Development of a Connected Smart Vest for Improved Roadside Work Zone Safety

April 2021 | Final Report

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SAFETY THROUGH DISRUPTION

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16. Abstract

Roadside work zones (WZs) present imminent safety threats for roadway workers as well as passing motorists. In 2016, 764 fatalities occurred in WZs in the United States due to motor vehicle traffic crashes. A number of factors (aging highway infrastructure, increased road work, increased levels of traffic and more nighttime WZs) have led to an increase in WZ crashes in the past few years. The standard WZ safety signage and personal protective equipment worn by workers at roadside WZs have not been completely effective in controlling WZ crashes. This project aims to address this issue by designing a wearable device to accurately localize, monitor, and predict potential collisions between WZ actors based on their movements and activities, and communicate potential collisions to workers, passing drivers, and connected and automated vehicles (CAVs). Through this project, a wearable worker localization and communication device (i.e., Smart Vest) was developed that utilizes the previously developed Threat Detection Algorithm to communicate workers' locations to passing CAVs and proactively warn workers and passing motorists of potential collisions. As a result, this research is expected to significantly improve the safety conditions of roadside WZs through prompt detection and communication of hazardous situations to workers and drivers.

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Abstract

Roadside work zones (WZs) present imminent safety threats for roadway workers as well as passing motorists. In 2016, 764 fatalities occurred in WZs in the United States due to motor vehicle traffic crashes. A number of factors (aging highway infrastructure, increased road work, increased levels of traffic and more nighttime WZs) have led to an increase in WZ crashes in the past few years. The standard WZ safety signage and personal protective equipment worn by workers at roadside WZs have not been completely effective in controlling WZ crashes. This project aims to address this issue by designing a wearable device to accurately localize, monitor, and predict potential collisions between WZ actors based on their movements and activities, and communicate potential collisions to workers, passing drivers, and connected and automated vehicles (CAVs). Through this project, a wearable worker localization and communication device (i.e., Smart Vest) was developed that utilizes the previously developed Threat Detection Algorithm to communicate workers' locations to passing CAVs and proactively warn workers and passing motorists of potential collisions. As a result, this research is expected to significantly improve the safety conditions of roadside WZs through prompt detection and communication of hazardous situations to workers and drivers.

Acknowledgements

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Table of Contents

List of Figures

List of Tables

Introduction

Roadside work zones (WZs) present imminent safety hazards for roadway workers as well as passing motorists. In 2016, 764 fatalities occurred in WZs in the United States due to motor vehicle traffic crashes (National Work Zone Safety Information Clearinghouse, 2017). In 2017, a WZ crash occurred once every 5.4 minutes in the U.S., adding up to an estimated 96,626 crashes in WZs, a 7.8% increase over 2014 and a 42% increase over 2013 (Work Zone Management Program, n.d.). The increase in WZ crashes can be attributed to a number of factors. The nation's highway infrastructure is aging, causing the need for rebuilding and improving existing roadways. This increased road work is being completed on roadways experiencing increased levels of traffic, especially in urban areas, often resulting in nighttime WZs to avoid peak travel times (Work Zone Management Program, n.d.). These factors result in more dangerous situations for workers and for passing vehicles. Accordingly, accidents involving motor vehicle collisions are a leading cause of roadside WZ fatalities. An average of 121 workers per year lost their lives at roadway WZs between 2003 and 2015 (Highway Work Zone Safety, 2017; Fyhrie et al., 2016). Transportation events accounted for 73% of these fatalities, 61% of which were due to a worker being struck by a vehicle in the WZ (Highway Work Zone Safety, 2017; Guo et al., 2017).

Between 2005 and 2010, vehicle collisions were the second most common cause of worker fatalities in roadside WZs, after runovers/backovers by construction equipment (Work Zone Management Program, n.d.). WZs and the presence of workers within them often violate driver expectations and as a result, workers and passing traffic are placed in unsafe proximity to each other. Successful WZ safety management hinges on detailed and early detection of threats, especially closeness of the workers to passing traffic, and sending timely information to workers and passing drivers. Furthermore, advanced warning of worker presence can help both human drivers and connected/automated vehicles (CAVs) prepare for and avoid collisions with WZ actors.

Standard WZ safety signage and personal protective equipment worn by workers at highway work sites have not been completely effective in controlling WZ crashes. Previous research conducted by team members has focused on improving roadway workers' safety through both worker trajectory planning (Roofigari-Esfahan et al., 2015; Roofigari-Esfahan et al., 2017) and the design of a wearable GPS-based communication system (Bowman & Martin, 2015). Additionally, in a previous Safe-D project (03-050), the project team developed and validated a Threat Detection Algorithm to detect potentially unsafe proximities between workers on foot, equipment, and CAVs. As such, the overarching goal of this research is to design and develop a smart wearable device that increases roadway workers' situational awareness and to inform workers and CAVs about detected hazardous situations to avoid imminent safety hazards. To this end, the team designed and built a prototype for a Smart Vest—a deployable roadside WZ wearable localization and warning system—to increase situational awareness of workers and CAVs by providing collision-imminent warnings. The Smart Vest utilizes current and emerging transformative technologies in conjunction with CAVs to minimize the increasing safety risks associated with roadside WZs. Equipping roadway workers with the technology to ultimately communicate with approaching CAVs can help eliminate imminent safety hazards associated with passing CAVs before they occur and reduce the occurrence of accidents by alerting workers about unsafe exposures.

