GEORGIA DOT RESEARCH PROJECT #18-17

FINAL REPORT

PHASE III: SMART PROXIMITY WORK ZONE SAFETY TECHNOLOGY DEPLOYMENT

GDOT

Georgia Department of Transportation

OFFICE OF PERFORMANCE-BASED MANAGEMENT AND RESEARCH

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16. Abstract:
The main objective of this research is to develop and deploy a low-cost and scalable smart Internet of Things(IoT) proximity alert system using the IoT mobile sensing technology for alerting workers and equipment operators in proximity hazard situations in highway work zones. This research consisted of 5 field tests, including a preliminary test and 4 evaluation tests. Through the tests, the technical and practical feasibility of the system was evaluated. The experiences of the workers who participated in the tests were investigated by collecting and analyzing a questionnaire survey. With the developed system, it is expected that GDOT can improve the safety in proximity between equipment and workers by deploying the low-cost proximity alert system.

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GDOT Research Project 18-17

Final Report

PHASE III: SMART PROXIMITY WORK ZONE SAFETY TECHNOLOGY DEPLOYMENT

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

Roadway construction and maintenance operations typically require workers to work in proximity to construction equipment and continuous traffic, leaving workers exposed to injury and death due to getting hit by construction equipment in the work zone. According to the Bureau of Labor Statistics report (BLS 2017), 609 workers were killed at road construction work zones from 2011 to 2015. Considering each death in the construction industry costs $4 million in direct and indirect expenses, fatalities caused in the road construction work zones have resulted in enormous expenses. Specific to the state of Georgia, a total of 60 deaths were reported in road work zones from 1973 to 2018 (Georgia Department of Transportation, 2019). Hence, it is important that the proximity hazard situations between the workers and construction equipment must be holistically detected by using a smart alarm system to reduce the risk in the highway work zones in Georgia. To address this issue, the team set the objective of the research to develop and deploy a low-cost and scaleable smart proximity alert system using the mobile Internet of Things (IoT) sensing technology. Three tasks are conducted to achieve the objective as follows.

- **Task 1. Development of a proximity hazard detection and alert system:** The team developed mobile sensing devices that provide auditory and vibratory alerts to the workers whenever they are in hazardous proximity situations. The developed devices have capabilities to measure distances to beacons attached to equipment, to communicate with a server, and to provide alerts with buzzer and vibration for workers and equipment operators.

- **Task 2**. **Design and development of a cloud server for remote data collection and analysis:** The team designed and developed a cloud server as a data management and analysis platform. The sensor data collected from the workers and equipment were stored in the server where the distances are calculated on a real-time basis. Also, the incident data were visualized in a web-based user interface so that managers can monitor safety conditions in jobsites and analyze historical data of individual workers.

- **Task 3. Field testing and validation:** The team conducted a series of field tests, including a preliminary test and four evaluation tests, to validate and evaluate the system's technical and practical feasibility from ongoing GDOT highway construction and maintenance projects.

As a result of Task 1, Personal Protection Units (PPUs) and Equipment Protection Units (EPUs) were developed and tested in the lab environment. They were equipped with a communication module, micro processing unit, buzzer, vibrator, and data storage. PPUs were designed to be attached to the back workers' neck area, and EPUs were designed to be mounted on the windshield or frames of the equipment. Each unit was able to communicate with the cloud server, and the buzzer and vibrator were triggered whenever the alerting range was detected.

The cloud server developed in Task 2, having sufficient computational capacity, is able to centralize any data including algorithmic changes and data analyses. Incident data, including the worker ID, equipment ID, and the number of incidents per worker, were visualized in the web-based user interface. The user interface was able to show the information on a real-time basis.

The proximity alert system was deployed in five different ongoing GDOT road construction and maintenance sites, as discussed in Task 3. Based on the analyzed data results and workers' feedback, the team concluded that the developed system could be effectively and efficiently utilized in the various types and sizes of GDOT highway construction and maintenance sites to improve safety in the work zones.

