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ORIGINAL PAPER

5G in construction: from deployment to evaluation for robotic applications

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Abstract

A stable, low-latency, and high-bandwidth communication infrastructure is indispensable for effective teleoperation or automated control of construction machinery. Despite the vital importance of this aspect, limited exploration has been undertaken thus far. Our work presents a comprehensive study that begins by detailing the strategic deployment of a 5G network, underscoring its tailored features and functionalities designed specifically to meet the demanding requirements of construction sites. Through a series of diverse experiments involving different types of full-scale construction machines, we vividly demonstrate the tangible benefits of 5G technology in this context. Leveraging comparative studies with WiFi technology and real-world tests, this methodology highlights the improvements in communication facilitated by 5G networks. This holistic exploration not only fills a critical gap in understanding the potential of 5G in construction machinery communication but also offers a roadmap for leveraging this technology to further develop the construction industry.

Keywords Construction robotics · 5G technology · Automated construction machines

1 Introduction

Construction encompasses projects from residences, roads, tunnels, and bridges to energy infrastructure such as nuclear and wind power plants. This industry plays an essential role in our society, and the projects' efficiency has a significant impact on our lives. Despite this considerable importance, the current degree of automation within construction is still relatively low compared to other industries, with difficulty and demand largely carried out manually by human workers. Here, construction sites constantly undergo changes throughout different stages of development, each presenting distinct hazardous conditions for human workers, such as heavy machinery operation, exposure to harmful materials, and the risk of falls from elevated structures. To mitigate these risks, teleoperation, which removes the necessity for control of heavy construction machinery in direct proximity, has become a crucial component in the construction industry today (Brell-Cokcan and Lee 2022).

Teleoperation commonly facilitates machinery control at the individual joint level, see Fig. 1. When a human operator remotely controls the machine, from a safety-controlled environment like a control container, their control relies heavily on visual feedback (Chen et al. 2007). In this context, the quality of visual feedback assumes a crucial role, with the provision of 3D information, including depth data, proving to enhance the telepresence experience for human operators. This enhancement contributes significantly to the operator's sense of being physically present and engaged in the remote operation of the machinery, which is essential for ensuring effective and safe teleoperation (Mast 2013). Moreover, as most construction machines are mobile machines due to the dynamic nature of construction sites, the control signals from the control device are often wirelessly transferred to the machines. Here, robust wireless communication between the control device and the machine is mandatory to ensure safe control.

As previously emphasized, a fundamental prerequisite for effective control of machines is the establishment of stable, low-latency communication with the machine, coupled with data transmission capabilities that maximize bandwidth to enhance the quality of visual feedback. Over the past few years, wireless communication technologies like WiFi and Fourth-Generation (4G) mobile networks have been

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Fig. 1 The human operator controls the machine solely based on intuition in direct proximity to the machine

employed to facilitate robust communication with machines or sensors for purposes such as monitoring hazardous areas, alerting workers in risky situations, and collecting on-site data (Johansson et al. 2018). While these communication technologies can partially address certain industry requirements, they fall short in meeting all demands, particularly those related to bandwidth and time-critical communication. In response to these challenges, the Fifth-Generation (5G) technology has emerged as a technology poised to fulfill the specific needs of the construction industry (3GPP 2020).

2 Literature review

2.1 Automated construction machine

Motivated by the achievements observed in various industries, notably the automotive sector, researchers have dedicated their efforts to integrating automated systems into construction sites since the 1970s. The primary goal has been to address the persistent productivity challenges that have plagued the construction industry (McKinsey Global Institute 2017). One notable example of this research direction is found in Lee and Brell-Cokcan (2023d), where researchers enhanced a teleoperated deconstruction machine to facilitate a more precise and semi-autonomous deconstruction process. Similarly, another study focused on augmenting an off-the-shelf excavator to enable partial automation of excavation tasks (Jud 2021).

In recent years, there has been a notable development in the automation of construction machinery, driven by data-driven methodologies. This modern approach involves techniques such as approximating the nonlinear behavior of hydraulic machinery by analyzing the operation data from the real world (Lee and Brell-Cokcan 2023a, b) and developing an efficient controller capable of successfully executing the task even in different scenarios (Lee and Brell-Cokcan 2023c). These advancements mark a significant shift in the construction automation landscape, as they leverage data and computational methods to improve the efficiency and adaptability of construction equipment.

In this context, the importance of on-site communication technology is huge, as it serves as the backbone for orchestrating the synchronized efforts of various automated construction machinery and systems. Real-time data exchange and communication networks enable these machines to share vital information, coordinate their activities, and adapt swiftly to changing conditions on the construction site. Moreover, this technology facilitates remote monitoring and control, allowing operators to oversee operations, identify issues, and make necessary adjustments in real-time, even from a distance. As construction automation continues to evolve, the role of robust and reliable on-site communication technology cannot be overstated, as it underpins the seamless integration and operation of the interconnected machinery that drives efficiency and productivity in the modern construction industry.

2.2 5G technology for construction site

Despite the immense potential that 5G networks hold for revolutionizing monitoring, control, and automation within the construction industry, there has been limited exploration of this area so far. Particularly in the context of teleoperated or automated construction machinery, establishing a reliable wireless communication system is paramount. It plays a crucial role in ensuring the safety and robustness of operations. Despite its fundamental importance on-site communication receives comparatively little attention in the existing literature. In the few available studies, communication technology is already recognized as a significant challenge in the context of automated construction machinery (Dadhich et al. 2016). Additionally, other works (Mendoza et al. 2021) introduce various concepts for integrating 5G technology into construction tasks. However, these efforts primarily provide theoretical frameworks and broad overviews, lacking empirical validation through real-world experiments conducted with on-site 5G networks. While the foundational concepts outlined in these studies are undeniably valuable, their applicability is limited due to the absence of practical implementation and testing.

