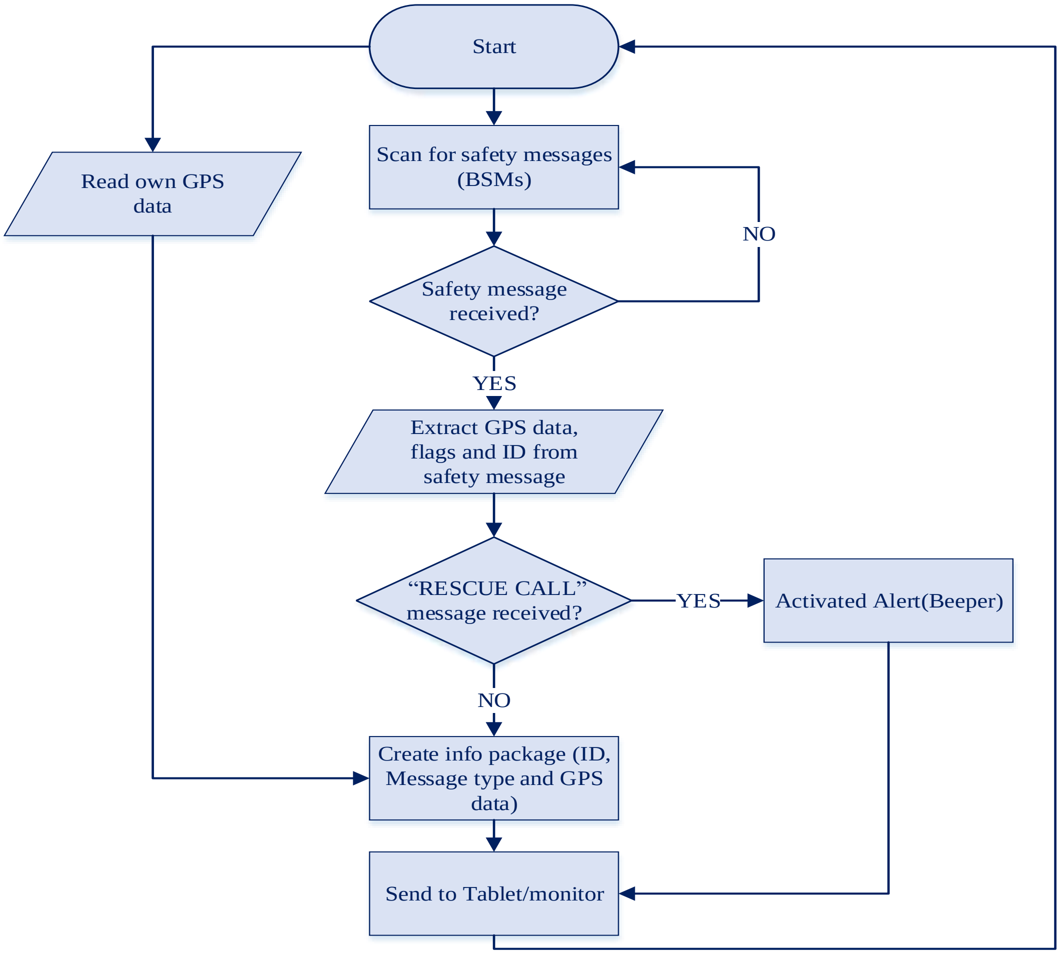

Figure 3.7 Construction Vehicle onboard DSRC device software flowchart

3.2.2 <u>Monitor screen software</u>

The Android tablet is interfaced with the onboard DSRC device via a local Wi-Fi network. This network is provided by the DSRC device and is independent of any other wireless communication services. Currently this Wi-Fi network only supports communications based on User Datagram Protocol (UDP). Even though the reception of data cannot be guaranteed at all times, due to inherent characteristic of UDP-based communication, the frequency of communication between the onboard DSRC device and the tablet is high enough to ensure the correct depiction of workers' location on tablet screen.

We have developed a Java-based software application for the Android tablet to display the workers' locations around the construction vehicle on the screen. The developed DSRC-monitor interface and Java-based application are used for the field tests of the proposed system, which are described later. The user interface is shown in Figure 3.8(a). The Construction vehicle is shown in a fixed position at the center of the screen, represented with a darker blue circle in Figure 3.8(a), the bigger and light-colored circle represents the research projected dimensions of the vehicle. The workers are represented with green colored circles in Figure 3.8(a).

It would be beneficial to provide the construction vehicle operator with a better understanding of the surrounding area of the work-zone, to this purpose we have also developed a Google maps-based user interface which can display the nearby area as well as workers' location on the screen. This application uses the off-line maps feature of the Google maps, which means that the maps of the work-zone area can be downloaded on the tablet once in the set-up stage and the application can be used off-line for the rest of the construction research project period. The user interface of the application is shown in Figure 3.8(b), the colors and placement of worker and construction vehicle have been kept the same as the customized Android application. It should be mentioned that this application was developed solely for research purposes, and the legal rights of such an application should be discussed with Google for commercial use.

Figure 3.8 Tablet Software application user interface of (a) Customized Android application (b)Google maps-based application

3.2.3 <u>Relative orientation issue</u>

During the initial testing of the system it was determined that the relative orientation or direction of the worker with respect to the construction vehicle can only be accurately shown to the operator as long as he or she is facing towards North. This is due to the fact that the relative direction between the construction vehicle and worker’s GPS positions can only be calculated with respect to a fixed reference direction. If the construction vehicle rotates while staying at the same geographical position, its GPS coordinates will remain the same but its relative direction to the worker will change. Consequently, the operator will not be able to locate the worker’s correct relative orientation on the tablet screen with respect to the vehicle. This problem is illustrated in Figure 3.9 where a worker is standing at about 20 m north of the construction vehicle while the construction vehicle is also facing north. The tablet snapshot given in Figure 3.9(a) shows this accurately, placing the worker about 20 m north of the construction vehicle (in front of it). When the construction vehicle rotates towards East at the same location, the worker is now actually on the construction vehicle left side at a distance of 20 m. However, the tablet will still show the worker erroneously in front of the construction vehicle as shown in Figure 3.9(b). This problem can be corrected if an absolute direction reference is provided to the construction vehicle. We have experimented with different methods to provide this direction reference to the construction vehicle.

