Gait Phase Optimization of Swing Foot for a Quadruped Robot

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Abstract. Quadruped robot has gained considerable interests since its wide applications in both military and entertainment scenarios. On the control and gait planning of quadruped robots, walking stability is the fundamental problem in most scenarios. In this paper, we proposed a gait phase optimization method on the swing foot of quadruped robots in walking gait. In the proposed gait optimization method, Lift-up and Touch-down phases are added in gait planning of swing foot, which aiming to improve the stability in walking phases. Finally we validate the proposed method on a quadruped robot, and experimental results indicate that the proposed gait phase optimization method has the ability to improve the stability of the quadruped robot in walking gait.

1 Introduction

Research on quadruped robots have increased significantly in recent years since they can be applied in many complex scenarios [1,2]. Compared to other autonomous robots such as wheeled robots and humanoid robots, quadruped robots not only have the ability to adapt unstructured environment (eg. field environment), but also can achieve higher speed in most scenarios. In early researches of quadruped robots, many quadruped robots with large body and high speed are developed as load carriers in field environment, such as BigDog [3], Legged-Squad 3 [4], WildCat [5], Cheetah [6] and SCalf [7] etc. These kinds of quadruped robots are hydraulic actuated which aiming to achieve higher running speed and carry heavier loads. As expanding of applications of quadruped robots, many small quadruped robots with motor actuated, such as SpotMini [8], HyQ [9,10], ANYmal [11,12], LittleDog [13,14] and Laikago [15] etc. These motor-driven quadruped robots has lower noise and most of them are focus on indoor environment.

On the research of fundamental technologies of quadruped robots, gait planning is the most important technology since suitable gait could improve the stability and motor ability of quadruped robots significantly. Gait planning methods of quadruped robots can be separated into three aspects: model-based [16], behavior-based [17] and bio-inspired methods [18]. This paper is focus on the model-based gait planning method in walking gait. Many gait models were proposed for walking gait, the most famous gait controller is proposed by Kolter

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which named as hierarchical gait controller [19]. In the proposed hierarchical controller, three hierarchies are implemented: the perception level modeled the path of Center of Gravity (CoG) through vision sensors, the planning level calculated positions of swing foots based on planned CoG, then the control level servo actuators of the quadruped robot for achieving planned gait. In order to achieve better stability and motor ability of walking gait, many researchers focus on the planning level and build different gait models for different applications [20–22]. In gait control of quadruped robots, a critical issue is how to reduce the compact force when the robot contact the ground. For solving this problem, many control methods based on impedance control strategy are proposed in the control level [23–25]. However, the biggest drawback of these methods are the requirement of accurate and multi-dimension force detection on foots of the quadruped robot. Hence, in order to reduce the complexity of sensory system of the quadruped robot, this problem should be solved in the planning level which require less sensory information.

In this paper, a gait phase optimization method is proposed to improve the stability in walking gait of a quadruped robot. In the proposed gait optimization method, a Lift-up and a Touch-down phase are added in the gait planning of swing foots. The proposed method is validated on a quadruped robot, and experimental results indicate that the proposed gait phase optimization method has the ability to improve the stability of the quadruped robot in walking gait.

The rest of this paper is organized as follows. Section 2 introduces the system design of a quadruped robot. In Sect. 3, the proposed gait optimization method is presented. Experimental results and discussions are described in Sect. 4. Finally, we conclude the paper in Sect. 5 and suggest the future work.

2 System Design of a Quadruped Robot

In this section, a quadruped robot platform with motor-actuated is introduced. Firstly, we briefly introduce the system architecture of the quadruped robot, and then give the detail of a sensitive force sensor which installed on feet of the quadruped robot.

2.1 System Architecture of the Quadruped Robot

Figure 1 illustrates the whole structure of the quadruped robot, which total weight is 34 kg (Length × Width × Height: 64 cm × 34 cm × 56 cm). As shown in Fig. 1, the whole quadruped robot can be separated as three sub-systems: mechanical system, sensory system and control system.