Research Questions

The research addresses the following research questions:

1. What are the design requirements for the Smart Vest, including localization, communication and human-machine interface (HMI) technologies?
2. What are the best hardware components currently available to satisfy the identified design requirements and how will those components work together to achieve the desired functionality from the Smart Vest?
3. What backend platform configuration will enable the desired functionalities? What strategies should be utilized for sensing, actuation, and communication?
4. What is the best physical layout for the Smart Vest that is convenient and comfortable for workers while minimizing distraction?

Method

The team completed the following tasks for developing the specification and prototype for the Smart Vest:

Task 1: Project Management

Throughout the life of this project, the project team held biweekly teleconferences to discuss project status. Status meetings included discussion of the milestones/deliverables' schedule to include quarterly reports, biannual activity surveys, and the final project report.

Task 2: Design Requirements

During this research task, the design requirements for the technologies used in the Smart Vest were investigated. For this purpose, the team completed an extensive review of current WZ safety practices and standards governing High Visibility Safety Apparel (HVSA) in terms of material, configuration and other requirements under various work conditions. The ANSI 2010 standard requirements for HVSA Type R (roadway) class II was reviewed to comply with Virginia Department of Transportation (VDOT) practices. The requirements included background and retroreflective materials as well as configuration and ergonomics of the apparel. The project was presented to construction industry professionals, including contractors and project managers, to collect feedback from field practitioners regarding practical requirements of a wearable device that can replace conventional HVSA and can be used without adding a burden to workers. Based on the discussions, the team concluded the most practical configuration for the vest was to design the technology components into detachable elements to augment the conventional vests (e.g., into detachable reflective bands around the waist).

The team conducted a comprehensive review of the literature and industry practices about sensing and human factors relating to a wearable vest and feasibility of the related technologies for use in roadway WZs. The investigated technologies included location sensing devices, HMI modes, and related sensors and communication technologies. The review focused on technical requirements for viable technologies that can be conveniently used in roadway WZ conditions and that can convey the required results. The location sensing requirements were studied in terms of requirements for accuracy, latency, durability, weight, and feasibility for use in roadway WZ environments. The viable HMI modes were found to be haptic, auditory and visual (lighting).

In order to collect user feedback regarding the comfort and practicality of each HMI mode and configuration, the team designed a user survey focusing on understanding worker preferences, priorities, convenient HMI modes, and optimal locations of the related technologies on a wearable vest. The survey was designed in online format and was sent to roadway construction practitioners, including private companies such as Keiwit, Forrestconstruction, WMJordan, etc. The survey was completed by 25 highway construction workers. Of those responding, 72.00% had more than 10 years' experience in the industry (Table 1). The occupations included project managers, safety specialists, flaggers, and paving workers.

Table 1. Participant Experience

Years of Experience	% of Total Participants	Count
0–3	0.00%	0
3–10	28.00%	7
> 10	72.00%	18
Total	100%	25

Noise (56.25% strongly agree), darkness (75% strongly agree), and weather (42.55%) were found to be the environmental elements that most negatively impact workers' ability to detect a hazard. To understand workers' alarm method preferences under different environmental situations as well as their working activities, a Likert scale with weighted numerical values were assigned a ranking from 1–7, with 7 being the most preferred. The top two alarm methods under each situation are presented in Table 2. Among all the alarm methods, the combination of Auditory + Haptic + Visual was the most preferred under all the circumstances. Auditory + Visual received the second highest score in almost all situations. Participants' responses further emphasized the importance of considering workers' activities in predicting unsafe proximities and selection of HMI method. For instance, although workers considered a haptic alarm to be the most robust method, the comfort of auditory and visual alarms were dependent upon the type of activities. For example, visual alarms were deemed more preferable for activities such as jackhammering work, where high levels of activity noise impair hearing. In addition, using combination warnings can help workers with visual or hearing disabilities better receive alarms and prevent imminent threats.

Table 2. The Top Two Alarm Methods in Different Environmental Situations and Activities

	Rank 1 Alarm	Total Score	Rank 2 Alarm	Total Score
Day	Auditory + Haptic +Visual	226	Auditory + Visual Auditory + Haptic	206
Night	Auditory + Haptic +Visual	231	Auditory + Visual	212
Walking	Auditory + Haptic + Visual	242	Auditory + Visual	202
Jackhammering	Auditory + Haptic + Visual	219	Visual	203
Rolling	Auditory + Haptic + Visual	217	Auditory + Visual	198
Guiding	Auditory + Haptic +Visual	232	Auditory + Visual	194
Random	Auditory + Haptic + Visual	227	Auditory + Visual	198

Task 3: Hardware Component Specification

The research team conducted a comprehensive review of the literature and off-the-shelf technologies to select alarm hardware components, focusing on identifying components that were small and lightweight, while satisfying the design requirements. A U-blox multi-band GNSS receiver (Figure 1), which provides real-time kinematic (RTK) GPS data, was selected for localization. This component is small and lightweight, has an advertised accuracy of 0.01 m, and utilizes the following GNSS: BeiDou, Galileo, GLONASS, and GPS/QZSS.

