REPORT ON SYSTEM DESIGN OPTIONS AND 5G/6G SETUP FOR EDGE ROBOTICS

Deliverable D2.2

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SHORT ABSTRACT	This document outlines a use case design and implementation options for edge-controlled robotics assembly in WP2. It focuses on the Line-less Mobile Assembly Systems' integration with 5G/6G connectivity, providing a requirement analysis and introducing four design options for advancing real-time communication in edge robotics.
KEY WORDS	Design options, testbed, edge robotics, manufacturing, 5G, 6G, real-time, mobile manipulator
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Executive Summary

The deliverable details the system design and implementation options for the edge-controlled robotics assembly (edge robotics) use case within the Work Package 2 (WP2) – Manufacturing. The primary focus is on the Line-less Mobile Assembly Systems (LMAS) and their seamless integration with 5G/6G connectivity at the *Werkzeugmaschinenlabor* (German) or Laboratory for Machine Tools and Production Engineering (WZL) of the *Rheinisch-Westfälische Technische Hochschule* (RWTH) Aachen University. The document aims to provide a 5G requirement analysis for various applications and communication streams involved in the use case, specifically using mobile manipulation. It also defines the intended 5G/6G technologies for the use case. Additionally, the document introduces four design options for the implementation phase, considering hardware and software aspects, and addressing components such as motion planning, object detection, and the communication layer's evaluation. The overall goal is to provide insights for the advancement of 5G/6G connectivity technologies in the field of edge robotics, using the WZL testbed for the development and analysis of communication stream requirements.

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List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
AGV	Automated Guided Vehicle
AI/ML	Artificial Intelligence/Machine Learning
CI/CD	Continuous Integration and Continuous Deployment
Connext DDS	Connext Data Distribution Service
CycloneDDS	Cyclone Data Distribution Service
DDS	Data Distribution Service
DOF	Degrees of Freedom
E2E	End-to-End
Fast RTPS	Fast Real-Time Publish-Subscribe
FIVE	Fivecomm
FR	Frequency Range
GPS	Global Positioning System
IMU	Inertial Measurement Unit
JCAS	Joint Communication and Sensing
LMAS	Line-less Mobile Assembly Systems
LiDAR	Light Detection and Ranging
MPC	Model Predictive Control
NR	New Radio
NSA	Non-Standalone
NW	Network
OMPL	Open Motion Planning Library
PRM	Probabilistic Roadmap
QoS	Quality of Service
QP	Quadratic Programming
RAN	Radio Access Network
RF	Radio Frequency
RRT	Rapidly Exploring Random Tree
ROS	Robot Operating System

ROS1	Robot Operating System 1
ROS2	Robot Operating System 2
RMW	ROS 2 Middleware
RWTH	Rheinisch-Westfälische Technische Hochschule (German)
TSN	Time-Sensitive Networking
TTFF	Time To First Fix
UE	User Equipment
URLLC	Ultra-Reliable and Low-Latency Communication
WZL	Werkzeugmaschinenlabor der RWTH Aachen (German)
WZL	Laboratory for Machine Tools and Production Engineering of RWTH Aachen University
WP1	Work Package 1
WP2	Work Package 2
WP6	Work Package 6

1 Introduction

In response to the manufacturing industry needs driven by factors such as a shortage of skilled workers, heightened market volatility, and the increasing demand for mass customization, there is a critical imperative for flexible automation solutions [1]. Traditional manufacturing paradigms, often rigid and reliant on fixed assembly lines, are proving insufficient in addressing these challenges [1]. This necessitates innovative approaches to automation that can seamlessly adapt to evolving production demands. The Line-less Mobile Assembly Systems (LMAS) emerges as a solution to these industry imperatives, with a specific focus on harnessing mobile robotics to facilitate product assembly by either transporting resources to robots or relocating robots to resources, allowing for continuous adaptation and optimization of production through the free allocation of jobs, goods, resources, time, and work locations within the factory [1].

The transition to assembly matrices from traditional assembly lines necessitates the deployment of assembly resources, with mobile robots being a prominent choice in this domain, where mobile manipulators have garnered widespread recognition for their suitability in LMAS scenarios. For an assembly system to meet the requirements of LMAS, it must exhibit adaptability by addressing critical technological challenges, such as adaptive control of mobile robots, adaptive process control strategies, and adaptive path planning [2]. In LMAS, assembly resources can move actively or passively [3]. Passively moving resources can be picked up by actively moving resources, underscoring the need for robotic perception capabilities. By enabling real-time object detection as demonstrated in recent studies [4] and [5], AI-based vision algorithms empower robots to autonomously adjust their actions and decision-making processes, ensuring seamless task execution across a variety of assembly scenarios.

Within this framework, the adoption of 5G/6G communication technologies becomes indispensable for LMAS, as the cutting-edge capabilities of 5G/6G enable seamless communication between mobile robotics and control systems, such as local servers with edge capabilities (edge cloud systems), facilitating the dynamic adaptation of assembly processes to evolving production demands. Figure 1.1 illustrates an assembly matrix in LMAS scenario with edge cloud capabilities.

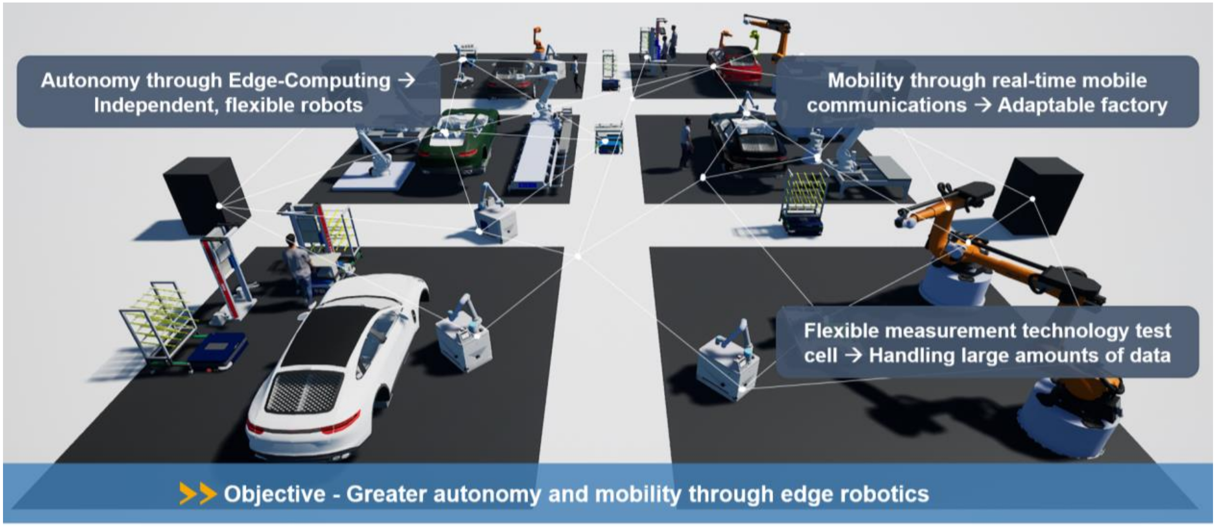

Figure 1.1: Illustration of an assembly matrix in LMAS with edge cloud capabilities. Each assembly station is an element of the assembly matrix. Source: adapted from [6].

In this context, the TARGET-X Work Package 2 (WP2) – Manufacturing, has as one of its goals to apply and test new 5G/6G functionalities for a use case of edge-controlled robotics assembly (edge robotics), responding to the demands of the manufacturing industry. Fomented within the WP2, the use case was titled "Edge-Controlled Automation with Mobile Manipulation".

This use case will be developed at the testbed of the *Werkzeugmaschinenlabor* (German) or Laboratory for Machine Tools and Production Engineering (WZL) of the *Rheinisch-Westfälische Technische Hochschule* (RWTH) Aachen University [7]. The WZL testbed exemplifies the practical application of LMAS, showcasing the potential of mobile manipulation and agile robotic systems, by leveraging 5G/6G connectivity in the context of the manufacturing industry.

Within the scope of the TARGET-X project, as a deliverable, there is the need to explore the intended use case system design and its implementation options, while establishing 5G/6G requirement analysis for the various applications and communication streams involved in the use case. Therefore, the need for this document as Deliverable 2.2 of the WP2. The terminology used in this deliverable is based on the common terminology of the project TARGET-X, which is available as a public contribution from TARGET-X on the project website [8].

1.1 Objectives of the document

The main objective of this document is to provide a 5G/6G requirement analysis for various applications and communication streams involved in the "Edge-Controlled Automation with Mobile Manipulation use case" in the context of LMAS and the integration of an edge cloud system. It also aims to define both functional and non-functional requirements associated with 5G technology, as well as provide insights for the intended advancement of 5G/6G connectivity technologies in the field of edge robotics at the WZL testbed. The document also seeks to explore four design options for implementing the use case, considering hardware and software aspects, and addressing technological aspects such as motion planning, object detection, and the communication layer's evaluation.

1.2 Structure of the document

The document is structured as follows. Section 1 is an introduction to the deliverable including the objective of the document and its structure. In Section 2, the testbed at WZL is described, providing details about the infrastructure, assets, measurement systems and the 5G Setup, with a focus on the LMAS concept. Section 3 delves into the 5G/6G setup of the use case for an edge-controlled automation with mobile manipulation. The use case is then first described, by covering aspects such as motion planning, object detection and communication layer performance evaluation. After exploring and defining the communication streams involved in the use case, the requirements towards 5G are defined. Additionally, Section 4 intends to explore the design options for the implementation phase of the use case, detailing hardware, and software setups, as well as four different implementations options for motion planning & control, each with its unique approach. The document concludes with a section that summarizes the achieved requirement analysis, the intended 5G/6G technologies, and the implementation options for the edge robotics use case within the manufacturing industry.

1.3 Relation to other activities

The content provided in this deliverable is closely related to other activities carried out in other WPs of the TARGET-X project. In particular, the initiatives related to establishing 5G network requirements and aligning use case requirements across TARGET-X verticals, led by WP1 (Methodological assessment framework) and WP6 (Technology evolution beyond 5G) as outlined in deliverable D1.1. These were essential in shaping the 5G setup of the deliverable D2.1 and the present document (D2.2) within WP2 (Manufacturing). Additionally, activities pertaining to the examination of the energy footprint in manufacturing use cases from WP3 (Energy) has strong dependence on the development of the WP2 use cases and therefore its deliverables, particularly for D2.2 concerning the installation of a device on the mobile manipulator. This integration is further detail in deliverables D3.1 and D3.2. Moreover, collaborative efforts between WP2 and WP6 resulted in the identification and definition of beyond 5G technologies for the specific use case outlined in WP2. These advancements are detailed in deliverables D6.1 and D6.3.

2 Testbed at WZL | RWTH Aachen University

In this chapter, the testbed at WZL is described, providing details about the infrastructure, assets, measurement systems and the 5G Setup integrated with a factory cloud system within a LMAS scenario.

