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Terrain-Aware Ego-Planner for Local Path Planning and Navigation of Quadruped Robots

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Abstract

Autonomous navigation in unknown environments remains a key challenge for quadruped robots operating in complex terrains. To improve the navigation capability of quadruped robots, this paper proposes a path planning and navigation framework for quadruped robots based on the Ego-Planner algorithm. A terrain height threshold is introduced to account for the terrain adaptability of quadruped locomotion, enabling the robot to traverse uneven regions within its locomotion capability. The planner formulates the trajectory generation problem as a continuous optimization task and performs online trajectory refinement according to locally perceived environmental information. Simulation experiments are conducted in a Gazebo-based environment, and real-world validation is carried out on a Unitree Go2 quadruped robot platform. Experimental results in corridor and stepped terrain environments demonstrate that the proposed method enables reliable obstacle avoidance and stable navigation in unknown environments.

KEYWORDS

Quadruped Robot, Ego-Planner, Path Planning, Autonomous locomotion

1 | INTRODUCTION

In recent years, the robotics industry has experienced rapid growth. With the increasing adoption of robots in domains such as warehouse logistics, intelligent inspection, and autonomous driving, the ability to navigate autonomously has become a crucial measure of system intelligence. As a fundamental component of autonomous navigation, path planning focuses on generating collision-free trajectories that guide the robot safely and efficiently from its starting position to the target within complex and dynamic environments. Research on enabling legged robots to rapidly adapt to various irregular and complex terrains holds broad prospects and carries significant scientific relevance for multiple fields, including military operations[1], exploration[2], rescue missions[3], and industrial production[4].

Cheng et al.[5] proposed a rail-mounted inspection robot system for power distribution rooms. By integrating vision and multi-sensor perception technologies, the system enables automatic acquisition of operating status data and anomaly detection of key equipment. Kim et al.[6] addressed the hazardous operating conditions in underground mines, such as tunnel collapse and toxic gases, by applying autonomous mobile robots to this scenario. They developed a compact autonomous driving robot,

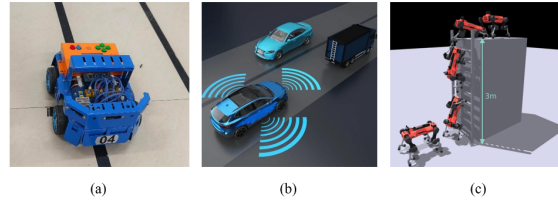


FIGURE 1 Examples of robot path planning applications: (a) mobile tracking car (b) autonomous driving (c) quadruped robot climbing stairs

ERP-42, designed for unmanned environmental monitoring in underground mining environments. Aziz et al.[7] designed a legged robot platform that enables robots to perform fire protection facility status monitoring tasks in complex environments. Takahiro Miki[8] proposed a terrain-aware locomotion controller for quadruped robots. The controller overcomes the limitations of previous approaches and enables robust traversal of challenging natural terrains, such as steep slopes, smooth surfaces, grass, and snow.

Quadruped robots are robotic systems designed by mimicking the limb structures of biological animals. They typically possess multiple legs, each equipped with several joints and actuators. Each leg can move and adjust independently, enabling the robot to traverse challenging terrains in natural environments with high robustness. As a result, legged robots exhibit superior stability, flexibility, and adaptability, as well as strong obstacle-crossing capabilities[9]. Designing and optimizing the locomotion and control algorithms of quadruped robots to achieve stable and efficient gaits remains a significant challenge. Many legged animals, such as humans and dogs, can traverse or run across various challenging terrains by predicting upcoming surfaces and planning their foot placement based on visual information[10].

This study constructs an environmental model by integrating multiple sensors. Based on the Ego-Planner path planning algorithm, the system plans in real time the safest locomotion strategy and an optimal path within the perceived terrain. The main contributions of this work can be summarized as follows:

- (1) A terrain-aware path planning framework based on the Ego-Planner algorithm is developed for quadruped robots operating in unknown environments.
- (2) The proposed framework is implemented on a Unitree Go2 quadruped robot platform and validated through both simulation and real-world experiments.
- (3) Experimental results in corridor and stepped terrain environments demonstrate that the proposed method achieves reliable obstacle avoidance and stable navigation.

