2022 IEEE International Conference on
Autonomous Robot Systems and Competitions (ICARSC)
Santa Maria da Feira, Portugal – April 29-30, 2022

2022 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC) | 978-1-6654-8217-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICARSC55462.2022.9784796

A survey on localization, mapping, and trajectory planning for quadruped robots in vineyards

Jorge Ferreira*‡, A. Paulo Moreira*‡, Manuel Silva†‡, Filipe Santos‡
*Faculty of Engineering, University of Porto, Portugal
†School of Engineering, Polytechnic Institute of Porto, Portugal
‡INESC TEC - INESC Technology and Science, Portugal
up201705604@edu.fe.up.pt,{antonio.p.moreira,manuel.s.silva,filipe.n.santos}@inesctec.pt

***Abstract*—In recent years, there has been great interest from researchers in legged robots. These robots have unique characteristics and are suitable for complex working environments with uneven terrains and unexpected obstacles. They can work on almost any type of terrain, overcome obstacles like stairs much more efficiently than wheeled or tracked robots, and cause a lower impact on the ground when compared with other locomotion systems.**

To expand the application of robotics to new complex areas, it is essential to accurately locate the robot and plan safe trajectories regardless of the environment, terrain, or weather conditions. Using a legged locomotion system raises some concerns regarding the 3D localization, mapping, and trajectory planning algorithms. This paper reviews those problems and describes the current approaches to localize a robot, map an environment and plan safe trajectories for quadruped robots.

***Index Terms*—localization, mapping, SLAM, trajectory planning, quadruped robots, legged robots**

I. INTRODUCTION

Recent advances in science and technology have allowed the development of increasingly intelligent robotic systems with a more diverse range of applications.

In the last three decades, the interest in mobile robots has grown exponentially, mainly because they can operate autonomously in complex environments and can replace or assist humans in various fields. Some applications of these robots are surveillance, rescue operations, loads transportation, or even the vacuuming or lawn mowing robots we may have at home.

Regarding the locomotion system of ground mobile robots, it can be classified into three main categories: wheeled robot, legged robot, or tracked robot. Wheeled robots are the most common, mainly because they are cheaper, simpler, and faster. However, they are not suitable for environments where they have to navigate over obstacles. Legged robots can walk, just like a person or an animal, and therefore overcome obstacles much more efficiently. They can also climb stairs or steps and work on almost any type of terrain, inducing a much lower impact on the ground when compared with the other locomotion systems. Finally, tracked robots handle uneven terrains easier than wheeled robots and are more stable than legged robots. On the other hand, they extremely impact the ground. To sum up, choosing the best design depends significantly on the workplace and the robot's tasks [1].

Recently, legged robots, especially those with four legs, have attracted much attention from researchers. More than 80% of the scientific publications related to legged or quadruped robots in INSPEC were made in the last two decades. It is a clear indicator of the researchers' interest in studying a different locomotion system that can revolutionize some areas where robotics is not yet well established, such as agriculture and forestry. Regarding these two activities, and in opposition to what happens in the industry, there are still few robotic solutions developed [2]. As such, new developments are expected soon. Also, farmers consider that the automation of these sectors is vital for them to remain competitive and for agriculture to be a viable activity.

Considering that much of the agricultural or forestry ground is challenging to access and has a very unstructured terrain, quadruped robots may be the solution to overcome these problems. They can assist people in tasks such as environmental monitoring of products, trees, and plants, harvesting, spraying, among others [2]. The development of these sectors is currently highly dependent on the evolution of robotics. There are almost no robotic solutions operating reliably in these conditions since the complexity, instability, and irregularity make it very difficult for robots with wheels to operate. In addition, environments with stairs, such as in industry, are currently a problem for wheeled or tracked robots, and robots with legs can easily overcome these obstacles. Moreover, legged robots do not compact the ground or damage plants as easily as wheels or tracks do. In this context, quadruped robots can help expand the application of robotics to other areas that have been little explored so far. Thus, it is essential to accurately locate the robot and plan safe trajectories regardless of the environment, terrain, or weather conditions.

