The Optimization Algorithm for Gait Planning and Foot Trajectory on the Quadruped Robot

Baoling Han(✉), Xiao Luo, Rui Zhao, Qingsheng Luo, and Guanhao Liang

Beijing Institute of Technology, NO 5 South, Zhongguancun Street, Haidian District, Beijing 100081, China
hanbl@bit.edu.cn

Abstract. The legged robot has strong structural flexibility and environmental adaptability, and can walk reliably under unstructured terrain such as mountains and hills. It has various uses and has become a research hotspot in the field of intelligent robots in recent years. In this paper, a quadruped robot is taken as the platform, and the gait planning of quadruped robot and the optimization method of its foot trajectory are studied: 1. the optimization design based on gait parameters. The optimization of step sequence focusing on static gait stability of quadruped robot problem, the optimal step sequence based on the stability margin of the support polygon is studied. 2. The optimization design based on foot trajectory. The influence of quadruped robot's motion performance by changing the local geometric characteristics of foot trajectory was studied. 3. The structure design and the idea of the physical prototype of the quadruped bio-robot are expounded systematically in the paper. Using the optimized Bezier curve as the robot foot trajectory, the validity of the optimal design of the foot trajectory was reliably verified.

Keywords: Quadruped robot · Gait planning · Gait parameters
Foot trajectory

1 Introduction

Mobile robots are generally classified into wheeled, tracked, and legged forms. Wheeled and tracked robots are suitable for running on relatively flat roads. Compared to wheeled and tracked robots, legged robots can adapt to complex terrain with various kinds of obstacles. According to statistics, more than 50% of the landscape on earth is similar to the complex terrain such as mountains and hills. Therefore, research on legged robots with excellent exercise performance, high load capacity and strong environmental adaptability has important theoretical significance and is of high engineering practical value [1, 2].

Gait refers to the order and timing of each leg when the robot is in motion, and the supporting and rearward walking patterns. According to the movement characteristics, gait can be divided into static gait and dynamic gait, in which the static gait is mainly walk gait, and the dynamic gait mainly includes trot, pace, bound, gallop and so on.

L. Cocchiarella (Ed.), *ICGG 2018—Proceedings of the 18th International Conference on Geometry and Graphics*, Advances in Intelligent Systems and Computing 809, pp. 1274–1279, 2019. https://doi.org/10.1007/978-3-319-95588-9_110

The gait parameters have a great influence on the quadruped robot's movement performance and are the basis of gait planning. In this paper, gait parameters that can affect the stability of motion of a quadruped robot are selected to be optimized.

2 Static Gait Stability and Parameter Design

The stability criterion refers to the criterion that can determine the positional relationship between the center of mass of the quadruped robot body and the location of the support foot. If the quadruped robot tends to maintain stability during the movement, the projection of its body centroid needs to be ensured inside the supporting polygon formed by the location of its supporting feet.

Moving in different step sequences has a huge impact on the quadruped robot's motion stability and energy consumption [3]. For the static gait stability [4] planning problem of quadruped robots, the optimal step sequence based on the stability criteria of supporting polygons is studied. Based on the theory of supporting triangles, the exhaustive method is used to enumerate and compare all possible step sequences. The quadruped robot's movement performance under different step sequences is compared in aspects of the center of gravity adjustment times and stability margin. MATLAB and ADAMS are used to verify the proposed optimization method by a series of simulation experiments, and finally the optimal step sequence of the quadruped robot in the static gait state is obtained.

The analysis of the static gait of the quadruped robot is the most basic part of its gait planning, and it is also the most important part of ensuring the stable walking of the quadruped robot. The walk gait is a commonly adopted gait by quadruped robots. The conventional research results are abundant, but there are few studies on the optimal step sequence of walk gait. The movement of quadruped robots in different step sequences will have a huge impact on the robot's motion stability and energy consumption [5]. The optimization of the step sequence has a strong practical significance for the improvement of the quadruped robot's movement performance. Some articles mentioned the optimal step sequence of the walk gait, but no clear and complete theoretical argument has been made. This article relies on a hydraulic-driven quadruped robot and adopts the criterion of the center of gravity adjustment times and stability margin in a walking cycle to determine the optimal step sequence by selecting the walking gait in different step sequences.

For the stability of the static gait, McGhee et al. proposed the concept of stability margin. When the quadruped robot walks in a static gait, there are at least three legs on the ground at any moment, i.e., the load factor is no less than 0.75. Therefore, it is possible to connect each supporting leg to a convex polygon, that is, a supporting polygon. The stability margin is the vertical projection of the center of gravity of the quadrupedal robot on the supporting polygon, and the obtained projection point is the shortest distance from each side of the supporting polygon. Stability margin S = min (d1, d2, d3) as shown in Fig. 1.