2.1 Description of the testbed

The development of the use case involving assembly and mobile robotics will take place within WZL's state-of-the-art testbed, depicted in Figure 2.1. The testbed is equipped with a diverse array of robots, authentic industrial product scenarios, expansive metrology systems, and a 5G/6G indoor network as part of the 5G-Industry Campus Europe (5G-ICE) [9] initiative. The robotic fleet within this facility is notably heterogeneous and can be operated using an open-source control architecture based on the open-source middleware Robot Operating System (ROS). The available robots encompass autonomous mobile robots, including the *Imetron Donkey-Motion*, *BÄR-Automated Guided Vehicle* (BÄR-AGV), *Festo Robotinos, Boston Dynamics' Spot,* and *Broetje Mobile Heavy-Duty Manipulator*. In addition to these, there are several mobile manipulators (2x *Robotnik RB-Kairos+ UR10 & 1x KUKA KR120*) and multiple semi-stationary industrial robots, one ABB IRB 4600 on a linear-axis and two on movable platforms.

Figure 2.1: Testbed at WZL. Source: provided by WZL | RWTH Aachen University [7].

For conducting real industrial process tests, industrial products sourced from automotive, truck, or aerospace assembly procedures from prior research projects are at disposal. In terms of large-scale metrology systems, WZL offers an array of measurement systems suitable for precise benchmarking of localization issues within a 125 m² area. Depending on the desired level of measurement accuracy, one can utilize the indoor Global Positioning System (GPS) system (offering 0.2 mm multi-target tracking), the motion-capturing system *OptiTrack* (providing 0.4 mm dynamic multi-target tracking), or a *Lasertracker* system (with 0.1 mm one-on-one tracking capabilities).

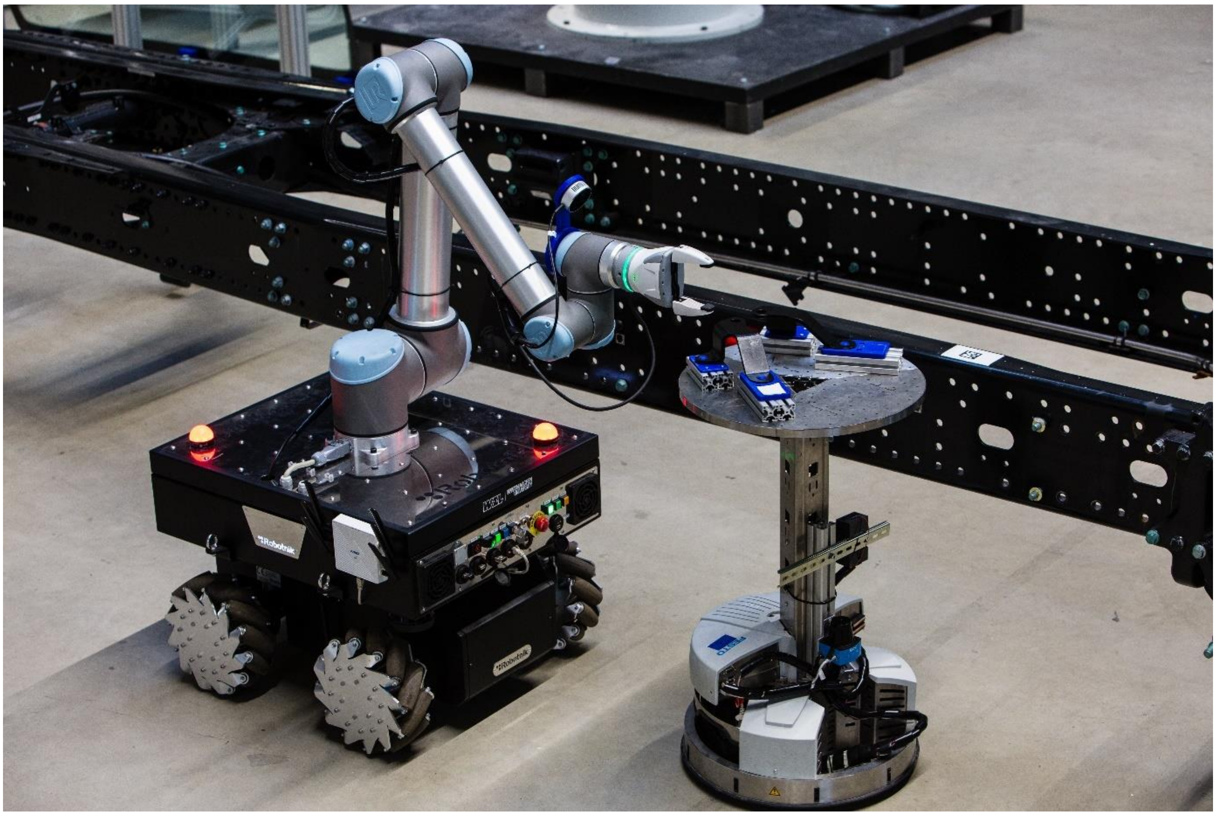

Figure 2.2: Mobile manipulator Robotnik Kairos UR10 and a Festo Robotino displayed in an industrial setting at WZL's testbed. Source: provided by WZL | RWTH Aachen University [7].

Additionally, the Ultra-Reliable and Low-Latency Communication (URLLC) testbed, located at Fraunhofer IPT, can be relocated to the adjacent shop floor at WZL. The existing infrastructure is available for the development, implementation, and validation of the testbeds (use cases). This laboratory faithfully emulates a modern industrial shop floor, ensuring that research results can be seamlessly applied to industry settings.

2.2 Factory Cloud System

An essential component of LMAS is a large communication network, that not only facilitates communication among actuators and sensors, promoting adaptability and flexibility in the manufacturing process, but it also integrates substantial computing resources such as edge cloud of multiple factory cloud systems. The term "factory cloud" refers to a local server system located near the assembly stations with cloud capabilities [10].

A factory cloud system in LMAS requires the deployment of mobile manipulators, creating temporary production cells in assembly stations. The factory cloud system can manage and control the deployment of these resources, coordinating the movements of mobile robots and other assembly assets to optimize the assembly process, ensuring that tasks are executed seamlessly. In Figure 1.1, one can see the illustration of an assembly matrix in LMAS, where each element (assembly station) of the presented assembly matrix is controlled by an edge cloud (factory cloud) system.

One factory cloud system is available at the testbed of WZL, which will be used for the development of the use case. The factory cloud system at WZL is mainly composed of a local server with cloud capabilities integrated to a 5G Non-Standalone (NSA) indoor network as part of 5G-ICE. Further technical specification of the local server is provided in Section 4.1.

3 Edge-Controlled Automation with Mobile Manipulation

This section describes the intended use case and its 5G/6G setup for the application scenario of edge robotics fomented within WP2 for the automation of an industrial task. The section first introduces an overall description of the intended use case by describing the expected storyline, layout, and the communication among its components. Subsequently, the section dives into the three main submodules of the application use case, substantiating their necessity: the planning & control of motion of the mobile manipulator, the picking of objects using object detection algorithms, and the possibility of performing a middleware evaluation for the communication layer. Once the communication streams associated to the submodules are clearly identified, the connectivity requirements for the application scenario are then defined. Additionally, the intended beyond 5G technologies (features) are indicated.

3.1 Use case description

The use case in edge robotics within the WP2 seeks to combine advanced technologies such as machine vision, transfer learning, mobile manipulators, and 5G communication to automate the industrial task of bin-picking or pick & place. It is also intended that the use case showcases the benefits of real-time decision-making, improved planning and control of motion, and efficient communication enabled by Beyond 5G technologies. The evaluation of different middleware setups and the performance assessment of the communication layer ensure optimal system performance and enhance the overall efficiency of the bin-picking operation.

The general storyline of the use case is described in the following automated tasks and in Figure 3.1. There, mobile manipulator:

1. Localizes itself on the shop floor.
2. Approaches an assembly station represented by a desk or bin.
3. Moves its arm into a scanning pose to scan the industrial object.
4. Detects the Object.
5. Moves its end-effector to the desk or bin, closes the gripper and removes the object.
6. Moves its arm into a transport pose for safe handling.
7. Navigates to the second assembly station (represented by a second desk or bin).
8. Moves its arm into a scanning pose to scan placing space.
9. Moves its end-effector to the second desk or bin, open the gripper and releases the object.
10. Navigates back to its initial starting position.

In this use case, the robot's control functions are transferred from factory cloud system to the robot's onboard system (downlink), whereas the sensor and camera data are transmitted from the robot to the factory cloud (uplink), as depicted in Figure 3.2. Within the factory cloud system, the robot controller computes the path the robot should follow and makes decisions about how to navigate its surroundings, considering obstacles [10]. The intelligence and the decisions rely on data transmitted by the mobile robot's sensors to the factory cloud system through wireless communication (uplink).

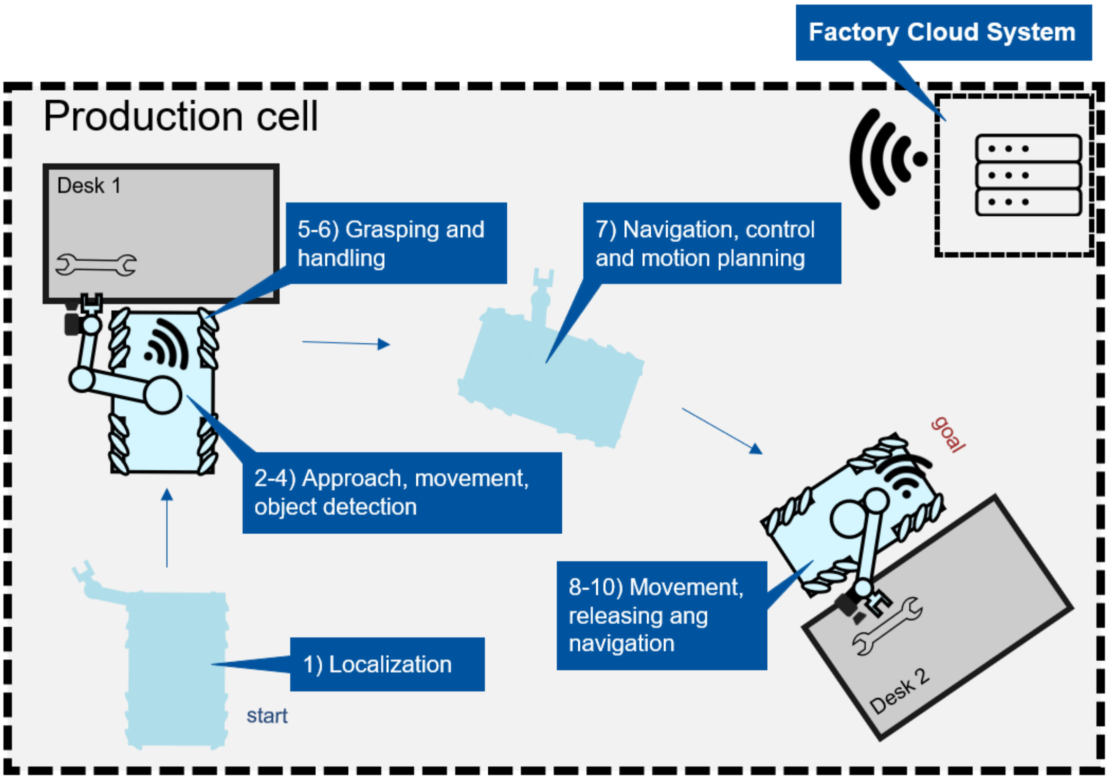

Figure 3.1: Execution of localization, navigation, perception, and motion planning on the edge cloud System. Source: provided by WZL [7].