In the study presented in Lee et al. (2022), the researchers embarked on a series of real-world experiments featuring a mobile robot, which, in collaboration with a WiFi network, aimed to facilitate 3D sensing applications within teleoperation scenarios. This research not only explored the feasibility of such applications but also delved into the intricacies of leveraging 5G technology to meet the evolving demands of these systems. In Xiang et al. (2021), the authors undertake a comprehensive investigation into the advantages afforded by 5G technology. By comparing the performance of 4G and 5G networks within a simulated environment, they analyzed the potential enhancements that 5G could bring to the construction industry. Nevertheless, it is important to note that both of these studies, while providing valuable insights into the promise of 5G, predominantly relied on WiFi networks or simulations for their experiments. As a result, critical questions regarding the practical implications unanswered and underscores the need for more comprehensive research and experimentation in this important domain.

In recent years, notable companies such as Doosan Infracore have successfully showcased the 5G-based remote control technology for construction machinery. However, while these demonstrations have piqued interest, the intricate technical details that underpin this technology have remained unpublished, as observed in Doosan Group (2019). Similarly, the noteworthy research conducted by You et al. (2021) has unveiled the advantages of harnessing on-site 5G networks within the context of unmanned bulldozers, operating in real-world scenarios. However, the study falls short in providing a comprehensive breakdown of the 5G network architecture and performance comparisons with WiFi or 4G alternatives. This deficiency in technical insights is particularly significant given the absence of information regarding the deployment strategy and the installation of an on-site 5G network. The construction site emerges as a dynamic environment characterized by the transitory nature of both its physical location and available resources. The construction sites, where projects typically last from 1 to several years, see a lot of shifting resources like containers and infrastructures. This makes it especially challenging to set up a stable wireless network, as the required network coverage changes. Also, the network signal is affected by the buildings being built and all the construction materials, such as concrete and metal. Thus, questions, such as how to deploy and install 5G networks, including their radio equipment and antennas, to work reliably in this ever-changing open field of construction sites, are of great importance and should not be neglected.

To bridge the knowledge gap, this paper introduces a comprehensive framework for implementing 5G technology on construction sites. It covers deployment strategies, network features, and benefits through a use case involving an automated construction machine. Additionally, it presents a hardware and software architecture for integrating 5G into this scenario.

3 On-site deployment of 5G network

As mentioned in the previous section, the construction site is a dynamic environment where the location and resources are both temporary. Often, small- and medium-scale projects last between 1 and 5 years. Moreover, the existing resources (containers, cranes, etc.) tend to be dynamic during this period. This, in turn, causes a hindrance in the scalability or maintenance of a stable wireless network. Additionally, signal coverage is affected by the presence of the buildings undergoing construction and large quantities of concrete and metal often found on construction sites. Thus, the natural question arises, how a 5G network, especially the radio units and antennas, can be deployed in this ever-changing working environment when the construction site consists of an open field (Fig. 2).

3.1 Deployment strategy

In this context, we utilize a tower crane as a transmission tower to which the radio units and antennas are attached. The use of heavy-payload machinery is common on construction sites. Especially the usage of cranes is predestined on construction sites to enable the lifting and movement of heavy materials and equipment. Leveraging the existing infrastructure of a tower crane provides several advantages for deploying a 5G network in such dynamic environments:

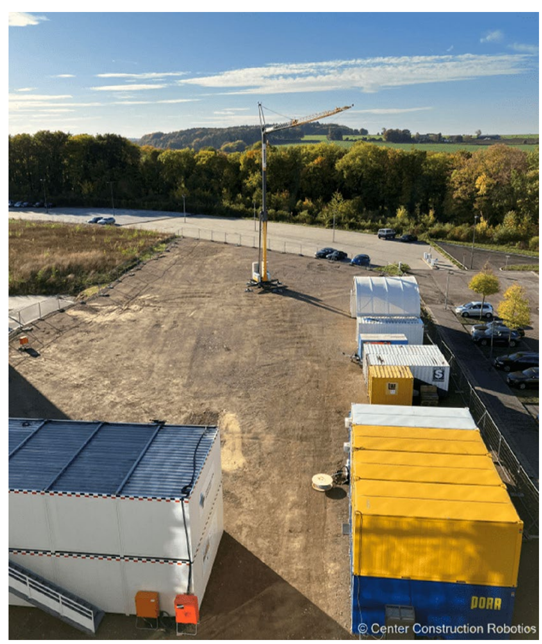


Fig. 2 Reference construction site at RWTH Campus Melaten

- First, tower cranes are typically positioned at central locations on construction sites, offering an elevated and strategic vantage point. This positioning enhances the line-of-sight communication between the radio units and antennas, minimizing signal obstructions caused by nearby structures or construction materials.
- Second, tower cranes possess robust structural stability, capable of withstanding heavy loads and adverse weather conditions. This inherent stability ensures the durability and reliability of the 5G network components attached to the crane, even in challenging environmental circumstances.
- Furthermore, tower cranes often have a high payload capacity, allowing for the installation of multiple radio units and antennas simultaneously. This multi-node deployment approach enhances network coverage and capacity, effectively mitigating the signal attenuation caused by obstacles commonly encountered in construction sites.
- To ensure seamless connectivity and efficient network operation, a dedicated power supply is established to energize the radio units and antennas attached to the tower crane. This power supply is typically integrated with the crane's electrical system, enabling continuous and reliable operation without relying solely on temporary or auxiliary power sources.

To the best of the authors' knowledge, the concept of utilizing a tower crane as a transmission mast has not been implemented by others.

