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A Review of Quadruped Robots and Environment Perception

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Abstract: As legged robots are suitable to be used in unstructured environments, it becomes a popular field of research nowadays. In this paper, the development of quadruped robots is summarized. And several typical and recent robot systems are addressed in details, such as HyQ series, StarlETH, ANYmal, MIT Cheetah and BigDog, etc. Furthermore, some key techniques of environment perception for quadruped robots, including sensors, feature extraction and identification, mapping and SLAM, are also discussed. Finally, future researches of quadruped robots in environment perception are given.

Keywords: Quadruped robot, environment perception, sensors, feature extraction, mapping and SLAM

1 Introduction

Mobile robots attract lots of attention at present. They can be classified into three categories according to devices they use to move [1]: legged robots, wheeled robots, and tracked robots. The main feature of legged robots is that the legs are able to step on rough terrains and keep the balance. Legged robots have the potential to work in unstructured, severe and dangerous environments [2]. However, they have the disadvantage of low efficiency of energy utilization. Therefore, the concrete selection of robotic type depends on the tasks and environmental constraints. Nowadays, the quadruped robots are widely studied [3]. In general, the quadruped robot can be classified into three kinds of robots according to actuation: hydraulic actuator, pneumatic actuator, and electrical actuator. The control precision of electric actuators is high but they cannot afford heavy load. Pneumatic actuators are difficult to control because of their nonlinear characteristics [4]. And hydraulic actuators are used widely because they have strong power. But the vibration is a little bigger. It is necessary to summarize the researches of quadruped robots and their environment perception progress, which is the main task of this paper.

This paper is organized as follows. First, recent development of quadruped robots and typical systems will be listed in Section II. Second, the environment perception of quadruped robots with key techniques will be discussed in Section III. Section IV summarizes this review and future work of quadruped robots is also given.

2 Progress in Quadruped Robots

2.1 Recent Research of Quadruped Robots

People have studied the walk patterns of animals many years, and so does the development for quadruped robots [5-7]. Marc Raibert from MIT and Shimoyama from Tokyo University conducted a kinematics research on quadruped robots in 1980s, which is viewed as the first systematic research of mammal quadruped robot [8]. Since 1976, the Hirose Fukushima Robotics Lab has focused on legged robots especially quadruped robots for about 40 years. The typical quadruped robots of this lab are the TITAN series [9], and most of them are electrically actuated. The most popular one of them may be TITAN VIII [10], which was used by many universities and research institutes in Japan. The newest quadruped robot of TITAN is TITAN XII [11], which is able to climb up large obstacles and its maximum speed is 1.5 m/s. And TITAN XII is controlled by external PC and microcontroller inside. Besides, some of the TITAN robots can work on steep slopes, such as TITAN VII [12] and TITAN XI [13, 14], and humanitarian mine detection and removal robot, such as TITAN IX [15, 16]. The research of quadruped robot became various after the late 1980s, such as Collie-1/Collie-2 designed by Tokyo University [17, 18], Scout I/Scout II constructed by McGill University [19, 20], BISAM proposed by Karlsruhe Institute of Technology [21], JROB-1/JROB-2 designed by Tohoku University [22, 23], WARP1 constructed by Royal Institute of Technology [24].

The performance of quadruped robot became better after 2000. Tekken IV is constructed by Kimura *et al.* [25, 26], which uses CPG (Central Pattern Generator) to control motion of legs and it fulfills several kinds of gaits. Spanish Council for Scientific Research developed SILO4 in 2003 [27], which is made for basic research and application of quadruped robot. It is electrical actuated and can walk in a simple terrain outside. Ohio State University and Stanford University cooperated to construct an artificial quadruped, named as OSU-Stanford Quadruped (OSQ) [28], which has a top speed of a single leg at about 4.15 m/s. And it was developed further by Stanford in 2007, named as KOLT [29, 30], which mainly focused on the legged locomotion in a gallop gait. Sungkyunkwan University developed MRWALLSPECT III [31], which is able to climb over slopes with concave corner, and tumbling of the robot and slipping of the legs can be avoided. And after then they constructed AiDIN I (Artificial Digitigrade for Natural Environment I) quadruped robot in 2007 and AiDIN III quadruped robot in 2013 [32, 33]. The speed of AiDIN III is 0.35 m/s and it can climb up a slope of 20° in a trot gait, and it is expected to able to carry maximum mass of 3 kg. Korea Institute of Industrial Technology proposed qRT-1/qRT-2 [4], which is a mobile robot with two legs

