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Synergetic Cooperation Between Robots and Humans

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Foreword

CLAWAR (Climbing and Walking Robots) started with a 6-month exploratory phase in 1996 by four European organizations, namely the University of Portsmouth, Royal Military Academy, FZI and RISO with the view to identify robotic stakeholders across Europe. The outcome was initiation of the CLAWAR thematic network of excellence supported by the European Commission over two phases, namely CLAWAR1 under the EC Brite Euram programme during 1998–2002 and CLAWAR2 under the EC GROWTH programme during 2002–2005.

CLAWAR Association was established by the end of 2005 to continue the activities of the CLAWAR Network globally, with the mission to advance robotics for the public benefit. The Association was registered in March 2006 with the Companies House in the UK as a non-profit making limited company by guarantee, and in 2012 with the Charities Commission in the UK as a charitable organization.

The CLAWAR annual conference series is one of the main activities of CLAWAR Association. The first nine issues of the conference starting from 1998 were held in locations across Europe, and further issues in various countries worldwide. The COVID-19 pandemic has had an impact on the mode of participation in the conference, and while issues to 22 (2019) were held in physical participation mode, virtual participation mode has been exercised for issues 23 (2020, Russian Federation) and issue 24 (2021, Japan). The CLAWAR conference series has established itself as a popular and high-profile platform for networking and dissemination of research and development findings in the area of mobile robotics and associated technologies.

Preface

CLAWAR 2023 is the twenty-sixth edition of the International Conference series on Climbing and Walking Robots and the Support Technologies for Mobile Machines. The conference is organized by the CLAWAR Association in collaboration with the Federal University of Santa Catarina, Brazil during 2–4 October 2023.

CLAWAR 2023 brings new developments and new research findings in robotics technologies within the framework of ‘synergetic cooperation between robots and humans’. The topics covered include wearable assistive robotics from augmentation to full support for those with mobility disorders, innovative designs of components and full systems and application-specific robotic solutions.

The CLAWAR 2023 conference includes a total of 55 regular and special submission articles, from research institutions worldwide. This number has been arrived at through rigorous review of initial submissions, where each paper initially submitted has received at least three reviews. The conference further features three plenary presentations;

Biped walking with robots and exoskeletons: Marching towards bionic gait
Arturo Forner-Cordero, Universidade de São Paulo, Brazil.
Multibody dynamics with contact-impact events: Roots, models and applications
Paulo Flores, University of Minho, Portugal.
Human-like bipedal locomotion
Karsten Berns, University of Kaiserslautern, Germany

It is believed that this book will serve as a source of inspiration and further innovation in research and development in the rapidly growing area of mobile service robotics.

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Education in Robotics and Robotics in Education

Hybrid and Convertible Unmanned Aerial Vehicles

Design and Development of an Omnidirectional Mecanum Platform for the RobotAtFactory 4.0 Competition

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Abstract. Robotics competitions are highly strategic tools to engage and motivate students, cultivating their curiosity and enthusiasm for technology and robotics. These competitions encompass various disciplines, such as programming, electronics, control systems, and prototyping, often beginning with developing a mobile platform. This paper focuses on designing and implementing an omnidirectional mecanum platform, encompassing aspects of mechatronics, mechanics, electronics, kinematics models, and control. Additionally, a simulation model is introduced and compared with the physical robot, providing a means to validate the proposed platform.

Keywords: Engineering Education, Industry 4.0, Omnidirectional Robot, Prototyping, Simulation, Kinematics, Control Theory, Education 4.0, Robotics Competition

1 Introduction

In recent years, mobile robots have become increasingly integrated into various daily tasks, such as cleaning, elderly and disability support, and surveillance

[1–3]. The field of robotics has also made significant contributions to industrial operations, particularly in the context of Industry 4.0, which has revolutionised global factory operations [4].

To enable efficient and optimised operations, Industry 4.0 relies on robotics systems that capture, interpret, and act upon data collected from the environment [4]. These systems utilise a range of sensors, including laser scanners, sonars, cameras, GPS, and encoders, to extract information necessary for decision-making in specific applications [5]. Promoting the development of new technologies, robot competitions provide a platform for participants to design and build robots capable of performing specific tasks, fostering innovative solutions to complex problems [6].

The RobotAtFactory 4.0 (RAF) competition holds particular significance in education as it offers a multidisciplinary approach for students from various technological fields [7]. The competition also serves as a platform to address challenges similar to those encountered in real industrial environments, pushing the boundaries of robotics and driving research and development in the field. Success in the RAF competition hinges on designing systems prioritising quality and reliability, leveraging advanced technologies and meticulous planning. This research focuses on developing a mecanum platform for the RAF competition.

