Integration of Optical Sensors and Encoders in Navigation Controllers for Omnidirectional Robots Using ROS2

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Abstract— **This article explores the integration of optical sensors and encoders in navigation controllers for omnidirectional robots, utilizing ROS2 as the development platform. Aiming to highlight the capabilities, challenges, and future directions in omnidirectional robotics, the study covers from the fundamentals of ROS2, through the importance of optical sensors and encoders in environmental perception and precise movement, to the integration and processing of sensory data for effective and autonomous navigation. A detailed analysis discusses strategies for obstacle avoidance, trajectory planning, and the interaction between multiple sensors and control systems. Significant challenges, including hardware and software limitations and the complexity of sensor integration, are addressed to highlight areas requiring attention and future development. The discussion extends to the research and development prospects necessary to overcome existing obstacles and unlock new capabilities for these robotic systems.**

I. Introduction

Robotics has advanced significantly in recent decades, marking its presence across various sectors of society, from advanced manufacturing to personalized services in domestic and public environments. One of the standout innovations in this field has been the development of omnidirectional robots. These robots, distinguished by their ability to move freely in any direction without reorientation, represent a qualitative leap in mobility and operational efficiency. The freedom of movement provided by omnidirectional mechanics increases the adaptability of robots in complex environments and crowded spaces, allowing for more fluid and natural interaction with the surrounding world.

Omnidirectional robots are equipped with unique wheels, such as Mecanum or omnidirectional wheels, allowing them to move in any direction, including sideways or diagonal. These characteristics make them ideal for tasks requiring high maneuverability and precision, such as internal logistics applications, hospital assistance, and domestic environments, where navigation in confined spaces is often necessary. Unlike differential robots, their ability to move without the need to reorient the robot's body facilitates the performance of multiple tasks simultaneously, such as carrying loads and operating instruments or tools.

However, the effectiveness of omnidirectional robots crucially depends on the integration and efficient management of various sensory systems. Optical sensors and encoders are necessary for precise navigation and environmental interaction. Optical sensors provide rich visual data for object recognition, environment mapping, and obstacle detection. On the other hand, by monitoring wheel rotation, encoders provide valuable information about the speed and direction of movement, which is fundamental for the precision of the positioning and trajectory of the robot.

This article explores the integration of optical sensors and encoders in navigation controllers for omnidirectional robots using the ROS2 development environment. This study seeks to contribute to the service robotics community by offering a detailed framework for developing more autonomous, efficient, and adaptable omnidirectional robotic systems. The subject was discussed by presenting the results from BRASERO 2019 [1], considering the architecture of the HERA Robot from the RoboFEI@Home Team. Currently, by combining the complementary capabilities of optical sensors and encoders within the ROS2 architecture, the aim is to significantly improve the navigation and functionality of robots in dynamic and unpredictable environments, updating information for the community involved in the topic.

II. ROS2 Fundamentals

The Robot Operating System (ROS) emerged as an open-source middleware platform designed to ease the inherent complexity of developing software for robotics. Over the years, ROS has become an indispensable tool in robotics research and development, providing a rich collection of tools, libraries, and conventions to simplify creating complex and interoperable behaviors among robots' hardware and software components [2]. However, as the robotics community progressed, the need for a new generation of ROS capable of handling the increasing demands for performance, security, and real-time systems support became evident, motivating the development of ROS2.

ROS2 was developed from the ground up to meet these emerging needs, maintaining the design philosophy and usability that made the original ROS famous. One of the main improvements of ROS2 over its predecessor is its redesigned communication architecture, based on the DDS (Data Distribution Service) standard for communication middleware. This change provides greater robustness and efficiency in node communication, essential for robotic systems operating in dynamic and possibly unreliable environments [3].

ROS2 introduces inherent security mechanisms that were absent or difficult to implement in ROS. These mechanisms include secure communication between nodes, node

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authentication, and access control, ensuring that only authorized components can access critical information or perform essential operations. These features are vital for robotics applications requiring high security and reliability, such as those in domestic, public, or industrial environments [4].