3.2 Installation of the 5G network

The deployment and testing of the 5G network in this study were conducted at the reference construction site located at RWTH Campus Melaten in Aachen, Germany, encompassing an area of approximately 4000 m^2. Figure 3 illustrates a snapshot of the construction site.

Here, in this open field, the establishment of a robust communication infrastructure is paramount for the successful deployment of a 5G-enabled robotic system. To achieve this, we utilized Ericsson Micro Radio 4408 units, which were purposefully designed to support 5G technology, ensuring seamless connectivity and communication within the network. In conjunction with these radio units, we employed 5G-capable dual-polarized omni-antennas. These antennas were chosen for their unique ability to provide omnidirectional coverage, enabling signal transmission and reception in all directions. The dual-polarized functionality further bolsters the efficiency of data exchange, thereby enhancing the overall performance of our communication network.

The installation phase required meticulous consideration of several crucial factors. The stability, weight capacity, and height of the crane were meticulously evaluated to guarantee the secure placement and operation of the mounted network equipment, even in adverse weather conditions. To achieve this objective, we meticulously chose the Liebherr L1–24 tower crane, carefully considering these pivotal parameters to guarantee comprehensive coverage of the reference construction site. The crane's specifications, including a maximum hook height of 19 ms, a lifting capacity of up to 2500 kgs, and a maximum radius of 25 ms, were pivotal factors in ensuring the adequacy and efficiency of our operations at the site.

During installation, the Ericsson Micro Radio 4408 units were securely affixed to the crane's structure, with meticulous attention given to ensuring their stability and protection against any potential vibrations or movements induced by the crane's operations. Subsequently, the 5G-capable dual-polarized omni-antenna was strategically positioned alongside the radio units on the crane. The height at which it was

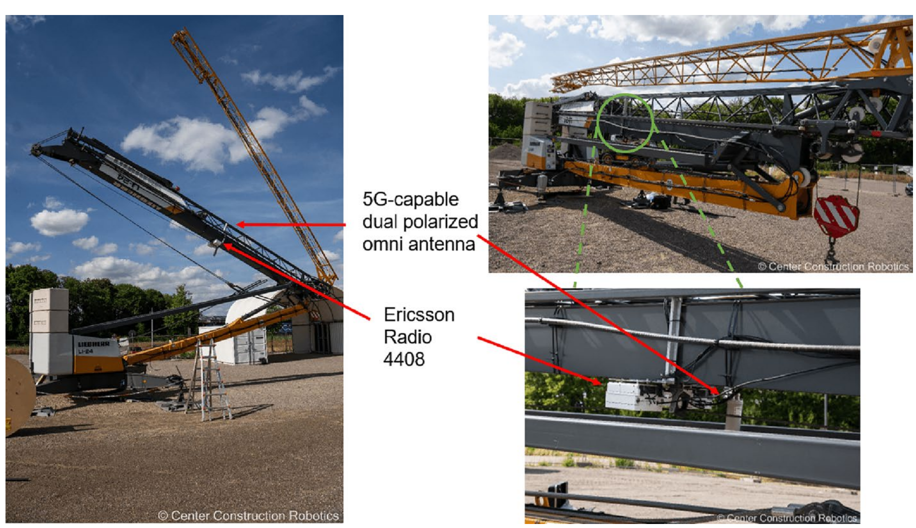


Fig. 3 On-site network setup, utilizing the tower crane as a transmission tower

mounted proved crucial in ensuring comprehensive coverage in all directions, free from interference caused by on-site structures and buildings. The choice of this specific antenna type was guided by its dual-polarized capabilities, which significantly enhance the efficiency of signal transmission and reception. This feature proves especially beneficial when the crane undergoes rotational maneuvers during its operational phases.

A critical aspect of our installation process was the management of cables. We placed significant emphasis on the delicate nature of fiber cables, necessitating their careful attachment to the crane's structural framework. This preemptive measure was taken to prevent any potential disruptions to the crane's maneuverability and to mitigate safety risks. Of particular note is the tower crane's ability to fold up or down in response to changing wind conditions. To accommodate this feature, we employed jumper cables in the crane's folding region, specifically concerning the fiber connections.

4 Construction machines

To demonstrate the benefits of utilizing the deployed 5G technology in the context of controlling construction machinery, we first provide a brief description of the necessary hardware modification of Brokk 170 that allows the 5G-based control. Next, the control method is introduced that takes the sensor readings as feedback via the 5G network and plans the next necessary motion to build a closed-loop mechanism.

When utilizing an automated construction machine like the Brokk 170 on a site, the incorporation of a visual sensor, exemplified by a camera, stands as a critical safety provision aimed at averting collisions with human beings. In this context, the camera serves as a critical component of the machine's sensory apparatus, facilitating the detection of human beings within its operational vicinity. However, inherent to any camera system is the limitation of a confined perspective, resulting in blind spots or dead angles that could compromise safety. To mitigate these limitations and ensure comprehensive surveillance, the consideration of alternative monitoring methods becomes pivotal. One such strategic approach involves utilizing a secondary construction machine as a third-eye for monitoring, complementing the camera's perspective and significantly enhancing the overall situational awareness. This approach effectively addresses the limitations of a single-camera viewpoint and offers a robust solution for ensuring the safety and efficiency of autonomous construction operations in dynamic and crowded environments.

The decision to opt for a secondary construction machine as a third-eye for monitoring, instead of integrating multiple cameras onto the automated construction machine, is driven by a holistic assessment considering various operational factors. While multiple cameras offer expanded visibility, their implementation introduces complexities in data processing, and system management, demanding sophisticated solutions and incurring higher costs. In contrast, employing an additional machine simplifies the setup and operational demands, ensuring a cost-effective approach. Although it necessitates an initial investment in acquiring another machine, its primary role in monitoring simplifies its technical requirements, maximizing its utility across multiple tasks when not actively engaged in surveillance. This strategic utilization of resources not only addresses blind spot concerns but also offers scalability, adaptability, and long-term cost-effectiveness over the project's lifecycle, making it an optimal choice for comprehensive site surveillance and safety in autonomous construction operations.

