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NCHRP IDEA Program

RULE-BASED AUTOMATED SAFETY MONITORING SYSTEM FOR WORK ZONE SAFETY

Final Report for
NCHRP IDEA Project 206

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Engineering, and Medicine

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EXECUTIVE SUMMARY

Construction is considered a hazardous industry responsible for a large portion of fatal and non-fatal work-related injuries. According to the Occupational Safety and Health Administration (OSHA), out of 4,674 work-related fatalities in 2017 in the entire US private sector, 971 (20.7%) deaths occurred in the construction industry [1]. The OSHA report estimates that approximately 582 lives could be saved by preventing the most prevalent safety hazards, namely falls, struck by objects, electrocution, and caught-in/between. Workers in road construction sites are frequently exposed to potential safety hazards related to moving equipment and vehicles. The National Institute for Occupational Safety and Health (NIOSH) reports that there were 1,844 (123 per year) work-related deaths at road construction sites from 2003 to 2017 [2]. During the last seven years of the NIOSH investigation (2011 and 2017) [2], 76% of all the fatal injuries that occurred were related to transportation events, and 60% of these transportation-related fatalities occurred inside work zones resulted from being struck by a vehicle or mobile equipment (pickup trucks and SUVs: 151, worker deaths, automobiles - 129, semi-trucks - 124, and dump trucks - 82). Another report states that, out of the total of 639 worker deaths in road construction sites from 2003 to 2007, nearly half (305 incidents) of these fatalities resulted from being struck by a vehicle or mobile equipment, with more workers killed by construction-related vehicles (38%) compared to vehicles not related to construction activities (33%) [3]. Though there are various causes, these statistics indicate that there is a strong need to prevent struck-by accidents inside road construction work zones.

Despite such efforts by the construction industry, many fatalities and injuries are still occurring due to dynamic and complex construction site conditions as one of the reasons. To overcome the limitations of manual safety monitoring, recent studies have developed worker tracking systems using different wireless technologies such as Bluetooth [10,11], ultra-wideband (UWB) [7,8], radio frequency identification (RFID) [9] to track the location of the worker inside construction sites. The research community has also designed solutions tracking vehicles in construction sites with wireless technologies such as Bluetooth [6], Global Positioning System (GPS) [10], and UWB [39,46-48]. Among these wireless technologies, UWB radios have more potential to provide feasible and accurate localization due to impulse-shaped signals and high bandwidth. The newer generation of UWB systems introduced precise location tracking of up to 2 cm – 15 cm accuracy in a controlled environment without requiring extensive infrastructure [11]. These UWB technologies hold a lot of promise to automatically detect unsafe situations in road construction sites by accurately tracking locations of workers and equipment. Past studies [13,14] demonstrated the potential of UWB technology to enable accurate location tracking of resources in construction sites. However, the performance of radios significantly degrades when there is an obstruction or blockage in the communication signal between the transmitter and receiver causing Non-Line of Sight (NLOS) situations like in a road construction environment with vehicles and heavy equipment.

This project developed a robust real-time UWB based location tracking and monitoring system called vehicle pose estimation using ultra-wide band radios (ViPER) that eliminates the effects of NLOS situations when they occur, thereby improving localization performance in those challenging scenarios. This project also designed and implemented a new localization approach and boundary estimation algorithm that accurately calculates the distance between tracked entities. Different configurations of ViPER were tested, evaluated, and visualized both for line-of-sight (LOS) and NLOS situations using Unity 3D application to show the experimental results from our study and finally, in a road construction site to track and estimate the distance between vehicles, equipment and workers for accurate localization. The results from these tests indicate tremendous improvements in location accuracy and update rate that are critical in the development of a safety management system. Important accomplishments and findings from the project are summarized:

Hardware and Software developed

- *Sensor hardware design and development*: A new radino TDOA with NLOS detection capability was designed based on the field experiments and tested in controlled environments and two real construction projects
- *Sensor signal processing software program*: A software program for radino TDOA was developed and upgraded in five versions that are called "baseline Radino TDOA," "ViPER" (vehicle pose estimation using ultra-wide band radios), "signal-power selection," "ViPER+", "ViPER V2".

Experiments and Insights

- *Evaluation of existing commercial solutions*: Experiments in controlled environments and construction projects found that commercially available UWB localization systems could not accurately track heavy construction equipment and workers in congested construction sites due to NLOS situations.
- *Evaluation of hardware and software developed in this project*: We evaluated the hardware and software developed in this project in a dynamic construction zone scenario in Houston area.
- *Overall results*: Excellent performance (location accuracy and update rate) of the last version of the system was demonstrated in experiments in realistic construction zone in Houston area.

IDEA PRODUCT

In road construction sites, there is a continuous movement of heavy equipment, workers, and vehicles that invariably lead to obstruction of signals. Therefore, a real-time safety monitoring system should be able to determine the poses of workers, equipment, and vehicles. By accurately estimating the poses, the safety monitoring system can track the boundaries of equipment or vehicles that are required to monitor the safety policies regulated to secure the workers and equipment. Although ultra-wideband (UWB) based tracking systems can provide sufficient accuracy for worker tracking [7,8] and vehicle tracking [12–14], the accuracy of these localization systems falls when they are exposed to Non-Line of Sight (NLOS) situation [15]. In construction sites the presence of trucks, loaders, and other obstacles in the field can block or diffract the signal on its way from the transmitter to the receiver causing NLOS situations. Previous studies [16–18] did not completely address the NLOS issue as their evaluations were done in simple environments without heavy machinery. In all safety tracking methods (relative and absolute), UWB radios need to exchange messages with each other. NLOS situations happen when the direct path from the sender radio to the receiver radio is partially or completely blocked by obstacles. This condition can affect the estimation of the location in UWB localization systems. To develop an effective safety tracking system, it is critical to consider the location accuracy and update rate. If the location of the objects is erroneous, the system is unable to determine whether the worker or the vehicle is in a hazardous situation and will end up producing false positive/false negative alarms. Low location update increases the delay in the detection process. The worker or the vehicle may enter or stay in a hazardous zone for a relatively short duration without being notified due to this latency. Our goal in this study is to design and evaluate the new localization system called **vehicle pose estimation using ultra-wide band radios (ViPER)**. This project creates a new localization method that can accurately and robustly track the locations as well as orientations of heavy construction equipment in work zones which has not been possible with any commercial products. By implementing the methods, agencies and contractors will be able to automatically detect potential unsafe situations quickly appearing and disappearing in dynamic construction environments and eventually lead to a reduced number of fatalities caused by contacts between equipment and workers on foot. With the fully implemented ViPER, construction projects can apply a new approach to monitoring highway work zone safety that include these steps: 1) locations of all the objects with UWB tags (worker tags and equipment tags) will be calculated based on known locations of stationary UWB tags, 2) static unsafe zones (e.g. trench, slope, outside the work zone, etc.) are registered by an onsite safety manager, and dynamic zones are created around moving equipment, and 3) predefined rules are applied to the locations to automatically detect workers and equipment associated with potentially unsafe situations.

CONCEPT AND INNOVATION

ViPER developed in our project is innovative because of three capabilities built into the localization system: 1) automated evaluation and reduction of NLOS effects on localization, 2) design and implementation of the new localization protocol to support the NLOS/LOS detection, and 3) design and implementation of a boundary estimation algorithm for objects with more than one localization tag to accurately calculate the distance between vehicles and workers. The structure of ViPER is composed of four main subsystems as shown in Figure 1.

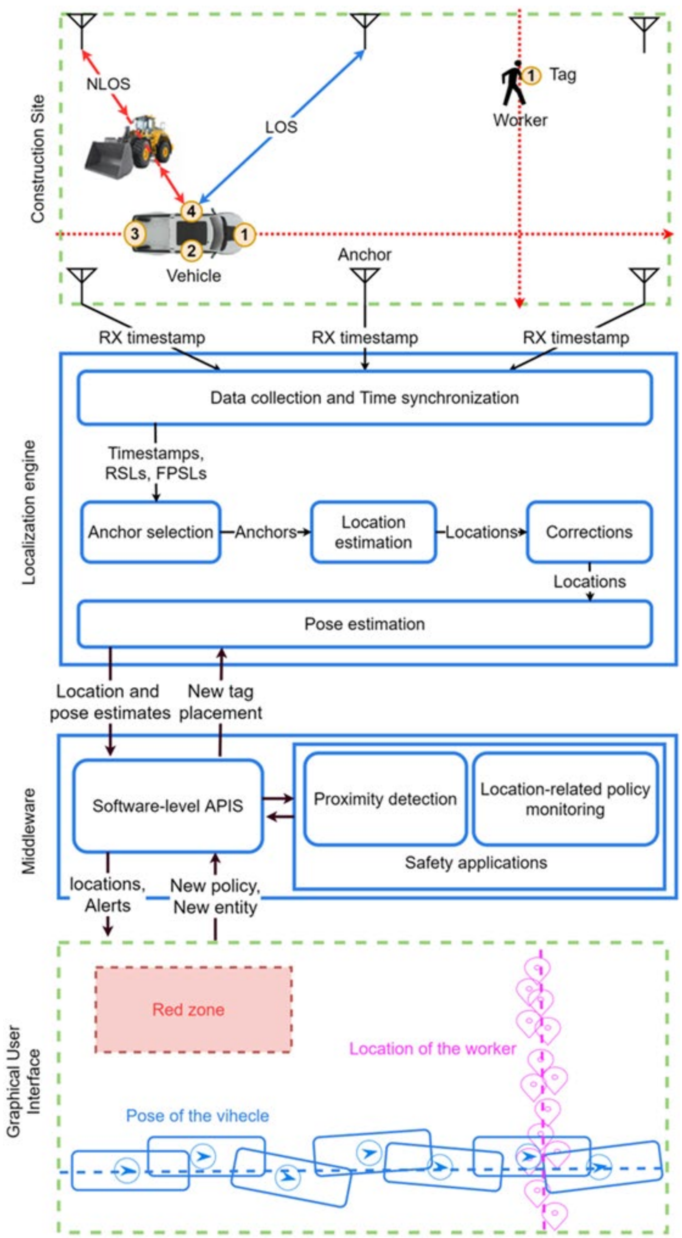


FIGURE 1: Overview of ViPER+

The first subsystem is related to sensor management that manages the communication of UWB tags and anchors. The second subsystem, called the localization subsystem, is responsible for estimating the location and pose of the entities. The Middleware subsystem is responsible for managing and monitoring the policies regulated by the users. It also acts as the software API that allows applications to use the localization service. Finally, the output layer is the Graphical User Interface (GUI) that interacts with the users.

