Importance of a 5G Network for Construction Sites: Limitation of WLAN in 3D Sensing Applications

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Abstract -

Teleoperated construction machinery dominates construction sites, as it can, with relatively little effort, prevent operators from working in dangerous conditions by keeping them in the control loop. However, the operators usually have to execute tasks with limited situational information due to poor depth perception from 2D camera images, reducing local accuracy and work efficiency. Thus, 3D sensing technology such as depth cameras is used more and more in combination with the teleoperated construction machinery. As these depth cameras are preferably mounted on a mobile robot to prevent the occlusion and observe the remote work place from several viewpoints, the corresponding on-site Information and Communication Technologies (ICTs) that can cover the required data transmission are of great importance for further developments. This paper presents a robotic platform capable of navigating and providing the 3D point cloud data of the remote work place from different viewpoints according to the operator's input. The captured information is transferred to the operator using the standard network Wireless Local Area Network (WLAN). To that end, first, the limitation of the WLAN in 3D sensing applications and the needs of the Fifth-Generation (5G) of mobile networks are jointly analyzed within the presented use case. Finally, the characteristics of 5G that address the test results are identified.

Keywords -

Robot-Assisted Construction; Construction Robots; Auto-mated Construction; 5G Network

1 Introduction

In the last decade, teleoperated heavy machinery has become an essential element for construction or disaster sites since it directly extends the operator's sensory-motor facilities. Remote teleoperation, however, has a major drawback, compromised human perception due to the decoupling of the human operator from the physical environment. Poor perception have often detrimental effects on safety and efficiency especially in dynamic environments like construction sites [1].

A safe operation of teleoperated machines requires the operator to have good spatial awareness of the environment at all times. Various image representations of the environments have been developed to facilitate this [2, 3, 5]. These often include using exteroceptive and proprioceptive sensors, mounted directly onto the construction machine, coupled with panoramic visual feedback with birds eye view. Typical control stations include multiple 2D camera views from different perspectives to increase the telepresence by projecting the obtained sensory information to a remote place. However, such approaches have shown to be problematic concerning the operator's divided attention, and overloaded network [6].

RGB-D cameras, which can capture geometrical information in 3D, are often employed to improve perception in remote environments. In [7], it has been shown that providing the operator an additional 3D representation of the environment resulted in increased task performance when compared to monocular RGB views. Moreover, changing the sight-of-view is another essential aspect for enhancing the manipulation capabilities of a teleoperated system, as confirmed in the study of Huang et al. [8]. These sensors are often mounted on an external mobile robot to provide a dynamic perspective of the ongoing operations. The gathered information needs to be sent to the remote control station over a reliable network connection. In the past, wired networks have been used to remotely operate the machines. There are multiple reasons for using a tethered mobile robot for exploration and remote sensing. It could serve as high bandwidth and low latency communication channel while maneuvering underwater or underground mines or to power the onboard sensors in search and rescue operations. However, without computationally expensive path planning algorithms [4], such tethers strongly restrict the maneuverability of the mobile robot in unstructured environments like construction sites, thereby increasing the chance of damage and decreasing the robustness of the system. Therefore, a further investigation into the wireless network is of great importance, especially for construction sites, as more mobile robotic applications are being integrated into construction sites, which has pushed recent developments in the direction of wireless networks [5, 9].

But the usage of WLAN comes at the cost of limited bandwidth and latency, which in turn affects the efficiency of the operation. Some methods have been developed to circumvent this such as sensor scheduling or lowering the frame rate of the sensor feedback [10]. These approaches while effective in resource-constrained systems, are not ideal for continuous operation on a construction site. Data compression methods are also often employed to shrink the amount of the data, allowing it to be stored and sent via a low-bandwidth channel. Such compression techniques aim to reduce data size by finding and removing statistical redundancy while keeping the original data [11] [12]. However, the compressed data size for wireless data transport remains rather large in multiple megabytes, and information loss still often occurs, necessitating appropriate network technology.

In line with this problem, several research initiatives are now focusing on the on-site usage of a more sophisticated network, such as the 5G of mobile networks (5G.NAMICO,2022). The basic characteristics for 5G have been detailed as: higher transmission rate, shorter latency, higher reliability, and more User Equipment (UE) connection. A recent study [13], has evaluated the benefits of using 5G technology in construction sites by comparing the performance of video streams from static cameras on the construction site. Yet, further investigations in line with the automated systems are needed to appropriately plan the deployment and usage of the 5G network on construction sites.

