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Safety Improvements for Personnel and Vehicles in Short-Term Construction Sites

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ABSTRACT Despite all efforts to enhance safety, construction sites remain a major location for traffic accidents. Short-term construction sites, in particular, face limitations in implementing extensive safety measures due to their condensed timelines. This paper seeks to enhance safety in short-term construction sites by alerting maintenance personnel and approaching vehicles to potentially dangerous scenarios. Focusing on defining the exact dimensions of static construction sites, this method employs high-precision Real-Time-Kinematics-GNSS for localizing traffic cones and deriving the construction site geometry through respective algorithms. By analyzing the geometry, we can identify situations where maintenance personnel are in close proximity to the active lane or when vehicles enter the construction site. To increase awareness of hazardous situations, we present methods for distributing information to maintenance personnel and vehicles, along with technical solutions for warning those involved. Additionally, we discuss the distribution of the construction site's geometry among approaching vehicles, which can provide future automated vehicles with crucial information on the site's exact start and end points.

INDEX TERMS Road works safety, V2X, GNSS, RTK.

I. INTRODUCTION

THE ADVANCEMENT of intelligent transportation systems (ITS) has primarily concentrated on distributing traffic-related information in recent years. However, the introduction of vehicles with higher levels of automation (SAE levels 3 and above) has led to new demands concerning detecting the surroundings, such as other traffic participants. One of the significant obstacles is temporary construction zones. These are short-term construction sites for road maintenance that involve various activities such as painting fresh road markings, repairing potholes, pruning trees, or conducting other work. Safety requirements and dimensions for these sites differ significantly from those of long-term construction sites. Typically, in the latter, physical barriers separate work zones from traffic flow. The environmental conditions under which work is conducted in short-term construction sites also differ. The velocity differences and possible sight obstruction make rural roads and the motorway environment intriguing cases. Framework conditions in the city environment vary greatly. Our research only concentrates on short-term construction sites on motorways.

The construction site can be distinguished by whether maintenance personnel need to be inside or outside the vehicle. Additionally, the site can be further differentiated when construction workers are working beside or on the road. For instance, mowing may be conducted either inside or outside a vehicle depending on the surrounding conditions. Generally, repairing potholes and painting lane markings occur on the road surface. Depending on regulations, construction sites may be equipped and defined with a variety of safety measures, such as traffic cones, delineator posts, or even traffic lights or signs. In other situations, no safety measures are taken. Furthermore, some construction sites are mobile, such as those involved in cleaning a lane or mowing, while others are static, such as those fixing a pothole. Depending on the street class, traffic flow, and

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local traffic signs, blocking trailers may be used as a safety measure.

During short-term construction projects, it is vital to prioritize the safety and well-being of maintenance personnel and ensure safe vehicle passage through or near the worksite. This involves careful attention to all components, such as the construction site's geometry and effective warning systems for both maintenance workers and nearby vehicles. The geometry of the construction site is particularly critical for two main reasons. The safe zones for maintenance personnel working on the construction site depend on accurately defining its dimensions. With this information, both workers within the construction zone and vehicles passing by can be warned if they are getting too close. Recognizing a construction site and the corresponding traffic signs is not always easy, for both automated vehicles and human drivers [1]. When trying to distinguish a site, it is important to consider essential questions such as: is there a construction site nearby? Is it pertinent to the route? Where does it begin and end? Legal frameworks exist to ensure the safety of construction site maintenance personnel [2], [3]. However, there is currently limited research regarding active safety measures (see Section II). The geometry of a short-term construction site is not always detectable. Without the use of safety materials (e.g., cones), there is no precise geometry to detect. If cones or delineator posts are utilized, a geometry can be detected. For safety reasons, the construction site's dimensions and safety material positions must be precise, with an accuracy of at least 10 cm. The dimensions of the construction site may be included in high-definition maps on the real-time map layer [4] for safety and guidance applications in connected vehicles, whether automated or manually driven. It is recommended that no extra steps be taken to make the maintenance personnel's job easier. Furthermore, the solution should not impede the maintenance staff, who already have a busy schedule.

This paper is structured as follows: Section II discusses research on the precise geometry of construction sites, including means to localize it accurately and the maintenance personnel within. Section III outlines our approach to the problem, including methodology. Section IV-A presents the results of our field trials and shows our organizational approaches. Section V concludes the paper, examines the results, and provides an outlook on open research questions.

II. RELATED WORK

Regarding construction sites in V2X communication, the day-1 use cases define a Road Works Warning [5], [6]. This warning provides details about the type of road works (short-term, long-term, etc.) and their approximate location, but omits information such as the start and end of the site or the number of occupied lanes. Notably, this service was the initial C-ITS service implemented on German roads. In April 2021, Die Autobahn GmbH des Bundes began installing C-ITS hardware on their mobile warning trailers [7] to disseminate Road Works Warning through ETSI ITS G5 during short-term construction sites. Initially, the system was only accessible in specific regions, but the aim is to deploy it nationwide by 2024. In Europe, C-ROADS [8] was established by road operators and member states of the European Union to standardize specifications and assess current standards (e.g., [9]) for the testing and deployment of C-ITS.