ROS2 also stands out for its reduced communication latency and enhanced support of real-time operating systems (RTOS). This is crucial for omnidirectional robots that rely on quick and accurate responses to sensory data for navigation and environmental interaction. Operating on RTOS allows ROS2 to provide runtime guarantees for critical processes, a crucial aspect for executing tasks that require high temporal precision, such as motion control.

ROS2 significantly simplifies the integration of optical sensors and encoders, crucial for the accurate navigation and environmental interaction of omnidirectional robots. The use of DDS in ROS2 enhances data handling and processing capabilities, supporting the management of high-frequency data streams from optical sensors and encoders. This ensures that data is prioritized and managed efficiently, minimizing delays and allowing real-time processing that is critical for maintaining accurate positioning and navigation.

ROS2's modular architecture facilitates the easy integration of these sensors and actuators into the system by allowing developers to add new nodes without needing to overhaul the existing structure. This flexibility is particularly beneficial in complex robotic systems where multiple sensors and inputs must work in harmony.

Furthermore, the robust and reliable integration features of ROS2, such as secure node communication and authentication, are crucial in environments where robots operate close to humans or sensitive equipment, ensuring operational safety and predictability.

III. Optical Sensors in Robotics

Optical sensors in robotics represent one of the fundamental pillars for developing efficient autonomous systems. By capturing visual information from the environment, these sensors play a crucial role in navigation, mapping, and the interaction of robots with the world around them. Among the various types of optical sensors, LIDAR, stereo cameras, and computer vision sensors stand out, each with its particularities and specific applications.

A. LIDAR

LIDAR (Light Detection and Ranging) is an optical sensor that measures the distance to an object or surface using a laser beam. By emitting pulses of light and measuring the time they return after reflecting off the object, LIDAR can generate accurate maps of the environment in three dimensions. This ability to provide precise distance measurements on a large scale makes it ideal for navigation and mapping applications in robotics, especially in outdoor or unknown environments, where three-dimensional accuracy is crucial.

B. Stereo Cameras

On the other hand, stereo cameras simulate human visual depth perception using two cameras slightly spaced apart. Through processing the images captured by both cameras, it is possible to calculate the parallax between corresponding points in the two images, allowing for estimating the distance of objects in the field of view. This technology is widely used in tasks that require real-time depth perception, such as navigation in indoor environments and object manipulation. Stereo cameras are precious in applications where integrating detailed visual information with depth perception is mandatory.

C. Computer Vision Sensors

Computer vision sensors encompass a wide range of devices capable of interpreting and processing real-world images to produce meaningful data for the robot. This category includes conventional RGB cameras, depth cameras that use various technologies to measure the distance of objects, and infrared cameras, among others. Through advanced image processing techniques and artificial intelligence algorithms, computer vision sensors enable a range of functionalities, such as object recognition, obstacle detection, and semantic mapping of the environment. These sensors are essential for intelligent interaction with the environment and autonomous navigation, especially in complex and dynamic environments where contextual understanding is necessary.

D. Applications in Omnidirectional Robotics

Optical sensors are crucial for the effective navigation and mapping of omnidirectional robots, enhancing their ability to move safely and efficiently in any direction. Each sensor type contributes uniquely to navigation tasks:

LIDAR is invaluable for its precise distance measurements and 360-degree environmental scans, making it ideal for complex outdoor navigation. However, it is costly and can be less effective in adverse weather conditions.

Stereo cameras provide depth perception cost-effectively, suitable for controlled indoor environments. They depend on good lighting and visible textures to function optimally, which limits their use in featureless areas.

Computer vision sensors offer advanced capabilities like object recognition and scene understanding, essential for dynamic settings. They require significant computational power and sophisticated algorithms to process varied environmental inputs effectively.