In this paper, we first present the robotic setup which can capture the remote working scene in a 3D point cloud and transmit it to the operator using the standards WLAN network. The mobile robot is based on a commercially available platform. It is further equipped with a 3D depth camera to provide 3D visual feedback from an arbitrary viewpoint of the remote workplace. Effective collaboration with the operator requires reliable data transfer of the captured visual information. Therefore, a speed test was conducted using the commonly used network, WLAN. Based on the test results, the limitations of the existing telecommunications technologies are highlighted. Then, the required characteristics and functionalities of the new 5G networks are identified. Furthermore, some of the possible challenges for installing 5G networks on the construction sites are discussed.

2 Mobile Robot Platform

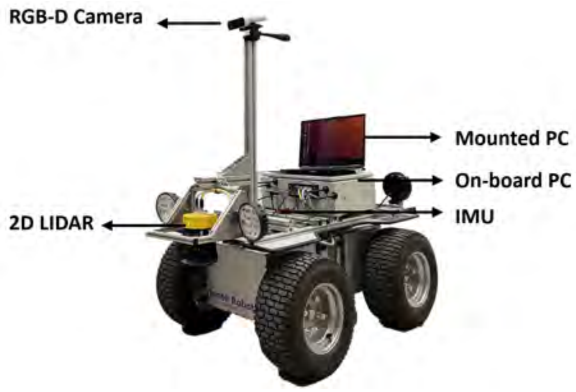

Figure 1. The mobile robot used in this work. It carries several sensors such as a IMU, 2D LIDAR and a RGB-D camera.

The mobile robot used in this work is based on a commercial platform from *Innok Robotics*. For observability of the environment and the systems states, various sensors are integrated in the robot. An inertial measurement unit (IMU) *Xsens MTi-30-2A8G4* is placed in the middle of the base and provides the rotational speed and acceleration information. The robot is also equipped with a 2D laser scanner *Sick microScan 3* to detect obstacles or create a 2D environment map for localization tasks. In order to visualize the working place in 3D, we use a RGB-D camera *Microsoft Azure Kinect DK* at the front of the mobile robot. It is worth mentioning that the used *Azure Kinect DK* is not designed to work outdoors as the camera relies on its infrared sensor to collect the depth information. The accuracy of the measurements are heavily influenced by the infrared interference from the sun [14]. The performance in outdoor environments might be guaranteed by using a stereo depth camera. However, such a device was not available at the time of this work.

The mobile robot is equipped with two computers, one on-board-PC with Intel Core i5-5350 CPU and 8GB RAM and another PC with *Intel* Core i7-9850 CPU and 16GB RAM are both mounted on the base (see Fig.1). The on-board-PC is responsible for the basic functionality such as controlling the wheels through the SPS controller and sending the most sensor data i.e., 2D laser scanner and IMU. The other PC is only responsible for processes related to the RGB-D camera which require more computational power. A radio remote controller is integrated into the mobile platform. A remote controller with joysticks is used to control the mobile platform. As an alternative, the on-board PC can communicate with another PC by using the integrated WLAN-router. Here, the communication is established in the Robot Operating System (ROS) envi-

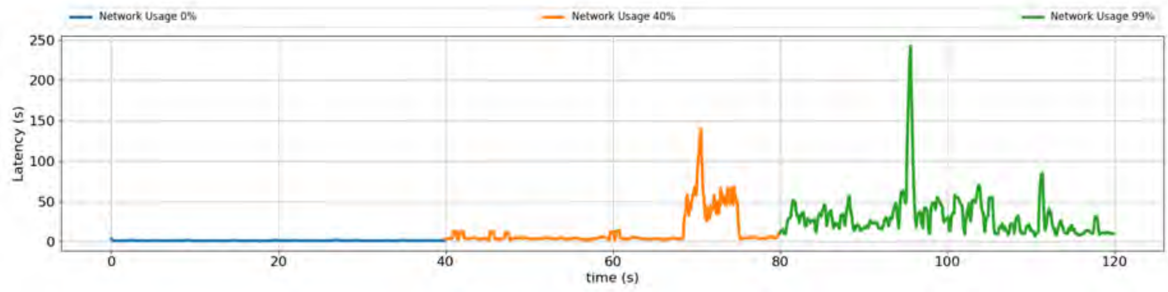

Figure 2. Latency measures for control commands of the size 17 KB from Experiment 3.1: blue (0% network usage), orange (40% usage) and green (100% usage).