The issue of uncertain construction site geometry is a common problem. Past efforts to detect construction sites have utilized computer vision with road signs that mark the beginning and end of a construction site [10]. However, "End of Construction Site" signs are not present for temporary sites in Germany. Another method, employing computer vision and artificial intelligence, has shown promise for long-term sites [11]. Although colored lane markings make cone positions more noticeable, the results cannot be directly applied to short-term construction sites. The primary method for obtaining dimensions is currently perceiving cone positions through internal sensors, such as video or radar/lidar. However, this approach carries the risk of missing cones due to imperfect sensors or the recognizing car being in the outermost lane. Meanwhile, a different vehicle may be positioned between the car and the construction site, making it difficult for the car to determine if the construction site has ended or if some cones were missed, and the car cannot identify where the end of the construction site is.

Ensuring the safety of maintenance personnel near the active lane requires precise geometry of the construction site. Therefore, it is advisable to leverage comparable technologies to locate both the construction site and the personnel.

There are various approaches to obtaining the geometry of a construction site, each with their pros and cons.

Computer vision and artificial intelligence are frequently used to locate and identify objects and humans. Research has been conducted on detecting traffic cones [12], monitoring construction workers [13], [14], and managing resources on construction sites in general [15]. One significant drawback of this approach is the need for precise calibration of the cameras. For instance, an error of one degree while calibrating the horizontal plane results in an error of approximately 17 centimeters for every 10-meter distance. Because cameras are frequently mounted onto construction site vehicles (CVs), any error in determining the vehicle's heading is added to the error of the camera itself. Moreover, there is an error in localizing the vehicle using GNSS, which also applies to localizing objects.

These issues pertain to all infrastructure-based (construction-vehicle) localization technologies, such as UWB, Bluetooth, or IEEE 802.11 WLAN, in addition to radar or lidar. The specific errors of these technologies add to those already mentioned. For example, UWB displays inaccuracies of a few decimeters already [16], [17], [18]. The Direction Finding feature of Bluetooth 5.1 results in comparable errors [19]. In contrast, the IEEE 802.11 standard's Collaborative Time of Arrival protocol only achieves errors in the range of 1 meter or more [20]. Lidar, on the other hand, faces the issue of diverging beams. For instance, a horizontal resolution of 0.1° - close to state-of-the-art lidar's lower limit [21] - would imply a distance of approximately 17 centimeters between two adjacent beams located 100 meters away from the lidar. All imaging methods, such as cameras, radar, and lidar, require an unobstructed line of sight, posing potential difficulties in curves or when larger equipment is present on the construction site. Otherwise, determining the position is impossible.

To prevent errors related to localizing construction vehicles, the necessary devices should be located on the maintenance personnel or on the traffic cone. Therefore, GNSS is the most suitable solution. While mobile radio localization is generally an option, using current LTE technology results in errors of several meters [22], [23]. When utilizing Real-Time Kinematics (RTK) with GNSS, achieving sub-cm accuracy is possible even with low-cost RTK receivers, particularly in rural areas where the majority of highways are situated, as per [24] and [25]. Our measurements in a rural/suburban area, using a u-blox ZED-F9P module and multiband (L1/L2/L5) helical antenna, also yielded precision below 1 cm (refer to Section IV-A and Figure 11). In Germany, SAPOS, an online service of the surveying authorities of the States of the Federal Republic of Germany, provides the RTK correction data [26].

Considering all these factors, the Global Navigation Satellite System (GNSS) is the optimal method for locating cones and maintenance personnel. The dimensions of the construction site can be used in digital twins to reduce uncertainty in data quality and environmental detection during the development of automated driving functions [27], [28], [29].

III. METHODOLOGY

Our system is based mainly on three parts:

1) A system to locate the positions of the construction site limiting cones/beacons and the maintenance personnel.
2) A central roadside unit on the construction site vehicle to aggregate information and process it.
3) A system to warn both maintenance personnel and approaching vehicles.

A. POSITIONING AND MEASUREMENTS

This section handles the two initial problems faced when developing a system to increase safety on a highway, especially for the maintenance personnel. As the system is designed to detect maintenance personnel being too close to the active lane, the location of this border needs to be determined. Here, the ASR [2] dictates a minimum distance (depending on the speed of passing vehicles) to a virtual line that connects all the cones/beacons set up to mark the edge of the construction site. Maintenance personnel are mandated to keep this distance at all times. As it is possible to secure a construction site using either cones or beacons [3], the system is designed to locate both. For the sake of simplicity, they will be referred to as cones in the following sections. Initially, the exact positions of the cones need to be known to the system, to determine the geometry of the virtual border line. As mentioned above, the precision of these measurements shall include an overall error (sum of absolute and relative error) smaller than 0.1 m. Due to the fact that this information usually does not change throughout the short-term construction site, it has to be gathered only once at the beginning of the road works. Further data required to decide whether maintenance personnel is in a keep-out area, is their exact position.

Contrary to the cones' positions, the maintenance personnel's positions dynamically change over time. Therefore, these positions must be tracked continuously in realtime. As the requirements for gathering the positions of cones and maintenance personnel differ, two different devices were used for the measurements.

To gather the correct positions of the construction site's border, measuring only the first and last cone is not sufficient, due to the fact that the construction site's geometry is not necessarily a straight line and can even extend onto additional traffic lines. As mentioned in Section II, the technology chosen to obtain positions is GNSS. The process of setting up the system is described in the following. At first, a single maintenance personnel measures the cone's positions after placing each cone, using a unique geometry measuring device, GMD. To reach the required precision, the GMD utilizes real-time kinematics (RTK) by using SAPOS correction data provided via cellular connection, forwarded by the roadside unit (RSU), which is located at the CV, via IEEE 802.11 (see Figure 1). For the measurement, the GMD must be plugged on top of the cone, and the position can be saved on the device. The system enables the maintenance personnel to place the cones and take the necessary measurements in a single work step. This means, that maintenance personnel does not have to wait until the whole construction site is set up, but urges them to measure the cone positions in the order they were set up, making the following calculations easier. When all cones have been recorded, the list of positions is sent to the RSU to process the data.

