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DEVELOPMENT OF A MOBILE ROBOT PLATFORM FOR SMART WAREHOUSE MANAGEMENT SYSTEM

Abstract

This study examines the TurtleBot3 Waffle Pi mobile robot's integration into warehouse logistics, highlighting its role in enhancing operational efficiency and reducing costs. Central to the research is the development of a Python-based navigation algorithm that employs LIDAR for autonomous navigation, complemented by a novel positioning strategy. This allows the robot to accurately navigate within a predefined imaginary grid, optimizing workflow, minimizing errors, and cutting operational expenses. A custom-designed lifting mechanism, fabricated via 3D printing, is introduced to improve pallet handling, showcasing the synergy between mechanical innovation and robotics. The integration with Wiren Board 7 controllers facilitates seamless operation, further enhanced by connecting the robot to the Honeywell Experion PKS system through OPC UA technology. This connectivity underscores the robot's capability to integrate into existing industrial control frameworks, offering a scalable solution for modernizing warehouse operations. Focusing on Kazakhstan's logistics sector, the application of such technologies demonstrates significant potential to elevate operational efficiency and competitiveness on a national scale. The study emphasizes the critical role of robotics and advanced control systems in logistics, advocating for further technological advancements to support economic growth and sustainability.

Key words: mobile robot, smart warehouse, warehouse management system, TurtleBot3, navigation, robotization.

Introduction

In the dynamic landscape of the 21st century, where technological advancements and automation redefine boundaries, the emergence of Smart Warehouse Management Systems signifies a pivotal shift towards operational efficiency, convenience, and environmental sustainability. Central to this evolution is the integration of robotics and intelligent automation technologies, which are set to transform traditional logistics and warehouse management practices.

This article explores the advent of the Smart Warehouse, a sophisticated paradigm in warehouse management that marries robotics, artificial intelligence (AI), and Internet of Things (IoT) technologies. The aim is to enhance the efficiency, cost-effectiveness, and adaptability of warehouse operations to meet the demands of contemporary commerce. By deploying mobile robots equipped with state-of-the-art sensors and AI-driven algorithms, these systems evolve warehouses into agile, self-optimizing entities capable of real-time adaptation to fluctuating demands and operational priorities. The impetus for this shift is the escalating pressures on the global logistics sector, driven by the exponential growth of e-commerce and heightened consumer expectations for rapid, accurate deliveries. Traditional warehousing approaches frequently fall short under these conditions, leading to operational bottlenecks, errors, and elevated costs. In response, the concept of Smart Warehouses with Mobile Robots emerges as a strategic solution to these challenges, offering a pathway to streamline operations, mitigate inefficiencies, and enhance delivery precision. Focusing on Kazakhstan, a nation poised strategically on the Eurasian trade corridors, the urgency for adopting technologically advanced logistics solutions is underscored. The country's expansive geography and pivotal economic position amplify the potential benefits of Smart Warehouse systems. Such innovations promise to refine goods distribution, lower transport expenses, improve inventory control, and catalyze economic advancement.

This research delves into the integration of the TurtleBot 3 Waffle Pi mobile robot within the Smart Warehouse ecosystem. Highlighting its Python-based navigation algorithm, custom-designed lifting mechanisms, and seamless connectivity to control systems via OPC UA technology, the article illustrates the robot's role in enhancing warehouse functionality. It positions the TurtleBot 3 Waffle Pi as a linchpin in the transition towards intelligent, automated warehousing solutions in Kazakhstan, with broader implications for global logistics practices.

Literature Review

The issue of warehouse management is becoming increasingly pressing by the day. Research conducted in China has revealed that the efficiency of the logistics industry is struggling to keep pace with rapid changes, leading to diminished goods turnover and adversely affecting the national economy. A promising solution to fully address this challenge lies in the realm of intelligent logistics. This approach aims to enhance the analytical capabilities of the logistics system, decision-making processes, and "intelligent execution through smart equipment". Moreover, it seeks to elevate the level of intelligence and automation across the entire logistics system, offering a strategic pathway to overcome existing limitations and drive significant improvements in warehouse operations [1]. Similar conclusions were reached following an analysis of Warehouse Management Systems (WMS) within major distribution companies in Bosnia and Herzegovina [2] and the third-party logistics industry in Sri Lanka [3]. Furthermore, the application of IoT technologies in warehouses storing harvests in India has provided a solution to the issue of rapid crop deterioration, significantly enhancing the efficiency of agricultural operations [4–6]. Additionally, beyond localized monitoring systems, comprehensive complexes for warehouse management are being developed: automated systems for searching, storing, and retrieving that both receive and dispatch goods [7, 8]. Moreover, these comprehensive systems can be augmented through the integration of cloud service technologies [9, 10]. In addition to monitoring and search systems that utilize static robotic manipulators for moving items, the deployment of mobile devices is becoming more prevalent. These include intelligent hand carts [11], mobile platforms [12], and unmanned ground vehicles (UGVs) [13]. As a method for localization, RFID tags are employed [14]. This method has proven to be quite reliable; the robot is capable of localizing itself with an error margin of less than 10 cm and an orientation error of less than 0.4 radians in 80% of instances [15]. It is noteworthy to mention the MONITOR project, developed by a research group from the University of Pisa, which introduced an RFID robot designed for clothing inventory purposes [16]. To address localization challenges, this robot was equipped with moving antennas [17], and a function for 3D localization was developed [18]. This innovation represents a significant advancement in the field of warehouse automation, particularly in the context of managing apparel inventories.