ronment [15]. To capture the remote working space from an arbitrary perspective, the operator can send the control commands (x_c, y_c, ψ_c) to move the robot in the XY-plane and rotate around z-axis. As a time discrepancy between these two PCs results in an inconsistent environment measurements, we use ROS and a time management software [16] to synchronize the clocks.

3 Experiments

To evaluate the capabilities of the frequently used WLAN in 3D sensing applications, we separately investigated the network latency and the data rate that the sensor suite on the mobile robot needs to transfer the data.

3.1 Latency in relation to network overload

The network latency is first obtained by estimating the time for command signals to arrive at the mobile robot from the control PC. The mobile robot platform used in this work is programmed in the ROS environment. Therefore, we transmit ROS control messages with a size of 17 KB at 30 Hz. We measure the time discrepancy between the transmission and arrival for each of these messages. We use the WLAN with the 802.11ac standard deployed in our lab facility for this data transmission. The router is positioned directly next to the control PC, and the mobile robot is positioned around 10 m away from the control PC and the router. To highlight the limitation of the WLAN, we measure the latency in three different settings: i) 0% usage of the network's full bandwidth, ii) 40% usage (approx. 60Mbps), and iii) 99% usage (approx. 200Mbps).

For each setting, the message is transmitted for 40 seconds. After 40 seconds, the network usage is changed. Fig. 2 shows the latency measurements during the experiment. In the first case, when the network is free, the average of the measured latency is around 1 ms. This value increases to 5 ms with the network usage of 40%. The figure clearly shows that the network stability deteriorates as the latency increases up to around 150 ms. In the last case, when other tasks use the full bandwidth of the network, the network is, in general, very unstable, and massive peaks in the latency constantly occur.

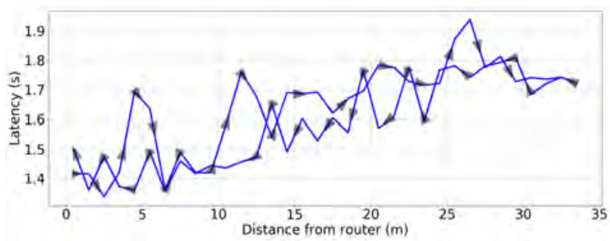

Figure 3. Latency measures in relation to distance from router, Experiment 3.2.

3.2 Latency in relation to distance from router

Due to the nature of the dynamic construction sites, the workspace for robots constantly changes. In this experiment, we demonstrate the impact of the distance between the WLAN router and the mobile robot, highlighting the limitation of the WLAN in the mobile robotic application. For the test, the mobile robot drives from its start position, 0.5 *m* away from the router, 34 meters straight forwards, and returns to its start position. While driving, we measure the latency that a point cloud data needs to travel from the mobile robot to the control PC. We use a pre-captured point cloud of size 29 MB to keep the data size constant throughout the test. The timestamp stored in the point cloud when leaving the mobile robot is compared with the arriving time to measure the latency.

Fig. 3 depicts the overall instability of the WLAN network. As the point cloud size requires the full bandwidth of the network, the latency fluctuates strongly and increases depending on the distance up to 35% from 1.4 s to 1.9 s within the test trajectory of 34 m. This is, in fact, critical, as due to the dynamic nature of construction sites, the on-site operations require large coverage

