Implementation of gaits for achieving omnidirectional walking in a quadruped robot

Conference Paper · July 2015

DOI: 10.1145/2783449.2783482

Samyukta Mogily
Stony Brook University

Divyanshu Goel
International Institute of Information Technology, Hyderabad

Nahas Pareekutty
International Institute of Information Technology, Hyderabad

S. V. Shah
Indian Institute of Technology Jodhpur

Implementation of Gaits for Achieving Omnidirectional Walking in a Quadruped Robot

T Komal Kumar *
komal.teru@gmail.com

R. Kumar †
rgrishav@gmail.com

S. Mogily †
samyuktamogili@gmail.com

D. Goel †
divyanshu.goel@gmail.com

N. Pareekutty †
nahas.pareekutty@gmail.com

S. V. Shah †
surilshah@iiit.ac.in

K Madhava Krishna †
mkrishna@iiit.ac.in

ABSTRACT

In this paper, we propose a better planning technique of the standard walking gaits for a quadruped robot than the conventional successive gait transition method to realize omnidirectional static walking. The technique involved planning the sequence as well as motion of the swinging and supporting legs. The relationship between the stability margin, the stride length and the duty factor are also formulated mathematically. The proposed modified crawl gait is compared to the conventional method with respect to the above parameters geometrically as well as mathematically and is shown to have positive stability margin at all times. The successive gait transition is demonstrated on the modified crawl and rotation gaits. Computer simulations of a model quadruped robot were performed to validate the theory proposed. Experiments were performed on an actual quadruped robot to realize the omnidirectional static walking with increased stability margin.

Keywords

Omnidirectional Static Walking, Stability Margin, Quadruped Robot

Figure 1: Experimental Quadruped Model

1. INTRODUCTION

Use of leg-based walking systems has proven to be quite popular in robotics. These systems offer better versatility over wheeled systems especially when handling uneven and unpredictable terrain. Superiority of legged robots in handling rough terrain and obstacles has been demonstrated in [1] and [2]. Among legged robots, quadrupeds have the advantage of possessing a simpler structure while satisfying the requirements for implementation of a static walking gait, such as a stable support polygon.

Research into quadruped gaits often has its origins in the study of biological walking gaits. Such studies have led to development of both static and dynamic walking gaits for legged robots [3]. Mimicking biological walking patterns also requires mimicking of their control principles, such as Neural Networks and Central Pattern Generators discussed in [4] and [5].

It is desirable to design and implement a robust and statically stable gait for simple quadruped robots with minimal actuation and sensing. Such robots can readily find purpose in reconnaissance, swarms and structural inspection. The features of their gaits would be repeatability of gait sequence and stability over uneven terrain. [4] describes a robust quadruped walking system that relies on complex mechanical and control structures. Use of a sophisticated sensing and feedback system to determine gait characteristics has been demonstrated by [4] and [2]. Improving walking on uneven terrain using prismatic joints has been demonstrated in [6]. While these systems offer advantages in efficiency and speed, they also introduce a significant amount of complexity, cost and computational load.

Gait sequences for quadrupeds have been discussed in [7]

*Electrical Engineering Department, Indian Institute of Technology, Kharagpur 721302, India

†Robotics Research Center, International Institute of Information Technology, Hyderabad 500032, India

AIR '15, July 02 - 04, 2015, Goa, India

DOI: http://dx.doi.org/10.1145/2783449.2783482

along with transitions between variations in gait, enabling omnidirectional static walking. However, maintaining static stability while traversing slopes or handling variations in CoG is not considered. In terms of stability, such gaits have a zero stability margin and is therefore feasible only when traversing level terrain under ideal conditions.

Stability criteria such as CoG, Support Polygon and Stability Margin are researched in [8] and [9]. Extensive comparison of crawling gaits w.r.t. stability and efficiency has been performed in [10]. However, these findings have not been extended to develop a stable set of translation and rotation gaits to handle various kinds of movements to be performed by a quadruped robot.

