INDOOR NAVIGATION OF QUADRUPED ROBOT USING SLAM ALGORITHMS

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Abstract: *This paper presents a comprehensive approach to enhancing perception and control capabilities in quadruped robots, focusing on the optimization of Simultaneous Localization and Mapping (SLAM) algorithms to improve localization accuracy and minimize potential errors. The research explores local navigation techniques that integrate advanced sensors to ensure continuous monitoring of the robot's orientation and position within its operational environment. One of the key sensors used in this context is Light Detection and Ranging (LIDAR), which operates independently of the Global Positioning System (GPS) and enables precise environmental mapping for safe and efficient navigation.*

Key words: *Quadruped robot, SLAM, Mapping, LiDAR.*

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1. Introduction

Navigation is a key challenge for autonomous quadruped robots. To achieve autonomous navigation, mobile robots must first localize themselves and then determine the optimal trajectory between two points with high accuracy and minimal processing time (Farag et al., 2011). Simultaneous Localization and Mapping (SLAM) aims to perform localization and map creation in real-time and can be implemented through various methods (Bajrami et al., 2016). Therefore, it is often considered a research field rather than a single algorithm. The implementation of SLAM relies on different algorithms that enable the robot to perceive its surrounding environment, integrate sensor data, plan future movements, and iteratively update the environmental map (Bailey et al., 2020, Bailey et al., 2006, Theodoridis et al., 2013, & Missura et al., 2019). Due to its significance in autonomous navigation, SLAM has been a major focus in robotics research. Different SLAM methods are characterized by unique features and advantages in fulfilling localization and mapping tasks. Some of the key methodologies include Visual SLAM, Lidar SLAM, and Multi-Sensor SLAM. Visual SLAM is widely used in mobile robots, and ongoing research is exploring new techniques to develop optimal methods for robot localization and map generation to facilitate movement (Kalogeiton et al., 2019). Lidar SLAM (Light Detection and Ranging) primarily uses a laser sensor (or distance sensor) for mapping and localization. Compared to cameras, Time-of-Flight (ToF) sensors, and other perception devices, laser sensors provide significantly higher accuracy. Multi-Sensor SLAM is a type of SLAM algorithm that integrates multiple sensors—including cameras, Inertial Measurement Units (IMUs), GPS, lidar, radar, and others—to enhance the accuracy and robustness of SLAM algorithms. A critical aspect of autonomous navigation is path planning (Bajrami et al., 2015), especially in environments with static and dynamic obstacles. Global path planning, also known as static planning, refers to the process in which the robot perceives its environment using sensors and determines the optimal path based on the collected data (Liu et al., 2021). SLAM relies on environmental perception through various sensors, scanning and measuring the distances of surrounding physical objects while detecting obstacles along the robot's path.

2. Kinematics of the A1 Robot

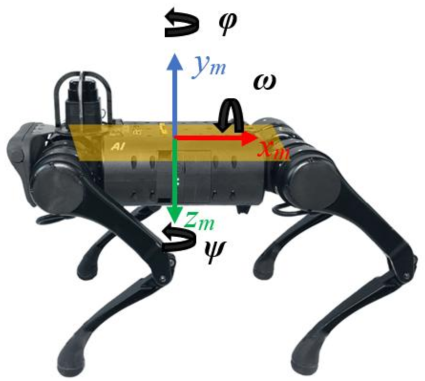

Fig. 1. Kinematic model of the quadruped robot

The A1 is a quadrupedal robot with 12 degrees of freedom (DoF), featuring three joints per leg Fig. 1. Its motion can be analyzed using two primary kinematic approaches.

2.1. Inverse kinematics

Inverse kinematics is used to determine the joint angles (θ_1, θ_2, θ_3) based on a desired foot position in space (x, y, z). The core calculations are based on the 2D planar model of the leg from figure 1. The rotation matrices for the x, y, and z axes are given as follows.

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\omega) & -\sin(\omega) & 0 \\ 0 & \sin(\omega) & \cos(\omega) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$R_y = \begin{bmatrix} \cos(\varphi) & 0 & \sin(\varphi) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\varphi) & 0 & \cos(\varphi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$R_z = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 & 0 \\ \sin(\psi) & \cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$R_{xyz} = R_x R_y R_z \tag{4}$$

The transformation matrix is shown in equation (5).

$$T_M = R_{xyz} \begin{bmatrix} 1 & 0 & 0 & x_m \\ 0 & 1 & 0 & y_m \\ 0 & 0 & 1 & z_m \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

2.2. Forward kinematics

Forward kinematics determines the position of the legs using the joint angles of the actuators. For the robot's leg, the position in the (x, y, z) space can be computed using Denavit-Hartenberg (DH) matrix transformations (Pajaziti et al., 2018). Next, we present the Denavit-Hartenberg (DH) parameters for the forward kinematics of the robot's leg in our case, the Unitree A1 robot table 1. Each matrix T_{i+1}usually follows the Denavit-Hartenberg (DH) convention.