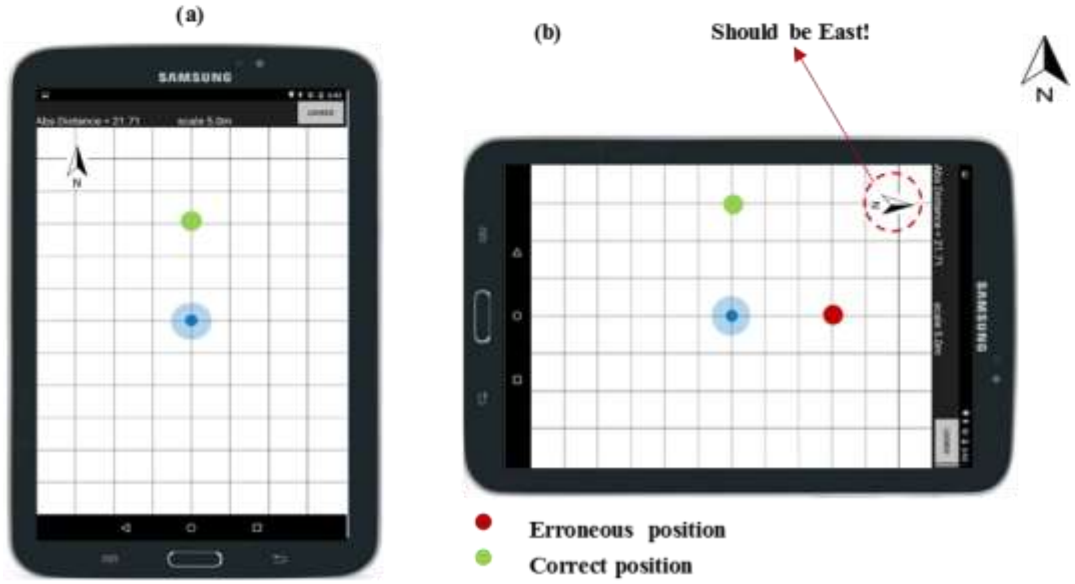

Figure 3.9 The issue of relative orientation of worker with respect to the construction vehicle.

3.2.3.1 Two-GPS Method

The most common way of determining the orientation of a vehicle is to compare two subsequent GPS positions of the moving vehicle to calculate the direction of the movement. These positions can form a vector and the angle of that vector with respect to true north will determine the direction that vehicle is facing. Similarly, if the construction vehicle keeps moving in addition to rotation, comparison of the two different positions obtained by the same GPS receiver can be used to determine the direction. However, this solution is not acceptable for a construction vehicle because it needs to rotate without moving in many of its operations. To overcome this issue, we have used two GPS receivers on the construction vehicle to provide the necessary direction reference.

In this method two GPS receivers can be placed at front and back of the construction vehicle. In the prototype testing we have also tested this method using the GPS receivers of the Android tablet and the onboard DSRC device by placing the tablet at the front of the vehicle while the DSRC device is positioned at the back. The GPS data from the DSRC device is compared to the GPS data acquired by the tablet and the application software uses this reference to set the orientation of the display. Using this method in our preliminary tests, the orientation of the worker was correctly shown to the operator of the vehicle when facing East. The test results using two-GPS method are shown in chapter 4 of this writing.

Using two GPS receivers, the necessary direction reference can be provided but the accuracy of final direction or orientation will depend upon the distance between the two receivers. The longer the distance between them, better the accuracy is. This concept is shown in Figure 3.10, where two GPS receivers are placed in different distances from each other while having the same GPS reading, as it can be seen in Figure 3.10(b), the error angle becomes smaller as the distance between the GPS receivers grows bigger as compared to the situation depicted in Figure 3.10(a). Depending on the size of the vehicle, we are suggesting that the two GPS antennas on the construction vehicle be placed at least 2 m apart as it was done in the tests descried in the results section of this writing. The direction error while using two GPS antennas with 2 m separation, was in the range of 15-20 degrees which is sufficient for visual guidance purposes.

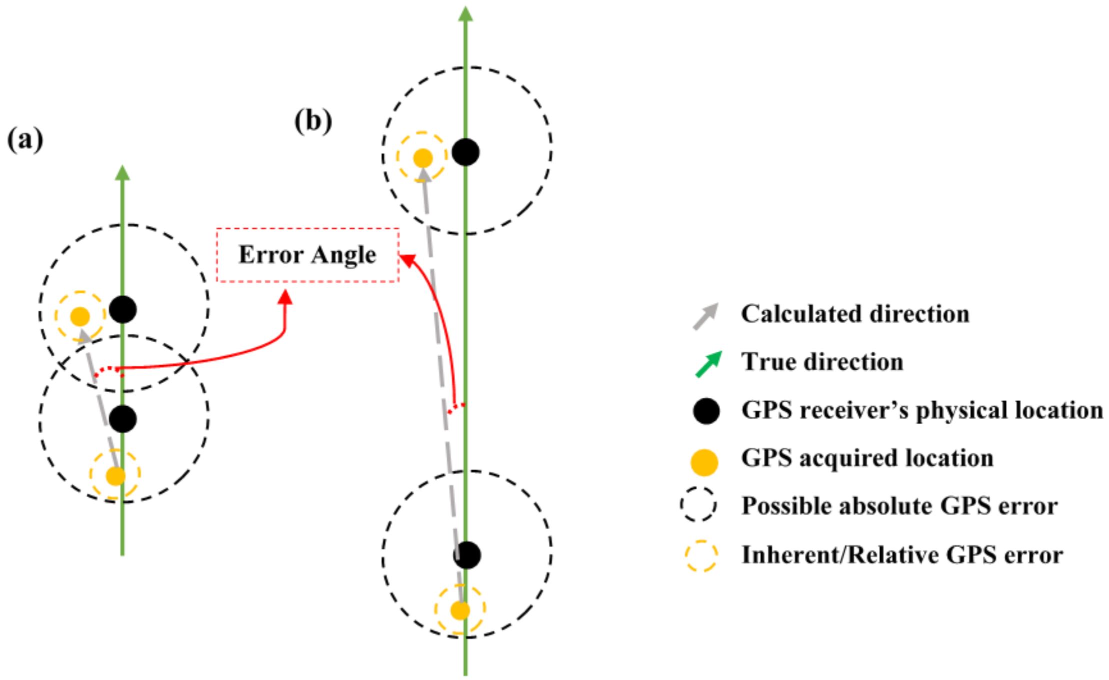

Figure 3.10 Two-GPS method accuracy with respect to distance.

