Cloud and edge computing to enable map overlays for the digitalization of construction sites

Valentin Resapow[1], Jan Stührenberg[1], Michael Schwall[2], Carlos Chillón Geck[1], Kay Smarsly[1]
[1]Hamburg University of Technology, Germany
[2]Volvo Construction Equipment GmbH, Germany
jan.stuehrenberg@tuhh.de

Abstract. Construction sites are typically characterized by inherent complexity, unstructured environments, dynamic changes, and susceptibility to environmental factors. Previous efforts to visualize events and processes at construction sites have been hampered by the absence of appropriate digital site representations. While virtual reality has received a lot of attention for visualizing construction sites, the integration of real-time information has rarely been explored. This study aims to integrate the cloud and edge computing paradigms to generate real-time map overlays of sites. The map overlays are updated by data collected from sensors mounted on machines operating on the construction site. Different overlays deployed to improve sustainability, safety, and efficiency are implemented and validated at the Volvo Construction Equipment GmbH test facility in Konz, Germany. The results show that the cloud and edge computing paradigms and the map overlays provide a solid foundation for real-time visualization and digitalization of construction sites.

1. Introduction

While the digitalization of construction sites is progressing, the construction machine industry is undergoing significant transformations, shifting from traditional business models, focusing on selling machines, to business models that stronger emphasize on providing data-driven services along with products (Roland Berger, 2016). One important enabler for the transformations is the increasing use of sensors equipped to construction machines, allowing to perceive and to digitalize the world around the construction machines (Jiang & He, 2020). Sensors, such as global navigation satellite system (GNSS) modules, video cameras, inertial measurement units, radio detection and ranging modules, and light detection and ranging modules, enable recording valuable perception data, i.e. data to be used for positioning, object detection, and mapping of the environment.

Another crucial differentiator in the construction machine industry is the collaborative work of construction machines. Collaboration requires machines with different skill sets to perform complex processes at a construction site (Abderrahim et. al., 2005). Taking a quarry operation as an example, an excavator loads a truck, the truck transports and dumps the load, and a wheel loader picks the load and fills it into a crusher. The collaborative work implies a strong correlation between the data perceived by the machines. Site process management can benefit from the consolidated perception data and centralized monitoring and steering systems.

Although the sensors installed on construction machines are able to generate large amounts of perception data, the construction machine industry currently falls short in collecting and further processing perception data (Jiang & He, 2020). Perception data is primarily used for on-board functionalities, such as driver assistance or safety features. One reason collecting and further processing of perception data is hindered is the absence of information technology (IT) infrastructure that provides communication networks and processing capabilities (Dave et. al., 2016). Since construction sites vary in size and topology, and construction machines are considered mobile off-road equipment, efficient wireless communication solutions are needed to meet high bandwidth and low latency requirements for machine-to-infrastructure communication. The perception data collected from the machines undergoes several processing steps that require high computational power in backend systems: filtering, correlation, conditioning and visualization. Previous efforts toward visualizing events and processes have been limited by a lack of digital representations of site information (Dave et. al., 2016). Therefore, there is a need to bridge the communication gap between construction machines and IT infrastructure to unlock the full capability of the perception data collected by construction machines.

The evolution of IT infrastructure is visible in various industries, particularly in industries deploying smart electronic devices. The trend toward centralized computing allows information from individual devices to be combined, resulting in reduced costs and increased capabilities and functionality. While focus has been laid on cloud computing initially, recent studies have highlighted the benefits of integrated approaches adding fog and edge computing. Multi-layered architectures using cloud, fog, and edge computing offer benefits, such as low latency and cost efficiency (Kalyani & Collier, 2021). The integration of the three computing paradigms has proven useful across various industrial sectors, such as smart cities (Syed et. al. 2021), industrial production (Liao et. al., 2018) and smart agriculture (Kalyani & Collier, 2021). Although the computing paradigms are already widely used in many domains, the paradigms are still in the early stages of adoption in the construction machine industry (Kochovski & Stankovski, 2021).