Thus, the system details and frameworks governing the INNOK444 mobile platform are outlined which informs Brokk 170 in the event of human presence nearby.

4.1 System description

This section presents an overview of the hardware configuration applied to the Brokk 170 construction machine, incorporating essential core adaptations tailored to allow the 5G-based control, see Figs. 4 and 5.

4.1.1 Brokk 170

Within the Brokk 170, the Controller Area Network (CAN) bus is facilitated to interconnect different sensors, actuators, and the machine control unit (MCU). In the off-the-shelf setting without any modification, the operator exclusively controls the machine by sending the control signals through the control interface, i.e., control joysticks. The communication between the control joysticks and the MCU is realized using radio devices. The received joystick signals in the form of CAN messages are translated into the corresponding pulse-width modulation (PWM) signals to actuate the valve systems and bring the manipulator in motion.

The fundamental additions to our system are depicted within the blue boxes in Fig. 5, with the basic concept originating from prior research (Lee and Brell-Cokcan 2023d). This concept revolves around the execution of resource-intensive tasks, such as motion planning and perception, on the Host PC, while relegating the onboard embedded PC to handle low-level control, specifically the actuation of valves and corresponding cylinders based on the provided control signals. By distributing tasks in this manner, we enable the possibility of substituting the Host PC with a cloud-based system in the future, capable of handling resource-intensive tasks for multiple interconnected construction machines.

Fig. 4 Brokk 170 (left) and INNOK 444 (right) with their hardware employed in this project for automated tracking of trajectories and detecting humans

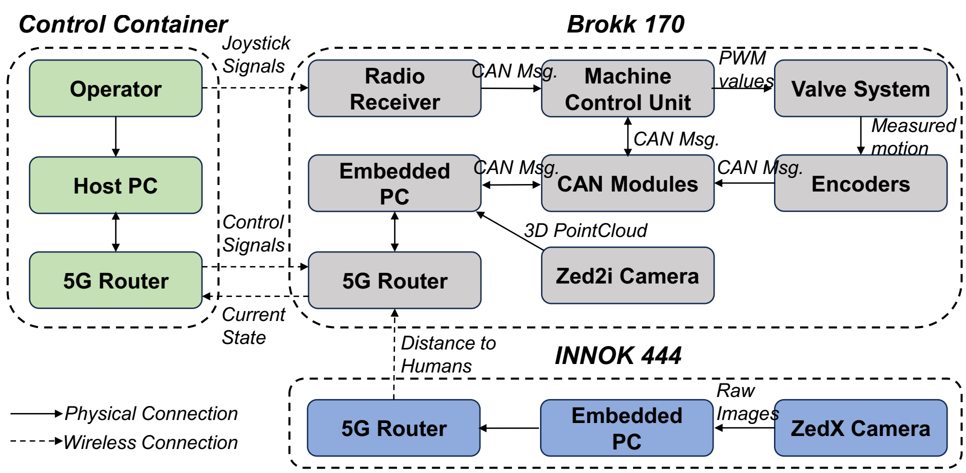


Fig. 5 Schematic representation of the hardware setup

This approach eliminates the necessity of acquiring costly computing components for each individual machine, leading to a more scalable solution. However, it is essential to acknowledge that since functions like motion planning are executed on a separate Host PC rather than directly on the onboard PC, ensuring minimal latency and robust communication between the Host PC and onboard PC becomes a paramount concern. To address this challenge, we have incorporated 5G routers on both ends of the communication link.

To allow the programming option of the teleoperated construction, we first establish a bridged communication link with the MCU with the onboard embedded PC. This onboard embedded PC is equipped with a CAN bus controller, serving as a crucial intermediary that handles message filtration and forwarding tasks, seamlessly bridging the connection with the Brokk 170's MCU. With this setup in place, the machine can be teleoperated using the original joystick inputs while simultaneously remaining receptive to signals generated by algorithms residing on the Host PC in programming mode. These algorithmically derived signals enable precise control over the machine's movements, resulting in optimized operational performance in terms of accuracy.

4.1.2 INNOK 444

In this project, we utilized the INNOK444 mobile platform for the mobile human detection process, as depicted in Fig. 4. The control box and chassis of the INNOK are rated IP65 and IP68, respectively, rendering them suitable for the challenging outdoor conditions commonly encountered on construction sites. Additionally, the platform's four-wheel differential drive enhances navigation on uneven and loose terrains.

To enable human detection as envisioned, we selected the ZedX stereo camera manufactured by Stereolabs, acclaimed for its expansive field of view spanning 110° × 80° and an effective depth range between 0.3 and 20 ms, ensuring a considerable detection scope for our experimental setup. Given the lack of a GPU in the initial compute module of the INNOK, we opted for a substitution, integrating the NVIDIA Jetson Xavier AGX 32GB model. This replacement facilitated seamless data and power transmission to the ZedX camera by employing a GMSL2 capture card connected directly to the Jetson module.

4.2 Control methods

The communication and processing of data and control signals among the INNOK, BROKK, and the control PC were established using the ROS framework. ROS, an open-source middleware framework, simplifies the development of robotic systems by offering features such as hardware abstraction, inter-process communication, and diagnostics.