However, the process of integrating IoT into industrial and logistics sectors is ongoing, leading to the emergence of new methods for device communication [19] and the development of solutions aimed at optimizing robot operations [20]. This continual evolution signifies a transformative phase in which connectivity and smart technologies are fundamentally reshaping the operational landscapes of warehouses and supply chains.

Drawing from the facts outlined above, it can be concluded that the process of integrating new technologies into warehouses is highly complex, necessitating extensive research, calculations, and prototype testing. However, the outcome of this intricate process promises to address significant logistics challenges, leading to economic growth, particularly in the territory of the Republic of Kazakhstan.

Statement of the problem is to develop of a mobile robot equipped with a lifting mechanism for raising pallets within the framework of a smart warehouse system.

Main Provision

The TurtleBot3 Waffle Pi is integral to smart warehouse innovation, excelling in SLAM (Simultaneous Localization and Mapping), Navigation, and Manipulation. It autonomously navigates warehouses using SLAM, accurately mapping its surroundings, and locating itself. As shown in Figure 1, a scalable structure of the TurtleBot3 Waffle Pi refers to the design and architecture of the robot that allows for easy expansion or customization to accommodate additional components, sensors, or accessories. This flexibility in the robot's structure enables users to adapt and modify it according to their specific needs and requirements. It often involves standardized interfaces, mounting points, and connectors to seamlessly integrate new hardware or extend the robot's capabilities while maintaining stability and performance.

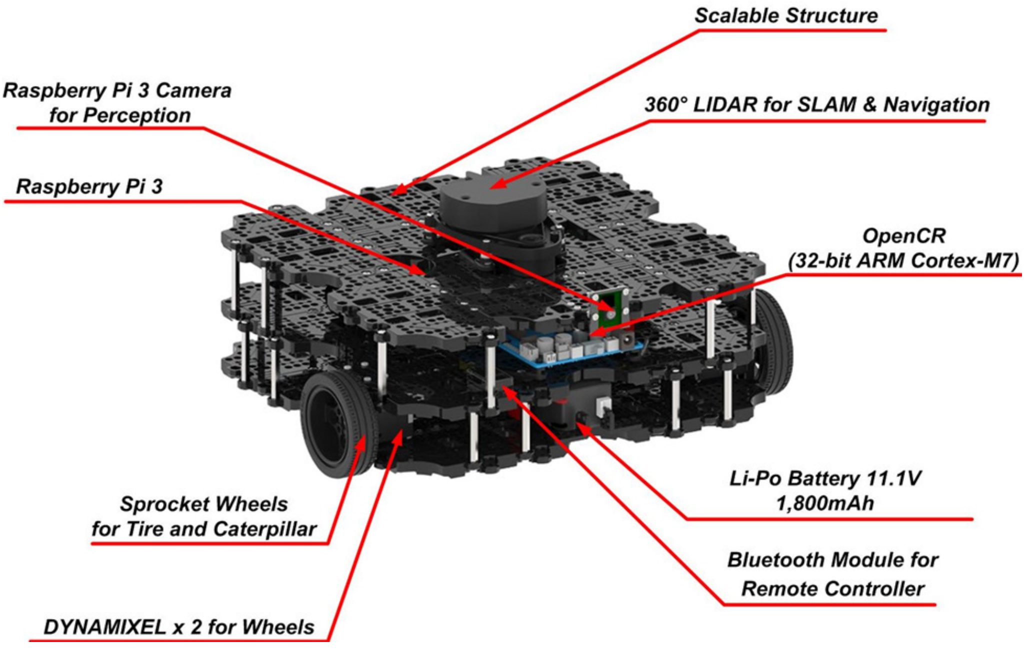

Figure 1 – TurtleBot3 Waffle Pi

It offers three power connectors: 3.3V/800mA, 5V/4A, and 12V/1A. The onboard lithium-polymer battery has a rating of 11.1V and 1800mAh, providing approximately 2 hours of continuous operation and 2 hours 30 minutes of charging time.

Robot kinematics and structural design

It is noted that the structure of this mobile robot is divided into several levels (layers), each comprising a distinct set of components and functions, as depicted in Figure 2 (p. 31).

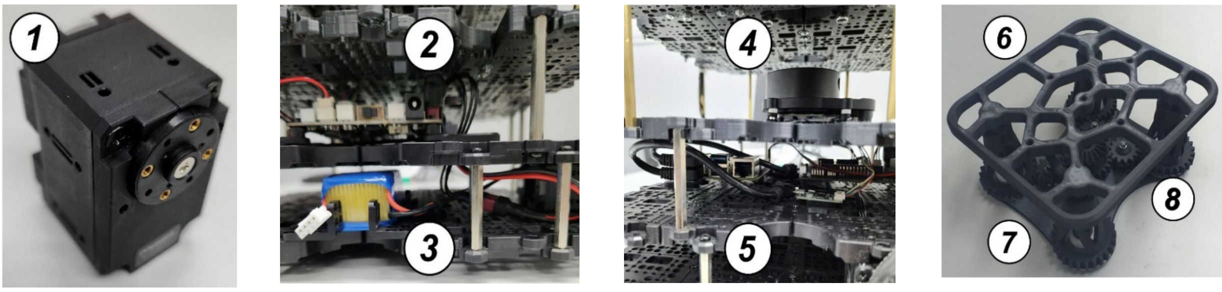

Figure 2 – Components of the robot: 1 – DYNAMIXEL XL430-W250;
2 – OpenCR 1.0; 3 – battery, 4 – LIDAR; 5 – Raspberry Pi 4;
6 – tabletop; 7 – baseplate; 8 – crank-handle mechanism

The first layer houses the DYNAMIXELs – highly capable servomotors from Robotis that support not only the robot's weight but also that of the pallet. This level also includes the attachment point for the battery. The second layer is home to the 'brains' of the robot – the OpenCR board, which manages motor control, and the Raspberry Pi 3, serving as the primary computational module. Positioned on the third layer is the LIDAR, essential for positioning and navigation, operating in tandem with a gyroscope on the OpenCR board. The final layer features the lifting platform, composed of three parts: the tabletop, baseplate, and crank-handle mechanism. The core function of this platform lies in the integration of a DYNAMIXEL with the crank-handle mechanism, enabling the automatic elevation and descent of the platform. The baseplate secures the platform to the robot, while the tabletop bears the weight of the pallet during transport.