Link	a_{i-1}	α_{i-1}	d_i	θ_i
0-1	L_1	0	0	θ_1
1-2	0	$-\pi/2$	0	$-\pi/2$
2-3	L_2	0	0	θ_2
3-4	L_3	0	0	θ_3

Tab. 1. Denavit-Hartenberg (DH) parameters

$$T = T_0^1 \cdot T_1^2 \cdot T_2^3 \cdot T_3^4 \tag{6}$$

Each transformation matrix is given in the equations below and the direct kinematic matrix is equation beloved.

$$T_0^1 = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & -\mathrm{L}_1\cos(\theta_1) \\ \sin(\theta_1) & \cos(\theta_1) & 0 & -\mathrm{L}_1\sin(\theta_1) \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

$$T_2^1 = \begin{bmatrix} 0 & 0 & -1 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

$$T_2^3 = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & \mathrm{L}_2\cos(\theta_2) \\ \sin(\theta_2) & \cos(\theta_2) & 0 & \mathrm{L}_2\sin(\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$T_3^4 = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & \mathrm{L}_3\cos(\theta_3) \\ \sin(\theta_3) & \cos(\theta_3) & 0 & \mathrm{L}_3\sin(\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$T = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ t_{41} & t_{42} & t_{43} & t_{44} \end{bmatrix} \tag{11}$$

$$\left.\begin{gathered}
t_{11} = \cos(\theta_2)\cos(\theta_3)\sin(\theta_1) - \sin(\theta_1)\sin(\theta_2)\sin(\theta_3) \\
t_{12} = -\cos(\theta_2)\sin(\theta_1)\sin(\theta_3) - \cos(\theta_3)\sin(\theta_1)\sin(\theta_2) \\
t_{13} = -\cos(\theta_1) \\
t_{14} = L_2 cos(\theta_2)\, sin(\theta_1) - L_1 cos(\theta_1) + L_2 cos(\theta_2)\, cos(\theta_3)\, sin(\theta_1) \\
- L_3 sin(\theta_1)\, sin(\theta_2)\, sin(\theta_3) \\
t_{21} = \cos(\theta_1) sin(\theta_2) sin(\theta_3) - cos(\theta_1) cos(\theta_2) cos(\theta_3) \\
t_{22} = \cos(\theta_1) cos(\theta_2) sin(\theta_3) + cos(\theta_1) cos(\theta_3) sin(\theta_2) \\
t_{23} = -sin(\theta_1) \\
t_{24} = \mathrm{L}_3\cos(1)\sin(\theta_2)\sin(\theta_3) - \mathrm{L}_2\cos(\theta_1)\cos(\theta_2) \\
- \mathrm{L}_3\cos(\theta_1)\cos(\theta_2)\cos(\theta_3) - \mathrm{L}_1\sin(\theta_1) \\
t_{31} = \cos(\theta_2)\sin(\theta_3) + \cos(\theta_3)\sin(\theta_2) \\
t_{32} = \cos(2)\cos(\theta_3) - \sin(\theta_2)\sin(\theta_3) \\
t_{33} = 0 \\
t_{34} = \mathrm{L}_2\sin(\theta_2) + \mathrm{L}_3\cos(\theta_2)\sin(\theta_3) + \mathrm{L}_3\cos(\theta_3)\sin(\theta_2) \\
t_{41} = t_{42} = t_{43} = 0\ , t_{44} = 1
\end{gathered}\right\} \tag{12}$$

3. Kinematics of the unitree a1 robot using Matlab

In this paper, we will analyze the kinematics of the Unitree A1 robot using MATLAB to generate and study the curves that describe the robot’s behavior over a specified period of time. Specifically, we will focus on analyzing changes in joint angles, the robot's position, and the movement of the center of mass (CoM) along a predefined trajectory.

Initially, we used kinematic algorithms to determine the leg positions of the robot based on Cartesian coordinates. MATLAB has provided the necessary tools to visualize these positions in real time, allowing us to gain a better understanding of the behavior of each leg during the robot's movement Fig. 2. This process is crucial for ensuring the robot's stability and for executing precise and coordinated movements.