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and two wheels. The qRT-1 can trot at a speed up to 1.3 m/s on the even surface and 0.7 m/s on the uneven surface. Besides, it is able to climb up and down a 20° incline and carry over 40 kg of payload. And a quadruped walking robot p2 [34] for energy minimization research is also developed. University of São Paulo presented a quadruped robot for tree climbing, called Kamanbaré [35], which is used for environment monitoring. Paulo Kyoto Institute of Technology proposed a quadruped robot "Kotetsu" [36, 37]. Based on leg loading and unloading information, rhythmic motion of each leg is achieved and dynamic walking in the low to medium speed range is realized. Vanderbilt University introduced a pneumatically actuated quadruped robot, named as VU quadruped [38]. It can carry 9.1 kg of payload, which is 130% of weight itself. Toyota Technological Institute reported their quadruped robot RoboCat-1 [39], which verifies the locomotion control algorithm and fulfills real-time trot-running cycles.

Harbin Institute of Technology constructed an external hydraulic actuated quadruped robot called MBBOT [40]. Mounted with force sensors and Inertial Measurement Units (IMU), it is able to run on the treadmill at 0.83 m/s. Shanghai Jiao Tong University developed a quadruped robot named as "Baby Elephant" in 2013 [41]. The maximum speed is 1.8 km/h, and it can walk on different kinds of terrains with a maximum load up to 100 kg. Beijing Institute of Technology designed a bionic quadruped robot in 2013 [42]. Marking time, squat, walking and trotting experiments are conducted, and the maximum speed of trotting is 3km/h. National University of Defense Technology proposed a kind of position/force control method and an operation space model, which helps their quadruped robot to adapt to the environment [43]. Scalf-1 is proposed by The Robotics Center of Shandong University in 2010 [44]. Its size is about 1100×490×1000 mm, weighs 123 kg. This quadruped robot can step onto slopes over 10°, and step across obstacles about 150 mm high. Trotting and scrawling is tested by the research group, and the highest speed of the robot is 5km/h. Experiments of running in complex terrains, step up and down the slopes, resistant of lateral impact and burden are conducted. And in 2012, Scalf-2 is constructed by the research group [45], and they improve the hydraulic power system and biomimetic structure, and a servo controller with 12-channels is designed and fulfilled. Besides, IMU and force sensors are occupied. China north vehicle research institute also introduced a quadruped robot [46] in 2014 China International Emergency Rescue Expo. It can afford a burden of 50 kg and weighs 130 kg itself. The robot can walk on different kinds of terrains and the maximum speed is 6km/h.

2.2 HyQ, HyQ2Max and HyQ2Centaur

HyQ (the abbreviation for Hydraulic Quadruped) [47, 48] is designed by Claudio Semini *et al.* from Italian Institute of Technology in 2010, as shown in Fig.1. The robot has 12 torque-controlled joints powered by a combination of hydraulic and electric actuators. This platform is designed to study not only highly dynamic motions such as running, hopping and jumping [49], but also navigation over rough terrain [50, 51]. On-board sensors contain position, force, pressure and IMU, whose data are processed by PC104 with real-time Linux. The robot utilizes CPG-inspired trajectory generator for the feet, which can be modulated according to terrain irregularities and the posture of the robot trunk. They also implemented a trunk motion control method for stability based on the null space of the Jacobian containing related velocities. In 2015, they developed HyQ2Max and HyQ2Centaur [52] for robustness, self-righting and manipulation research. HyQ2Max is an improved version of HyQ with a stereo camera on pan-tilt unit, and this robot is 1.2 m long and 0.9 m high. HyQ2Centaur is the combination of HyQ2Max and a pair of hydraulic manipulator arms. The range of the arm's six hydraulic joints are between 90°-210° and maximum joint torques are between 60 Nm-126 Nm.