Regarding the kinematics of the robot's movement, it is illustrated in Figure 3. Here, point Or identifies the robot's center of motion, enabling free movement along the X and Y axes, coupled with the capacity for a full 360-degree rotation around Or, indicated by the angular velocity ω.

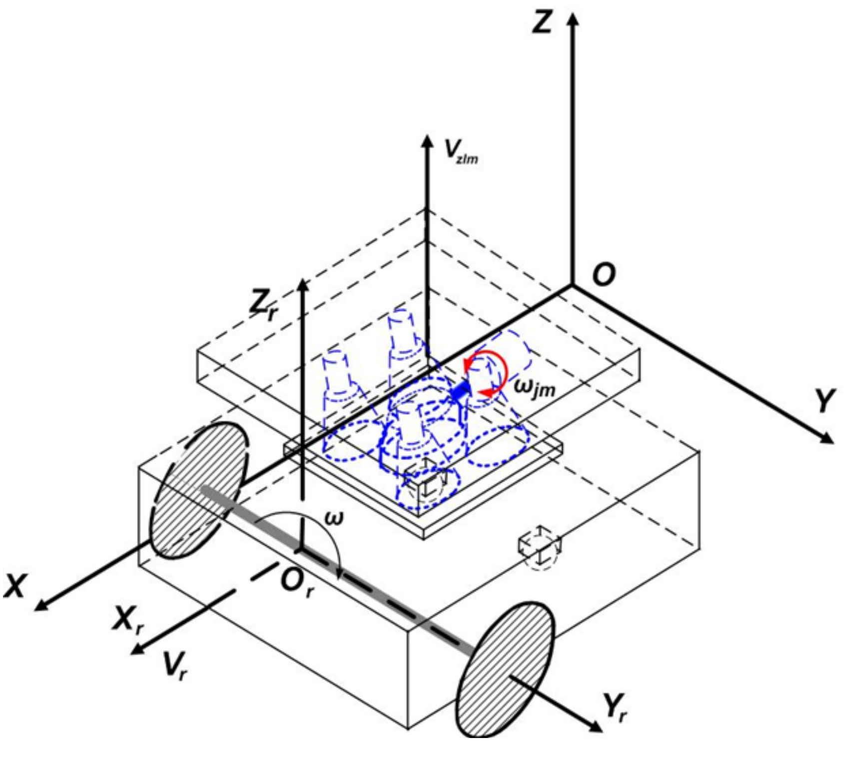

Figure 3 – Kinematic model of the robot

The overall motion of the robot is encapsulated by the vector Vr, which integrates its translational and rotational movements. The lifting mechanism operates with a dedicated motion vector Vzlm along the Z axis, while the motor responsible for this lifting mechanism exhibits an angular velocity ωjm, ensuring coordinated vertical movements essential for the robot's interaction with objects within its operational environment.

Materials and Methods

For the analysis of system behaviors, long-term data collection is crucial. This method provides a thorough understanding of how the system operates. The DYNAMIXEL Wizard 2.0, a dedicated software for monitoring motor performance in real-time, was utilized in this study. The software proved vital for documenting detailed motor performance, which is essential for analyzing the system's dynamics. The connections within the system are depicted in Figure 4.

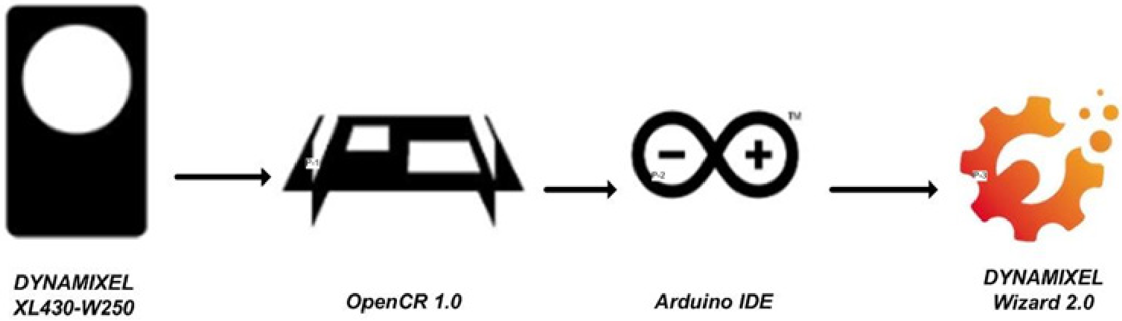

Figure 4 – DYNAMIXEL Wizard 2.0 connection

Data regarding the motor's variations were efficiently collected within minutes using this approach. Subsequently, the challenge arose in processing this information effectively. The data retrieved from the DYNAMIXEL servo was exported into a comma-separated values (*.csv) file, as shown in Table 1. This raw dataset contained superfluous details, presenting a potential for inaccuracies in subsequent model identification phases. To address this, a tailored Python script was crafted to streamline the data, filtering out irrelevant information and preparing it for precise analysis.