INVEGTIGATION

To satisfy the requirements of the safety system, we need to resolve the NLOS problem in location estimates. By removing incorrect measurements, the accuracy of the estimations is expected to increase. The number of failed estimates will also decrease by removing incorrect inputs. Therefore, this project developed five versions of ViPER via 1) evaluation and reduction of NLOS effect on localization in a road construction environment, 2) design and implementation of the new localization approach as part of a road construction safety monitoring system, and 3) design and implementation of a boundary estimation algorithm for objects with more than one localization tag to accurately calculate the distance between vehicles and workers. The second version of ViPER [12] developed in this project was the first study that addressed this issue by studying the accuracy of localization inside a road construction. The next two versions of ViPER+ extended the efficacy of ViPER by developing a more robust UWB based safety monitoring system that tracks and monitors the boundary of workers and vehicles on construction sites with specific objectives of evaluating and reducing NLOS effect on localization, designing and implementing a new localization approach and boundary estimation algorithm that accurately calculates the distance between vehicles and workers for tracked objects with more than one localization tag. ViPER+ eliminates NLOS detection and mitigation assumption made in ViPER which causes some errors. The final version of ViPER, which we call ViPER V2, incorporates several enhancements to achieve higher update rate and removes the low-pass filter to eliminate assumptions about data. ViPER V2 + was tested, evaluated, and visualized using Unity 3D application to show the proximity of entities and finally, in a road construction site. Detailed design information of ViPER V2 is given in section 1.1 (sensor hardware) and section 1.2 (sensor software).

1. DESIGO FOR NEW RADINO TDOA: SENSOR HARDWARE

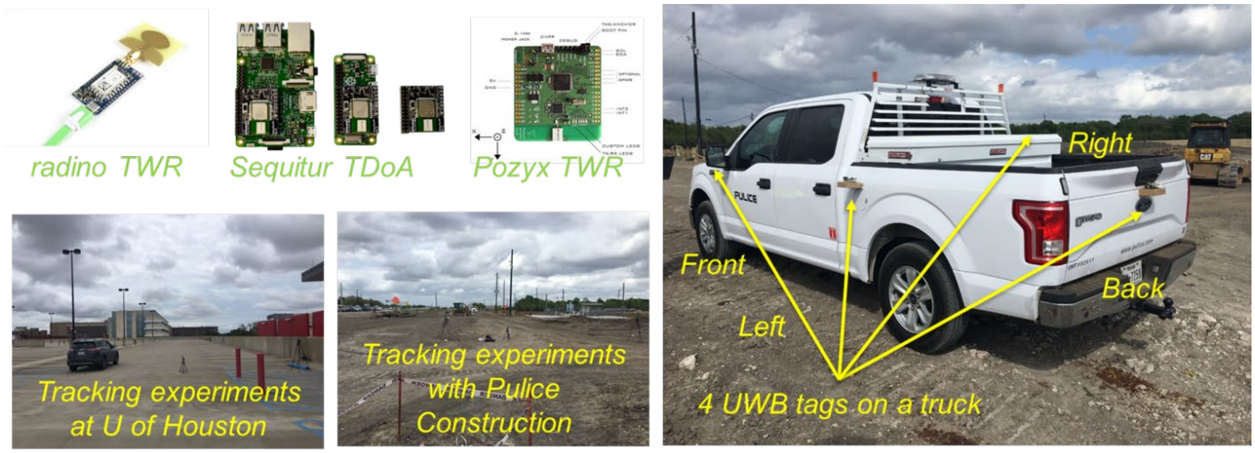


FIGURE 2: Three commercial UWB sensors (radino32 DW1000, Sequitur TDOA, and Pozyx TWR) tested in controlled environments and construction sites

In the first stage of this project, the project team evaluated multiple UWB localization tools [Radino two-way ranging (TWR), Sequitur TDOA, and Pozyx TWR)] and developed additional capabilities including motion sensor fusion and NLOS detection. Experiments in controlled environment (10 times) and a road work zone (1 time) (Figure 2 and Figure 3) led to the following answers that led to a new design of the Radino UWB TDOA system and overcame limitations.

- Question 1: Between TDOA (Sequitur) and TWR (radino) communication protocols, which one is more suitable technique to monitor multiple objects in a work zone? Answer: **TDOA is more suitable protocol to handle a large number of sensors to be deployed. At least 4 tags need to be attached to one equipment.**
- Question 2: Can we use sensors with smaller antennas (Sequitur) instead of those with large antennas (radino) to make the nodes compact? Answer: **Larger antennas are believed to be a better solution to overcome current lack data points from equipment tracking.**
- Question 3: Can we use a commercially available tool (Sequitur) for accurate tracking of 30+ objects in a work zone? If not, what features should be incorporated into a new tool? Answer: **None of the commercial tools can be used without significant improvements. So, the project team developed a new tool that combines all the required functionalities (Table 1).**

	Sequitur TDOA	radino TWR	radino TDOA
Protocol	**TDOA**	TWR	**TDOA**
NLOS Detection	No	**Yes**	**Yes**
On Tag Trilateration	**Yes**	No	**Yes**
Antenna Size	Small	**Large**	**Large**
Motion Sensor Fusion	**Yes**	No	**Yes**

TABLE 1: Proposed development of radino TDOA with NLOS detection

FIGURE 3: Truck and bulldozer tracking experiment at Pulice Construction work zone

2. DEVELOPMENT OF ViPER+: SOFTWARE FOR NEW RADINO TDOA

2.1 Sensor management subsystem

ViPER+ exploits the Time of Arrival (TOA) of the UWB packet to calculate the location of the tag. Among all TOA methods, Time Difference of Arrival (TDOA) is suited to be the best option for real-world localization due to the lower number of messages needed [19]. In this algorithm, a minimum of four anchors is required to determine the location of the tag. The tag transmits a signal that is received by anchors. The anchors then estimate the timestamp of the received signal and report it for localization. In our implementation, we placed six anchors around the field (three each on the two sides of the tracking zone). Having more anchors increases the robustness of the localization process when one or more anchors are blocked by construction equipment. In addition to this, extra anchors provide us with more inputs regarding the transmitted signal. This information can be used for correcting the inputs or removing the erroneous ones.

Tag/Anchor Communication: In ViPER+, the UWB radios which are used as the location sensors are divided into two main roles, tags and anchors. Tags are the transmitters of the localization messages while anchors are the receivers. The only exception is the time-sync anchor that is responsible for transmitting time synchronization messages. For an accurate localization, time synchronization messages are exchanged between the time-sync anchor and the other anchors. One of the anchor nodes is responsible for sending time synchronization messages periodically to avoid clock drift and clock skew across all anchors. Besides anchors, tags also use the time synchronization messages to schedule their next transmission time. To avoid collision between messages, tags use the Time Division Multiple Access (TDMA) approach to send localization messages.

Data Collection and Time Synchronization: When anchors receive the time-sync or localization signals, the payload of the message along with diagnostic information is reported to the server using WiFi infrastructure connecting anchors to the server. When data is collected at the server, the first step is to apply timestamp correction on the received timestamps. Due to the clock drift between anchors, the server needs to apply clock skew correction to correct the received timestamp from anchors before further processing. In this step, the server uses the information from the time synchronization messages to estimate the clock skew to correct the timestamps.

