





Continuous monitoring of construction sites using mobile machinery - a case study

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Abstract: Regularly monitoring construction sites is essential for progress tracking and safety evaluation during a construction project. Conventional methods rely on periodic surveys and manual data collection through site personnel. Additionally, current research investigates the use of unmanned ground/aerial vehicles. However, both approaches present limitations, such as time and labor inefficiency, or unreliable navigation and susceptibility to harsh outdoor conditions. In this paper, we present a novel approach for site monitoring by augmenting mobile construction machinery with sensors and leveraging their mobility onsite. To validate this approach, a wheel loader was equipped with a setup consisting of LiDAR, Camera, and GNSS sensors and deployed it over multiple months during a real road construction project. This paper analyzes the setup's performance during outdoor operation and the quality of the collected data for the implementation of automated and continuous mapping. Afterward, the encountered challenges and advantages of our approach are discussed. The results demonstrate the feasibility of using mobile machinery for this task and are a first step for an automated site monitoring system.

Keywords: outdoor monitoring, construction site, mobile machinery, LiDAR, automation



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1 Introduction

Monitoring the state of a construction site is an integral process of every construction project. Time and resource management, quality control, and safety evaluation are directly dependent on the employed monitoring methods, as they require information about what is done onsite, when and by whom. Conventional monitoring is mostly achieved through periodic reports by the foreman and more extensive bi-weekly to monthly visits to the site. Important observations are noted on a site plan, supported by comments and photographs. This approach is time-inefficient, relies almost entirely on frequent manual labor, and is error-prone due to its subjective nature [1]. Moreover, such documentation tends to come from different sources and in different formats, making it more difficult to analyze and manage it [2]. These issues are being tackled by the current trend of automated data collection via unmanned aerial or unmanned ground vehicles (UAV/UGV), which, however, has

barriers of its own [3], [4]. One important issue is robust navigation in the dynamic, rough and often unstructured environments of construction sites. Moreover, unmanned vehicles must avoid collisions or obstructions of workers and machines.

In comparison, mobile machinery (e.g. a wheel loader) already constantly traverses the construction site and operates near areas where construction is actively taking place. Equipping it with sensors normally used with UGVs results in a mobile mapping system (MMS) that operates "autonomously", as it does not require additional personnel to control the vehicle apart from the already employed machine operator. This paper explores this approach of automated site monitoring by first presenting the design and deployment of a demonstrator on a real construction site, and then analysing the gathered monitoring data and discussing the strengths and weaknesses of this approach.

2 Related works

MMSs are used in several domains for automatically obtaining updated and accurate geospatial data. Some of the domains where MMSs have been extensively utilized include road asset management and condition assessment, Building Information Modeling for archaeological reconstruction and transportation infrastructure analysis, emergency and disaster response, riverine vegetation mapping and detection, tree detection and measurement and digital heritage conservation [5].

On construction sites, UAVs are often the choice for a MMS and are mainly used for inspection and surveying [3]. An example for real-time reconstruction of a construction site was demonstrated by Shang and Shen [6] by using Visual Simultaneous Location and Mapping (SLAM). Since UAVs normally need an operator and are susceptible to bad weather, there is a trend to combine them with UGVs for better results. The general idea is to use the UAV's aerial view of the scene to provide the UGV with a clearer understanding of its surroundings and allow for robust navigation. This strategy was implemented, for example, by Kim et. al. [7] for an outdoor environment and by Asad et. al. [8] for an indoor environment, respectively. Other methods are extensively described by Rao et al. [9], however, almost all identified use cases for monitoring dynamic environments used stationary sensor setups. Only two examples mention mobile sensors setups—one on a car for earthwork monitoring and another on a crane for safety monitoring of crane operation.

Typical sensors used in MMSs are light detection and ranging (LiDAR) and high-resolution cameras for data acquisition of objects and areas of interest, as well as global navigation satellite system (GNSS) and inertial measurement unit (IMU) for positioning and georeferencing. However, there is no single, standardized MMS setup that is widely adopted because the selection of sensors depends on several use case specific factors such as budget, sensor availability, scene contents, processing strategies and accessible platforms for the MMS mounting [5].