As mentioned before, the positions of maintenance personnel need to be tracked continuously. Therefore, each maintenance personnel has a personal Maintenance Personnel Device (MPD). The MPD also uses RTK for its position localization, receiving correction data from the RSU. The current corrected position of each device is individually sent at 10 Hz to the RSU using 2,4 GHz IEEE 802.11. The frequency of 10 Hz is chosen, as with a typical walking speed of a human being of about one m/s, the maintenance personnel walks about 0.1 m between two position updates, the same number as the required accuracy of the GNSS system. The u-blox ZED-F9P module is used in all devices to provide the GNSS position. During the measurements, all GNSSs currently available (GPS, Galileo, GLONASS, ...)

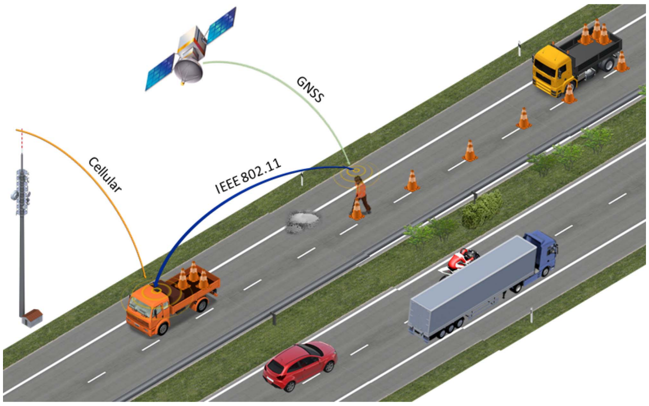

FIGURE 1. Positioning of traffic cones and maintenance personnel, © [30], [31].

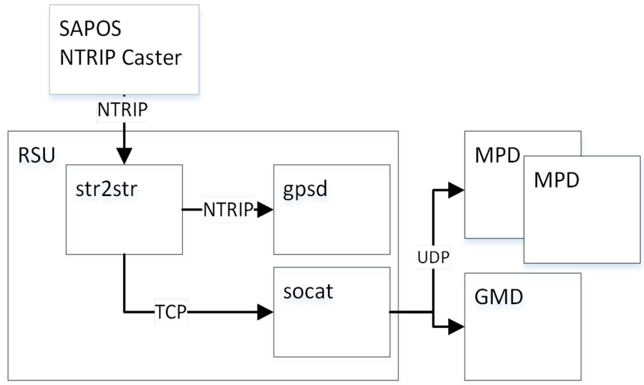

FIGURE 2. Dissemination of GNSS correction data.

are used. The GNSS receiver's positions are used without further postprocessing or filtering. In the first step, neither an averaging of the positions nor a hysteresis is considered.

B. INFORMATION AGGREGATION AND PROCESSING

The RSU in the construction site vehicle provides the needed edge computing power to process all data. The incoming data are:

- Correction data (Networked Transport of RTCM (Radio Technical Commission for Maritime Services) via Internet Protocol (NTRIP) [32]) provided by SAPOS
- Positions of the cones
- Position of the maintenance personnel
- Received V2X messages

The outgoing data are:

- Broadcasting of RTK-correction data
- Warnings to the maintenance personnel (see Section III-C)
- Warnings and information to approaching vehicles (see Section III-C)

The correction data are received using a cellular network and are used to improve the position of the RSU itself. The data are forwarded to the MPDs and GMD via 2.4 GHz IEEE 802.11, without further processing. The CV first estimates its position using standard GNSS to obtain an optimal correction data set. This position can then be used to request NTRIP data as a virtual reference station (VRS). The RSU uses a variant of the str2str application of the RTKLIB [33] software package to request and receive the correction data. It connects to the SAPOS service provider as an NTRIP client and requests the VRS with the initial estimated position. The received RTCM3 [34] correction data is offered locally via NTRIP caster and TCP. The positioning application of the RSU itself connects to the local NTRIP caster as a client, receives the correction data, and forwards it to its GNSS receiver. To deliver the correction data to the MPDs and GMD via IEEE 802.11, the RSU uses socat [35] to relay the TCP stream to a UDP broadcast to all connected devices (see Figure 2).

Once all cones have been captured by the GMD, they are sent to the RSU. On receipt of the list, the RSU calculates the geometry of the worksite. A short-term construction site consists of two areas: i) the safety area, which the maintenance personnel must not enter in the direction of the moving traffic, and ii) the work area, where the actual work takes place. To calculate these areas, the positions of all cones (P_0 - P_n) and the position of the construction vehicle are taken into account. First, for each cone position P_i, a line is calculated crossing P_i being perpendicular to the connection $P_{i-1} - P_i$ (as this obviously would not work for the first cone, the line perpendicular to $P_0 - P_1$ is also used). In the next step, the position of the CV is used to determine on which side of the cones the construction site is located (the CV should always be located within the construction site). Therefore, the cone closest to the CV is identified (P_c), and the bearing between this cone and the CV is calculated. This bearing is compared to the bearing of the construction site (or consecutive cones) to determine on which side of the cones the construction site is located, if

