Design and Requirement Analysis of an Outdoor Autonomous Mobile Manipulator

Zoltán Szilágyi
Óbuda University
Alba Regia Technical Faculty

Székesfehérvár, Hungary
szilagyi.zoltan@amk.uni-obuda.hu

Csaba Hajdu
Széchenyi István University
Department of Informatics

Győr, Hungary
hajdu.csaba@ga.sze.hu

Abstract— Industrial Mobile Robots (IMRs) gained prominence in research and technical applications. Besides their original interior application environment, the expanding demand for such devices has recently led to their growing application in exterior environments. In general, the external setting challenges robots with higher complexity and variety in the sense of tasks and the target environment.

This article presents the proposal of a mobile manipulator robot suitable for external applications like industrial and urban settings. The robot achieves flexible manipulation freedom with two manipulator arms and a revolving base beneficial in solving a wide variety of complex tasks. The related research process included additional characteristic requirements for similar external devices. These requirements include IP protection, rough ground mobility, acceptable movement range, and autonomous self-monitoring and control capabilities. The research further focuses on analyzing system-wide capabilities with the help of computer simulations and virtual test environments. Besides developing a novel robotic device, the further goal is to survey the potentials and challenges of external robotic applications and to summarize the gained technical knowledge and experience.

Keywords—mobile robotics, IMR, mobile manipulator

I. Introduction

The theme of industrial robots has been a paramount research field and market since the 60s. Traditionally, arm-like kinematic structures – robotic manipulators - were sufficient in automatizing many industrial applications. However, parallel with the optimization of manipulator solutions, autonomous mobile robots gained individual attention in the industry to automatize material handling in industrial departments.

The field of Industrial Mobile Robots (IMR) is a currently prominent subfield regarding its market size and research opportunities. Mobile robots are perfect candidates to automatize tasks in an industrial setting, like material handling and other collaboration tasks with human actors. For example, the growing Automatic Ground Vehicles (AGV) market focuses on material handling between factory departments, with only a minimal extension of existing infrastructure. Furthermore, new regulations and standards are applied to the robots to overcome possible safety and reliability issues.

Overall, most interior industrial tasks can be addressed with currently available solutions. On the other hand, some tasks that require precise manipulation capability or fine movement still need to be addressed by most market-ready mobile robots. An example is when a robot moves in a workshop setting handling equipment.

The market typically omits exterior industrial tasks for a good reason. The internal industrial environment is usually more controllable, requiring minimal preparations inside the departments to install the robot. External settings are much more stochastic, with the minimal capability to change and equip the infrastructure of the operating environment. Also, exterior robots require a more rugged structure to resist weather and terrain effects (e.g., vibration, rough ground, rain, and electrical disturbances). The exterior setting usually requires high manipulability (e.g., with a robotic arm) as specific tasks can be complex and tedious pick-and-place scenarios. Furthermore, subtasks can vary even during the execution of the task, such as in an agricultural setting. Many industrial fields await flexible automatization of monotonous yet complex tasks. The development of a multi-purpose highly maneuverable with refined manipulator capabilities could be beneficial in many application areas such as agricultural, urban, mining, and the traditional military applications of mobile robots.

This paper presents the design of an autonomous mobile robot equipped with dual robot manipulators to overcome the actuation challenges of exterior industrial use cases. In the presented attempt, the primary goal was to combine the precise capabilities of a robotic manipulator with the endurance and mobility of a mobile robot platform suited for exterior use. The robot is currently in the design phase, with organized related requirements and concepts to provide rugged, highly maneuverable, and swift manipulation capabilities. As the design is unconventional, the current scope of the paper is exploratory research organizing the conceptual design and posed requirements. In addition, the current paper also attempts to provide a flexible software architecture inspired by currently prominent software frameworks for autonomous vehicles and distributed robotic system paradigms.