4.2.1 Human detection pipeline

We developed a custom ROS package dedicated to identifying human poses in 3D Cartesian coordinates. The foundational component of our detection pipeline was the Zed SDK, an open-source resource (Stereolabs 2023). This SDK facilitated image extraction and enabled human detection within the image stream. Operating at 1080p resolution and 30 fps, the camera initialization process set the stage for our analysis. Utilizing a pretrained model embedded within the Zed SDK, we detected humans within the RGB images, extracting the center of the respective bounding boxes to derive their 3D poses. These poses were converted into the Euler distances for each detection and published this information to Brokk 170 via the 5G network and WiFi5, respectively.

Throughout this work, the suggested human detection pipeline was utilized on a single spot while maintaining the INNOK robot stationary. This strategic approach aimed to emphasize and meticulously evaluate the performance of the network infrastructure supporting the communication between the INNOK and Brokk. By intentionally confining the testing to a fixed spot and halting the robot's movements, the focus centered on scrutinizing the network's reliability and latency factors. Within this controlled environment, a thorough evaluation can be conducted to appraise the network's resilience and effectiveness in enabling uninterrupted communication within this time-sensitive context. This aspect aligns closely with the pivotal focus of this research-examining the influence of 5G technology on automated machine control.

4.2.2 Trajectory control

In the context of trajectory planning, our methodology involves pre-defining a path for the tool center point (TCP), specifically the hammer tip, and tracking along this designated path. This process initiates with the trajectory planner generating waypoints based on the current joint configuration. Subsequently, we convert the desired transitions between these waypoints into control inputs, notably PWM values, using the low-level controller, functioning here as the PID controller. To establish a closed-loop control system, we implement a control framework based on the Robot Operating System (ROS) (Coleman et al. 2014). The central control loop of this system operates at a fixed rate of 20 Hz. At each iteration of this loop, the system updates sensor data, such as the robot's joint states, and computes commands for individual joints to guide the manipulator along the operator-defined trajectory. In our study, employing pre-defined paths allows us to precisely track the same path under consistent conditions using both 5G and WiFi5 technologies. The pre-defined path is structured to involve the activation of multiple joints, moving across diverse directions.

5 Experimental results

5.1 Performance evaluation of the 5G network

In this section, we introduce the methodology used for evaluating network performance and detail the experimental setup implemented to measure these metrics at the construction site, see Fig. 6.

5.1.1 RRT test during crane operations

The primary focus of our testing revolves around assessing how the use of tower cranes impacts network performance. Specifically, we evaluate network performance by conducting round trip time (RRT) measurement tests during crane operations.

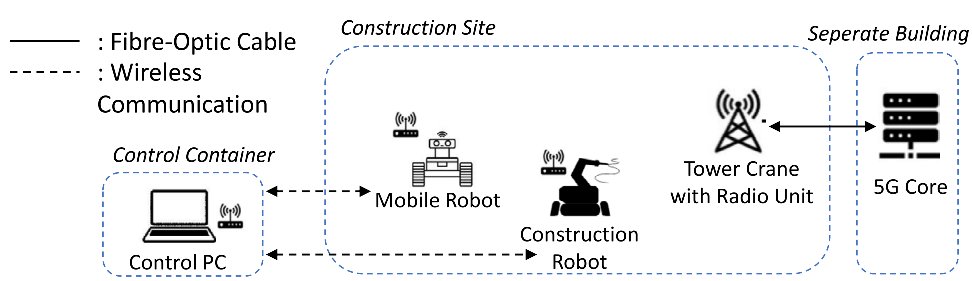


Fig. 6 Schematic overview of the network setup

Although the RRT measurements depicted in Fig. 7 show slightly higher latency in 5G networks compared to WiFi5 in controlled environments, it is crucial to contextualize these findings within their respective experiment settings. WiFi5 is optimized for confined areas such as homes, offices, or specific public spaces, excelling in delivering rapid internet speeds within limited ranges, ensuring efficient data transmission. In contrast, 5G operates as a cellular network tailored for broad coverage, enabling connectivity across expansive geographical regions.

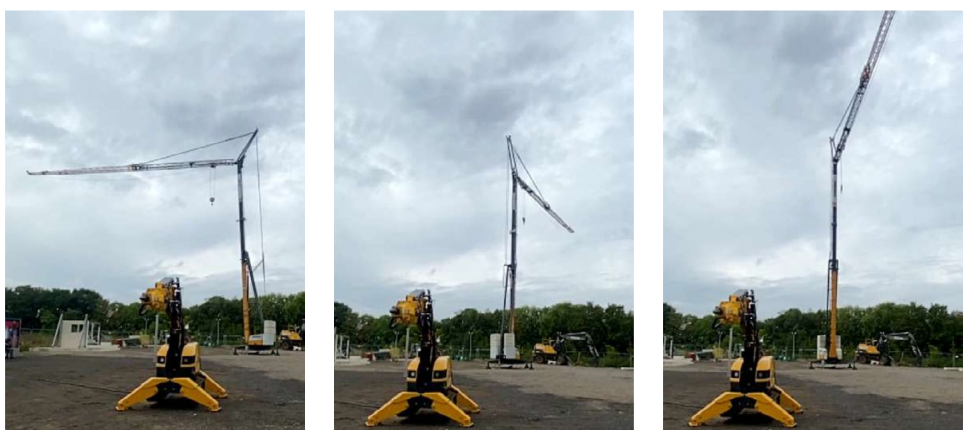
The results obtained from the crane's utilization of the 5G network demonstrate commendable network quality even during the active operations of tower cranes. Significantly, in the WiFi5 test, the WiFi routers were positioned approximately 10 ms apart, spanning directly from the control PC housed in the control container to the Brokk 170 construction machine. With the 5G network, wireless communication encompasses additional interaction with the radio unit affixed to the crane. Nevertheless, the findings reveal that 5G demonstrates a performance on par with WiFi5, even in scenarios where WiFi typically excels.