Sensor fusion integrates the strengths of each sensor to overcome individual limitations, offering robust navigation solutions. For example, LIDAR's accuracy combined with the contextual data from stereo cameras and computer vision enhances overall obstacle detection and environmental awareness.

This integrated approach allows omnidirectional robots to adapt to diverse operational scenarios, significantly broadening their application in sophisticated and autonomous robotic systems.

IV. Encoders and Motion Measurement

Precision in motion control is critical in robotics, especially in omnidirectional robots, where the ability to execute complex and precise movements is fundamental. Encoders, devices that measure the rotation of wheels or other mechanical components, are essential for this task. They provide vital data about the speed and direction of movement, allowing the robot's control systems to adjust their actions in real-time to achieve the desired objectives with high precision.

Encoders can be classified into two main types: absolute encoders and incremental encoders. Absolute encoders provide the exact position of the axis to which they are attached, regardless of the starting point. In contrast, incremental encoders provide information about the amount of movement from a known position, requiring a reference point to determine the absolute position.

In practice, incremental encoders are widely used in robotics due to their cost-effectiveness and simplicity. They operate by generating electrical pulses in response to the rotation of the axis. Counting these pulses allows for calculating the total rotation of the axis and, by extension, the speed and direction of the robot's movement. The accuracy of these measurements depends on the encoder's resolution, that is, the number of pulses generated per complete turn of the axis.

The information provided by encoders is essential for the implementation of effective control strategies in omnidirectional robots. By integrating this data with control algorithms, it is possible to dynamically adjust the speed and direction of the robot's wheels to achieve the desired trajectory. This process involves complex calculation operations that consider the measurements from the encoders and the data from other sensors, such as optical sensors, for precise and adaptive navigation.

Furthermore, encoders are fundamental for implementing closed-loop control techniques, where the feedback data from encoders are continuously compared with the desired values. Any detected deviations are corrected by adjustments in the control signals sent to the motors, ensuring that the robot follows the planned trajectory with high fidelity. This approach is critical in dynamic environments, where the robot must respond to unexpected changes and maintain the desired navigation behavior.

Effectively integrating encoder data into the robot's control systems presents significant challenges. One of the main challenges is the need for real-time processing to interpret the data from the encoders and adjust the robot's behavior quickly and accurately. Additionally, mechanical wear and electrical interference can affect the accuracy of encoder measurements, requiring robust data filtering and correction solutions.

In the context of omnidirectional robots, integrating encoder data with information from optical sensors and other detection systems expands the capabilities of autonomous navigation, allowing for more sophisticated and adaptive movements. Using platforms like ROS2, it is possible to develop advanced control systems that make the most of the detailed motion information provided by encoders, resulting in more precise and efficient robots.

V. Sensor Integration in ROS2

Effective sensor integration is crucial for developing omnidirectional robots capable of autonomously and safely navigating complex environments. ROS2 (Robot Operating System 2) provides a robust platform for integrating and managing various types of sensors, including optical sensors and encoders. This section discusses how ROS2 supports the combination of these sensors, emphasizing the role of sensor fusion and the implementation of filtering algorithms to enhance the accuracy of navigation and mapping.

Sensor fusion involves combining data from different sensors to achieve a more accurate and reliable understanding of the environment. In the context of omnidirectional robots, integrating data from optical sensors, such as LIDAR, stereo cameras, and computer vision sensors, with data from encoders that provide information about motion and orientation is essential. ROS2 facilitates this integration through its distributed messaging system and services, enabling efficient communication between nodes (software components) that handle different sensors or processing tasks.

Filtering algorithms like the Kalman filter or particle filters are essential in robotics to estimate the system's state (e.g., the position and orientation of a robot) from noisy or partially uncertain measurements. In ROS2, these algorithms can be implemented to optimally combine data from various sensors, significantly enhancing the accuracy of the robot's state estimates. This precision is particularly critical for omnidirectional robots, where accurate motion perception and environmental mapping are vital for precise navigation and obstacle avoidance.