Table 1 – Data before filtering

Time, ms	Realtime Tick	Present Velocity, rev/min	Present Input Voltage, V	Present PWM, %
4029	32663	263	120	885
4049	32683	263	120	885
4069	32703	260	120	655
…	…	…	…	…

The application of the Python script for post-processing substantially enhanced the clarity of the data, enabling the refinement and retrieval of any missing elements. The results of this refined data processing are depicted in Table 2 (p. 33), demonstrating the efficacy of the script in preparing the dataset for more accurate and reliable model identification.

The analysis of the dataset revealed essential details about time, PWM (Pulse Width Modulation), and velocity, crucial for assessing the servo's operation. To examine the engine data within MATLAB, a specific script was created. This script imports engine parameter values from the database to MATLAB, turning them into variables ready for analysis. It also adjusts axis scaling to make data visuals clearer and more precise. Running this script generates a file that reflects the current database session. Importantly, this file lists potential system transfer functions, each distinguished by its poles and zeros configuration, offering different models for identifying the system's behavior. Table 3 in the study outlines the features of these transfer functions. This table is key to understanding each option and guides the next step of comparing them.

Table 2 – Data after filtering

Time, ms	Present Velocity, rev/min	Present PWM, %
4029	263	885
4049	263	885
4069	260	655
…	…	…

Table 3 – List of possible transfer functions

Name of a transfer function	Equation	Number of poles	Number of zeros
TF1	$\frac{0.0593}{1-0.808z^{-1}}$	1	0
TF2	$\frac{0.02524}{1-1.53z^{-1}+0.6153z^{-2}}$	2	0
TF3	$\frac{0.01488}{1-2.185z^{-1}+1.714z^{-2}-0.4792z^{-3}}$	3	0
TF4	$\frac{0.01014}{1-2.766z^{-1}+3.144z^{-2}-1.724z^{-3}+0.3801z^{-4}}$	4	0
TF5	$\frac{0.07405z^{-1}}{1-0.7552z^{-1}}$	1	1
TF6	$\frac{0.0397z^{-1}}{1-1.366z^{-1}+0.5006z^{-2}}$	2	1
TF7	$\frac{0.02874z^{-1}}{1-1.848z^{-1}+1.27z^{-2}-0.3246z^{-3}}$	3	1
TF8	$\frac{0.02396z^{-1}}{1-2.196z^{-1}+2.075z^{-2}-0.9994z^{-3}+0.2034z^{-4}}$	4	1
TF9	$\frac{-0.004356z^{-1}+0.1034z^{-2}}{1-0.6655z^{-1}}$	1	2
TF10	$\frac{0.01064z^{-1}+0.05601z^{-2}}{1-1.085z^{-1}+0.3122z^{-2}}$	2	2
TF11	$\frac{0.01355z^{-1}+0.4422z^{-2}}{1-1.292z^{-1}+0.5904z^{-2}-0.1023z^{-3}}$	3	2
TF12	$\frac{0.0139z^{-1}+0.04148z^{-2}}{1-1.373z^{-1}+0.744z^{-2}-0.2137z^{-3}+0.03076z^{-4}}$	4	2

TF13	$\dfrac{0.01415z^{-1} + 0.04579z^{-2} + 0.05361z^{-3}}{1 - 0.6149z^{-1}}$	1	3
TF14	$\dfrac{0.01412z^{-1} + 0{,}04626z^{-2} + 0.0204z^{-3}}{1 - 0.9535z^{-1} + 0.2281z^{-2}}$	2	3
TF15	$\dfrac{0.01412z^{-1} + 0.04581z^{-2} + 0.01826z^{-3}}{1 - 0.9931z^{-1} + 0.2716z^{-2} - 0.0128z^{-3}}$	3	3
TF16	$\dfrac{0.01412z^{-1} + 0.04761z^{-2} + 0.02358z^{-3}}{1 - 0.8654z^{-1} + 0.1006z^{-2} + 0.07088z^{-3} - 0.01616z^{-4}}$	4	3

This comparison looks at how well the real data matches up with the models in Table 3, crucial for choosing the transfer function that best captures the system's dynamics. However, transfer functions with more than three degrees are not considered to keep the analysis simple. This approach avoids the complexity and potential inaccuracies of more complicated models. Thus, the focus is on simpler models that accurately reflect the data and are straightforward to work with, ensuring the chosen transfer function is both accurate and practical for understanding the system's behavior.

Results and Discussion

In the analysis, model TF11 was identified as the most effective transfer function:

$$TF_{11} = \frac{0.01355z^{-1} + 0.4422z^{-2}}{1 - 1.292z^{-1} + 0.5904z^{-2} - 0.1023z^{-3}}$$

This model stands out because it requires fewer processing resources and closely aligns with actual data, achieving a 96.47% match as shown in Figure 5.