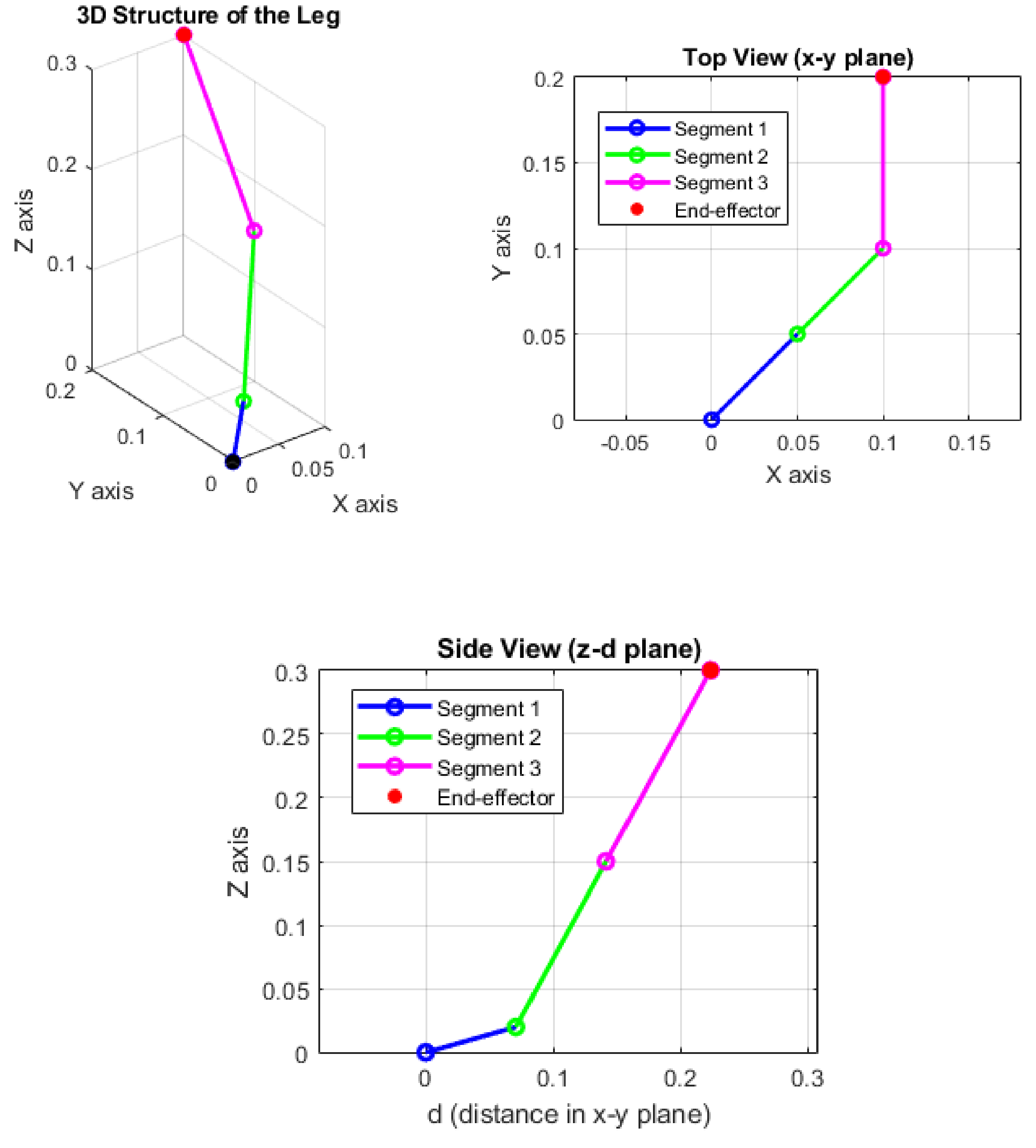

Fig. 2. The position of the robot's legs in 3D, as well as views from different perspectives from above and from the side.

These curves illustrate how the robot's joint angles change over time during the execution of a specific trajectory. Each leg of the robot is equipped with three main joints: the hip joint, the knee joint, and the ankle joint Fig. 3. The curves we have generated show the behavior of these joints in response to various movement command compositions, providing a clear insight into how the robot manages its balance and movement.

In addition to the joint angles, it is crucial to analyze the robot's trajectory in space. We have created curves that describe the change in the robot's overall position during movement Fig. 4. These curves are essential for understanding how the robot moves in space, considering its entire structure. With the help of these curves, we can analyze and optimize the robot’s trajectory to achieve various objectives, such as walking, turning, or performing other dynamic tasks.

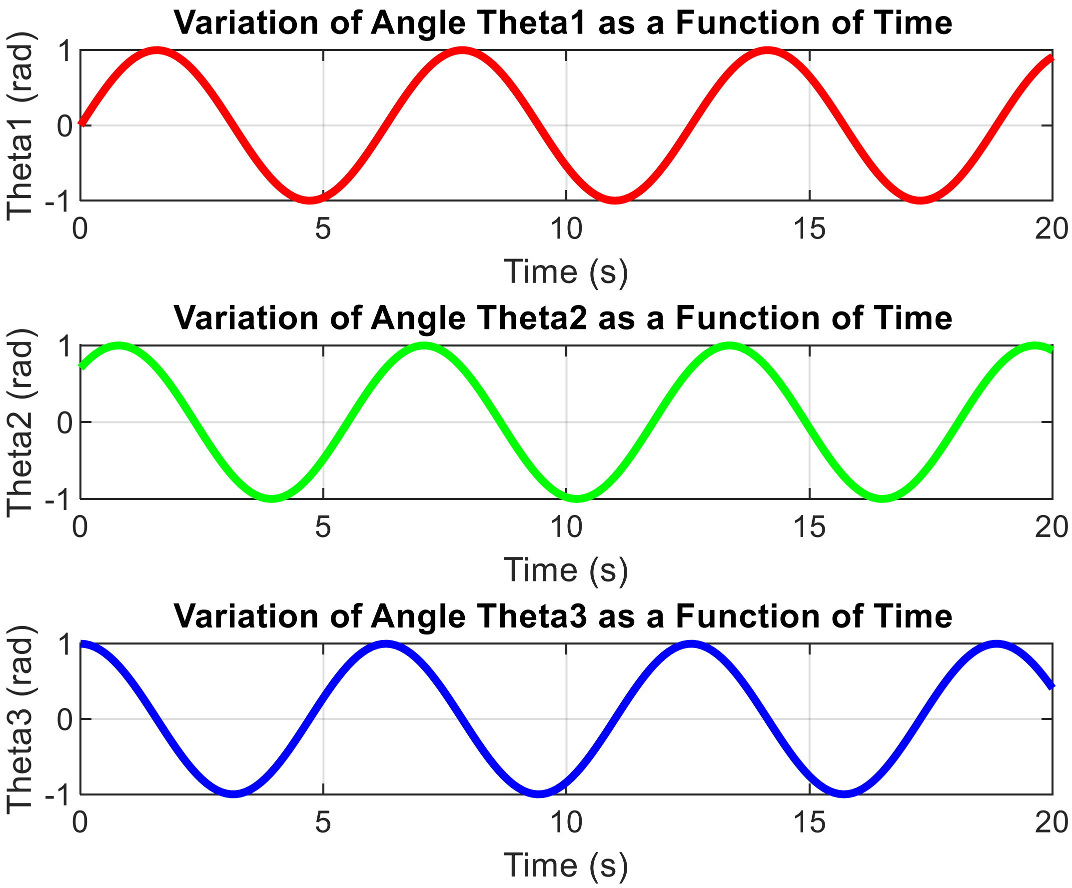

Fig. 3. The presentation of curves showing the change in joint angles over a period of 20 seconds

The center of mass (CoM) is a key element in maintaining the robot's stability, especially during complex movements or on uneven terrains. The curves representing the movement of the robot's center of mass show how its position changes over time. This analysis is critical for evaluating the robot’s ability to maintain balance and prevent tipping during rapid or unexpected movements Fig. 5.