On the mechanical design, the quadruped robot has totally 12 Degree-of-Freedoms (DOFs), in which 3 DOFs for each leg (knee joint, hip joint and yaw joint). As shown in Fig. 1, each joint is activated by a DC servo motor for serving active torques. Upon legs of the quadruped robot, a body structure is designed for installing the control hardware and carrying loads.

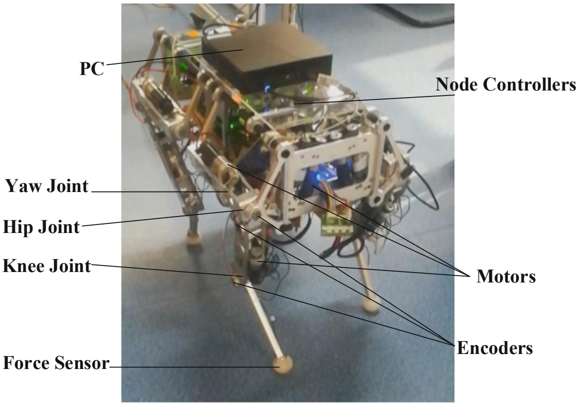


Fig. 1. The whole structure of the quadruped robot.

The sensory system of the quadruped robot consists three types of sensors: (1) Encoders for recording joints' state of the quadruped robot; (2) IMU sensor is installed on the body of the quadruped robot for obtaining the state of the body; (3) Force sensors are embedded on feet of the quadruped robot which aiming to measure the foot pressure during walking.

The control system of the quadruped robot is design as a distributed control system, with a main controller and 12 node controllers. The main controller is a PC installed on the body of the quadruped robot, which runs gait planning algorithms. Node controllers are designed for controlling each active joint, which runs control algorithms for each joint. In order to achieve real-time performance, we employ Control Area Network (CAN) for the communication between the main controller and node controllers.

2.2 Sensitive Force Sensor Design

In the design of gait control algorithms of quadruped robots (the same for the proposed gait planning method in this paper), the most important sensory information is the pressure of each foot. Hence, a sensitive force sensor is design for the quadruped robot, which aiming to obtain accurate force feedback during walking gait.

Figure 2 shows the mechanical structure of the sensitive force sensor. As shown in Fig. 2, a spring is added between the contact surface and the pressure sensor, which aiming to reduce the impact forces when the foot contacts the ground. Moreover, though the energy restored in the spring structure, the force sensor can measure the contact force immediately when the interaction force between the contact surface and the ground changes.

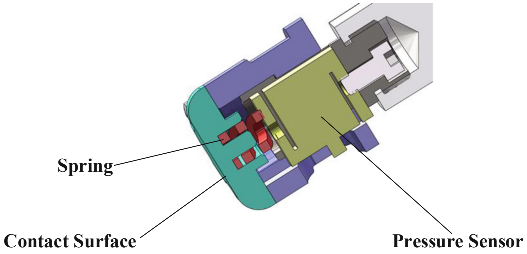


Fig. 2. Mechanical structure of the sensitive force sensor on feet of the quadruped robot.

3 Gait Phase Optimization of Swing Foot

In this section, the proposed gait phase optimization method will be presented in detail. First a gait planning method of swing foot based on a traditional gait planning method, then a gait phase optimization method is introduced which aiming to reduce compact of the swing foot.

3.1 Gait Planning of Swing Foot

In this paper, we utilize a gait planning method which plans trajectory of the swing foot with a box pattern [26]. The advantage of this method is that the quadruped robot can avoid bigger obstacles in walking gait. Figure 3 shows the schematic diagram of the gait planning method of swing foot.