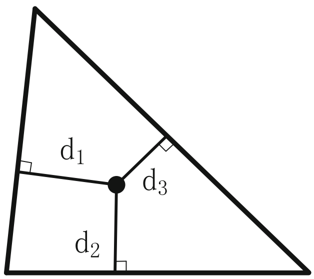

Fig. 1. Stability Margin

When using the supporting triangle to measure the stability margin and analyzing energy consumption as another criterion, we found that the criterion for stability margin is mainly reflected in the shape of the supporting triangles. Different step sequence creates triangles with obtuse angles and triangles with acute angles. The latter triangles are more similar to the shape of an equilateral triangle. This latter kind supporting triangle is very beneficial to the improvement of the stability margin.

In the step sequence diagram of Fig. 2, the thick solid lines represent the robot body and the legs of the robot, the thin solid lines represent the current support triangles, the two-dot chain lines represent the support triangles after the step, the numbers represent the serial numbers of the corresponding legs, and the arrows represent the direction of the movement. Quadruped robots share 24 step sequences based on the order of their legs. By analyzing the step sequence diagram, it can be found that the 4-2-3-1 step sequence has more obvious advantages which can be summarized into three points as explained below.

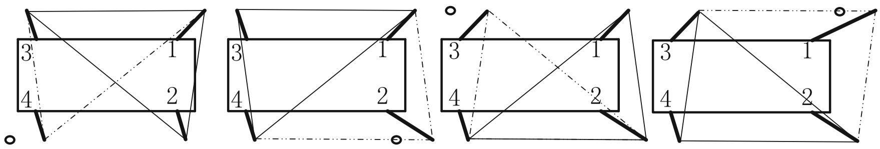

Fig. 2. 4-2-3-1 Step Sequence Diagram

(1) The 4-2-3-1 step sequence moves the legs 4 and 2 first which are relatively closer to the back during the initial movement, so that the gap between the front legs and the back legs is reduced. And the longest edge of the supporting triangle can always be used. In combination with the above two points, a support triangle is formed with a large area and all acute angles that is conducive to improving the stability margin.
(2) During the movement, the current support triangle and the support triangle after the move are mostly on one side, which is conducive to arranging the lateral adjustment of the robot body.

(3) The 4-2-3-1 sequence does not require any rear motion adjustment regarding robot body during the movement. This is very beneficial to reduce energy loss. For example, when the leg 2 moves, the supporting triangle changes from Δ134 to Δ124, and Δ124 is located on the front side. Therefore, when the leg 3 moves, the center of gravity of the body moves forward to ensure that the center of gravity is always in the stable domain. As the robot body continues to move forward, the stability margin is getting larger and the entire system is becoming more and more stable.

3 Simulation Experiment and Comparison

In order to verify the correctness of the optimal step sequence argumentation, the theoretical analysis of the optimal step sequence 4-2-3-1 and randomly selected 1-3-4-2 step sequence are simulated in Adams. Parameter setting is set as load factor $\beta = 0.78$; walking cycle $T = 1.6$ s; step distance $\lambda = 240$ mm; single leg span $A = 0.06$ m. In the simulation, the forward direction is attached to X axis, the vertical direction is attached to Y axis, and rolling direction is attached to Z axis, and the resulting displacement and roll angle results in each direction are compared as follows:

The roll angle is an important parameter for evaluating the stability of the robot body. The smaller the standard deviation, the more stable the robot body. Through the comparison of the results, it was found that the roll angle fluctuation of the 4-2-3-1 step sequence is obviously less than 1-3-4-2 step sequence, in other words, 4-2-3-1 step sequence has better stability (Fig. 3).

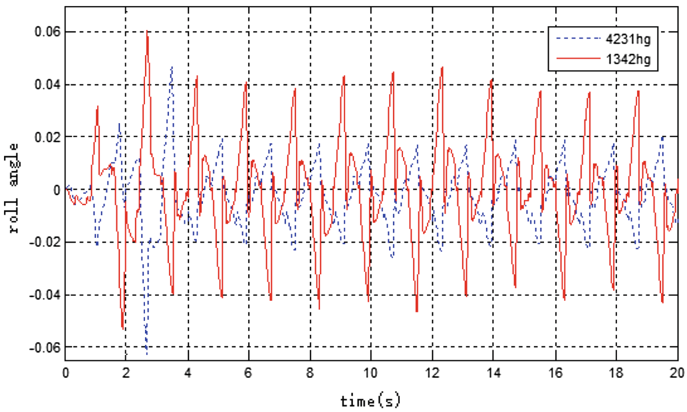

Fig. 3. Roll Angle

The displacement in the X direction is the displacement in the forward direction. The greater the displacement, the higher the efficiency of the step. Through the comparison of the experimental results, it was found that the X-displacement of the 4-2-3-1 step sequence is about 4500 mm within 35 s while the X-displacement of the 1-3-4-2 sequence is about 4000 mm. The 4-2-3-1 step sequence has better efficiency (Fig. 4).