This paper builds on the work done in [7] and [8]. We present the theory and implementation of walking gaits for a simple quadruped robot which are both statically stable and utilizes the concept of a positive stability margin to overcome potential inconsistencies in terrain and weight distribution. These concepts have been extended to gaits required for omnidirectional walking. The efficacy of the proposed approach is demonstrated using numerical simulations, and experimental studies on the robot shown in Fig. 1.

The rest of the paper is organized as follows: Section 2 discusses issues and improvements in crawl and rotation gait. Section 3 discusses the associated planning methodology of the modified omnidirectional static walking along with the transition between the standard gaits. Section 4 shows the results on simulation models as well as experimental prototype of the quadruped robot. Finally, the conclusions are given in Section 5.

2. ISSUES AND IMPROVEMENT IN OMNIDIRECTIONAL STATIC WALKING

The two standard gaits of omnidirectional static walking are crawl gait and rotation gait. While the crawl gait is for traversing linear paths, the rotation gait is for in-place rotation. The gaits described above have at most one leg in the air at any time instant. Thus, the support polygon is a triangle with the other three legs on the ground at the vertices of this triangle. We call the gait to be statically stable if the vertical projection of the centre of gravity (CoG) at any instant of time lies within the support polygon. The static stability criterion for a robot, therefore, requires it to stable in its position, if the robot is stopped at a time instant.

In this section, we improve upon the planning technique as suggested by [7], identifying issues in it and proving our improvements geometrically as well as mathematically.

2.1 Issues in conventional crawl gait

Ma et al. in [7] have described the planning technique of crawl and rotation gait of a quadruped robot. The resultant crawl gait is shown in Fig. 2. A major criterion to evaluate the static stability of the robot is the stability margin (S). It is defined as the minimum distance of the CoG from the edges of the support polygon in the direction of movement.

The crawl gait in Fig. 2 has four steps per cycle and has stability margin equal to 0 in the second and the fourth phases. When the swinging leg lifts off the ground the center of mass of the system will not be at the geometric centre as assumed. It will dislocate to a position whose vertical projection might not be within the support polygon due to which the robot will topple at this stage.

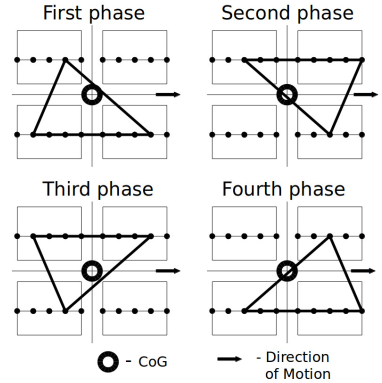

Figure 2: Position of CoG w.r.t support triangle during phases of conventional crawl gait.

In order to overcome this disadvantage, the following section systematically establishes relationship between gait parameters such as stability margin, stride length and duty factor.

2.2 Quantitative Analysis

We first familiarize ourselves with two gait parameters relevant to our analysis - Duty Factor and Stride Length. The duty factor of a gait with stability margin S is defined as the fraction of time for which the leg i is in contact with the supporting surface, in our case the ground, during one complete cycle of the gait such that it has a stability margin of S. It is denoted by $\beta_i(S)$. The stride length is defined as the total length traversed by the body of the robot during one complete cycle of the gait with a stability margin of S. It is denoted by $\lambda(S)$.

The symbol E is the distance on the supporting surface traveled by a leg within the reachable limits of each leg. For the crawl gait shown in Fig. 4, it is simply the distance between the points 0 and 5.

Here, we compare the metrics of the conventional gait to our modified gait. We try to mathematically establish the facts we theoretically explained in the preceding sections. We also show that in a standard gait with a positive stability margin, all the legs need to be in support phase for sometime during one complete cycle.