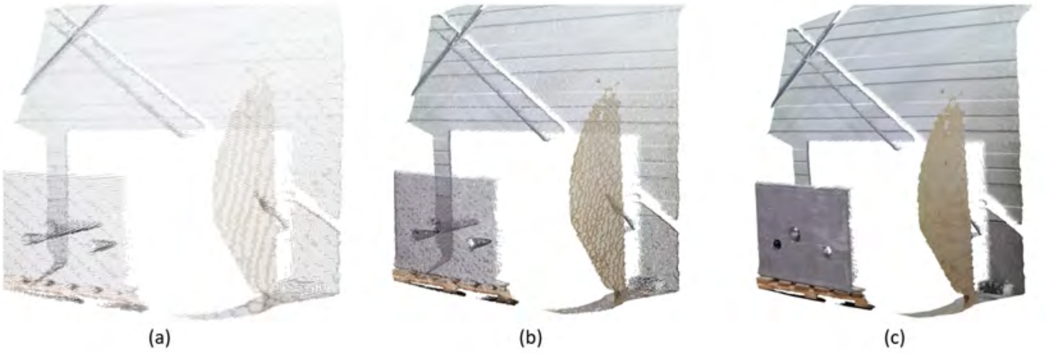

Figure 4. Captured 3D point clouds in different resolutions: a) 1 cm, b) 0.5 cm and c) 0.2 cm.

Type	Resolution [cm] or [px x px]	Frequency [Hz]	Msg Size [MB]	Req. data rate [Mbps]
Point Cloud (Low)	1	22	0.2	35.2
Point Cloud (Med.)	0.5	22	0.6	105.6
Point Cloud (High)	0.2	22	1.2	211.2
3D map	1	1	1.1	8.8
RGB Views (Comp.)	640 x 576	22	0.12	21.12

Table 1. Measured message sizes and corresponding data rate for different compression levels and data type

of the network. However, if the latency time varies, as the experiment shows, it can lead to the malfunction of on-site construction robots and cause a safety issue. The WLAN coverage area can be expanded by adding more access points, but this raises another issue: how to mitigate the impact of momentary communication instability between the access points.

3.3 Capturing 3D information

We capture the scene in 3D using the RGB-D camera mounted on the mobile platform. The captured information is then converted into point clouds. As raw point clouds are in the size of several tens of megabytes, we first compress the point clouds using the point cloud library (PCL) [17] and send them to the host PC (i.e., the user) via the WLAN network. In this experiment, the robot drives three times to the object with varying compression levels for point clouds: a) 1 cm, b) 0.05 cm c) 0.02 cm (see Fig. 4). We demonstrate the quality and the required network throughput trade-off. To control the motion of the mobile robot, the ROS navigation stack is used [18]. The estimated control inputs are forwarded to the robot controller by using the driver library provided by the Innok Robotics [19].

The final column of Fig. 5 clearly identifies the distinct features of the visual feedback. However, as Table 1 illustrates, the full bandwidth of the WLAN network (~200Mbps) is needed to transmit the point cloud in the high-level compression without any delay. While the 3D point clouds provide depth information and support the telepresence, the 2D camera images generally have greater resolution than the 3D point clouds (see Fig. 6). Consequently, the 2D camera pictures acquired by the resolution 640 x 576 are also transmitted parallel to the 3D point clouds as baseline information, requiring an extra data rate of 21.12 Mbps. Although the 2D and 3D camera views give comprehensive scene information, the operator cannot analyze the complete remote scene, as the captured data disappears as soon as the robot continues to drive. Real-time appearance-based mapping (RTAB-Map) [20] is used to perform the online processing of the 3D map by detecting the loop closure with the extracted key features and building a global 3D map with it. Here, we transmit the optimally generated 3D map every 1 second, generated in the fixed 1cm resolution. Although the needed data rate is recorded at 8.8 Mbps throughout the drive, it needs to be recognized that this data rate will steadily rise as the map grows.

3.4 Summary and Discussion

In this paper, a WLAN ac 802.11ac network was used to send and receive data. The experiment findings clearly illustrate that the quality of the visual feedback largely relies on the compression level (i.e., resolution). However, the findings also reveal that the network's capacity is completely utilized to provide the information to the user wirelessly. The problem is aggravated if 2D camera views and the 3D map data are transmitted at the same time. Although the tests were done in an ideal indoor setting, the limitations of the present WLAN network in terms of the

