Static Gait Scheme for Horizontal Posture Slope Climbing with Quadruped Robot

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Abstract: With a view to expanding serviceability in different applications, the slope climbing ability of a quadruped robot is important. In this paper, a gait scheme i.e. walking algorithm for slope climbing is proposed. It differs from the previous studies in terms of the posture of the robot while climbing. The presented scheme is designed such a way that the body of the robot maintains horizontal posture with positive static stability which can be used for carrying a load and disabled while climbing the slope. For this proposed scheme, different parameters of gait are shown. The algorithm is tested with a multibody simulation and based on the results of transformation of the inertial frame about the world frame; it is proven to be steady.

Keywords: Quadruped Robot, Static Gait Planning, Slope Climbing

1. Introduction

Legged robots are extensively studied in recent times due to having high Maneuver-ability and terrain adaptability. Quadruped robots are a good trade-off between all the legged robots in terms of stability and complexity \citep{1}. Gait planning\ i.e. walking algorithms have been studied by researchers and different schemes for different terrain conditions are proposed. All these efforts lead to the prospective possibility of the use of robots in all the terrain conditions which can be and cannot be explored by humans. With this capability, the quadruped robot can be used in the applications like mining, nuclear plant, interplanetary missions, healthcare, etc. For these kinds of applications, one of the important required capabilities of the quadruped robot is to climb the slopes with positive stability.

Gait planning of quadruped robot for slope climbing was first proposed in \citep{2}, in which the concept of Energy Stability Margin \citep{3} was implemented. As per that, the stability is maintained by balancing the potential energy on front and hind side of the robot. The schemes were developed for the straightforward movement of the robot. In \citep{4}–\citep{7} efforts were made to develop schemes that enable the robot to become omnidirectional that can move in any direction about its longitudinal axis. In all such works, the robot is expected to maintain a posture, parallel to the slope. It was observed in \citep{8} that in the parallel posture, the stability decreases, and in a horizontal posture, the length of leg stroke decreases. In that study, a novel robot structure was proposed having a vertical waist joint in which the front part of the robot torso remains parallel to the slope and the hind part becomes horizontal. Based
on that structure, the gait scheme having zig-zag movement of CG was proposed for slope climbing. Gait transition from regular to the slope terrain was proposed in [9], [10]. In [11] an adaptive gait scheme was presented in which the slope angle need not be predefined and can be computed based on the reaction forces, sensed from the force sensors. Based on the instantaneous computed angle of the slope, the foot trajectories were planned. A similar idea was proposed in [12] using CPG. For such adaptive slope walking, the controller is designed to correct the posture of robot using IMU feedback.

To the best of the knowledge of the authors of this study, the slope climbing algorithm for quadruped robots having horizontal robot posture with positive static stability has not been explored yet. Limitation in stroke length for horizontal slope climbing, mentioned in [8] can be resolved using sprawling type [13] leg structure, in which the knees can go above the torso in the swing phase. With a successful implementation of such a gait scheme, a robot can be used in load carrying and as a wheelchair for the disabled who is not possible with the above-mentioned algorithms, where the robot torso maintains parallel posture with the slope. In this paper, a gait scheme based on a 2-phase discontinuous gait [14], [15] is proposed for slope climbing with horizontal posture. Event sequences and positions of foot tips at each event are stated. The proposed algorithm is tested using multi-body simulation. In [17], friction compensation based fuzzy control scheme was proposed for slope climbing of quadruped robot. In [18], a survey has been carried out on complex terrain maneuvering of quadruped robot and slope climbing ability is discussed in detail.

In section 2, the geometric modeling is shown which is followed by the description of the proposed slope climbing gait in section 3. Simulation of the presented gait is shown in section 4 and section 5 states the conclusion of the study.

2. Modeling

For the proposed slope climbing algorithm, a standard quadruped model as shown in figure 1, having 4 articulated type legs [13] is considered. Each leg has two links and three degrees of freedom and has a Sprawling type structure [1]. Two joints are placed at the hip and one joint is at the knee in each leg. Lengths of upper and lower links are L1 and L2 respectively.