Mecanum wheels present distinct advantages over traditional wheeled robots, offering enhanced mobility, flexibility, and efficiency, thus finding value in various robotics applications. The omnidirectional movement capability of mecanum wheels enables robots to navigate in any direction during competitions, facilitating manoeuvring in tight spaces and avoiding collisions with other robots and objects. Furthermore, this mobility promotes effective collaboration and optimisation of the manufacturing process, augmenting the agility and flexibility of mecanum-based platforms.

This research presents the development of a mecanum platform specifically designed for the RAF competition, along with a validation and testing methodology based on a ground truth location system [8].

2 State of the art

In education, robotics has been used to promote competition and achieve a factor of progress [9, 10]. As observed in [11], robotic competitions bring students and researchers a way to evolution, and this progress can be of value to the industry's paradigms. With the increase of Automated Guided Vehicles (AGVs) in the industry, different problems related to this type of transportation in the industrial environment have arisen, especially regarding obstacles in front of the robot [12, 13].

The Portuguese Society of Robotics promotes different types of competition to encourage the development of human-robot cooperation. One is the RobotAtFactory 4.0 competition, which consists of an emulated factory plant with AMRs to perform tasks. This competition drives concepts of simulation, hardware-inloop, and timed finite state machine, where the students need to validate their solutions in the actual robot prototype [7].

For this type of competition, maximizing the robot's efficiency in completing the tasks is essential. Several works promoted solutions for communication and robot team coordination, optimizing the manufacturing process through machine learning and artificial intelligence algorithms, and efficient task allocation [7, 14, 15]. In [16], a new hardware approach introduces Wi-Fi communication with the referee server as the provider of the parts description and requests directly to the robot. With this approach, it is possible to improve the robot's capability to schedule the movements since the information comes from the referee before reading the part. Additionally, the authors from [17] developed an automatic referee for the RAF competition based on computer vision-driven AI. Finally, Costa et al. [6] presented an approach implemented in the RobotAtFactory competition regarding an omnidirectional robot's control, localization, and navigation methods. As a result, improve the approaches' capability to avoid methods that need changing the environment where the robot must operate.

The main objective of the RobotAtFactory 4.0 competition is to present real problems that exist in the industrial context, and that must be solved by autonomous mobile robotic platforms, whose main objective is to transport, collect, and position materials between warehouses or machines in an environment that simulates the factory floor of an industrial zone. For this, the robot must be able to move fluidly, locate itself in an environment of different obstacles and navigate quickly to save time and energy in the face of the requirements imposed by the competition.

The RAF competition arena comprises an area measuring 1.7 x 1.2 meters, with two machines (A and B) and two warehouses (entry and exit), through which the robot must transport the produced parts. In addition, the arena comprises fiducial markers (ArUco) arranged on the floor with a white background and on the walls of the machines and warehouses. Figure 1 illustrates the RobotAtFactory 4.0 competition arena environment.

Based on the characteristics of the RAF competition arena, the fiducial markers' objective is to provide their respective global and orientation positions. In this sense, it becomes possible to take advantage of the information provided by the ArUcos markers, processing their information to estimate the robot's location, such as a ground truth system that can be used to validate the robot's localization system. This system was implemented in work published by Braun et al. [8], whose robotic platform presented a much simpler hardware architecture than the one presented in this work, featuring a pair of conventional wheels and a perception system based on computer vision.

The architecture of the ground truth system consists of an RGB camera (RPi NoIR Camera V2) fixed in the centre of a table that monitors the scenario of the RAF competition. From observing the camera in a controlled environment and with diffused sunlight, the system locates all the fiducial markers, assuming that the global reference frame is situated on ArUco 13. The ArUcos 16 and 4 are used to estimate the x and y axes. In this way, it becomes possible to estimate