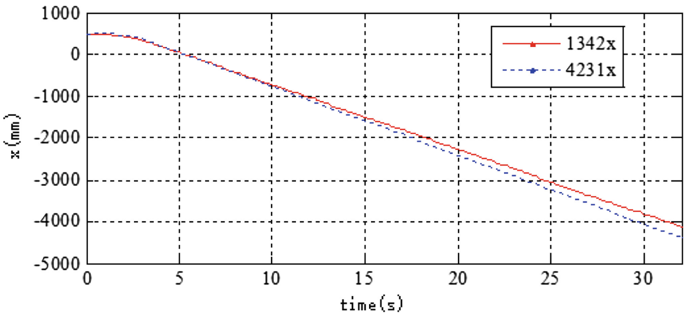

Fig. 4. X Direction Displacement

The displacements in the Y direction and the Z direction respectively represent fluctuations in the vertical direction and the roll direction of the airframe. The smaller the displacement in these two directions, the smaller the fluctuation of the robot body and the more stable the robot body. The comparison of the experimental results shows that the displacements in the Y-direction (Fig. 5) and Z-direction (Fig. 6) using the 4-2-3-1 step sequence are all less than using 1-3-4-2 step sequence, indicating the 4-2-3-1 step sequence is better in stability than 1-3-4-2 step sequence.

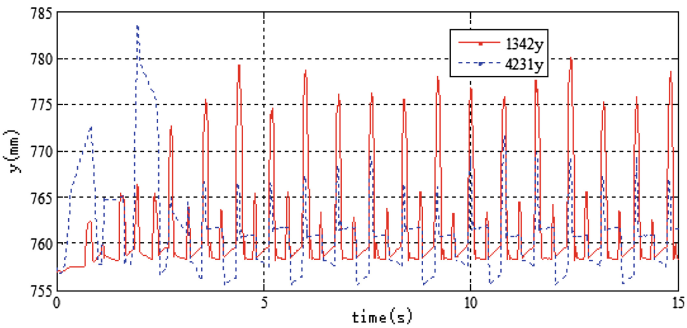

Fig. 5. Y Direction Displacement

In summary, analysis of the experimental results shows that the 4-2-3-1 step sequence is significantly better than 1-3-4-2 step sequence in the roll angle and X, Y, and Z direction displacements, so the 4-2-3-1 step sequence is the optimal step sequence of the walk gait.

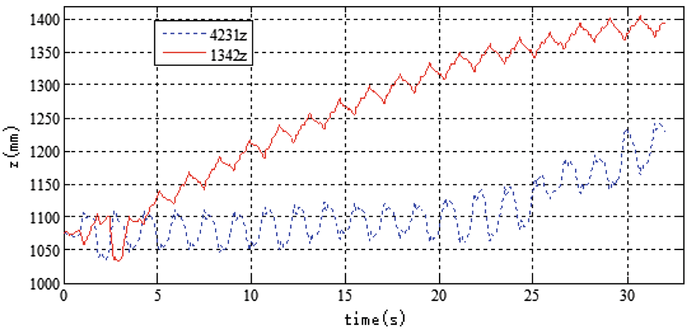

Fig. 6. Z Direction Displacement

4 Conclusion

Through the discussion and simulation analysis of the quadruped robot's walk step sequence, the following conclusions are drawn:

(1) Due to the symmetry of the quadruped robot body design (Fig. 7), the step sequence of stepping the front leg (i.e., leg 1 and leg 2) first can always find the corresponding step sequence in those of stepping rear leg (i.e., leg 3 and leg 4) first. Moving rear legs first is conducive to the formation of a supporting triangle formed by acute angels which is helpful to improve the stability margin of the robot. Therefore, the step sequence of the moving rear legs first is better than that of moving front leg first.

(2) In the step sequences of moving rear legs first, the 4-2-3-1 step sequence has obvious advantages in reducing energy consumption, increasing stability margin and resisting lateral impact, etc., and is the best step sequence in the walk gait.

References

1. Raibert, M., Blankespoor, K., Nelson, N., etal.: BigDog, the rough-terrain quadruped robot. In: Proceedings of the 17th Word Congress, The International Federation of Automatic Control, IFAC, July 6 2008–July 11 2008, Seoul, Korea, Republic of. Elsevier (2008)
2. Hirose, S., Fukuda, Y., Yoneda, K., et al.: Quadruped Walking Robots at Tokyo Institute of Technology Design, Analysis, and Gait Control Methods. IEEE Robot. Autom. Mag. **16**(2), 104–114 (2009)
3. Mosher, R.S.: Test and evaluation of a versatile walking truck. In: Proceedings of off-road mobility research symposium, pp. 359–379 (1968)
4. Chen, X., Gao, F., Qi, C., et al.: Gait planning for a quadruped robot with one faulty actuator. Chinese J. Mech. Eng. 1–9 (2005)
5. Mcghee, R.B.: Some finite state aspects of legged locomotion. Mathe. Biosci. 67–84 (1968)