II. Related work

Traditionally, scholars tend to differentiate between mobile and industrial robots, categorizing their usage and capabilities. Industrial robot manipulators are regulated under different standards for example, in ANSI/RIA R15.06 and ISO 15066:2016 (more safety-focused standard). Apparently, due to the increasing popularity of mobile robots in an industrial context, a similar standardization process has been recently started to define proper and standard requirements for mobile robots. As different approaches and solutions appeared, manufacturers started to designate robots under varying terminology, with no precise term scope (popular terms are listed in TABLE I.). Regarding mobile robots in the industry, manufacturers typically differentiate between the following two categories:

- **Autonomous mobile robots (AMRs):** are expected to handle complex and unexpected situations in a low infrastructure setup, with vast capabilities of human interactions and a relatively high degree of autonomous operation. Although, their maximum payload and speed are typically limited for safety reasons.
- **Automatic Ground Vehicles (AGVs):** these robots are expected to handle only a limited set of tasks (e.g., material handling) in a built-up support infrastructure setting. Their human interaction capabilities are limited and not expected to resolve complex interferences autonomously.
- **Industrial Mobile Robot (IMRs):** a mobile robot targeted explicitly for usage in an industrial environment.

TABLE I. OVERVIEW OF POPULAR ABBREVIATIONS IN ROBOTIC INDUSTRY

Abbreviation	Term
AGV	Automatic Guided Vehicles
AMP	Autonomous Mobile Platform
AMR	Autonomous Mobile Robot
IMR	Industrial Mobile Robot
UGV	Unmanned Guided Vehicle
UAV	Unmanned Aerial Vehicle

Mobile robots equipped with a robot manipulator are typically referred to as mobile manipulators. These robots are expected to carry out simple pick-and-place tasks and similar manipulation tasks. The requirement for manipulation is prominent in the traditional use of mobile robots in military and surveillance applications.

Due to the growing market of autonomous mobile robots in industrial applications, new standards targeting IMRs appeared. A relatively new standard, ANSI/RIA R15.08-2020 defines a broad terminology for IMRs:

- **IMR Type A:** autonomous mobile robot, with only an autonomous mobile platform (essential capability to move and navigate through free space).
- **IMR Type B:** a base platform with any (passive or active) attachment that is not a manipulator, beyond the capability to navigate autonomously.
- **IMR Type C:** a mobile manipulator qualifying to R15.06 as an attachment on an IMR Type A mobile platform or an AGV as the base.

Exterior applications have been under massive development in recent years. Traditionally, mobile robots are applied in military and academic context with special tasks and highly qualified support. However, as mobile robots became widespread, numerous industrial applications applied robots for automatization. In this article, the agricultural context is further investigated. Some authors envisioned that mobile robots and unmanned aerial vehicles (UAVs) could aid in agricultural tasks [1], which are demanding for agricultural workers and monotonous. Promising results have been achieved in the cultivation of crops, vineyards, and crop monitoring [2]. As a result, many manufacturers started to provide robotized solutions for agricultural tasks.

The software system of the robot must be flexible in regards of extendibility and adjustability, implying the capabilities can be adjusted as components and the refining of components can be changed during a mission. A general control loop model for autonomous mobile robots popularized by Siegwart et al. [3], indicates mandatory tasks for autonomous operation. The model is derived from the widespread sense-think-act cognitive model [4]. In this model, the robot software is organized into a set of components each associated with sensing (i.e., proprioceptive/exteroceptive perception, processing), thinking (i.e., planning, inferring) and actuation (i.e., control of motors, manipulators) each bound to a valid input/output interface closing the control the loop. This model does not rigidly define each subtask but rather provides a starting framework for robot software design. The control loop, with some addition to mobile robot manipulators in detail, is depicted in Fig. 1, with additional elements inspired by the field of Cognitive Infocommunications (CogInfoCom) [5].

Nowadays, new software systems tend to be organized into cooperating components (i.e., microservices) besides robotic systems. In robotic systems, this approach is beneficial and evident regarding the development and verification subtasks. For example, a trajectory planner can be developed and tested as a separate component and then integrated and refined in the target robot's context. This approach is currently favored in the design of cyber-physical systems (CPS), providing numerous communication frameworks (e.g., Data Distribution Service- DDS [6]). In robotic systems, Robot Operating System 2 (ROS2) [7] [8] started to gain high prominence and support from academic and industrial actors alike. It should be noted that ROS 2 uses DDS as an intermediate framework to achieve automotive- and military-grade stability and reliability [9].