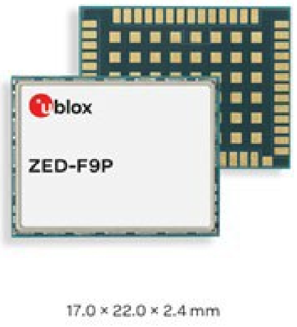

Figure 1. U-Blox receiver.

The communications component selected by the project team was a Digi XBee 3 Zigbee 3 module (Figure 2). This component supports communications between each Smart Vest unit (or node) and the gateway, broadcasting the RTK GPS data and sending HMI requests to trigger the associated Smart Vest sensors based on the collision detection algorithm. This unit is compact (13 mm x 19 mm). The gateway or sentinel device is the central unit that facilitates communication between the Virginia Connected Corridor (VCC) Could Server and the Smart Vest nodes.

Figure 2. Zigbee communications module.

A Raspberry Pi 4 was selected as the microprocessor acting as the "brain" of the gateway (Figure 3).

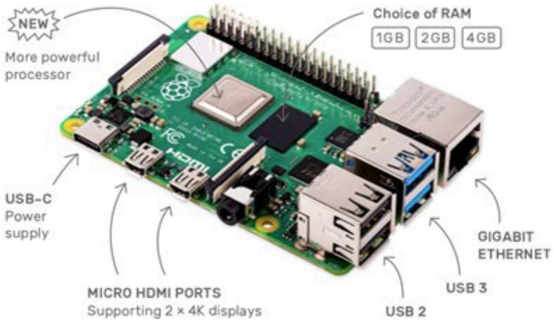

Figure 3. Gateway microprocessor (Raspberry Pi 4).

The gateway runs a threat detection algorithm developed by the research team that utilizes polygons representing roadside WZ boundaries, and detects when the Smart Vest nodes needs to be alerted of potential threats. The polygons can be created using two methods. First, a physical device can be used at

WZs to plot out the points of a polygon that make up a WZ's activity area. This device is considered another node, similar to the Smart Vest nodes, but does not contain an HMI component. Second, the system will be integrated with the VCC Cloud and can utilize the Work Zone Builder application (a mobile application that members of the research team created to digitize roadside WZ boundaries and other components) and the digital boundaries identified for each WZ created by the application.

The HMI sensors integrated into the Smart Vests include LEDs, haptic tactors, and audio speakers that provide patterned warnings to alert roadside workers of various conditions while working. These sensors are controlled by a processor embedded into the Smart Vest board.

The LED strips chosen by the team (two per vest) are flexible. The white LED light strips are shown in Figure 4 below.

Figure 4. LED strips

The haptic tactors (four per vest) are small (8.7 mm) and provide a vibration speed of 13,800 rpm and 7 G amplitude (see Figure 5).

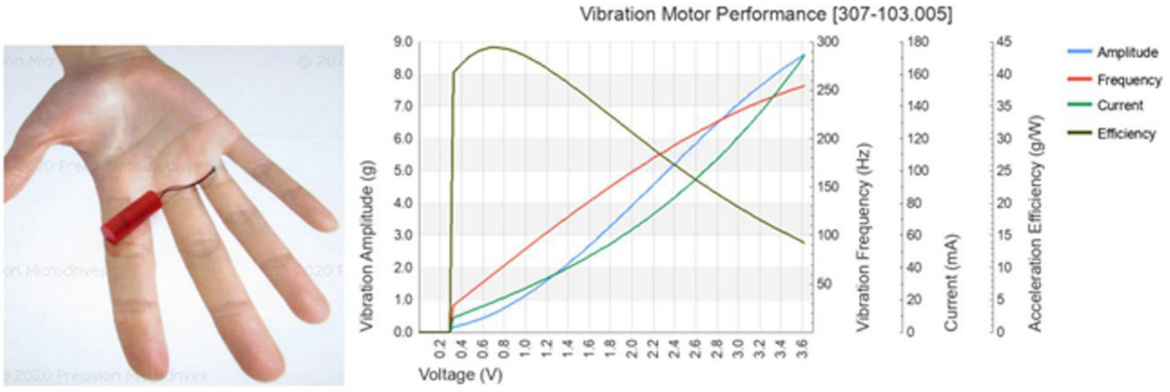

Figure 5. Haptic tactors.

The buzzers/speakers (two per vest) provide 100 dB at 5 V as shown in Figure 6 below.

Figure 6. Audio buzzer.

Based on the user feedback collected through the survey and discussion with industry practitioners, the team concluded that sensors should be built as easily detachable components from the vest garment, so that the garment can be laundered as needed. Therefore, the equipment was integrated into a harness (Figure 7) which will be worn underneath the conventional vest. The designed harness can be attached to a Class 3 roadside worker vest that can be purchased separately.

Figure 7. Harness used to mount sensors.

Task 4: Platform Development

The gateway hosts the developed software and algorithms that constantly localize workers, detect potential threats, and warn workers about those threats. To this end, the gateway is integrated with a GPS plotter device. This allows the GPS points that correspond with a roadside WZ to be instantiated into the system and used to determine potential threats to the Smart Vest wearers and passing CAVs. The gateway can also receive information regarding WZ boundaries from the Work Zone Builder Smartphone application. The Builder Smartphone application uses HERE map technology to create a WZ layout which meets VDOT requirements and generates a GEOJson file which can be downloaded by the Smart Vest base station to determine potential threats automatically, without needing to use the physical GPS plotter device. The WZ boundaries are then used to detect extreme proximity to the border (low hazard zone), or when a user is passing the WZ and stepping into the traffic path (high hazard zone). The system components are detailed in the following section.