The IT infrastructure proposed in this study is based on the edge and cloud computing paradigms known from Internet of Things (IoT) technologies. The edge layer brings computational resources physically closer to the source of data, in this scenario, to the construction site. The edge layer allows fast data transmission and processing since communication shortcomings with cloud servers are avoided. Therefore, an edge server is placed at the construction site. A wireless communication system allows to transmit the perception data between the machines and the edge server with high bandwidth and low latency. The edge server handles computationally intensive and time-critical tasks, such as object detection and classification, and sends the computing results to the cloud for post-processing and visualization. Site operators utilize clients to access the data in the cloud.

Furthermore, in this study, the cloud and edge computing paradigms are coupled to generate real-time map overlays of construction sites. Perception data collected from the machines operating at construction sites is processed to feed and update map overlays. Different map overlays, deployed to improve sustainability, safety and efficiency, are implemented and validated at the Volvo Construction Equipment GmbH test facility in Konz, Germany. The remainder of the paper is organized as follows. In Section 2, the methodology and implementation of the cloud and edge computing paradigms for map overlays is described. Section 3 covers the validation tests and results, and Section 4 summarizes and concludes the paper.

2. Cloud and edge computing paradigms to enable map overlays

In this study, the edge and cloud computing paradigms are adopted and implemented for real-time visualization of construction sites. Cloud computing is defined as “an on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction” (Mell & Grance, 2021). While cloud computing offers flexibility, scalability, and efficiency for users and providers, it requires reliable and high bandwidth communication networks, which may be an issue in areas with limited connectivity, particularly relevant to construction sites due to their size and varying topology. Latency in transferring data to and from remote servers may affect the performance of mission-critical applications. In addition, storing data in remote locations poses security risks, particularly when the data crosses national borders. Consequently, edge computing is an evolving computing paradigm that addresses the shortcomings of cloud computing. A fundamental difference between edge and cloud computing is the location of the layers. Placing storage and computing at the edge layer of a network significantly reduces latency (Khan et al., 2019), which is relevant for time- and security-critical processes, enables local data storage, and minimizes the risk of data attacks during transmission (Wang et al., 2018). In this section, the utilization of the edge and cloud computing paradigms for the digitalization of construction sites is described. A system architecture, including an edge server located at a construction site and edge nodes mounted on construction machines, is proposed. Finally, the generation of real-time map overlays, facilitating the edge and cloud computing architecture, is covered, and examples with signal strength and person detection map overlays are provided.

2.1 System architecture

The system architecture of the edge and cloud infrastructure on site is shown in Figure 1. The architecture builds upon the Robot Operating System 2 (ROS 2) framework (Macenski et. al., 2022), which employs the data distribution service (DDS) for data transmission (Pardo-Castellote, 2003). The DDS uses a publish-subscribe pattern with configurable quality of service settings and is suitable for real-time and industrial applications, even under challenging network conditions. Furthermore, the DDS provides a unified API across programming languages, facilitating data exchange across platforms while handling low-level operations, such as data format, discovery, and connections.

The edge server is installed in a mobile radio tower along with a network switch, a long-term evolution (LTE) router, and three Wi-Fi 6 access points mounted on top. The edge server uses two databases, (i) a non-relational database (MongoDB) for machine information and authentication and (ii) a time-series database (InfluxDB) for storing perception data. Multiple ROS 2 nodes run on the edge server to handle the perception data. In addition to the databases and the ROS 2 nodes, the edge server hosts various web servers and clients, including TCP clients. A Flask web server is hosted for visualizing data in the form of map overlays. The edge server runs advanced neural network models for specialized tasks, such as object recognition for the creation of person detection map overlays.