2.2 Location estimation subsystem

In the TDOA algorithm, a group of four or more measured timestamps is used to calculate the location of the tag. In the first step, one of these anchors is selected as the reference anchor. The reference, along with the selected anchors are given to a non-convex optimizer. The optimization solver estimates the best location based on the given timestamps and the location of anchors. The first step of this process is calculating the TDOA inputs based on the given timestamps. Eq. 1 calculates the TDOA input for anchor *a* defined as is I_a, which is the difference between each timestamp and the timestamp at the reference anchor, multiplied by *c*, the speed of light. When all inputs are calculated, an objective function is defined. In Eq. 2, the objective function is created. Table 2 explains the parameters used in Eq. 2.

$$I_a = c \times (t_a - t_{ref}) \qquad (1)$$

$$f(x,y) = \sum_a^{anchors}\left(\sqrt{(x-x_a)^2 + (y-y_a)^2} - I_a\right)^2 \qquad (2)$$

(x_a, y_a)	Location of anchor a
(x,y)	Location of the tag
I_a	TDOA input for anchor a

TABLE 2: Parameters of the objective function

Finally, the optimizer determines the location that minimized the value of the objective function. In Eq. 3, the (x^*, y^*) is the estimated location of the tag.

$$(x^*, y^*) = \underset{x,y}{\operatorname{argmin}} f(x, y) \qquad (3)$$

Anchor and Reference Selection: Choosing the right reference anchor can have a significant effect on the accuracy of the location estimation [12]. Thus, in TDOA algorithms, the reference selection method tries to choose the best anchor as the reference that has the lowest error in estimating the time of arrival. Besides the reference selection, the selection of anchors for localization is also important. TDOA algorithm requires at least four anchors to report the timestamp of the received signal. In implementations with more than four anchors, the number of reported timestamps may exceed the minimum required timestamp for localization. For each signal, the accuracy of received timestamp estimation may be different for each anchor, since each anchor received the signal in a different condition. The anchor selection process removes those anchors that have lower accuracy in estimating the received timestamp. Researchers have proposed different methods for both anchor and reference selection. Rene et al. [20] proposed a method for reference selection that considers the shortest distance as the reference anchor because incorrect measurements tend to have longer distances compared to correct ones. Although this solution works for some situations, it is not generalizable to all environments. Another study [21] found the best selection for anchors and the reference by comparing all possible inputs that could be used for localization. Although this solution finds the best estimation, the process is computationally intensive. Hence, powerful computers would be required to calculate the location with this method within a reasonable time required for safety monitoring applications. One of the feasible solutions to this challenge is to detect NLOS signals and try to correct them or eliminate them from the localization pipeline. Wann et al. [22] proposed a correction method that removes the NLOS error by applying Kalman Filter on the previous ranging. ViPER [12] used low-pass filter to detect and correct NLOS signals. The challenge with these two methods is that they require receiving equal number of signals from all anchors, which was unplausible in most construction areas. Due to the presence of large machines, this requirement cannot be always fulfilled in construction environments. In addition to these NLOS mitigation methods, there is a group of solutions that focus on the characteristic of the signal mostly calculated from the Channel Impulse Response (CIR) to estimate the channel's status. Some studies [23–25] used machine learning methods for NLOS detection. These approaches require a preliminary dataset for the learning process that should be consistent with the real data. Due to this reason, these solutions are not practical because they require a training dataset that covers all possible NLOS and LOS situations in construction sites, which is challenging when dynamic changes are frequent in the environment. Another category of studies relied on applying statistical methods on CIR for NLOS detection [26–28]. Instead of feature extraction and finding the patterns, these solutions try to study the behavior of the signal in LOS and NLOS situations. Therefore, this group of solutions does not require extensive data collection for the training phase. We chose one of these real-time NLOS detection methods for our anchor and reference selection described before.

Power difference NLOS detection: To improve the result of localization, we need to exploit a NLOS detection method that does not rely on a large dataset and constant data stream. In this work, we chose the power difference method suggested by Decawave [29] and was evaluated by researchers[26]. This method considers the difference between the direct path signal power and the received signal power. Figure 4 displays a pair of nodes communicating using wireless technology. As it is depicted, there is a straight line from one node to the other called the direct path or the first path. The direct path is the shortest distance from the sender to the receiver. In the absence of objects reflecting the signal, the receiver will only get the direct path component of the signal.

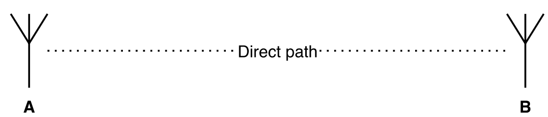


FIGURE 4: Direct path between the sender and the receiver. The receiver will only receive this component when there is no reflection in the environment.

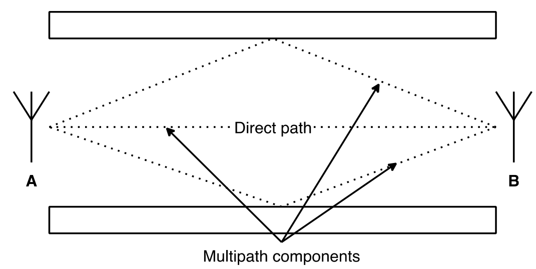


FIGURE 5: Signal reception in an environment with reflecting objects. In this situation, the receiver will receive signals from different paths. Each path is called a multipath component that also includes the direct path

However, in most real-world conditions with objects reflecting the signal shown in Figure 5, the receiver will receive the signal from different paths. These components are called multipath components that also include the direct path. In UWB radios, because of the large frequency bandwidth and consequently the impulse shape of the signals, the receiver can distinguish the first path component from others by analyzing the CIR. Then it uses the direct path component to calculate the received timestamp of the signal. Along with the timestamp of the direct path signal, UWB radio also reports the received signal power level (RSL), which is the power level of the whole signal, and the first path signal level (FPSL), which is the power level of the direct path detected by the radio chip. If there is a LOS connection between the nodes, the receiver can receive all multipath components. In this case, the direct-path component has higher reception power compared to other components because it traversed the shortest distance and the difference between the RSL and FPSL is low. In NLOS situation, however, the direct path is blocked by an external object and the receiver only obtains the reflections of the transmitted signal. In this condition, the receiver considers one of the reflections as the direct path component leading to miscalculation of the received timestamp. The reflected signals have a lower power level compared to the direct path. Therefore, the FPSL is not high and the difference between RSL and FPSL is large. The recommended solution suggested 6 dB difference to be the threshold for NLOS detections. If the difference of RSL and FPSL falls below this threshold, then the communication was LOS and the estimated timestamp is accepted. We also considered this threshold for our experiment to distinguish NLOS signals.

Using Low-pass Filter for Location Correction: Low pass filters are used to remove high frequencies and have many different applications. They can be used to remove the noise from data when it is assumed that the values are not changing frequently. In our localization application, we can assume that the location of entities does not have frequent changes when the inter-sample time is relatively slow. Thus, we applied low-pass filter on the distance differences, which is the localization input to the TDOA algorithm to further reduce the localization error. One of the parameters in the low-pass filter is the cut-off frequency which is related to the frequency of changes in the data. When choosing a high cut-off frequency, the filter considers noises as a change in the data and will keep them. On the other hand, choosing a low value causes the filter to consider the changes as noise removing some useful information. Therefore, this value should be tuned according to the environment. We chose the value of 5 Hz for cutoff based on our observations in the original ViPER implementation and we continue to use it in ViPER+ but the low-power filter was deemed not needed in ViPER V2 implementation.

Pose Estimation: Pose estimation is used to estimate the boundary of vehicles and large equipment with multiple tags mounted on them. In proximity detection applications, reporting a single location is not sufficient for all entities. In Figure 6, the pose of the vehicle is displayed as an example. Similar to the vehicle, the pose of other equipment is described as a pair of location and orientation $((x, y), \theta)$.

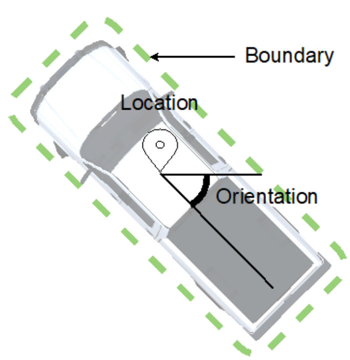


FIGURE 6: Definition of boundary for vehicles in ViPER+

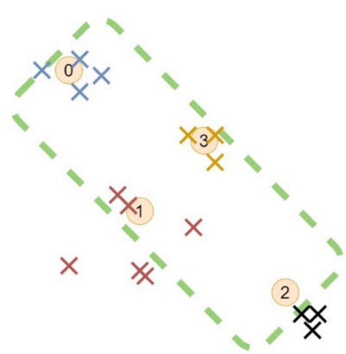


FIGURE 7: The pose estimator calculates the boundary by matching the positions of the mounted tag on the vehicle (circles) with the estimated locations (cross).

Figure 7 illustrates the process of pose estimation in our work. There are two inputs in pose estimation. The first input is the physical characteristics of the equipment that includes the shape of the equipment (dashed line) and the placement of the tags on the object (circles). The second input is the output location from the localization process. The pose estimator determines the boundary of the object by matching the two inputs. The challenge in this process is that the locations of the tags do not perfectly match with the placements like tags 1 and 2. To tackle this issue, we developed an objective function described in Eq. (4).

$$f(x, y, \theta) = \sum_i^T \sum_j^{size_i} \sqrt{\left(X_i - x_{i,j}\right)^2 + \left(Y_i - y_{i,j}\right)^2} \tag{4}$$

(X_i, Y_i) *is calculated based on the* $Eq. 5$.

$$\begin{bmatrix} X_i \\ Y_i \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \times \begin{bmatrix} p_{x,i} \\ p_{y,i} \end{bmatrix} + \begin{bmatrix} x \\ y \end{bmatrix} \tag{5}$$

The rest of the parameters are calculated based on Table 3. This function calculates the distance between the location of the tags in a given boundary and the estimated locations for that tag. To find the best boundary that matches the input point, we need to find a boundary (x^*, y^*, θ^*) with minimum value. This can be found by solving a non-linear optimization problem. The output of the optimization method represents the boundary of the vehicle.