Smart Vest RTK System

The Smart Vest GPS RTK system consists of three main components (Figure 8):

1) Base Station
2) Communication
3) Rover

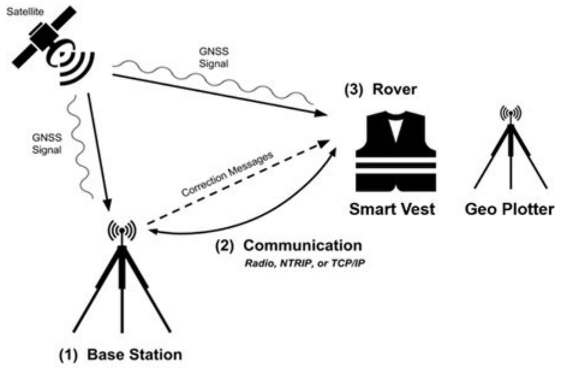

Figure 8. Smart Vest RTK System.

The base station system is the main computing component, transmitting RTK corrections using an XBee link to the Rovers. It also receives GPS data from the Rovers at 10 Hz and conducts the following computation tasks:

- Geofencing and Alert triggering for Smart Vest Rover: Each Smart Vest Rover Node can receive an HMI trigger when there is a WZ polygon in place and the base station detects a change between a safe zone to a low/high level alert zone. The Smart Vest Rover transmits GPS and inertial measurement unit (IMU) data to the base station in real-time in order to make the above calculations. The IMU data (acceleration) is used to determine specific activities performed by the user and provide specific alerts while those activities are close to a safety-critical geofence.
- Local WZ polygon creation using Geo-Plotter Rover: The Geo-Plotter Rover is used to send precise GPS position data to the base station for each polygon vertex (WZ boundary coordinates). The Geo-Plotter has a push button that sends GPS data to the base station for 10 seconds in order to average and insert it into the polygon creation engine.

Rovers, including the Smart Vest system and the Geo-Plotter for WZ polygon creation, can get within 3 cm accuracy using the base station's RTK data. Both systems use a 32-bit microprocessor to receive RTK corrections and redirect them to the on-board GPS unit to compute and provide a high precision GPS output back to the microprocessor. The accurate GPS coordinates are then forwarded as GPS packets to the base station. Communication between the Base Station and Rovers is established using an XBee Link. Providing up to a 150 m range and multi-node support, the small XBee provides a reliable wireless communications support mesh, multi-hop, and direct link data transmission. As shown in Figure 9, the final system configuration shows the Smart Vest device, the Base Station, and the 4G Link to download RTK corrections from Virginia Tech Transportation Institute's (VTTI's) NTRIP Server and to communicate with the VCC Cloud Server. Both Base Station and Smart Vest devices use the Ublox ZED-F9P RTK-capable GPS receiver to compute very precise GPS location and transmit that data along with IMU data using the XBee 3.0 RF Link. VTTI designed a stack hardware board which houses the GPS transceiver and the HMI circuitry for alert triggering. This board goes on top of an NXP development board (FDRM KL28Z), which uses the NXP KL28Z ARM Microprocessor.

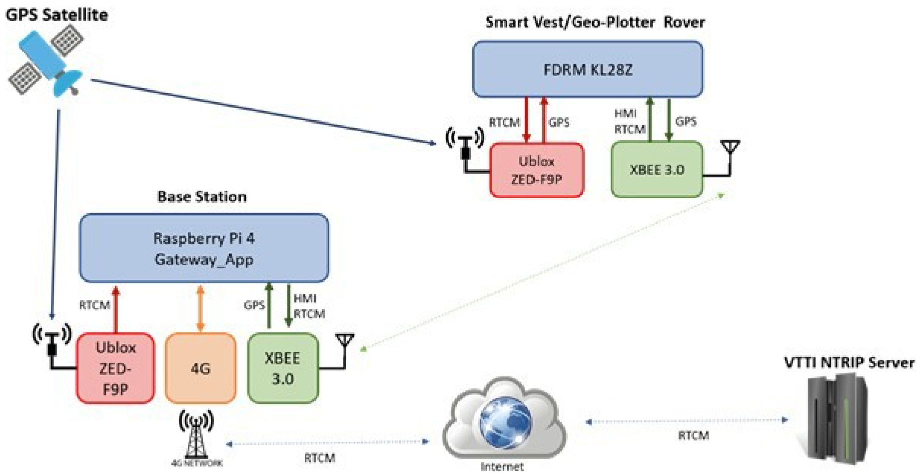

Figure 9. Final system configuration.

GPS RTK Verification

The GPS RTK sub-system is based on the Ublox ZED-F9P GPS chip, which provides multiband GNSS technology and RTK functionality, leading to within 1 cm precision and converge time of less than 10 seconds. Multi-constellation support includes GPS and GLONASS, Galileo, and BeiDou. Using Ublox's U-Center software, the Rover can provide high precision GPS data and RTK data reception for GPS solution computation. Figure 10 shows Ublox's GUI, which provides very specific information about the GPS receiver, satellite information, precision, computation quality, and RTK status. VTTI used this tool to confirm the GPS accuracy (which averages 2 cm), RTCM/RTK packets (six different packets) and the GPS computation level (3D/DGNSS/FLOAT) .

