http://dx.doi.org/10.25673/111744

Intralogistics application with a fleet of robots on a private 5G campus network

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Abstract: This paper presents the concept and the current state of implementation of a semi-autonomous robot fleet for logistics applications in a campus environment. The communication is realized via a private 5G SA network. The robot fleet performs its logistics tasks semi-autonomously on campus and can deliver mail or parcels, for example. Sensor data (GPS, camera images, 2D and 3D laser scanners, ...) is sent to a central computing unit in the control center via the 5G interface to analyze and store live data and influence the robot's actions at real time to save costs of the robot and conserve energy to increase operating time. The operator in the control center can intervene in unusual situations at any time and remotely control the robots via 5G. The described system is being tested with a fixed private 5G SA network and a nomadic 5G SA network as public cellular networks are not performant enough in regards to low latency and upload bandwidth. The nomadic network approach opens up further application scenarios such as company premises or events. The system has so far been built and tested with one robot. The expansion of the robot fleet with different platforms is currently in progress.

Keywords: 5G, controlcenter, intralogistics, private network, robot fleet, teleoperator, ROS2

1 Introduction

Logistics tasks arise in many areas of industry and also in the private sector. Size, weight and geometry of the transported goods as well as environment, time schedule and safety makes those tasks highly heterogeneous. The tasks can be very varied in size, weight and geometry of the object to be transported. The completion of these tasks is time-consuming and expensive. If chosen carefully, some tasks can be structured and reduced in complexity to be automated. Due to their clear structure and low complexity of the actual task, they can be automated. In a closed system, such as a fully automated warehouse, this is already state of the art. Structurally more complex environments - e.g. including interaction with people and in heterogeneous environments - automation becomes more complex. In more complex environments and in environments with interaction with people the implementation is much more complicated. The presented concept of a semi-automated logistics system in combination with a private 5G network tries to close this gap. The diversity and complexity created by such an environment are reflected in the concept software requirements, as well

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as the radio communication requirements. Both aspects are explained and illustrated by measurements below.

2 5G and Intralogistics

A semi-autonomous robot fleet that can be centrally managed by one operator places new demands on communication technology. Common non-cellular wireless communication technologies like WiFi or LoRaWAN are not able to fulfill some of the rising demands. These non-cellular wireless communication technologies are still predominant especially in the industrial environment [3]. However, none of them can cover all the aspects that are required to be able to map a multidimensional use case such as this one due to coverage, throughput and latency deficiencies. The deployment of such a fleet of robots raises questions about communications technology.

Can 5G cover the requirements for:

- Remote Control of the Robot?
- Semi-Autonomous Driving?
- Outsourcing Sensor Evaluation?

As an example, uploading 3D point clouds can require a data rate of up to 1 Gbps per robot [5]. These and other questions regarding 5G communications will be addressed and investigated with the use case.

3 System Description

Figure 1 shows the schematic overview of the intralogistics concept where the robot generally drives in autonomous mode and can directly communicate with infrastructure like doors and elevators. Logistics orders can be created and managed by the operator from the

Fig. 1: Schematic System Overview

control station. The robot performs its logistics tasks semi-autonomously, i.e. it is able to independently plan and travel its route to the destination on campus. In its typical operation mode the AGV completes its tasks autonomously and awaits the next order without the operator having to intervene. In the event of an incident (unknown obstacles, roadblock, critical sensor values, etc.), the robot reports to the control station and passes the decision on how to proceed to the operator. If the situation has been bypassed or is not critical, the operator can switch back to autonomous operation. This concept allows the operator to manage and monitor the complete robot fleet. The robot is also able to communicate with the campus infrastructure via 5G and, for example, call the elevator and send it to the desired floor.

3.1 System Architecture

Components of the demonstrated use case are the robot fleet, the control center and the campus infrastructure. All components communicate via the 5G network and make the data available in a centralized data base which is used for a central dashboard in the control center. The individual components are presented in this section.

3.2 Private 5G Network

The campus of RPTU and the area of the adjacent research institutions in Kaiserslautern are covered by five outdoor radio sites. Each site consists of one radio head split into two 2x2 sectors for optimal coverage. The radio heads are connected to the central base band unit (BBU) centrally located in the data center of the university. The BBU is connected to the core whose local breakout is directly connected to the control center hardware and edge cloud for the sensor data offloading. Compared to public cellular networks private 5G networks can be adapted to fit a lot of different applications. Cellular networks have the advantage of predictable network access times through centralized medium access control instead of best effort medium control in Wi-Fi and can therefore achieve lower and more reliable latencies [7]. Using dedicated spectrum, cellular networks do not suffer from interference from surrounding networks and have greater coverage area with one base station. The drawback of cellular networks is higher capex and opex costs compared to enterprise Wi-Fi. Private cellular networks provide high configurability compared to public cellular networks, but require highly trained staff to operate. Table 1 shows the performance of different cellular networks.