3 System design

3.1 Physical setup

For this study, a wheel loader was equipped with a setup of different sensors, shown in Figure 1. It consists of a monocular webcam at the front, four LiDARs (*Ouster OS1-64*, two *Velodyne VLP-16* and *Blickfeld Cube 1*) pointing in different directions and a *GNSS receiver*. This selection was motivated

by the availability of the sensors to the authors. As shown on the top left in Figure 1, the sensors and a control cabinet, that houses the hardware infrastructure, were mounted on a rack consisting of aluminum profiles. This allows the entire setup to be pre-assembled, tested and initially calibrated. All sensors, the switch cabinet and its cable glands had an ingress protection rating of at least IP66. The whole setup was then installed on the roof of a wheel loader, as shown on the bottom left in Figure 1. Consequently, operations on the construction site only had to be interrupted for a short time. The mobility and versatility of a wheel loader on-site motivated its choice for this study. The chosen machine was a CAT 908M provided by the construction company working on the site. Apart from possibly different mounting techniques and positions of the sensors, this setup can be adapted to different models and even types of construction machines.

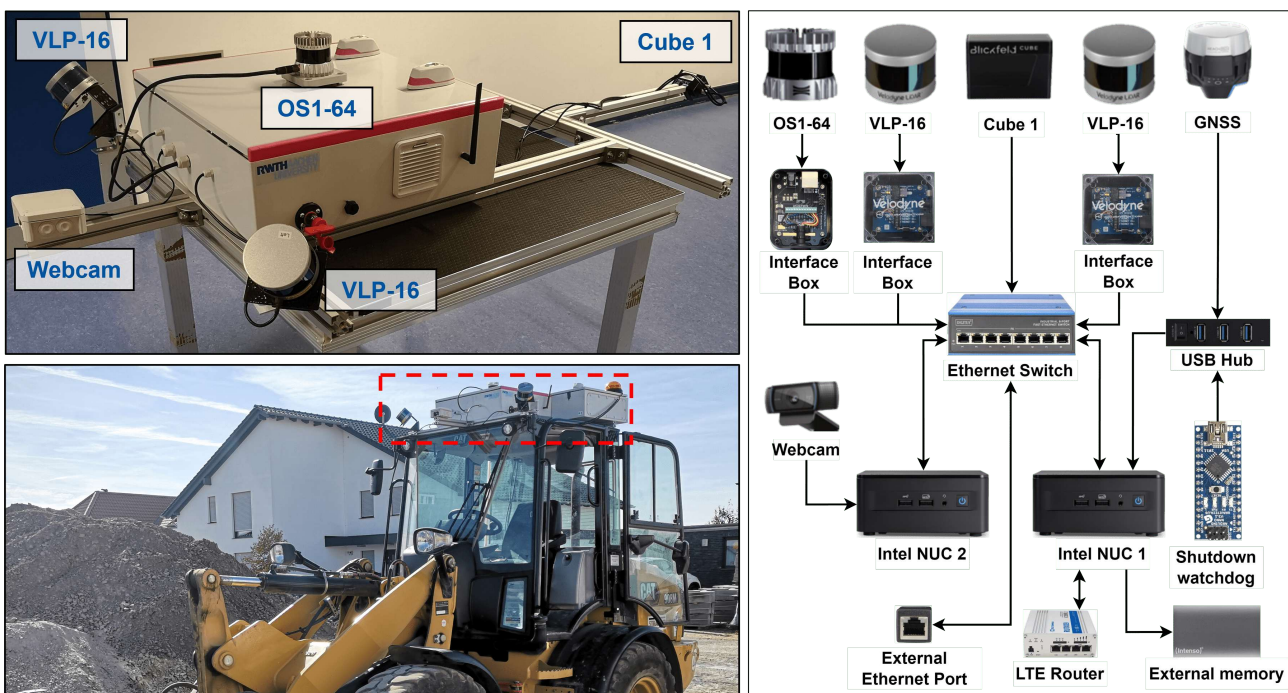


Figure 1: Top left: Sensor setup with positions of visible sensors. The GNSS receiver is inside the switch cabinet. Bottom left: Sensor setup mounted on the wheel loader¹. Right: Schematic structure of sensor setup.

The right side of Figure 1 shows the internal architecture of the setup. It was connected to the 12 V battery of the wheel loader. One exception is the shutdown watchdog, which is connected to both ignition and continuous plus to detect when the wheel loader is turned off to safely power down the sensor system and prevent unwanted power drainage. Electrical components such as voltage converters or fuses are left out of the diagram for better readability.