A digital connection of the edge server to edge nodes, which correspond to on-board units mounted on construction machines, is established through a wireless local area network on site that is designed for high-bandwidth and low-latency communication. The on-board unit contains an embedded Linux PC, equipped with a controller area network (CAN) adapter and a network switch supporting power over ethernet (PoE). In addition, the on-board unit includes a GNSS antenna and a Wi-Fi 6 transceiver, and it is connected to a stereo camera. The embedded Linux PC running a real-time operating system runs ROS 2 nodes to pre-process the data collected by the sensors for tasks such as signal strength recording. The pre-processed data is sent to the edge server via the Wi-Fi 6 network.

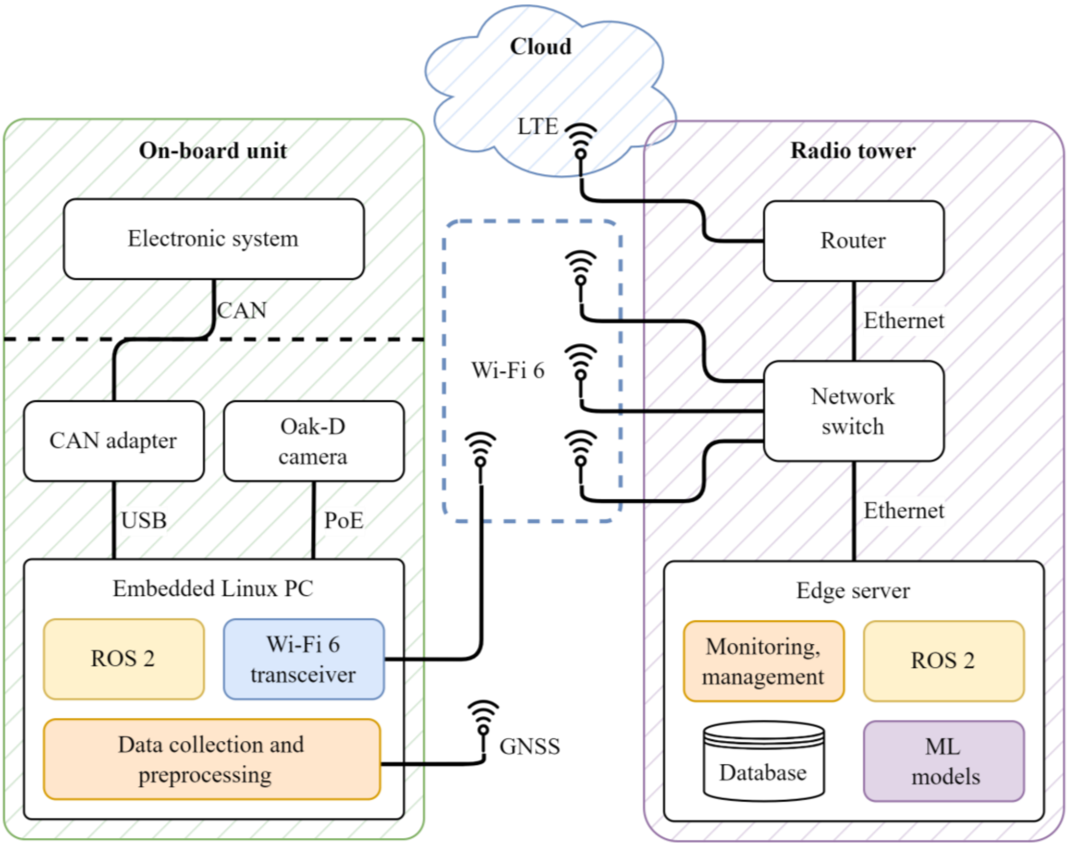

Figure 1: System architecture of the IT infrastructure on site

The on-board units are compact, box-shaped devices used for rapid prototyping purposes. The design of the on-board units enables retrofitting on any construction machine and enables seamless communication with the edge server. The on-board units offer several interfaces to attach sensors, such as depth cameras. The edge server and a construction machine equipped with an on-board unit are shown in Figure 2.