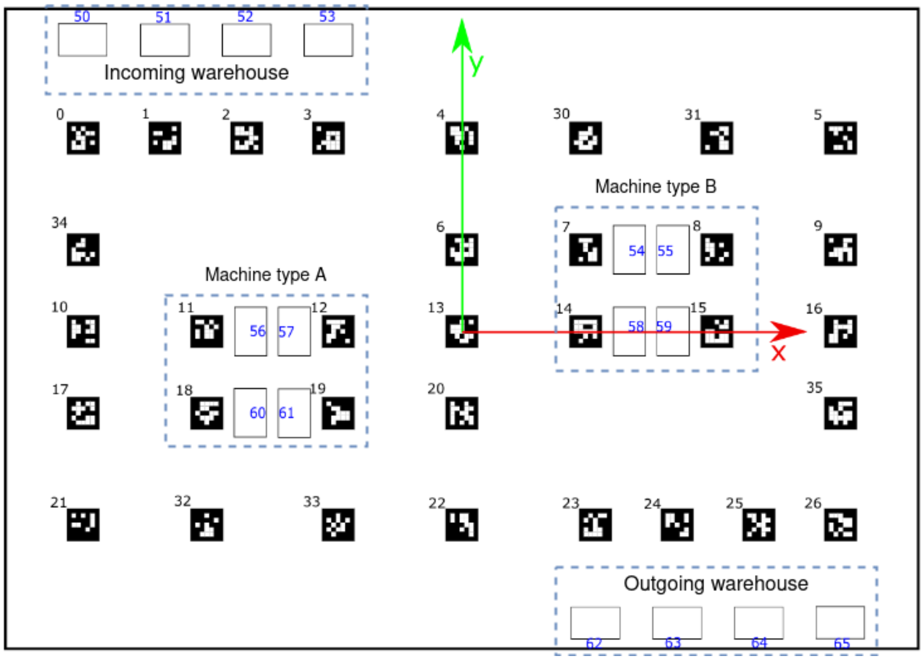


Fig. 1: RAF competition arena.

the position and orientation of all markers contained in the arena. In addition, to improve the accuracy of the mecanum robot pose estimation, a pair of ArUco markers was added over its upper central region, whose purpose is to calculate the position of these two markers and obtain the orientation and position of the robot in relation to the environment.

3 Development & Results

In this section, we present the results of our study, which include the hardware architecture, kinematics models, and the comparison between simulation and real scenarios.

3.1 Hardware Architecture

The mobile robot created for the RobotAtFactory competition is designed with a systematic top-down approach, beginning from the hardware components to the final integration of software. The hardware architecture of the robot is visually represented in Figure 2.

As shown in Figure 2, the system can be divided into different categories, namely input devices, control devices, power management components, and output devices.

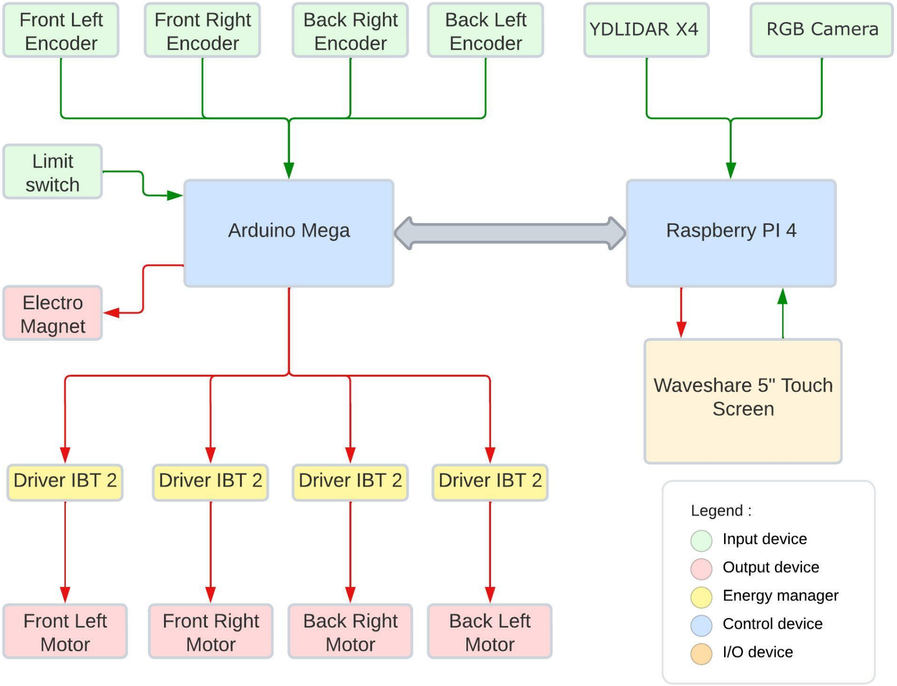


Fig. 2: Input/Output diagram illustrating the connectivity between the robot hardware components.