5.1.2 On-site heatmap analysis using RRT

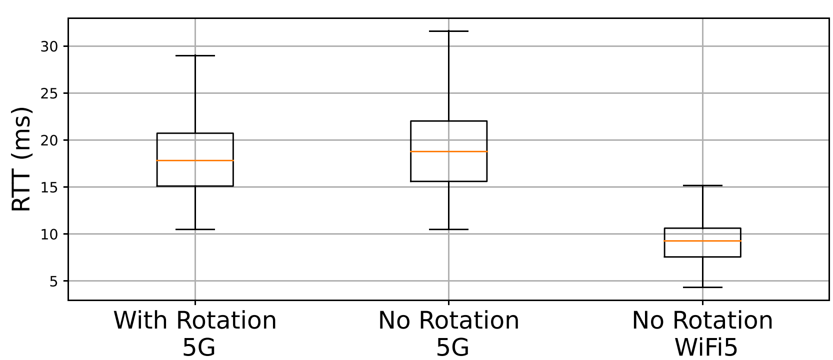
As mentioned earlier, 5G is well known for its broad coverage. Here, we perform ping tests between the control PC and a mobile robot moving along a pre-defined straight-line path, originating from two different starting positions identified as 1 and 2, see Fig. 8. The objective is to comprehensively analyze network performance across the whole construction site in varying conditions, specifically under WiFi5 and 5G networks. These tests are conducted while the network experiences different occupancy levels, ranging from 0 Mbps to approximately 40 Mbps. Through this extensive experimental setup and assessment, the goal is to understand the potential impacts in situations where seamless real-time communication with mobile robots holds significant importance within construction sites.

The heatmap analysis in Fig. 8 illustrates a discernible performance contrast between the 5G and WiFi5 networks. Notably, the 5G network showcases a more consistent RRT throughout the mobile robot's trajectories. Conversely, the WiFi5 network displays more fluctuations in RRT values along the mobile robot's paths, indicating variability in performance at different points during its movement. This distinction in RRT stability highlights the superior reliability and steadiness of the 5G network compared to WiFi5,

Fig. 7 RTT comparison in different scenarios, when the crane is rotating and when it is stationary



(a) Different antenna position during the crane rotation



(b) RTT to Brokk 170 with 5G and WiFi5

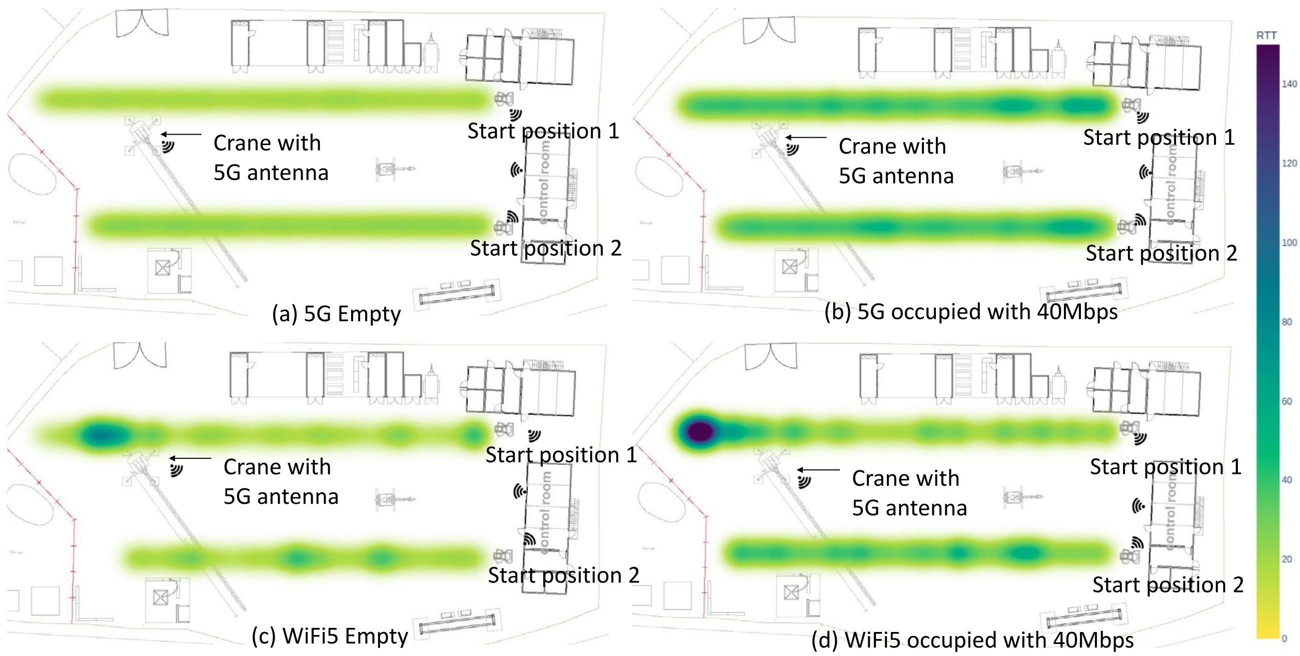


Fig. 8 Assessing round trip time: Monitoring control room communication with a mobile robot along a straight-line trajectory from start positions 1 and 2 under WiFi5 and 5G networks, respectively, with occupancies of ~ 40 Mbps

Table 1 Uplink and downlink speeds for 5G and WiFi5 networks

	5 G	WiFi5
Uplink (Mbps)	~ 80	~ 180
Downlink (Mbps)	~ 80	~ 180

emphasizing its potential for consistent communication and data transfer in dynamic operational environments. The test was reiterated under identical conditions but with varying network occupancy at 40 Mbps, representing 50% and 22% of the maximum bandwidth of 5G and WiFi5, respectively. The maximum bandwidth values from Table 1 was established through experimental iperf3 TCP measurements. This highlights the consistency of the test while exploring network performance under different utilization levels.