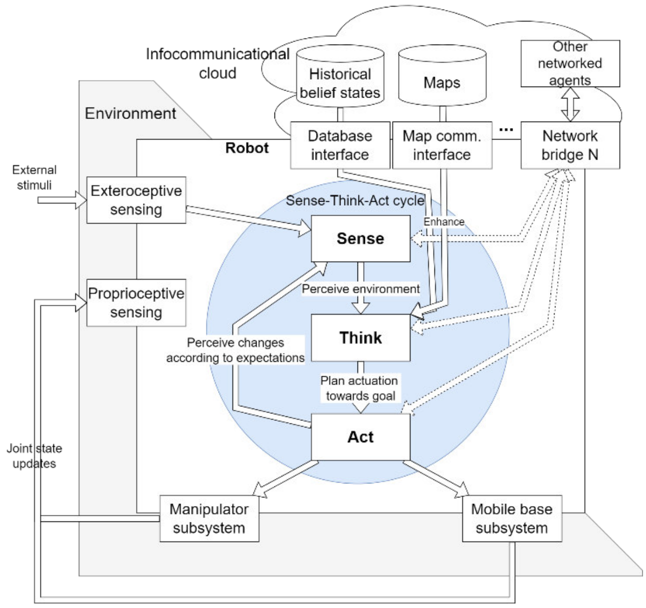

Fig. 1. Modified sense-think-act cognitive model for mobile robots

III. CONCPETUAL DESIGN

In the following chapter, the conceptual design is discussed in detail, including the typical use cases, requirements based on industry-related standards, and physical requirements related to the electronic equipment, structural integrity, and safety of the robot. Additionally, the specific requirements for each possible environment setting are briefly discussed.

A. *High-level description*

In the following subsection, the primary modules of the robot are identified according to its primary goal. The discussed robot conceptually is a composition of a mobile robot platform (with a low-level platform controller) equipped with two industrial manipulators (each with its independent controller system). While this robot design is relatively widespread in academic research [10] and disaster management [11] in industrial applications, this kinematic setup remains quite unconventional. At a bare minimum, the robot provides proprioceptive information of its joint states (motor states), thus its whole kinematic structure by the controller systems. Proprioceptive information can be amended with inertial data (IMU sensor) in the frame of the platform and arms joints. The mobile robot platform must provide a way to the extension with additional sensor equipment (e.g., cameras, LiDARS, further IMUs, GNSS) to process external sensory information in a modular way. The perception extension point on the robot should be placed distant from the working space and payload of the robot (*perception module*). *Power management* is treated as a separate component, as all other components must be powered. Notably, a possible significant difference between the electric supply of the mobile base and both manipulators. *High-level control* (i.e., cognitive) is composed of computers with extensive computational capabilities (e.g., perception, mapping, and planning tasks). *Low-level control* (i.e., actuator-close) indicates the computational units that presumably have real-time capabilities and high reliability with direct access to the actuators of the robot. The overview of the robot with the highlight of mandatory components is depicted in Fig. 2.

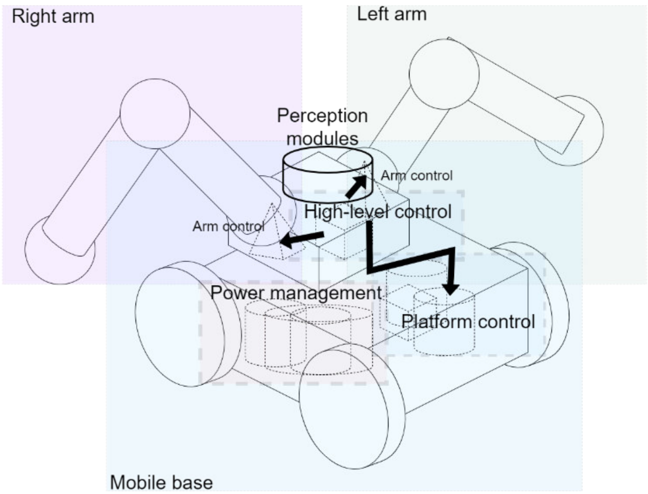

Fig. 2. Overview of the robot with the indication of important components

B. *Requirements analysis*

The robot is designed to operate in an exterior environment, categorized as:

- **External industrial environment:** the ground is typically paved, and the infrastructure is well-developed. Typical environments include urban and industrial environments (e.g., large factories, oil refineries).
- **External natural environment:** the ground is unpaved (rough) with scarce infrastructural development. Typical environments include agricultural areas, natural reserves, raw material extraction, and military training grounds.

Compared to mobile autonomous robots operating in an industrial environment, exterior mobile robots are posed with numerous additional challenges (summarized in Fig. 3). In the following subsections, these main challenges are discussed in detail.