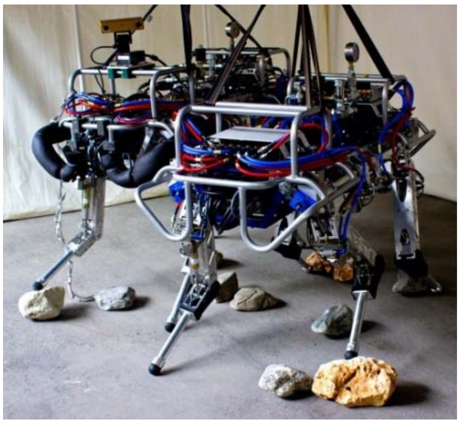

Fig. 1: HyQ v1.3 with several rocks [53]

2.3 StarlETH and ANYmal

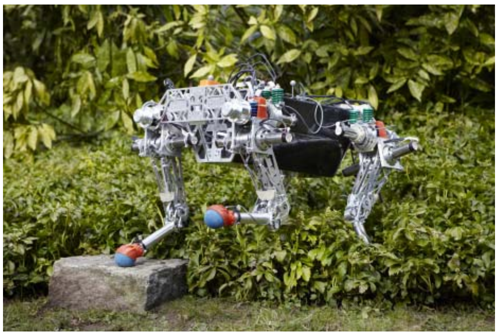

Fig.2: StarlETH in a park [54]

Fig.3: ANYmal in a complex environment [55]

StarlETH was developed by Swiss Federal Institute of Technology Zurich in 2010, which is motivated by electrical power, as shown in Fig. 2 [56-58]. StarlETH can trot at a maximum speed of 0.7 m/s, and is able to stand up with an additional payload of 25 kg. StarlETH can cope with some impacts from the environment, for example, it won't be harmed after dropped from a height of full leg length. This robot can traverse the environments with obstacles and climb up and down stairs. They also formulate a robot-centric elevation mapping method, which allows for mapping a terrain with uncertainty estimates at 20Hz [59]. The research group has begun to develop a new quadruped robot named ANYmal since 2015 [55], which is designed for autonomous operation in challenge environments, as shown in Fig.3. ANYmal can perceive the environment information around it for map creating and localization using laser sensors and cameras. Thus, this mobile robot can select proper footholds while walking and plan its navigation path autonomously. Other sensory equipment includes active lighting, thermal cameras, gas-detection, and microphones, with which the robot weighs less than 30 kg

2.4 MIT Cheetah 1 and 2

Massachusetts Institute of Technology (MIT) introduced a quadruped robot called MIT Cheetah [60] in 2013. This quadruped robot is able to run at 2.3 m/s and the cost of transport (COT) is 0.51. Later the ability of energy efficient of the robot is improved [61], and four design principles are discussed for high utilization efficiency. In 2015, they constructed MIT Cheetah 2 [62], which is also an untethered quadruped robot, as shown in Fig. 4. It is able to run on grassy fields with speed ranging from 0 to 4.5 m/s using bounding gait. An impulse planning algorithm that allows variable-speed running is fulfilled. What's more, MIT Cheetah 1 and 2 are both electric actuation systems for the study of high speed quadrupedal locomotion.

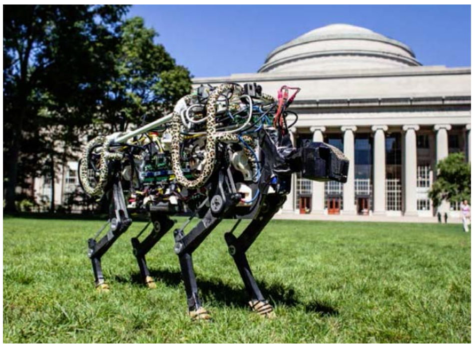

Fig. 4: MIT Cheetah 2 [62]