Figure 2: Radio tower with edge server (left) and construction machine with an on-board unit (right)

2.2 Map overlays

Building upon the IT infrastructure, the edge server compiles perception data collected from the construction machines to visualize location-dependent information in map overlays. The overlays support site management by providing intuitive representations of events and processes on site. The map overlays are designed as two-dimensional, discretized maps consisting of square cells covering the construction site. The size of the cells can be chosen to provide a reasonable balance between data resolution, storage requirements, and intuitiveness. The map overlays contain geospatial data and visualize perception data across the construction site. Each cell in a map overlay represents a sensor reading taken at a specific geographic location. To align the geospatial data with satellite images or topographical maps, the latitude and longitude coordinates are converted to orthogonal grids using the Universal Transverse Mercator (UTM) coordinate system. The Flask framework serves as the backbone for running a web interface that hosts the map overlays. The web interface employs Leaflet, an open-source JavaScript library, to create interactive map overlays. Leaflet allows the addition of various elements to the map overlays, such as pop-ups and custom images. Map overlays are saved as Portable Network Graphics (PNG) images, where the pixel size of the image corresponds to the cell size of the map overlay. In this study, the map overlays consist of cells of 1 m². The PNG images employ the RGBA format, where the color channels encode the perception data, and the alpha channel controls the opacity. If no perception data exists for a particular area, the alpha channel is set to zero, rendering the cell of the map overlay transparent.

To demonstrate the potential and adaptability of the concept proposed in this study, two different map overlays are implemented. The map overlays include a heat map to assess the quality of the wireless communication network and a visualization of people near construction machines on site. Both use cases illustrate the usefulness and versatility of the map overlay methodology for different practical applications in construction sites. An overview of the map overlay concept and the map overlays implemented in this study are given in Figure 3. The following subsections describe the implementation of the signal strength map overlay and the person detection overlay.

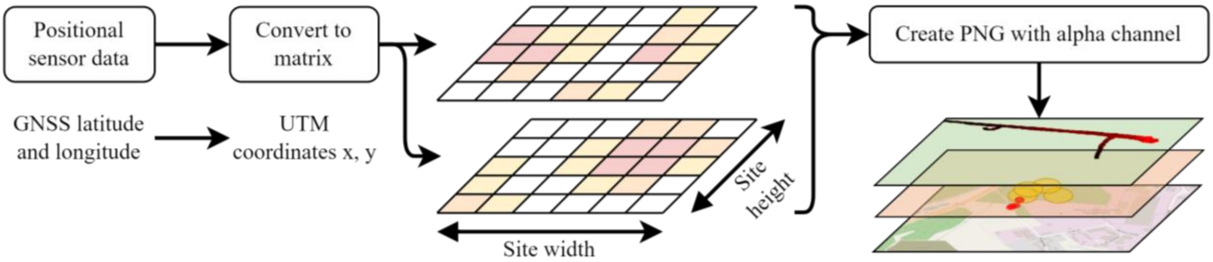

Figure 3: Map overlay concept

Signal strength map overlay

The signal strength map overlay is developed to assess the quality of the wireless communication network, which is crucial for construction machines to communicate with the edge server. Figure 4 shows the signal strength data collection pipeline. The `iwconfig` command-line interface tool collects signal parameters from the Wi-Fi 6 module. A ROS 2 node publishes the parameters including the received signal strength indicator (RSSI) value, the extended service set identifier for identifying the access point, and the transmission frequency using a custom created ROS 2 message. Data collected by the GNSS module is published using the *NavSatFix* ROS 2 message. The edge server subscribes to the Wi-Fi 6 and GNSS topics, relates the Wi-Fi 6 signal parameters to geographic locations in the UTM coordinate system using the GNSS data, and saves the geospatial Wi-Fi 6 signal parameters in a database hosted on the edge server using the *InfluxDBClient* Python API. The geospatial signal strength data stored in the Influx database is displayed in a map overlay. The map overlay is updated upon new data input to the Influx database to provide real-time visualization of the signal strength data in a heat map.