3.2.3.2 Electronic Compass Module Method:

An alternative way to determine the direction towards which the vehicle is facing is to use the method which is used in handheld devices such as cellphones and tablets. Such devices use data from internal Gradiometer and Accelerometer chips to determine the device orientation. Gradiometer and accelerometer are sensors that detect the changes in measurements like the magnetic field, the earths incline and the pull of gravity. The data from these sensors can be acquired and manipulated to calculate the direction/orientation of the tablet.

It should be noted that these gradiometer chips are present in most of the modern day tablets/phones. Perusing this technique, we programmed the Android tablet (which is being used as the monitor screen onboard of the construction vehicle in this research project) to access the data from the integrated sensors in the tablet and adjust the direction of the user interface display of the safety system. The results of this experiment were less than satisfactory. The direction acquired was not accurate enough and the frequent need for calibrating the application (moving the tablet in an 8-shaped motion) made this solution impractical for the purpose of this research project.

We determined that a better approach to this technique would be using external Gradiometer /Accelerometer chips. In this approach an electronic compass chip (LSM303DLHC) would be interfaced with a microcontroller (Arduino Uno) using I2C communication protocol. The microcontroller would then read sensor values from the electronic compass and calculate the direction towards which the tablet is facing and then send this information to the onboard DSRC device through serial connection/port. This external electronic compass requires far less manual re-calibration and the results are highly accurate (within 1-degree error). table 3.6 shows the accuracy level offered by the chip-sets that were used to examine this method of acquiring direction.

Table 3.6 LSM303HDLC e-Compass specifications

Direction Accuracy	Less than 1-degree error
Communication Interface	I2C
No. of Channels	3 magnetic, 3 acceleration
Operating temperatures	-40 to +85 degree Celsius

3.2.3.3 Two-GPS and Electronic Compass method comparison

Although, the accuracy of the two-GPS method is highly dependent on the distance between the GPS receivers as explained earlier, in rare cases, if one or both GPS receivers lose satellite lock, then the direction error can be much larger especially, if the distance between the two is smaller.

Even though the accuracy of the two-GPS method can be controlled by choosing the correct distance there might be cases that the construction vehicle does not offer large enough area to place the two GPS receivers at the optimal locations.

As mentioned above using the external electronic compass chip is a very efficient way of determining the direction with up to 1 degree of accuracy as shown in Figure 3.11. In addition to this, as opposed to the two-GPS method, the e-compass can be integrated with the system without the need of taking the vehicle size into consideration.

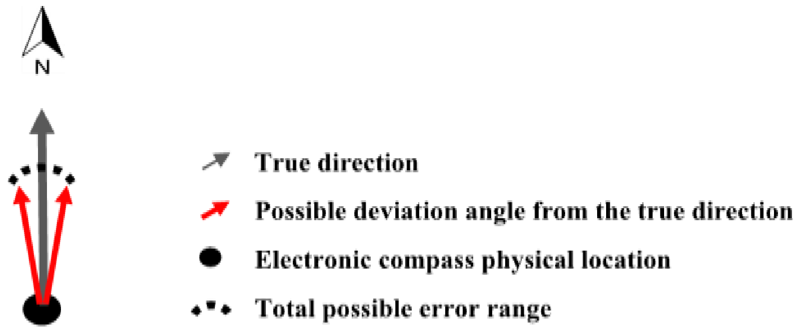

Figure 3.11 Conceptual diagram to show direction accuracy of the e-Compass method

The results of field tests conducted to compare the e-compass method and two-GPS method are presented in the next chapter of this writing and they clearly indicate that the e-compass method is the better choice to determine the direction for the proposed safety system.

3.3 DSRC-equipped VMS

Another crucial aspect of the proposed system is to inform the drivers of passing vehicles about the presence of the workers and post a variable speed limit depending upon if workers are present in the vicinity which will enhance traffic mobility on the roads with work-zones, and make the drivers more cautious while driving on such roads.

VMSs are usually controlled either by using a hand-held terminal connected to the sign, or by using a remote central computer which requires an operator to control the messages that need to be displayed on the sign. In either case, the human input is necessary to make proper use of the VMS on the construction sites, which is prone to human error as well as issues like delays when the sign needs to be changed to a different message due to local work-zone situational changes.

Figure 3.12 Conceptual diagram of DSRC-VMS interface

The proposed system eliminates human error by auto-detecting workers' presence in an active work-zone and displays a suitable message without the need for any kind of manual input. To accomplish this, the VMS needs to be equipped with a DSRC device as shown in Figure 3.12. The DSRC device installed on the VMS receives location signals from nearby workers and is able to post a speed limit depending upon workers’ presence in the vicinity, in addition to speed limits, VMS could also warn the passing-by drivers about the presence of the workers on a particular section of the work-zone, by displaying caution messages.

Figure 3.13 (a) Front and (b) Back views of the Variable Message Sign used in the development of the proposed system.

For the purpose of this research project a DSRC device is interfaced with the VMS, shown in Figure 3.13, via serial communication (RS-232). The device is connected to the central or laptop serial port of the VMS controller and becomes the main portal for communicating instructions to the VMS (Figure 3.14). A similar program to the one installed on the construction vehicle onboard device is present on the DSRC device connected to the VMS, so that the device can detect the presence of workers in a specific area of the work-zone via DSRC communication. Speed limits and warning messages are coded into the DSRC device, and the program installed on the device decides which message needs to be displayed on the sign based on presence and location of the workers.

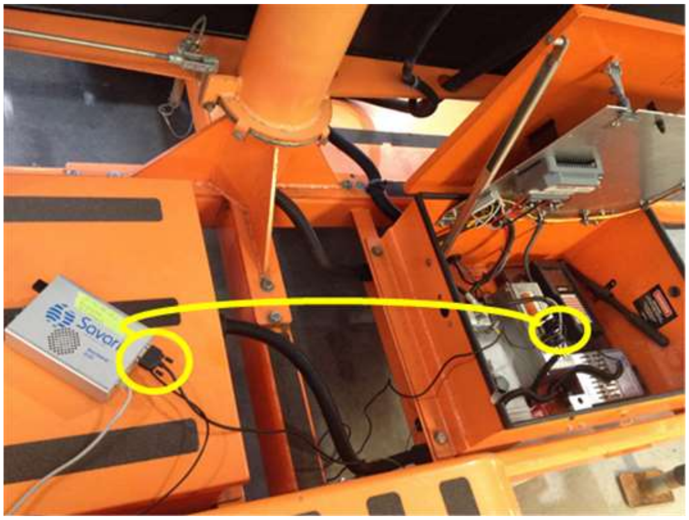

Figure 3.14 Serial connection between VMS and DSRC device.