(x, y)	Location of the vehicle
θ	Orientation of the vehicle
T	Number of tags mounted on the vehicle
$size_i$	Number of locations from tag *i*
$(x_{i,j}, y_{i,j})$	j^{th} location of tag *i*
$(p_{x,i}, p_{y,i})$	Position of tags relative to the center of the vehicle

TABLE 3: Parameter table for pose estimation optimizer

2.3 Middleware Layer

This layer is designed to manage the policies regulated for construction safety. It can also be used to as an intermediary to connect the localization system to other applications requiring localization service through software-level APIs.

2.4 Graphical User Interface

This part is used to interact with human users of the system. The pose of all entities along with safety policies is displayed and updated frequently so that the users could monitor the safety of the workers and equipment in the area as shown in Figure 8.

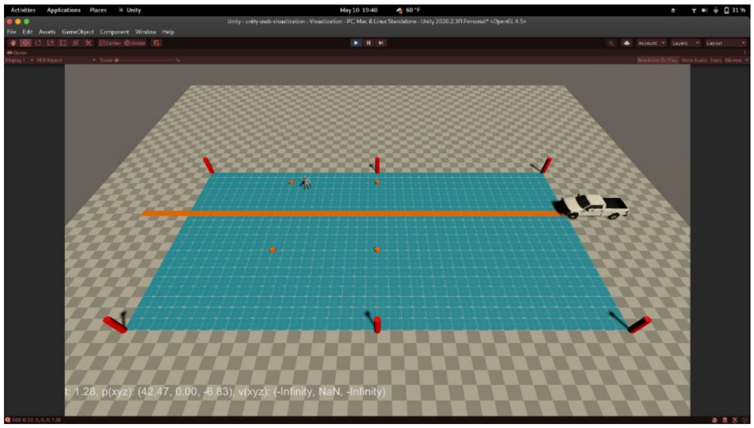


FIGURE 8: The pose estimator calculates the boundary by matching the positions of the mounted tag on the vehicle (circles) with the estimated locations (cross).

3. DEPLOYMENT AND EVALUATION 1

In this part, our goal is to evaluate our ideas we designed in this work. First, we evaluate the NLOS detection algorithm. Then, we compare the results of our localization and pose estimation output with the baseline method and ViPER to measure the improvement gained when these methods are applied.

3.1. Experiment setup

We implemented our solution in a road construction site that is one of the real-world testing environments for our system. We dedicated a 40 m x 20 m field shown in Figure 9 to track the workers and vehicles. The field was surrounded by six anchors marked with numbers from 0 to 5.

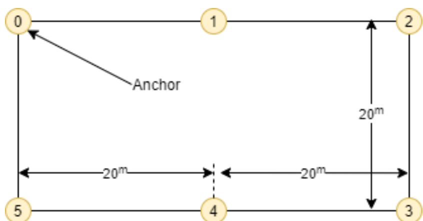


FIGURE 9: Tracking zone and the anchor placement

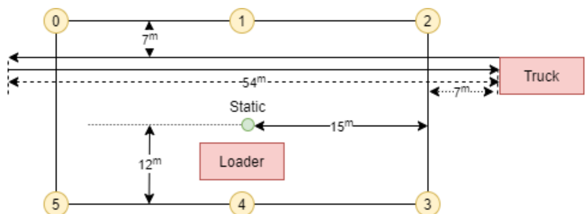


FIGURE 10: NLOS detection scenario

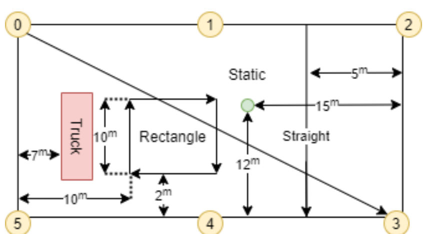


FIGURE 11: Worker tracking for single tag localization

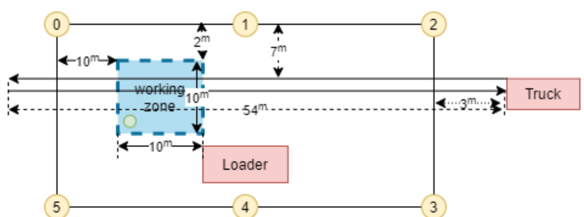


FIGURE 12: Safety tracking including worker and vehicle

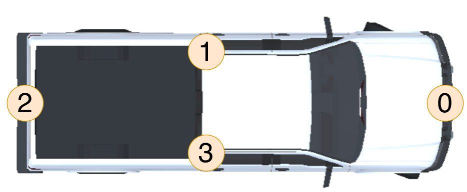


FIGURE 13: Tag placement on the vehicle for vehicle tracking experiment

Our first experiment evaluated the NLOS detection method. Figure 10 shows the setting for this scenario. The next evaluation focused on tracking workers. Three workers were holding UWB tags while walking on the trajectories indicated in Figure 11. Our final experiment evaluated a real-world scenario of worker and vehicle as shown in Figure 12. In this scenario, a working zone is defined by the administrators. This area is dedicated only for workers and the presence of vehicles is prohibited. A vehicle travels in a straight direction passing through the working area and returns. A worker is also standing on one of the corners of the working area. The tag placement for tracking the vehicle is shown in Figure 13.

3.2 Implementation

We implemented our solution using UWB radios and an in-circuit radino32L4 radio module for UWB communication. UWB anchors are managed by Raspberry Pi running Raspbian. A WiFi infrastructure is used to connect anchors to the server for data communication. A Dell Precision 7720 is used as a server to collect and process data from the anchors. It also monitored the data flow from the anchors to ensure they are contiuously functioning during the experiments. Since tags use TDMA approach for transmission, the location of tags is updated every 0.2s. This value is derived from the maximum error that is acceptable in our application. Regarding previous works in safety applications, the error of under one meter is tolerable in proximity detection applications. We also considered this value as the maximum error between the estimated pose of the entity and the real pose. In our case, the restrictions of the work environment prohibited vehicles to move faster than 4.47 m/s (10 mph). Considering the value of the delay between two updates and the maximum speed of the vehicles, the maximum distance of the vehicle between the latest estimated location and its current location will not exceed one meter.

3.3 Evaluation criteria

In this part, we define the parameters used to evaluate the performance of our solution. There are two important factors in safety tracking systems that need to be considered. First, the system needs to track the entities at all times and the delay between two measurements should not exceed more than a certain time interval. Second, the estimation error should be within an acceptable threshold to avoid false alarms. We chose two metrics to measure the above-mentioned factors. The first metric is the update ratio, which is defined as the fraction of time the system can estimate the location of the tag. As we mentioned in section 5.2, the tolerable maximum time between two consecutive pose or location updates is 0.2s. For example, if we receive location updates for the first 0.6 second every 0.2 second and we do not receive any update during (0.6,1) interval, then the update ratio is 0.6. The second parameter is the error ratio. Previously in section 5.2, we mentioned that the 1m of pose estimation error is acceptable in our solution. Error ratio is defined as the ratio of the pose estimates with the error of more than one meter compared to all estimated poses. For vehicles that are presented with location and orientation, we converted the orientation error to distance by multiplying it by the length of the vehicle and added that to the location estimation error.

3.4. Signal-level anchor and reference selection

In this experiment, we placed a tag that transmits localization signals. Then we placed a loader to completely block the path between the tag and anchor #4. We also had a moving truck to cause a dynamic NLOS situation between the tag and other anchors. We recorded the difference between RSL and FPSL for all signals across all anchors.

Figure 14 displays the time series of the recorded power differences. According to this plot, anchor #4 was completely in NLOS, had a power difference higher than 6 dB. Anchors #0, #1, #2 that were mostly in LOS situations indicated lower than 6 dB power difference in most recordings. The peak in their recordings indicates the NLOS situation that happened due to truck movement. Finally, anchors #3, #5 that was in LOS at all times, had lower than 6 dB power difference throughout the recordings. Therefore, 6 dB can be a suitable threshold in our experiment settings.

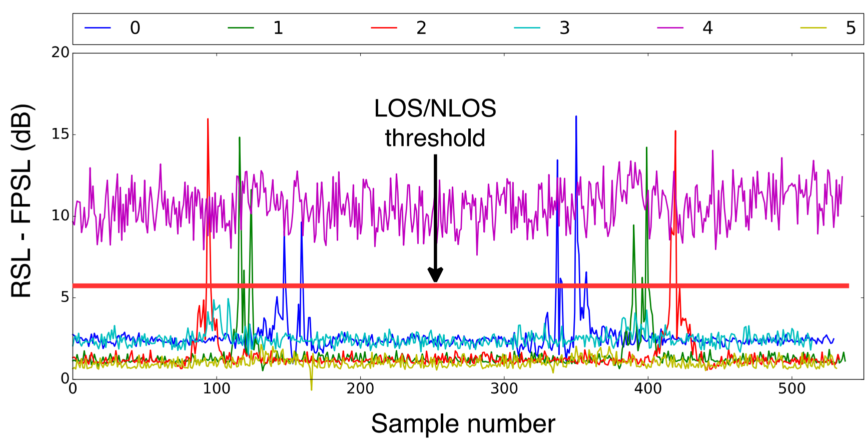


FIGURE 14: Power difference diagram for the static tag in LOS and NLOS situations. 6 dB threshold is a suitable threshold for NLOS detection in our experiment settings.