2 | RELATED WORKS

Ego-Planner algorithm was proposed by Fei Gao et al.[11] from Zhejiang University for autonomous flight of quadrotor UAVs in unknown environments. Ego-Planner is a local path planning algorithm designed for unmanned aerial vehicles and mobile robots. Its key feature lies in formulating the local trajectory planning problem as a continuously differentiable optimization problem through the construction of a unified objective function. This objective function is typically composed of multiple weighted cost terms, enabling the generation of smooth and safe trajectories while avoiding the dependence on environmental distance fields commonly required by traditional approaches. Owing to its strong real-time performance and effective obstacle avoidance capability in complex and dynamic scenarios, it has since been widely applied in autonomous UAV navigation[12], industrial inspection, and other robotic applications.

Based on the Ego-Planner framework, this study develops a path planning approach tailored for quadruped robots. The algorithm is implemented on the Unitree Go2 platform and evaluated through both simulation experiments and real-world tests. Compared with conventional two-dimensional path planning methods designed primarily for wheeled robots, like DWA[13] and TEB[14], the proposed approach takes into account the terrain adaptability of quadruped locomotion. In particular, a terrain height threshold is introduced, allowing the planner to generate paths that can traverse certain uneven or elevated regions that remain within the robot's locomotion capability.

3 | METHOD

The idea of Ego-Planner is to formulate the path planning task as a mathematical optimization problem by constructing an objective function and representing the trajectory using minimum-control polynomial trajectories. The overall path planning pipeline of Ego-Planner is illustrated in Fig. 2.

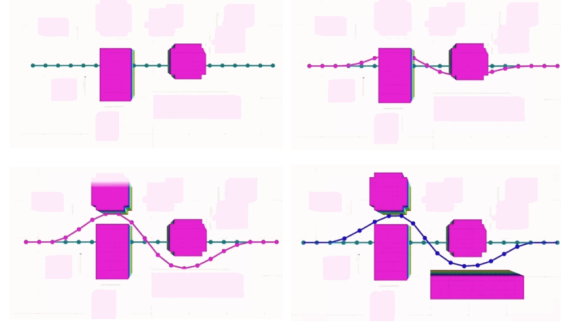


FIGURE 2 Ego-Planner algorithm path planning process

Fifth- or seventh-order polynomials are commonly employed to parameterize the robot's motion trajectory within each time segment. The trajectory along a single axis can be shown as the following form.

$$p(t) = \sum_{i=0}^5 a_i t^i \quad (1)$$

Ego-Planner models the planning task as a constrained nonlinear optimization problem. Its objective function typically comprises smooth, collision, and dynamic feasibility, which is defined as the following form.

$$J = \lambda_s J_{smooth} + \lambda_c J_{collision} + \lambda_d J_{dynamic} \quad (2)$$

Ego-Planner defines smooth using acceleration and the rate of change of acceleration, thereby producing smoother trajectories.

$$J_{smooth} = \sum_{i=0}^{N_c-2} \|A_i\|_2^2 + \sum_{i=0}^{N_c-3} \|J_i\|_2^2 \quad (3)$$

Where A_i is the acceleration and J_i is the rate of change of acceleration.

The Ego-Planner algorithm replaces the ESDF with a force-based formulation. To ensure that the trajectory does not collide with obstacles, the minimum distance between obstacles, d_{ij} must exceed a safety margin. The distance d_{ij} is defined as:

$$d_{ij} = (Q_i - p_{ij}) \cdot v_{ij} \quad (4)$$

The safety margin is denoted by s_f , and the corresponding collision cost function is defined as

$$j_c(i, j) = \begin{cases} 0, & (s_f - d_{ij} < 0) \\ (s_f - d_{ij})^3, & (0 < s_f - d_{ij} < s_f) \\ s_f^3 + 3s_f^2 d_{ij} - 3s_f d_{ij}^2, & (s_f < s_f - d_{ij}) \end{cases} \quad (5)$$

The total collision cost over all control points is shown as follows:

$$J_{collision} = \sum_{i=0}^{N_c} \sum_{j=0}^{N_p} j_c(i, j) \quad (6)$$

Where N_p denotes the number of (p,v) pairs for a single control point.

The dynamic term $J_{dynamic}$ is introduced to constrain the trajectory, which is constructed based on the analytical formulation of B-spline control points. A soft penalty function is applied to penalize dynamic quantities that exceed the physical limits of the system. The dynamic term is shown as follows.

$$J_{dynamic} = \sum_{i=1}^{N_c-1} \omega_v F(V_i) + \sum_{i=1}^{N_c-2} \omega_a F(A_i) + \sum_{i=1}^{N_c-3} \omega_j F(J_i) \quad (7)$$

In contrast to conventional sampling-based planning approaches, Ego-Planner eliminates the need for random sampling and instead performs direct optimization of trajectory parameters within a continuous space, which yields trajectories of higher quality. A coarse feasible path is rapidly generated and then used to initialize the polynomial trajectory, thereby significantly improving the planning success rate in complex environments.