The remainder of this paper is structured as follows: Section II presents a review on quadruped robots, followed by the current challenges for quadruped robots in Section III. Section IV details work related to 6-DoF localization and mapping algorithms, and Section V describes current approaches to

This work is financed by National Funds through the Portuguese funding agency, FCT - Fundação para a Ciência e a Tecnologia, within project UIDB/50014/2020.

978-1-6654-8217-2/22/$31.00 ©2022 IEEE

solve the trajectory planning problem in legged robots. Finally, conclusions are outlined in Section VI.

II. QUADRUPED ROBOTS HISTORY

Quadruped robots have unique characteristics. Having four legs instead of wheels or tracks allows them to overcome obstacles that other locomotion systems cannot, such as stairs. Also, their excellent maneuverability enables them to deal with unexpected obstacles easily. Finally, the ability to operate on any terrain, be it soft or uneven, flat or sloping, and with a reasonable payload capacity, makes this locomotion system ideal to operate in unstructured or unknown environments.

From the beginning, quadruped robots have always been the subject of great interest by researchers. Marc Raibert from MIT and Shimoyama from Tokyo University conducted what is seen as the first systematic research on a quadruped robot [6]. Since the 1980s, the Hirose Fukushima Robotics Lab has developed several legged robots. Most of them have electric actuators, and the most known robots are from the TITAN series. In parallel, several other quadruped robots have been developed: Collie-1 and Collie-2 by the University of Tokyo, Scout I and Scout II by McGill University, WARP1 by the Royal Institute of Technology, among others [6]. These robots were mainly used by universities and research institutes to study new mechanisms like walking, balance, obstacle avoidance, among others, and to improve the reliability and ruggedness of the robots.

Recently, after the 2000s and driven by the Defense Advanced Research Projects Agency (DARPA) large-scale research programs, quadruped robots experienced a considerable evolution that made them viable for real-world applications. Boston Dynamics started by building BigDog [7] (Fig. 1a), the first quadruped robot to be tested in a real-world application. It is a military robot whose purpose is to transport soldiers' gear across uneven terrains. Its hydraulic actuators allow the robot to have a greater payload and endurance capacity. It runs on fuel, meaning that the robot can operate almost continuously, only needing to refuel approximately every 19 km. This robot has a perception system consisting of a stereo camera and a Light Detection And Ranging (LiDAR) sensor, mapping the terrain and perceiving the obstacles. Testing on the field, the robot reached the destination position in 23 out of 26 rounds, navigating for over 130 m in a single round without any human intervention or failure. Later, the same company improved this robot and named it AlphaDog (or LS3) [8]. It has the same military purposes as the BigDog but has a higher payload and range capacity [6].

Other robots have achieved similar performance, such as the HyQ and its successors [1], MIT's Cheetah robots [1], and the StarlETH robot, which was developed by ETH and is driven by a series of elastic actuators [9]. These robots have been demonstrated to adapt to uneven terrains and dynamically overcome obstacles. However, none of these systems have been used in real-life.

Currently, there are three quadruped robots capable of being employed in real-world operations: Aliengo [4], from Unitree Robotics (Fig. 1b), ANYmal [10] from ANYbotics (Fig. 1c), and Spot [1], from Boston Dynamics (Fig. 1d). These robots are similar and their purposes are to perform tasks such as inspection and data collection. The three robots work well in dynamic environments and can operate in different environmental conditions such as in the sun, rain, and snow. Overall they have a relatively small payload capacity, so the choice of the components to install should be very judicious. The Aliengo stands out with 4.5 hours of continuous operation. However, the other two robots also have reasonable battery autonomy for their current tasks.

In terms of proprioceptive and exteroceptive systems, they are also very similar. Force sensors and an IMU are usually employed to obtain estimates of the body velocity, the ground plane orientation, and the world-frame pose of the robot. Additionally, some other sensors can provide information about the robot's status, e.g., power and temperature. Optionally, some exteroceptive sensors can also be added. The most common ones are the LiDAR scanners, stereo cameras, and GPS receivers.