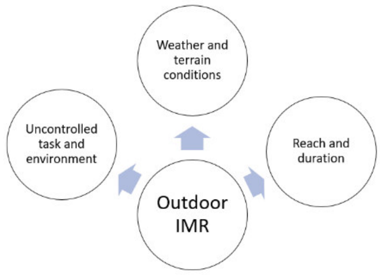

Fig. 3. Challenges for outdoor IMR

1) *Weather and terrain conditions*

In contrast to a controlled industrial environment, outdoor applications must cope with unpredictable weather and varied terrain conditions. Even in a built environment, the device faces many challenges: rough road conditions, potholes, inclines, slopes, and curbs. The road surface is built from materials of different mechanical attributes, such as asphalt, concrete, gravel, and unpaved dirt. Moreover, the weather condition is a stochastically and rapidly changing factor. Rain or strong wind can be just as problematic as intense sunshine. Defense against these conditions requires appropriate countermeasures, all in such a way that the device itself has to apply for the appropriate protection since usually there is no possibility for operator intervention during autonomous work.

2) *Range and runtime duration*

Another set of challenges is the question of operating range and runtime. Compared to typical industrial applications, the device is intended to operate in a much higher distance range from the mission starting point and usually is idle in this position for much longer. These use cases place a double requirement on the device. The high distance range requires a high degree of autonomy, problem-solving, and adaptation for various missions. On the other hand, this requirement also sets higher performance and movement speed standards than widespread applications. The movement speed of traditional industrial mobile robots is typically unfeasible to cover several kilometers in a typical exterior mission time or is only possible to a very limited extent. The environment requires a traveling speed of at least 15-20 km/h or faster, which corresponds to the average speed of a cyclist. The runtime duration must be also adjusted to cover the operating range with electronic equipment.

3) *Uncontrolled task and environment*

In the controlled industrial environment, the tasks of the mobile robots are optimized and precalculated. Nowadays, the entire operation of robots is managed under constant monitoring in a relatively static environment. However, in the case of outdoor applications, the environment is much more variable and nondeterministic. As a result, the tasks that arise are not controlled, and their solution in many cases requires autonomous problem solving and swift improvisation from the mobile robot. In summary, the nature of the tasks and the environment pose the primary challenge to the robot's systems (especially to its software). Therefore, the robot components must be flexible, modular, and standardized as possible.

C. Conceptual design of the robot

1) Drive system

Mobility is a primary requirement for the presented robot. The requirement for IMRs varies widely. In our case, the drive system requirements are high-precision positioning at low speed, starting with high torque, and traveling at high speed are also among the requirements. Low speed and high accuracy are usually characteristics of some servo drive systems, so their application is essential in the current case. High starting torque is also a characteristic of synchronous motors, which is also satisfied by the previously mentioned servo systems. On the other hand, moving at high speed and momentum requires a different speed and torque range, which is more characteristic of asynchronous drives [12]. Based on these, using a hybrid, synchronous-asynchronous drive system would be most favorable in outdoor robots.

2) Power management

Ensuring the power supply is critical for an outdoor autonomous mobile robot, especially if the primary requirement of increased distance range is considered. Furthermore, breakdown or discharge events can also be a problem. Therefore, a power supply system that includes redundancy and self-management capability is required. The self-management capability means that the robot can control the power of individual subsystems. The associated tasks include, for example, determining the required energy needed for return to the base location and preventing an unexpected event by shutting down the least critical individual subsystems. Continuous energy management is fundamental to the operation of the robot. The power supply module must manage the charging process, the state of the accumulator, and individual subsystem energy consumption. Providing the possibility of remote monitoring and intervention is also a mandatory capability. Power management must operate in the most energy-efficient way possible. The issue of on-the-go charging and energy recovery may also arise, which can be implemented with solar panel or energy feedback-generator methods.

IV. DETAILED DESIGN

In the following chapter, the robot's design in more detail is discussed. This includes some insights to mechanical design, software architecture, and simulation.

A. Mechanical design

The mechanical design of the robot considered the challenges listed in the previous chapter. Optimally low weight and low center of gravity generally benefit long-range and higher speed. The loading area located in the structure of the robot platform (similarly as depicted in Fig. 4) allows the main geometric parameters of the robot to be displayed unchanged even when transporting cargo. This mechanical design contrasts with the solution for indoor industrial applications, where the robot carries the payload on top. The design with two manipulators is a means of high flexibility and adaptability, but proper energy management is necessary to avoid unwanted leakage.