Although the theoretical wireless range of DSRC technology is 1 km, the practical range is about 500 m [*15*]. Therefore, if multiple VMSs need to be placed along the work-zone, the preferred spacing between two adjacent VMSs is 1 km so that a worker present at any place over the span of 1 km can be detected at least by one of the two VMSs. The programming of the VMSs can take into account the traffic direction, and the relative location of the workers with respect to the VMS to post appropriate speed limits for the incoming vehicles. However, a detailed study of state safety requirements about posting variable speed limits according to workers' presence in and around a work-zone is needed before programming DSRC-equipped VMSs and determining the spacing between them.

CHAPTER 4: FIELD TESTS AND DISCUSSION

This chapter is dedicated to the performance evaluation of the developed prototype system. The tests for the visual safety warning system and DSRC-equipped VMS were performed separately, as these tests were not implemented on an actual work-zone. The detailed test results are given below.

4.1 Construction Vehicle Visual Monitor Alert System

The DSRC-Monitor interface for construction vehicle was developed using an Android based tablet and a DSRC onboard unit. Since the actual WSD has not yet been developed, same kind of DSRC units were used for the construction vehicle as well as the worker, simulating WSD. However, we developed separate software applications for these units. The DSRC units used in the field tests had built in GPS receivers, which were programmed to retrieve the needed location data.

The worker's DSRC unit was programmed to periodically acquire its GPS location, and transmit that information using the standard DSRC Basic Safety Message (BSM). BSMs were used only because a WSD has not yet been developed and a regular vehicle DSRC device was used for the worker to evaluate the system performance. As discussed in the previous chapter, once a WSD is developed, it does not have to use a standard BSM to communicate the location information because most data fields in a BSM contain vehicle specific information. Instead, a different message standard could be used to represent worker specific information including worker's location, however developing a worker specific message will need careful study of the standards and regulations of the DSRC protocol.

The construction vehicle DSRC unit is programmed to acquire its own GPS position, and calculate relative distance between itself and the positions of those workers from which it has received location information in the form of BSMs. After calculating relative distances, construction vehicle DSRC unit sends this information to the Android tablet using UDP data packets on a local Wi-Fi connection. This process is repeated every second to update workers' positions on the tablet. The conceptual setup of the field tests is shown in Figure 4.1.

Figure 4.1 Conceptual set up for the Safety system field tests.

4.1.1 Field Test Set-up

The experimental setup of the field tests is shown in Figure 4.2, which also shows pictures of the developed construction vehicle monitor system (Android tablet and DSRC/GPS antenna) and a worker's DSRC unit, which is powered by a portable battery and being carried in a basket in one of the pictures. We used a regular vehicle as the construction vehicle as shown in Figure 4.2 to demonstrate functionality of the system. The field tests were performed in a parking lot instead of an actual work-zone to demonstrate proof of concept.

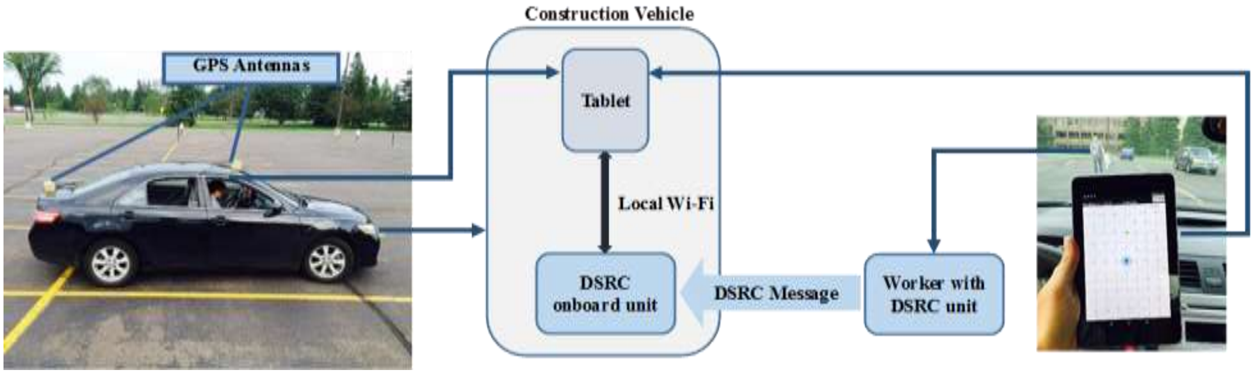

Figure 4.2 Experimental set up for the Safety system field tests.

4.2 Results and Discussion

4.2.1 Worker's Relative Distance

Using the experimental setup of Figure 4.2, the accuracy of worker's displayed position with respect to construction vehicle was evaluated against the physically measured distance. Only one worker was considered close to the construction vehicle for these tests. The test results are shown in Figure 4.3 where snapshots of tablet screen are given for three distinct worker positions. First, the worker was placed in approximately South-East direction of the construction vehicle at a distance of 5 and 7 m shown in Figure 4.3(a) and (b). The point in the center of the tablet screen shows the position of the GPS receiver on the construction vehicle. The bigger blue circle around the center point of the tablet screen has a 2 m radius showing the approximate boundaries of the construction vehicle. In these tests, the position of the worker is continuously updated every second for one minute to see the error distribution of relative position acquired through GPS. For measured distances of 5 and 7 m, the average distance was respectively 6.19 and 7.55 m, and the standard deviation was respectively 0.9 and 0.86 m. Finally, the worker was placed at a 2 m distance from the construction vehicle (at the border line of construction vehicle) in the North direction as shown in Figure 4.3(c). The average calculated distance was 1.78 m with standard deviation of 0.47 m against the measured 2 m distance. To conduct these tests only one GPS receiver was used for the construction vehicle (GPS receiver built in the DSRC unit) and achieved relative distance accuracy was within the range of 1 – 2 m.