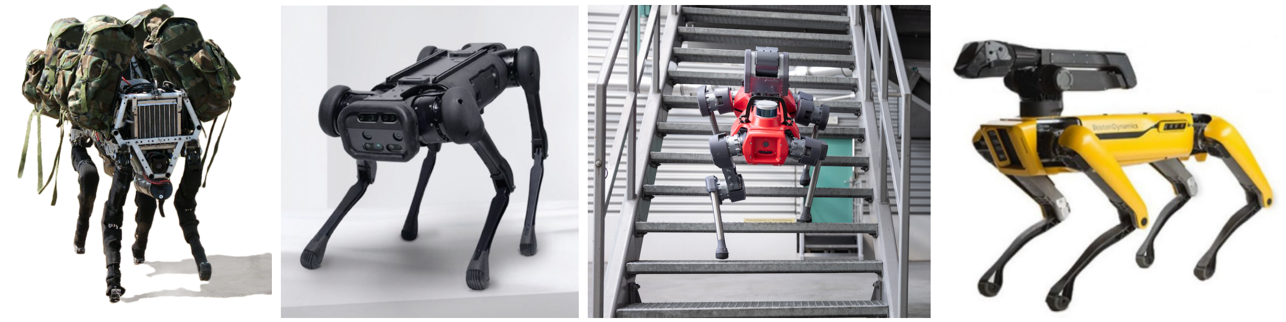
Very recently, Xiaomi released 1000 units of its first quadruped robot, CyberDog [11] to encourage developers worldwide to join forces and contribute creatively. Although they indicate that it can be used in real-world situations, there are still no records that prove its capability.

The remarkable evolution of these systems, especially during the last two decades, can be seen in Table I, which summarizes the quadruped robots described. Most robots have been developed with research in mind, which has allowed these systems' capabilities to improve. Today, we already have several models capable of operating autonomously in complex situations. However, some challenges still need to be solved to make these robots even better.

III. CURRENT CHALLENGES ON QUADRUPED ROBOTS

The use of quadruped robots brings a lot of new challenges. The simple fact of not having wheels implies finding an alternative to wheels odometry to estimate the robot's motion. Furthermore, due to the nature of its locomotion, this kind of robot presents much more oscillations than a robot with wheels, which may significantly affect the measurements of the Inertial Measurement Units (IMUs) and consequently the results obtained with the localization algorithm. Besides that, quadruped robots have a low energy capacity, so it is essential to carefully select the payload to be installed and the algorithms to be used in order to maximize the operation time.

The localization of these robots in unknown irregular environments remains a pending problem. There are still no algorithms that can accurately locate a robot in large wild unknown terrains. The approaches usually used are based on Simultaneous Localization and Mapping (SLAM) [2], [6]. However, much research is nowadays focused on 3D SLAM in outdoor environments, so new developments are expected soon.



(a) BigDog [3], from Boston Dynamics (b) Aliengo [4], from Unitree Robotics (c) ANYmal [5], from ANYbotics (d) Spot [1], from Boston Dynamics

Fig. 1: Some quadruped robots developed. BigDog was the first one to be released and tested in reality. The others are currently the most prepared quadruped robots for real-world applications.