$$(B(P_{c-1}|P_c) - B(P_c|CV)) mod 360^\circ > 180^\circ \quad (1)$$

it is on the right side of the cones, otherwise on the left side. The single areas are then created by projecting the cone positions P_i towards their respective perpendicular (see Figure 3 and Figure 4). The width of the safety area depends on the current speed limit and is given in the ASR [2], e.g., for a maximum speed of 80 km/h, a width of 90 cm is designated. As the cones are always placed on the markings, the width of the working area (including the safety area) is one lane width, between 3.25 m and 3.75 m on German highways [36]. The working area does not need to be as precise as the safety area, as it is only used to detect if a car crashes into the construction site. Therefore, a distance of 3.75m is always used. Figure 3 shows the simplest version of a construction site, where only one lane is closed. The safety area is the one defined by the cone positions P_0 to P_5 and the respective projections $P_{0'}$ to $P_{5'}$, while the working area is spanned by the cone projections $P_{0'}$ to $P_{5'}$ and the projections P_{0^*} to P_{5^*}.

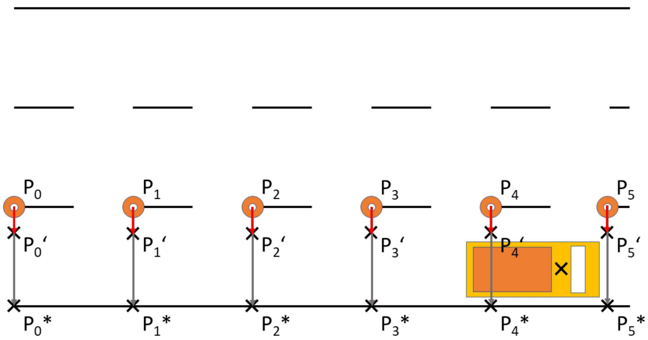

FIGURE 3. Single-lane construction site.

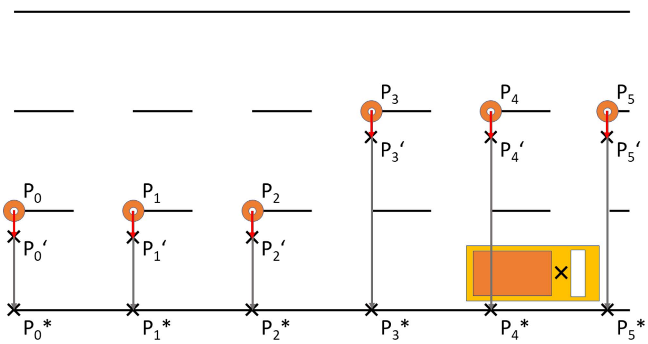

FIGURE 4. Multi-lane construction site.

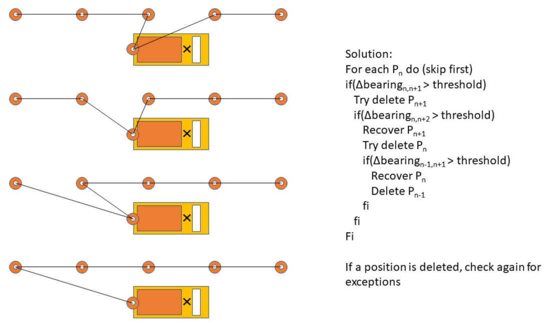

FIGURE 5. Exceptional cone detection (with pseudocode).

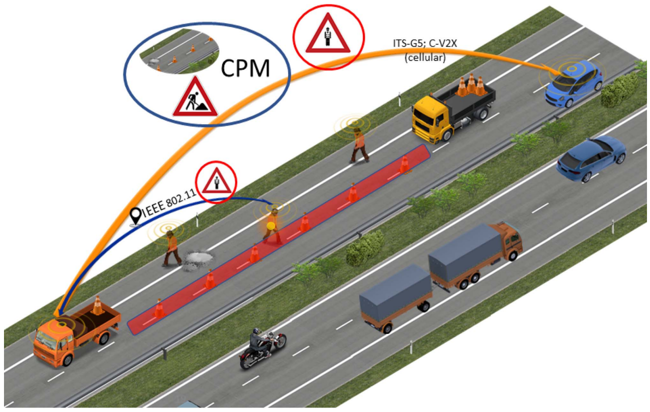

FIGURE 6. Illustration of a dangerous situation in a STRWS; © [30].

In real life, it also happens that a construction site will cover several lanes, as depicted in Figure 4. The bearing between two consecutive cones ($B(P_i|P_{i+1})$) is calculated for each consecutive pair of cones. If the difference between consecutive bearings

$$\Delta B = |B(P_i|P_{i+1}) - B(P_{i-1}|P_i)| \tag{2}$$

exceeds a certain threshold, it indicates a step in the construction site. The distance between two cones corresponds to the distance between two markings on German highways, which is 18 m. Assuming a lane width of 3.75 m, this results in a difference of about 12°. For our calculations, we have chosen a threshold of 10°. In the next step, we compare the bearing difference before and after the step, which should be below a certain threshold. For a straight street, a threshold of 1° would be sufficient. In the example shown in Figure 4, the system would recognize a step if $|B(P_2|P_3) - B(P_1|P_2)|$ is above the threshold, while $|B(P_3|P_4) - B(P_1|P_2)|$ is nearly zero. To span the working area, the cone positions P_3 to P_5 are projected two lane widths, unless another step is detected later using the same method.