CHAPTER 1. INTRODUCTION

The needs of an effective, advanced warning system to reduce the risk of injury and death of workers due to getting hit by construction equipment are continuously rising. Roadway construction and maintenance operations typically require workers to conduct their work in proximity to construction equipment and continuous traffic; therefore, workers in roadway work zones are always exposed to possible injury and death. This results in hazardous situations for both workers and passing drivers. According to the Bureau of Labor Statistics report (BLS 2017), 609 workers were killed at road construction work zones from 2011 to 2015, which means more than an average of 100 workers are killed each year; 2 workers are killed every week and 30 are injured every day (Sant, 2015). Each death in the construction industry costs $4 million in direct and indirect expenses; each injury resulting in lost workdays costs $42,000 (Sant, 2015). Specific to the state of Georgia, a total of 60 deaths were reported in road work zones from 1973 to 2018 (Georgia Department of Transportation, 2019). Hence, it is urgent that this significant issue needs a smart alarm system that holistically detects proximity situations between workers and construction equipment to reduce the risk in the highway work zones in Georgia.

CHAPTER 2. OBJECTIVE

The goal of this research is to develop a low-cost and scalable smart IoT proximity alert system using Bluetooth mobile sensing technology for alerting workers and equipment operators in hazardous proximity situations in highway work zones. This research includes three tasks to achieve the objective as follows:

1) Design and develop an Equipment Protection Unit (EPU) and a Personal Protection Unit (PPU) for practical use for proximity hazard detection and alert at the highway work zone,
2) Develop a cloud server system for automated data collection and analysis, and
3) Deploy the developed systems at GDOT's ongoing projects for system performance evaluation.

CHAPTER 3. DEVELOPMENT OF A PROXIMITY HAZARD DETECTION AND ALERT SYSTEM (TASK 1)

The research team developed mobile sensing devices that detect proximity hazards between the equipment and pedestrian workers. The system included Equipment Protection Unit (EPU) and Personal Protection Unit (PPU), which requires a circuit board design to reduce the unit size for the practical application. PPU is a device designed to be an embedded device. The main functionalities of a PPU are to measure distances to nearby construction equipment or prohibited areas, to alarm the worker who carries the PPU to notify that an imminent collision to construction equipment or he/she is entering into the prohibited zone, to collect the measured sensor data and the alert information, and to send the information to the cloud server when it's connected to the network for further analysis.

Bluetooth 5.0 technology was utilized in this system. Bluetooth Low Energy (BLE) beacons are attached to the construction equipment. A PPU measures the signal strength to the beacons, and the Received Signal Strength Indicator (RSSI) values are converted to the estimated distance to the beacons. As the measurement of RSSI is highly noisy, a noise-filtering algorithm has been adopted for more accurate distance estimation.

When the distance is in the alerting range, the PPU records the event and makes a sound and vibration to notify the worker who's carrying it. From the previous research (Park et al. 2016, 2017), we found that workers prefer a portable standalone device rather than their personal smartphones as PPU due to privacy and battery preservation issues when they use their own smartphones. Multiple BLE beacons are attached to construction equipment in different locations of the equipment, and the location of the worker is estimated to send the alert to the operator of the equipment and ground workers in proximity. The recorded event and measurements are stored in the PPU, and when it is connected to a cell or WiFi network, the information is sent to a cloud server so that the safety manager in a remote place can observe the events.

EPU is a device designed to be used for construction equipment operators. It has a light indicator to alert the operators with sound and vibration. An EPU can be mounted on the equipment with a wireless network router. When a worker comes into a close range to the equipment, the PPU that the worker is carrying connects to the network router and sends the events and measurements to the cloud server.

CHAPTER 4. DESIGN AND DEVELOPMENT OF A CLOUD SERVER FOR REMOT DATA COLLECTION AND ANALYSIS (TASK 2)

This research makes use of a cloud server as a data management and analysis platform for all the sensor data collected by EPUs and PPUs. The cloud server keeps all the data centralized so that any algorithmic changes and software updates can be performed directly on the cloud without individually updating each EPU and PPU device. The cloud server is hosted on Google Cloud, and the domain name is registered at awaresite.net. Each EPU and PPU device is able to connect to the cloud server through WiFi. The cloud server consists of three main components, which are the (i) relational database, (ii) localization manager, and (iii) incident manager.