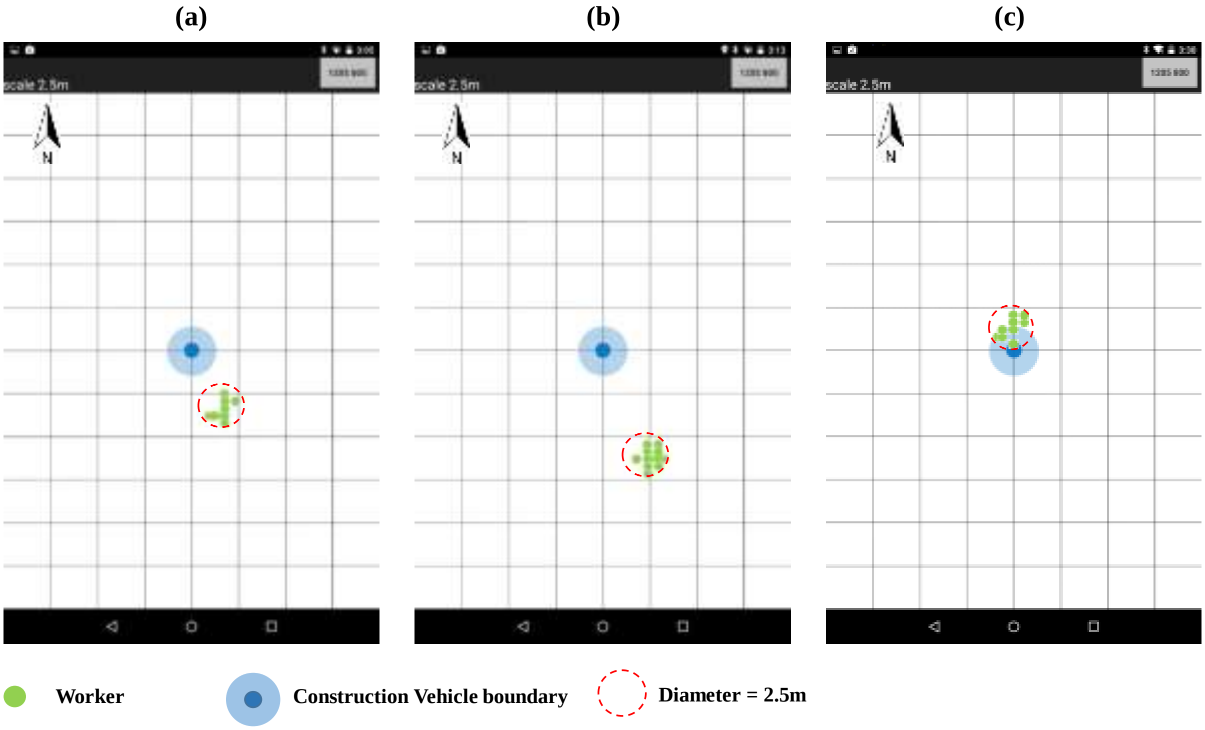

Figure 4.3 Tablet screen snapshots showing distance accuracy when the worker is (a) 5 m (b) 7 m, and (c) 2 m from the construction vehicle.

To conduct these tests only one GPS receiver was used for the construction vehicle (GPS receiver built in the DSRC unit) and achieved relative distance accuracy was within the range of 1 – 2 m. The spread of relative location error is shown in Figure 4.4, as it can be observed from the chart the error is less than 1.5m in more than 80% of the GPS readings.

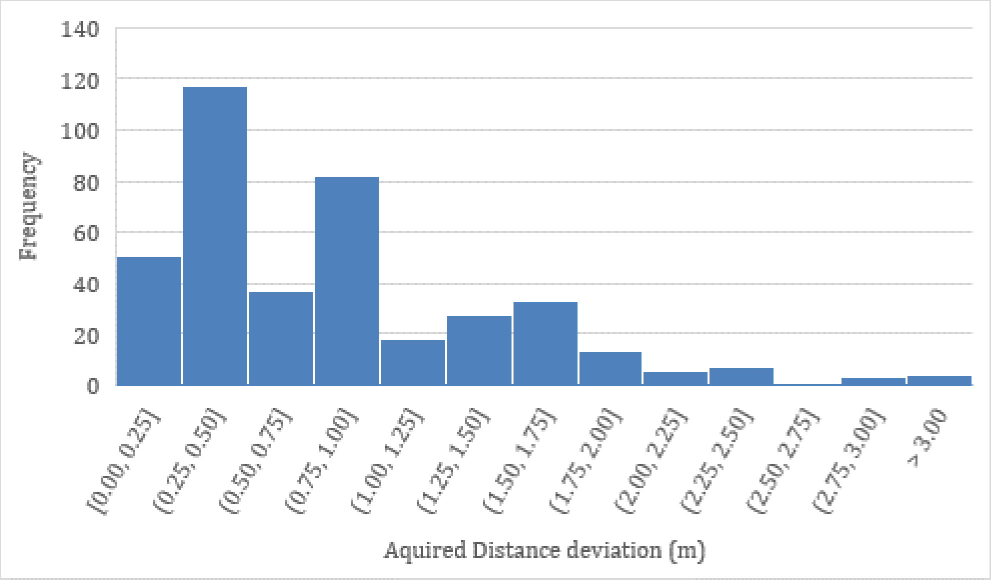

Figure 4.4 Error spread of relative GPS locations

4.2.2 Worker’s Relative Orientation

As discussed in chapter 3 of this writing a direction reference needs to be provided to the system so that the orientation of the construction vehicle and the workers with respect to each other can be correctly determined. Using the two-GPS receiver method, discussed in chapter 3.2.3.1, the necessary direction reference can be provided but the accuracy of final direction or orientation will depend upon the distance between the two receivers. The longer the distance between them, better the accuracy is. Depending on the size of the vehicle, we are suggesting that the two GPS antennas on the construction vehicle be placed at least 2 m apart as it was done in the tests descried above. The direction error while using two GPS antennas with 2 m separation, was in the range of 15-20 degrees which is sufficient for visual guidance purposes i.e., the operator was able to easily locate the position of the worker around the vehicle in the correct direction.

As mentioned before using the external electronic compass chip is a very efficient way of determining the direction. In addition to this, as opposed to the two-GPS method, the E-compass can be integrated with the system without the need of taking the vehicle size into consideration.