Another method of obtaining a significant difference between two consecutive bearings is the unlikely event of recording an incorrect position. For instance, Figure 5 displays several cases where maintenance personnel unintentionally recorded a cone position when returning to the construction site vehicle to get more cones. In this case, a threshold is also exceeded, but there is no intended step following, as the difference between the former and the latter bearing is no longer negligible. Therefore, the corresponding cones are reversibly deleted from the list to see whether a valid line of cones results. If this does not work with the first cone expected to be responsible for exceeding ΔB, that one is restored, and the next one is deleted. Proceeding, the responsible cone should be found and removed, and the algorithm should be run again to look for further incorrect cone positions. It has to be mentioned that the pseudocode in Figure 5 is only applicable in case there is no step. The general case is more complex.

After calculating the exact position and geometry of the site, the system begins to continuously track the positions of the maintenance personnel. It compares with the geometry of the construction site. As a result, a list of registered MPDs is constantly updated. When an MPDs position is not updated for more than 1000 ms (ten potential position updates), this MPD will be set as deprecated and removed from the list. This ensures that all existing positions are valid.

As mentioned, maintenance personnel must be warned if they enter the safety area (see Figure 6). The system can also distinguish whether the maintenance personnel is still in the safety area (towards the construction site) or even in the active lane. The warning process is described in more detail in the following section.

C. WARNING/DISSEMINATION

The proposed system distributes information and warnings amongst maintenance personnel and traffic participants.

Despite an idle mode after switching on the system (where no warnings/information are sent), the construction site can be in one of three different states: setting up, on duty, or dismantling. The first stage of setting up the construction site (1.) is initiated by the site personnel using an HMI in the construction site vehicle to start setting up the site. This step involves measuring the cone positions. Once the geometry of the construction site is provided to the RSU, the system automatically switches to the "in duty" state (2.). From this point on, the conditions are met to locate the maintenance personnel within the site geometry and to be able to detect dangerous situations, leading to warnings. In the last state, the site personnel manually initiate the end of their work and start the dismantling the construction site (3.). After dismantling, the system is deactivated via the HMI and returned to idle mode.

To sum up, the construction site states are as follows:

0. The system is running in idle mode.
1. The construction site is being set up.
2. The construction site is on duty (with geometry).
3. The construction site is being dismantled.

In the initial state, warning messages (general roadworks warning) are disseminated to approaching vehicles using Decentralized Environmental Notification Messages (DENMs [37]) via ETSI-ITS-G5 [38] or C-V2X [39]. Besides short-range (V2X-) communication, the information can also be transmitted via the cellular network using Geo-Messaging [40] to make the information available to distant vehicles or those without dedicated V2X hardware. DENMs are transmitted periodically at a frequency of 1 Hz in all three states from setting up to system deactivation. Warnings in the first and third state do not differ regardless of the position of the road works in case the CV has moved in the meantime. In contrast, in the "in duty" state, the RSU transmits information about the construction site geometry inside the DENM À-La-Carte container. This information can be useful for future use cases in automated driving. In the second state, messages also include the positions of maintenance personnel. Once the system is deactivated, no further warning messages are sent.

By using the geometry of the construction site in the form of a polygon with the defined safety area and the position tracking of the maintenance personnel, it is possible to determine the moment when the maintenance personnel enters the safety area.

The warning conditions during the second state "construction site is in duty" are:

a. Maintenance personnel enters the safety area
b. Maintenance personnel enters the active traffic lane
c. The approaching vehicle enters the construction site

The first warning (a.) addresses the concerned maintenance personnel (the MPD) with an acoustic and visual alert. For this purpose, the MPD is equipped with an LED and a piezo buzzer facing toward the worker (see Figures 7, left, and 8, top right corner). The warning is sent via IEEE 802.11

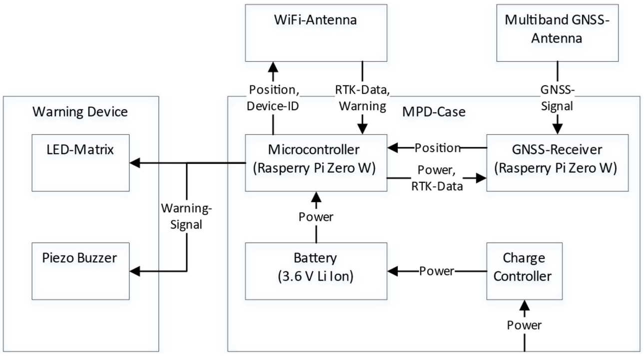

FIGURE 7. Block diagram of the MPD, for details see Figures 8 and 10.

FIGURE 8. MPD; left: attached to a vest; upper right: warning device; lower right: inside of the MPD: a) GNSS receiver; b) Microcontroller; c) battery and charge controller (see Figure 7).

from the construction site vehicle to the concerned worker. In addition, a DENM is generated and sent to approaching vehicles. The exact location of the maintenance personnel is set as the geographical position of the detected event (event position) inside the DENM. It is transmitted at a repetition rate of 10 Hz to update its position.

If a worker enters the active lane (b.), a warning is triggered similarly to the warning (a.). Only the Sub-Cause-Code of the DENM differs, so the approaching vehicle is warned that maintenance personnel are in their driving lane. When receiving the DENM, the approaching vehicle always displays the most dangerous situation. More safety-critical events, such as "maintenance personnel in the active lane," are given higher priority than the "construction site in duty" event.