TABLE I: Summary of some quadruped robots developed in the last years

Robot	**Year**	**Maximum speed (m/s)**	**Estimated autonomy (h)**	**Payload (kg)**	**Actuators**	**Purpose**
BigDog [7]	2004	1.8	2.9	50	Hydraulic	Assist soldiers in carrying heavy gear over rough terrain.
StarlETH [9]	2010	1	2	25	Eletric	Study actuation, design and locomotion control principles in laboratory experiments.
LittleDog [12]	2010	0.25	0.5	-	Eletric	Educational robot used for research on legged-locomotion.
LS3 [6]	2010	-	4.9	181	Hydraulic	Assist soldiers in carrying heavy gear over rough terrain.
HyQ [1]	2011	2	-	10	Hydraulic, Eletric	Study highly dynamic motions and navigation over rough terrain.
TITAN XIII [13]	2016	1.38	0.33	5	Eletric	Improve the performance and energy efficiency of a sprawling-type robot.
MIT Cheetah 3 [1]	2018	6	-	20	Eletric	Research on dynamic locomotion control strategies.
ANYmal [10]	2019	1	2	15	Eletric	Autonomous operation in challenging environments.
Aliengo [4]	2019	1.5	4.5	12	Eletric	Research, education, inspection, rescue operations, etc.
Spot [1]	2019	1.6	1.5	14	Eletric	Automate routine inspection tasks and data capture safely, accuratey, and frequently.
CyberDog [11]	2021	3.2	-	3	Eletric	Encourage the collaboration of worldwide experts to develop Xiaomi's first quadruped robot.

IV. LOCALIZATION AND MAPPING

Nowadays, there are a lot of localization and mapping algorithms. However, most of them are only suitable for flat and hard terrains, as they only consider it a 2D problem [2]. This paper focuses on 3D methods to extract the 6-DoF pose of the robot, allowing a much more comprehensive knowledge of the current state of the robot and its surrounding environment, which is particularly useful in complex or uneven terrains. Regarding these methods, the most common way to localize and map an environment is to do both tasks simultaneously, as is done in SLAM.

The first major contribution to 3D SLAM was done by Zhang and Singh in 2014 when they proposed a LiDAR Odometry And Mapping algorithm (LOAM) [14], which applies scan-matching techniques to estimate the odometry, and performs point cloud registration to add the current scan's

TABLE II: Summary of 3D SLAM methods

Name	**Sensors used**	**Localization Approach**	**Mapping Approach**
LOAM (2014) [14]	LiDAR	Estimate the odometry performing scan-to-scan alignment	Point cloud registration
ORB-SLAM (2015) [15]	Monocular, Stereo or RGB-D cameras	Uses the ORB feature extractor to get keypoints from the scene and tracks them between consecutive frames to estimate the location of the robot	Track keypoints between consecutive frames and add the valid ones to the map
LeGO-LOAM (2018) [16]	LiDAR	Segments the point cloud to filter out the noise and performs point-to-edge and point-to-plane scan-matching to get the 6-DoF transformation between two consecutive scans	Point cloud registration
VINS-Mono (2018) [17]	Camera, IMU	Fuses preintegrated IMU measurements and feature observations to estimate the relative motion between consecutive observations	Track keypoints between consecutive frames and add the valid ones to the map
RTAB-Map (2019) [18]	LiDAR, RGB-D, Stereo	Graph-Based SLAM approach based on an incremental appearance-based loop closure detector. Works with lidar odometry and visual odometry	Scan-to-map registration
LIO-SAM (2020) [19]	LiDAR, IMU	Fuses IMU and LiDAR motion estimations to produce more accurate results. Performs scan-matching at a local scale rather than matching LiDAR scans to a global map, to significantly improve the real-time performance	Point cloud registration
FAST-LIO2 (2021) [20]	LiDAR, IMU	Estimate the ego-motion fusing LiDAR odometry and IMU odometry, using an efficient tightly-coupled Kalman filter	Point cloud registration
Self-supervised Learning of LiDAR Odometry for Robotic Applications (2021) [21]	LiDAR	Uses a self-supervised neural network to estimate the LiDAR odometry	Uses LOAM's mapping approach
VineSLAM (2022) [22]	Camera, LiDAR	Extracts point and semi-plane features from 3D point clouds to feed the Particle Filter localization algorithm	Point and semi-plane based registration

points to the existing map. This algorithm generates two outputs at different rates: The robot's location on the map is estimated 10 times per second, and the map is updated every second.