Mobile Manipulators enable new sets of use cases, and to make them a reality, it's crucial to have dependable real-time communication for these robots. Establishing reliable real-time communication between the mobile manipulators and the factory cloud system facilitates collaborative decision-making tasks and advanced AI/ML techniques, which were previously impossible when relying solely on onboard processing in the robots [10].

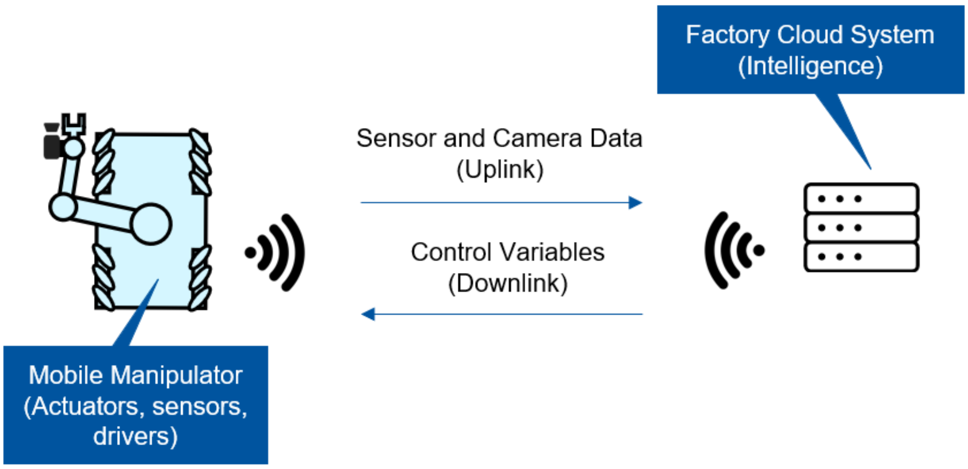

Figure 3.2: Communication between mobile manipulator and the factory cloud system. Source: provided by WZL [7].

3.1.1 Planning & Control of Motion

Mobile manipulators have great potential but face challenges in localization, navigation, and obstacle detection. Safe human-robot cooperation is limited by sensor technology. The main limitation is speed, detection, and reaction time. 5G technology addresses these issues by providing low-latency, high-reliability communication, enabling mobile manipulators to connect to factory cloud systems, offloading computational tasks for complex algorithms related to localization, motion planning and obstacle detection [10].

A mobile manipulator usually has 9 Degrees of Freedom (DOFs) or higher (3-DOF mobile platform and 6-DOF robot manipulator), making the system kinematically redundant. This redundancy allows the system to be flexible when operating in complex environments but complicates the planning process as there are infinite solutions to the inverse kinematics problem (reaching a specified goal pose), as illustrated in Figure 3.3. In this regard, motion planning and reactive controllers play a crucial role, as it can determine the trajectory of robots while avoiding collisions with obstacles.

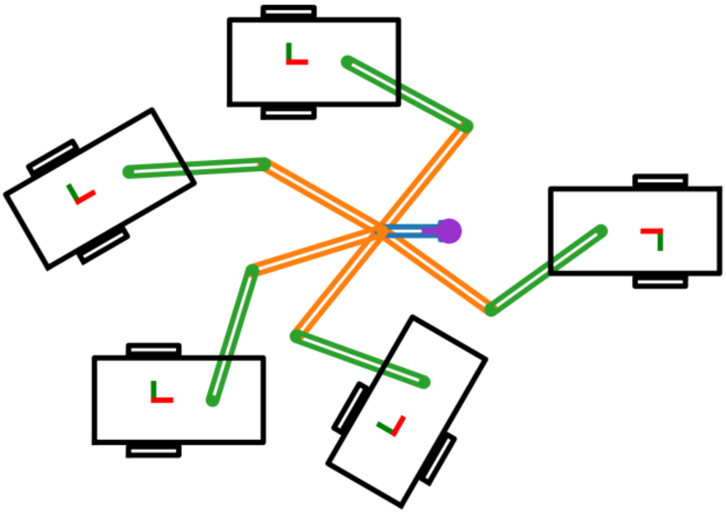

Figure 3.3: Different configurations for reaching the same goal. Source: [11].

Motion planning is one of the fundamental fields of research in robotics and its primary goal for mobile manipulators is to enable them to both move in their environment (as mobile robot) and manipulate objects or perform tasks (as manipulators) in either in a sequential or simultaneous motion. This involves developing algorithms and strategies that allow the robot to autonomously plan and execute movements while avoiding obstacles, ensuring stability, and achieving its tasks efficiently.

Alternatively, reactive controllers for mobile manipulators can improve the speed and fluidity of motion, making the system more efficient in performing tasks, offering a valuable tool in robotics research and practical applications where agile, adaptable, and efficient mobile manipulation is required for the automation of an industrial task such as Picking of Objects using Object Detection.

For planning and controlling, mobile manipulators rely on cameras, LiDAR, depth sensors, and proximity sensors, to perceive their environment. These sensors provide data about the robot's surroundings, including obstacles, objects, and the configuration of the environment. In the context of the 5G/6G setup for the factory cloud system, there are two main communication streams involved in the planning and control of the mobile manipulator motion: the LiDAR sensors and the control variables. Network requirements regarding these communication streams will be further discussed in Section 3.2.

In summary, reducing the execution time of automated industrial tasks is a significant benefit of the motion planning algorithms and reactive controllers for mobile manipulators, specifically if algorithms are employed considering simultaneous motion (base + arm) in the industry. This reduction in execution time is advantageous since it improves efficiency, productivity, adaptability, energy savings, and competitiveness. This results in cost savings, improved resource allocation, and enhanced performance across production systems in the LMAS context.

3.1.2 Picking of Objects using Object Detection

The pick and place task integrated with object detection is a cutting-edge technology that has revolutionized various industrial processes, particularly in the field of automation. One notable application of this technology is bin-picking with machine vision and transfer learning. The industrial task of bin-picking involves the automated extraction of objects from a bin, a task that was traditionally performed manually by human workers. This process often demands high precision and speed, making it well-suited for automation.

The object detection via pose estimation integrated into the pick and place system helps identify and locate objects within the bin or deposed over a desk, enabling a robotic arm (manipulator) or gripper to precisely pick and place the items as required, as shown in **Error! Reference source not found.**. This application is commonly seen in industries such as manufacturing assembly.

Figure 3.4: On the left is the generated synthetic data used for the training of the pose estimation algorithms for object detection [7]. On the right is the pick and place with object detection [12].

Real-time communication is vital for the success of these systems. The camera stream is the key communication stream, transmitting video and image data from the camera to robots to the factory cloud system. Additionally, communication from the factory cloud system to the robot ensures fast decision-making and can be facilitated through 5G/6G, enhancing the system's performance. Network requirements regarding this communication stream will be further discussed in Section 3.2.

3.1.3 Performance evaluation of the communication layer

In this use case, a performance assessment study is intended to occur in parallel to the implementation. This study involves evaluating the performance and security of various robotics middlewares that use the communication layer of the Robot Operating System 2 (ROS2), as shown in **Error! Reference source not found.**.

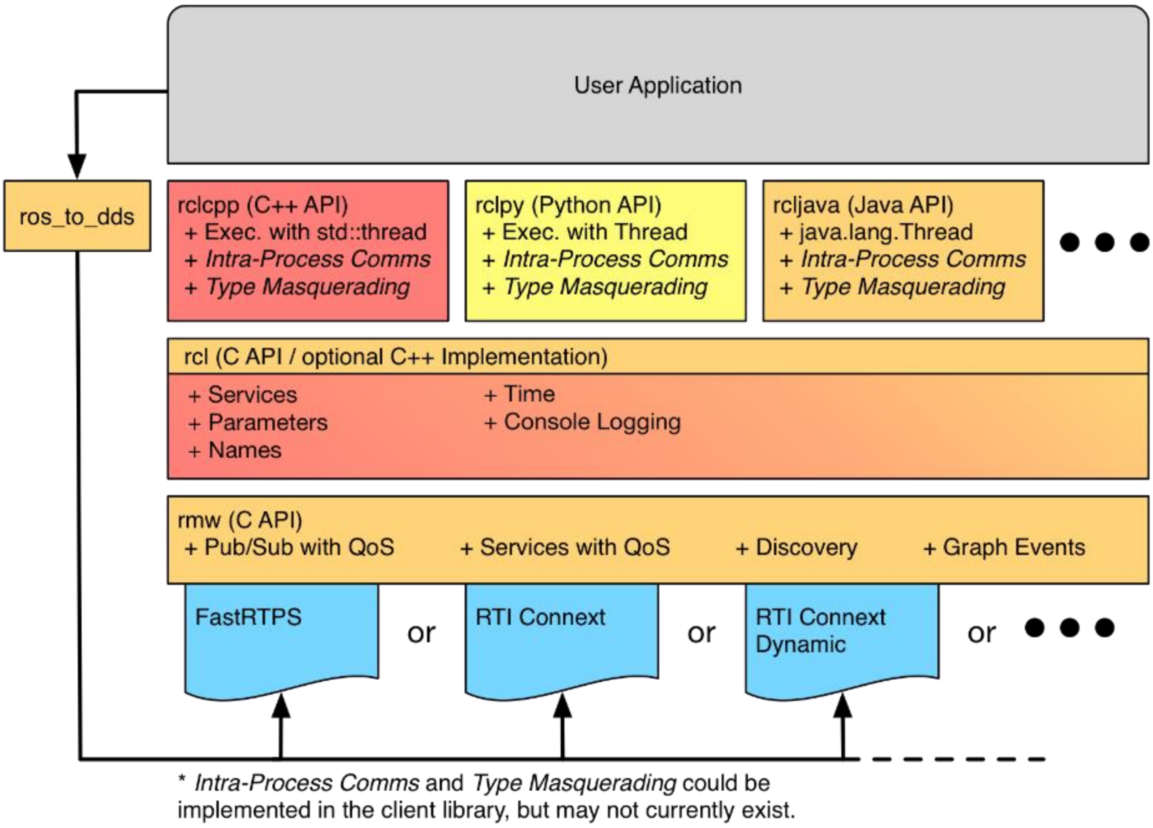

Figure 3.5: ROS2 Architecture Overview [13].

Middleware for robotics development must meet demanding requirements for real-time distributed embedded systems. However, the ROS1 is not suitable for real-time embedded systems because it does not satisfy real-time requirements and only runs on a few operating systems. To address this problem, ROS1 is undergoing a significant upgrade to ROS2 by utilizing the Data Distribution Service (DDS). Therefore, the assessment study will only take place for the Design Options 3 and 4, described in Sections 4.3.3-4.3.4.