2.2.1 Conventional crawl gait

For the marginally stable conventional crawl gait, let the length of each of the three parts of each leg's path in Fig. 2 be equal to $A(0)$. In case of the conventional gait, the legs reach is three parts of the four segments shown in Fig. 2. Thus,

$$E = 3A(0)$$

The stride length, λ, is given by

$$\lambda = 4A(0)$$

The duty factor, by definition, is given by the ratio of distance traveled by one leg to the total distance traveled

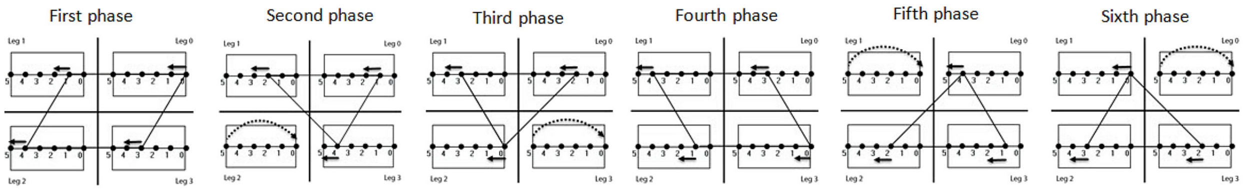

Figure 3: Modified Crawl gait

by the whole body in one complete cycle of the gait. So,

$$\beta = \frac{E}{\lambda} = \frac{3A(0)}{4A(0)} = \frac{3}{4} \tag{1}$$

Thus, it is established that in conventional crawl gait with zero stability margin, the duty factor is equal to 0.75.

2.2.2 *Modified Crawl gait*

In order to improve the stability margin, we introduce an additional phase to the conventional crawl gait in which all the legs are in support phase as shown in [8]. In this phase, the CoG is moved in the forward direction to facilitate enhanced stability margin in the subsequent phase. It is worth noting that any addition of such phase is at the cost of speed of the quadruped robot. Therefore, number of such additions has to be minimum just to ensure required stability margin. Keeping above trade-off in mind, we present the modified crawl gait as shown in Fig. 3. The motion of the robot in each phase is summarized in Table 1.

Next, we derive the condition for positive stability margin using the general relationship between duty factor, stride length and stability margin.

In contrast to conventional crawl gait, the modified version uses the entire reachable region of each leg as E. From Fig. 4, the leg's reachable region is given by

$$E = A(S) + 2S + A(S) + A(S) + 2S \tag{2}$$

Thus,

$$A(S) = \frac{E - 4S}{3} \tag{3}$$

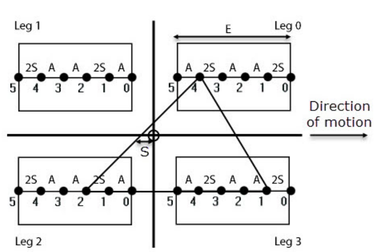

Figure 4: Foothold positions in X-crawl

Now, from the Table 1, we can calculate the distance traveled by the CoG after one complete cycle, that is after all the six phases. This is nothing but the stride length $\lambda(S)$,

$$\lambda(S) = 2S + A(S) + A(S) + 2S + A(S) + A(S) \tag{4}$$

Phases	1	2	3	4	5	6
Leg 0 position	0	1	2	3	4	5
Leg 1 position	1	2	3	4	5	0
Leg 2 position	4	5	0	1	2	3
Leg 3 position	3	4	5	0	1	2
Body moves	$2S$	$A(S)$	$A(S)$	$2S$	$A(S)$	$A(S)$
Transfer leg	x	2	3	x	1	0

Table 1: Summary of the motion in modified crawl gait

Upon substituting Eq. (3) in the above, one obtains

$$= \frac{4}{3}(E - S) \tag{5}$$

The duty factor, $\beta(S)$, is given by

$$\beta = \frac{E}{\lambda(S)} = \frac{E}{\frac{4}{3}(E - S)} = \frac{3}{4}\frac{E}{E - S} \tag{6}$$

For a positive stability margin, $S \geq 0$, it is clear from the Eq. (6) that

$$\beta \geq \frac{3}{4} \tag{7}$$

The same can be alternatively arrived at as follows. From the definition of duty factor one can obtain,

$$E = \lambda(S)\beta$$

Solving Eq. (5) and substituting the above expression for E, we get

$$S = \lambda\Big(\beta - \frac{3}{4}\Big) \tag{8}$$

From Eq. (8), $S \geq 0$ if and only if $\beta \geq \frac{3}{4}$.