To account for the terrain adaptability of the quadruped robot, a terrain height threshold is introduced in this study. When the height difference between adjacent grid cells is below this threshold, the terrain is considered traversable. The function is defined as:

$$|h_i - h_j| < \Delta h \quad (8)$$

4 | EXPERIMENTS

4.1 | Simulation Experiments

In this section, path planning simulation experiments for the quadruped robot are conducted in a virtual environment to validate the effectiveness of the Ego-Planner algorithm. The simulation environment and quadruped robot model were built using Gazebo[15] on an Ubuntu 20.04 operating system, with communication implemented through ROS. Patchwork was employed for ground segmentation, allowing the planner to process 3D point cloud data in the PointCloud2 format. After segmenting the ground point cloud, the data are projected onto a 2D plane to construct a 2D grid map for planning. The initialized simulation environment is shown in Fig. 3 .

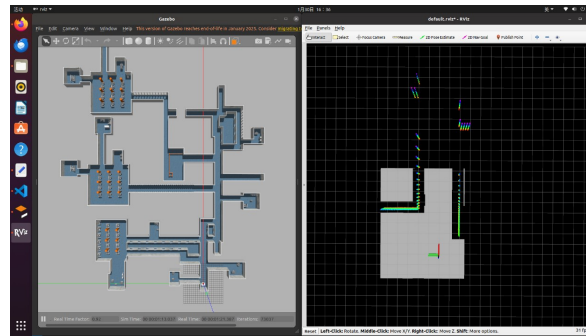


FIGURE 3 Simulation environment

In RViz, the planner is launched with the quadruped robot's starting position set at the origin of the world coordinate system. In this system, the robot continuously acquires distance information of surrounding obstacles using LiDAR and generates a local grid map or point cloud map based on a SLAM algorithm, providing the environmental basis for local path planning. Using the 2D Nav Goal feature in the RViz visualization tool, the operator specifies the target position and orientation within the visual