3.5. Single tag localization for worker tracking

In the worker tracking scenario, we captured the data collected by anchors and applied four different approaches to estimate the pose of the workers. The first approach was the baseline method that only uses TDOA method without any correction. The second method is ViPER that was previously developed by this group. The third method is NLOS method that uses NLOS detection to select anchors and the reference. The final method is ViPER+ that adds low-pass filter to NLOS method for further correction.

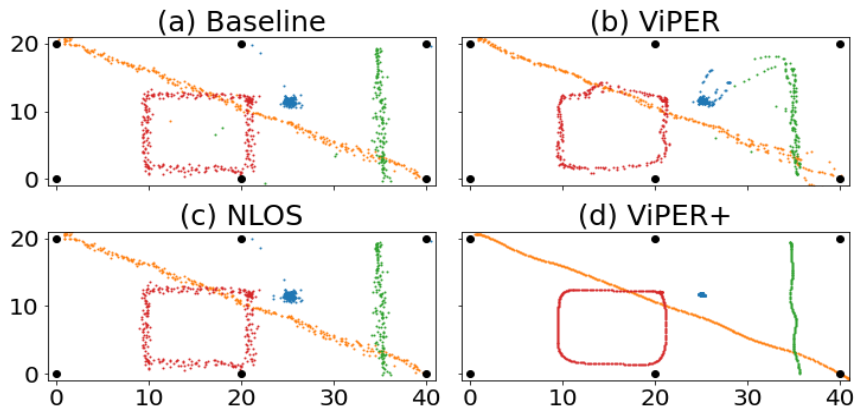


FIGURE 15: Output result for worker tracking with single tag localization using (a) baseline, (b) ViPER, (c) NLOS anchor and reference selection, (d) ViPER+

	Baseline		ViPER		NLOS anchor and reference selection		ViPER+	
trajectory	Update rate	Error rate	Update rate	Error rate	Update rate	Error rate	Update rate	Error rate
Static	5.0	0.06	5.0	0.10	5.0	0.05	4.9	0.0
Straight	5.0	0.04	5.0	0.07	5.0	0.05	4.9	0.0
Diagonal	5.0	0.11	5.0	0.13	5.0	0.05	4.8	0.0
Rectangle	5.0	0.00	4.7	0.06	4	0.0	4.9	0.0

TABLE 4: Performance of proposed case studies for single tag localization.

Figure 15 and Table 4 describe the performance of the four test cases for single tag localization. According to this table, the ratio of errors (exceeding one meter) that leads to a false alarm in ViPER is between 6% to 13% which is even higher than the baseline method. This means that ViPER had no improvement in this scenario. By using NLOS method for anchor selection instead of low-pass filter, the errors were reduced to a maximum of 5% and by using low-pass filter on this phase, all the errors were eliminated.

3.6 Multiple tag pose estimation for vehicle tracking

In this part, we evaluate the error and update ratio for vehicle pose estimation shown in figure 11. Table 5 provides the quantitative results for this experiment. According to this table, 30% of the measurements done by ViPER produced false alarms. Our proposed solution (ViPER+) was able to reduce this ratio to zero meaning that no measurement had the error of more than one meter in distance and orientation. For further analysis, we illustrate the output of localization and pose estimation for this scenario in Figure 16. The images on the left column represent the localization output while the right column displays the output of the pose estimation along with ground truth indicated with two parallel lines. According to the figure, the number of estimated locations by ViPER which is one of the inputs of pose estimation is lower than other methods. This lack of inputs results in lower pose estimation accuracy compared to the NLOS method and

ViPER+. We also applied our method to scenarios mentioned in the previous ViPER paper to evaluate our solution in that scenario as well. Table 5 shows the results of our evaluation.

	Baseline	ViPER	NLOS anchor and reference selection	**ViPER+**
Update ratio	0.93	0.97	0.96	**1.0**
Error ratio	0.33	0.30	0.12	**0.0**

TABLE 5: Vehicle pose estimation result: by modifying the localization process in ViPER+. (the number of locations increases which improves the accuracy of the pose estimation process leading to a reduction of error rate)

	Baseline	ViPER	NLOS anchor and reference selection	**ViPER+**
Update ratio	0.93	0.99	0.98	**0.99**
Error ratio	0.20	0.29	0.16	**0.03**

TABLE 6: Vehicle pose estimation result: by modifying the localization process in ViPER+. (the number of locations increases which improves the accuracy of the pose estimation process leading to a reduction of error rate)

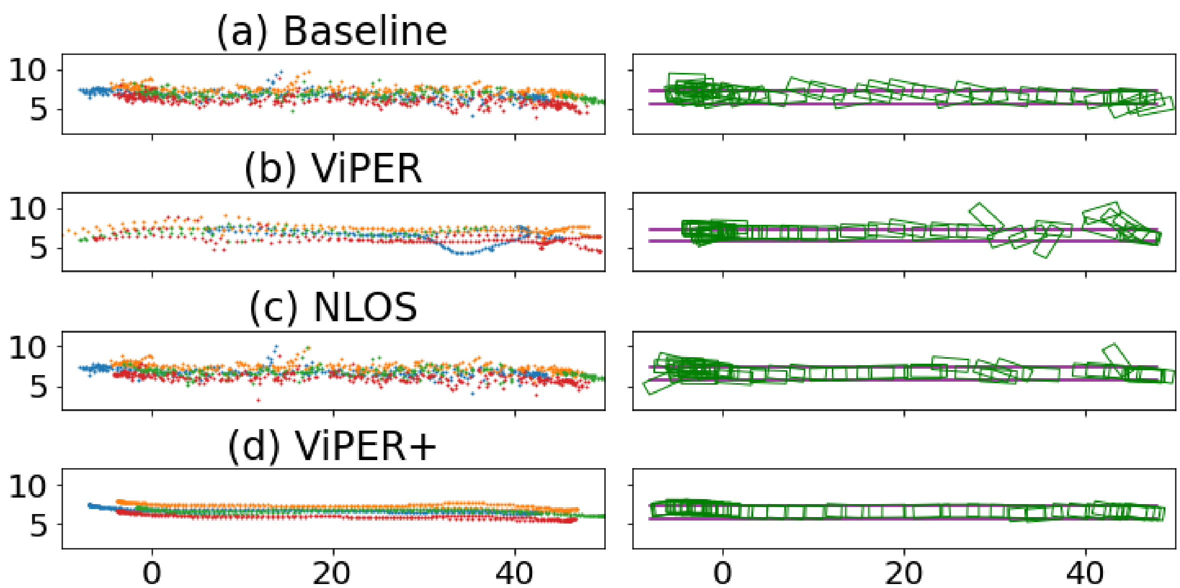


FIGURE 16: Output result for multiple tag pose estimation for the moving track scenario. Figures on the left column display the location output, and the figures on the right column display the pose of the vehicle throughout the scenario. The ground truth is indicated with two parallel purple lines.

3.7 Proximity detection with ViPER+

In the next step, our goal is to implement one of the safety-related applications to evaluate the impact of our improvement on a safety application that monitors the distance between entities. In this scenario, we considered both the worker and the vehicle and estimated the distance between the front of the vehicle and the location of the worker. Table 7 shows the quantitative results from this experiment. The update ratio of ViPER was 70% meaning that the location of the vehicle or worker was not present 30% of the time to calculate the distance. The number of estimated locations was low for ViPER. This leads to a lower number of distances reported for this method. In addition to the update ratio, 62% of the estimated distances had higher error. Figure 17 shows the distance output during the experiment. The continuous line represents the ground truth distance between the worker and the front of the vehicle and the estimated distances are shown as dots in this figure.

Method Name	Pose update ratio	Pose update rate	Error ratio
Baseline	0.94	4.70	0.30
ViPER	0.70	3.48	0.62
NLOS anchor and reference selection	0.96	4.82	0.28
ViPER+	1.00	4.98	0.0

TABLE 7: Output result for multiple tag pose estimation for the moving truck scenario. Figures on the left column display the location output, and the figures on the right column display the pose of the vehicle throughout the scenario. The ground truth is indicated with two parallel purple lines.

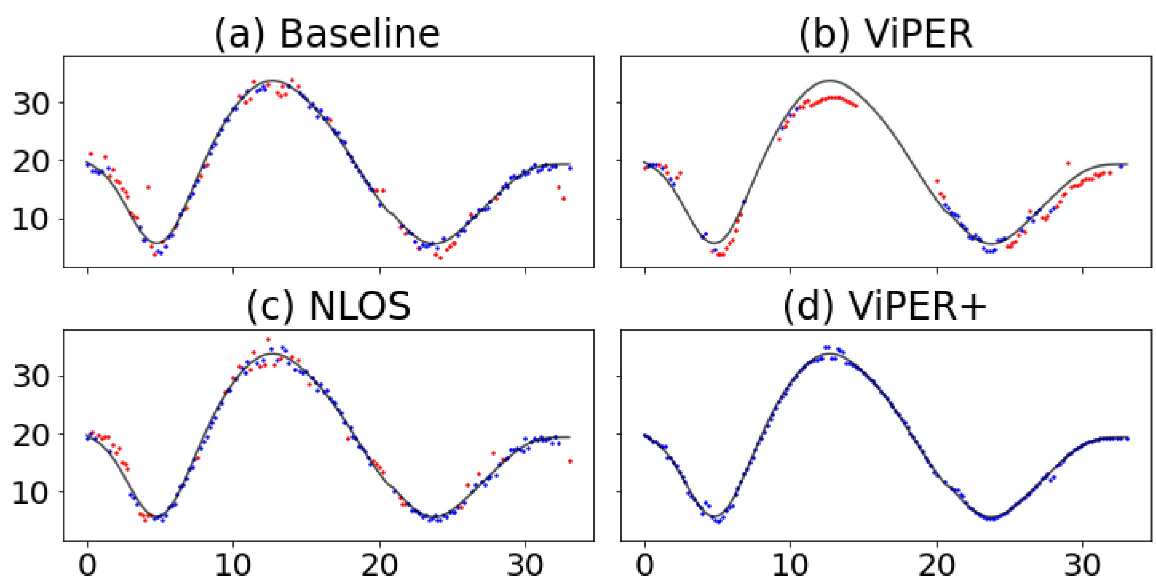


FIGURE 17: Distance between the vehicle and the static tag. Continuous line is the ground truth and the dots are estimates.