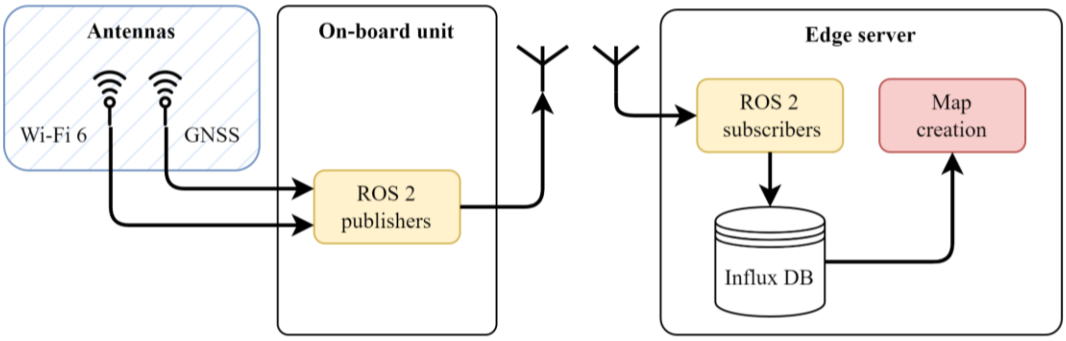

Figure 4: Data collection and processing pipeline for the signal strength map overlay

Person detection map overlay

The person detection map overlay acts as a warning system to alert operators of construction machines to persons in the vicinity of the construction machine for safety reasons. The person detection pipeline is depicted in Figure 5. In this study, the *OAK-D Pro PoE* depth camera is used for person detection (Luxonis, 2022). The depth camera records an RGB video stream and calculates depth information from two monocular video streams. Both the RGB video stream and the depth video stream are compressed to save bandwidth and sent from the on-board unit to the edge server via the Wi-Fi 6 network. The edge server receives the RGB and depth video streams and performs person detection using the state-of-the-art You Only Look Once (YOLO) object detection system (Redmon, 2016) on the RGB video stream. In this study, the latest YOLOv8x model, which provides high detection accuracy, is employed. Upon person detection in the RGB video stream, the coordinates of the bounding boxes around detected persons are used to look up the distance to the persons in the depth video stream and to calculate relative poses from the depth camera to the persons. The relative pose data is stored in the Influx database.

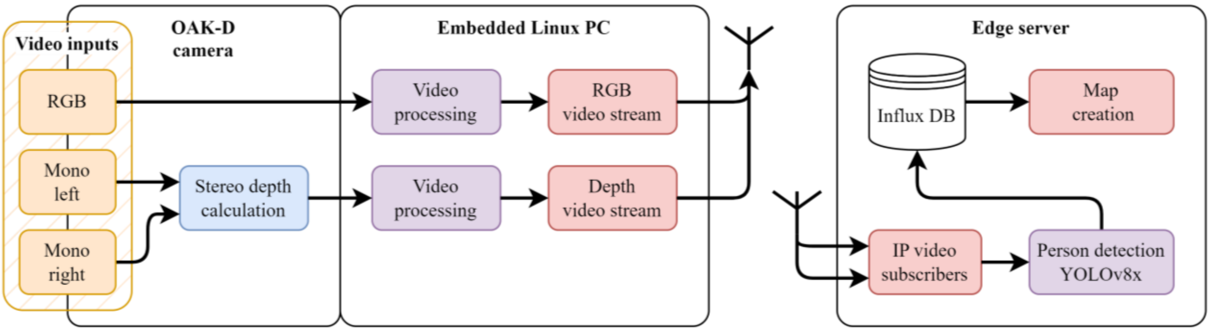

Figure 5: Data collection and processing pipeline for the person detection map overlay

As with the signal strength pipeline, GNSS data is used to transform the information on detected persons to UTM coordinates. The person detection is visualized in a map overlay by placing circles using the Leaflet library. The color and size of the circles are adjusted to highlight the distances to persons detected, and the opacity decreases with time to account for outdated detections, as depicted in Figure 6. The visualization provides an intuitive system for estimating the distance and risk level of persons detected in the vicinity of construction machines.