Thus, for the conventional crawl gait shown in Fig.2, $\beta = 0.75$ as given by Eq.1. There is no time instant in the whole cycle of the gait when all four legs are on the ground. $\beta > \frac{3}{4}$ means that all the legs will be on the ground for some time. Thus, the modified crawl gait, illustrated in Fig. 3, has a positive stability margin at all times and forces all of the legs to be in support phase for some time in one complete cycle.

3. PLANNING METHODOLOGY OF OMNIDIRECTIONAL STATIC WALKING

Based on above observations, we modified the crawl gait with some positive stability margin. Planning of the standard gaits can be broken down into following tasks:

1. Planning the lifting and landing positions of the feet within each leg's workspace.

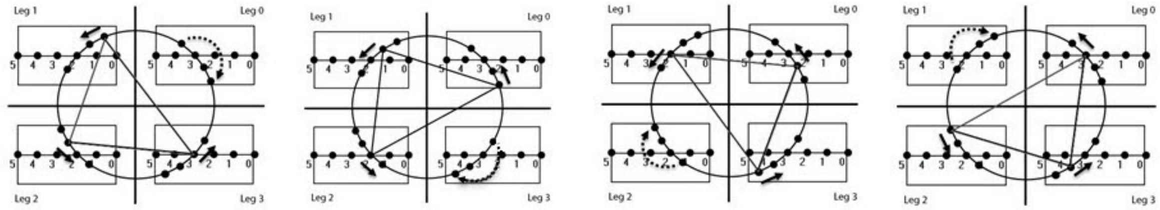

Figure 5: Rotation gait

2. Planning the support and swing sequences of the legs according to the gait chosen.
3. Planning the trajectory of the legs keeping in mind the mechanical constraints of each leg.
4. Planning the transition between gaits with minimum number of steps.

3.1 Lifting and landing positions of the feet

The different phases of modified crawl gait and rotation gait over one complete cycle are shown in Fig. 3 and Fig. 5 respectively. The rectangle represents the boundary of the workspace of each leg while the marked positions (0,1...,5) are the points through which the feet traverses as it moves. The frame of reference is attached to the CoG of the robot and hence is represented by the origin of the co-ordinate axes. A leg enters its flight phase when it reaches the end of the reachable workspace in the direction opposite to the direction of walking. The leg then swings ahead to maintain repeatability of the gait. The legs in the support phase keep sliding one step back until they enter the flight phase. This makes the body move forward and achieve the state of walking. In rotation gait, the trajectory of each leg is a circle about the CoG of the robot.

3.2 Planning the support and swing sequences of the legs

The standard gaits of omnidirectional static walking viz. crawl gait and rotation gaits have defined support and swing sequence of the legs. Direction-based variants of these two gaits constitute the X-Crawl, RX-Crawl, Y-Crawl, RY-Crawl, O-Rotation and RO-Rotation gaits. Here, X, Y represents the direction of crawl, O represents anti-clockwise rotation and 'R' indicates reverse crawl/rotation. In these gaits, the sequence of the swinging leg differs which depends on the direction in which the robot is moving forward or turning about.

3.3 Planning the trajectory of the legs

The supporting legs have to move in a straight line in between the two successive points for the body to move one step without wobbling. The trajectory of supporting legs can be posed as the problem of moving an end-effector from its initial position to a goal position in a certain amount of time. The set of joint angles that correspond to the goal position and orientation can be calculated using Inverse Kinematics. For the joint angle function we choose a cubic polynomial and try to solve for the coefficients with the joint velocity and joint position as known information.