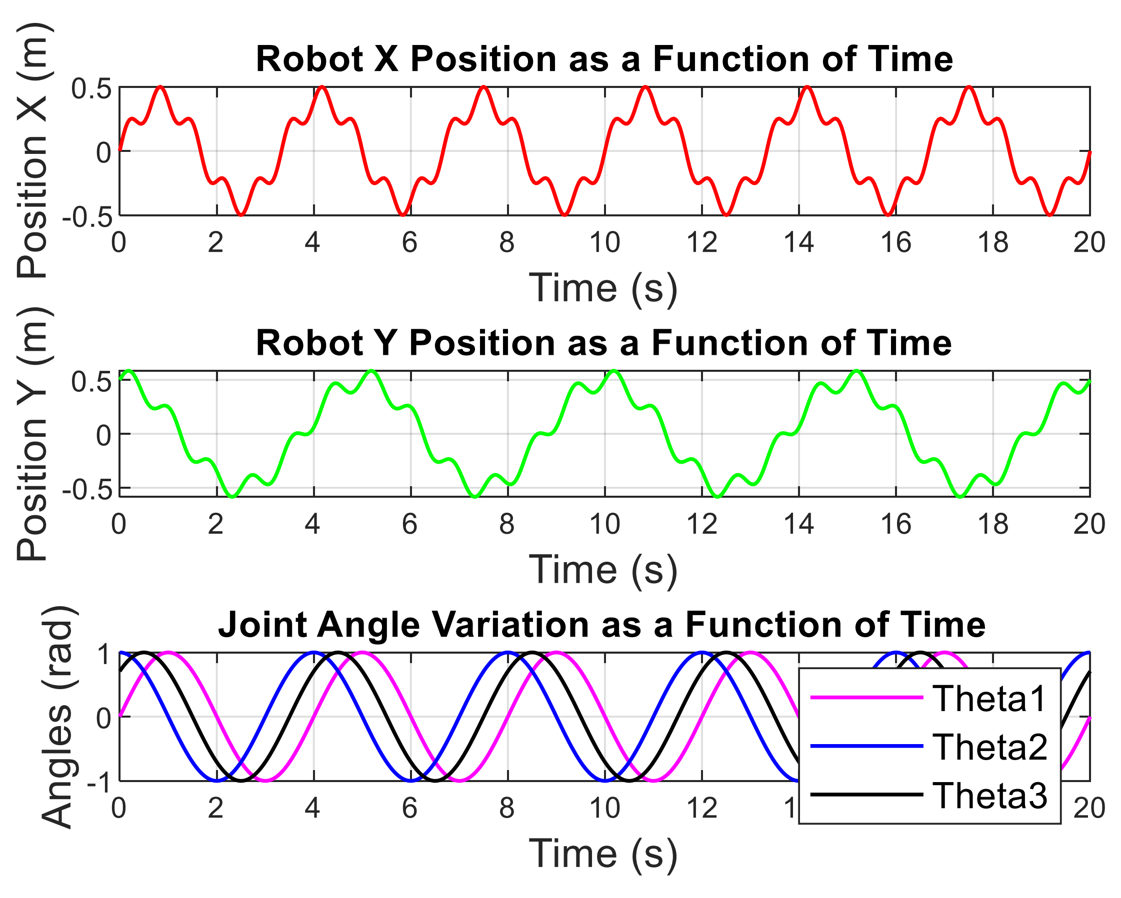

Fig. 4. The change in the robot's position along the X and Y axes is represented by these curves, as well as the change in the three angles at a given point.

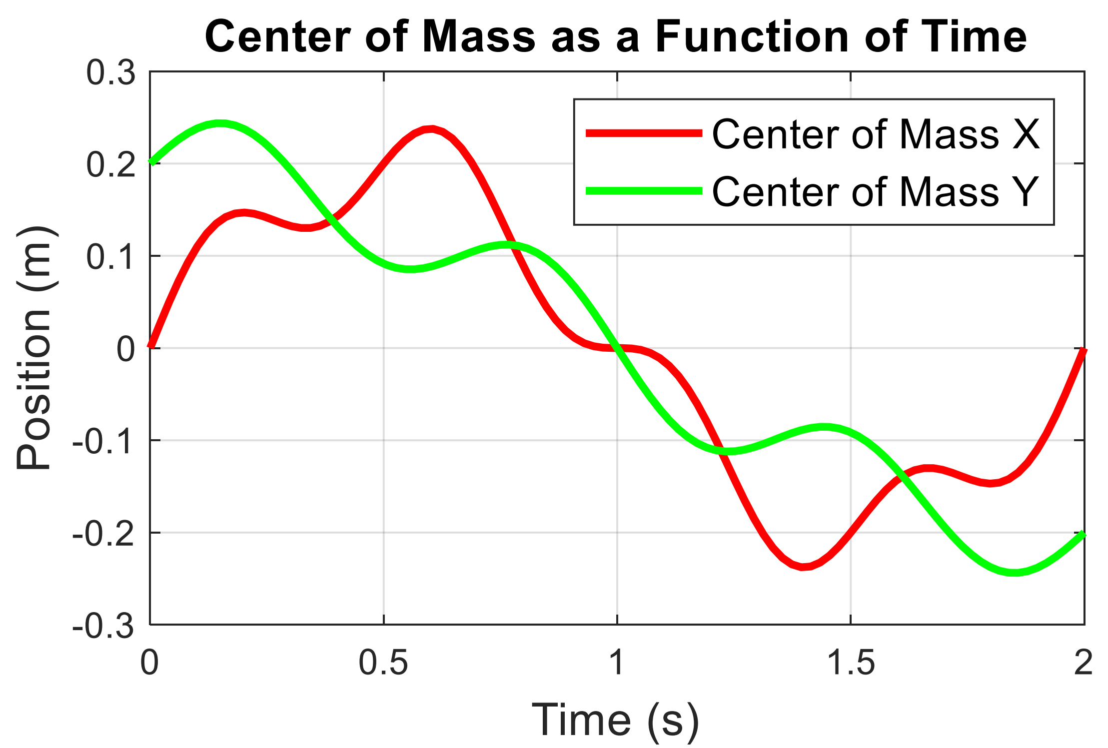

Fig. 1. The presentation of curves showing how the center of mass changes as a function of time.