The last warning condition is met when an approaching vehicle enters the construction site (c.). This situation is detected by evaluating incoming Cooperative Awareness Messages (CAMs [41]; ETSI-ITS-G5 or C-V2X) from passing connected vehicles. The CAMs are received and processed by the RSU. If the vehicle's position is within the construction site's geo area, the warning condition is met, and warning messages are sent. As a protection measure for the maintenance personnel, a broadcast warning is sent

TABLE 1. Warnings sent towards an approaching vehicle, including sub-cause-code, trigger, repetition interval, and the event position.

Description	Sub-Cause-Code	Trigger	Repetition Interval	Event Position
Construction site in duty (with geometry)	ShortTermStationaryRoadworks (4)	GMD sends geometry to CV	1 Hz	Position of the first cone
Maintenance personnel in the safety area	New definition (7)	Maintenance personnel enters the safety area	10 Hz	Position of maintenance personnel
Maintenance personnel in the active lane	New definition (8)	Maintenance personnel steps over the construction site area toward the roadway	10 Hz	Position of maintenance personnel
Vehicle in the construction site	New definition (9)	Vehicle drives into the construction site	10 Hz	Position of accident vehicle
Dismantling	Unavailable (0)	"Dismantling" mode button is pressed on CV-HMI	1 Hz	Position of CV

to all maintenance personnel, resulting in an acoustic and visual alert that differs from the first two by the flashing colors of the LED and a more aggressive sound. This is analogous to life, where an intruding vehicle triggers a flight reflex, either due to the sound of an impact or a shouting colleague.

Furthermore, the approaching traffic is warned via DENM that a vehicle is at the construction site. The vehicle system inside the construction site can also display a specific message on its HMI. On the receiver side, the distinction is made by comparing the station ID of the intruding vehicle. The station identifier is transmitted in the À-La-Carte container inside the DENM. Table 1 provides an overview of all the different DENMs being sent. The cause code is always 3 (Road Works Warning). The table shows the sub-cause codes, the trigger conditions, the event position, and the repetition interval. The warnings related to the different states (1./2./3.) are sent starting with the given trigger and ending with the trigger of the following state, while the warnings during the second state are sent as long as the respective condition is met.

In addition, in the In-duty-state the positions of the maintenance personnel are continuously distributed to approaching vehicles using Collective Perception Messages (CPM [42]). Highly automated vehicles can use this additional information to gain an comprehensive overview of the traffic situation.

To ensure that the MPD receives all warnings, the RSU continuously monitors all connected MPDs. If a device loses its connection to the RSU for more than one second (configurable parameter), it is marked as non-functional on the RSU. In parallel, the MPD also detects leaving the broadcast area. While a green light is displayed during regular operation, the irregular state is indicated by shining blue LEDs and short buzzer signals. As soon as the device re-enters the broadcast area, it will revert to regular operation mode, and the RSU will re-integrate the device into the system.

FIGURE 9. GMD; left and middle: detailed views; right: in usage.

IV. RESULTS

A. POSITIONING AND MEASUREMENTS

The MPD's current version is displayed in Figures 7 (block diagram) and 8. The MPD, along with the warning device, is attached to the front of a warning vest, while the antenna is placed at a suitable, exposed location. It is important to note the precise positioning of the antenna for optimal performance. The antenna is crucial for acquiring accurate position data. It must be positioned in an exposed location to ensure an unobstructed line of sight to as many GNSS satellites as possible.

On the other hand, the antenna must be positioned as close as possible to the center of the person wearing the device to avoid significant differences between its position and different edges of the maintenance personnel's body. To optimize the requirements, the ideal choice would be to mount the antenna on the construction worker's head. However, this is not possible as they are not wearing a hard hat. As demonstrated in Figure 10 (middle and right), a solution with the antenna positioned between the shoulders was deemed a reasonable trade-off. The GMD, depicted in Figure 9, has its antenna located on the opposite side of the pin. To determine the exact center position of the cone, align it with the center of the cones.

In the next step, we measure the accuracy and precision of the presented solution by determining the exact coordinates

FIGURE 10. Setup to measure accuracy and precision; upper left: GRP; lower left: GMD on GRP; middle: MPD over GRP; right: Detail on antenna/

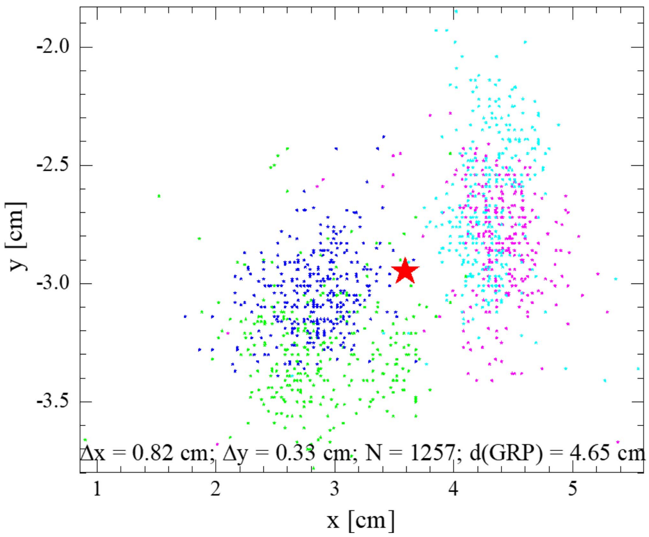

FIGURE 11. Results of GMD measurement; Δx and Δy: standard deviations in W-E and N-S direction; N: number of points: d(GRP): distance of mean (red star) to GRP.