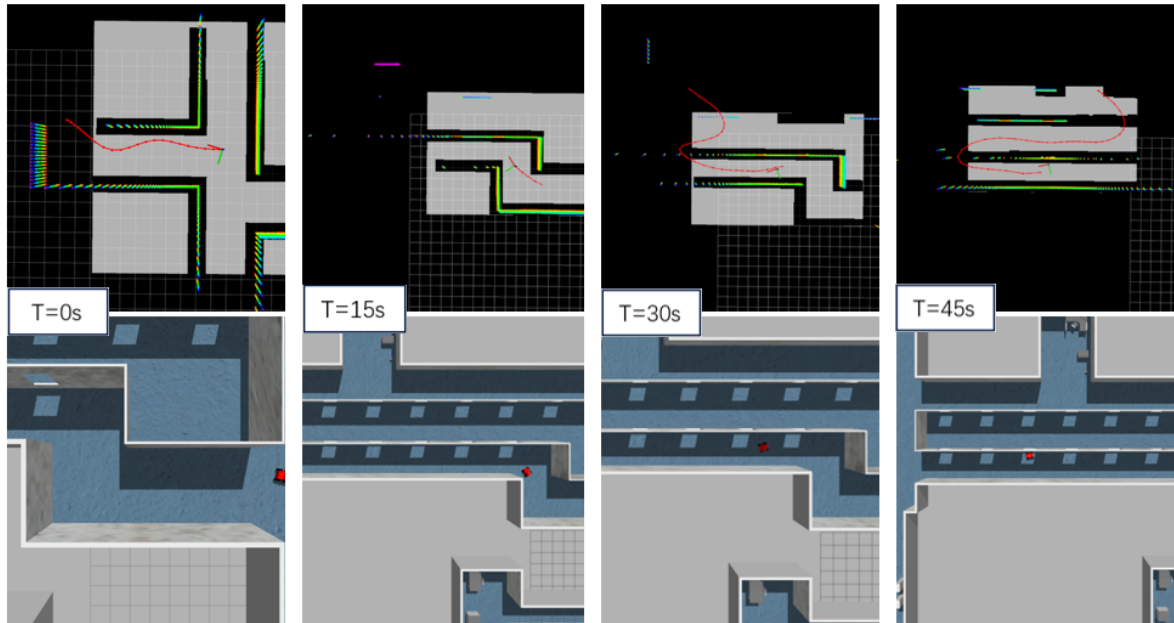


FIGURE 4 Short-range task implementation

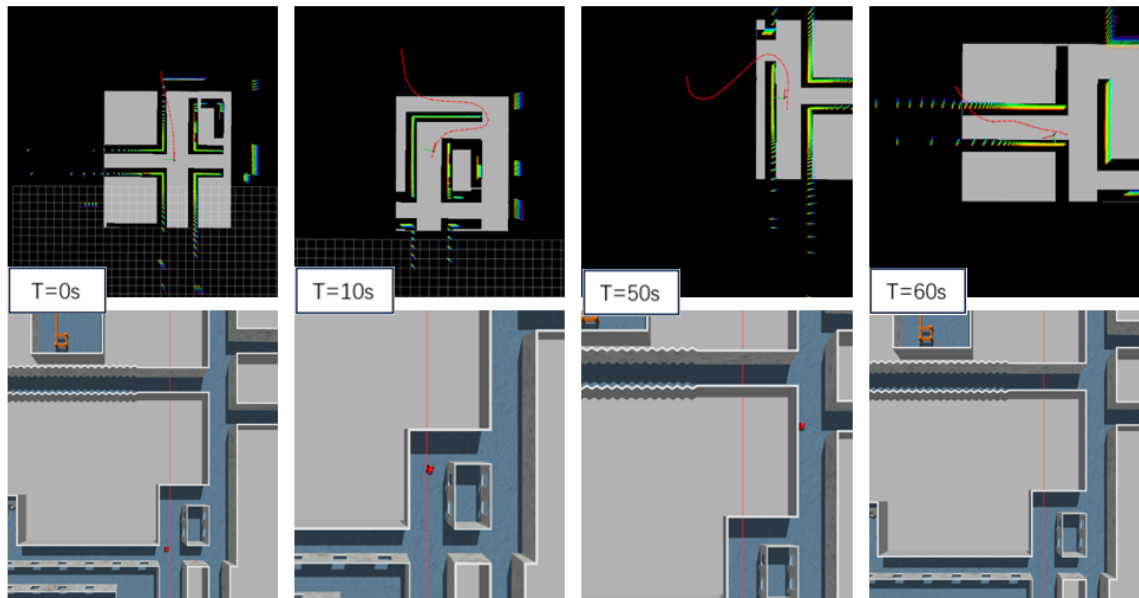


FIGURE 5 Long-range task implementation

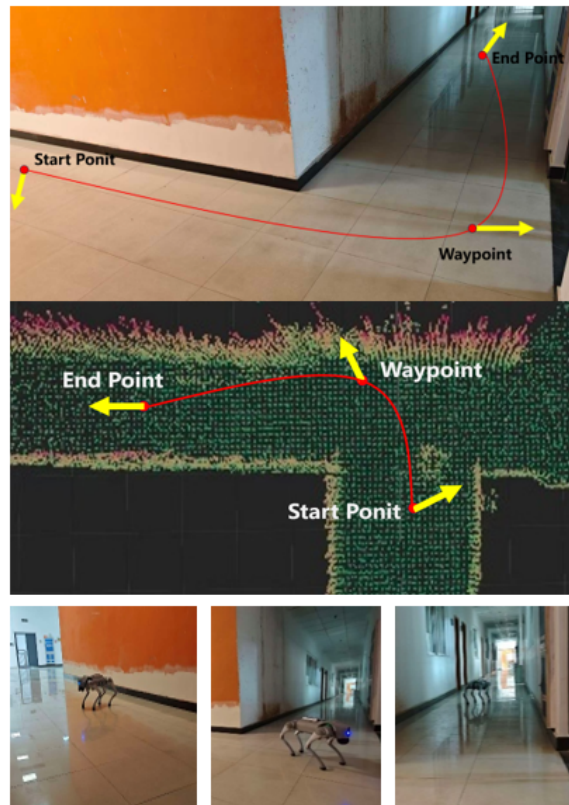


FIGURE 6 Path planning results in a flat corridor environment

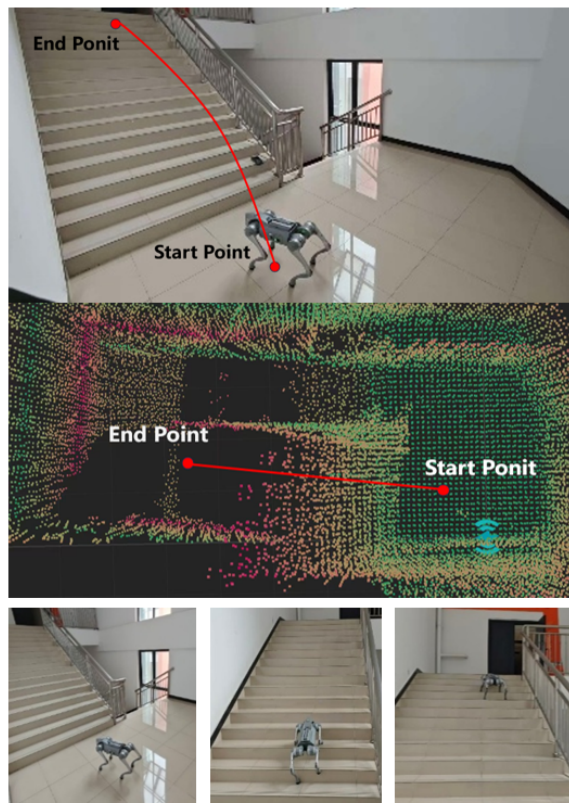


FIGURE 7 Path planning results in a stepped terrain environment

interface.

Fig. 4 illustrates the motion of the quadruped robot in a simulated short-distance corridor with occlusions. The planner initially generates a shortest-path straight-line trajectory based on the start and goal positions, and then performs real-time local adjustments according to the environment information currently perceived by the LiDAR. At 30s and 45s of the simulation, it can be clearly observed that when the robot is in blind spots where obstacles have not yet been detected, the planner follows the shortest-distance direction. As the LiDAR gradually senses obstacles in the environment, the planner recomputes the trajectory based on the updated environmental information, effectively avoiding obstacles while continuing toward the goal.

As shown in Fig. 5, this simulation experiment further increases the terrain complexity between the start and goal positions. In unknown environments without global path planning, the quadruped robot cannot utilize a complete environmental map to generate a globally optimal path, and a straight-line trajectory may pass through previously unknown obstacle regions. This path planning approach has several limitations: The shortest straight-line path may lead into impassable areas, reducing the success rate of navigation. As the robot moves along this path and gradually detects obstacles, it is forced to perform local replanning, which increases the risk of collisions. Frequent local trajectory replanning can also produce jagged or discontinuous paths, adding to the computational burden.

4.2 | Physical Prototype Deployment