The database is made up of multiple data tables that are linked to one another through ID keys. Some examples of data tables are sensor calibration parameters, historical sensor values, worker statistics, equipment statistics, and historical incident records. An application can obtain data from one or more data tables in the database through a data query, which specifies the number, type, and criteria of data to extract. The localization manager publishes the distance between the worker and the equipment in meters. The incident manager receives distance data from the localization manager and analyzes the data to determine whether a safety incident (e.g., near-miss or collision accident) occurs or not.

The operation of the cloud server can be visualized through a web user interface as shown in Figure 1. The user interface consists of a webpage frontend that is linked to the cloud server backend. Once logged in to this website, users can view real-time incident statistics. The homepage dashboard is divided into three sections: live alerts, history of past alerts, and graph of alerts per day. Workers' and equipment's profiles and their incident counts can also be monitored in the user interface as shown in Figures 2 and 3.

Figure 1. Screen shot. The web-based user interface- project overview page.

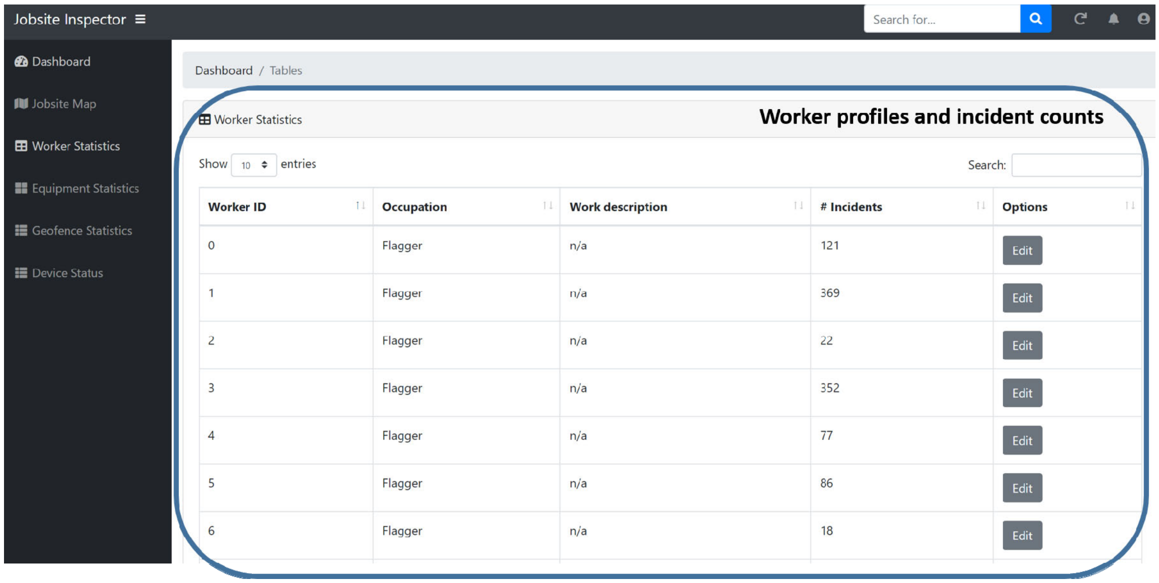

Figure 2. Screen shot. Worker statistics page in the user interface.