The analyses conducted using MATLAB have provided us with an in-depth insight into the kinematic behavior of the Unitree A1 robot. The generated curves have helped us better understand how the robot manages its movements in a given space and how it responds to changes in movement commands. These results are crucial for the further development of control algorithms and for improving the overall performance of the robot in practical applications.

4. Quadruped robot navigation

Quadruped robots have gained significant importance in the field of robotics and artificial intelligence due to their ability to move with flexibility and stability across various terrains. With advancements in technology, these robots have become capable of handling complex challenges, including obstacle traversal, navigation in uncertain environments, and performing tasks that require a high degree of autonomy. Navigation is one of the most critical aspects of quadruped robot functionality, as it determines their ability to reach designated destinations safely and efficiently while minimizing risks and optimizing the path. A process known as Simultaneous Localization and Mapping (SLAM) is implemented to map the local environment and identify reference landmarks. This technique enables a mobile robot to autonomously correct its position and orientation, thereby creating an updated perception of its surroundings. Furthermore, the integration of motor encoder sensors along with LIDAR enhances the accuracy and autonomy of the robot's movement, contributing to a high level of performance in operations within complex environments.

4.1 Types of slam methods

Simultaneous Localization and Mapping (SLAM) is a fundamental approach in robotics that enables the creation of environmental maps while simultaneously determining the robot's position within them. As the robot moves, it integrates data from various measurements to generate an accurate and stable map. The primary SLAM methods include visual SLAM, LiDAR-based SLAM, and multi-sensor SLAM.

4.2 Visual slam

Visual SLAM (vSLAM) utilizes camera images to construct maps and determine the robot's position. Camera-based SLAM is a cost-effective solution that provides a rich amount of visual information. There are two main approaches to vSLAM: sparse methods, which rely on image features (e.g., ORB-SLAM, PTAM), and dense methods, which analyze the full image structure (e.g., LSD-SLAM, DSO). However, key challenges include depth estimation and low-light conditions, which can be mitigated by integrating additional sensors such as an Inertial Measurement Unit (IMU). RPLidar S1 is a LiDAR (Zhang et al., 2025) sensor that utilizes laser pulses to measure distances and generate a detailed environmental map. This sensor is widely used in robotics, autonomous systems, and localization and mapping studies, providing high accuracy and real-time performance. It has been used in our case study. RPLidar S1 enables 360° scanning with a measurement range of up to 40 meters, utilizing Time of Flight (ToF) technology for precise distance estimation.

With a scanning speed of up to 18,000 measurements per second and an update frequency between 10 and 20 Hz, it ensures fast real-time data processing. Its accuracy of ±3 cm and operational stability in temperatures ranging from -10°C to 45°C make it suitable for a wide range of robotic applications. RPLidar S1 operates by emitting laser pulses and measuring their return time after reflecting off objects, generating a point cloud representation of the environment.

Its rotating mechanism enables continuous scanning, ensuring precise and stable measurements for navigation and mapping. This sensor is essential for Simultaneous Localization and Mapping (SLAM), autonomous navigation, and obstacle avoidance, with seamless integration into the Robot Operating System (ROS). By processing real-time data, RPLidar S1 enables robots to map their surroundings and move safely. RPLidar S1 is widely used in robotics, autonomous vehicles, drones, and industrial applications for path planning, obstacle avoidance, and autonomous navigation. Despite certain limitations, it remains a key component in the advancement of modern localization and mapping technologies.

4.3 Lidar slam

LiDAR-based SLAM employs laser sensors to generate highly accurate 2D Fig. 6 and 3D maps in Fig.7 (Gan et al., 2025). LiDAR sensors measure distances by analyzing the time it takes for light pulses to return, providing a detailed representation of the environment. Common algorithms used for processing point clouds include Iterative Closest Point (ICP) and Normal Distributions Transform (NDT), which assist in registration and localization. This method is particularly advantageous in low-light environments or areas with complex structures.

Fig. 2. SLAM with 2D LiDAR

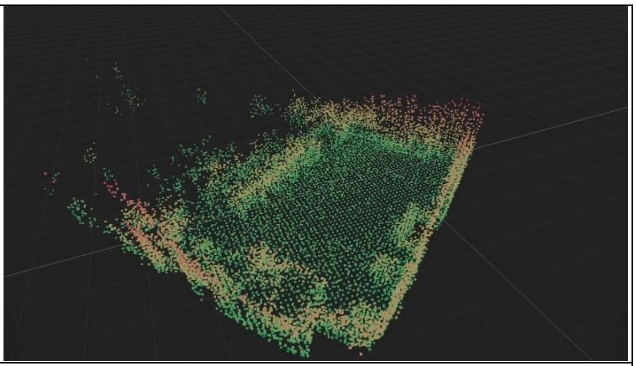

Fig. 3. SLAM with 3D LiDAR

Multi-sensor SLAM integrates data from cameras, LiDAR, IMU, GPS, and other sensors to enhance accuracy and robustness. The fusion of different data sources through factor graph optimization enables better positioning. For example, while cameras provide rich visual information, LiDAR ensures precise depth perception, compensating for each other's limitations. This approach is especially useful in applications requiring precise localization, such as autonomous vehicles and industrial robotics.

5. Results and Discussion

In Fig. 8, we create a detailed map using the Paint 3D application. The map highlights two key points: the starting point and the goal, which are essential for planning the robot's movement. The starting point represents the robot's initial position, where its mission begins, while the goal marks the destination it must reach.

Fig. 8. The map created in Paint 3D.