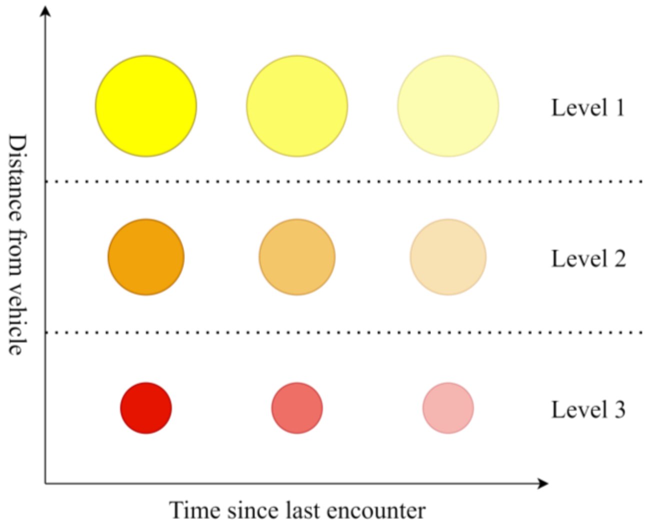

Figure 6: Markers to highlight risk levels in the person detection map overlay

3. Validation and results

This section describes the field tests conducted to validate the signal strength and person detection map overlay pipelines. The validation tests are devised to evaluate the IT infrastructure based on the edge and cloud computing paradigms for creating the map overlays, including assessing the signal strength on site and the accuracy of the person detection. The validation tests are conducted at the Volvo Construction Equipment GmbH site in Konz, Germany, as shown in Figure 7. The test site measures 350 m by 170 m and includes different terrains, such as flat land, sandy areas, and hills. The radio tower, including the edge server, is placed in a central location on site.

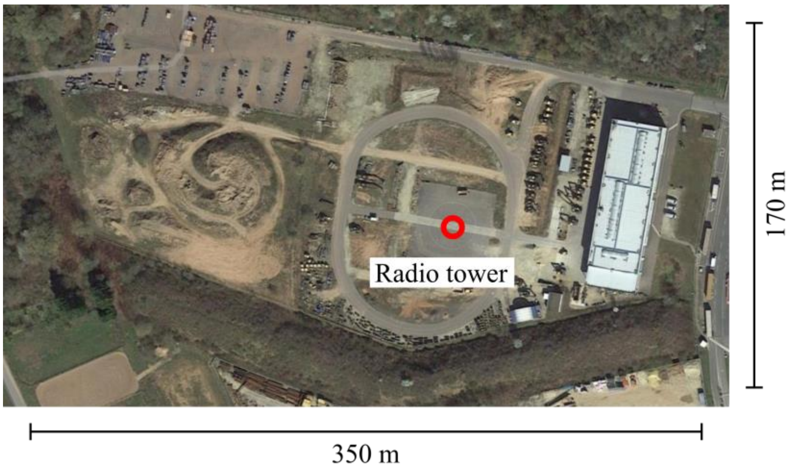

Figure 7: Volvo Construction Equipment GmbH site in Konz

The on-board unit is attached to the cabin roof of a loader. An operator drives the loader following a predefined route on the test site. The GNSS and Wi-Fi 6 signal parameter data are transmitted to the edge server, where the data is stored, and the map overlay is created. The resulting signal strength map overlay is shown in Figure 8.

Figure 8: Results of the signal strength test displayed in the signal strength map overlay

The RSSI value decreases with increasing distance to the radio tower with the edge server. By placing the radio tower in the center of the test site, sufficient quality of the wireless communication network is ensured. The reliability and accuracy of the person detection pipeline is evaluated under different ambient and lighting conditions, including daylight, twilight, darkness, and lighting from construction machines from different angles. An example of a person detected in the RGB video stream of the depth camera and visualized in the person detection map overlay is shown in Figure 9.