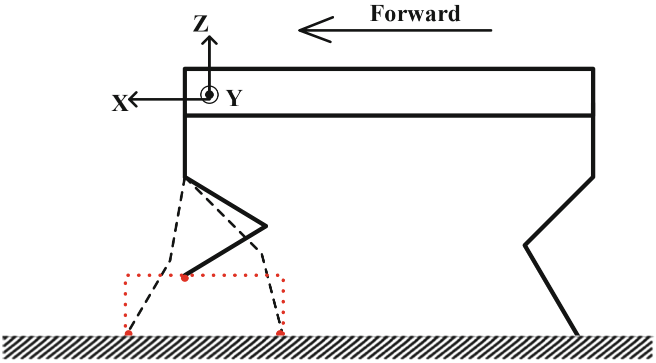


Fig. 3. Schematic diagram of the gait planning method of swing foot.

The swing movement of swing foot can be separated into three phases: lifting phase, forward phase and falling phase. In order to increase the stability of the quadruped robot, the falling phase is planned as two times longer than other two phases. Thus, assuming the whole swing phase cost time T_{swing}, duration of the lifting phase and forward phase is $T_{swing}/4$, and falling phase is $T_{swing}/2$. The detail description of foot trajectories are presented as follows.

(1) Lifting Phase: In the lifting phase, the swing foot of the quadruped robot is lifting up vertically along the Z direction, with the highest position H. The foot trajectories of the lifting phase can be described as follows:

$$\begin{cases} x(t) = 0, \\ y(t) = 0, \\ z(t) = \dfrac{4 \cdot H}{T_{swing}} \cdot t, t \in [0, \dfrac{T_{swing}}{4}]. \end{cases} \tag{1}$$

(2) Forward Phase: In the forward phase, the swing foot move in the X direction and Y direction, which aiming to move the foot to the goal position in XOY plane. Assuming that the goal position in XOY plane is $(L_x, /L_y)$, we can obtain the foot trajectories of the forward phase as follows:

$$\begin{cases} x(t) = \dfrac{4 \cdot L_x}{T_{swing}} \cdot (t - \dfrac{T_{swing}}{4}), \\ y(t) = \dfrac{4 \cdot L_y}{T_{swing}} \cdot (t - \dfrac{T_{swing}}{4}), \\ z(t) = H, t \in [\dfrac{T_{swing}}{4}, \dfrac{T_{swing}}{2}]. \end{cases} \tag{2}$$

(3) Falling Phase: In the falling phase, the swing foot of the quadruped robot is falling down vertically along the Z direction, from the highest position H to the ground. In order to ensure the foot contacts the ground during the duration of swing phase T_{swing}, we set a contact parameter β in which $\beta = 0$ indicates the foot has already touch the ground, otherwise $\beta = 1$. The foot trajectories can be described as follows in the falling phase:

$$\begin{cases} x(t) = L_x, \\ y(t) = L_y, \\ z(t) = \beta \cdot \dfrac{2 \cdot H}{T_{swing}} \cdot (t - \dfrac{T_{swing}}{2}), t \in [\dfrac{T_{swing}}{2}, T_{swing}]. \end{cases} \tag{3}$$

3.2 Gait Phase Optimization

After planning gait trajectories of the swing foot with box pattern, another issue is how to increase the stability performance in the whole swing phase. In this paper, we propose a gait phase optimization method to increase the stability performance of the quadruped robot in walking gait.

Figure 4 illustrates gait phases of the swing foot after optimization. As shown in Fig. 4, two phases are added in the swing phase of quadruped robot in walking gait: lift-up phase and touch-down phase.

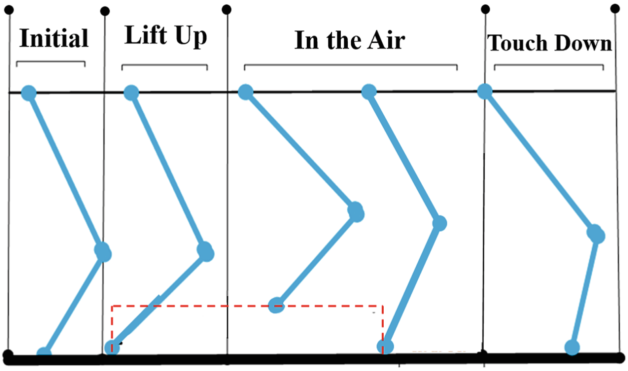


Fig. 4. Gait phase optimization of swing foot. Lift-up phase: the plantar force become smaller until the foot is off the ground; In the air: swing to the goal height and position; Touch-down phase: The plantar force become larger until the threshold.