3.2 Software setup

Minimizing interference with usual processes during active construction was an important design goal of the measurement system. To achieve this, easy on-site and remote access to the actual software

¹An additional switch cabinet can be seen. Its only function was to store the rather expensive sensors during longer downtimes, such as winter break, as the particular site didn't offer any security measures against vandalism or theft.

stack was implemented. Additionally, the system was programmed robustly, so short issues during a recording did not corrupt the whole file.

The implemented software stack is based on *Ubuntu 22.04* with *ROS2 iron* running on two *Intel NUCs*, distributing the workload between them. The communication between the NUCs, as well as several sensors, was done via an Ethernet network (see Figure 1). An external RJ45 jack and a bridged Wi-Fi Hotspot from one of the NUCs granted access to this network. Everything was saved to two solid-state drives (SSDs) connected to the system via *USB3*. To automatically distribute the recordings across both drives, *MergerFS*² was used. It combined both SSDs into one large drive by distributing the files evenly between them. The new and flexible standard *MCAP* was chosen as the format for the recordings. In order to upload the recordings to a storage system for further processing, the drives were exchanged regularly, circa every two weeks.

The load of recording was shared between both NUCs. While the first mainly managed the LiDAR sensors, GNSS, and the actual recording, the second NUC was responsible for the camera input and image compression. Every ROS component was configured to be part of the system auto-start via *systemd*, as well as the trigger for recording using *ROS bags*. By distributing everything to its own process, managed by *systemd*, a failure in one part of the system was not cascaded to another part, and the rest of the data remained usable. Additionally, a service was implemented to monitor the LiDAR data to trigger a restart of the drivers and sensors in case they stopped sending data. To facilitate a clean shutdown, the ignition of the wheel loader is monitored by the shutdown watchdog. If the ignition is turned off for a certain duration, both NUCs individually trigger a shutdown, resulting in a clean recording stop. In case this did not work, there was a safety relay in front of the complete system, which cuts power to everything after 3 min, to avoid draining the battery and causing problems for the actual construction work.

As the system is intended to run without regular involvement, a remote monitoring functionality was added. This included a remote accessing tool as well as regular notifications that e.g. reported startup times or current drive usage to better plan the next drive change. A remote monitoring tool was used to provide *ssh* access to the running system to inspect and resolve possible problems. The internet connection was provided through a USB LTE Modem connected to one of the NUCs. The internet was bridged into the local network as well, allowing the GNSS to download Real-Time Kinematic correction data from a Satellite Positioning Service³, so it could work independently of any locally setup reference point.

4 Experiments

The setup was mounted on a wheel loader for several months to validate the proposed approach and investigate the resulting coverage of the construction site. The selected site is a final road construction project with an area of approximately 16000 m² and a house stock of 80 %. The sensor setup stayed on the machine from September 2023 until May 2024, experiencing different challenging weather conditions. During this time, data was collected on 75 full workdays. The setup turned itself on only when the wheel loader started operating. This results on average in nine individual measurements per

²<https://github.com/trapexit/mergerfs>

³<https://sapos.de>

day with an average duration of 153 min (min. 3 min, max. 300 min). A standard deviation of 71 min reflects the fluctuations in operational times.

Figure 2 shows a synchronized example of the three main data types collected with the described setup. The top left pane displays the camera image, oriented towards the wheel loader's shovel, providing a direct view of the materials being handled by the machine. The bottom left map shows the GPS signal over time, with the specific point in time indicated by a darker dot in the map. Finally, the right pane shows a 3D view of the four LiDAR sensors used, with the machine's direction of view depicted as a red arrow. The gravel pile visible on the right side of the camera image can also be recognized in blue within the point clouds, slightly further in the direction of view. Some house fronts and multiple containers can be seen on the left of the machine. The OS1-64, positioned on top, covers the mid to long-range environment displayed here with dark blue points. Both VLP-16 sensors complement it with measurements directly around the wheel loader. The left sensor is displayed in orange and the right one in green. The Cube 1 at the rear is dedicated to measuring the space behind the machine, with its points concentrated in a small area behind the machine. The acquired LiDAR