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{9}$$

With the function of joint angle given over time, the end-effector i.e. the foot in our case, can be moved from one point to other. Using the solved coefficients of the polynomial, we can only ensure the initial and final values of joint positions and velocities. Since no restrictions are placed on the values in between, the path taken by the foot need not be a straight line. To overcome this problem, we use a piece-wise approach and specify many closely separated via points lying on a straight line for crawl gait or on a circular arc for rotation gait. This way, the foot will appear to follow a straight line or a circular arc, regardless of the choice of smooth function that interconnects the via points. All we need to ensure is that the velocities are continuous at each point.

The trajectory of the swinging leg does not affect the support polygon. Its effect on the movement of CoG is also limited. Therefore, it just has to be within mechanical constraints and should lift above the ground to a sufficient height. Thus, we specify just one intermediate point to ensure the leg lifts high enough to not graze the ground while moving.

3.4 Successive gait transitions

To achieve omnidirectional walking, the robot needs to switch between the variants of the standard gaits quickly and efficiently. Therefore, gait transitions have to be implemented to enable this. In successive gait transition, the feet positions in each gait are chosen in a way so that there are some common feet positions between them for the transition to happen in minimum number of steps. The same is illustrated in the Fig. 6. The transition using the common point should follow the same static stability criteria described earlier.

Gait transitions can be between two crawl gaits or between a crawl gait and a rotation gait. The gait transition from X-crawl to Rotation is shown in Fig. 7. Here, Leg 0 is at the common point during the transition. Other transitions like X-Crawl to Y-Crawl are executed in a similar fashion and shown in Fig. 8.

4. SIMULATIONS AND EXPERIMENTAL RESULTS

To validate the methodology proposed in previous sections, simulations and experiments were performed, the results of which are discussed below.

4.1 Simulation Results

Simulation tests were performed to validate the stability of the modified crawl gait. The quadruped model with three joints in each leg was used for simulation. The observations