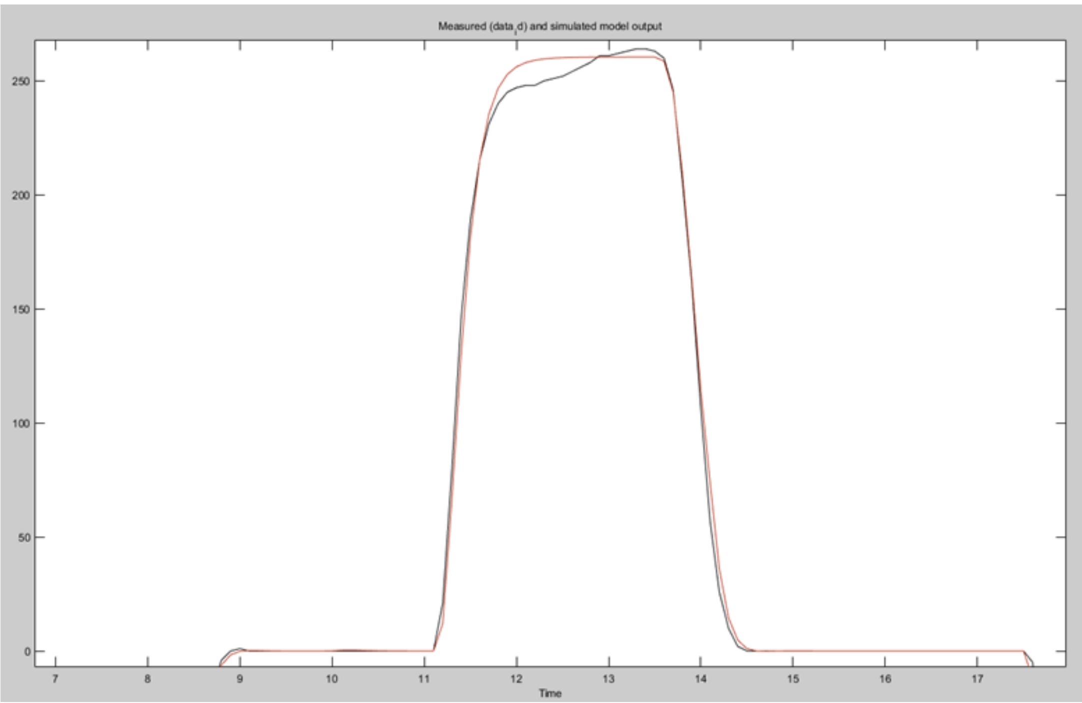

Figure 5 – Measured data and simulated model output

This high degree of similarity underscores TF11's precision and effectiveness in modeling the system's behavior. The data acquired from the system identification process facilitate the assessment of accuracy and stability in the motor system of the robotic manipulator. The discovered transfer function enables a deeper understanding of the dynamic behavior of these systems. It provides a mathematical model that captures how input signals, such as motor commands, are transformed into outputs, like robotic movements. This model is crucial for predicting the system's response under various conditions and for designing control strategies that enhance the robot's performance in terms of precision and reliability.

Program realization

To orchestrate the robot's spatial navigation and localization, an algorithm was methodically devised. The operational logic of this algorithm is encapsulated in a block diagram depicted in Figure 6. This diagrammatic representation delineates the procedural logic that the robot adheres to, initiating with the activation of the robot and subsequent verification of all modular components for operational integrity. Post initialization, the robot employs LIDAR sensors in conjunction with Dynamixel actuators to triangulate its position within the environmental context. Selecting a predetermined navigational map, the robot establishes its trajectory by defining origin and destination coordinates.