	private 5G SA	public 4G	public 5G NSA
Avg. throughput Downlink	~ 700 Mbit/s	~ 90 Mbit/s	~ 240 Mbit/s
Avg. throughput Uplink	~ 300 Mbit/s	~ 18 Mbit/s	~ 110 Mbit/s
Latency	~ 10 ms	~ 25 ms	~ 20 ms

Tab. 1: Performance Data of Cellular Networks [7]

3.3 Intralogistics Robot Hardware

The general idea is a heterogeneous fleet of robots that is adapted to the logistics task at hand. A common carrier platform and different body types for the individual tasks are also conceivable. The robot already built consists of the base (drive unit), the outer webs with sensors and a rugged, industrial computer, and the exchangeable transport box. This transport box is independent of the robot and has its own 5G interface, display and GPS module. The robot is equipped with a comprehensive sensor package, which enables it to operate on a busy site such as a university campus. The sensor package includes safety-relevant sensor technology for the robot and its environment such as the two 2D laser scanners as virtual bumpers on the corners of the robot. A 3D laser scanner to create maps of its environment, and two stereo cameras (front and rear) for remote or autonomous operation. Two easily accessible emergency stop switches on the body can switch off the drive locally, in addition to software emergency stop routines.

Fig. 2: Intralogistic Robot at the RPTU

Figure 3 gives a schematic overview of the internal hardware connections. The Industrial Computer serves as the main computational unit, running open source robotics software as described in details in Section 3.4. Consequently, all sensor, communication and actuation interfaces must finally converge to it on this higher software level. 5G communication with the private network as described in Section 2 is enabled by a Quectel RM500Q module. Low level software in actuation and sensors is handled by a Pixhawk 4, which again connects to Sabertooth motor drivers, a built-in 9-degrees-of-freedom IMU, encoders and a GPS module. The high level sensors are connected to the industrial computer according to Figure 3. The Ouster OS0-128 is a high-resolution 3D LiDAR on top of the robot, which enables navigation in complex environments. Both Sick Tim561 2D LiDARs are mounted on diagonal corners of the robot. They provide safety by minimizing blind angles. ZED2 stereo cameras with a broad field of view at the front and rear of the robot enable video streaming for a remote human operator and can be included in autonomous navigation.

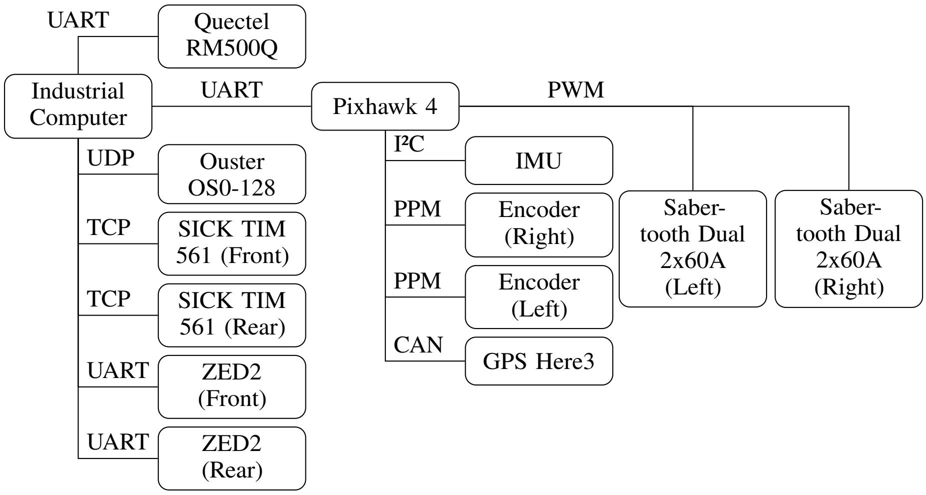

Fig. 3: Intralogistics Robot - Hardware Connection Graph

3.4 Intralogistics Robot Software

The main computational unit runs Robot Operating System 2 (ROS2) as middle-ware software. Robot Operating System is an open-source robotics middle-ware software framework. It provides a flexible distributed software architecture, utilizing Data Distribution Service (DDS) [4] real-time communication. [2]. Consequently, all sensors, communication and actuation must finally converge to the computer on this higher software level. Once data is available within the ROS network, it can be broadcasted to any other network client within the same network - i.e. via 5G.