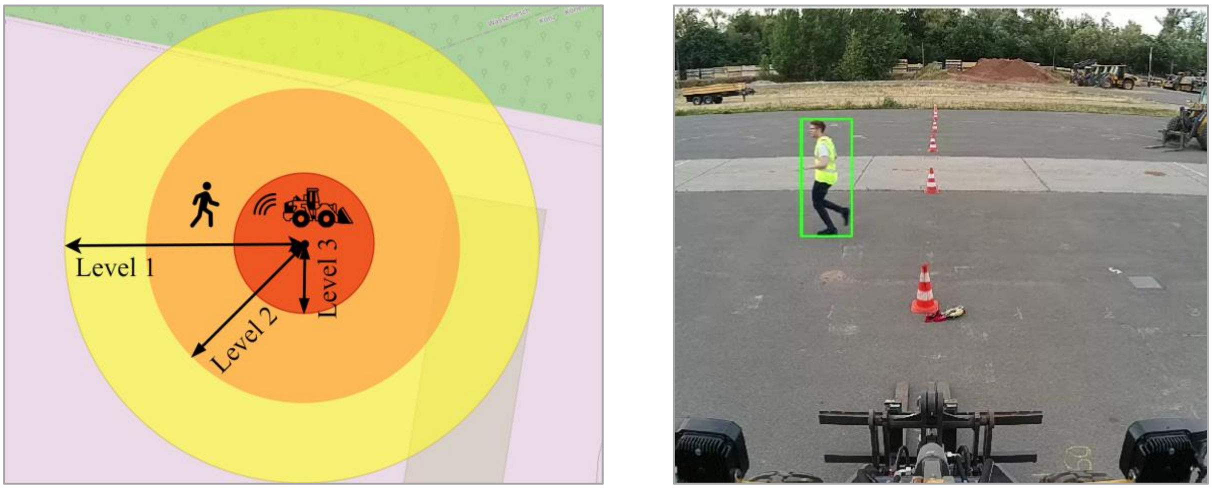

Figure 9: Person detection map overlay (left) displaying warnings due to a person detected in the RGB video stream (right)

The validation tests for the person detection show a maximum person detection distance of approximately 30 m. Wearing a safety vest slightly improves the detection accuracy. The detection accuracy is reduced in darkness. Vehicle lighting, both from front and back, generally improves detection accuracy. Overall, the person detection performs reliably, with a few misclassifications under difficult lighting conditions.

4. Summary and conclusions

The absence of suitable IT infrastructure on construction sites has prevented the use of perception data for real-time visualization and digitalization. In this study, the edge and cloud computing paradigms have been adopted to establish an IT infrastructure on site. On-board units mounted on construction machines pre-process perception data collected by sensors and send the data, via a wireless local area network, to an edge server located in a radio tower. The edge server collects, processes, and stores the perception data, and it generates map overlays. In this study, a signal strength map overlay and a person detection map overlay have been created. The map overlays can be accessed from the cloud and provide real-time information on the construction site.

Real-world experiments at the Volvo Construction Equipment GmbH test facility demonstrate the suitability of the cloud and edge paradigms and the map overlays for the foundation of digitalized construction sites. The signal strength map overlay effectively visualizes the network quality on site. The person detection processed in the edge server achieves high detection accuracy. The person detection map overlay provides an intuitive visualization of the risk of persons in the vicinity of construction machines.

In conclusion, the edge layer provides high bandwidth and low latency connections, which is required for mission-critical information, such as safety-related information. The cloud layer enables stakeholders and site managers to access the map overlays for an up-to-date visualization of construction sites, without having to be physically present to make high-level decisions. It can be concluded that the IT infrastructure presented in this study lays the foundation for a digitalized construction site enabling real-time visualization. Future work may address the generation of additional map overlays for other applications to visualize construction site events and processes. Furthermore, the number of construction machines may be increased to test the bandwidth and latency of the wireless local area network with higher network traffic.

Acknowledgments

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