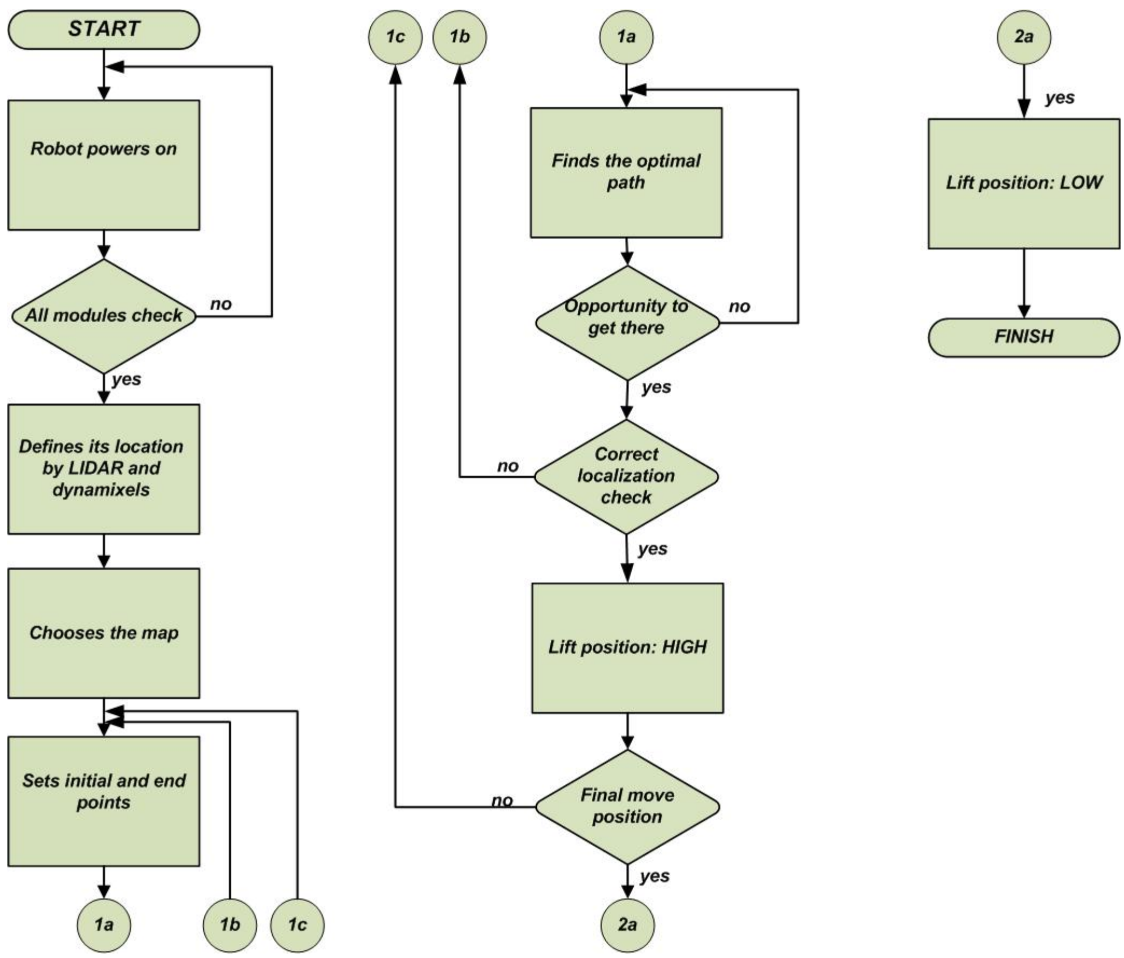

Figure 6 – Process block diagram

The algorithm then engages in optimal path determination, scrutinizing the feasibility of the intended route. Should any discrepancies in localization accuracy arise, the system is designed to recalibrate before proceeding. A pivotal element of the robot's task sequence involves the positional adjustment of the lifting mechanism, which must be accurately aligned to either a designated "HIGH" or "LOW" state to facilitate the continuation of the operation. This sequence concludes with the robot attaining its final programmed position, at which point the task is deemed complete, thereby illustrating the algorithm's efficacy in guiding the autonomous system through its intended operational parameters.

The operational principle of the robot's rotation within the Python script involves a series of programmed commands that direct the robot to adjust its orientation and navigate to a specified location within its operational environment. The script initiates with the robot determining its current position and orientation through sensor input. It then calculates the necessary rotation to align itself with a target direction, based on coordinates that correspond to a grid or cell-based layout of the operational area.

After calculating the desired angle of rotation, the robot executes a rotation maneuver, adjusting its orientation until the target angle is achieved. This precise control of rotation is essential for the robot to face the correct direction before commencing movement towards its goal, as shown in Figure 7.

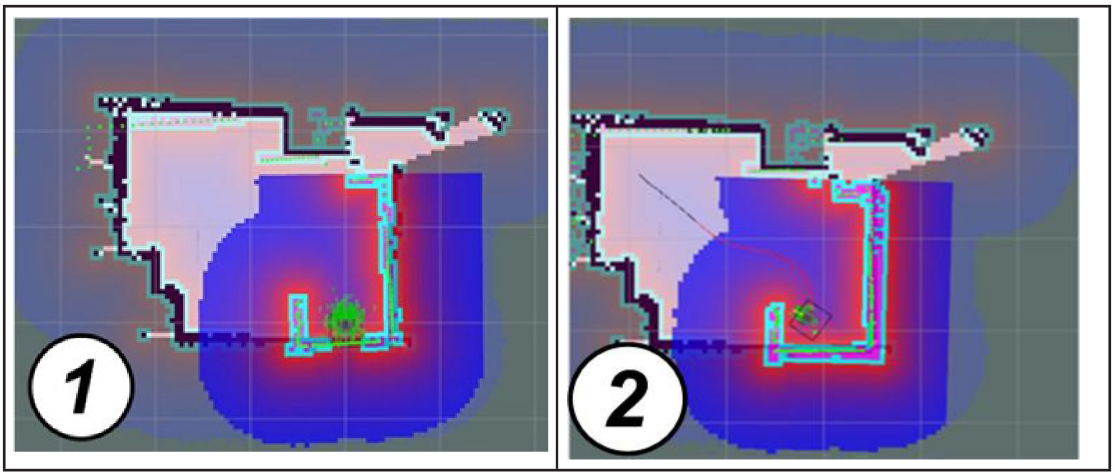

Figure 7 – Stages of robot movement: 1 – scanning the area with LIDAR;
2 – building the shortest route

Once oriented correctly, the robot proceeds to navigate towards the target location. It uses a pathfinding algorithm to identify the most efficient route, considering the robot's current position and the desired endpoint. The robot's movement is characterized by smooth translation along this path, demonstrating the algorithm's ability to guide the robot through its environment accurately.

Regarding the code for actuating the lift platform, the operational dynamics are somewhat distinct. This program embodies a methodology for actuating a robotic lifting mechanism through a sequence of discrete operational commands. Within the context of a robotic operating system, the script initiates a publishing node to emit control signals at a predetermined frequency, corresponding to the actuation and cessation of the lifting platform's movement. The operational logic is structured around the emission of a control value, indicative of the lift's activation, followed by a cessation command, which signals the termination of the action. This cyclical command sequence is paramount for achieving precise control over the lifting mechanism's operational state, facilitating its engagement and disengagement in a controlled manner.

In the development of navigation algorithms for robotics, a fundamental approach involves partitioning the floor space into discrete segments, commonly referred to as "cells" or "squares". This method facilitates a clearer understanding of the robot's current sector since both the "initial" and "final" positions of the robot are defined in terms of these cells through which it moves. This structure has also been implemented in the Human-Machine Interface (HMI) variant for robots, realized in the HMIWebDisplay software by Honeywell, illustrated in Figure 8.