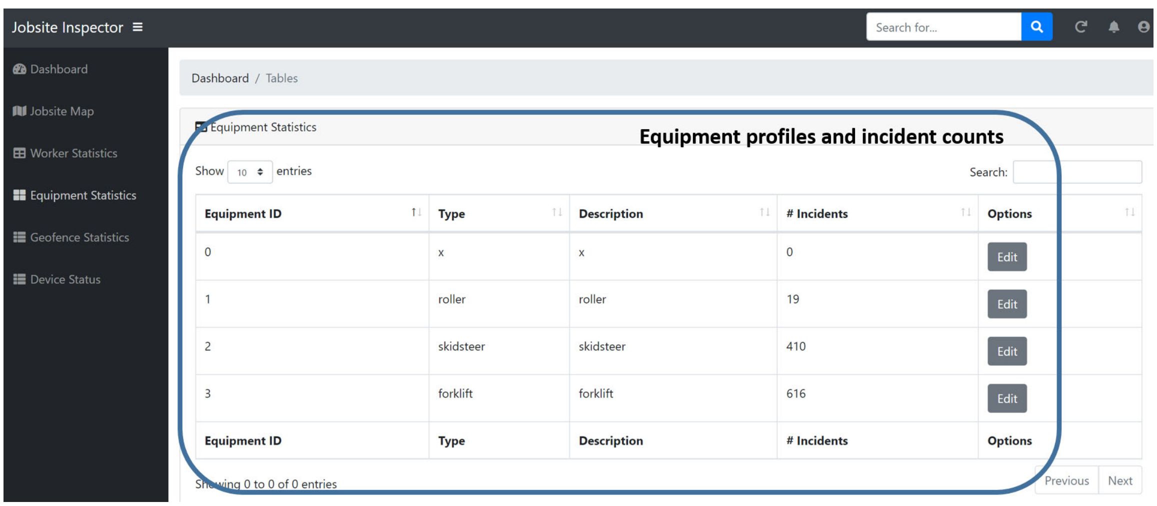

Figure 3. Screen shot. Equipment statistics page in the user interface.

Integrating the PPUs, EPUs, and a cloud server, the developed system has an IoT-based architecture, as shown in Figure 4.

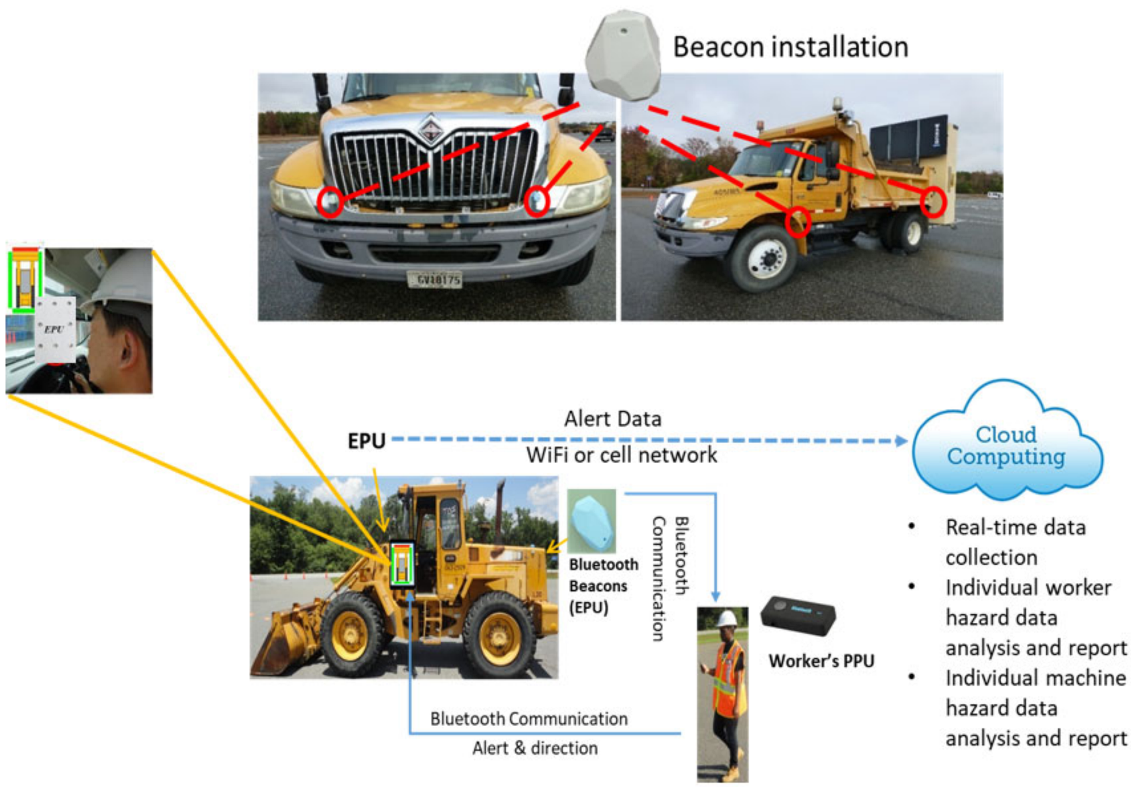

Figure 4. Illustration. Architecture of the developed system.