The evaluation of communication layer aims to identify the strengths and weaknesses of each middleware, with a focus on their ability to handle high volumes of data, maintain real-time communication between distributed robotic systems, and provide secure data transfer. To conduct the evaluation, various ROS Middleware (RMW) implementations will be tested, including Fast RTPS, CycloneDDS, Connext DDS, and Zenoh. Each RMW implementation will be assessed based on metrics such as data rate, frequency, latency, throughput, scalability, and security features. The results will be compared to determine which middleware is most effective in meeting the 5G/6G requirements for mobile robotics applications in all its communication streams. The evaluation will be performed during the implementation phase and its results will be described in deliverables D2.3 and D2.5.

3.2 Requirements towards 5G

This section outlines the network needs for the "Edge-Controlled Automation of Industrial Tasks using Mobile Manipulators" scenario, focusing on its reliance on 5G/6G connectivity. It's crucial to note that the criteria and terminology defining these requirements were established in WP1, ensuring a consistent portrayal of the use cases across the TARGET-X verticals and testbeds. Further details are given in D1.1.

After considering the WZL testbed and its network infrastructure, it was defined among WP1, WP2 and WP6, that the 5G connectivity for the intended use case scenario needs to support the following basic features based on the functional requirements established in WP1 for the Unification of Use Case Descriptions (also described in D1.1):

1. *Network configuration management* is required for monitoring and managing the system that is provisioned for the 5G testbed. This is essential to allow specifying application service properties such as Quality of Service (QoS) demands, collecting network-related performance metrics and deploying software in the factory cloud system by authorized applications.
2. *Mobility management support* is required for the end devices, such as the mobile manipulator with the mobility demands that fit to the limited-size space of a factory or production cell.
3. *End-to-end (E2E) QoS support* is required for communication services with QoS demands in terms of latency, reliability and/or average throughput, covering all required segments of the 5G system (e.g. access and core networks).

For the advancement of 5G technologies in the TARGET-X use cases, it is crucial to clearly outline what communication streams (data flows) are part of the use cases. In this context, in collaboration with WP1 and WP6, an analysis of the intended use case scenario and its submodules was made to clearly define the communication streams involved. The following communication streams were then defined, as illustrated in Figure 3.6:

- Camera stream (raw color images but in a compressed format) – Uplink.
- LiDAR sensors (2D inner LiDAR scanner and 3D mounted point cloud LiDAR scanner) – Uplink.
- Control variables (including Base and Arm of the mobile manipulator) – Downlink.

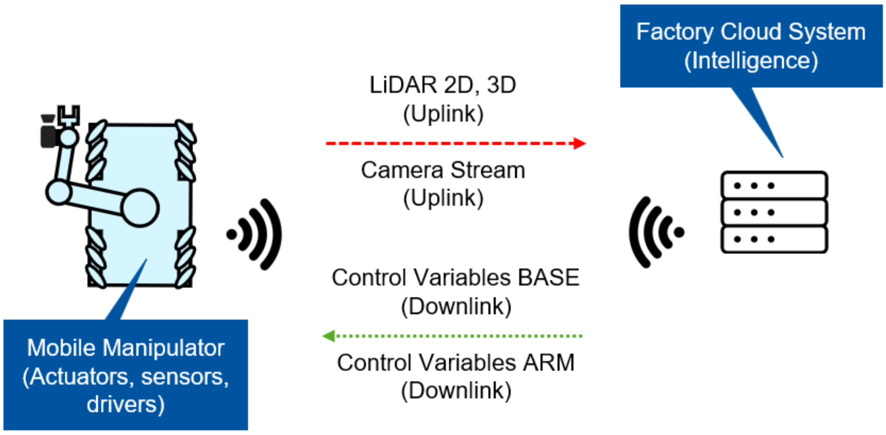

Figure 3.6: Communication streams (data flow) involved in the edge robotics use case. Source: provided by WZL [7].

Even though, it is presented 2D and 3D LiDAR sensors in this use case, a decision whether to adopt the mounted 3D point cloud LiDAR scanner is still pending on the choice if the implementation options presented in Section 4. The design options 1-3 favor the utilization of only 2D inner LiDAR sensors, whereas the design option 4 favors the use of both 2D and 3D LiDAR sensors, this will be decided in the implementation phase.

Following the definitions, parameters for the performance requirements of each data flow of the use case scenario were defined. The parameters such as average data rate, latency and availability were introduced by WP1 across all the TARGET-X verticals to seek differentiation among the communication streams.

The Table 1 presents the performance requirements values for the given use case scenario. The data showcased in the table is derived from a set of measurements conducted at WZL testbed via ROS commands while running the current full-stack implementation, complemented by informed estimations and extrapolations leveraging the expertise of both WP6 and WZL (WP2).

Table 1: Performance requirements for each data flow of the use case.

DATA FLOW		AVERAGE DATA RATES (Mbit/s)	LATENCY (ms)	AVAILABILITY (%)
CAMERA		> 17	$< L_{ARM}$	≥ 99.99
LIDAR SENSOR	2D	> 3	< 40	≥ 99.99
	3D	> 52	< 40	≥ 99.99
CONTROL VARIABLES	BASE	> 3	< 40	≥ 99.99
	ARM	> 6	$L_{ARM} < 11$[1]	≥ 99.99

The average data rate of the camera stream was obtained via ROS commands (for bandwidth) of the ROS topic *raw color images compressed*. For the inner 2D LiDAR, the average data rate was obtained via ROS commands (for bandwidth) of the topic *merged laser*, which merges data from 2 x 2D LiDAR sensors inner to mobile manipulator, whereas the mounted 3D LiDAR, was obtained via ROS commands (for bandwidth) of the topic *velodyne* (name of the vendor) points. For the control variables of the base, the average data rate was obtained via ROS commands (for bandwidth) of the topic *cmd_vel* (associated to the *teleop* ROS package). Since the ROS implementation of the arm in the full stack is still in progress, the values of the control variables of the arm were then estimated based on the number of DOFs and necessary commands variables. All the values in the average data rates column were set to be the minimum expected value for the use case to work seamlessly.

The latency values displayed in Table 1 correspond to a transport latency, in a since that these values were not obtained via air, given that the measurement of such values would require an experimental setup that is not available at WZL testbed. Additionally, latency measurements of the current 5G network at WZL testbed are out of the scope of the D2.2. In this context, the transport latency values were calculated considering the associated speed of the User Equipment (UE) and a given tolerance (distance) based on the expected position of the robot. The maximum UE speed is given in Section 4.1 and the set (desired) speed for the use case is given in Table 2. The time value (latency) here would be based on the reaction of the robot's movement within the expected position. For the control variables of the base of the mobile manipulator, a tolerance of 1 cm was considered (based on WZL researchers). The calculated value associated with the control variable of the arm is stricter because the speed here is holistic (base + arm), and the tolerance for the position of the arm movement is also stricter, where the repeatability between sending a goal pose and actual robot pose would be 5 mm by default. Assuming that the obtained value is a minimum criterium L_{ARM}, the camera stream should have a lower transport latency than the L_{ARM}, since the camera is attached to the end effector of the arm. The speeds of the LiDAR sensors are the same as the base and assuming a similar tolerance as the control variable of the base, it was then obtained the same values of transport latency.

The rationing for the above calculations was conducted in conjunction with WP6 experts. The availability is a desired parameter for the seamless performance and execution of the use case, and it was set at 99.99 % for all the communication streams after consultation with WP6. One can notice that for each data flow, the values of average data rate are different (as well as for some values of transport latency), that confirms the different network demands of each communication stream.

Subsequently, complementary parameters for the performance requirements of each data flow of the use case scenario were also established. The parameters such as message size, transfer interval, UE speed, number of UE and service area were again introduced by WP1 across all the TARGET-X verticals to seek differentiation among the communication streams.

The Table 2 presents the complementary performance requirements values for the given use case scenario. The data showcased in the table is also derived from the same set of measurements conducted at WZL testbed via ROS commands while running the current full-stack implementation, complemented by informed estimations and extrapolations leveraging the expertise of both WP6 and WZL (WP2).

Table 2: Complementary requirements for each data flow of the use case.

DATA FLOW		MESSAGE SIZE (Bytes)	TRANSFER INTERVAL (ms)	UE VELOCITY (m/s)	# UE	SERVICE AREA (m²)
CAMERA		70 k	40	0.45	1	20
LIDAR SENSOR	2D	35 k	120	0.25	1	20
	3D	640 k	100	0.25	1	20
CONTROL VARIABLES	BASE	50	500	0.25	1	20
	ARM	100	10*	0.45[1]	1	20

The message size of the camera stream was also obtained via ROS commands (for bandwidth) of the ROS topic *raw color images compressed*, considering the maximum output value. For the inner 2D LiDAR, the message size was also obtained via ROS commands (for bandwidth, also considering the maximum outputted value) of the topic *merged laser*, whereas the 3D LiDAR, was obtained via ROS commands (also for bandwidth and considering the maximum outputted value) of the topic *velodyne* points. For the control variables of the base, the message size was obtained via ROS commands (for bandwidth, considering the maximum output value) of the topic *cmd_vel*. Since the ROS implementation of the arm is still in progress, once again the values of the control variables of the arm were then estimated based on the number of DOFs and necessary commands variables. The different values for each data flow reflect the different volumes of data that each communication stream needs to transfer for the seamless work of the use case.

In a similar procedure, the transfer interval of the camera stream was also obtained via ROS commands (for frequency) of the same previously mentioned ROS topic, considering the maximum output value. For the inner 2D LiDAR, the transfer interval was also obtained via ROS commands (for frequency considering the maximum outputted value) of the same previous mentioned ROS topic, whereas the 3D LiDAR, was obtained via ROS commands (for frequency considering the maximum outputted value) of the topic *velodyne* points. For the control variables of the base, the transfer interval was obtained via ROS commands (for frequency, considering the maximum output value) of the topic *cmd_vel*. Since the ROS implementation of the arm is still in progress, the value for transfer interval was obtained directly from the technical specification of the UR10 arm, as indicated in Section 4.1. The differences for each data flow once again reflect the different needs of each communication stream.

Moreover, the UE speed value was set based on the desired speed of the base of the manipulator for the intended case, being an admissible speed at WZL testbed, commonly used by our researchers. As indicated before, the speed of the arm was considered in the best case of holistic (simultaneous) movement of base + manipulator. Additionally, one UE was considered for each communication stream of the intended use case, even for the 2 x 2D inner LiDAR sensors, since their data are merged

[1] Calculation based on the speed of Base + Arm = 0.25 m/s (desired) + 0.2 m/s (default)

in one ROS topic. The service area was indicated considering the necessary are for the execution of the intended use case.

3.3 Beyond 5G features intended for the use case

Besides using the current available 5G features, different technologies are intended to be tested and validated in collaboration with WP1 and WP6 to match the defined network requirements of the use case. More details about these technologies and their characteristics are given in D6.1. Upon consultation with WP6, the following technologies are intended for the use case "Edge-Controlled Automation with Mobile Manipulation":

Service Differentiation & Network (NW) Convergence (QoS): In the context of 5G and the upcoming 6G evolution, service differentiation involves tailoring diverse services through advanced technologies, while network convergence aims to unify different networks for a seamless user experience. Quality of Service (QoS) classes prioritize traffic, but a comprehensive strategy is essential as network traffic patterns evolve. Technologies like Radio Access Network (RAN) slicing, and traffic steering optimize spectrum usage. As 6G introduces new spectrum ranges, observability becomes vital for cognitive networks employing AI/ML algorithms. In the intended use case, challenges might arise due to limited infrastructure control, but diverse means can be utilized for data traffic identification. The use case in edge robotics and the WZL testbed provide insights for experimenting with QoS strategies and developing platforms for cognitive network evolution.