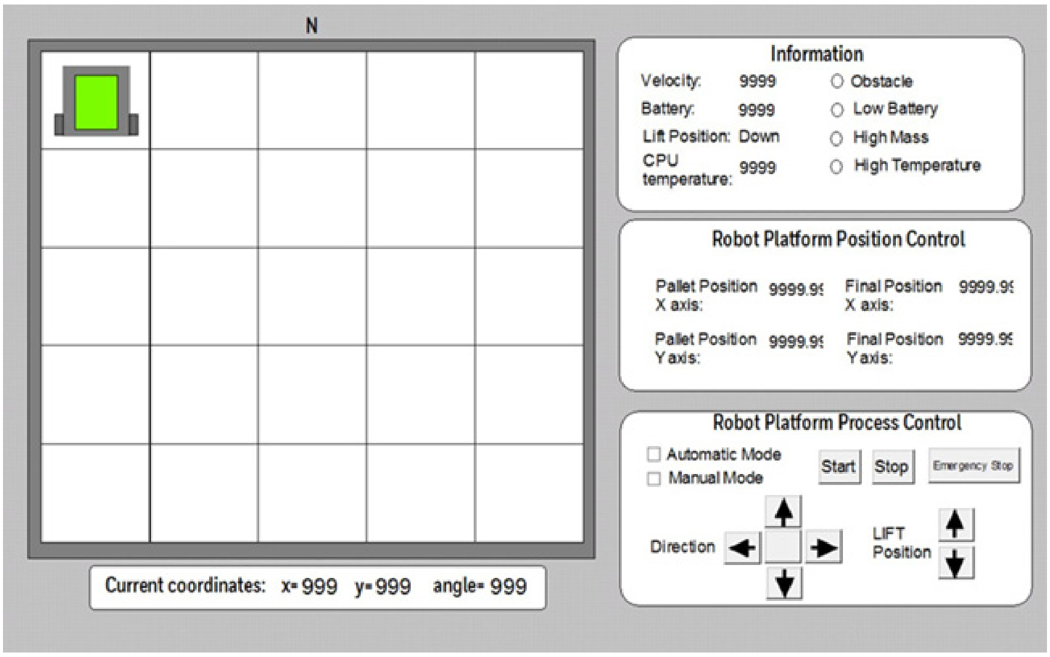

Figure 8 – HMI-display realization

However, as previously mentioned, establishing an efficient smart warehouse system requires the creation of a network of interconnected components. This is the rationale behind the development of a capability to connect the TurtleBot3 Waffle Pi to the Wiren Board 7, a programmable automation controller (PAC).

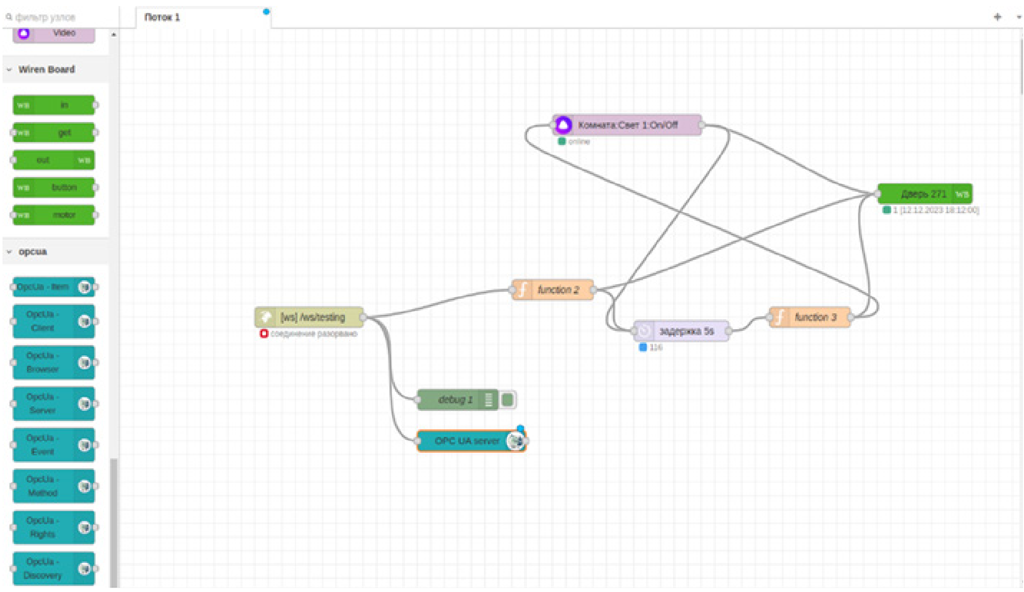

Figure 9 – Output values from Wiren board to OPC UA Server

The Figure 9 delineates an instance of a Node-RED interface, which is employed as a visual tool for integrating distinct hardware and software entities. The integration of a TurtleBot3 Waffle Pi with a Wiren Board 7 is facilitated through the implementation of the OPC UA protocol, a staple in industrial automation for its robust and secure data exchange capabilities. Within this framework, the Node-RED flow is constituted by a series of nodes indicative of the OPC UA communication standards. These nodes establish a bidirectional data stream, enabling the TurtleBot3 Waffle Pi to transmit its operational data to the Wiren Board 7, and vice versa. The flow is further augmented by function nodes which serve as the logical intermediaries, processing the incoming data and orchestrating the subsequent control commands. Moreover, the debug nodes punctuating the flow are indicative of a monitoring mechanism to scrutinize the message payloads, which are crucial for validation and troubleshooting throughout the development phase. This architecture epitomizes a modular approach, ensuring that the TurtleBot3 Waffle Pi can be seamlessly integrated into the automated warehouse ecosystem, thereby enhancing the efficiency and responsiveness of the system. The OPC UA protocol ensures that the communication is not only seamless but also adheres to industry standards for security and reliability.