CHAPTER 5. FIELD TESTING AND VALIDATION (TASK 3)

To evaluate the developed system, 5 field tests, including a preliminary test and 4 evaluation tests, were conducted in GDOT's ongoing highway construction or maintenance projects. A preliminary test was conducted to test the functionalities of the system and establish the test protocol for the validation. Based on the preliminary test, 4 evaluation tests were conducted to evaluate and validate the system with regard to the technical and practical feasibility.

Preliminary test

The preliminary test was conducted on Mar. 18 - 19, 2019. The purpose of the preliminary test was to better understand real-world paving situations, technical needs, and required resources before comprehensive field tests were conducted. The sensors were installed to equipment a day before the test day, as shown in Figure 5. In the test day, PPUs and EPUs were distributed to 9 workers at the beginning of the work, as shown in Figures 6 and 7. Figure 8 shows the jobsite scene. The given work was paving a parking lot of one of the state district information centers. 3 pieces of equipment were utilized in the test: a roller, backhoe, and asphalt paver. The workers who worked as an equipment operator were excluded because they were on the equipment during the operation, which can cause false alarms. The tests, including the preliminary test and evaluation tests, did not require any additional action except for carrying the devices and wearing the safety vests. The WiFi hotspot device was utilized to connect the PPUs and EPUs to the server. Also, the team utilized multiple cameras to record the movements of the workers and equipment, which were used as ground truth. During the test, incident logs with workers and equipment's IDs were automatically stored in the server whenever each worker was in an alerting range.

Figure 5. Photo. Sensor installation.

Figure 6. Photo. Placing a PPU to a worker's safety vest.

Figure 7. Photo. EPU mounted on the equipment.

Figure 8. Photo. Jobsite scene of the preliminary test.

The performance of the system was evaluated by calculating precision and recall from the classification result. Recorded video data (e.g., ground truth) was manually collected from several video cameras and compared to the data gathered by the EPUs and PPUs in order to calculate sensor accuracy. Each incident was then placed into the categories, classifying each incident into 4 possible cases: true positive, false positive, false negative, and true negative.

- The true positive means that a worker was in the alerting range and the system did alarm.
- The false positive means that a worker was out of the alerting range, but the system did alarm.
- The false negative means that a worker is in the alerting range, but the system did not alarm.
- The true negative means that a worker was out of the alerting range and the system did not alarm. The true negative case was not counted because the case is a safe situation that does not require an alert.

Figures 10, 11, and 12 illustrate the example scenes of the cases. Precision and recall were calculated using these equations(see figure 9).

$$Precision = \frac{True\ positive}{(True\ positive\ + False\ positive)}$$

$$Recall = \frac{True\ positive}{(True\ positive\ + False\ negative)}$$

Figure 9. Equation. Precision and recall equations

Figure 10. Photo. An example of true-positive cases.

Figure 11. Photo. An example of false-positive cases.

Figure 12. Photo. An example of false-negative cases.

As a result, the system showed a precision of 63.99% and a recall of 88.41%, as shown in Table 1. From the preliminary test, the team found several considerations for the future implementation of the system in jobsites. Firstly, the asphalt paver was not suitable for the test because it barely moved during the paving work. Since the system was designed to be utilized in a dynamic environment, the asphalt paver did not generate evaluable cases. Second, signal processing should be conducted to accurately calculate the range so that the alerting range can be determined as designed.

Table 1. Classification and evaluation results of the preliminary test.

True Positive	False Positive	False Negative
183	103	24

Precision	Recall
63.99%	88.41%

First comprehensive evaluation test

Based on the experience from the preliminary test, the system functions and filed data collection methodologies were improved, and the first comprehensive evaluation test was conducted on June 25 and 27, 2019. 2 pieces of equipment were utilized in the test; a roller and a skid steer. 6 workers participated in each day; in total, 12 workers participated in the test. The given work was the road pavement, as shown in Figure 13. The procedure of the test was the same as the preliminary test, with the considerations derived from the preliminary test.