In this paper, the planner was deployed on a Go2 Edu quadruped robot prototype developed by Unitree Robotics for testing. During deployment, the control framework remained fully consistent with that used in the simulation. The difference was the replacement of simulated sensors with physical devices, including a depth camera, LiDAR, IMU, joint motors, and foot-end sensors, with data acquired through the respective hardware SDKs. The physical parameters of the quadruped robots are listed as follows.

TABLE 1 Physical parameters of Go2

Parameter	Value	Unit
Weight	15	kg
Body Length	70	cm
Body Width	21	cm
Stand Height	40	cm
Prone Height	20	cm
Motion Speed	[0,3.7]	m/s
Hip Joint	[-48,48]	°
Thigh Joint	[-200,90]	°
Shank Joint	[-156,48]	°

To verify the effectiveness of the proposed path planning algorithm in real-world environments, the robot platform was manually controlled using a remote controller to perform mapping. During the SLAM process, a strategy of slow movement combined with looped traversal was adopted to ensure the completeness and coverage of the generated map. After mapping was completed, the environmental map was saved for subsequent navigation, path planning, and localization tasks.

The path planning results in the corridor environment are shown in Fig. 6. At 0s, the quadruped robot completes path planning according to the specified target point and begins to move along the planned trajectory. At 12.4s, the robot reaches the first waypoint, indicating that the planned path is feasible. Finally, at 27.3s, the robot successfully arrives at the target destination.

The results of the path planning experiment in the stepped terrain are presented in Fig. 7. At 0s, the quadruped robot generates

TABLE 2 Navigation performance metrics

Terrain	Navigation point	Type		Average value	Standard deviation	Max
Flat Co-rddidor	Waypoint	Elapsed Time	(s)	12.4	0.57	13.1
		Deviation (m)		0.023	0.013	0.051
	End Point	Elapsed Time	(s)	12.4	0.57	13.1
		Deviation (m)		27.3	0.64	28.5
	Step Point	Elapsed Time	(s)	15.31	0.61	16.36
		Deviation (m)		0.13	0.02	0.17

a path according to the designated target point and starts moving along the planned trajectory. Around 3s, the robot's foot first contacts the side surface of the step, after which it climbs onto the step while continuing to track the planned path. At approximately 15.3s, the robot arrives at the target position, thereby completing the navigation task from the starting point to the goal.