5.1.3 Time critical human detection test

To confirm the reliability of the 5G network in a time-sensitive situation, specifically when the control PC transmits wireless commands to the Brokk 170 construction machine and detects a human approaching the workspace, a validation was conducted. The mobile robot, acting as an additional surveillance measure alongside the Brokk 170 alerts the construction machine to halt its operations once the distance to the human falls below 6.0 ms, see Fig. 9a.

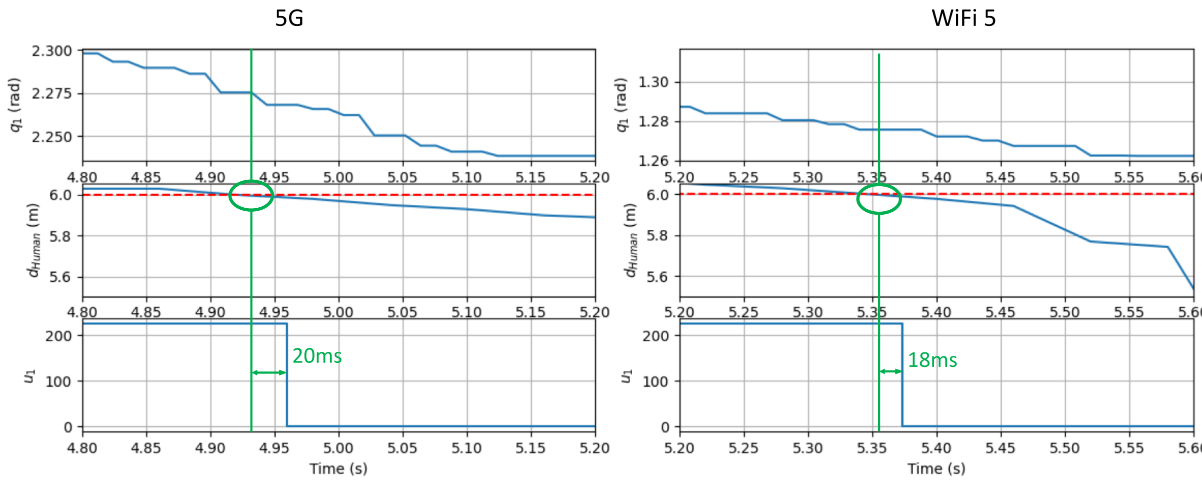
The Brokk 170's base underwent rotation with a constant PWM value of 220 represented by u_1. Whenever the mobile robot detects a human within 6 ms of Brokk 170, Brokk 170 overrides the u_1 value, setting it to 0. The third plot within Fig. 9 displays the time interval between human detection and the alteration of the control command. In this time-sensitive experimental setup, the 5G network showcases performance akin to that of WiFi 5. This verification not only underscores the effectiveness of the 5G network but also establishes its practicality in enabling time-critical maneuvers within robotic systems.

5.1.4 5G-based control of construction machine

This experiment evaluates the impact of the 5G network within the implemented tracking performance at the TCP path level. For this purpose, a TCP path is pre-defined where multiple joints need to change motion direction to complete the task, as depicted in Fig. 10. The impact of the 5 G network is directly compared by preserving the gains of the low-level controller PID and simply replacing the utilized network, where the average and maximum position errors are reported. The used metrics and the corresponding formulas are listed in Table 2, where (x^D, y^D, z^D) and (x, y, z) are the target and actual positions, respectively, where N denotes the number of sample points.

The results are visualized in Fig. 10 and summarized in Table 3. For the pre-defined TCP path, the results clearly

(a) Stillshots from the human detection test



(b) Brokk 170's responses according to the estimated distance from humans with 5G (left) and WiFi5 (right) network, respectively, where the user-defined threshold of 6 meters is indicated by the red dashed line.

Fig. 9 Results from the human detection test: the mobile robot signals the presence of humans to the construction machine

Table 2 Metrics and corresponding formulas used for the evaluation of TCP path-tracking