Integrating optical sensors and encoders in ROS2 starts with capturing raw data from each sensor. This data is then published on specific topics within the ROS2 system using a publish/subscribe model. This allows different nodes to subscribe to topics of interest and process the received data. For sensor fusion, a specific node may be designated to receive data from multiple sensors, apply filtering and fusion algorithms, and produce a unified estimate of the robot's state. This modular and flexible approach encourages experimentation and fine-tuning of perception and navigation systems.

Sensor integration in ROS2 involves challenges, such as synchronizing sensor data that may operate at different update rates and managing the volume of data generated. Moreover, selecting appropriate filtering and sensor fusion algorithms must consider the specific characteristics of the sensors and the requirements of the robotic application.

By addressing these challenges, integrating optical sensors and encoders in ROS2 enables the development of highly capable omnidirectional robots for applications in various fields, including logistics, residential support, and healthcare, enhancing safety, efficiency, and adaptability in navigation.

VI. Practical Experiences

To advance the capabilities of omnidirectional robotics, our team embarked on a comprehensive integration of optical sensors and encoders with ROS2 navigation controllers. This section delineates the practical experiences and methodologies adopted during the integration process, highlighting the challenges faced and the solutions devised to overcome them.

A. Circuit Design and Motor Control

The foundation of our integration process commenced with developing an electrical circuit for motor control, utilizing a Sabertooth driver board alongside the Arduino Due. This initial step was crucial for ensuring precise control over the motors, which is essential for the omnidirectional movement of the robot. Integrating magnetic encoders with the motors facilitated the real-time monitoring of wheel rotation, providing valuable data for motion control and navigation.

B. Encoder Data Conversion

A pivotal aspect of our integration was the conversion of distance measurements obtained from the encoders into velocity data. This conversion was instrumental in communicating speed information to the hardware interface of the navigation controller. Through meticulous calibration and testing, we established a reliable method for translating encoder outputs into meaningful velocity data, which significantly enhanced the accuracy of the robot's movement.

C. ROS2 and Motor Control Integration

The incorporation of motor control into the ROS2 framework was achieved by utilizing the ros_control package. This integration facilitated the management of individual wheel speeds, allowing for precise control over the robot's omnidirectional movements. The seamless interaction between ROS2 and the motor controllers underscored the effectiveness of ROS2 in orchestrating complex robotic systems.

D. Custom Pull-Up Resistors for Encoder Readings

We engineered custom pull-up resistors to address the challenge of accurately reading signals from the magnetic encoders. These resistors played a critical role in stabilizing the signal, ensuring the encoder data's reliability. This modification improved the signal quality and demonstrated the necessity of hardware adaptations in robotic integration projects.

E. Laser Integration with Navigation Control

Integrating the laser (optical distance and mapping sensor) with the navigation controller represented a significant milestone in our project. This process involved inserting the laser's 3D model description into the robot's configuration and the subsequent fusion of laser-generated data with the ROS2 navigation framework. This integration enhanced the robot's environmental perception and spatial navigation capabilities, enabling it to maneuver more autonomously and precisely.

These practical experiences underscore the multifaceted challenges inherent in integrating optical sensors and encoders into navigation controllers for omnidirectional robots. Through innovative problem-solving and rigorous testing, we advanced the state of our robotic platform, laying the groundwork for future enhancements in robotic mobility and autonomy.

VII. Navigation and Control Algorithms in ROS2 for Omnidirectional Robots

The navigation and control of omnidirectional robots, especially in dynamic and unpredictable environments, require sophisticated algorithms to ensure precise, safe, and efficient movements. In ROS2, a range of algorithms and tools is available to address these needs, allowing for the implementation of advanced strategies for obstacle avoidance and trajectory planning. This section discusses the main algorithms used and how they can be applied to omnidirectional robots, complemented with code examples to illustrate integration in ROS2.