Figure 13. Photo. Jobsite scene of the first evaluation test.

As a result, the system showed a precision of 87.39% and a recall of 95.10%, as shown in Table 2. The team implemented a mean filter to find the optimal parameters of the sensor. The team found that the performance was improved when the signal processing technique, i.e., a mean filter, was applied.

Table 2. Classification and evaluation results of the first evaluation test.

True Positive	False Positive	False Negative	Precision	Recall
194	28	10	87.39%	95.10%

Second evaluation test

The second evaluation test was conducted on September 11, 2019. 2 pieces of equipment, including a roller and skid steer, and 4 workers participated in the test. The given work was the road pavement as shown in Figure 14. In this test, three filtering methods, such as a mean filter, Kalman filter, and particle filter, were tested to find the optimal method for signal processing.

Figure 14. Photo. Jobsite scene of the second evaluation test.

As a result, the system showed better performance with the particle filtering method as shown in Tables 3, 4, and 5, which includes fewer false-negative cases and higher precision.

Table 3. Classification and evaluation results of the second evaluation test with a mean filter.

True Positive	False Positive	False Negative
86	30	4

Precision	Recall
74.14%	95.55%

Table 4. Classification and evaluation results of the second evaluation test with a Kalman filter.

True Positive	False Positive	False Negative
70	18	2

Precision	Recall
79.55%	97.22%

Table 5. Classification and evaluation results of the second evaluation test with a particle filter.

True Positive	False Positive	False Negative
65	14	2

Precision	Recall
83.33%	97.01%

Third evaluation test

The third evaluation test was conducted on September 23, 2019. 2 pieces of equipment, including a roller and skid steer, and 4 workers participated in the test. The given work was the road pavement, as shown in Figure 15.

Figure 15. Photo. Jobsite scene of the third evaluation test.

As a result, the system showed a precision of 82.35% and a recall of 95.15%, as shown in Table 6. Based on the finding from the second evaluation test, the particle filter was used in the third evaluation test, which showed the anticipated performance.

Table 6. Classification and evaluation results of the third evaluation test with a particle filter.

True Positive	False Positive	False Negative
98	21	5

Precision	Recall
82.35%	95.15%

Fourth evaluation test

The fourth evaluation test was conducted on October 28, 2019. Mcdermott Internations, Inc. provided the construction site located in Sabine Pass, TX. It is an LNG plant construction site, and the work was mainly earthmoving and moving temporary facilities, e.g., job trailers. The team determined to conduct the test, focusing on the part of the site where the workers and equipment moved dynamically. 2 pieces of equipment, such as a dozer and a skid steer, and 6 workers participated in the test. The given work was to move the barricades and temporary restroom, as shown in Figures 16 and 17.

Figure 16. Photo. Jobsite scene of the fourth evaluation test (side view).

Figure 17. Photo. Jobsite scene of the fourth evaluation test (top view).

As a result, the system showed a precision of 89.21% and a recall of 97.45%, as shown in Table 7.

Table 7. Classification and evaluation results of the fourth evaluation test with a particle filter.

True Positive	False Positive	False Negative
306	37	8

Precision	Recall
89.21%	97.45%

Qualitative evaluation through a questionnaire survey

The team conducted the questionnaire survey after each test with the workers who participated in the test to collect their opinions with regard to the performance of the system. The survey included questions about the noticeability of the alerts, the effectiveness of the system, and the preferred shortest alerting distance. The results from the survey with 27 responses are shown in Tables 8 and 9 and Figure 18.

Table 8. Results of the question about the noticeability of the alert.