In 2018, Shan and Englot presented a new method, based on LOAM but lighter and optimized for ground robots, called LeGO-LOAM [16], which uses the Levenberg-Marquardt optimization technique to calculate the 6-DoF transformation between consecutive scans, using some features like planes and corners. Recently, the same authors released an updated version, LIO-SAM [19], that combines the LiDAR observations with the inertial measurements to have more robust estimates for the odometry. A similar approach is proposed in FAST-LIO2 [20], however this algorithm is much efficient and faster than LIO-SAM. In addition, it also works with any type of LiDAR. According to Hroob et al. [23], the open-source RTAB-Map implementation can be more accurate than LIO-SAM and ORB-SLAM in simulated vineyards environments. A great advantage of RTAB-Map is that it is very versatile, accepting inputs from RGB-D cameras, stereo cameras, or LiDAR sensors.

Other approaches using visual sensors have also been presented. Mur-Artal et al. [15] proposed a monocular SLAM system that operates in real-time both indoors and outdoors and uses Oriented FAST and Rotated BRIEF (ORB) to extract features from the scene. Wang et al. propose DV-LOAM [24], a framework that fuses visual sensors and a LiDAR, aiming to take advantage of the efficiency of the Visual Odometry (VO) module and the accuracy of the LiDAR scan-to-map matching method, thereby improving the performance achieved so far.

Aguiar et al. [22] developed a localization procedure for agricultural environments based on the Particle Filter that uses points and semi-plane features extracted from 3D point clouds. The field tests performed in a vineyard show that this algorithm outperforms LeGO-LOAM and is the most appropriate for operating in these environments.

Recently, Nubert et al. [21] proposed a novel approach to estimate the LiDAR odometry, combining a self-supervised learning process that estimates the 6-DoF robot pose with the mapping technique of LOAM. The presented method can operate in real-time on a mobile CPU and does not require labeled or ground-truth data for the training process. The real-world tests done with legged, tracked, and wheeled robots demonstrated the suitability of learning-based approaches to estimate the LiDAR odometry and for real application in complex environments. However, the integration of multi-modal sensory information would improve the quality of the estimation process.

Table II briefly details the above methods, describing the sensors used and the approaches applied to localization and mapping. Starting with the sensors, most algorithms use a LiDAR to obtain a set of sparse points of the surrounding environment and combine this sensor with a camera or an IMU to obtain better estimates for the odometry. Regarding the localization approaches, there is a clear tendency to use scan-matching algorithms to estimate the relative motion between two consecutive scans of the LiDAR. This result can later be fused with other relative motion estimation strategies to better estimate the ego-motion that occurred in the meantime. On the other hand, it is worth mentioning the increasing application of machine learning algorithms, which have been achieving better results than many conventional methods currently used. Finally, the mapping operation is commonly performed by registering the point cloud of the current LiDAR scan with the set of points from the map, taking into account the robot's current position, which thus restricts the set of map points to be used in this operation.

V. TRAJECTORY PLANNING

Planning physically feasible trajectories in highly uneven and cluttered environments for legged robots is a difficult task and is still an open problem [25], [26]. Some of the most promising results have come from the DARPA Learning Locomotion project, using the LittleDog robot [27], and from the DARPA Subterranean Challenge, with the ANYmal-C robot [28].

In legged systems, the trajectory planning problem is usually decoupled into three sub-problems:

1) First, perceive and model the environment, usually in occupancy grid maps;
2) Then, apply the path planning algorithm to find the best route from the start to the final point, according to the cost function;
3) Finally, plan the footholds taking into account the capabilities of the robot (kinematics and dynamics) and the terrain's shape.

Most path planning techniques focus only on two-dimensional (2D) or 2.5-dimensional (2.5D) methods to simplify the creation of efficient and safe paths for the robot. This approximation works quite well in flat terrains, but when the robot faces more challenging, unstructured, and complex environments, 3D path planning algorithms are needed. Some of the most successful 3D path planning techniques are Rapidly-exploring Random Trees (RRT), Probabilistic Road Maps (PRM), Artificial Potential Field, Mixed-Integer Programming, and some node-based algorithms like Dijkstra and A* [29].