3.8 GUI evaluation

In this part, we describe the GUI that was designed to display the pose of entities along with the safety policies regulated for the tracking zone. Figure 18 shows the experiment scenario in our GUI. In this figure, the tracking zone, location of six anchors, pose of the vehicle, and worker are shown. The trajectory of the vehicle is also indicated. According to this figure, the truck enters the “red zone” twice throughout its trajectory, once moving forward and once moving backward.

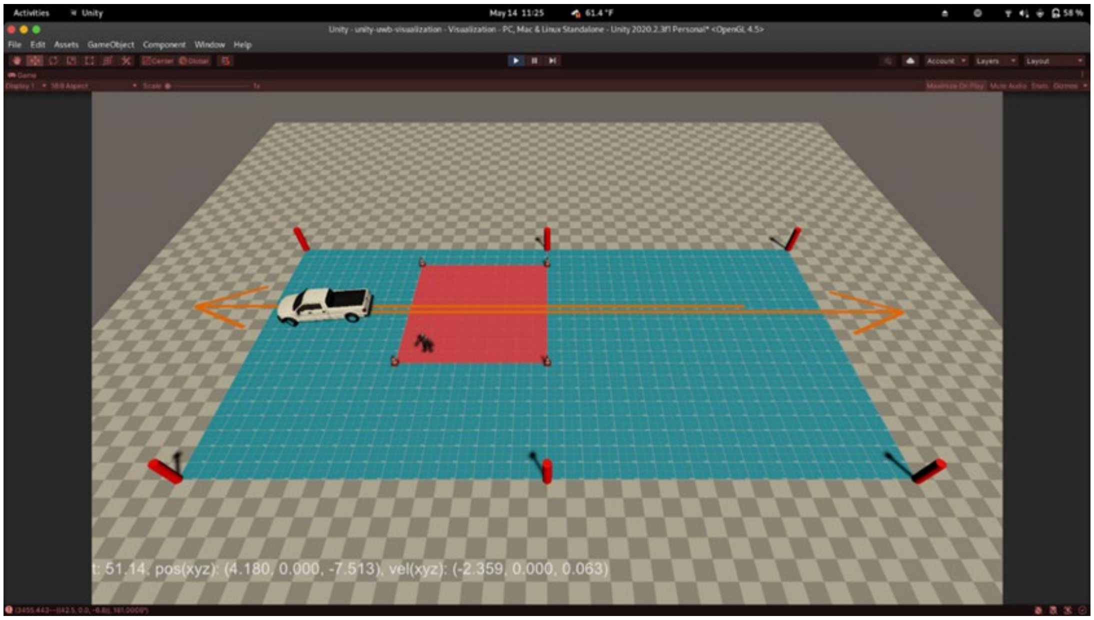
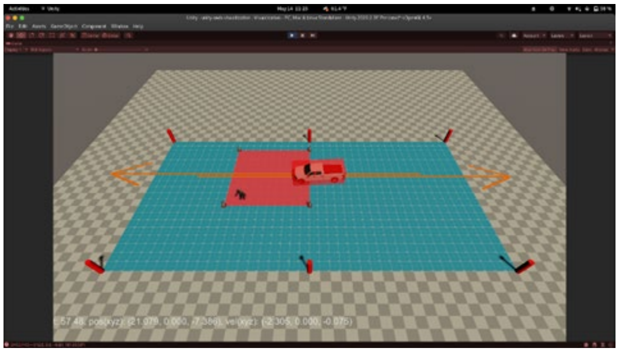
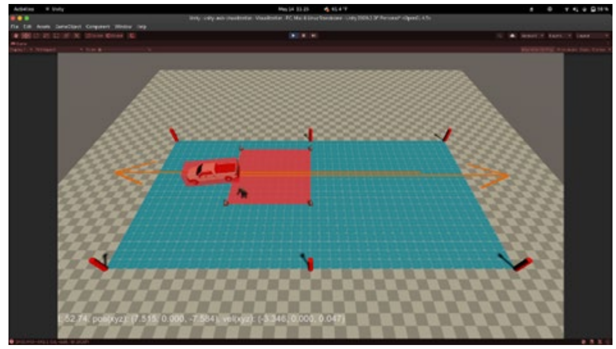


FIGURE 18: The graphical output of the experiment with GUI. The position of worker and truck are displayed in the map. The “red zone” is displayed as a red square and the trajectory of the truck is indicated with two arrows.

We regulated a safety policy by dedicating a zone as “red zone”. The policy prohibits trucks and vehicles to enter this zone to avoid collision between the workers and the vehicles. However, in our scenario, this policy was violated by the truck twice during its trajectory. Figure 19 shows this violation in our GUI application. According to these figures, the vehicle has entered this zone once with the front side Figure 19 (a) and once with the backside Figure 17 (b). Both occurrences have been detected by the system and the vehicle has been marked with a different color indicating a violation of policy.



(a) Front side entrance



(b) Back side entrance

FIGURE 19: Vehicle entering the "red zone" area during its trajectory violating one of the safety policies regulated for the safety of the workers. The entrance was detected by our system and the vehicle was marked with different color as an alarm.

4. DEPLOYMENT AND EVALUATION 2

The ViPER project was designed to improve construction site safety by tracking the location of entities in the environment. Our first deployment of the project (ViPER v1.0) took place in a road construction site with three workers and a truck. In our first round of data collection, we designed and developed ViPER that corrected input data from sensors by removing the noise in the inputs. The second round of evaluation took place at an urban construction site. Despite the improvement of ViPER in the first phase, we encountered a huge quality drop compared to the baseline method when using ViPER in this new environment. Therefore, we improved the design of ViPER and ViPER+ and designed ViPER V2. Here, we compare the results of the baseline, ViPER and ViPER V2 methods for vehicle and worker tracking.

4.1. Scenarios

We designed three experiments to evaluate the performance of ViPER V2. The first experiment was designed to evaluate the performance of ViPER V2 when there is no obstacle creating NLOS situations except the workers (in our case students) walking with the tags. In the second experiment, the trajectories of the workers were like the first experiment. We placed two construction vehicles in the center of the tracking zone to create additional NLOS effect and measure the effect of NLOS on the performance. One of the vehicles had tags on it for pose tracking. Finally, our last scenario focuses on location tracking and pose estimation using ViPER V2. In this experiment, we dedicate a path for one of the construction vehicle (the one with the tags) and recorded the location of the tags while some workers were moving with their tags in their hands.

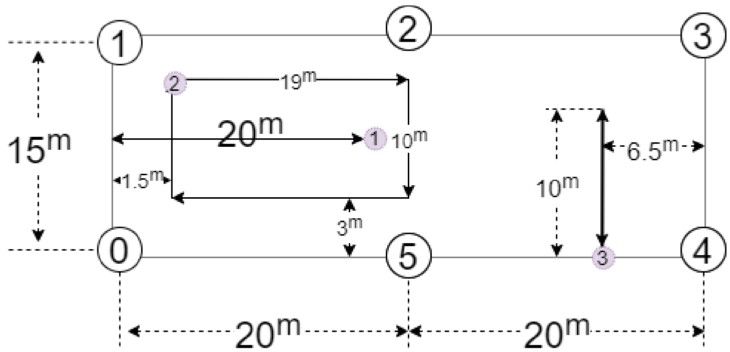


FIGURE 20: Experiment 1: worker tracking with no obstacles

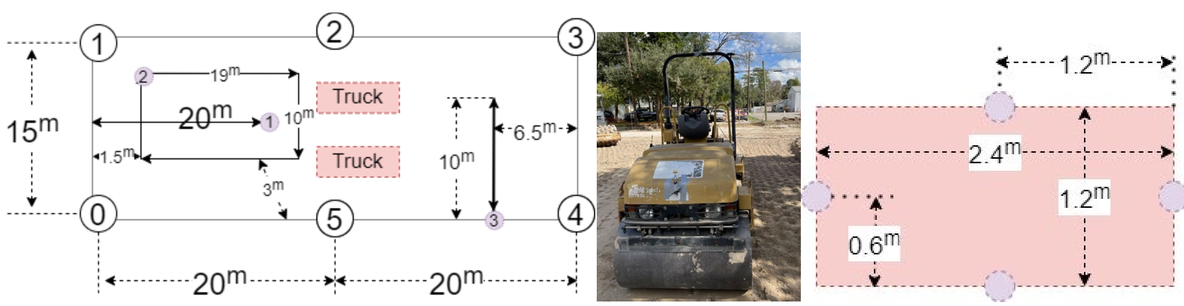


FIGURE 21: Experiment 2: worker tracking with obstacles and dimensions of the equipment used

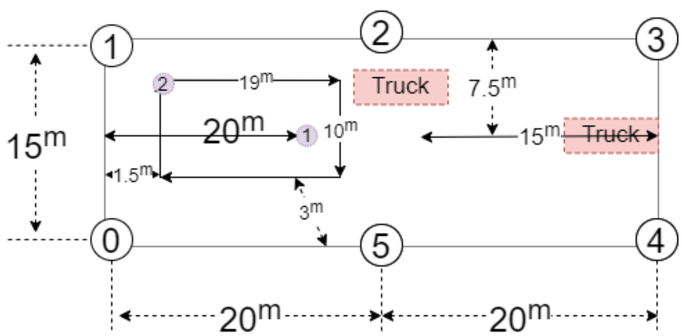


FIGURE 22: Experiment 3: equipment tracking with obstacles

4.2. Comparison method

Since the goal of ViPER was to develop a safety monitoring system, the accuracy of the estimated location and the location update ratio are two critical parameters that must be evaluated.