![Figure 1. Geometric Model of Robot.](image)

The CG of robot is considered at the centroid of torso by assuming the legs massless and the inertial coordinate frame is placed at CG. The X-axis of the inertial frame is heading forward, Y-axis in the lateral direction and Z-axis is heading upwards. The hips of all four legs are attached at the corners of the torso and at the hip of each leg, the leg’s coordinate systems are placed with respect to which the positions of their foot tips shall be defined. The X and Z-axis of the leg’s coordinate frames are oriented the same as the inertial frame. Length of the robot torso is Tx. All four foot tips are expected to maintain a fixed distance in Y-direction, away from the torso while maneuvering over the slope. The overall mathematic model has been prepared assuming that sufficient friction is produced between the foot tip and the terrain and there is no slippage. The robot maintains horizontal posture while climbing the slope and hence ‘Longitudinal Stability Margin’ (LSM) [16] is considered as the parameter of the stability which is based on static stability. As per that, the vertical projection of the CG of robot on the ground must always fall under the support polygon. Support polygon is a three or four-sided polygon, formed by the vertical projection of the foot tips on the ground. When one of the
legs is in the swing phase, the support polygon becomes three-sided and when all four legs are in the support phase, a four-sided polygon is formed. The value of LSM is calculated as the longitudinal distance on the forward or backward side from the vertical projection of CG to the nearest support boundary. Such values of LSM are computed for all the events of the locomotion cycle and then the minimum value of that is considered as the critical LSM of the gait cycle.

3. Proposed Slope Climbing Gait

The proposed slope climbing gait is inspired by 2-phase discontinuous gait in which there are 2 body movement phases and 4 events of leg swing. The event sequence is the same as the original 2-phase discontinuous gait, which is for flat terrain but here, for slope climbing operation, the trajectories of foot tips are changed for stable climbing. TS is the time required for Leg Swing and TM is a time of Body Movement in one phase. T is the total cycle time. During Leg Swing, the foot tip of each leg will travel in by S in X direction and $S \tan \theta$ in the Z direction. The angle of the slope is $\theta$. During climbing, the CG of the robot is expected to maintain a vertical height of RH from the Slope Surface as shown in figure 2. The lateral distance between the foot tip and vertical projection of the torso edge on the ground is Y. The sloped terrain on which the robot is expected to walk is assumed to be obstacle-free and smooth.

![Figure 2. Key foot points and slope parameters.](image)

In figure 3, gait diagram of the proposed slope climbing gait is shown. The key time instances when events take place are shown on the horizontal axis. The time of start and end of support and swing phases of all four legs and body movement phases is mentioned. The cycle starts with the swing of leg-4, which is followed by the swing of leg-2. Then, in the body movement phase, the body will move forward and upward, with the same inclination of a slope by $S/2$ and $S/2 \tan \theta$ respectively. After that, the swing of leg-3 and leg-1 happens and the cycle is ended by a similar body movement phase. At the end of the cycle, the CG of robot is displaced by distances S and $S \tan \theta$ in X and Z-direction respectively by maintaining the same value of RH throughout the cycle.

![Figure 3. Gait Diagram.](image)
In figure 4, each stage of the gait is shown. The actual configuration of legs may be different as per the joint configuration and joint limits but here for the representation, the legs and foot tips are shown in front view. B1, B2, B3 and F1, F2, F3 are key points of hind and front legs respectively. In (a) the initial state is shown. In (b), (c), (e), and (f) the configuration of the robot after leg swing 4, 2, 3, and 1 are shown respectively. In (d) and (g), body movement phases are shown, where the position of the key points changes as the position of the torso changes. In the end, the same posture as the initial is achieved that makes the gait periodic.

![Figure 4](image)

**Figure 4.** Steps of the gait scheme.

In table 1, the positions of the key points are mentioned about the respective leg’s coordinate frame.
Table 1. Coordinates of key points.

| Points | X-Coordinate | Z-Coordinate |
|--------|--------------|--------------|
| F1     | $-\frac{S}{2}$ | $\tan \theta \left( \frac{T_x}{2} - \frac{S}{2} \right) - RH$ |
| F2     | 0            | $\tan \theta \left( \frac{T_x}{2} \right) - RH$ |
| F3     | $\frac{S}{2}$ | $\tan \theta \left( \frac{T_x}{2} + \frac{S}{2} \right) - RH$ |
| B1     | $-\frac{S}{2}$ | $-\tan \theta \left( \frac{T_x}{2} + \frac{S}{2} \right) - RH$ |
| B2     | 0            | $-\tan \theta \left( \frac{T_x}{2} \right) - RH$ |
| B3     | $\frac{S}{2}$ | $-\tan \theta \left( \frac{T_x}{2} - \frac{S}{2} \right) - RH$ |