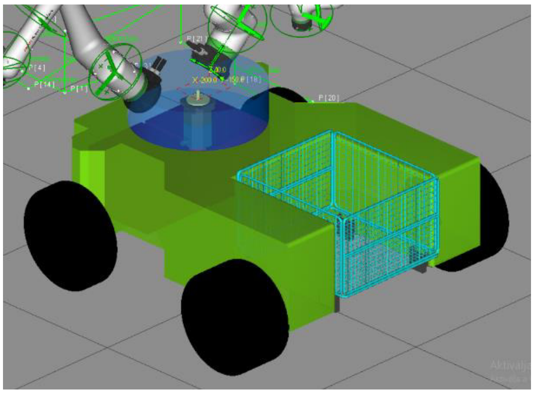

Fig. 4. Payload area located in the structure of the robot.

B. Software system design

The software system should fulfill current expectations of modern robotic software paradigms, such as modularity and distributed organization. Recent development in robotic software frameworks provides a flexible toolset to develop and integrate different software functionalities into a working robot. Widespread frameworks (e.g., ROS2) model (remote and memory-resident) component communication with a communicational graph providing a realization of popular machine-to-machine communicational patterns (e.g., Publisher/Subscriber, Remote Procedure Call), aiding the development of specialized but interconnected components can be created that can be each verified separately or replaced according to the task. This approach corresponds with modern software design and provides a solid framework for iterative testing and development but is also congruent with the connectionist approach in cognitive psychology.

Using the extended sense-think-act model and inspired by the advances in advanced-driving assistance systems (ADAS) [13], the minimal subset of tasks can be identified to perform autonomous tasks:

- **Sensing:** the interface to the robot's sensors (proprioceptive and exteroceptive) and minimal processing, e.g., a camera driver, GNSS equipment driver.
- **Perception:** the processing of sensory data, detection of features, or sensor fusion, e.g., object detection & tracking, state estimation [14].
- **Mapping:** is the estimation of the robot's position on a wide global range (i.e., estimating its geocoordinate state) by using historically processed sensory data and external sources (e.g., geographical maps, landmark databases). In short, placing the robot on a constructed map. Example components include SLAM methods and geographical mapping.
- **Inference representation:** based on instantaneous and historical sensory data, the robot infers a formally representable state of its belief state, with different features weighted according to the current scenario. The most straightforward solution is to represent the belief state as a grid, but more complex and computationally efficient solutions are preferred, especially in an outdoor setting. It should be noted that many widespread solutions treat the representation of the environment and belief state as a monolithic part of planning. New research focuses

on separating representation as sets of independent components [15].

- **Planning:** based on historical state estimates, current environment representation, and detected features, the robot navigates towards its goal and optionally provides manipulator working trajectories. This plan could be a set of abstract actions (using a planning language) or minimally a trajectory towards a state. Most researchers approach the planning problem with a hierarchical solution, separating *global* planning (the robot's environment in a wide range) and refining the intermediate result by *local planning* (close surroundings of the robot). Widespread planners are sampling-based (e.g., RRT derivatives [16]), graph-based (e.g., A*, Hybrid A* [17]), and rely on some semantic data (e.g., kinematic structure, dynamic parameters) related to the robot or its surrounding environment elements. Separately for arm manipulators, specialized software suites are available with an interface for other software components (e.g., MoveIt2 [18]). Ultimately, the planner provides data for the control components, thus connecting other components with the actuators.
- **Control:** control components continuously provide reliable control signals for the actuation drivers based on the output of the planner components. If the planner provides a trajectory, the control components attempt to track this trajectory based on the instantaneous state estimate and an optimum strategy, therefore solving an optimization problem in this regard. Some methods can integrate local trajectory planning with control tasks with direct application to manipulators [19, p.].
- **Actuation:** the direct access to the actuator components (i.e., motors) through the provided control signals, e.g., motor drivers, gripper control.
- **Interaction:** the interface that provides interaction and monitoring capabilities for external actors (e.g., human users, other robots, other software), e.g., runtime monitors, user interfaces.

These cognitive components, their instantiation on one of the computational units of the robot, and their intermediate relationships are summarized in Fig. 5.

C. Simulation and verification

Simulation of robots typically aids the development of robots in every phase. In addition to the apparent boost to continuous software development, it also provides a way to verify different subsystems of the robot continuously. However, in the case of the presented robot, each manipulator and the platform could operate independently. Consequently, the simulation of each part must be checked and revised alongside the integrated system.