To measure the accuracy of the localization, we extracted the ground truth of each tag using the videos we captured during the experiment in the construction site. Then, we calculated the location for each entity and matched the location with the ground truth. Figure 23 shows an example of indicating the ground truth. In the left picture, we marked the time when the tag passed each cone. The right picture shows the location timeseries for both the x and y axis. The marked spots on the left were indicated in the right picture using vertical black lines on the time axis and horizontal red line to mark the values of the x axis.

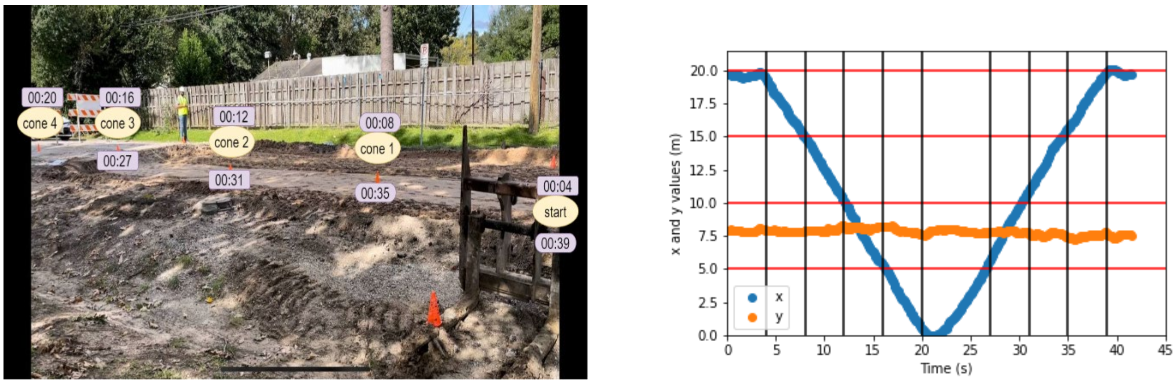


FIGURE 23: Ground truth identification in the evaluation and location timeseries

For measuring the update ratio, we looked for discontinuity in the timeseries of the tag based on the timestamp of the received location. We calculated the percentage of the time that the localization system was unable to estimate the location of the tag or the pose of the vehicle. In addition to the metrics and the calculation methods, we also need to define a threshold for each metric to determine if the performance metric is within an acceptable margin, or it violated the requirements of the application. The estimated locations can have different values compared to their ground truth locations which is considered as error. This error can be caused by either the people who were conducting the experiment or the noise in the collected data. We considered a margin of 1.5 m as the threshold for location accuracy. As for update ratio, we chose the value of 1s as the threshold for time gap between two consecutive location estimates.

4.3. Evaluation

Location estimation evaluation for worker tracking

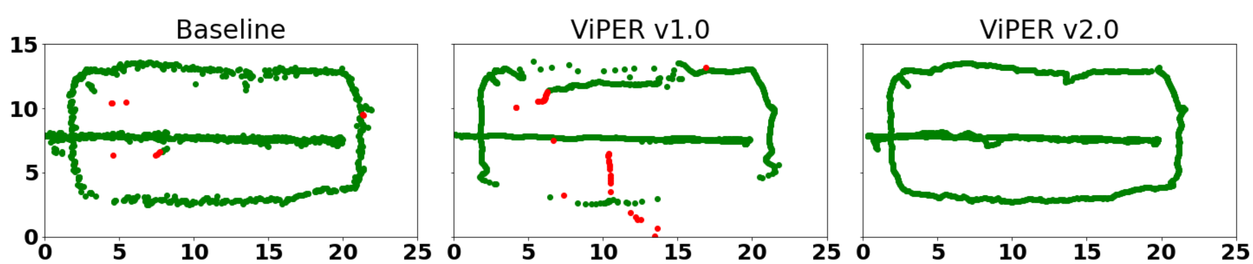


FIGURE 24: Evaluation of worker tracking. Previous version of ViPER which was previously used to remove the error of the baseline method had lower performance in the second experiment set

In our evaluation, we evaluate the results of experiments where both workers and vehicle were moving in the construction site while another static vehicle was causing NLOS situations. The results of the worker tracking evaluation are shown in Figure 24. Each dot represents a location estimated by each of the localization method. The green dots are estimations within the margin of error threshold for location accuracy and the red dots are estimations with error more that accuracy threshold. According to the results, when the previous implementation of ViPER was used, 5% of the estimated locations for tag #2 and 3% for tag #1 had more than 1.5 m error compared to their ground truth values. Meanwhile, both baseline and ViPER V2.0 had no errors in their location estimations. In addition to location accuracy, we can also see some parts of the location trace is missing when ViPER method was used. Figure 25 provides another demonstration of location updates. The Y axis represents the moving tags and the X axis represents the timeline of the experiment. The start of the X axis is the time each tag started moving and the end of the X axis is the time each tag finished its track and got disconnected.

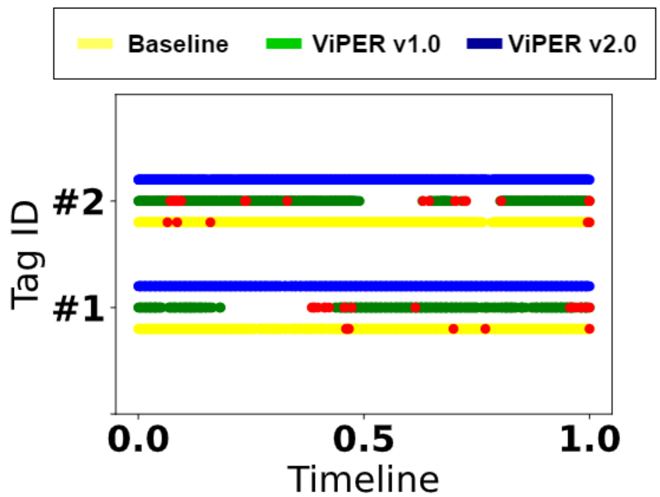


FIGURE 25: Location update timeline for tags #1 and #2. The red dots represent timelines when locations were estimated incorrectly and the discontinuity in the lines represents the times when the chosen method was unable to provide any estimation.

According to this figure, the original implementation of ViPER was unable to estimate the location of tag #2 for approximately 12 seconds (two periods of 5s and 7s) which is approximately 35% of the track. The same phenomenon also happened with tag #1 where the ViPER method failed to estimate the location for 12 seconds which 25% of the time before this tag reaches half of its track.

4.4. Pose estimation evaluation for vehicle tracking

In addition to worker tracking, we also evaluated our pose estimation method for vehicle tracking. In this comparison, the ViPER V2 was compared to ViPER and the baseline. The baseline method used the geometric approach to estimate the position of the vehicle while in ViPER, we used an optimization approach. In ViPER V2 we used the same method in the previous implementation. However, due to modifications in our localization method, the input to the pose estimation algorithm might lead to different results with ViPER V2 compared to the original ViPER. The pose of the vehicle includes the location and the orientation of the vehicle. Therefore, for the pose estimation process, the location and the orientation of the vehicle had to be compared for these three methods. We show the timeline results for pose estimation in Figure 26. The timelines show the orientation and the location estimated by three different methods used in this evaluation. According to the figure, all three methods were able to correctly estimate the location of the vehicle. However, for vehicles in construction site, the orientation of the vehicle is also critical since applications might have different distance policy for front, back, and sides of the vehicles. When comparing the orientation estimation, baseline method miscalculated 45% of the estimation while ViPER method had under 1% and ViPER V2 had 1.6% error in determining the location of the vehicle.

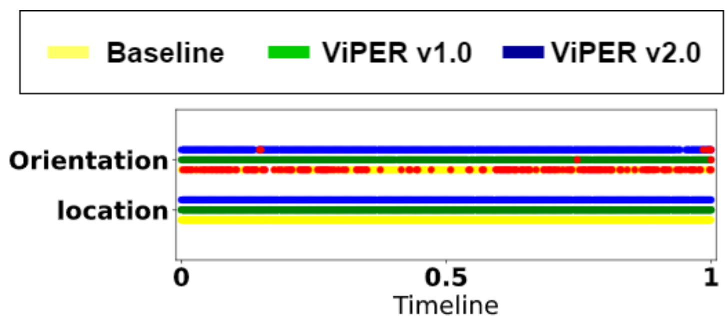


FIGURE 26: Vehicle pose estimation timeline for ViPER v2.0 evaluation. Both the orientation and the location estimations are shown in two separate timelines for all the methods. The red dots represent incorrect estimations in location or orientation compared to the ground truth.