Conclusion

In conclusion, the development and integration of the TurtleBot3 Waffle Pi into a Smart Warehouse system, as delineated in this study, represents a commendable initial stride towards redefining warehouse automation. Although the scope of this research is an initial foray and not an exhaustive exploration into the vast potential of smart warehousing, the outcomes are promising.

The advancements presented here – the adaptation of the TurtleBot3 Waffle Pi with an innovative lifting mechanism, the pioneering cell-based navigation algorithm, and the strategic networking with the Wiren Board 7 via OPC UA – form a foundational platform for further development. The integration of the Honeywell HMIWebDisplay stands as a testament to the potential for sophisticated, user-centric control interfaces in operational settings. This initial phase has yielded positive results, demonstrating the feasibility and benefits of such integrative approaches. While acknowledging that this is merely the beginning of a larger journey towards comprehensive Smart Warehouse systems, the research paves the way for subsequent in-depth studies and the refinement of technologies.

Moving forward, it will be imperative to build upon these initial findings, to explore scalability, to enhance system robustness, and to address any emergent challenges. The journey towards fully autonomous, highly efficient Smart Warehouses is complex and requires incremental advancements. This study serves as a stepping stone in that ongoing process, offering insights and a proof of concept that will, undoubtedly, inform and inspire future innovations within Kazakhstan and the broader global context of warehouse logistics.

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ҚОЙМАЛАРДЫ БАСҚАРУДЫҢ АҚЫЛДЫ ЖҮЙЕСІНЕ АРНАЛҒАН МОБИЛЬДІ РОБОТ ПЛАТФОРМАСЫН ӘЗІРЛЕУ

Аңдатпа

Бұл зерттеу TurtleBot3 Waffle Pi мобильді роботының қойма логистикасына интеграциясын зерттейді және оның операциялық тиімділікті арттырудағы, шығындарды азайтудағы рөлін көрсетеді. Зерттеудің негізгі бағыты – жаңа позициялау стратегиясымен толықтырылған автономды навигация үшін LIDAR пайдаланатын Python негізіндегі навигациялық алгоритмді әзірлеу. Бұл роботқа жұмыс процесін оңтайландыру, қателерді азайту және операциялық шығындарды азайту арқылы алдын ала елестетілген торында дәл шарлауға мүмкіндік береді. Механикалық инновациялар мен робототехника арасындағы синергияны көрсете отырып, паллеттерді өңдеуді жақсарту үшін 3D басып шығару арқылы арнайы әзірленген көтеру механизмі енгізілген. Honeywell Experion PKS жүйесіне OPC UA технологиясы арқылы Wiren Board 7 контроллерлермен бірігіп, роботтың үздіксіз жұмыс істеуін қамтамасыз етеді. Бұл қосылу роботтың қолданыстағы өндірістік бақылау жүйелеріне интеграциялану қабілетін көрсетіп, қоймалардағы операцияларды модернизациялаудың ауқымды шешімін ұсынады. Қазақстандық логистика секторына баса назар аудара отырып, мұндай технологияларды қолдану операциялық тиімділік пен бәсекеге қабілеттілікті ұлттық ауқымда арттырудың айтарлықтай әлеуетін көрсетеді. Зерттеу робототехника мен озық басқару жүйелерінің логистикадағы маңызды рөлін атап көрсетеді, сонымен бірге экономикалық өсу мен тұрақтылықты қолдау үшін одан әрі технологиялық жетістіктерді қолдайды.

Тірек сөздер: мобильді робот, ақылды қойма, қойманы басқару жүйесі, TurtleBot3, навигация, роботтандыру.

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РАЗРАБОТКА МОБИЛЬНОЙ РОБОТОТЕХНИЧЕСКОЙ ПЛАТФОРМЫ ДЛЯ УМНОЙ СИСТЕМЫ УПРАВЛЕНИЯ СКЛАДОМ

Аннотация

Данное исследование рассматривает интеграцию мобильного робота TurtleBot3 Waffle Pi в логистику складских операций, подчеркивая его роль в повышении операционной эффективности и снижении затрат. В центре внимания исследования находится разработка навигационного алгоритма на языке Python, использующего LIDAR для автономной навигации, дополненного новаторской стратегией позиционирования. Это позволяет роботу точно перемещаться в пределах заранее определенной воображаемой сетки, оптимизируя рабочий процесс, минимизируя ошибки и сокращая операционные расходы. Введено в эксплуатацию специально разработанное подъемное устройство, изготовленное с помощью 3D-печати, чтобы улучшить обращение с паллетами, что демонстрирует синергию механических инноваций и робототехники. Интеграция с контроллерами Wiren Board 7 обеспечивает бесперебойную работу, которая дополнительно усиливается подключением робота к системе Honeywell Experion PKS через технологию OPC UA. Это подключение подчеркивает способность робота интегрироваться в существующие промышленные контрольные системы, предлагая масштабируемое решение для модернизации операций на складах. Сосредоточив внимание на логистическом секторе Казахстана, применение таких технологий демонстрирует значительный потенциал для повышения операционной эффективности и конкурентоспособности на национальном уровне. Исследование подчеркивает критическую роль робототехники и продвинутых систем управления в логистике, выступая за дальнейшее технологическое развитие для поддержки экономического роста и устойчивости.

Ключевые слова: мобильный робот, умный склад, система управления складом, TurtleBot3, навигация, роботизация.