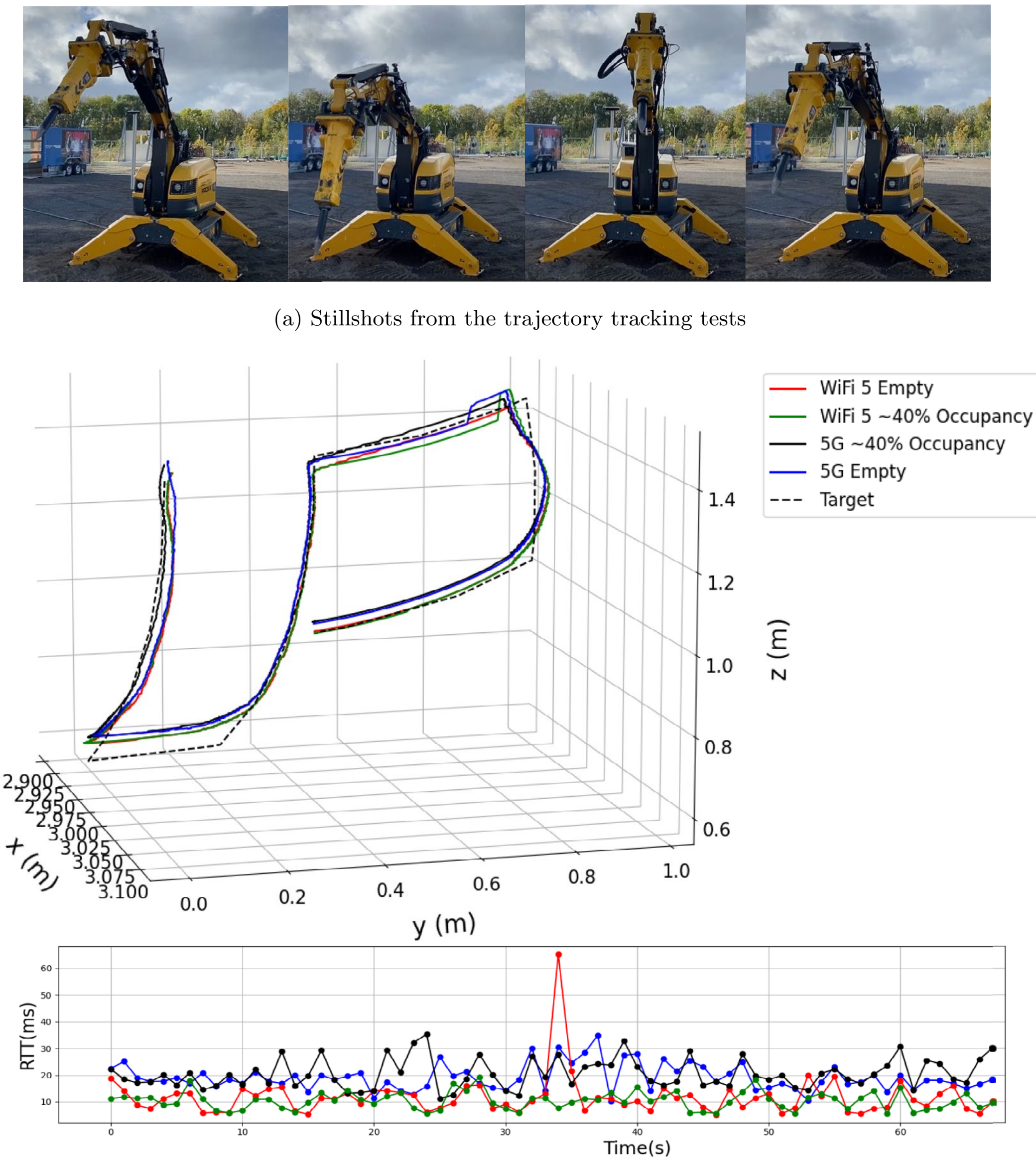
Metric	Formula
e_{p_avg}	$\frac{1}{N}\sum\sqrt{(x_t^D - x_t)^2 + (y_t^D - y_t)^2 + (z_t^D - z_t)^2}$
e_{p_max}	$\max\sqrt{(x_t^D - x_t)^2 + (y_t^D - y_t)^2 + (z_t^D - z_t)^2}$

Table 3 Trajectory tracking performance

Used network	e_{p_avg} [cm]	e_{p_max} [cm]
5 G empty	5.3	10.3
WiFi5 empty	5.1	9.1
5 G ~ 40% occupancy	4.6	9.7
WiFi5 ~ 40% occupancy	5.8	10.2

demonstrate the capability of the proposed control framework. The most significant error occurs when multiple joints simultaneously change direction. Also, the reported error is partially caused by the limitation of the low-level controller. Due to the nonlinearity of the hydraulic system, the fine-tuned gains of the PID controller yields varying results depending on the direction of movement and the velocity amplitude (Lee and Brell-Cokcan 2023a).

Although both 5G and WiFi5 facilitate communication within control systems, the constraints of WiFi5 become increasingly evident within this particular application. Despite the measured RRT showing better latency outcomes for WiFi5, 5G distinguishes itself through its robustness, notably reducing unpredictable outcomes linked to reliable communication with the control PC, as illustrated by the peak in Fig. 10b. Even though the resulting trajectory plot does not visually reflect this peak's impact, its presence underscores the significance of stable and consistent communication. The limitations of WiFi5 in this context become more pronounced when considering the intricacies of control frameworks requiring real-time, precise data communication. While the latency measurements might suggest an advantage for WiFi5, the robustness and reliability demonstrated by 5G, especially during critical control operations, position it as the more suitable choice for ensuring dependable communication and minimizing unforeseen fluctuations in performance.



(a) Stillshots from the trajectory tracking tests

(b) TCP path tracking results (Top) and the corresponding RRT measurement between the control PC and Brokk 170, where only the network configuration varies

Fig. 10 Results from the TCP path-tracking tests

6 Conclusions

This paper presents a comprehensive framework for implementing on-site 5G technology within the construction sector. It starts by detailing the strategic deployment of a 5G network, emphasizing its key features and functionalities tailored to construction site requirements. The exploration of a specific use case involving an automated construction machine vividly illustrates the tangible benefits of 5G technology in this context. Furthermore, this study compares the performance of the 5G technology with another type of communication technology, WiFi and highlights the imperative for further research. Overall, this presented work offers a holistic perspective, showcasing the potential and practicality of 5G in the context of automated construction machines.

In outdoor construction sites where automated machine control becomes more important, 5G technology excels in providing enhanced robustness and reliability, effectively managing uncertainties associated with heavy-duty construction equipment. Its superior performance is evident in maintaining consistent RRT throughout the entire construction site, reducing the potential for unexpected disruptions during critical operations. Serving as a reliable backbone for latency minimal and accurate communication, 5G emerges as the preferred option for ensuring consistent and uninterrupted connectivity in dynamic operational settings.

Future research pathways involve delving deeper into the core attributes of 5G technology, particularly the exploration of Massive Machine-Type Communication (mMTC). In the existing network configuration, three end-devices—control PC, Brokk 170, and INNOK444—were employed. However, forthcoming investigations could encompass a broader array of end-devices commonly used at construction sites, aiming to scrutinize their performance variance compared to WiFi technology.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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