4.5. Summary of results

Table 8 shows the error rate and Table 9 illustrates the update rate for worker and vehicle tracking. The performance of ViPER was inefficient for safety monitoring applications due to low location update ratio for tags. The baseline method had higher performance in worker tracking compared to previous implementation of ViPER. However, the baseline method had inadequate performance in tracking the pose of the vehicle. Since none of the previous methods had enough performance for safety tracking applications, we modified the implementation of ViPER. ViPER V2 provides sufficient performance that satisfies the requirement of a safety monitoring system for both worker and vehicle tracking in construction sites.

	Baseline	ViPER	ViPER V2
Worker tracking	3%	5%	0%
Vehicle tracking	45%	1%	1.6%

TABLE 8: Location error rate for both worker and vehicle tracking in all three methods.

	Baseline	ViPER	ViPER V2
Worker tracking	100%	65%	100%
Vehicle tracking	100%	100%	100%

TABLE 9: Location error rate for both worker and vehicle tracking in all three methods.

PLANS FOR IMPLEMENTATION

There are two major areas of work that is needed to bring the technology close to real world.

(1) **Improve accuracy and scalability**. The system developed as part of this project has achieved accuracy and reliability needed for the applications considered but the system may not be able to maintain such accuracy in even more challenging situations that are rare but may arise, for example, when there is even larger obstruction due to piles of rocks in the area, or even larger equipment. Making such improvement will require further development of signal processing, noise filtering, and data fusion algorithm. Another area of work that would be of interest is combining location system with different characteristics, e.g., location tracking with LoRA. It is important to scale the current system to beyond approximately 40 tags supported. This will require development of better hardware and software that can keep track of communication and localization rounds so that each location estimate can be done more quickly leaving plenty of time to accommodate more tags.

(2) **More rigorous testing**. For any technology to be trusted in a safety critical application, it has to be tested as widely as possible in as diverse situations as possible. Although the project team did two different tests with the technology in two real construction sites, we would like to further do testing incorporating more and less challenging situations, larger and smaller sites, and different types of construction.

We plan to submit grant proposals to Texas Department of Transportation (Tx DOT) and Nebraska Department of Transportation (NDOT) in order to further enhance the system as discussed above and bring the technology closer to real world impact.

DISCUSSION AND CONCLUSION

In this study, we designed a pose estimation system for monitoring construction safety. For evaluation, we deployed our system in a real-world road construction environment with trucks and loaders causing NLOS and obstruction. We evaluated our proposed method with three other approaches that were used previously for pose estimation. Our proposed solution was developed and evaluated using DecaWave DW1000 radio chip on RadinoL4 platform. We used Raspberry Pi devices to establish connections between the server and anchors. Our evaluation scenarios mostly focused on scenarios that ViPER was unable to perform sufficiently. The results of our experiments indicate that in previous studies, obstruction of the signals caused location/pose unavailability in some scenarios. This unavailability is not acceptable in real-time monitoring systems since they might miss a considerable number of alarms by not having the status of all entities. In ViPER V2, these gaps were removed when using NLOS anchor and reference selection method, and the error was corrected with the low-pass filter.

One of the important limitations of ViPER V2 is the maximum number of tags that the system can track at the same time. To avoid packet corruption in our design, only one tag can transmit a message at a time. This regulation limits the maximum number of tags that could be tracked in ViPER V2. Currently, ViPER V2 can track up to 40 tags. However, this number needs to increase to support the needs of construction applications. Another limitation of our work is the distance of the entities from the anchors. In ViPER V2, it is assumed that all the entities are within an area called tracking zone that is surrounded by anchors. If an entity is outside of the tracking zone, the system will not guarantee to address the error rate and update rate requirement for that entity. The 6 dB NLOS detection algorithm has proven to be successful in most situations. However, there are some corner cases in which the algorithm is unable to detect LOS/NLOS situations as mentioned in [15] . Further research on this topic will focus on the design and implementation of an alerting system for communication between the server and the entities. The system needs to notify users about their situations and help them avoid hazardous situations.

In this study, we designed, implemented, and evaluated our vehicle pose estimation system that enables safety monitoring in construction environments. Previously, wireless radio-based pose estimation systems were unable to provide sufficient accuracy and pose reception rate required for safety monitoring. Our NLOS detection and correction methods were able to enhance these two critical factors in pose estimation, enabling safety monitoring in construction sites. The proposed improvements were investigated in a series of case studies for worker and construction vehicle tracking scenarios under LOS and NLOS conditions. Our results indicate an increase in accuracy by reducing the error rate by 92% along with 30% improvement in pose reception rate for the combined scenario compared to the state-of-the-art solution (ViPER). The result shows the potentials of NLOS anchor and reference selection algorithm in safety monitoring applications or experiments with the increased location reception rate and pose estimation for tracked items in both LOS and NLOS conditions recorded in the case studies.

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Research Results

Work Zone Equipment Tracking with UWB Radio

Vehicle Pose Estimation using Ultra-Wide Band Radios (ViPER) for Heavy Equipment Tracking in Work Zone with Non-Line of Sight (NLOS)

Program Steering Committee:

NCHRP IDEA Program Committee

Project Title:

Rule-Based Automated Safety Monitoring System for Highway Work Zone Safety

Month and Year: March 2022

Project Number: NCHRP-IDEA 206

Start Date: May 1, 2018

Completion Date: April 30, 2022

Principal Investigator:
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UWB sensors attached to vehicle and equipment

WHAT WAS THE NEED? There is an urgent need to prevent accidents inside road construction work zones caused by collision between mobile equipment and workers on foot. Recent projects have developed worker tracking systems using different wireless technologies such as Bluetooth, ultra-wideband (UWB), and radio frequency identification (RFID) to track the location of the worker inside construction sites. Among various solutions, UWB radios hold a great promise to provide accurate localization of entities suitable for safety tracking.

However, the performance of radios significantly degrades when there is an obstruction or blockage in the communication signal between the transmitter and receiver causing **Non-Line of Sight (NLOS) situations** like in a road construction with vehicles and heavy equipment. With inaccurate location tracking, it is not feasible to develop a system to alert the workers of dangers in a dynamic work zone environment.

WHAT WAS OUR GOAL? The goal of this project was to develop a robust real-time UWB based location tracking and monitoring that eliminates the effects of NLOS situations when they occur, thereby improving localization performance in those challenging scenarios.

Research Results

WHAT DID WE DO?

We first evaluated commercially available UWB tracking tools. We found that none of the commercial tools can be used without significant improvements to overcome NLOS situations and enhance robustness. Then, we developed a new radino TDOA platform that combines strengths of different platforms. On this new platform, we developed a software program called vehicle pose estimation using ultra-wide band radios (ViPER) that eliminates the effects of NLOS situations when they occur, thereby improving localization performance in those challenging scenarios. Five versions of ViPER were developed and evaluated in controlled environments and road construction sites with both line-of-sight (LOS) and NLOS situations.

WHAT WAS THE OUTCOME?

This project produced a real-time location tracking system that can track vehicles, heavy equipment, and workers on foot and estimate the distance between. The evaluation of the system in a demonstration in a real construction zone in Houston area indicated an increase in accuracy by reducing the error rate by 92% along with 30% improvement in pose reception rate for the combined scenario compared to the state-of-the-art solution.

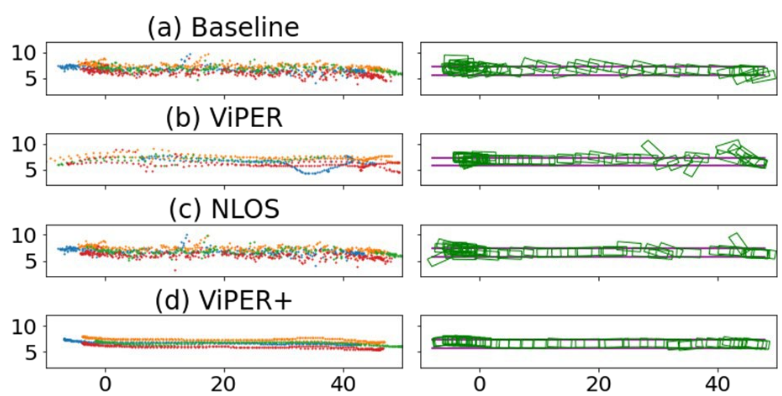
WHAT IS THE BENEFIT?

Our project created and tested the first approach that directly addresses the critical challenges of adopting localization and pose estimating into road construction work zones with NOS and NLOS conditions. This project suggested a promising direction toward the realistic implementation of location tracking for worker safety in congested road construction work zones which was not possible with existing tools.

LEARN MORE

To view the complete report:

http://www2.cs.uh.edu/~gnawali/workzonesafety/



Enhanced vehicle pose estimation: Output result for multiple tag pose estimation for the moving track scenario. ViPER+ (this project) has highest accuracy. Left column displays the location out- put. Right column displays the pose of the vehicle throughout the scenario.

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