(1) Lift-Up Phase: The goal of lift-up phase it to make the plantar force change to zero slowly. Since if the foot accelerate with a large acceleration, the quadruped robot will be not able to adjust its Center of Gravity (COG) immediately, which could make the system not stable.
(2) In the Air: This phase is the phase to run the planned gait trajectories of swing foot, which aiming to move the foot to the goal position.
(3) Touch-Down Phase: The goal of touch-down phase is decelerating the late swing phase of the swing foot. On the motor servo of gait trajectories, the controller can not servo motion trajectories accurately sometimes. Therefore, for some cases, the foot will touch the ground earlier than the planned gait. In order to increase the stability performance in these cases, the touch-down phase is added into the whole swing phase of the quadruped robot.

With the planned gait trajectory of swing foot and gait phase optimization, the quadruped robot can achieve better stability performance in walking gait in swing phase. Experiments on the quadruped robot in the next section will show the efficiency of the proposed gait phase optimization method.

4 Experiments

In this section, we evaluate the proposed gait phase optimization method on the quadruped robot. At first the experimental setup will be introduced briefly, then the experiments and results will be discussed.

4.1 Experimental Setup

The proposed gait phase optimization method is validated on the quadruped robot which introduced in Sect. 2. During all the experiments, we do not add extra loads on the quadruped robot. In order to evaluate the performance of each gait phase independently, two experiments are established: the first one is only add the touch-down phase, another one is only add the lift-up phase. At the end of experimental discussions, we discuss the stability performance of both these two situations.

4.2 Results and Discussions

The first experiment on the quadruped robot only adds the lift-up phase based on the proposed gait phase optimization method, which aiming to analysis the performance of the lift-up phase in walking gait. In the late description of figure results in this paper, we utilized LF, RF, LB, RB to represent the Left-Front leg, Right-Front leg, Left-Back leg and Right-Back leg, respectively. Figure 5 shows the comparison of RB leg and RF leg with two situations: without lift-up phase and with lift-up phase.

As shown in Fig. 5, the swing foot (RB leg in Fig. 5(a) and (c), RF leg in Fig. 5(b) and (d)) of the quadruped robot lift from the ground at around 1 second. In the original gait planning method without lift-up phase shown in Fig. 5(a) and (b), the other three legs are not stable after the swing foot lifting up (LF leg in Fig. 5(a), LB and RB leg in Fig. 5(b)).

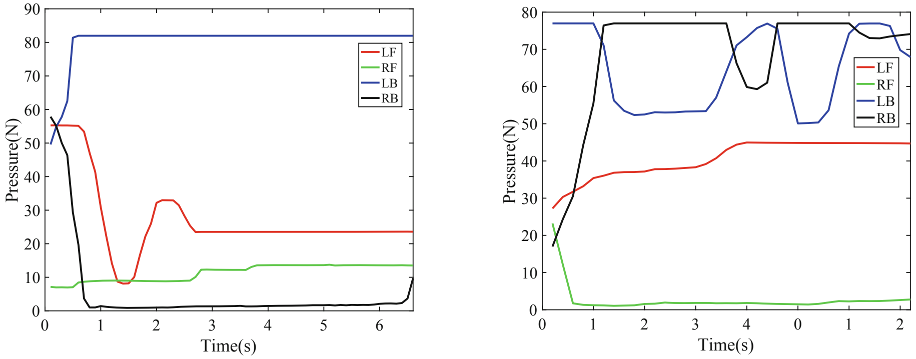
Figure 5(c) and (d) show performances of the proposed gait phase optimization method with the lift-up phase. As shown in Fig. 5(c) and (d), the other three legs (except the swing leg) keep stable when the swing foot lifting in walking gait. From the results shown in Fig. 5, it is obviously that the quadruped robot obtained a stable gait with the proposed gait phase optimization method in lift-up phase.