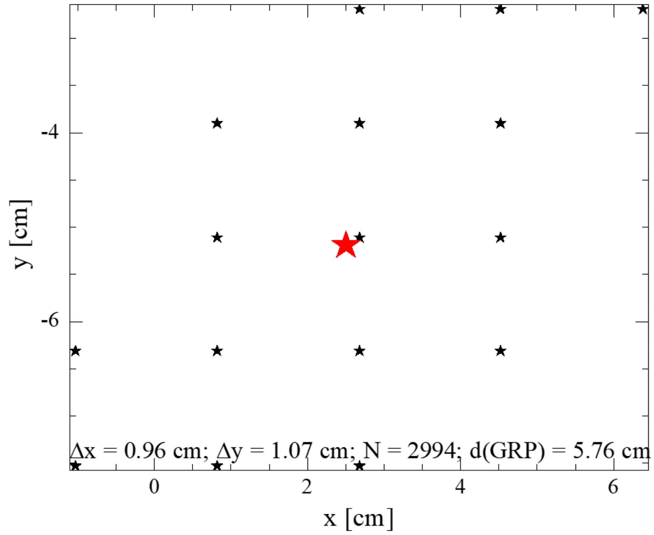

FIGURE 12. Results of MPD measurement; Δx and Δy: standard deviations in W-E and N-S direction; N: number of points; d(GRP): distance of mean (red star) to GRP.

of a Geographical Reference Point (GRP) located near the htw saar premises (refer to Figure 10, upper left).The Saarland regional authorities of surveying, geoinformation, and land development (referred to as the 'Landesamt für Vermessung, Geoinformation und Landentwicklung') provided the data used in the testing of both MPD and GMD against this GRP. The testing setup is illustrated in Figure 10.

Figure 11 displays the results obtained by placing a GMD precisely on the GRP (refer to Figure 10, lower left). The results were obtained through two measurements (represented by the dark blue and green dots in Fig. 11). The measurements took approximately five minutes and were taken for both light blue and purple (the latter being the second color). All measured positions are plotted within a 2 cm x 5 cm box, indicating a standard deviation of 0.33 cm in the north-south direction and 0.82 cm in the west-east direction. The mean of this measurement is only 4.65 cm away from the calculated reference point, demonstrating good accuracy.

Figure 12 displays the results of the MPD. The device was worn by an employee of htw saar (refer to Figure 10, right) and measured for approximately 5 minutes at the same reference point. The initial noticeable difference from the measurement of the The GMD presents a more discrete distribution of the measured values compared to the values sent to the construction site vehicle, which were already rounded for sending.

This is because the GMD uses the raw data. Another difference between the GMD and MPD is their frequency of measurement. The GMD does not require as frequent position measurements as the MPD. The GMD does not require as frequent position measurements as the MPD. The GMD does not require as frequent position measurements as the MPD. In this particular measurement, approximately ten times as many measuring points were recorded simultaneously compared to the GMD measurement.

In this case, the precision (standard deviation: N-S:1.07 cm; E-W: 0.96 cm) and accuracy (5.76 cm) are slightly worse than the results of the GMD. This may be due to the difficulty of standing completely still for 5 minutes without any movement. However, both precision and accuracy are within the range required for our system, so no further measurements were taken for the worn MPD.

B. INFORMATION AGGREGATION AND PROCESSING

Figure 13 to Figure 15 show examples of the calculation of the construction site. To achieve this, we set up simulated construction sites at the htw saar premises and measured them using our system. The htw saar site was chosen instead of a real construction site due to legal restrictions on flying drones over motorways. The yellow circles on the left side of each figure indicate the measured cones, while the calculated areas are displayed on the right. A mobile ITS Roadside Station with a functioning system was positioned between

(a) cone positions marked with yellow circles (b) calculated area based on cone positions

FIGURE 13. **Drone images of a simulated single-lane construction site.**

(a) cone positions marked with yellow circles (b) calculated area based on cone positions

FIGURE 14. **Drone images of a simulated multi-lane construction site.**

two cars in the parking lot to simulate a construction site vehicle. The red area describes the safety area, while the blue area marks the remaining working area. Figure 13 shows the sunny day use case of a single-lane construction site where all cones are placed in a row, which results in a straight construction site with the respective safety and working area.

Figure 14 shows a construction site extended to two lanes, while Figure 15 shows the case of an "erroneously" taken position within the construction site. It can be seen that while the former results in a step and widening of the construction site, the latter ignores the erroneously taken position and spans a construction site just without this cone position. At this point, it should be mentioned that this procedure of calculating the step using the perpendiculars of the lines between two cones has led to a particular error in the width of the areas at the step-diagonal. But as described, the angle between the direction of the construction site and the diagonal at the step is about 12°, which, with a given width of 90 cm of the safety area, results in an error of about 2 cm, as this width scales with the cosine of the mentioned angle. Regarding the errors occurring during position measurements, these errors in the area width are acceptable.

(a) cone positions marked with yellow circles (b) calculated area based on cone positions

FIGURE 15. **Drone images of a simulated single-lane construction site with a falsely recorded position.**

C. WARNING/DISSEMINIATION

Measurements were performed to prove the stability at the edge of the necessary communication range of the MPD. Therefore, the minimum distance between the RSU and the MPD was set to 200 m. The measurements were performed on public roads near the htw saar campus (see Figure 16; this time, the premises of htw saar were chosen instead of an actual construction site because the visited ones were much shorter than the targeted 200 m). The htw saar employee wore the MPD while standing still or moving slightly to avoid significant changes in distance during the measurement. This measurement aimed to demonstrate the packet loss at the maximum communication range over 120 s period with a message transmission frequency of 10 Hz. The experiment was conducted four times to ensure accuracy. The outcome is shown in Table 2, indicating a packet loss ranging between 1,64% and 0,08%.