5G NR mmWave: The mmWave spectrum, as defined by the 3rd Generation Partnership Project (3GPP), comprises two frequency ranges for 5G New Radio (NR). Frequency Range 1 (FR1) spans 410 MHz to 7125 MHz, labeled 'sub-6,' while Frequency Range 2 (FR2) covers 24 GHz to 71 GHz, with 5G utilizing up to 40 GHz. Europe allocates 24-28 GHz for 5G. Often referred to as 'mmWave' due to its millimeter-range wavelengths, this spectrum is crucial for 5G. Understanding its advantages and drawbacks is essential for effective network planning. The "Edge-Controlled Automation with Mobile Manipulation" use case provides insights for industrial deployment. Propagation studies in diverse settings optimize spectrum use. Beamforming enhances signal quality by directing energy, enabling higher data rates and lower latency. Indoor mmWave cells offer flexibility, exploring Time Division Duplex patterns. Therefore, TARGET-X introduces mmWave to manufacturing & robotics testbeds, with two phases: technology introduction and validation, and use case-oriented experimentation for service differentiation and real-time ecosystems. Deployment strategies will be chosen based on a further consortium evaluation.

Positioning with 5G NR: The positioning with 5G NR in TARGET-X is centered around indoor positioning techniques, recognizing its significance in various industries. The project initially focuses on calculating position estimates using signals between 5G UE and 5G gNodeB, a node in a cellular network that provides connectivity between UE, aligning with 3GPP Release 16 standards. The primary application lies in enhancing accuracy for path planning and safety in mobile robotics, which utilize a range of sensors. Therefore, the aim is to integrate existing sensor data with 5G NR-derived position estimates to optimize precision. Key considerations include the challenges of achieving high accuracy, the impact of processing time on information accuracy, and the importance of Time to First Fix (TTFF) for time-sensitive applications. In the WZL testbed, indoor positioning with 5G is a primary focus, with two defined phases: technology implementation and validation. The overarching goal is to understand, improve, and prepare for the evolution of positioning technologies toward 6G and Joint Communication and Sensing (JCAS).

Other beyond 5G technologies (features), that are being study among other verticals and WPs and are not intended for the edge robotics use case, are: Asset Administration Shell (AAS) and network orchestration, real-time Ecosystem and Time-Sensitive Networking (TSN), and Reduced Capability (RedCap).

4 Design Options for the Use Case Implementation

In this section, the planned hardware and software setup for the implementation of the edge-controlled mobile manipulation scenario is introduced, featuring the real robot (mobile manipulator), the factory cloud system, the intended middleware, and a containerization platform. Additionally, this section dives into different architectures in the middleware level to provide different alternatives (design options) on handling the challenges involved in the motion of mobile manipulators in the use case application scenario within WP2. These different design options not only offer technological solutions in the field robotics, but also provide insights for the advancement of the 5G technologies across the manufacturing vertical, especially when adopting state of art approaches related to open-source middleware for the autonomy of mobile robotics applications. The design implementation options include sequential motion planning, whole-body motion sampling-based planning, holistic reactive motion control without explicit planning, and whole-body motion hybrid planning for optimal, collision-free motion.

4.1 Hardware setup

The scenario for the edge-controlled automation with mobile manipulation use case basically comprises two main hardware setups, the mobile manipulator robot, and the local server system (the factory cloud system) that leverages the network infrastructure provided at WZL testbed. In Figure 4.1 both setups are illustrated.

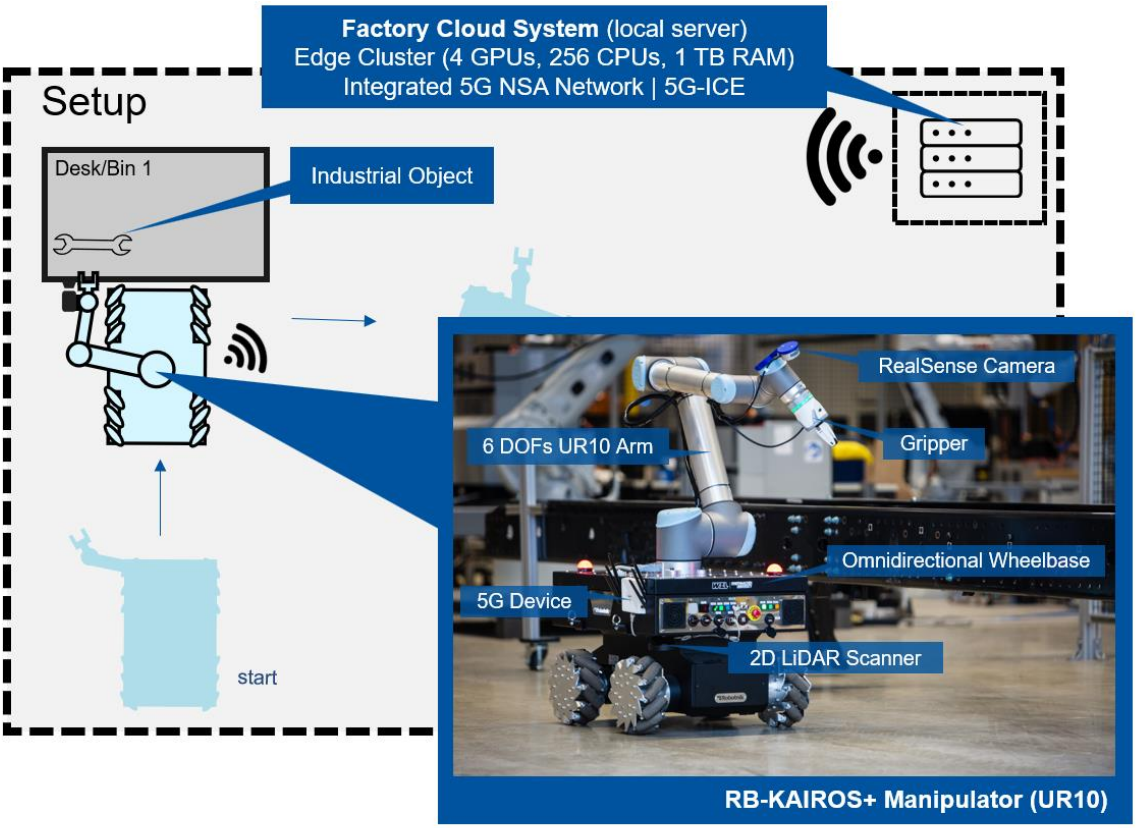

Figure 4.1: The two main hardware setup of the intended use case: the mobile manipulator robot and the local server system (the factory cloud system) at WZL testbed. Source: provided by WZL [7].

In its simplest form, a mobile manipulator comprises a power source, a base, a manipulator, a computing and control unit, and multiple sensors. Depending on the specific applications and needs, the mobile robot can be customized with additional components like a loading unit or conveyor belt for transportation. The mobile manipulator intended for the development of this use case and available at the WZL testbed is the RB-Kairos+ Manipulator, a mobile manipulator robot with an omnidirectional wheel-base and the 6 DOFs UR10 robot arm (manipulator) allowing agile and versatile movement within confined spaces and around complex assembly setups. The UR10 robotic arm features a two-finger gripper, a RealSense L515 end-effector camera with depth and RGB sensors, and a pair of inner SICK S300 laser scanners (2D LiDAR sensors) for a 360° field of view. An integrated inertial measurement unit (IMU) and hall effect encoders ensure precise motion tracking, as shown in Figure 4.1. The maximum speed is 1.5 m/s. For the UR10, the maximum speed of the third wrist where the camera holder is attached is 180 °/s = 0.2 m/s [14]. For the UR10 current setup, the repeatability between sending a goal pose and the actual robot pose is about 5 mm. The 5G device is mounted on the base of RB-Kairos+. For the further implementation is expected that Fivecomm (partner within WP2) will provide new 5G Rel-16 UE devices for this use case, that will be mounted on base of Kairos.

The local server system serves as the central intelligence hub within the edge robotics use case for executing the computationally intensive and necessary software components. Since the robotic software stack will require dedicated computing power, the edge system hardware components in Table 3 were selected, once again leveraging the factory cloud infrastructure provided at WZL trial site:

Table 3: Local server system hardware configuration. Source: provided by WZL [7].

Component	**Specification**
Processors	2x AMD EPYC 75F3, 32 CPU cores, 2.95GHz
Memory	16x 16 GB RDIMM, 3.200 MT/s, Dual Rank
Storage	2x 960GB SSD SAS ISE Read Intensive, 12Gbps
Graphics Processing	Processing NVIDIA Ampere A10 GPU, 24GB Memory

A further integration with the Qualcomm robotics kit (RB5) mounted on the end-effector of the arm of the mobile manipulators is being studied for the enhancement of Object Detection. The RB5, as shown in Figure 4.2, could improve the overall accuracy of the information obtained.

Figure 4.2: Qualcomm robotics kit RB5. Source: adapted from [15].

4.2 Software setup

The software architecture for the use case, regardless of the implementations options, is designed to offload computation-intensive tasks from the robot's internal computation unit to the factory cloud system. Shifting computationally intensive software components to the factory cloud system is a strategic decision to optimize system performance and scalability within the framework. This offloading not only enhances the robot's responsiveness but also ensures that the limited computational resources onboard the robots are dedicated to critical low-level control tasks.

All software components within the robotic system are containerized using the container application software *Docker*, thereby ensuring the portability and isolation of their respective environments. The software components such as Localization, Navigation, perception, and global motion planning are run (in containerized form) in the factory cloud system, whereas the software components such as Base & Arm Controller and Sensor Drivers run (in containerized form) in the robot, as shown in the Continuous Integration and Continuous Deployment (CI/CD) Pipeline illustrated in Figure 4-3. This approach simplifies deployment procedures, enhances compatibility across platforms, and effectively mitigates conflicts arising from dependencies and library requirements. Consequently, a native ROS2 installation is not required, streamlining system configuration and management.