We have conducted tests to compare the direction accuracy acquired by the E-compass and the two-GPS methods. Figure 4.5 shows screen shots of the tablet during one of the many repetitions of the experiment. In these tests, the location of the worker was acquired and displayed on the tablet screen for 1-minute time spans with 1-second intervals. Also the worker was assumed to be at a fixed location in front of the construction vehicle to eliminate the effects of positioning error, as a result, the fluctuations in the location of the worker on the tablet screen is purely because of errors in determining the relative direction. As it can be observed from the figure, the E-compass method is clearly the better choice to determine the relative direction for the proposed safety system since the direction acquired using this method changes in a range of 2-3degrees as opposed to 5-20 degrees for the two-GPS method.

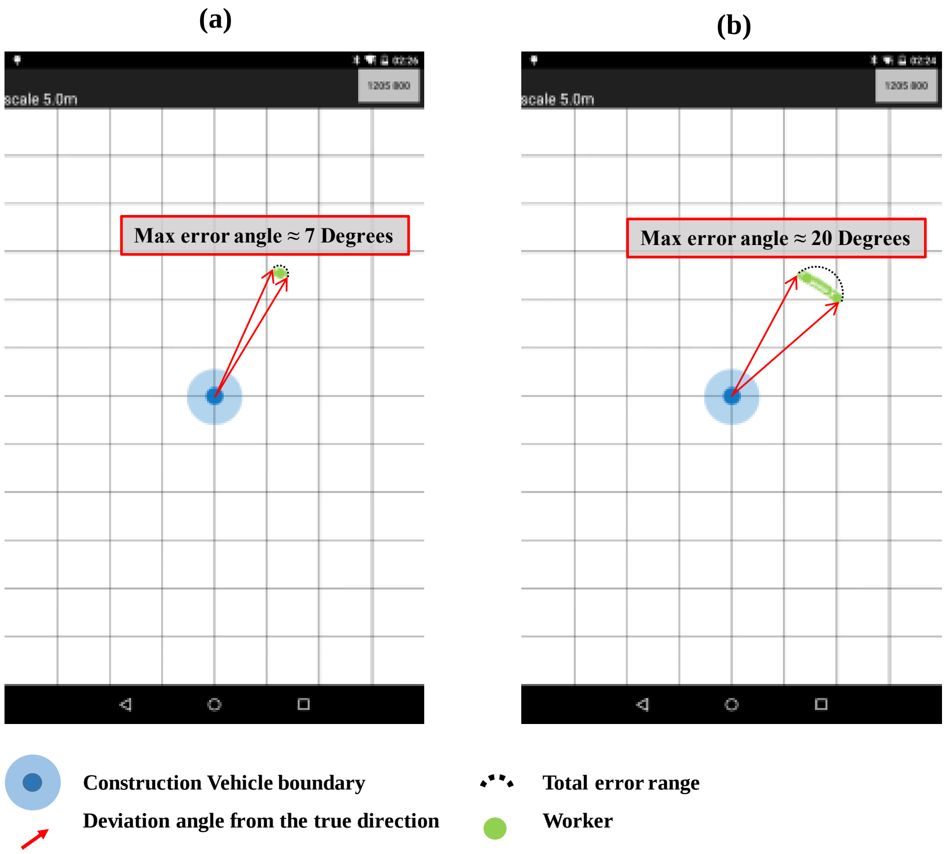

Figure 4.5 Direction accuracy of (a) E-Compass method (b) Two-GPS method

We also repeated these tests without eliminating the GPS error effect. Figure 4.6 shows the results of the experiment for four sets of data while the worker was stationary but the location of the worker reported to the system was changing because of GPS error. As described above each set of data was acquired by obtaining GPS information for 1-minunte with 1-second intervals. Results for 4 different sets of location data are shown using different colors on the tablet screen to demonstrate the error spread for each of the two methods respectively.

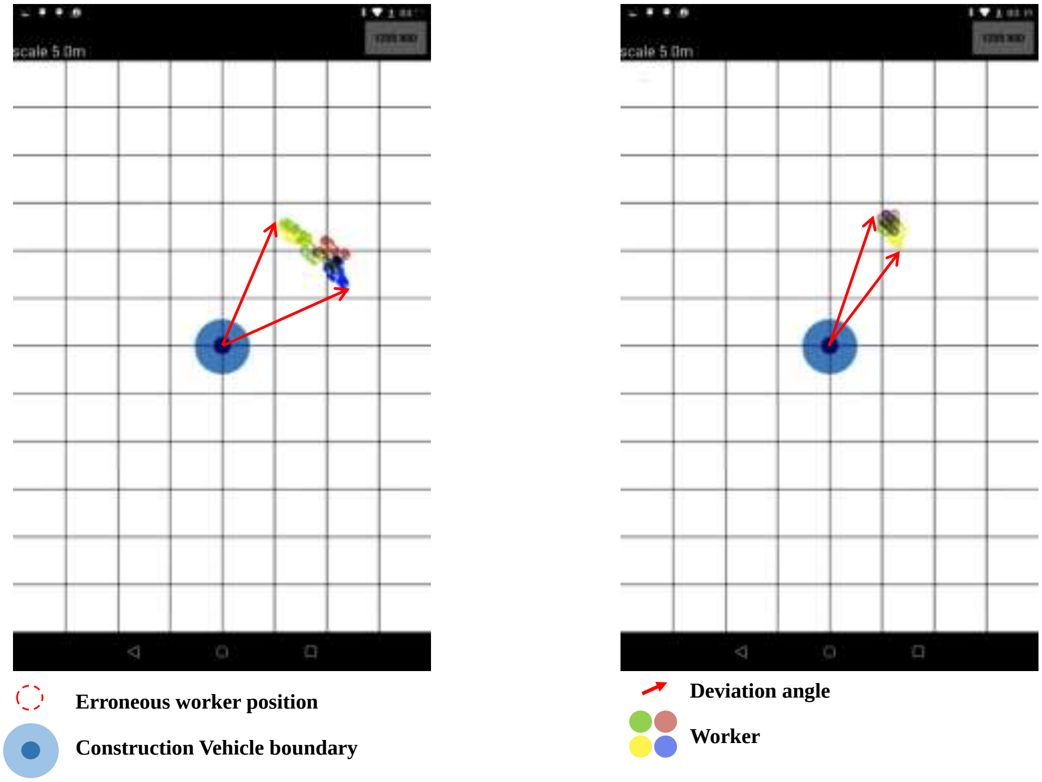

Figure 4.6 Tablet screen snapshots showing relative orientation of worker with respect to the construction vehicle and the spread in detected direction using two-GPS method (left) and e-compass method (right)

Finally, in this set of tests, the construction vehicle stayed at one place without moving or rotating and the worker moved around it in a circle. Regardless of which direction the construction vehicle was facing, the operator was able to locate the correct orientation of the worker on the tablet as shown in Figure 4.7.