For general robotic systems, widespread rigid-body simulators (e.g., Gazebo [20]) are available. Such simulators enable the proper simulation of multiple robots and provide a mockup of their actuator-sensor interface for programs. With this methodology, it is possible to simultaneously develop programs for the simulated and the actual physical robot.

In the case of the presented dual-manipulator mobile robot, the construction and the low-level interfacing of components are challenging, making the physical robot available only in a later phase. A conceptual mockup can be created to start software development.

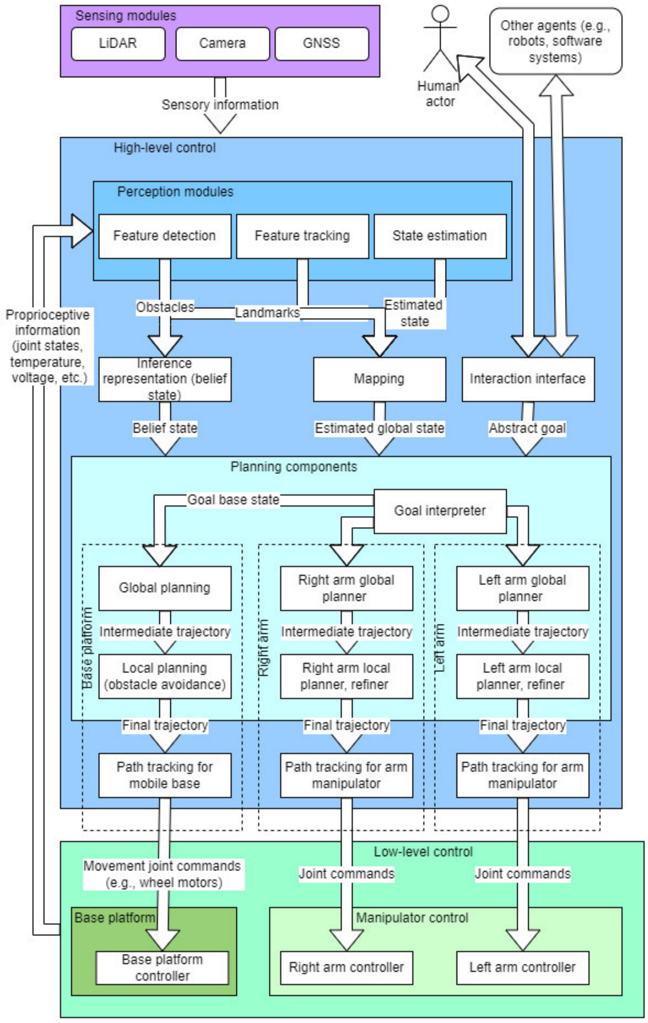

Fig. 5. Proposed software architecture of dual arm mobile robot

V. FUTURE WORK

The construction of the presented robot is a challenging and promising project from research and industrial aspects. This section discusses some further development steps ahead.

Creating the simulation mockup is mandatory in terms of software and mechanical verification. Therefore, the next step is to create a conceptual simulation of the robot with a set of different test scenes, each testing the capabilities of the robot. On the other hand, parallel with the simulation, a physical scaled mockup could be created to test the kinematic and mechanical attributes of the robot.

A scaled physical mockup would help integrate electronic components such as power supply, motor drivers, and low-level control. The electronics would be customized to some degree in the case of low-level control requiring substantial verification before use. An important step is the electronical integration of all low-level control components with related software bridge components. The sensory and actuation equipment requires further integration steps and additional bridging component. A considerable future milestone is the electronic integration of each independent component, followed by the composed setup.

Even a coarse simulation could be used to develop the essential identified software components. For example, the development of planner and perception components requires only a conceptual model of the robot. Therefore, creating working test scenarios and environment setups that are meaningful and challenging enough is the focus of implementing simulation tasks.

VI. Conclusion

This paper presented a dual-arm mobile manipulator for intended industrial use. The presented setup is somewhat widespread in academic and military applications but rather unconventional in industrial applications, particularly not in outdoor environments. This paper presented the challenges and basic requirements posed to the robot. The paper also conceptualizes the software architecture of the robot enhanced for dual-arm application. Finally, the paper discusses the development steps, including the simulation. In summary, many tests and developments are required to achieve the outlined results with promising measurements. The number of solution options is high, and the challenge includes a variable and unpredictable element, possibly leading to pitfalls and breakthroughs in robotic development.

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