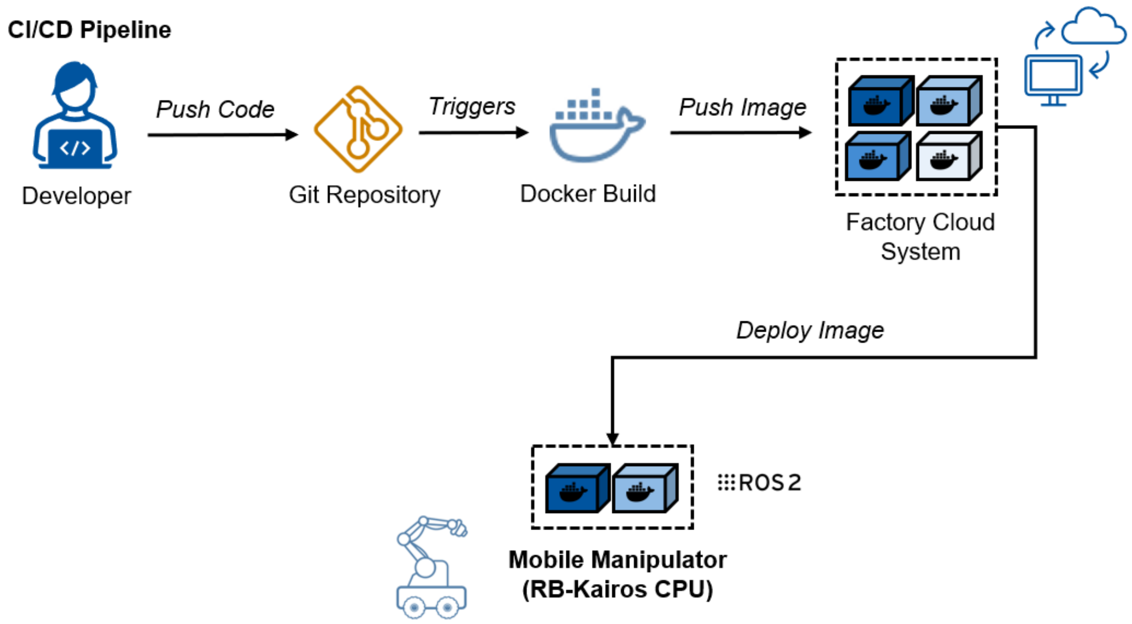

Figure 4.3: Deployment of the proposed edge-controlled use case. Source: provided by WZL [7].

ROS2 offers a data-centric communication model by decoupling nodes and allowing them to publish and subscribe to data topics, promoting modularity and flexibility of the framework. Coupling ROS2 with *Zenoh* offers several advantages for edge robotics in LMAS. The *Zenoh* bridge for Data Distribution Service (DDS) facilitates bridging DDS communication between ROS2 nodes. Integrating ROS2 and *Zenoh* within the factory cloud system enhances data sharing, scalability, and efficiency, making it ideal for robotic systems in assembly environments.

4.3 Planning & control of motion of the mobile manipulator

This section presents different architectures on the middleware level to provide design options on handling the already mentioned challenges (introduced in Sections 3.1) regarding the planning and control of the motion of mobile manipulators. Besides presenting different technological solutions in robotics, these different design options also offer great insights for the advancement of the 5G technologies across the manufacturing vertical, especially when adopting state of art approaches related to open-source middleware for the autonomy of mobile robotics applications. The section also presents the design options from simpler to complex. The Figure 4.4 illustrates the complexity and introduces the core features of each design option for further comparisons. approaches

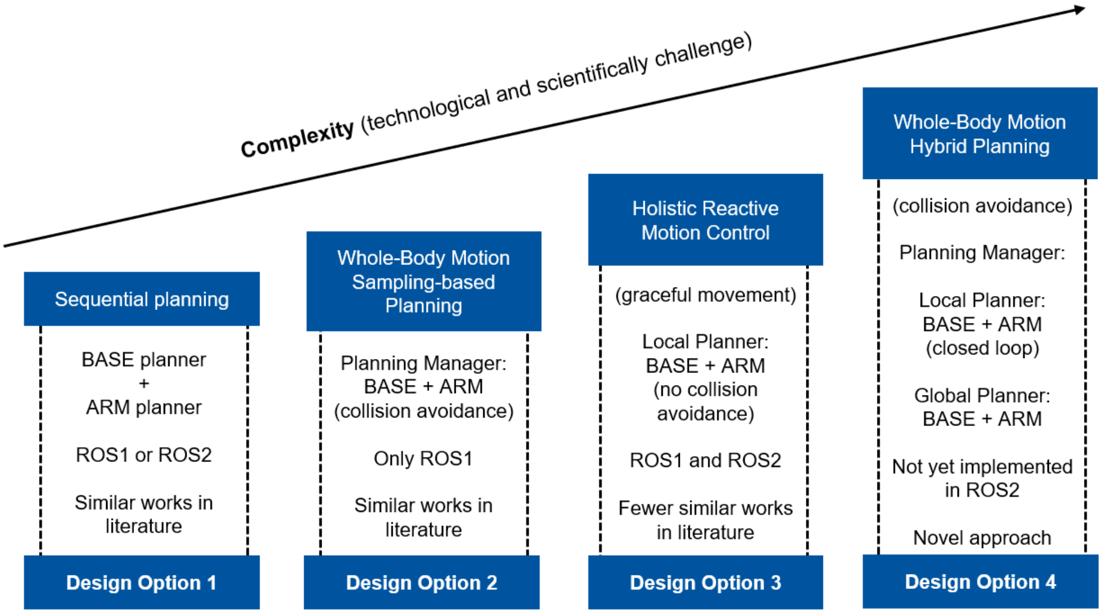

Figure 4.4: complexity order of the proposed design option for tackling the challenges in planning & control of the mobile manipulator motion. Source: provided by WZL [7].

4.3.1 Design option 1: Sequential Montion Planning

Mobile manipulators are sophisticated systems characterized by high DOFs and complex constraints in their system dynamics. Typically, their kinematic redundancy arises from the numerous DOFs, providing flexibility in navigating complex environments. While this redundancy enhances adaptability, it introduces challenges in planning due to the infinite solutions to the inverse kinematics problem [11]. Adding to the complexity, the mobile base and manipulator presents different dynamic characteristics, with the mobile base having higher inertia than the manipulator. Despite the dynamics differences, these systems are intricately linked, resulting in complex dynamic behaviors that further compound the planning complexity. Various approaches are employed to address the motion planning challenge for mobile manipulators, categorized based on whether the planning algorithm accounts for the behavioral disparities between the mobile base and the robot manipulator [11].

Frequently, a complex task is broken down into a series of sub-tasks, and planning is conducted independently for each sub-task. This essentially involves separating the planning processes for the mobile base and robot manipulator – two subsystems with separate planning. While there are various planning algorithms in the literature for the mobile base and manipulator, they have not been specifically implemented for mobile manipulators [11]. When motion planning is executed independently for the mobile base and manipulator, the existing algorithms for the mobile base and the manipulator can be applied once a goal configuration is determined for both the mobile base and manipulator as depicted in Figure 4.5. In state-of-the-art industrial motion planning frameworks, motions are independently planned for the manipulator and base using ROS.

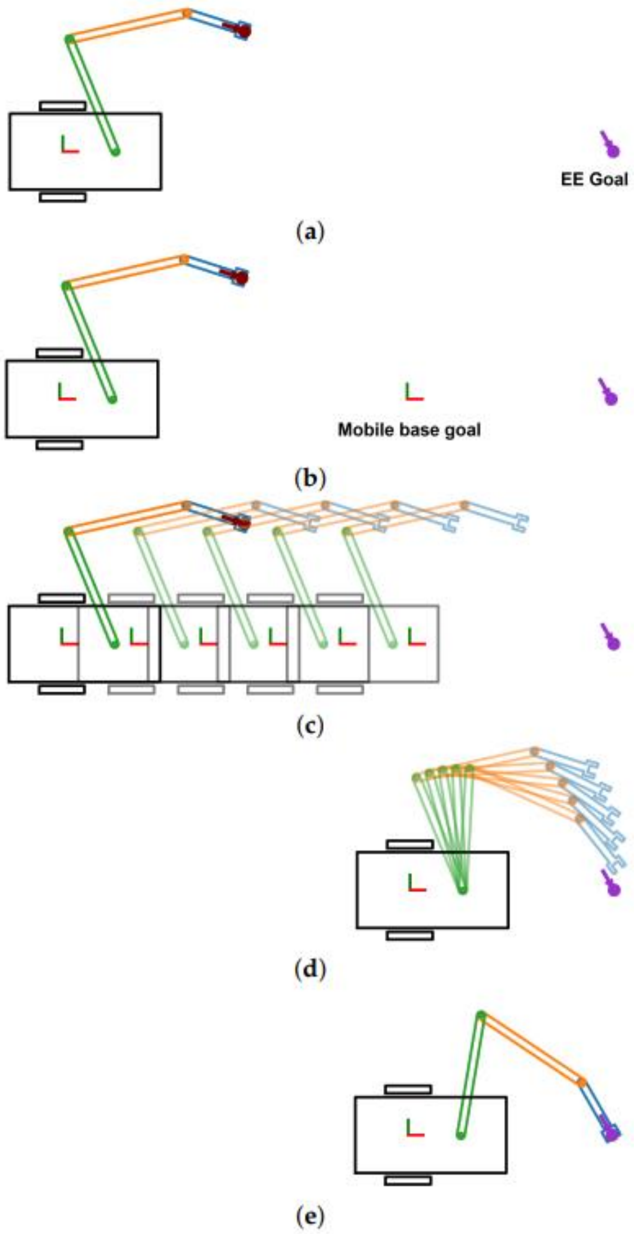

Figure 4.5: Sequential planning for mobile base and manipulator. (a) Task space goal. (b) Goal for mobile base. (c) Motion plan for the mobile base. (d) Motion plan for the manipulator. (e) Task space goal reached. Source: [11].

In this implementation design, the sequential planning for mobile manipulators can lead to suboptimal plans, lack of coordination, increased execution time, and difficulties in handling dynamic environments. The approach may result in longer overall execution times due to the need for frequent switching between mobility and manipulation modes. Integrating separate planning modules can be complex, and the system may be sensitive to uncertainties, limiting adaptability. To address these issues, researchers are exploring integrated planning approaches that consider both mobility and manipulation simultaneously for more efficient and adaptable mobile manipulator systems [11].

The sequential planning approach has already been implemented at the WZL testbed for ROS1 and is currently underway in our full ROS2 stack integrated with the existing 5G network setup. Adapting this approach to the specific use case scenario within WP2 promises a simplified implementation within a shorter timeframe. In terms of network requirements, this approach demands less from the communication stream, especially concerning control variables of the arm. This is attributed to the fact that the approach avoids holistic movement (simultaneous movements) of the mobile manipulator. Consequently, prioritizing the communication stream sequentially alleviates the network demands.

4.3.2 Design option 2: Whole-Body Motion Sampling-based Planning

As described in the previous section, motion planning for mobile robots is usually separated into motion planning for the manipulator and the mobile base. In recent works indicated by the literature review on motion planning for mobile manipulators [11], planning for the mobile manipulator as one system (whole-body planning) is gaining popularity. Whole-body motion planning represents a comprehensive approach, including the entire robot arm and the mobile base to perform optimal and efficient movements. This results in more efficient and smoother trajectories, minimizing unnecessary movements and reducing the overall execution time in LMAS.

Planning whole-body motions can be achieved through the utilization of optimization- and sampling-based planning algorithms. Optimization-based approaches swiftly generate trajectories for high-dimensional problems without the need for post-processing. However, challenges such as local minima and limited generalization arise due to the specificity of cost functions and collision distance computation for particular use cases. On the other hand, sampling-based planning algorithms offer a solution for a wide range of problems and are commonly employed in planning manipulator movements. The availability of stable implementations and numerous algorithms makes them widely used. Nevertheless, post-processing is essential to produce time-parameterized and smooth trajectories. In this context, sampling-based planning algorithms are chosen for their established effectiveness and applicability to a diverse set of problems, with path post-processing addressed using state-of-the-art algorithms.