The entire software stack can be separated into ROS nodes - executables - each communicating via DDS with other nodes forming a graph. Any node within the graph can run on any of the aforementioned network clients - provided they do not have explicit hardware connection. See Figure 3, hardware modules Pixhawk 4 and ZED2 each connect to the ROS graph with their own ROS nodes, yet use UART (USB) communication and therefore must run on the industrial computer. The Quectel RM500Q is not part of the ROS network, but provides operating system level network access. This leaves Ouster OS0-128 and Sick Tim 561 as viable choices to provide access solely via 5G - even if the sensors are physically on the same robot. Still, such architecture lacks justification. Benefits in smaller required local computational power using cloud servers, smaller power consumption or cost in hardware on the robot are insignificant.

Nonetheless, a robot powered by 5G and running ROS can be closely monitored and subject to manual intervention, allowing for adjustments to its behavior or parameters as needed. This creates opportunities for human operators to oversee and manage multiple robots simultaneously, including human emergency backup operation, remote diagnostics and error handling, remote robot operation and decision making in non-accessible or dangerous environment. As an example and simplified:

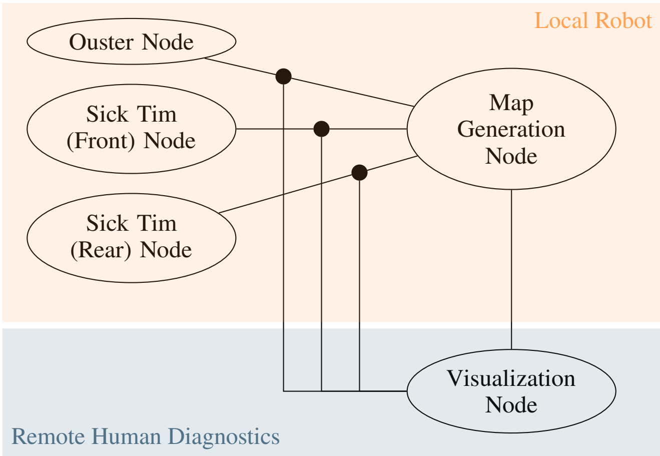

Fig. 4: ROS2 Distributed Software Architecture - Remote Human Diagnostics

Locally some sensor data (e.g. Ouster and two Sick Tim) is transferred to another ROS node which builds a map. An operator can now observe both raw sensor data and the resulting map - where all data is transferred in real-time via 5G. The resulting remote visualization can be seen in Figure 5, where grey and black color represent a global map, white dots

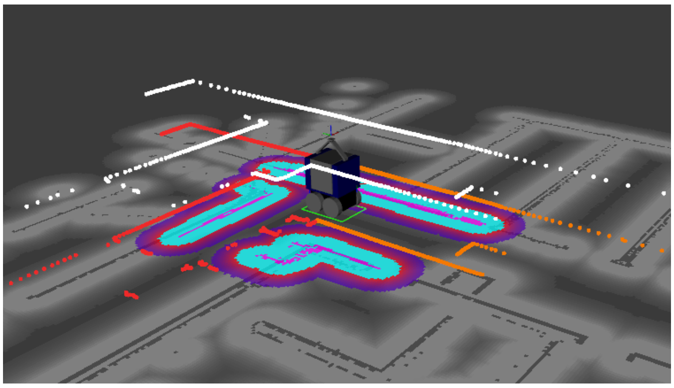

Fig. 5: Remote Diagnostics Visualization

represent a single line of Ouster's 3D pointcloud, and both light and dark orange nuances represent the front and rear Sick Tim respectively. Any node-to-node communication can be observed by an operator, where currently the software opens approximately 50 active nodes and 100 vertices. The requirements in communication for such an architecture is discussed in details in Section 4 and Section 5.

3.5 Control Center

All data generated by and about the 5G network and the robots is systematically gathered and stored within a database, facilitating real-time analysis as well as future utilization. This data repository paves the way for a multitude of applications, such as enhancing artificial intelligence capabilities or the creation of digital twins. The collected data can be harnessed to train and improve artificial intelligence algorithms, enabling more efficient decision-making and automation. By leveraging this data, it becomes possible to create digital replicas or twins of physical systems, aiding in simulations, monitoring, and predictive maintenance. Utilizing historical and real-time data, predictive analytics can be employed to foresee potential issues, optimize operations, and streamline resource allocation. Accurate data can inform resource allocation, helping organizations allocate resources effectively and minimize costs. Real-Time data analysis allows the user to control and monitor the whole process conveniently from a central point.