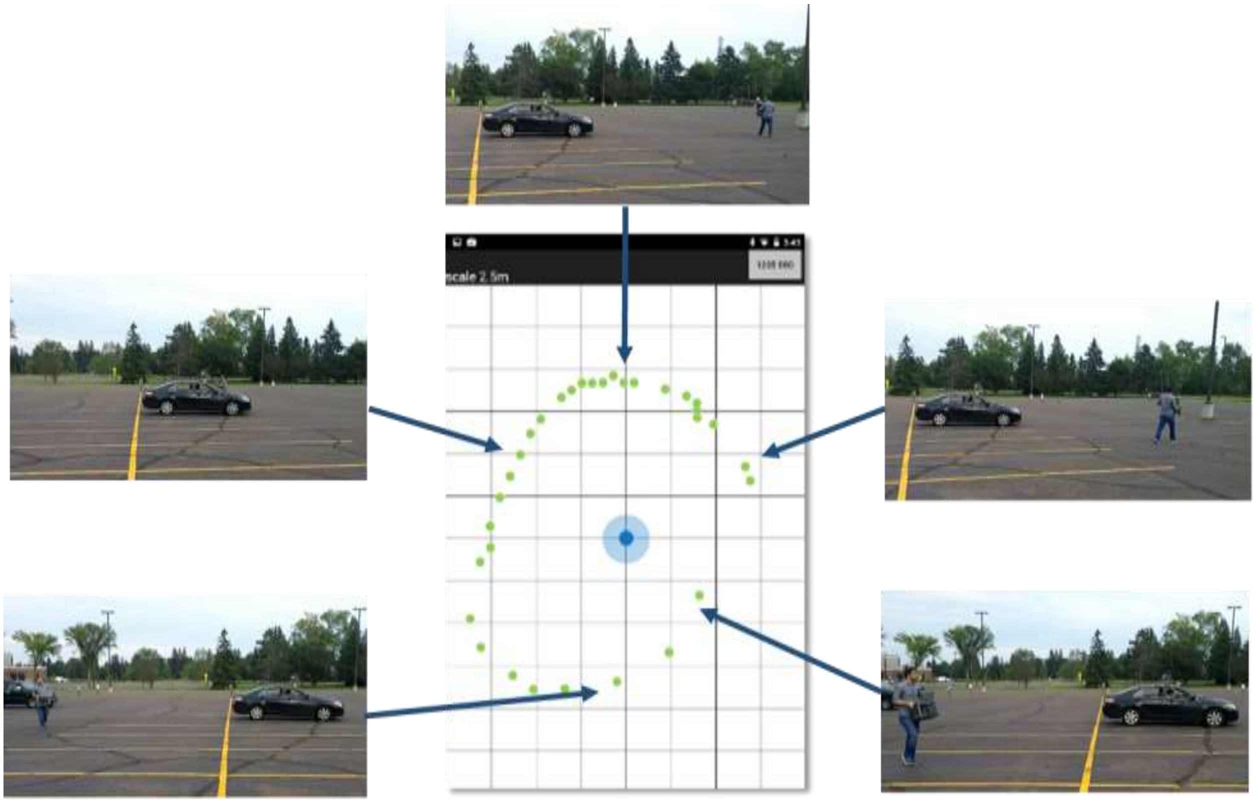

Figure 4.7 Tablet screen snapshot showing the trajectory of a worker walking around the construction vehicle in a circle.

4.2.3 <u>Multiple Workers and cross-platform functionality</u>

The developed visual warning system for construction vehicles is capable of handling multiple workers at the same time. The proposed system was tested for multiple workers present around the construction vehicle using three DSRC devices for three workers as shown in Figure 4.8. All three workers were simultaneously shown on the tablet (Figure 4.9) with acceptable distance and direction accuracies.

Although the multiple-worker functionality of the system was tested using only three DSRC devices, it can potentially handle a large number of workers equipped with DSRC devices. As a part of an ongoing research effort by National Highway Traffic Safety Administration (NHTSA) and Crash Avoidance Metrics Partnership (CAMP), the scalability of V2V communication has been tested and it has been determined that DSRC safety messages can be communicated reliably between at least 60 vehicles or more (200 to 400) depending on the application and communication rate *[16-17]*. This number indicates that the number of workers present in a typical work-zone within the DSRC range will not impose any restrictions on the functionality of this system.

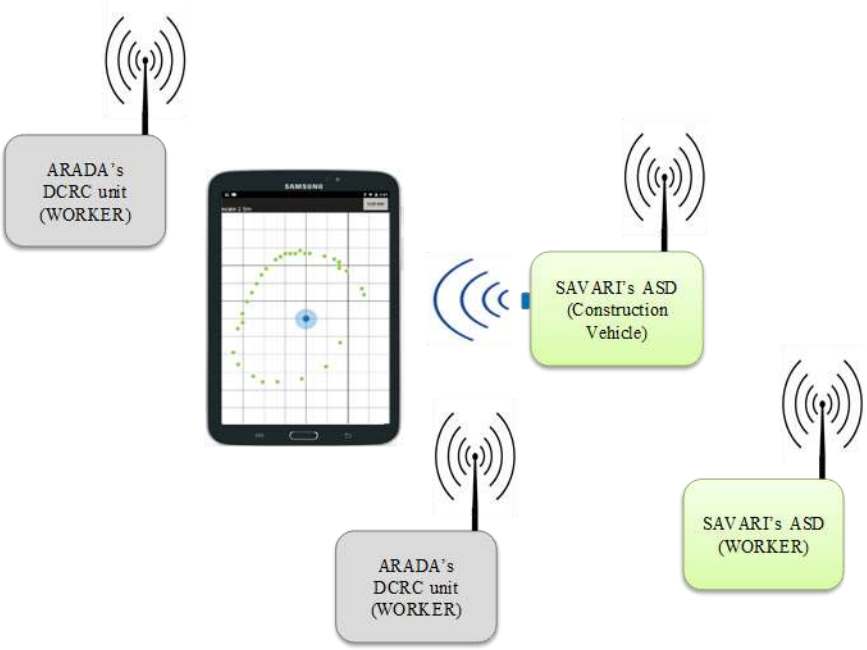

Figure 4.8 Conceptual multi worker field test set up

We also examined the functionality of the system for a situation where DSRC devices of different manufacturers would be used in the development of the system. Even though the DSRC devices follow the same standards and are meant to communicate with each other regardless of the manufacturing company, we discovered that due to programming differences between different DSRC devices, there needs to be additional adjustments to the default software applications provided on the DSRC devices manufactured by separate manufacturers.