In the context of this use case, this implementation solution would be executed in the factory cloud system, aiming to show the feasibility of whole-body motion planning in industrial environments within the Robot Operating System 1 (ROS1), using the Open Motion Planning Library (OMPL). The whole-body motion planning application plans trajectories for the mobile manipulator by using sampling-based motion planning algorithms. The mobile manipulator can be modeled using a nine DOF holistic state space composed of the manipulator and mobile base configuration.

The sampling-based planning approach consists of five modules as shown in Figure 4.6. The core module provides generic planning capabilities, while four additional modules tailor the planning for mobile manipulators. The scene module handles kinematics and environment information, the collision detection module ensures sample validity, and the inverse kinematics solving-module computes goal configurations. The trajectory processing module adds timing information for real robot execution.

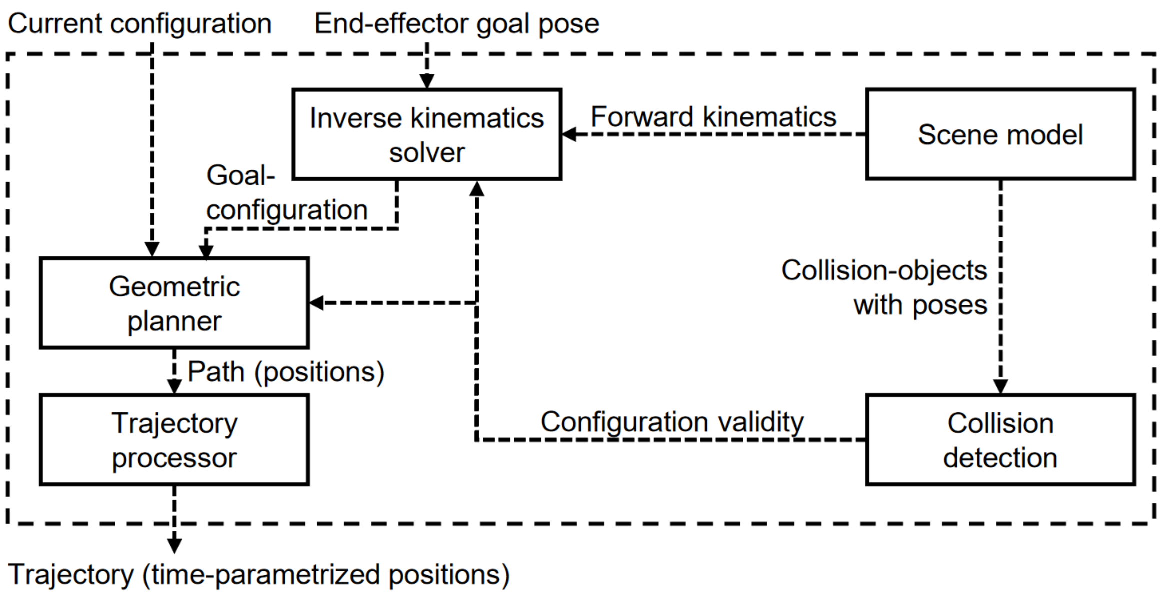

Figure 4.6: Planned architecture for the whole-body motion sampling-based planning using ROS1. Source: provided by WZL [7].

However, the current state of the art implementation for this approach in ROS1 presents several challenges for whole body motion planning, including communication overhead and lack of real-time capabilities due to publish-subscribe model. The framework's limited support for complex kinematics, inadequate simulation environments, and a lack of standardization can hinder the development and integration of precise motion planning algorithms for robots with intricate structures.

It's worth noting that ROS2 has been introduced to address many of these limitations. ROS2 offers improvements in terms of real-time capabilities, security, communication efficiency, and more. When considering whole-body motion planning for industrial applications, it may be beneficial to explore implementation in ROS2 as a more modern and capable alternative [16].

The presented approach has already been implemented at the WZL testbed for ROS1 using communication setups via Wi-Fi network and no architecture using factory cloud system has yet been implemented. Adapting this approach to the specific use case scenario within WP2 promises a relatively simplified implementation within a shorter timeframe, although the support for ROS1 applications and real-time communication are limiting factors for this design. Consequentially, this approach does not reflect the industrial demands in the field of edge robotics. In terms of network requirements, this approach will demand certain volumes of data from the communication stream, especially concerning control variables of the arm. This is attributed to the fact that the approach will perform holistic movement (simultaneous movements) of the mobile manipulator. Consequently, prioritizing certain communication streams might be necessary using technologies from the beyond 5G features.

4.3.3 Design option 3: Holistic Reactive Motion Control

As mentioned before, planning for the mobile manipulator as one system (whole-body planning) presents several challenges. Most systems address this challenge by combining planning and reactivity. Planning involves analyzing the current and desired states of the world and generating a trajectory for the robot to achieve the desired change. While these solutions are optimal based on certain criteria, the execution of the plan is performed in an open-loop manner. The success of the plan is thus heavily dependent on the accuracy of the initial world state provided and the robot's ability to follow the plan. Although contemporary planning systems exhibit high capabilities, efficiently handling problems with numerous DOFs and constraints, the planning process itself can take a considerable amount of time, often a significant fraction of a second or more [17].

The technical implementation solution of a reactive motion controller treats the mobile manipulator's base and arm DOFs as a holistic system (6 + 3 DOFs). The core of this approach features a robust and reactive motion controller, capable of achieving a desired end-effector pose while avoiding joint position and velocity limits. This ensures the mobile manipulator's maneuverability throughout the trajectory, supporting sensor-based behaviors like closed-loop visual grasping, as shown in Figure 4.7.

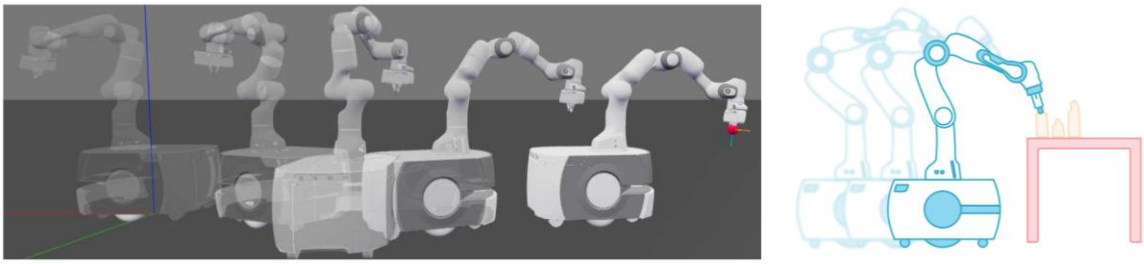

Figure 4.7: A holistic approach to reactive mobile manipulation [17].

Notably, the approach eliminates the need for explicit planning, preventing the mobile manipulator from being stationary during decision-making. The versatility of the holistic motion controller can be demonstrated through the implementation of the pick-and-place task system using behavior trees on a 9 DOF mobile manipulator as depicted in Figure 4.8. The advantages of using reactive controllers in terms of execution time make them particularly suitable for industrial automation of task requiring quick, adaptive, and real-time responses in dynamic environments in the context of LMAS.

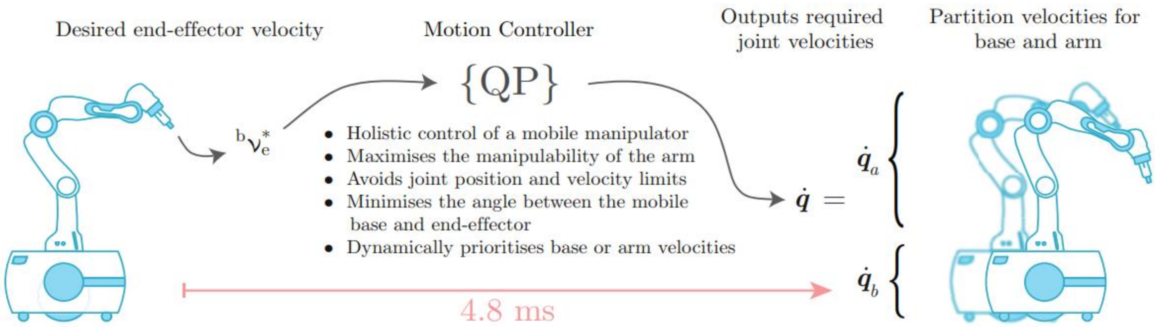

Figure 4.8: Overview of the holistic approach. The motion controller is expressed as a quadratic program (QP) [17].

Additionally, an open-source implementation of the motion controller is provided for both non-holonomic and omnidirectional mobile manipulators by [17]. Nevertheless, to implement the described mobile manipulation approach with ROS2, a ROS2 packages for motion control, perception, and any other functionalities needed to be developed for the mobile manipulator.

the approach is relatively novel especially when considering the architecture using factory cloud system and 5G network features. Developing this approach to the specific use case scenario within WP2 promises higher complexity compared to previous mentioned designs in the field of edge robotics due to the technological challenges in the implementation regarding ROS2. Additionally, time constraints as a design option might weight on this approach since the available pipelines by the authors [17] needs to be heavily adapted. In terms of network requirements, this approach will demand higher volumes of data from the communication stream, especially concerning the 2D inner LiDAR sensors and the control variables of the arm. This is attributed to the fact that the approach will also perform the holistic movement (simultaneous movements) of the mobile manipulator. However, no collision avoidance is expected in this approach. Consequently, prioritizing certain communication streams might also be necessary using technologies from the beyond 5G features.

4.3.4 Design option 4: Whole-Body Motion Hybrid Planning (with collision avoidance)

Current state-of-the-art approaches such as sampling-based planning and robot base navigation algorithms prove to be time-consuming in systems with a high degree of freedom due to the long sampling time. Conventional robot base navigation algorithms do not consider the manipulator's simultaneous, collision-free motion.

The main objective of this implementation is to introduce an approach allowing simultaneous motion planning for the combined mobile base and the manipulator with perception and collision avoidance. The Figure 4.9 exemplifies the intended simultaneous movement of the mobile manipulator. Global motion planning and local motion control architecture are defined for this approach.

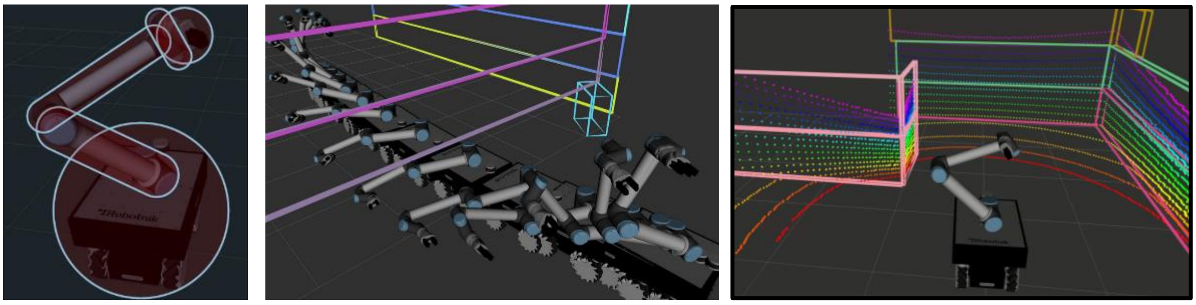

Figure 4.9: Simulation environment for the whole-body motion hybrid planning. Source: provided by WZL [7].