To better illustrate the map, multiple images from different perspectives are presented. These visualizations help describe the robot's path during its movement, emphasizing key features and potential obstacles that may arise along the trajectory Fig. 9.

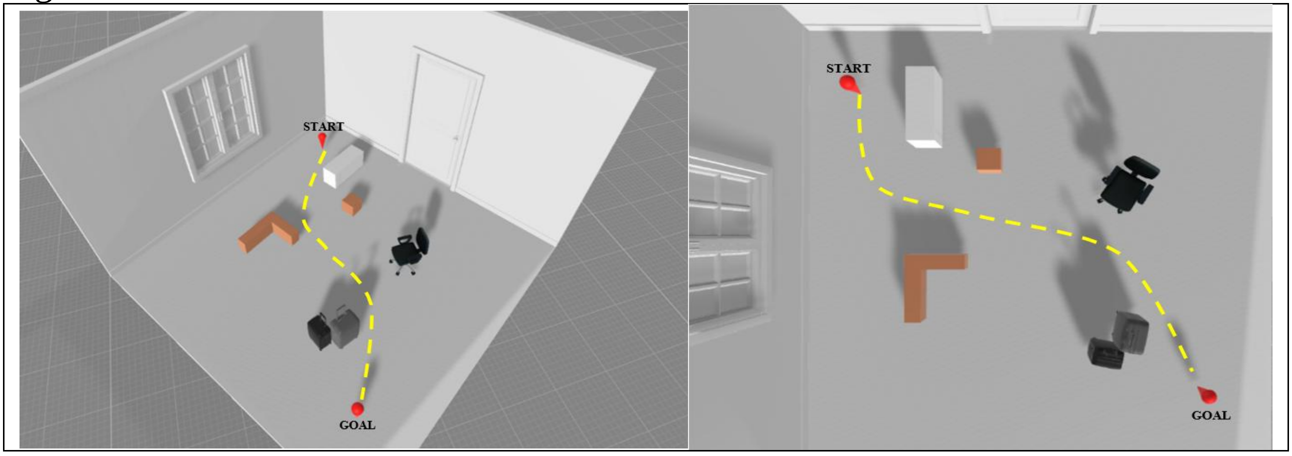

Fig. 9. Visualization of the robot's trajectory on the created map.

This section also examines the robot's navigation process using RPLIDAR S1 and Simultaneous Localization and Mapping (SLAM) technologies. This system enables the robot to move from the starting point to the goal while avoiding obstacles in its environment. At the beginning of its path, the robot activates the RPLIDAR S1 sensor to scan its surroundings. This LiDAR sensor provides real-time information about potential obstacles and the environment's configuration, allowing the robot to construct an accurate map of its surroundings. During this phase, the robot analyzes the acquired data and plans the most efficient path to reach its destination Fig.10.

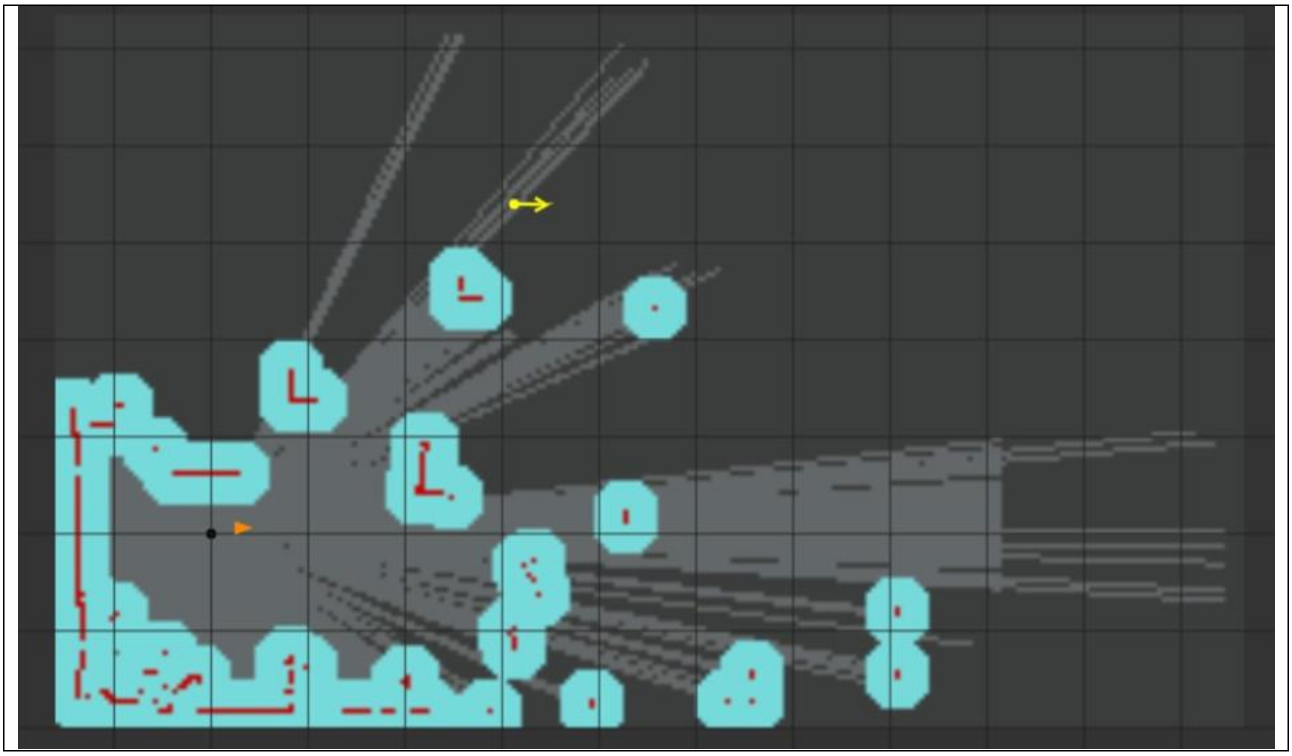

Fig. 10. Preparation of the robot at the starting point for navigation.