2.5 BigDog 1st and 2nd, LittleDog, LS3, CHEETAH and Wildcat

Boston Dynamics Corporation constructed BigDog 1st generation in 2005 [63]. This quadruped robot takes PC104 with QNX as its brain and can be controlled through WLAN. A stereo vision system is integrated with the robot, which resolution is about 320×240 and frame rate is 29 fps during slope detection and large obstacle prediction. The frame rate of visual odometry and ground plane estimation is about 14 fps. It can step onto 35° inclines, trot at 0.8 m/s and move with a 50 kg load. In 2008, the 2nd generation of BigDog was introduced, which had a better performance [64]. The sensing system including stereo vision and LiDAR is integrated with the robot, which is used for 3D terrain reconstruction. These sensors are utilized to find accessible path and to follow the navigator. The success rate of following the navigator test is about 23/26, and its longest distance that the robot can follow without operator involvement is 130 m. It can trot at 1.6 m/s, crawl at 0.2 m/s and its highest speed is 3.1 m/s. The gaits can be converted to each other freely when traversing in the wild. The robot can climb over the obstacles of piled up square bricks with a burden of 50 kg, as shown in Fig.5. The maximum burden it can carry is 154 kg, and it can walk across muddy field or field covered with snow.

Fig. 5: BigDog 2nd climbing a simulated rubble pile using a crawl gait [64]

Fig.6: Legged Squad Support System [65]

The robot was further improved in 2009, named as LS3 (Legged Squad Support System, also called AlphaDog) [66], as shown in Fig.6. This robot can follow the navigator to the target place using stereo vision for terrain detection and GPS for localization. It is able to carry up to 181 kg of gear, and finish a mission of 32km lasting for 24h. In 2015, a marker tracking system using infrared cameras, retro-reflective markers and LiDAR was proposed [67], which is able to detect and track a leader through unconstrained and cluttered off-road environments under a wide variety of illumination and motion conditions. And a quantitative evaluation shows that the correct tracking rate is about 98.8% of the total 67 hours manually-labeled dataset.

The research group also introduced a quadruped robot called LittleDog [68] for learning rough terrain locomotion, which is used by many universities and robot labs. The fastest quadruped robot in the world is constructed by Boston Dynamics in 2011, named as CHEETAH [69], which can start, turn and stop immediately. Its highest speed is over 45km/h, but this tethered robot has to run on treadmills. In 2013, the company improved CHEETAH and a new robot called WildCat was introduced [70], which is fastest untethered quadruped robot.

3 Key Techniques of Environment Perception for Quadruped Robots

Environment perception is the basic and critical technology for mobile robots. Localization and navigation by themselves cannot be achieved without environment perception [71]. Meanwhile, with the development of sensor technology and the application of multi-sensor data fusion technology [72], the ability of environment perception is improved. Besides, the SLAM (Simultaneous Localization And Mapping) method is viewed as the key technology for autonomous traversing in unknown environments. In this section, the details of environment perception are discussed.

3.1 Sensors

Sensors are basic and crucial for environment perception. For example, high-speed cameras with embedded processing units will accelerate the process of information acquiring; 3D multilayer LiDAR based on distance measurement theory will obtain enough data for fast obstacles detection. Environment information acquiring by sensors is the technology which helps robots to obtain information about their own states and environment information around them. These sensors can be called proprioceptive sensors and exteroceptive sensors, respectively [73]. For instance, the BigDog has about 50 sensors to perceive its own states and external environment information [74]. The sensors related to exteroceptive sensors can be divided into visual sensors and non-visual sensors [75]. The information that vision sensors can acquire are so various that this kind of sensors are irreplaceable for environment information acquiring in some cases. But the vision sensors are vulnerable to be affected by illumination and shadow. Non-visual sensors, such as laser sensors, ultrasonic sensors and infrared sensors, are based on distance measurement theory, and their measurement precision is higher than visual sensors. But the information from these sensors is limited to distance and intensity and they are vulnerable to be affected by mirror reflection or diffuse reflection. Other sensors, such as forces, tactile sensors, also take important roles in robot environment perception.

3.2 Features extraction and identification

Features extraction is the critical process among the whole pipeline of environment process. Good features can always be easily detected and they are often well mathematically described. While data acquired from sensors are important, a good feature has a great influence on the effect of robot's environment understanding, which is critical procedure of the environment perception.