The robot is equipped with four Mecanum wheels, facilitating omnidirectional movement. Each wheel is powered by a 12 VDC Pololu D37 motor and controlled by an IBT-2 H-bridge, capable of supplying voltages from 6 to 27 VDC and current up to 43A. A 4-cell LiPo battery (16.8 VDC, 5200 mA) fuels the motors and the H-bridges. An LM2596 step-down DC-DC converter is integrated into the system to stabilize the voltage to 5 VDC, which is needed for other electronic devices embedded in the robot.

The Arduino Mega 2560 controller board manages the motor speed by taking encoder readings from each wheel. It also handles the input from the contact switches and controls the electromagnet used for material handling within the RobotAtFactory competition arena. These are represented as green symbols in the diagram, indicating their roles as input devices.

The Raspberry Pi 4 controller board, shown in blue, handles sensory perception. It interfaces with the YDLIDAR-X4 LASER scanning sensor and the Raspcam Noir camera, both acting as input devices. These components are used for beacon detection within the competition area. The camera, in particular, identifies ArUco fiducial markers, estimating the robot's position and orientation based on this data.

The Arduino Mega and the Raspberry Pi 4 also interface with the WaveShare 5" touchscreen display, shown in orange, which acts as an I/O device. This display provides real-time feedback about the robot's control states, including detected ArUco references, wheel speeds, and the status of contact switches.

Finally, the robot is equipped with an electromagnet and four motors (represented in red) acting as output devices. The electromagnet is directly controlled by the Arduino Mega, whereas the motors are managed by the four IBT-2 H-bridge driver modules. These modules are highlighted in yellow to signify their roles as power management components.

The validation of the robot's performance leverages a ground truth localization system that uses ArUco tags, a methodology previously outlined by Braun et al. [8]. Positioned at the centre of the table, an RPi NoIR Camera V2 scrutinizes the RobotAtFactory competition environment. Through the detection and subsequent analysis of the ArUco fiducial markers, this system yields precise estimates of the robot's position and orientation.

3.2 Kinematics Models

The robot's kinematics can be divided into forward and inverse kinematics models. The forward kinematics model allows the computation of the chassis' speeds relative to the robot's frame based on the angular speed of each wheel. The inverse kinematics model, on the other hand, computes the wheels' angular speeds from the desired chassis speeds. Figure 3 depicts the kinematic architecture of the robot.

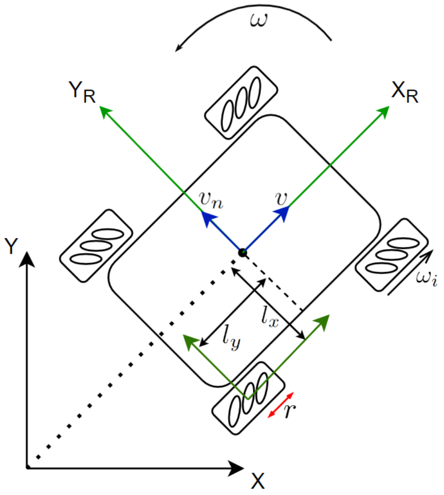


Fig. 3: Robot's kinematic architecture. Adapted from [18].

The forward kinematics model can be expressed by the following equations, where X_R and Y_R represent the Cartesian coordinate system associated with the robot's frame, l_x and l_y denote the distances between the midpoint of a wheel and the X_R and Y_R axes, respectively, v and v_n are the robot's linear speeds, ω is the robot's angular speed, and ω_i represents the wheels' angular speeds:

$$\begin{bmatrix} v \\ v_n \\ \omega \end{bmatrix} = \frac{r}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ -\frac{1}{l_x+l_y} & \frac{1}{l_x+l_y} & -\frac{1}{l_x+l_y} & \frac{1}{l_x+l_y} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \tag{1}$$

The inverse kinematics model can be expressed by the following equations, where the wheels' angular speeds ω_1, ω_2, ω_3, and ω_4 are computed based on the desired chassis speeds v, v_n, and ω:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & -1 & -(l_x+l_y) \\ 1 & 1 & (l_x+l_y) \\ 1 & 1 & -(l_x+l_y) \\ 1 & -1 & (l_x+l_y) \end{bmatrix} \begin{bmatrix} v \\ v_n \\ \omega \end{bmatrix} \tag{2}$$

These kinematics models allow the robot to accurately control its movement and ensure precise maneuverability within the RobotAtFactory competition arena.