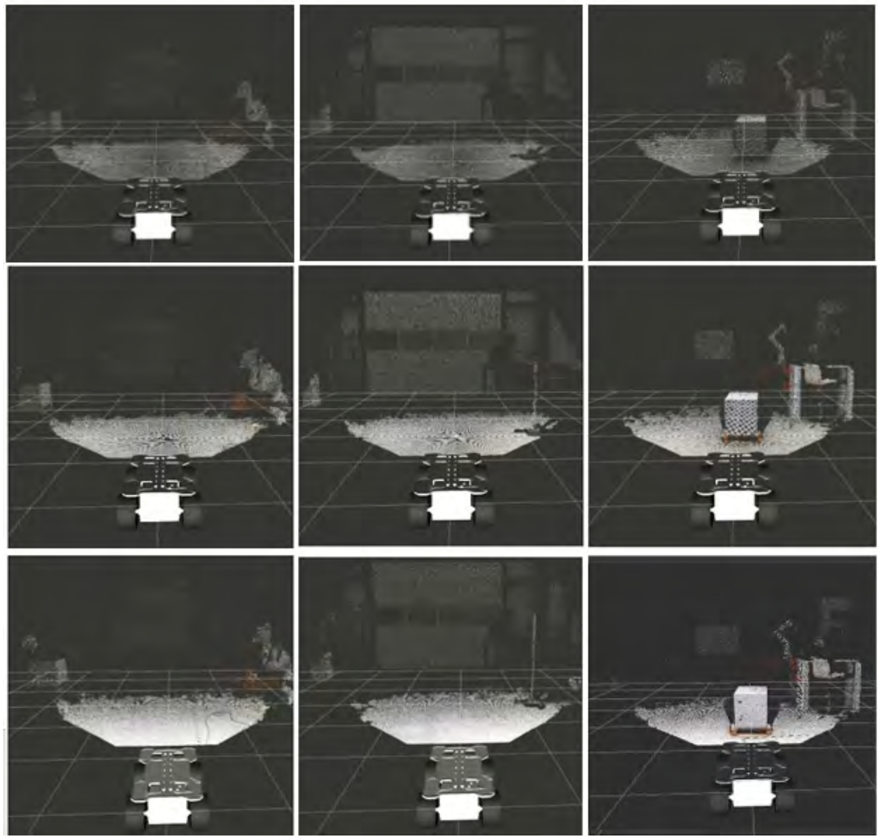

Figure 5. During the drive towards the concrete object, 3D point clouds were compressed in different resolutions and transmitted to the operator via the WLAN network(the first row: 1 cm, the second row: 0.5 cm and the third row: 0.2 cm).

bandwidth and the accompanying latency could be shown. Without these ideal conditions, we expect that the issue would be compounded on large construction sites with multiple equipment and machines using the same network which may result in reduced work performance and critical safety issues.

4 Chances and Challenges for 5G

4.1 Chances for 5G

One possibility to overcome the described shortcomings and fulfill the criteria for teleoperated construction machinery is the usage of the 5G mobile networking standard. 5G was developed to meet industrial requirements and thereby serves as an enabler for the digitalization of various industrial applications [21, 22]. While previous generations of wireless network standards did not provide many opportunities for adaption, development for 5G and its individual releases follows a different approach. One of the main principles of 5G is its service-based architecture (SBA) that offers a lot of customization potential [23]. Instead of the a uniform solution for all use cases, modifications in network architecture allow users to take a variety of heterogenous requirements of different use cases into account [24]. The three most important performance characteristics 5G offers are:

- Ultra-Reliable Low Latency Communication (URLLC)
- Enhanced Mobile Broadband (eMBB)
- Massive Machine-Type Communication (mMTC)

URLLC enables 5G networks to have a less than 1 ms end-to-end latency with the reliability of more than 99.999%. eMBB enables the transfer of a high data rate through wireless communication with up to 20 Gbit/s for downlink (DL) and up to 10 Gbit/s for uplink (UL). mMTC enables the setup of communication networks with up to 1 million devices per square kilometer [25]. Current measurements of 5G implementations (Release 15/16) in an industrial setup show the potentials of 5G: With background traffic but no specific load tests, measurements show that for a 1 kB message with URLLC the

Figure 6. The visual feedback visualized to the user in the control PC (Left: 2D camera views in 640 x 576, Right: 3D map generated with the captured point clouds

latency of 1 ms is kept with 99.9%. In the setup, however, the median latency is increased from 12 ms up to 25 ms in an eMBB configuration [26].