A. Obstacle Avoidance Strategies

Obstacle avoidance is critical for the autonomous operation of robots in real environments. In ROS2, algorithms such as the potential field method and A* (A star) are commonly used. The potential field method treats the robot and obstacles in the environment as charged particles that repel each other, guiding the robot on a path free of obstacles. On the other hand, A* is a search algorithm that finds the shortest path from one point to another, considering the presence of obstacles. Example ROS2 code for obstacle avoidance:

```
import rclpy
from rclpy.node import Node
from sensor_msgs.msg import LaserScan
from geometry_msgs.msg import Twist
class ObstacleAvoidanceNode(Node):
    def __init__(self):
        super().__init__('obstacle_avoidance_node')
        self.subscription = self.create_subscription(
            LaserScan,
            '/scan',
            self.laser_callback,
            10)
        self.publisher = self.create_publisher(Twist, '/cmd_vel', 10)
        self.obstacle_distance_threshold = 0.5
    def laser_callback(self, msg):
        regions = {
            'right':  min(min(msg.ranges[0:143]), 10),
            'front':  min(min(msg.ranges[144:287]), 10),
            'left':   min(min(msg.ranges[288:431]), 10),
        }
        self.avoid_obstacles(regions)
    def avoid_obstacles(self, regions):
```

```
        msg = Twist()
        if regions['front'] > self.
            obstacle_distance_threshold:
            msg.linear.x = 0.5  #move forward
        else:
            msg.angular.z = 0.5 #rotate left
        self.publisher.publish(msg)
def main(args=None):
    rclpy.init(args=args)
    node = ObstacleAvoidanceNode()
    rclpy.spin(node)
    rclpy.shutdown()
if __name__ == '__main__':
    main()
```

Listing 1. Example of obstacle avoidance in ROS2

This example uses data from a LIDAR sensor to detect obstacles before the robot and make simple avoidance decisions, moving forward or turning to avoid collisions.

B. Trajectory Planning

Trajectory planning involves determining the optimal path the robot should follow to reach a destination, considering the geometry of the environment and the obstacles present. In ROS2, the 'nav2' (Navigation 2) package offers a robust suite for trajectory planning in mobile robots, including algorithms like Dijkstra for global planning and the local controller 'DWB' (Dynamic-Window Approach) for avoiding obstacles in real-time.

The specific code for trajectory planning is complex and highly dependent on the specific configurations of the robot and the environment. However, integration with 'nav2' involves setting up YAML parameters that define the planner's behavior and launching ROS2 nodes that execute the planning algorithms.

VIII. Challenges and Limitations

The integration of sensors and the navigation of omnidirectional robots represent a challenging frontier in robotics, facing technical challenges and limitations at both the hardware and software levels. These difficulties directly impact the performance and applicability of these systems in real scenarios, with problems ranging from the accuracy and reliability of the sensors to the complexity of integrating the components.

Regarding hardware, in addition to limitations imposed by environmental factors such as variations in lighting, the presence of reflections, and possible obstructions, inherent factors of the sensors also play a crucial role. In encoders, for example, the number of pulses per rotation can limit the accuracy of wheel rotation measurement, directly affecting the determination of robot movement. For optical sensors, the minimum and maximum distance they can measure and the angle of their "vision" define the range and effectiveness with which obstacles and environmental elements can be detected. Moreover, the power supply voltage is a critical factor for both types of sensors, as the data collected are often calculated proportionally to the voltage received by the signal pins. Thus, variations in power supply voltage can lead to errors in interpreting sensory data, requiring careful management of sensor power supply and calibration of processing algorithms.

The need for careful engineering to effectively integrate multiple sensors and actuators into a single robotic platform brings additional challenges, including electromagnetic interference between components and efficient energy consumption management. Additionally, the cost and availability of advanced components limit accessibility for projects with restricted budgets. Furthermore, another limiting factor in the performance of omnidirectional robotic systems is the construction and choice of materials for the wheel. Its architecture must allow the base to move without generating friction loss with the ground, which would lead to a disparity between the actual distance traveled and the distance read by the encoder.