The multiple worker tests were conducted using devices manufactured by “Savari Inc.” and “Arada Networks” after making the required changes in the software of the devices to make them compatible with each other.

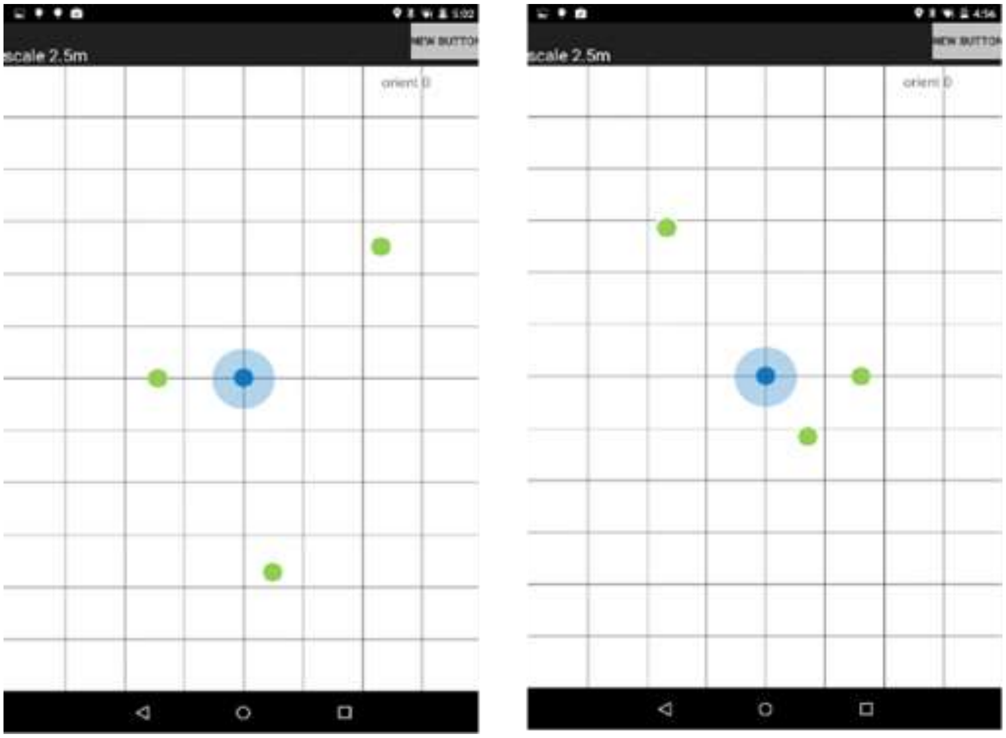

Figure 4.9 Two tablet screen snapshots showing three workers simultaneously present around the construction vehicle.

4.3 VMS Interfaced with DSRC Unit

To evaluate the performance of the DSRC-equipped VMS regarding its ability to detect workers' presence in the work-zone and posting a corresponding message, a DSCR unit was interfaced with a VMS unit via serial communication connection.

The DSRC unit was programmed to control the display messages on the VMS based upon whether it receives a worker's transmitted message or not. If the DSRC detects at least one worker, it will assume the workers are present in the work-zone and that work-zone section is active at least in a radius of 500 m (DSRC's practical wireless access range). In this case, the DSRC sends the command to the VMS to alternatively display two messages, "WORKERS PRESENT" and "SPEED LIMIT 35 MPH". This is assuming that the work-zone is located on a road with a regular speed limit of 55 MPH. In case the DSRC unit of the VMS does not receive any messages from a nearby worker, it will send a command to VMS to post the regular speed limit i.e., "SPEED LIMIT 55 MPH". The speed limits and alternating message timings are set in compliance with the Minnesota Department of Transportation's guidelines [*18*-*19*].

4.3.1 VSM Result

The DSRC-VMS interface was successfully tested in the lab and the results are shown in Figure 4.10. The worker was successfully and quickly detected when the worker's DSRC unit was turned on, indicating that a worker is present in the work-zone around the VMS, and VMS message was successfully changed. Similarly, when the worker's DSRC unit was turned off, the DSRC unit of VMS could not detect the worker and successfully changed the VMS message.

(a) DSRC unit connected to the VMS through serial connection.

(b) Alternating Messages when worker is present in the field.

(c) Worker is not present. (DSRC is off)

Figure 4.10 Experimental setup to demonstrate DSRC-VMS interface to detect the presence of a worker and post a message accordingly.

CHAPTER 5: CONCLUSION AND FUTURE WORK

A warning system for work-zones was proposed and developed to enhance workers' safety by providing visual guidance to the operators of the construction vehicles. The proposed system requires each worker to wear a device containing a GPS receiver and a DSRC radio to periodically transmit its location information. The system also requires construction vehicles to be equipped with a DSRC onboard unit, which can receive the location information from nearby workers. The construction vehicle is also equipped with a monitor screen to show the positions of the workers in the vicinity. In addition to the enhanced worker safety, the system also improves traffic mobility by dynamically posting suitable speed limits and/or warning messages on the VMSs around the work-zone. This requires each VMS to be equipped with a DSRC unit, so that it can detect the presence of the workers to determine the message that needs to be posted for oncoming traffic.

A prototype system was developed and field tests were conducted to demonstrate functionality and evaluate the performance of the proposed system. The test results show that the system displays the workers' positions on an Android-based tablet with acceptable distance (1.5 – 2 m) and direction (15 – 20 degrees) errors for successful visual guidance. We have also worked on a different method to improve the direction accuracy; this method has resulted in a much improved accuracy (1 – 5 degrees) in our field tests. Furthermore, the test results show that the DSRC-equipped VMS can post a variable speed limit depending on the presence of a worker in its vicinity.

In the future, the system could be deployed to an actual work-zone to evaluate how well it works in a real field environment. For that purpose, we will need to develop the WSD for implementing the complete safety system in the field.

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