3.3 Simulation and Real Scenario Comparison

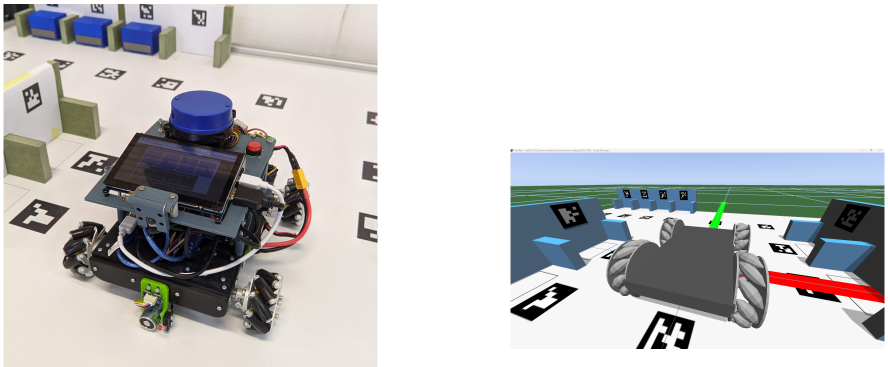
This section presents a validation of the performance of the four-wheeled mecanum robot by contrasting its behaviour in both a simulated and real-world environment. The simulated environment was modelled using the SimTwo simulator, whereas the real-world scenario mirrored the conditions of an actual RobotAtFactory competition (Figure 4).

The robots in both settings performed the same trajectory. While minor variations are present, the trajectories exhibit a significant level of consistency. These variations could be traced back to factors such as the quality of the mecanum wheels, frictional forces, weight distribution, and inaccuracies introduced by human error in measurements required for computing the homogeneous transformations between the sensor frames and the robot's centre (Figure 5).

Dynamic Time Warping (DTW) was employed to compare the simulated and real-world robot trajectories quantitatively. The resulting DTW distances were 8.64 and 0.86 for the xy position and orientation, respectively.

The DTW path for the xy position (Figure 6) has less warping than the path for orientation, with a notable stretch in the middle. This could be due to controller behaviour, real-world constraints, or wheel quality affecting the robot's speed.

In contrast, the orientation DTW path (Figure 7) demonstrates two substantial warps, suggesting discrepancies in the robot's orientation, possibly due to the same factors that affect the xy position.



(a) Robot in the real environment.

(b) Robot in the simulated environment.

Fig. 4: Comparison of the robot in real and simulated environments.

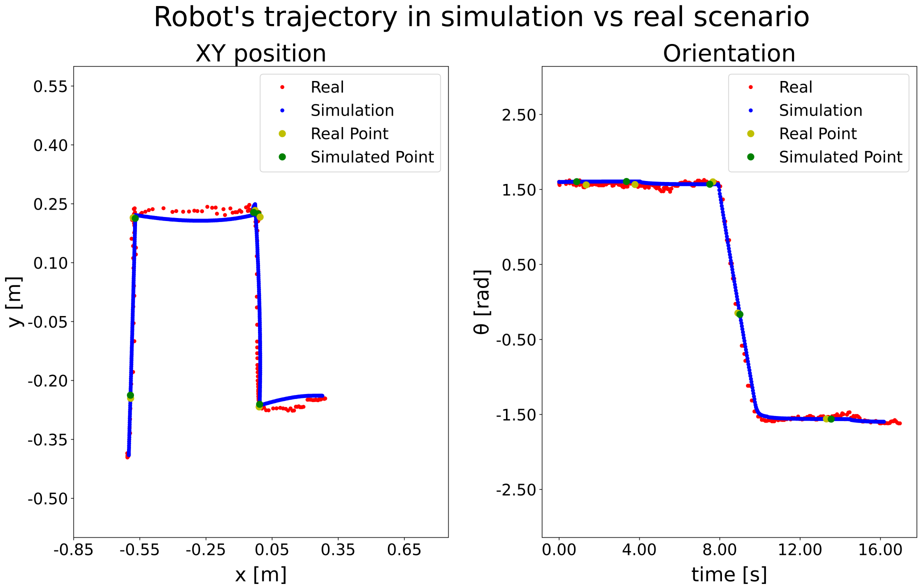


Fig. 5: Trajectory executed in the simulation and real scenarios.

Given the disparities in time scales, sampling frequencies, and robot speeds in both scenarios, traditional statistical tools such as Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), or standard deviation would not yield meaningful results. Hence, it was decided to compute absolute pose errors at strategically chosen points along the trajectories. They can be seen in Table 1.