On the software side, fusing data from different sensors requires advanced algorithms that can process and filter information effectively and reliably in real-time, translating into a complex task. The large amount of data generated by sensors demands optimized processing, storage, and analysis to avoid overloading the system's computational resources. Moreover, the need to adapt flexible tools, such as those offered by ROS2, for specific applications can increase project complexity and prolong development cycles. The dependency on third-party software introduces additional security, compatibility, and customization concerns, requiring continuous efforts to keep the system updated and secure.

Overcoming these challenges demands a collaborative and multidisciplinary effort, combining mechanical engineering, electronics, computer science, and artificial intelligence expertise. With technological advancement, innovative solutions are expected to address these issues, expanding the capabilities of omnidirectional robots and opening new possibilities for application in various fields. Collaboration and knowledge exchange within the ROS2 community and among professionals in the field will be essential to confronting and overcoming the existing obstacles in sensor integration and navigation of omnidirectional robots.

IX. Advances in Omnidirectional Robotics with ROS2

The evolution of omnidirectional robotics, especially in harmony with the ongoing development of ROS2, promises significant transformations through the advanced incorporation of artificial intelligence (AI) and machine learning (ML). These technologies are at the core of future directions for omnidirectional robots, promising significant autonomy, adaptability, and operational efficiency improvements. As we move toward these new horizons, several research areas stand out as fundamental to achieving these advancements.

Integrating AI and ML algorithms into omnidirectional robots promises more autonomous systems capable of learning from their experiences, adapting to new environments, and making complex real-time decisions. This includes optimizing trajectories in dynamic environments and enhancing the ability to navigate and avoid obstacles more precisely.

Algorithms such as SLAM (Simultaneous Localization and Mapping) can use machine learning to utilize the data provided by the encoders and optical sensors more precisely in order to create more detailed maps of the environment, allowing the robot to navigate smoother in complex surroundings.

The evolution of omnidirectional robots will also depend on significant advancements in sensory perception. This involves not just the integration of more sophisticated sensors but also the development of sensory processing algorithms capable of interpreting complex data more effectively [5]. Utilizing deep learning techniques, for example, robots can significantly improve their object recognition, environmental mapping, and obstacle detection capabilities, increasing their functionality and safety in autonomous operations.

Another promising direction is research focused on advanced interaction and collaboration between omnidirectional robots and humans, as well as among multiple robots. This involves developing systems capable of understanding and predicting human actions, adapting to them, and working with humans in shared tasks. Likewise, coordination among multiple robots through efficient communication networks can lead to more synchronized and effective operations in warehouses and factories.

Security and robustness in autonomous systems remain a central concern, requiring ongoing research to ensure the reliable operation of omnidirectional robots in all environments. This includes enhancing resistance to failures and cyber-attacks and the ability to operate efficiently under variable and uncertain conditions. Developing frameworks and algorithms that can ensure operational safety and data protection will be strategic for the success of applications.

Future directions in omnidirectional robotics with ROS2 involve exploring new system architectures, adaptive algorithms, and interaction methods that can lead to greater autonomy and efficiency. Future research should focus on developing powerful, efficient, transparent, and explainable AI and ML algorithms. Moreover, integrating emerging technologies, such as the Internet of Things (IoT) and advanced communication networks, promises to open new pathways for omnidirectional robotics, allowing these systems to integrate more deeply into our daily lives and work environments. Research focuses on robot behavior during navigation [6] and its behavior according to the context of application [7].

X. Conclusion

The journey through the complexities and potentialities of integrating optical sensors and encoders in omnidirectional robots, using ROS2 as a development platform, unveils a rich and diverse field of innovation and practical application. The discussion spanned from the theoretical and technical foundation of these technologies to the exploration of actual use cases, highlighting the challenges and future directions for research and development.