During the field tests, the warning messages were distributed to the approaching vehicles, matching the respective

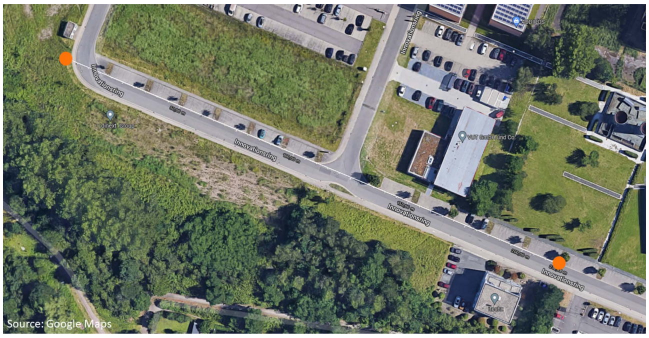

FIGURE 16. Measurements of the communication reliability between CV and MPD at htw saar premises.

TABLE 2. Results of reliability measurements.

#	Duration of measurement [s]	Received messages [#]	Received messages [%]
1	124.4	1240	99.60
2	124.1	1239	99.76
3	128.8	1288	99.92
4	128.2	1262	98.36

trigger conditions. The RSU in the CV detects the various events, generates the corresponding DENMs, and distributes them to approaching vehicles. Upon receiving the DENMs, the warnings are displayed on the HMIs of the connected vehicles. The warning advice informs the driver of the detected event type and distance. Since multiple events can co-occur simultaneously, the warning advice with the most safety-critical warning is always displayed. Figure 17 shows an example of a warning that appears in a vehicle approaching the safety area where maintenance personnel are present. The exact geometry was also distributed but not displayed, as it has no value for the driver, although it may be of interest for autonomous vehicles.

Furthermore, in our use cases, a relevance check logic is implemented on the receiving side to prevent the opposite traffic from processing messages that do not match their driving direction.

D. BOUNDARIES OF THE SYSTEM

The system has some minor limitations due to its prototypical nature and its main use case. As the main use case considered is on motorways, the localisation technology chosen was GNSS. This technology has obvious disadvantages when used in tunnels or in urban areas where there is not necessarily a clear view of the sky and satellite reception is poor. In these cases, complementary positioning techniques would be required. This is where the infrastructure-based techniques mentioned in chapter II become more interesting. In tunnels, for example, it is possible to have more anchor points for techniques such as UWB localisation or similar. These anchors can be placed at reasonable distances for triangulation/trilateration. The location of the anchors is easier to determine when they are mounted on a fixed structure, as it only needs to be measured once. This is in contrast to anchors mounted on a vehicle. With a small increase in the accuracy of these technologies, they will become reasonable alternatives for the edge cases mentioned above, such as tunnels or dense urban areas. Especially in urban areas, the use of next-generation cellular radio (5G/6G) could be considered, as base station densities are increasing, frequencies are increasing, and new technologies such as ICAS/JCAS [43] are being developed.

FIGURE 17. Example of an HMI warning inside an approaching vehicle.

Another aspect that could be improved, mainly because of its prototypical nature, is the alerting of maintenance personnel. In an environment with a lot of noise, changing lights, etc., it is difficult to provide a reliable warning using an external device. This problem could be minimized by integrating the system into the workwear, e.g., by incorporating loudspeakers into the hearing protection or by sewing flashing/vibrating devices into the clothing. These measures would probably also increase acceptance of the system, but were outside the scope of this work.

V. CONCLUSION/OUTLOOK

With advanced and inexpensive RTK-GNSS technology and corresponding algorithms, it is feasible to precisely and accurately determine the geometry of a construction site and the location of maintenance personnel. This enables identification of critical situations and taking appropriate measures to distribute the information to the relevant road users and maintenance personnel, resulting in generating appropriate warnings. The initial field tests yielded positive feedback from maintenance personnel working at actual construction sites, however, additional long-term studies are necessary to determine the overall system stability, particularly in regards to the reliability of warnings and to maintain a low false positive rate. One apparent weakness of the system is that GNSS is ineffective in tunnels or under bridges. To address this issue, additional localization techniques that do not require a clear line of sight to the sky are necessary. The maintenance personnel device must also be further miniaturized or even integrated into everyday workwear to improve acceptance. Furthermore, the introduction of additional sub-cause codes for disseminated V2X warnings to distinguish between different severity levels has proven effective and should be consolidated into the respective standards. Our system enhances the communication of connected vehicles by expanding the use case for stationary short-term roadworks with additional details regarding maintenance personnel. We have created new codes that provide construction site warnings with increased information value, deviating from the existing standardized cause and sub-cause codes. The system has issued alerts for maintenance personnel in the safety zone, maintenance personnel in the active lane, and intruding vehicles within the construction zone. Also, aiming to integrate into existing systems, such as C-ROADS, is necessary to avoid the creation of too many independent systems. Integrating the appropriate technical components into the construction vehicles of the worksite should be a priority to automate the activation of various worksite states, leading to greater reliability and acceptance. Another aspect addressed in this study is the provision of precise and dependable information regarding the dimensions and layout of the construction site for automated vehicles, in particular to know where the end of the site is, thus improving traffic flow.

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