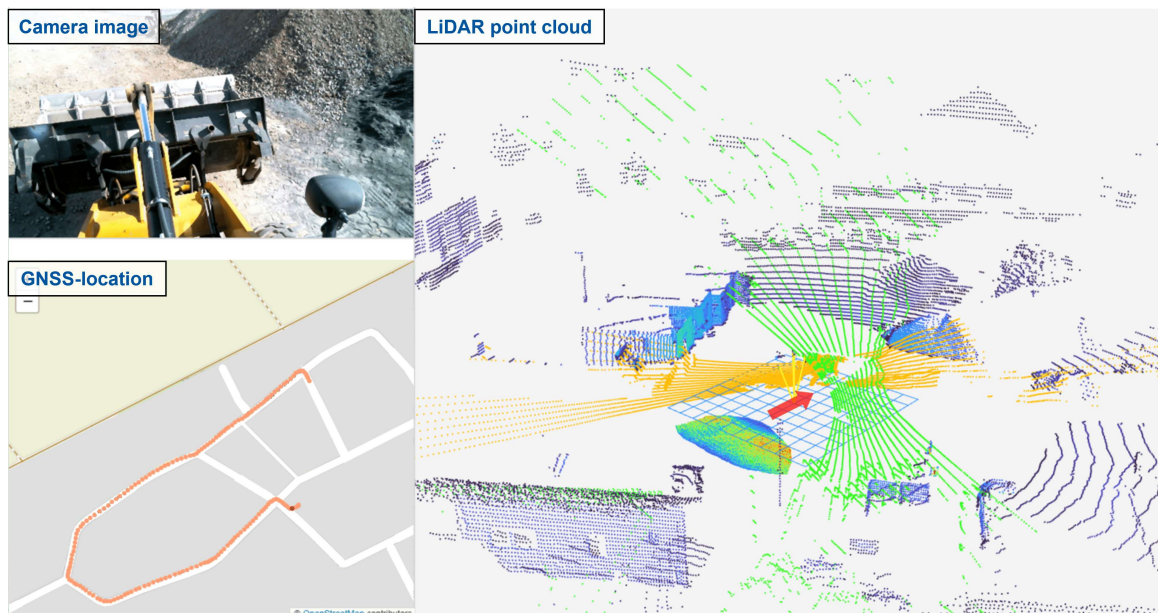


Figure 2: Visualization example of the collected data: Camera images (top left), GPS coordinates (bottom left), and LiDAR point clouds (right). These are shown at the same point in time. The red arrow symbolizes the direction the machine is facing.

scans were assembled into point clouds of the environment using a SLAM-based algorithm⁴ as the first iteration of data processing. A visual examination of the recordings showed good quality of the dataset. Figure 3 illustrates the successful recreation of the construction site environment. The left and right sub-figures depict the same location several days apart, with clearly noticeable changes to the site. In the top right quadrants, a short wall and an earth heap were removed, the area leveled, and an outline for future construction created. Additionally, multiple palettes with stones and some barriers were moved during pavement work, as seen on the left sides of the sub-figures. This exemplifies the

⁴https://github.com/rsasaki0109/lidarslam_ros2

usability of the data for automatic and continuous mapping. Further iterations of the processing will also include images from the camera.

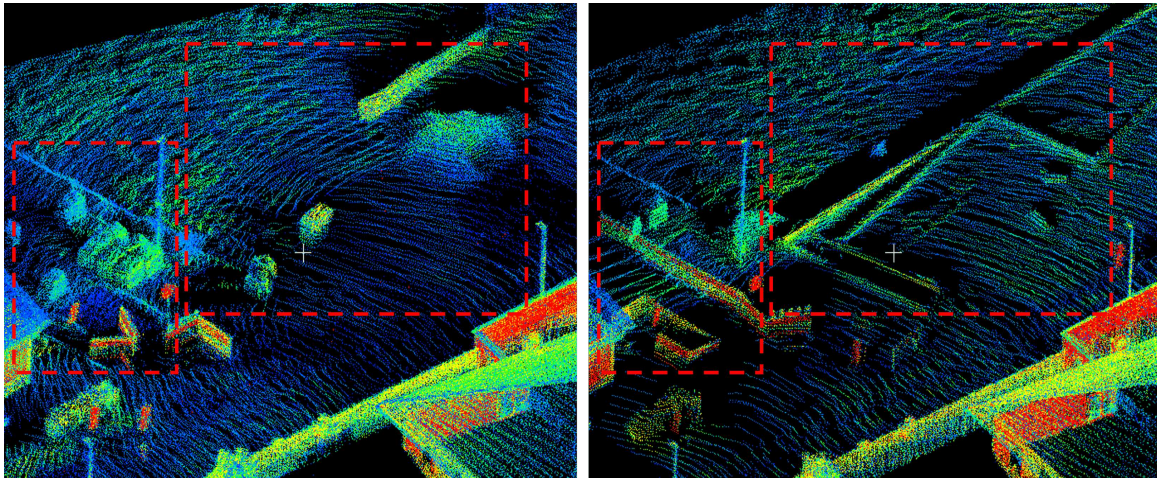


Figure 3: Generated point clouds of the same area from two different scans a few days apart. The progress on the site can be seen from left to right sub-figure, especially inside the corresponding highlighted area. The points are colored by the return intensity of the laser.