The successful implementation of navigation systems in omnidirectional robots represents a milestone in robotics, offering new possibilities for automation and interaction across a variety of environments, motivated by the experience of the RoboFEI@Home Team focused on performing domestic activities using an open robotic platform [8]. Advances in sensor integration and algorithmic processing promote greater autonomy, precision, and safety, facilitating a harmonious and productive coexistence between robots and humans.

However, the inherent challenges in hardware and software integration, large-scale data management, and the need for safe and reliable autonomous systems highlight the importance of continuous research. Overcoming these obstacles requires a multidisciplinary approach that encompasses mechanical engineering, electronics, computer science, and artificial intelligence, reinforcing the need for collaboration among researchers, developers, and industries.

Future directions in omnidirectional robotics with ROS2 pave the way for significant innovations, especially by applying advanced artificial intelligence and machine learning techniques. These technologies have the potential to transform omnidirectional robots into even more adaptable, intelligent systems capable of performing complex tasks with an autonomy that will stand out. Future research focused on improving sensory perception, robot-human and robot-robot interaction, and the robustness and security of autonomous systems will be fundamental to achieving these advancements. Thus, the integration of optical sensors and encoders in omnidirectional robots, anchored by ROS2, not only strengthens the current state of robotics but also lights the path to future innovations. As we explore these new frontiers, we continue to unlock the vast potential of omnidirectional robots.

References

[1] P. T. A. Junior, B. d. F. V. Perez, R. Meneghetti, F. d. A. M. Pimentel, G. N. Marostica, J. G. R. Amorim, L. C. Neves, L. I. Gazignato, M. Y. Gonbata, R. Souza, *et al.*, "Hera: Home environment robot assistant," in *II BRAHUR and III Brazilian workshop on service robotics*, 2019.

[2] A. Koubaa, Ed., *Robot Operating System (ROS): The Complete Reference (Volume 3)*, ser. Studies in Computational Intelligence. Cham: Springer, 2018, vol. 778.

[3] S. Macenski, T. Foote, B. Gerkey, C. Lalancette, and W. Woodall, "Robot operating system 2: Design, architecture, and uses in the wild," *Science Robotics*, vol. 7, no. 66, p. eabm6074, 2022.

[4] S. Macenski, A. Soragna, M. Carroll, and Z. Ge, "Impact of ros 2 node composition in robotic systems," *IEEE Robotics and Autonomous Letters (RA-L)*, 2023.

[5] F. Pimentel and P. Aquino, "Performance evaluation of ros local trajectory planning algorithms to social navigation," in *2019 Latin American Robotics Symposium (LARS), 2019 Brazilian Symposium on Robotics (SBR) and 2019 Workshop on Robotics in Education (WRE)*, 2019, pp. 156–161.

[6] F. d. A. M. Pimentel and P. T. Aquino-Jr, "Evaluation of ros navigation stack for social navigation in simulated environments," *Journal of Intelligent & Robotic Systems*, vol. 102, no. 4, p. 87, Jul 2021.

[7] F. Pimentel and P. Aquino-Jr, "Study on the comfort of people in spatial interactions with a social robot," in *Anais Estendidos do XIV Simpósio Brasileiro de Robótica e XIX Simpósio Latino-Americano de Robótica*. Porto Alegre, RS, Brasil: SBC, 2022, pp. 13–24.

[8] G. Nicolau Marostica, N. A. Grotti Meireles Aguiar, F. d. A. Moura Pimentel, and P. T. Aquino-Junior, "Robofei@home: Winning team of the robocup@home open platform league 2022," in *RoboCup 2022: Robot World Cup XXV*, A. Eguchi, N. Lau, M. Paetzel-Prüsmann, and T. Wanichanon, Eds. Cham: Springer International Publishing, 2023, pp. 325–336.