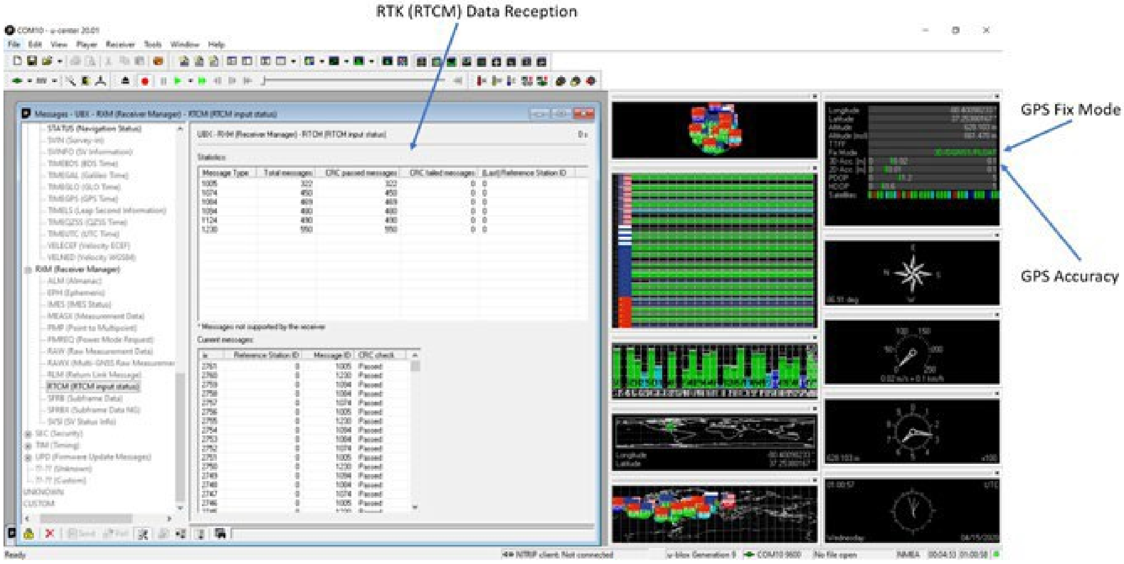

Figure 10. GPS RTK correction.

GPS Fix Mode can be explained as follows:

- <u>3D</u>: a position solution is achieved with at least four satellites compared to a 2D solution with three satellites and altitude/vertical metrics locked to a preset value.

- DGNSS: corrections are provided from a source that measures the differences between what pseudo range values (the signal's time-of-flight approximately indicates distance using speed of light through a medium) for each satellite should be at the precisely surveyed reference station compared to what is reported by its navigation computation. The differences are generally caused by time-varying ionospheric perturbations in the path from satellite to the reference station and the nearby rover. If the rover and reference are too far apart, the separate signal paths may have different perturbations and the correction data are less effective.
- Float and fixed: in precise navigation, the receiver tries to lock onto carrier phase (within the 19 cm wavelength) to resolve the exact wavelengths and fractions to each satellite. If this exactitude is achieved, the status is "fixed" since phase markers can be locked. If precise wavelengths and fraction are not achieved, ambiguity persists, and the status is "float" since the carrier phase markers are not locked but "floating around" in mathematical computation. The difference in fixed position accuracy is in mm compared to the cm-level float accuracy.

RTCM packets can be classified as follows:

1005	**Stationary RTK Reference Station ARP** Commonly called the Station Description, this message includes the Earth-Centered, Earth-Fixed location of the antenna (the antenna reference point [ARP] not the phase center) and the quarter phase alignment details. The datum field is not used/defined, which often leads to confusion if a local datum is used. See message types 1006 and 1032. The 1006 message also adds a height about the ARP value.
1074	**GPS MSM4** The type 4 Multiple Signal Message (MSM) format for the U.S.'s GPS system. This is one of the most common messages found when MSM is being used
1084	**GLONASS MSM4** The type 4 MSM format for the Russian GLONASS system.
1094	**Galileo MSM4** The type 4 MSM format for Europe's Galileo system.
1124	**BeiDou MSM4** The type 4 MSM format for China's BeiDou system.
1230	**GLONASS L1 and L2 Code-Phase Biases** This message provides corrections for the inter-frequency bias caused by the different frequency-division multiple access frequencies (FDMA; k, from -7 to 6) used.

Task 5: Build the Smart Vest

The team built upon the two prior versions of the Smart Vest (Alpha and Alpha Plus) to create the final Beta version. Final hardware selections have been made as described in the Task 3 section of this report. The team worked with a fashion designer to build three Smart Vests (Beta Version). Working together with a fashion designer allowed the Vest to be as flat as possible to avoid any issues that might cause discomfort for the wearer. The harness has snap-on buttons, allowing the Smart Vest to de-attach for cleaning/maintenance or upgrade purposes. On the belt section, an industrial Velcro strip allows the tractors to be adjusted in location to provide better sensitivity depending on the wearer's preferences.