For all the key points, the Y-coordinate of Leg-1 and Leg-3 is ‘Y’ and Leg-2 and Leg-4 is ‘-Y’. In table 2, the position of each foot tip at the key time instances are mentioned, where the dark boxes indicate the swing phase of legs. Here, for keeping this solution generalized, only initial and final foot tip positions are shown for the leg swing events. During a swing, the foot tip is lifted from the backside (F1 or B1), and by following a predefined trajectory, it is then placed at the front side (F3 or B3). The type of trajectory doesn’t affect the kinematic solution as the static stability is maintained by the remaining three legs during that particular time.

Table 2. Position of foot tips.

| Time    | Leg-1 | Leg-2 | Leg-3 | Leg-4 |
|---------|-------|-------|-------|-------|
| 0       | F2    | F1    | B2    | B1    |
| $T_s$   | F2    | **F1**| B2    | **B3**|
| $2* T_s$| F2    | **F3**| B2    | B3    |
| $T_M + 2* T_s$ | F1  | F2    | **B1**| B2    |
| $T_M + 3* T_s$ | **F1**| F2    | **B3**| B2    |
| $T_M + 4* T_s$ | **F3**| F2    | B3    | B2    |
| T i.e. ($2*T_M + 4* T_s$) | F2    | F1    | B2    | B1    |

As mentioned in the previous section, while calculating the value of LSM, only vertical projections of the CG and foot tips are taken. Using geometrical computations for all the events, LSM can be calculated for each of them. Out of those, the critical value of the locomotion cycle is least of them, which is found out to be $S/4$.

4. Simulation

The proposed gait scheme is simulated in the multibody simulation with a 20° slope as shown in figure 5. The length of the torso ($T_x$) is 600 mm. The length of the upper and lower links is 36 mm. Longitudinal distance between B1 & B3 and F1 & F3 i.e. leg stroke ($S$) is 50 mm. The vertical height
of the CG from the slope surface (RH) is 40 mm. Lateral distance between foot tips and torso (Y) is 25 mm. The cycle time of the locomotion (T) is 28 seconds.

Figure 5. Simulation model of the robot.

Figure 6 shows the translation of robot CG about the world coordinate frame. Y-coordinate is zero throughout the cycle. X and Z coordinates are 600 and 618.4 mm respectively at the initial stage and 1088 and 796 mm respectively at the final stage. Hence, the CG of robot has traveled by 519.3 mm in 20° inclination.

Figure 6. Translation of robot about the world coordinate frame.

Figure 7 shows the rotation of CG about the X, Y, and Z-axis of the world coordinate frame. All the three angles are zero with the maximum change in the value of less than 0.01°. It illustrates that the horizontal posture is maintained throughout the cycle with static stability.
Figure 7. Rotation of robot about the world coordinate frame.

Figure 8 shows the actuation torque required for the motion in each of the joints. Based on this information, actuator selection can be carried out. Maximum torque can be observed in all the 12 actuators during body movement phases (12 to 14 seconds and 26 to 28 seconds) as all the motors together give effort to displace the robot.

Figure 8. Torque in each actuator.

Figure 9, 10 and 11 shows the angular position, velocity and acceleration respectively of 12 joints.
Figure 9. Angular Position of Actuators.

Figure 10. Angular Velocity of Actuators.
Figure 11. Angular Acceleration of Actuators.

5. Conclusions

Quadruped robots’ slope climbing capability has been explored in this paper. The idea behind keeping the robot body horizontal can lay a foundation for many advanced gaits of static as well as dynamic type. The proposed algorithm can also be modified for the irregular terrain using adaptive gaits. The presented scheme is based on a 2-phase discontinuous gait which is the most stable static gait out of all the proposed gait so far for straightforward motion. Therefore, the proposed gait is the most stable slope climbing having an LSM value of S/4. The scheme is validated using multibody simulation. During climbing, throughout the cycle, maximum value of rotation about all three axes is less than 0.01° that signifies that not a single time robot has become unstable. The result suggests that the robot climbs the slope with positive stability. The result of angular acceleration of actuators shows that maximum acceleration is less than 0.0006 degree/sec² which signifies that the trajectory planning is smooth. The study can further be extended for crab and circular motion of robot on the stair.

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