According to Yang et al. [29], besides the great improvement that has occurred in the last years, there are still problems that need to be solved, e.g., real-time planning, and their recommendation is to combine many approaches to obtain a more robust system that can better deal with complex situations.

In the literature, there are already some interesting path planning methods: Santos et al. [30] developed an open-source Agricultural Robotic Path Planning framework (AgRobPP) that combines the A* algorithm with a multi-layer occupation grid map, an altitude map, and the robot's Center of Mass (CoM) to plan safe trajectories for wheeled ground robots in steep slope vineyards. This framework was already tested in real complex situations and has demonstrated great performance so far.

Liu et al. [31] suggested combining a path planning algorithm based on Dijkstra with an obstacle avoidance strategy that applies the Artificial Potential Field theory. The path planner finds the best route for the autonomous navigation task of a quadruped robot, and the obstacle avoidance method uses a local map to allow the robot to go around unexpected objects. Geisert et al. [25], building on a previous work done by Tonneau et al. [32] for humanoid robots, proposed an adaptation of that algorithm for the quadruped robot ANYmal. The main idea behind these works is generating a guide path for the robot and then calculating the best foothold for each leg over time, along that trajectory. These methods are based on approximations and heuristics and use the Bi-RRT algorithm [24] to plan the path from the start to the goal position, applying a reachability condition.

In the DARPA Subterranean Challenge scope, Dang et al. [33], [34] developed a novel path planning method for subterranean exploration with aerial and quadruped robots. This algorithm uses a local planner to identify paths that optimize the exploration efficiency within a local sub-space while avoiding obstacles and respecting traversability and robot physic constraints. It also has a global planning layer that incrementally builds a sparse global graph and is engaged when the system must return to a previously identified location of the space explored so far.

Regarding the legged robot's locomotion, Winkler et al. [26] developed a trajectory optimization software for walking robots that automatically determines the gait sequence, step timings, footholds, and six-dimensional body motion over non-flat terrains without any additional modules.

A machine-learning approach was proposed by Lee et al. [28] in their novel solution to incorporate proprioceptive feedback in the locomotion control. This work aims to obtain a robust controller for legged locomotion capable of generalizing for situations that it has never encountered. It extracts proprioceptive data from a simulated quadruped robot and trains a neural network by reinforcement learning, using only proprioceptive signals. Miki et al. [35] further extended the latter work by proposing an attention-based recurrent encoder that combines proprioceptive and exteroceptive information. The addition of exteroceptive information allows faster and more efficient locomotion since the robot perceives the terrain before making contact with it, adapting and planning the gait ahead of time to maintain speed and stability. However, relying solely on exteroceptive data is challenging and prone to errors, so general solutions adopt proprioceptive information. In this work, the encoder is trained end-to-end and learns to combine the different perception modalities without resorting to heuristics. The obtained results show a fast and high robust legged locomotion controller that was tested in a one-hour-long hiking loop 2.2 km long and completed the circuit in the same time recommended for human hikers.

VI. CONCLUSION

The localization/mapping and trajectory planning problems are not recent and there are already several interesting methods to solve these issues. Although they have been around for a while, quadruped robots have only started to gain more emphasis in the last two decades. Nowadays, they have robust systems capable of performing highly complex operations. Some models are already operating in real situations, mainly performing inspection tasks.

The most common technique for globally locating a robot on a map is SLAM, which simultaneously performs localization and mapping. Most SLAM algorithms use a LiDAR to create a geometric representation of the environment in the form of a point cloud. Usually, this sensor is combined with IMUs or depth cameras to obtain better estimations for odometry and, therefore, better representations of the environment.

Regarding trajectory planning, the use of 2D planners is already a well-established method with much work-related. On the other hand, for three-dimensional planning, and focusing on robots with legs, trajectory planning is much more complicated. Two aspects must be taken into account: the robot's stability and the place to put each of the legs along the path, ensuring that the robot can overcome the obstacles without falling.