Fig. 6: Control Center with Operator at the RPTU Kaiserslautern

The operator can access any robot from the fleet at any time from his workstation and display its data separately. An overview map of the complete campus operational area including all current robot locations is provided. In the event of a detected abnormal situation, the operator can display the video streams (front and back) and all sensor data at his workstation to assess the situation and make a decision. This semi-automated process with human-in-the-loop allows constant improvement towards full automation.

4 Differentiation of 5G from other Wireless Technologies

To weigh which of the sensor data can potentially be offloaded to an edge cloud server, knowledge of the required bandwidths is crucial. Safety-relevant data, such as the Sick safety lidar, are not considered further here, since the evaluation of these must always happen on the platform. Table 2 gives an overview of the required bandwidths of the very data-intensive applications such as video and point cloud stream of the ZED and the 3D ouster lidar, where the specified data for the camera applies only to the front camera.

Pointcloud				Video-Stream			
Dots	Lines	Frequency	Data Rate	Resolution		Freuqency	Data Rate
512	128	10 Hz	62 Mbit/s	WQHD	1440p	15 fps	8.5 Mbit/s
1024	128	10 Hz	123 Mbit/s	FullHD	1080p	30 fps	12.5 Mbit/s
2048	128	10 Hz	247 Mbit/s	HD	720p	60 fps	7 Mbit/s

Tab. 2: Required bandwidth of sensor data

An overview of average throughputs and latencies in cellular networks has already been given in Table 1 in Section 2. The following table shows the average throughput and the maximal range in the various WiFi standards.

#	Standard (IEEE)	Frequency	Theoretical Data Rate	Practical Data Rate	Max. Range
4	802.11n	2,4 / 5 GHz	600 Mbit/s	300 Mbit/s	100 m
5	802.11ac	5 GHz	6936 Mbit/s	870 Mbit/s	50 m
6 / 6E	802.11ax	2,4 / 5 / 6 GHz	9608 Mbit/s	1200 Mbit/s	50 m

Tab. 3: Data throughput of WiFi [6]

The specified theoretical data rate corresponds to the calculated maximum of the data rate, taking into account all performance features provided for in the respective standard. In practical implementation, however, there are limitations due to which this data rate cannot be realized. A practical data rate that is closer to the WiFi equipment in practice is therefore more suitable for comparing WiFi standards. The specified practical data rate corresponds to the data rate that is usually possible with purchasable devices. Two antennas and a channel width of 80 MHz in the frequency range of 5 GHz are taken into account. Depending on the equipment, the value of this practical transmission rate can also be higher or lower.

Figure 7 qualitatively differentiates actual WiFi from public mobile radio standards such as 5G and LTE. Especially in use cases of autonomous driving in complex large public environments like the university campus in Kaiserslautern with adjacent research institutes show the necessity of using 5G. While LTE simply offers too little bandwidth, the coverage of WiFi is insufficient and justified by only small ranges of the access points. In addition, the bandwidth of WiFi networks decreases significantly and latencies even more, especially in busy environments with many end devices. 5G offers a variety of methods to minimize these disadvantages and to adapt the network more optimally to the needs of the respective network subscribers. Examples include carrier aggregation, the possibility of using small cells or multi-antenna systems (MIMO), variable alignment to the end device (beamforming) and virtually shared networks (networkslicing). Another key benefit of using 5G is significantly lower latency. This is particularly crucial for applications in which robots in busy environments have to be controlled remotely from the control center.

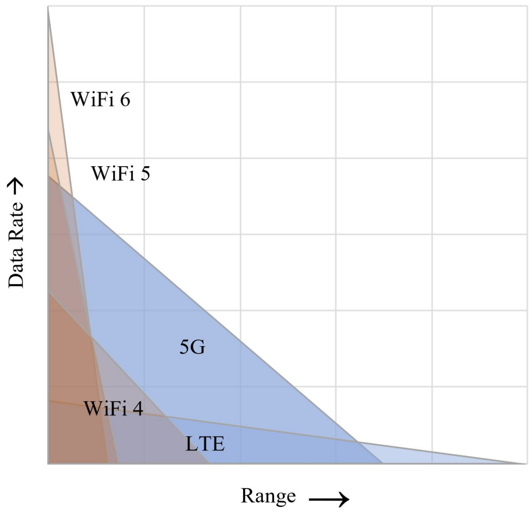

Fig. 7: Qualitative delimitation of WiFi, LTE and 5G

5 Conclusion and Future Work

The presented concept and implementation shows a possible handling of robotics applications in a busy environment like a university campus. A fully autonomous operation would be difficult both legally and technically. Nevertheless, the semi-autonomous approach with an operator in the control center allows an economical use of the robot fleet [1]. In the future, the existing robot will be joined by robots of other designs and their operation tested in terms of manageability by the operator and utilization of the 5G network.

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