The GPS antenna has a small ground plate on the right shoulder area, which also has a snap-on button. The ground plate is necessary to acquire more precise satellite data and improve the GPS antenna's performance.

The harness is connected to the vest through a cable connector (left side), which powers and controls the LED strips.

The Smart Vest Beta version and its physical hardware components are shown below in Figure 11.

Smart Vest Beta Version

Smart Vest GPS antenna with ground plane attached to harness using snap on button

Smart Vest electronics are protected with a waterproof fabric and neoprene which are secured using snap on buttons

Smart Vest tactors attached to the belt using a Velcro strip allowing adjustments, if needed

Smart Vest hardware board which has a GPS receiver and controls the HMI outputs (LEDs, buzzers and tactors)

Figure 11. Physical hardware of the Smart Vest.

Results

Smart Road Tests

Work Zone Polygon Validation

The base station software can acquire an N-vertex convex polygon and classify/check if a Smart Vest Rover is in the following zones:

Table 3. Developed Safety Zones

Zone	Definition
High Level threat zone	Any GPS location outside the defined WZ polygon
Low Level threat zone	Any GPS location in between the pseudo-polygon region which is 2 meters under the WZ polygon shape.
Safe Zone	Any GPS location below/inside 2-meter offset from WZ polygon

For this WZ polygon validation, Geo-Plotter was used to create a 4-vertex polygon and acquire GPS data from one Smart Vest Rover. The base station computer system records a log file with each GPS entry and the proper classification. The picture below shows the classification: red (high level), blue (low level), green (safe zone) and 4-vertex polygon (yellow).

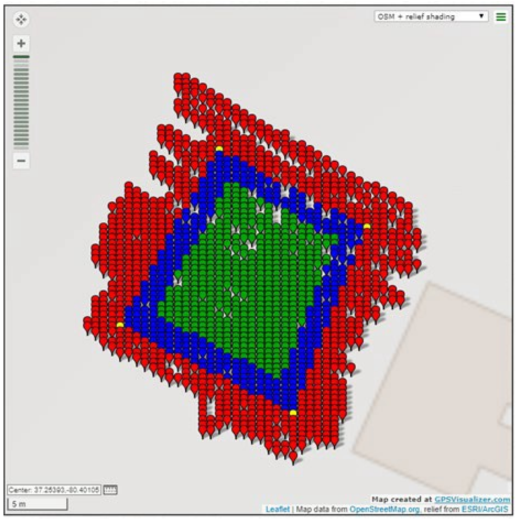

Figure 12. Validation of safety zones.

For this field test, the following systems were used (Figure 13):

Base Station

Raspberry Pi 4 running Linux OS
Ublox ZED-F9P GPS Module and antenn
XBEE Transmitter
USB Battery pack

Geo-Plotter

- KL28Z Development Board
- Ublox ZED-F9P GPS Module and antenn
- XBEE Transmitter
- Push Button
- USB Battery pack

Smart Vest (No HMI)

- KL28Z Development Board
- VTTI Smart Vest Board with GPS and XB SoCs.
- GPS Antenna
- USB Battery pack

Figure 13. GPS system hardware components.

Smart Vest Assessment

The team conducted testing to evaluate the three developed Smart Vest Beta versions to verify GPS accuracy, communications range, and battery life. GPS accuracy validation was verified at the VTTI Automation Hub location, where a rectangle area was marked as a WZ activity area using the GPS Plotter (four GPS points) as shown in the picture below.

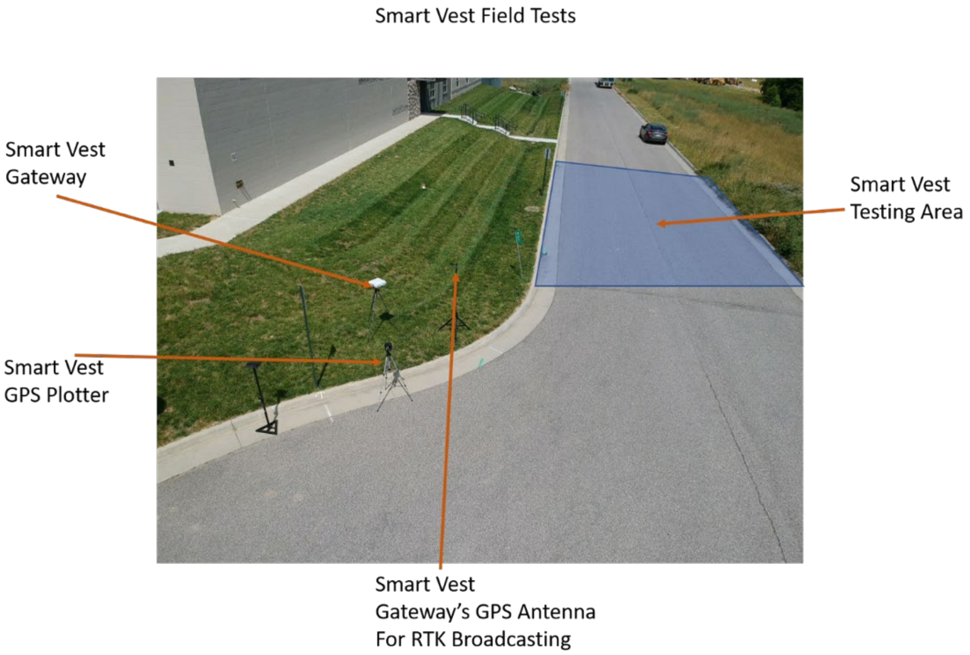

Figure 14. Smart Vest assessment setup.