REFERENCES

[1] P. Biswal and P. K. Mohanty, "Development of quadruped walking robots: A review," *Ain Shams Engineering Journal*, vol. 12, no. 2, pp. 2017–2031, 2021.

[2] A. S. Aguiar, F. N. D. Santos, J. B. Cunha, H. Sobreira, and A. J. Sousa, "Localization and mapping for robots in agriculture and forestry: A survey," *Robotics*, vol. 9, no. 4, pp. 1–23, 2020.

[3] "Boston dynamics legacy." [Online]. Available: https://www.bostondynamics.com/legacy

[4] "Aliengo." [Online]. Available: https://www.unitree.com/products/aliengo/

[5] "Meet anymal, your new inspector." [Online]. Available: https://www.anybotics.com/anymal-autonomous-legged-robot/

[6] X. Meng, S. Wang, Z. Cao, and L. Zhang, "A review of quadruped robots and environment perception," *Chinese Control Conference, CCC*, vol. 2016-Augus, pp. 6350–6356, 2016.

[7] D. Wooden, M. Malchano, K. Blankespoor, A. Howardy, A. A. Rizzi, and M. Raibert, "Autonomous navigation for BigDog," in *Proceedings - IEEE International Conference on Robotics and Automation*, 2010, pp. 4736–4741.

[8] "Ls3 pack mule." [Online]. Available: https://www.darpa.mil/about-us/timeline/legged-squad-support-system

[9] M. . Hutter, C. . Gehring, M. . Bloesch, M. A. . Hoepflinger, C. D. . Remy, and R. Siegwart, "STARLETH," 2013.

[10] M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, K. Bodie, P. Fankhauser, M. Bloesch, R. Diethelm, S. Bachmann, A. Melzer, and M. Hoepflinger, "ANYmal - A highly mobile and dynamic quadrupedal robot," *IEEE International Conference on Intelligent Robots and Systems*, vol. 2016-Novem, pp. 38–44, nov 2016.

[11] "Xiaomi cyberdog." [Online]. Available: https://www.giztop.com/xiaomi-cyberdog.html

[12] J. R. Rebula, P. D. Neuhaus, B. V. Bonnlander, M. J. Johnson, and J. E. Pratt, "A controller for the LittleDog quadruped walking on rough terrain," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 1467–1473, 2007.

[13] S. Kitano, S. Hirose, A. Horigome, and G. Endo, "TITAN-XIII: sprawling-type quadruped robot with ability of fast and energy-efficient walking," *ROBOMECH Journal*, vol. 3, no. 1, pp. 1–16, dec 2016.

[14] J. Zhang and S. Singh, "LOAM: Lidar Odometry and Mapping in Real-time."

[15] R. Mur-Artal, J. M. M. Montiel, and J. D. Tardós, "ORB-SLAM: a Versatile and Accurate Monocular SLAM System," 2015.

[16] T. Shan and B. Englot, "LeGO-LOAM: Lightweight and Ground-Optimized Lidar Odometry and Mapping on Variable Terrain," in *IEEE International Conference on Intelligent Robots and Systems*. Institute of Electrical and Electronics Engineers Inc., dec 2018, pp. 4758–4765.

[17] T. Qin, P. Li, and S. Shen, "VINS-Mono: A Robust and Versatile Monocular Visual-Inertial State Estimator," *IEEE Transactions on Robotics*, vol. 34, no. 4, pp. 1004–1020, aug 2018.

[18] M. Labbé and F. Michaud, "RTAB-Map as an open-source lidar and visual simultaneous localization and mapping library for large-scale and long-term online operation," *Journal of Field Robotics*, vol. 36, no. 2, pp. 416–446, mar 2019.

[19] T. Shan, B. Englot, D. Meyers, W. Wang, C. Ratti, and D. Rus, "LIO-SAM: Tightly-coupled Lidar Inertial Odometry via Smoothing and Mapping," *IEEE International Conference on Intelligent Robots and Systems*, pp. 5135–5142, jul 2020.