Noticeability of the alert		
Answers	Counts	Percentage
No answer	4	N/A
Imperceptible	2	9%
Less noticeable	0	0%
Noticeable	12	52%
Noticeable – Clear	2	9%
Very Clear	7	30%
Total	27	100%

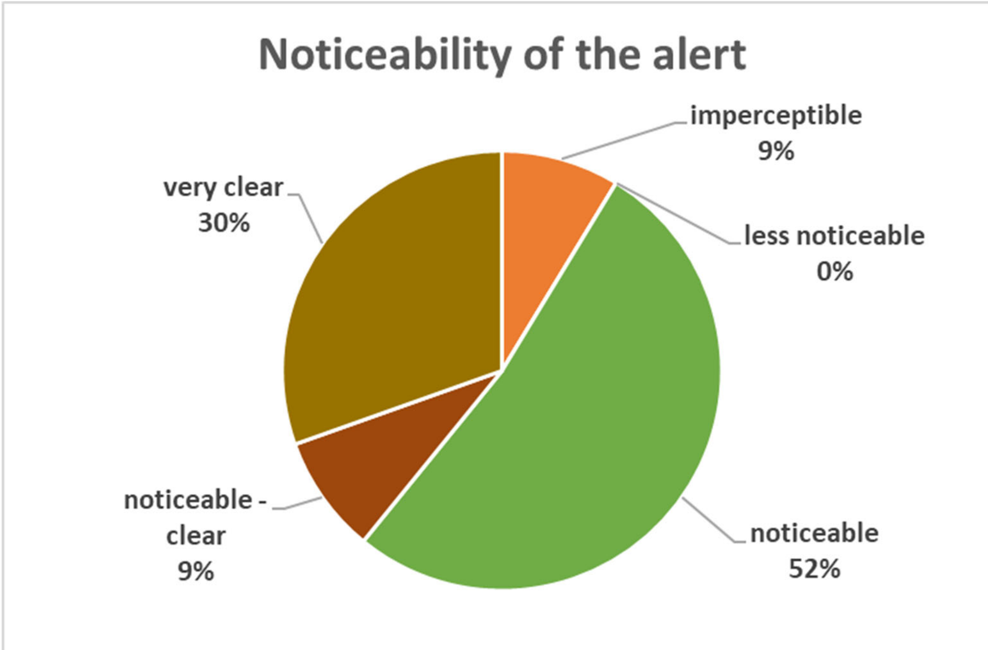

Figure 18. Chart. Noticeability of the alert.

Table 9. Results of the question about the effectiveness of the system.

Effectiveness of the system		
Answers	Counts	Percentage
No answer	3	0
0 (Not effective at all)	0	0%
1	2	8.33%
2	0	0%
3	2	8.33%
4	0	0%
5	3	12.5%
6	4	16.67%
7	5	20.83%
8	1	4.17%
9	2	8.33%
10 (Completely effective)	5	20.83%
Average	6.58	N/A
Total	27	100%

As a result, the responses showed that 91% of the workers answered that they were able to notice the alerts in proximity situations. This question is important to ask because construction sites are commonly very noisy and have many sources of vibration, which make it difficult for the workers to sense alert feedback from a device, e.g., beep sound and vibration. Regarding the effectiveness of the system in proximity situations, the average of the score was 7.5 out of 10. The preferred shortest alerting distance from the survey was 11.5 feet. They also answered that it would be great if the distance is set differently based on the types of equipment.

CHAPTER 6. CONCLUSION

In summary, the team developed a low-cost and scaleable smart proximity alert system for the work zone safety using mobile IoT sensing technology. In Task 1, the team developed PPUs and EPUs. The system has capabilities to measure the distances between ground workers and equipment, to communicate with the server, and to alert the workers and equipment operators with a buzzer and vibration. In Task 2, the cloud server and user interface were developed. The server stored the incident data, including sensor measurements, worker IDs, equipment IDs, and timestamps. Meanwhile, the distances were continuously calculated on a real-time basis in the server so that it could trigger the alerting functionality of PPUs and EPUs. The web-based user interface visualized the stored incident data so that remote managers could monitor the proximity hazards in jobsites. In Task 3, the team conducted five field tests, including the preliminary test and four evaluation tests to practically validate the system in the GDOT's highway projects. Through a series of tests, the team found that the system successfully identified the proximity hazard situations and provided auditory and vibratory alerts to the workers. Also, the team conducted a questionnaire survey to investigate the subjective opinions of the workers who participated in the tests. It showed that the workers were able to recognize the alerts through the developed system in noisy and congested field environments. It is highly expected that the GDOT can improve the safety conditions of the highway construction and maintenance sites by deploying the low-cost and smart proximity alert system.

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