The second experiment only adds the touch-down phase based on the proposed gait phase optimization method. Figure 6 compares the change on foot pressure of two situations: without touch-down phase and with touch-down phase.

As shown in Fig. 6, the LB leg (with blue line) of the quadruped robot touch the ground at around 5 second in the experiment. In the original gait planning method without touch-down phase shown in Fig. 6(a), the pressure on LB leg increases quickly and makes the quadruped robot not stable in the late swing phase (which makes the pressure on the LF leg and RB leg decrease quickly).

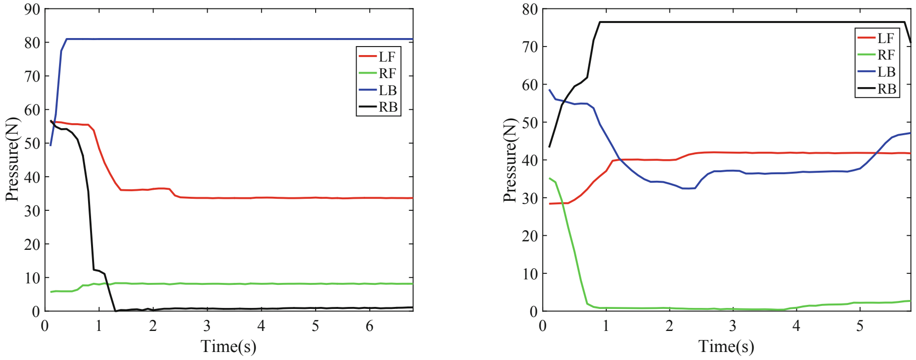
Figure 6(b) shows the performance of the proposed gait optimization method with touch-down phase. As shown in Fig. 6(b), the pressure on the swing foot (LB leg) increases slowly and the other three legs keeps stable in the late swing phase. From the experimental results we can see that, after adding the touch-down phase during normal gait, the quadruped robot could increase the stability in the late swing phase.

Furthermore, in order to evaluate the performance of proposed gait phase optimization method, we analyze the variation of the posture of the quadruped robot. As introduced in Sect. 2, sensory information of the IMU sensor (installed on the body of the quadruped robot) is utilized to analyze the stability of the



(a) RB leg Without lift-up phase

(b) RF leg Without lift-up phase



(c) RB leg With lift-up phase

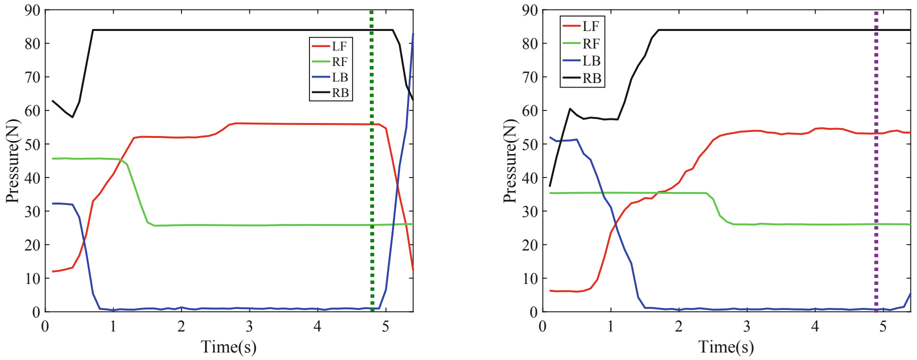
(d) RF leg With lift-up phase

Fig. 5. Comparison of foot pressure with/without lift-up phase.

quadruped robot. In this experiment, we employ the proposed gait phase optimization method in a whole walking gait cycle (taking a step for each leg).