Upon reaching the midpoint of its journey, the robot demonstrates significant progress. The use of SLAM allows continuous updates to its position and enables adaptive motion planning based on encountered obstacles. This phase is critical, as the robot must showcase its ability to navigate accurately within a dynamic environment Fig. 11.

Fig. 11. The robot at the halfway point, avoiding obstacles.

When the robot reaches the goal, it has successfully completed its mission while avoiding all encountered obstacles Fig.12. This process not only demonstrates the effectiveness of RPLIDAR S1 and SLAM but also highlights the potential of advanced robotic technologies in enhancing autonomy and performance across diverse environments.

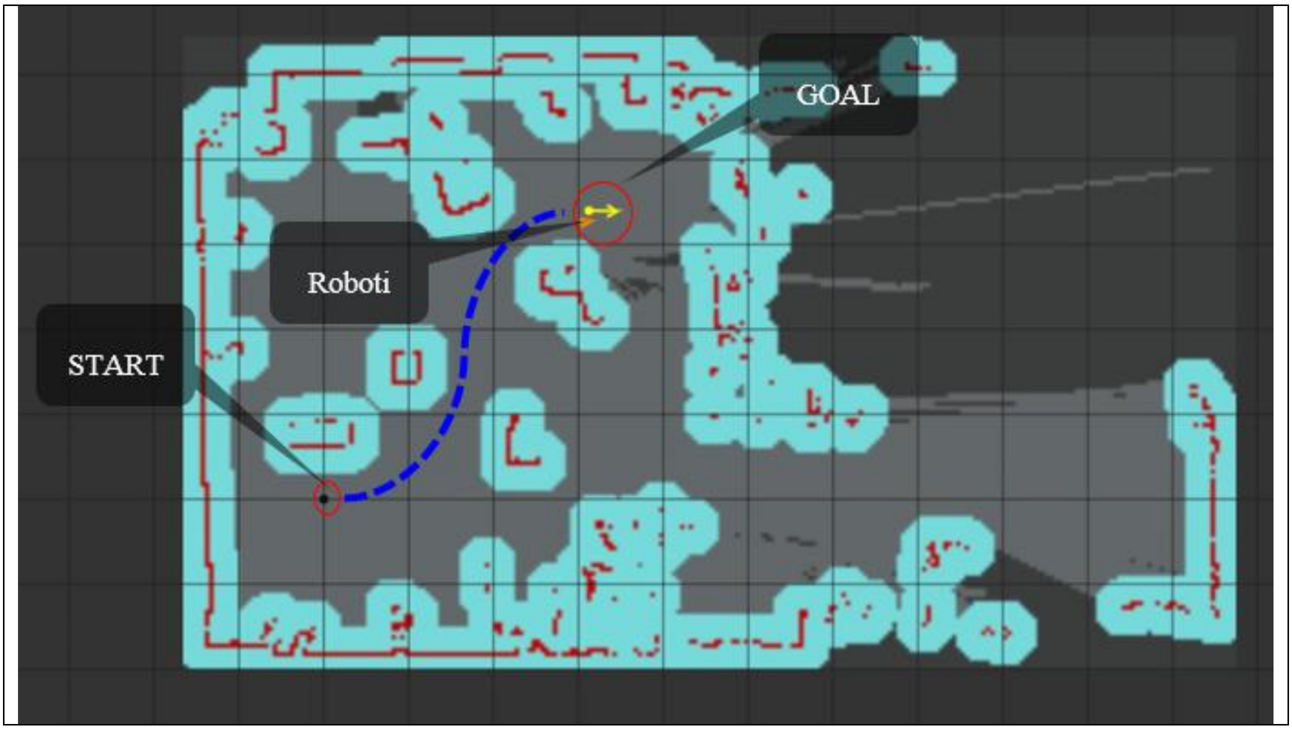

Fig. 12. The robot successfully reaches the goal after completing the navigation process.