A team member wearing the Smart Vest walked across the blue region while transmitting GPS position data and a log file was created with area detection and classification. The GPS points were classified as safe zone (green), low-level warning (blue), and high-level warning (red).

Figure 15. Safety zone validation.

The second test verified the communications range from the Smart Vest Gateway to any node. Using both versions of the wireless transceiver (XBee) with internal/external antennas, the achieved range was around 300 m.

Figure 16. Communication range validation.

The third test executed was related to battery life. Having a full charged battery, two scenarios were tested:

1) Smart Vest transmitting only GPS data to Smart Vest Gateway (normal scenario): Battery lasted 20 hours.
2) Smart Vest transmitting GPS and triggering HMI alerts (LEDs, buzzers, and tactors) every 2 seconds: Battery lasted 10 hours.

Demonstration

The team built an additional set consisting of a Smart Vest, GPS Plotter and Base station. These were used during VTTI's Smart Vest demo at the Virginia Smart Roads (Figure 17). VCC Connectivity was added to the Smart Vest software package for this demonstration. The system can connect to VCC and upload basic safety message packets using Smart Vest GPS locations and can generate virtual worker dots on the VCC Monitor tool. Future development efforts will allow the Work Zone Builder application support to retrieve Activity Area information for easy polygon geo-fencing setup.

Smart Vest's Base Station
The Base Station was used to process Smart Vest GPS data and trigger HMI warnings.

Smart Vest's GPS Plotter
The GPS Plotter was used to create a virtual geo-fence polygon.

Smart Vest
Smart Vest in action triggering HMI alerts when the worker approaches to the cones. These cones are part of the virtual geo-fence polygon on this setup.

Figure 17. VTTI's Smart Vest demo at the Virginia Smart Roads.

Field Experiment

The team received Institutional Review Board (IRB) approval and ran a session of field experiments for testing the three Smart Vest Beta setups to verify GPS accuracy, communications range, and battery life at a highway construction site at Elliston, VA.

GPS accuracy validation was verified at the worksite, where a rectangle area was marked as a WZ activity area using the GPS Plotter (four GPS points) as shown in yellow in the picture below.

Figure 18. Realization of the worksite and collected location data for field study.

Data was collected from two construction workers wearing the Smart Vest as they conducted earth work and placed base stones, and a log file was created with area detection and classification. The GPS points were classified as safe zone (green), low-level warning (blue; within one meter from the border), and high-level warning (red; at the border). These can also be seen in Figure 18.

The test verified the communications range from the Smart Vest Gateway to any node. Using both versions of the wireless transceiver (XBee) with internal/external antennas, the achieved range covered the WZ length of about 500 m. Figure 19 below shows the setting of the experiments and study participants during different construction activities.

Figure 19. WZ setting for the field experiment.

Feedback was also collected from the participants about the comfort and alarms received using the vest. The collected feedback will be used in the future research to improve the layout of the vest.

Discussion

A number of challenges were encountered during the course of the research. Due to the user-centered nature of the design, the team decided to conduct a comprehensive formal user survey in addition to the review of literature and technologies (as discussed in Task 2). The IRB process required for this and collecting the user preferences delayed the subsequent activities. In addition, during the literature review and user survey, the importance of accurate activity recognition for predicting unsafe proximities and minimizing false positive alarms was highlighted. However, the current algorithm does not provide the required accuracy and requires extensive computational modeling. We believe that this is an essential component that needs to be addressed for successful implementation of the Smart Vest. As a result, the Smart Vest Rover has an built-in IMU, which can be used for further activity detection. The research team is working on a subsequent project (funded by Center for Innovative Technologies) to expand functionalities of the vest and include the activity recognition in the current algorithm. To this end, a series of field experiments at highway jobsites will be conducted while using the Smart Vest developed in this research to collect data during various highway construction activities.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the Safe-D website here. The final project dataset is located on the Safe-D Dataverse.

Education and Workforce Development Products

Dr Roofigari-Esfahan developed a graduate course, Advanced Digital Construction and Manufacturing, that she will teach in Spring 2021. The Smart Vest technologies are presented as technologies that will change the future of the industry. A demonstration of the vest was given to her undergraduate course (BC 2114-IT in Construction and Design) in Fall 2019 and Fall 2020.

Dr Roofigari-Esfahan presented and discussed the Smart Vest at three committees she is involved in (construction management, traffic control in WZs and information systems and technology) at the Transportation Research Board's (TRB's) annual meeting in January 2020. She also presented the technologies at the Construction Research Council (CRC) conference in March 2020.

The vest was also presented to a group of 45 female high school students interested in Construction Engineering in an event held by the Department of Building Construction at Virginia Tech. The students had the chance to wear and experience different features of the vest.

Dr. Roofigari-Esfahan has been invited to present her research, including the Smart Vest, as a keynote speaker at the International Conference and Exhibition on Smart Material and Construction Technology to be held in Dubai in November 2021.