As one can see, the minor discrepancies are negligible for the case study. In other words, the close correspondence between the real and simulated trajec-

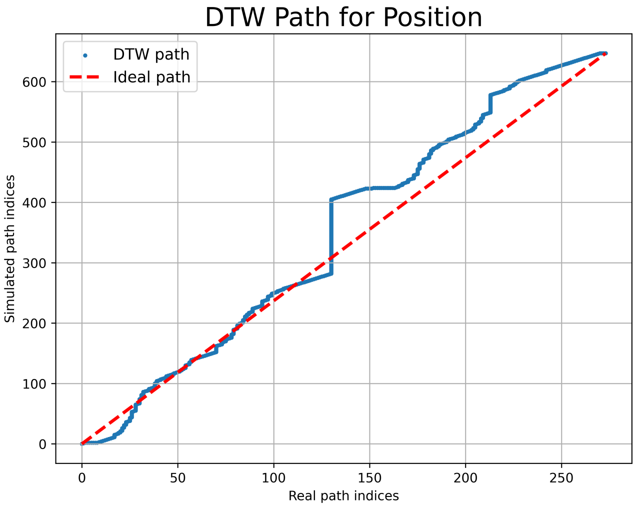


Fig. 6: DTW path for the position trajectory.

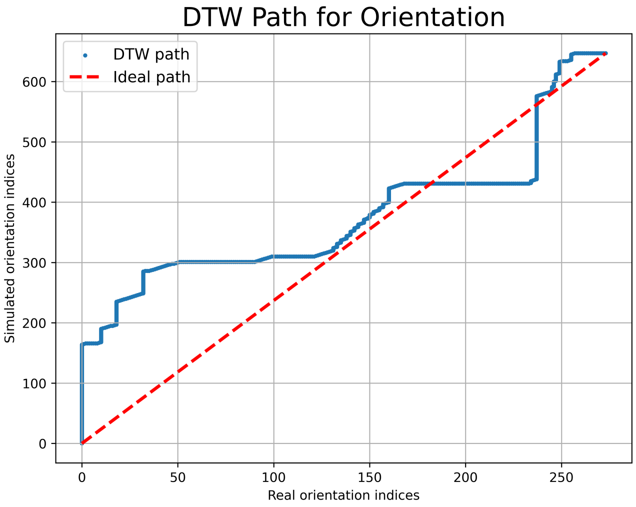


Fig. 7: DTW Path for orientation.

tories underscores the effectiveness of the robot's control algorithms, as well as the utility of the simulation as a tool for designing the localization system and control platform. Possible areas for enhancement could include the quality of the mecanum wheels, reliability of the localization system and ground truth by reducing noise and improving precision, optimization of weight distribution, increased accuracy of centre computation, and fine-tuning the robot's controllers.

Table 1: Absolute pose error between the simulated and real trajectories at specific points.

Point	**x-coordinate [m]**	**y-coordinate [m]**	**Orientation (θ) [rad]**
First	0.001	−0.008	−0.043
Second	−0.009	0.002	−0.040
Third	−0.013	0.009	0.031
Fourth	0.030	−0.012	0.018
Fifth	−0.002	−0.007	0.002

4 Conclusion

This paper presents an application of theoretical knowledge in robotics and automation, with a specific focus on the RobotAtFactory competition. By utilizing the existing localization system and ground truth validation methodology, this study contributes significantly to the academic discourse, providing a useful case study for real-world applications. Moreover, this work offers valuable insights into implementing a four-wheeled mecanum AMR platform in an industrial setting. The conducted comparison of the robot's performances in simulated and real-world environments underscores the platform's effectiveness and practical potential. It bridges the gap between theory and application, laying the groundwork for future research and innovation.

Implementing the mecanum AMR platform in automated warehouse competitions demonstrates its unique capabilities. Its omnidirectional movement allows efficient path planning, precise positioning, and enhanced manoeuvrability in confined spaces in contrast to the differential-drive robots' constraints. The ability of this platform to collaborate optimizes resource use, paving the way for efficient logistics systems for tasks such as order picking and item transportation.

In conclusion, the primary contribution of this paper lies in demonstrating the practical application of theoretical knowledge in robotics within industrial settings. It underscores the importance of robotics research in advancing automation technologies, particularly in the context of automated warehouse competitions, and sparks inspiration for future advancements in various industrial sectors. Despite the overall performance of the mecanum AMR platform being validated, minor discrepancies between the simulated and real-world trajectories were noted. These discrepancies can serve as a focus for future work, driving further refinement in the simulation model, enhancing the quality of the mecanum wheels, improving the precision of the localization system, and fine-tuning the robot's controllers.

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