The presented architecture aims to reduce the planning time and to enable an optimal, collision-free, and reactive robot motion considering known and unknown obstacles. The results of this use case could contribute to optimizing the motion planning of mobile manipulators and acceleration of mobile manipulation processes and thus making them more economically and technically feasible for modular and reconfigurable assembly tasks.

As described in Figure 4-10, the motion planning framework for mobile manipulators consists of a global planner, local planner, and a motion capturing algorithm using LIDAR sensor data. The LiDAR sensors intended for this approach are a combination of 2D and 3D. The approach also aims to transfer the framework from ROS1 to ROS2, leveraging a selected middleware for the communication layer. The selection of the middleware will depend on the intended evaluation (mentioned in Section 3.1.3) of the RMWs (Fast RTPS, CycloneDDS, Connext DDS, and Zenoh). Evaluation of the different middleware setups allows for the best choice.

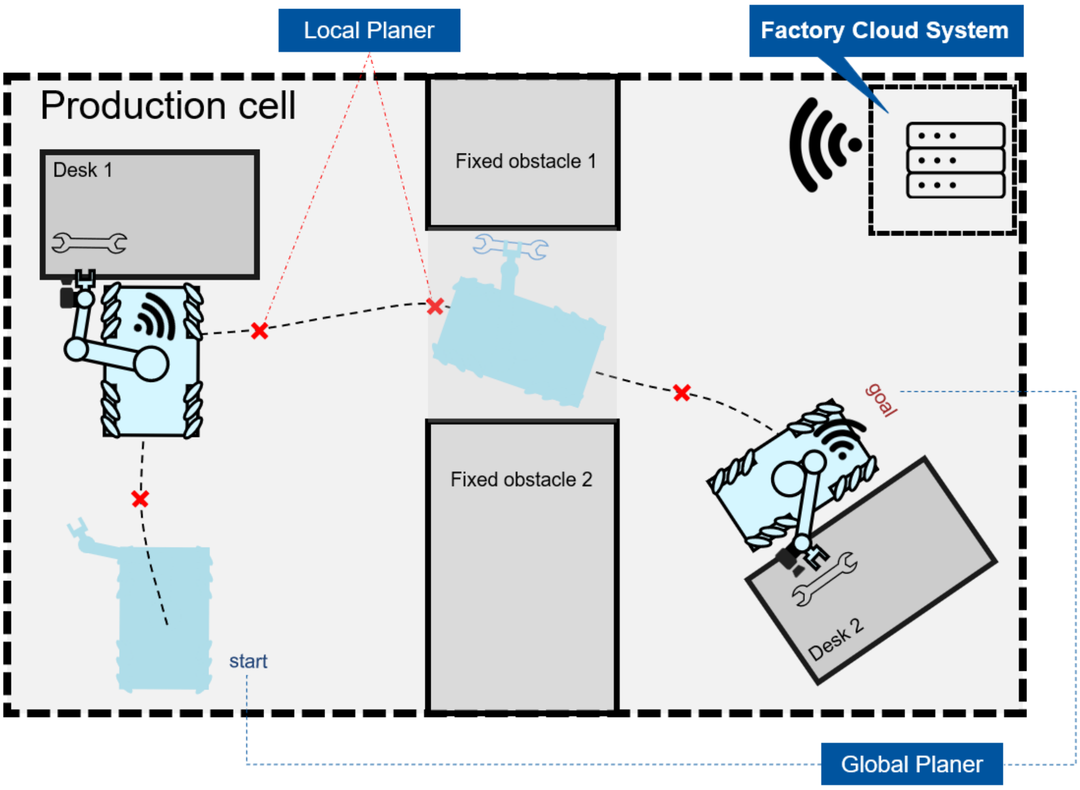

Figure 4.10: Layout of the whole-body motion hybrid planning with collision avoidance of fixed obstacles. Source: provided by WZL [7].

ROS2 integration provides better insights into communication and performance, aiding in component allocation decisions. As illustrated in Figure 4.11, the Hybrid Planning architecture is structured in the following [18]:

1. Hybrid Planning Manager: provides a ROS action for Hybrid Planning requests and runs the planning logic and coordinates the planners.
2. Global Planner: solves the global planning problem and publishes the solution trajectory.
3. Local Planner: processes incoming global trajectory updates and solves the local planning problem based on robot state, world and reference trajectory and sends position/velocity commands to the robot driver.

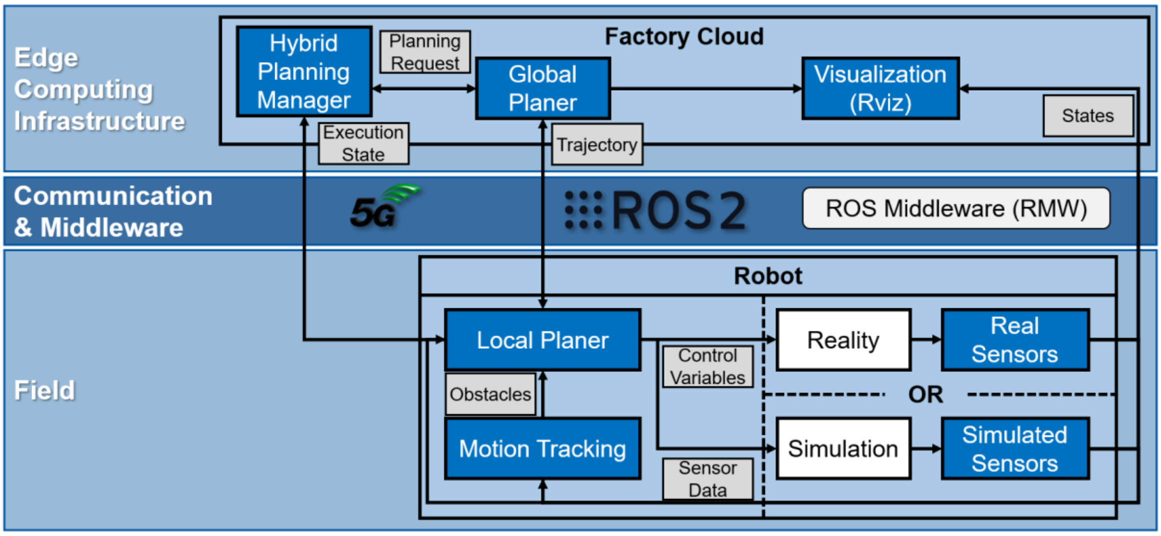

Figure 4.11: Hybrid planning architecture for the whole-body motion of the mobile manipulator. Source: provided by WZL [7].

The global planner generates high-level motion plans, refined by the local planner considering robot constraints. The motion capturing algorithm utilizes LIDAR data for accurate environment perception and plan updates. Different middleware setups like peer-to-peer and router clients can be used, optimizing communication and performance. The local planner consists of Locally optimal movement planning using velocity obstacles via Model predictive control (MPC) for local trajectory optimization, as shown in Figure 4.12.

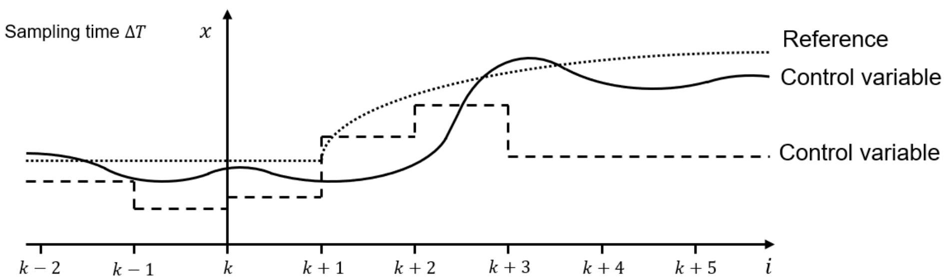

Figure 4.12: MPC for local trajectory optimization. Quadratic optimization over the next movements under linear constraints. Source: provided by WZL [7].

This framework enhances mobile manipulator efficiency, enabling real-time decision-making and improved motion planning, but has not yet been implemented for ROS2. The approach is novel especially when considering the architecture using factory cloud system and 5G network features. Developing this approach to the specific use case scenario within WP2 promises academical complexity in the field of edge robotics due to the technological challenges in the implementation regarding ROS2. Additionally, time constraints as a design option weigh this approach. In terms of network requirements, this approach will demand higher volumes of data from the communication stream, especially concerning 3D LiDAR sensors and the control variables of the arm. This is attributed to the fact that the approach will also perform the holistic movement (simultaneous movements) of the mobile manipulator, as well as the collision avoidance of fixed objects. Consequently, prioritizing certain communication streams might also be necessary using technologies from the beyond 5G features.

5 Conclusion

This deliverable detailed the system design of the edge robotics use case scenario within the WP2 with a focus on LMAS and 5G/6G connectivity to be developed at WZL tested. Subsequently the document presented design options for the implementation as technical solutions for the challenges in planning & control of the mobile manipulator motion.

The document aimed to provide a 5G requirement analysis for the communication streams involved in the use case scenario, and for that, the communication streams (data flows) were cleanly defined. With the definition, functional requirements were set based on the service demand of the use case scenario. Additionally, measurements and estimations were performed from the current full stack at WZL testbed, providing values for the performance and complementary requirements of the expected networks for the use case within the TARGET-X use case unification provided WP1. From the five communication streams identified, it was understood that different (data flows) will have different demands, therefore different network prioritization in the use case scenario, bringing insights on the intended 5G/6G technologies, that were subsequentially established with WP6 support.

In the document also introduced the challenges that the use case scenario faces regarding the planning and control of the motion of the mobile manipulator. To address these challenges, the document dives into different architectures at the middleware level to provide alternatives on handling the motion of mobile manipulators. The different design options not only offered technological solutions in the field robotics, but also provide insights for the advancement of the 5G technologies across the manufacturing vertical, especially when adopting state of art approaches related to open-source middleware for the autonomy of mobile robotics applications. The design implementation options include: the sequential motion planning, which presents limitations regarding industrial demands (longer time in executability of a task), but offers simplicity and lower implementation time for the project; the whole-body motion sampling-based planning, which meets the industrial demands with a holistic (simultaneous) movement of the arm and the base, but has limitation at the middeware (ROS1), not corresponding real-time demands; the holistic reactive motion control without explicit planning, which offers the holistic movement, but not offering collision avoidance; and the whole-body motion hybrid planning for optimal, collision-free motion, which is the most complex approach, demanding longer implementation time.

Regarding the next steps within WP2 and the choice (decision), the WP2 is in favor if the Design option 3, since it is not a complex approach, offering graceful movement and a not so long implementation time, fitting quite well the timeframe in TARGET-X | WP2. Nevertheless, the framework needs to be deployed and adapted to a factory could system within LMAS leveraging 5G/6G communication and taking into account the available RB-Kairos at the WZL testbed.

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