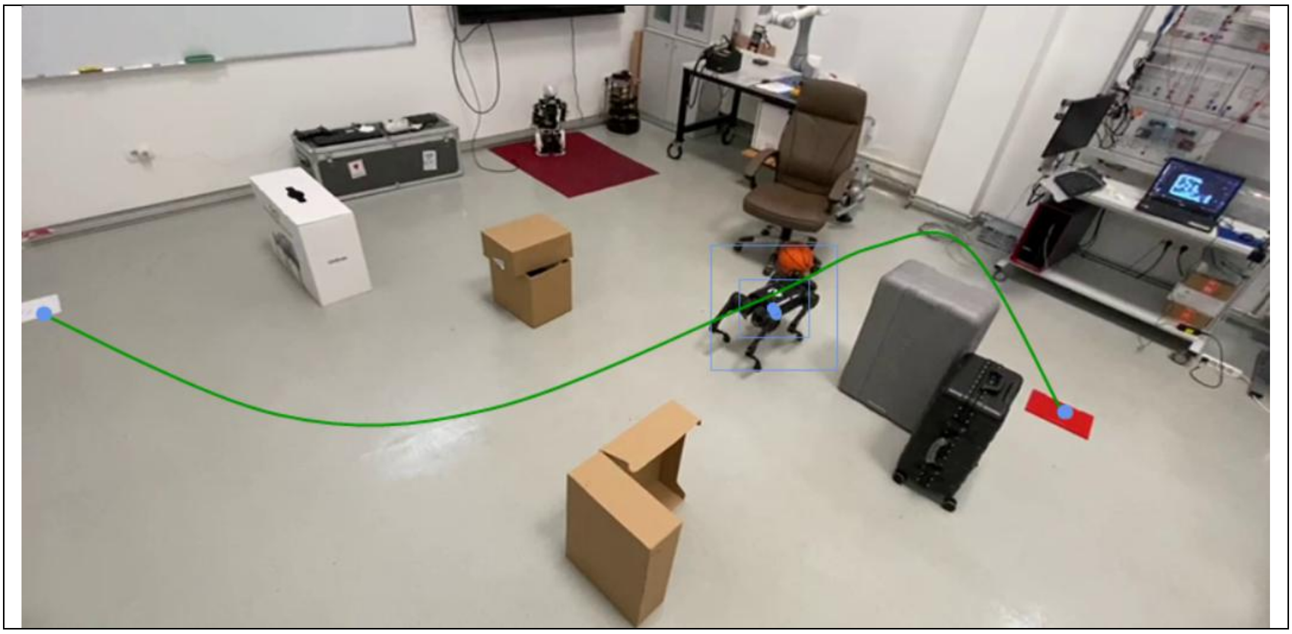

Fig. 13. Quadruped Robot Navigation in an Indoor Environment Using SLAM at the laboratory of Mechatronics

Figure 13 shows a quadruped robot navigating through an indoor laboratory environment using Simultaneous Localization and Mapping (SLAM). The robot is autonomously following a predefined path (marked by the green trajectory) while avoiding various static obstacles, such as cardboard boxes and equipment. The SLAM algorithm enables the robot to build a map of the environment in real-time and localize itself within it. The scene demonstrates obstacle avoidance, path planning, and real-time localization, highlighting the robot's capability to operate autonomously in cluttered environments.

6. Conclusion

This paper emphasizes the significance of the Unitree A1 quadruped robot in enhancing perception and control in complex environments. Through the conducted tests and simulations, it has been demonstrated that this technology provides effective solutions for autonomous navigation, obstacle avoidance, and accurate mapping using advanced SLAM algorithms. The results have shown significant improvements in safety, stability, and interaction with the environment, contributing to the increased efficiency of the robot in uncertain and dynamic settings. The advanced integration and coordination of sensors represent crucial steps toward the development of more sophisticated and reliable robots, with high potential for applications in various technological challenges. This paper investigates the Unitree A1 robot and its notable improvements in the field of perception and control in complex environments. The use of RPLIDAR sensors and SLAM algorithms has led to significant enhancements in the robot’s ability to navigate and interact within these environments. Experimental results from simulations and real-world tests have demonstrated the success of the applied method, improving localization accuracy and the robot’s ability to avoid obstacles. This approach has enhanced the safety and stability of the robot's movement, enabling real-time autonomous decision-making, a key capability for advanced applications such as search and rescue and industrial inspection.

7. References

Farag, K. K. A., Shehata, H. H., & El-Batsh, H. M. (2021). Mobile robot obstacle avoidance based on neural network with a standardization technique. Journal of Robotics, 2021(1), 1129872.

Bajrami, X., Dermaku, A., Demaku, N., Maloku, S., Kikaj, A., & Kokaj, A. (2016). Genetic and Fuzzy logic algorithms for robot path finding. In 2016 5th Mediterranean Conference on Embedded Computing (MECO) (pp. 195-199). IEEE.

Teame, W. G., Zhongmin, W., & Yu, Y. (2020). Optimization of SLAM Gmapping based on simulation. Int. J. Eng. Res. Technol, 9(4), 74-81.

Bailey, T., & Durrant-Whyte, H. (2006). Simultaneous localization and mapping (SLAM): Part II. IEEE robotics & automation magazine, 13(3), 108-117.

Theodoridis, T., Hu, H., McDonald-Maier, K., & Gu, D. (2013). Kinect enabled monte carlo localisation for a robotic wheelchair. Frontiers of Intelligent Autonomous Systems, 17-27.

Missura, M., & Bennewitz, M. (2019). Predictive collision avoidance for the dynamic window approach. In 2019 International Conference on Robotics and Automation (ICRA) (pp. 8620-8626). IEEE.

Kalogeiton, V. S., Ioannidis, K., Sirakoulis, G. C., & Kosmatopoulos, E. B. (2019). Real-time active SLAM and obstacle avoidance for an autonomous robot based on stereo vision. Cybernetics and Systems, 50(3), 239-260.

MathWorks. (n.d.). Simultaneous Localization and Mapping (SLAM). Retrieved September 2, 2024, from https://www.mathworks.com/discovery/slam.html

Unitree Robotics. (2020). A1 software developer guide (Version 1.0)

Ouster. (n.d.). Introduction to SLAM (Simultaneous Localization and Mapping). Retrieved September 2, 2024, from https://ouster.com/insights/blog/introduction-to-slam-simultaneous-localization-and-mapping

Pajaziti, A., Cheok, K. C., & Bajrami, X. (2013). Semi Autonomous Mobile Robot for Mine Detection. In International Symposium “Humanitarian Demining 2013” (p. 105).

Bajrami, X., Dërmaku, A., & Demaku, N. (2015). Artificial neural fuzzy logic algorithm for robot path finding. IFAC-PapersOnLine, 48(24), 123-127.

Gan, V. J., Hu, D., Wang, Y., & Zhai, R. (2025). Automated indoor 3D scene reconstruction with decoupled mapping using quadruped robot and LiDAR sensor. Computer-Aided Civil and Infrastructure Engineering.

Zhang, H., Li, L., Jiang, A., Xu, J., Shen, H., Li, Y., ... & Wang, Z. (2025). LICFM3-SLAM: LiDAR-Inertial-Camera Fusion and Multi-modal Multi-level Matching for Bionic Quadruped Inspection Robot Mapping. IEEE Transactions on Instrumentation and Measurement.

Pajaziti, A., Bajrami, X., & Paliqi, A. (2018). Path Control of Quadruped Robot through Convolutional Neural Networks. IFAC-PapersOnLine, 51(30), 610-615.