Fitting, classification and clustering methods are suitable for distance information processing, and especially the data obtained are discrete point cloud. For example, Hough [76], RANSAC [77], EM [78] algorithms are suitable for fitting, while some researchers uses SVM [79], SVDD [80] for terrain classification. Features extracted from videos and images contain color, shape, texture, and so on, which are used for image understanding. For image feature extraction, there are two common kinds of detectors: corner detectors and blob detectors. And typical detectors are FAST [81], SURF [82] detectors, etc. With the development of RGB-D cameras, the pictures with depth information show their superiority when analyzing environment information [83]. And the using of low-cost 3D multilayer LiDAR nowadays also leads to more and more researches related to mobile robot [84].

Still, feature extraction is not an indispensable procedure for every activity. For instance, the robot can use raw data directly from the sensors in order to save time in an emergency. It becomes obvious that feature extraction is an essential procedure for sophisticated and long-term perceptual tasks [73].

3.3 Mapping and SLAM

Maps describing environments can take many forms. Common mapping methods consist of grid map [85], geometrical map [86], topological map [87] and hybrid map, etc. For grid map, the space is classified into grid units of a certain scale, and the probability of whether each unit is occupied by obstacles is estimated. It is easy for calculation but the contradiction between resolution ratio and storage space is also outstanding. For geometrical map, the environment is expressed by points, lines, polygons and circles, etc. So this kind of map is suitable for reading but it is not suitable for analysis through parameterized methods. And for topological map, the environment is expressed by key points and their connection relationships. This kind of map is suitable for large but simple environments. The storage of topological map is smallest among these three maps. However, recognition of key points and localization of the robot are not easy to fulfill using this kind of map.

Based on the ideas of maps discussed above, hybrid maps may be a good choice for quadruped robots in the unstructured environments. The hybrid maps combine the advantages of two or three map models, but the management of environment information is complex. Researchers also come up with some new mapping methods nowadays. Armin *et al.* constructed a mapping method called OctoMap [88] which is based on octrees and uses probabilistic occupied space. Sheraz *et al.* [89] proposed RMAP that using axis aligned rectangular cuboids to provide efficient environment representations for 3D mapping.

In unknown wild environment, localization is an outstanding problem except for mapping. To solve this problem, researchers utilize SLAM algorithms. The robot can determine its own location when it generates maps at the same time. SLAM methods include EKF SLAM [90], FastSLAM [91], UKF SLAM [92], Graph SLAM [93], MonoSLAM [94], CoSLAM [95], etc. There are more and more SLAM researches which are focused on 3D or outdoor environments nowadays [96-98]. However, it seems that almost all the SLAM algorithms cannot generate consistent maps for large areas. Reasons are as follows. Although feature identification, recognition and planning are critically important sub-problems of SLAM, SLAM is often most closely related to data filtering problem [75]. That means updating estimates and an associated uncertainty model, and the model is associated with a covariance matrix relating error in the elements of the state. And the computational complexities increase as the map becomes larger.

4 Conclusion and Future Researches

This paper summarizes recent development of quadruped robots and several typical robot systems, such as HyQ series, StarlETH, ANYmal, MIT Cheetah and BigDog, etc. The critical technologies of quadruped robots is new biomimetic structure, high power density of actuator, real-time control methods and integrated environment perception. Each of them is important for developing high performance quadruped robot. Especially, the key techniques of environment perception in mobile robots are discussed, including sensors, feature extraction and identification, mapping and SLAM. In the following, the future work of integrated environment perception is listed below.

4.1 Multi-sensor Data Fusion

Sensors used by quadruped robots are so various that how to organize and utilize this information is a problem to be solved. Coordination and distribution of different sensors, real-time information processing and optimization of fusion algorithms including decreasing fusion error rate and uncertainty are the main aspects.. If they are solved, the ability of environment perception will be greatly improved. Kalman Filters, Markov chain, and Monte Carlo method are common techniques used nowadays. However, they cannot fully solve this problem.

4.2 Intelligent techniques

The simple environment perception nowadays is not enough for quadruped robots. The future work should be focused upon helping the robot to recognize, memorize and learn the environments. Recognizing where the robot has already been will increase the efficiency of environment perception. Recognizing also means that the robot has the ability of memorizing the necessary information of the environment. Finally, with the development of intelligence algorithms and deep learning, the quadruped robots will adapt themselves to the environment by training in advance and learning in real time.

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