[20] W. Xu, Y. Cai, D. He, J. Lin, and F. Zhang, "FAST-LIO2: Fast Direct LiDAR-inertial Odometry," *IEEE Transactions on Robotics*, jul 2021.

[21] J. Nubert, S. Khattak, and M. Hutter, "Self-supervised Learning of LiDAR Odometry for Robotic Applications." [Online]. Available: https://github.com/leggedrobotics/DeLORA

[22] A. S. Aguiar, F. Neves dos Santos, H. Sobreira, J. Boaventura-Cunha, and A. J. Sousa, "Localization and Mapping on Agriculture Based on Point-Feature Extraction and Semiplanes Segmentation From 3D LiDAR Data," *Frontiers in Robotics and AI*, vol. 0, p. 12, jan 2022.

[23] I. Hroob, R. Polvara, S. Molina, G. Cielniak, and M. Hanheide, "Benchmark of visual and 3D lidar SLAM systems in simulation environment for vineyards," *Lecture Notes in Computer Science*, vol. 13054 LNAI, pp. 168–177, jul 2021.

[24] W. Wang, J. Liu, C. Wang, B. Luo, and C. Zhang, "DV-LOAM: Direct Visual LiDAR Odometry and Mapping," *Remote Sensing 2021, Vol. 13, Page 3340*, vol. 13, no. 16, p. 3340, aug 2021.

[25] M. Geisert, T. Yates, A. Orgen, P. Fernbach, and I. Havoutis, "Acyclic Reachability-Based Planner," 2019. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02097212v3

[26] A. W. Winkler, C. D. Bellicoso, M. Hutter, and J. Buchli, "Gait and Trajectory Optimization for Legged Systems Through Phase-Based End-Effector Parameterization," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 1560–1567, jul 2018.

[27] M. Kalakrishnan, J. Buchli, P. Pastor, M. Mistry, and S. Schaal, "Learning, planning, and control for quadruped locomotion over challenging terrain," *International Journal of Robotics Research*, vol. 30, no. 2, pp. 236–258, 2011.

[28] J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter, "Learning quadrupedal locomotion over challenging terrain," *Science Robotics*, vol. 5, no. 47, p. 5986, 2020.

[29] L. Yang, J. Qi, D. Song, J. Xiao, J. Han, and Y. Xia, "Survey of Robot 3D Path Planning Algorithms," 2016.

[30] L. Santos, F. Santos, J. Mendes, P. Costa, J. Lima, R. Reis, and P. Shinde, "Path Planning Aware of Robot's Center of Mass for Steep Slope Vineyards," *Robotica*, vol. 38, no. 4, pp. 684–698, 2020.

[31] Y. Liu, L. Jiang, F. Zou, B. Xing, Z. Wang, and B. Su, "Research on path planning of quadruped robot based on globally mapping localization," *Proceedings of 2020 3rd International Conference on Unmanned Systems, ICUS 2020*, pp. 346–351, nov 2020.

[32] S. Tonneau, A. Del Prete, J. Pettré, C. Park, D. Manocha, N. Mansard, and A. D. Prete, "An efficient acyclic contact planner for multiped robots," *IEEE Transactions on Robotics*, vol. 34, no. 3, 2018. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01267345v3

[33] T. Dang, M. Tranzatto, S. Khattak, F. Mascarich, K. Alexis, and M. Hutter, "Graph-based subterranean exploration path planning using aerial and legged robots," *Journal of Field Robotics*, vol. 37, no. 8, pp. 1363–1388, dec 2020.

[34] M. Kulkarni, M. Dharmadhikari, M. Tranzatto, S. Zimmermann, V. Reijgwart, P. De Petris, H. Nguyen, N. Khedekar, C. Papachristos, L. Ott, R. Siegwart, M. Hutter, and K. Alexis, "Autonomous Teamed Exploration of Subterranean Environments using Legged and Aerial Robots," nov 2021.

[35] T. Miki, J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter, "Learning robust perceptive locomotion for quadrupedal robots in the wild," *Science Robotics*, vol. 7, no. 62, jan 2022.