5 Discussion

The conducted experiments confirm some of the assumed advantages of using mobile construction machines as mapping systems. Two of the main concerns of UGVs on construction sites are robust navigation in the often unstructured and dynamic environment, and safety and acceptance by the other agents on-site [10]. Both topics have been successfully addressed through the non-invasive design of the equipment and the use of the already employed machine. Aside from a brief session, where the setup was mounted and connected to the power supply, the workers made no changes to their work schedule or task execution while enabling mobile mapping on the site. Furthermore, this approach diminishes possible fears of future competition with robots on the construction site, as it only extends the performance of the existing workforce.

As the technical setup was deployed on a real construction site during autumn, winter and spring, it was exposed to a rough working environment. Rain, dust, direct sunlight or low temperatures are normally formidable challenges for other mobile mapping systems. However, during the complete duration of the experiment, no technical failures or deterioration of measurement quality were observed. Only one issue was encountered when a power plug got loose through the vibration of the wheel loader. Luckily, this can be easily prevented in a future iteration by using a latching type of plug.

The positioning and selection of the LiDAR sensors enabled a comprehensive coverage of the surrounding area at relevant heights, providing sufficient resolution to effectively recognize objects and structures within the environment. Notably, the Cube 1 positioned in the rear offers highly detailed measurements of the ground, which could be used for soil condition studies. The front-facing camera collects image data crucial for texture-dependent object detection, particularly for identifying materials handled by the machine. This enhances the detailed monitoring of relevant objects and materials processed by the machine.

However, the field of view and angle of the camera limit the visible area, restricting material recognition based on texture to the frontal area only. This limitation can be addressed by incorporating additional cameras to cover a wider angle of the environment. Another challenge encountered with the current setup is the heterogeneity of the sensors, which require more computational power to execute fusion algorithms for data consolidation. This issue can be mitigated by employing a factory pre-calibrated sensor suite.

Analysis of the wheel loader pathing showed that although the machine traversed and mapped the majority of the site, some areas were rarely visited, yielding no updates. This can be explained in two ways: construction was simply happening somewhere else as those parts have been mostly finished, or alternatively, tasks were carried out by different machines at that time, as only one of two wheel loaders on this site was equipped with sensors. To achieve complete coverage, all involved machines should participate in the monitoring process. Another possibility is an automatic evaluation of the achieved coverage that warns if an area has not been visited in a while.

Lastly, continuous monitoring always raises the question about total surveillance of workers near the proposed MMS or the privacy of people living next to the construction site. As a result, further development of this system needs a built-in anonymization of people, license plates, predefined areas, etc. in the point clouds and images as well as a secure and transparent access policy to the data and the derived insights.

6 Conclusion

In this paper, a new approach to construction site monitoring was presented. By equipping mobile construction machines with typical sensors used for mobile mapping, the state of their surroundings can be surveyed. This solution can safely navigate the site and does not require additional personnel, as the already employed human operator simply carries out his usual tasks, giving it an edge over current unmanned aerial/ground vehicle based approaches. A demonstrator was built and mounted on a wheel loader. It consisted of four LiDARs, one camera and a GNSS receiver, giving a broad all-round view. The hardware infrastructure was mounted inside a switch cabinet on top of the machine and the power connected to its battery. The modified machine was used on a real construction site for several months during autumn, winter and spring. Remarkably, this setup worked robustly in the rough environment and gathered reliable data about the changes to the surroundings. This demonstrated the feasibility of the approach and builds the basis for an automated site monitoring system.

The next steps consist of further processing and automatic extraction of changes on the site between different points in time, such as position of materials and digital elevation models, and then validating the results with data from the site surveyor. Additionally, future iterations of the sensor setup will include more cameras to improve image coverage of the environment. A factory pre-calibrated sensor suite will be used to reduce the computational load and streamline data integration. This also offers the opportunity to implement the data processing directly on the edge computer and connect it to a digital twin of the site, which stores and visualizes the construction progress. Finally, multiple machines can be equipped and used at the same time to provide a more complete picture of the construction site.

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