At this point, it is important to mention that fulfilling all three performance characteristics at once is not possible in the same network. Optimizing a network towards one characteristic leads to a degradation in the other characteristics. 5G uses network slicing to adapt to the needs of the respective use cases. With network slicing, 5G builds different logical networks on the same physical infrastructure. These logical networks meet the different needs of the use cases regarding the quality of services (QoS) characteristics like latency or data rates and also take into account different security needs [27].

Examples of use cases requiring different QoS characteristics are the transmission of critical control messages needing a high reliability but only low data rates, in comparison to the transmission of camera images needing high data rates but a not so high reliability [28].

For application scenarios with high data rates, 5G offers an experienced data rate of 1 Gbps for DL and 500 Mbps for UL for an indoor hotspot [29]. Furthermore, for a message with the size of 15 kB to 250 kB, 5G provides the target values for a transfer interval (latency) of 10 ms to 100 ms [30]. Since the message size of the ROS control messages for our experiment is 17 kB, the transfer interval can be assumed to be somewhere between 10 ms and 20 ms. Both, the data rate and the latency represent a clear improvement over the measured values using the WLAN network. Another advantage of 5G is the possibility to guarantee the specified latency through prioritizing traffic in the network [31]. This allows sending the critical ROS control messages with low latency even if the full bandwidth of the network is used. Therefore, we assume that 5G is suitable for high-bandwidth and time-critical applications on construction sites.

Further, 5G supports higher mobility than WLAN. If the connected device, the mobile robot, drives from one access point to another, it needs to change its connection between different access points. The device using WLAN needs to authenticate itself leading to a momentary loss of connection or significantly higher latency [32]. This limitation is critical for safe on-site operations, given the present trend in the construction sector, which involves many digital sensor systems and robotic machinery. As a result, it is vital to investigate the implementation and use of 5G on construction sites, which can provide high-bandwidth time-critical communication capabilities.

4.2 Challenges for 5G

So far, the use of 5G for wireless communication on construction sites is not yet widely explored. One main problem of the existing research gaps lies in the on-site installation of a 5G network. Unlike most industrial production environments, the workspace of construction sites is subject to continuous changes in infrastructure. In building projects, the workspace keeps changing as the building grows. Also, the environment where the network is deployed is changing as more building components such as walls can cause signal interference. Thus, very high adaptability is required for the deployed 5G network. Another challenge is the possible adverse environmental conditions that a 5G network might be facing on a construction site. Dust, dirt, and water are potential sources of disturbances for equipment and transmitted signals, so their influence on the installation and usage of the network might be challenging.

5 Future Works

This section describes possible research directions related with the use of the 5G network on construction sites:

- To address the aforementioned challenges, future research aims to investigate the requirements of an on-site 5G network and implement the required 5G network architecture first on the reference construction site on Aachen West. Standard network technologies such as WiFi, LoRaWAN, and MQTT are already deployed on the test site. Therefore, the development and benchmark of the designed 5G network can be performed under conclusive and realistic conditions.
- Another line that future research can focus on is the transferability of the developed solution. Most of the time, the developed solutions in research works are isolated without considering the transferability of the solution to other use cases. To avoid this, we aim at investigating the 5G uses in underground and above-ground construction works at the same time. Particularly in the underground works, the investigation of how 5G signals behave in the individual sections of the underground, especially in the expanding last mile, and how it can be propagated over spatially limited distances under adverse conditions, such as mineral dust, humidity, are of great interest. Using the synergy effects of these similar but different environments, we aim to maximize the transferability of the developed 5G solution.

6 Conclusion

Technology such as robotics presents significant opportunities for the construction industry and involved on-site human workers. One fundamental requirement for such emerging technology is that the communication to the robot is stable with a minimum latency and data communication is realized with a minimum delay. In this paper, the clear limitation of the existing WLAN is demonstrated in the context of using a mobile robot for the remote sensing application. In this way, the required specification for the new 5G technology was first defined, and corresponding core characteristics (URLLC, eMBB, and mMTC) were described. Next, the 5G technology's chances for the construction industry and the challenges that might arise from the installation and usage of the 5G technology on the construction sites were shortly described. In the last part, an outlook into future works was established to address the potential challenges.

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