Technology Transfer Products

The Smart Vest was presented to industry professionals in different safety events throughout the course of the research and was very well received. Examples of T2 activities include the following:

Dr. Roofigari-Esfahan presented the initial version of the Smart Vest at Virginia Asphalt Association (VAA)'s Mid-Atlantic conference and expo on December 11–12, 2019, in Richmond, VA. She demonstrated the Smart Vest for asphalt workers and collected feedback regarding different features of the vest. She also presented the Smart Vest and discussed its safety features at the VAA’s Safety committee meeting.

Dr. Roofigari-Esfahan presented the Smart Vest to the Virginia Tech Honors College’s Industry Board (consisting of the representatives from Boeing, GE and Caterpillar) on February, 25, 2020. The event was attended by 20 professionals.

A workshop was held at VTTI on March 11, focusing on another VTTI project that included 12 infrastructure owner/operator (IOO) representatives, including DBi Services, VDOT/VTRC, and Transurban. During a portion of this workshop, Dr. Mollenhauer presented the overall goals of the Smart Vest project, the current progress of the Smart Vest project, and demonstrated the Alpha Plus version of the vest.

Dr. Mollenhauer presented the Smart Vest project goals and status at the ATSSA Annual Convention and Traffic Expo on January 27, 2021. This presentation was attended by an estimated 45 attendees in New Orleans.

Dr. Roofigari-Esfahan discussed the Smart Vest features with the TRB Construction management committee members on June 26 2020. The meeting was attended by 30 professionals.

Dr. Mollenhauer presented the Smart Vest project goals and status at the American Association of State Highway and Transportation Officials’ Safety Summit meeting on June 17, 2020. This presentation was attended by an estimated 77 people, including many DOT officials.

Dr. Roofigari-Esfahan discussed the Smart Vest features with the Construction Industry Institute’s (CII’s) Technology and innovation committee members on September 15, 2020. The meeting was attended by 65 professionals. Interest was shown to demonstrate the Vest at CII’s 2021 conference.

VTTI demonstrated Smart Vest functionality along with other project’s as part of the WZ technologies of the future. Virginia Tech’s University Relations made a video showing how the Smart Vest can help and alert works during dangerous situations on the road.

Dr Roofigari-Esfahan is invited to present and discuss the opportunity of further developments of the Smart Vest at CPWR (the Center for Construction Research and Training) in Maryland. The meeting was postponed due to the COVID-19 and is expected to be scheduled in summer 2021.

Dr Roofigari-Esfahan is invited to present and discuss the Smart Vest and associated topics in regards to worker protection innovations at American Traffic Safety Services Association’s virtual Annual Convention and Traffic Expo in February 2021.

Dr. Mollenhauer presented the Smart Vest in different events including:

- PA DOT presentation – 10/1/20
- Autonomous Maintenance Technology Pooled Fund – 10/26/20
- 5GAA Virtual Event – 10/27/20
- IOO/OEM RSZW (reduced speed zone warning) subgroup – 11/9/20
- VDOT SORAC meeting – 11/5/20

Data Products

The data uploaded to the Dataverse includes 39,286 datapoints collected on a field test WZ setup at VTTI's Automation Hub. The collected data set includes data entries for three Smart Vest devices while moving around a virtual polygon area defined by the Smart Vest Geo Plotter device. The virtual polygon area was defined using a four-point polygon (square shape). The three Smart Vests were worn inside and outside the virtual polygon and their GPS location was processed to calculate their classification and trigger the proper HMI warnings accordingly when crossing between safe zone, low-level warning areas, and high-level warning areas. The dataset can be accessed at: DOI:10.15787/VTT1/PMIRWK

References

1. Bowman, D. S. & Martin, T. L. (2015). An innovative intelligent awareness system for roadway workers using dedicated short-range communications. Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC): https://cvi-utc.org/wp-content/uploads/2015/10/Bowman_Final.pdf

2. Fyhrie, P.B. (2016). *Work zone intrusion alarms for highway workers*. Caltrans Division of Research, Innovation and System Information. ⟨http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/work_zone_warning_preliminary_investigation.pdf⟩ (November 1, 2018).

3. Guo, H., Y. Yu, T. Xiang, H. Li and D. Zhang (2017). The availability of wearable-device-based physical data for the measurement of construction workers' psychological status on site: From the perspective of safety management. *Automation in Construction, 82*, 207-217.

4. Highway work zone safety. (2017, June 19). Centers for Disease Control and Prevention https://www.cdc.gov/niosh/topics/highwayworkzones/default.html

5. National Work Zone Safety Information Clearinghouse (2017, October 24). workzonesafety.org. https://www.workzonesafety.org/crash-information/workzone-fatalities/fatalities-motor-vehicle-traffic-crashes-state-work-zone-2016/

6. Roofigari-Esfahan, N., Wang, J & Razavi, S. (2015), Measuring Construction Workers' Attention Using Eye-Tracking Technology. In *Proceedings of Canadian Society for Civil Engineering (CSCE) 5th International/11th Construction Specialty Conference*, Vancouver, UBC, Canada.

7. Roofigari-Esfahan, R., Du, S., Anumba, C., & Razavi, S. (2017). Smart tracking of highway construction projects. In *Computing in Civil Engineering 2017*, 187-195.

8. Work zone management program. (n.d.). U.S. Department of Transportation.