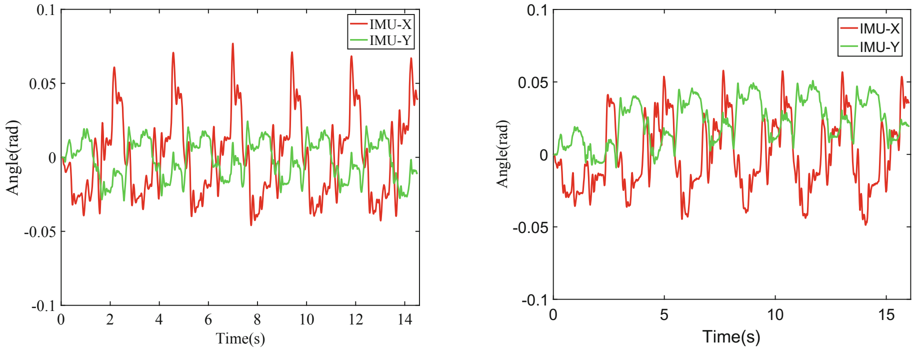
Figure 7 shows the comparison of the IMU sensory information of the quadruped robot with/without gait phase optimization method. Compared with experimental results in Fig. 7(a) and (d), it is obviously that the proposed gait phase optimization method has improved the stability of the quadruped robot significantly, in which the acceleration in both X direction and Y direction decreased. The experimental results also show that even only consider lift-up phase (in Fig. 7(b)) or touch-down phase (in Fig. 7(c)), the improved gait planning method can increase the stability of the quadruped robot in walking gait.

With experiments on the quadruped robot, the proposed gait phase optimization method improves the stability of the quadruped robot in walking gait significantly. Experimental results show that the proposed method has the ability to obtain stable gait in normal walking gait of quadruped robots.

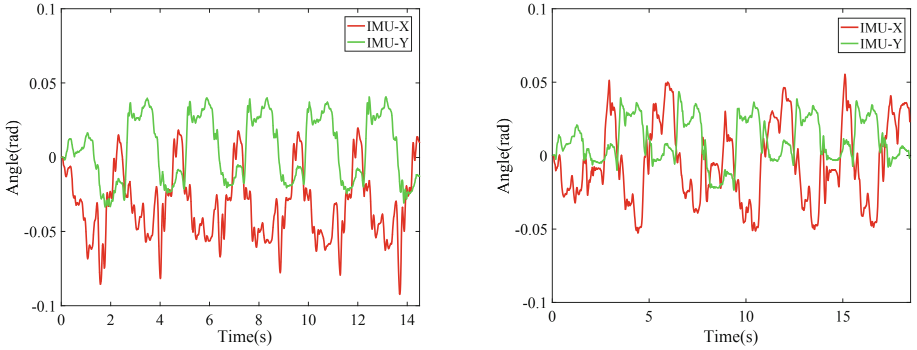


(a) Without touch-down phase (b) With touch-down phase

Fig. 6. Comparison of foot pressure with/without touch-down phase. (Color figure online)



(a) Without lift-up phase and touch-down phase (b) Without lift-up phase



(c) Without touch-down phase (d) With optimization gait phases

Fig. 7. Comparison of the IMU sensory information of the quadruped robot with/without gait phase optimization method.

5 Conclusions and Future Work

In this paper, we proposed a gait phase optimization method on the swing foot of quadruped robots in walking gait. We firstly added lift-up and touch-down phases in gait planning of swing foot to improve the stability in walking phases. Then we applied the proposed method to a quadruped robot, and the experimental results indicate that the proposed gait phase optimization method has the ability to improve the stability of the quadruped robot in walking gait.

Our future work will go along with impedance control strategy and joint torque adaptive control strategy to decrease the force between foots and the environment, which could improve the stability of the robot in different walking patterns.

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