As shown in Table 2, each experiment is repeated five times and similar results are botained.

5 | CONCLUSION

Simulation results for the Ego-Planner path planner demonstrate that, in scenarios where the global environment is unknown, the planner relies on locally perceived information to perform online trajectory optimization. Initially, when obstacles have not yet been detected, the planner generates paths primarily based on the shortest distance from the start to the goal. As the quadruped robot moves and environmental data is incrementally updated, the planner dynamically modifies the trajectory according to the newly perceived information, actively avoiding obstacle regions to maintain safe and feasible navigation. The proposed method demonstrates the feasibility of applying Ego-Planner to quadruped robot navigation in unknown environments and provides a practical solution for terrain-aware path planning.

6 | DISCUSSION AND LIMITATIONS

Due to the quadruped robot's high terrain adaptability, its flexible leg structure enables it to negotiate ditches and uneven surfaces while evaluating the traversability of the terrain based on its own locomotion capabilities. Nonetheless, this study does not provide a detailed analysis of the traversability of the terrain in highly complex or rugged environments, nor does it quantify its specific impact on path planning performance. The proposed path planning algorithm in this paper has only been evaluated in static environments. Its effectiveness in the presence of dynamic obstacles that were not included in the modeled environment still requires further investigation.

Future work will focus on extending the framework to dynamic environments and integrating terrain traversability analysis based on learning-based perception methods.

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REFERENCES

- [1] B. Katz, J. Di Carlo, S. Kim, "Mini cheetah: A platform for pushing the limits of dynamic quadruped control," *International Conference on Robotics and Automation* 2019, pp. 6295-6301.
- [2] J. Hwangbo, J. Lee, A. Dosovitskiy, D. Bellicoso, V. Tsounis, V. Koltun, M. Hutter, "Learning agile and dynamic motor skills for legged robots," *Science Robotics* 2019.
- [3] J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, M. Hutter, "Learning quadrupedal locomotion over challenging terrain," *Science Robotics* 2020.
- [4] H. Park, P. Wensing, S. Kim, "Learning quadrupedal locomotion over challenging terrain," *Jumping over obstacles with MIT Cheetah 2, Robotics and Autonomous Systems* 2021, p. 103703.
- [5] M. Cheng, D. Xiang, "The design and application of a track-type autonomous inspection robot for electrical distribution room," *Robotica* 2020, vol. 38, pp. 185-206.
- [6] H. Kim, Y. Choi, "Self-driving algorithm and location estimation method for small environmental monitoring robot in underground mines," *Computer Modeling in Engineering Sciences* 2021, vol.127, no.3, pp. 943-964.
- [7] A. Aziz, P. Herbers, H. Bayer, et al, "Fully autonomous fire safety equipment inspection missions on a legged robot," *Computing in Civil Engineering* 2023, pp. 804-812.
- [8] T. Miki, J. Lee, L. Wellhausen, M. Hutter, "Learning to walk in confined spaces using 3D representation," *IEEE* (2024).
- [9] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, "Bigdog, the rough-terrain quadruped robot," *IFAC Proceedings Volumes* 2018, pp. 10822-10825.
- [10] J. Matthis, J. Yates, M. Hayhoe, "Gaze and the control of foot placement when walking in natural terrain" *Current Biology* 2018, pp. 1224–1233.
- [11] B. Zhou, F. Gao, L. Wang, Liu C., S. Shen, "EGO-Planner: An ESDF-free Gradient-based Local Planner for Quadrotors," *IEEE Robotics and Automation Letters* 2020.
- [12] S. Karaman, E. Frazzoli, "Sampling-based Algorithms for Optimal Motion Planning," *The International Journal of Robotics Research* 2021.
- [13] D. Fox, W. Burgard, S. Thrun, "The dynamic window approach to collision avoidance," *IEEE Robotics and Automation Magazine* 1997, vol.4, no.1, pp. 23-33.
- [14] C. Rösmann, W. Feiten, T. Wösch, et al, "Trajectory modification considering dynamic constraints of autonomous robots" *7th German Conference on Robotics* 2012, pp.1-6.
- [15] W. Qian, Z. Xia, J. Xiong, et al, "Manipulation task simulation using ROS and Gazebo," *IEEE International Conference on Robotics and Biomimetics* 2014, pp. 2594-2598.



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