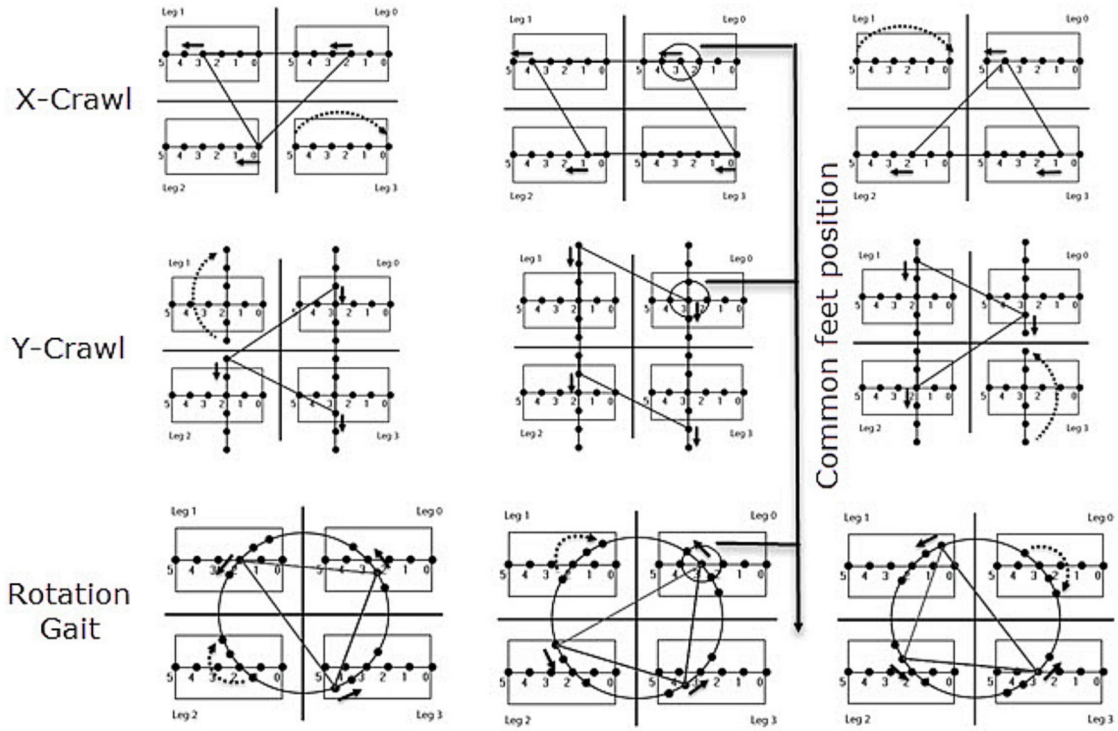

Figure 6: Common feet position in all the basic gaits

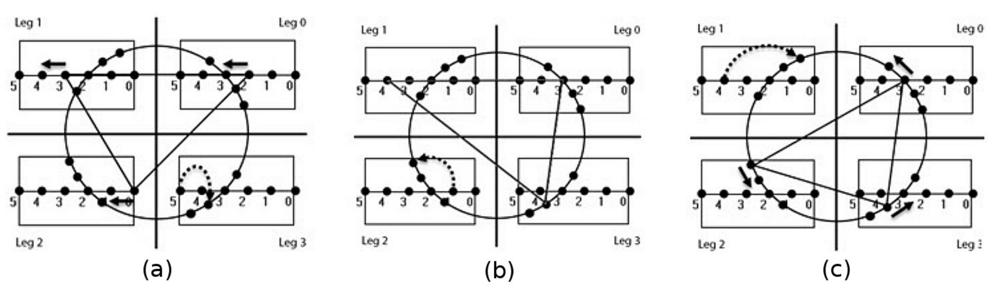

Figure 7: Transition from X-crawl to Clockwise Rotation. (a) Leg 3 swings to its new position with the other three moving one step back with respect to CoG. Leg 0 reaches the common point of the transition. (b) Leg 2 moves to its new position with the other three legs stationary. (c) Leg 1 swings to the new position with the other three moving one step in anti-clockwise direction with respect to CoG.

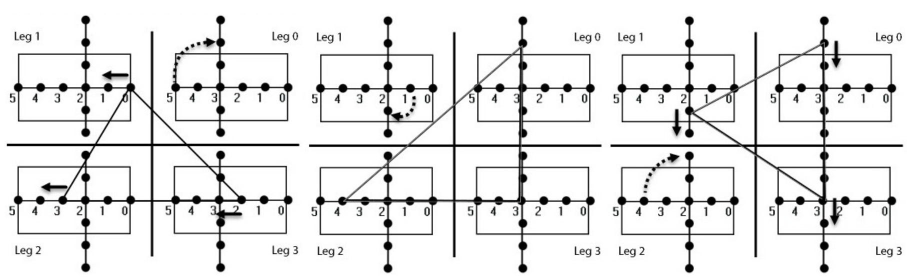

Figure 8: Transition from X-crawl to Y-crawl. Leg 3 is the common point of the transition.

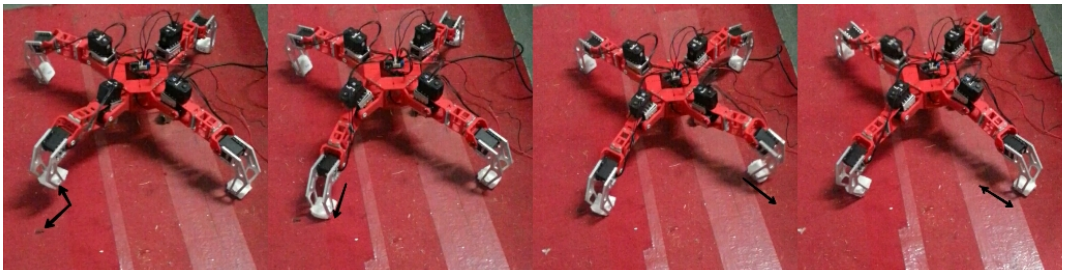

Figure 9: Walking of the robot in X-direction. In a) and b) the front left leg is shown moving a distance in the forward direction. This is the third phase described in Fig. 4. In c) and d) the front right leg is shown moving a distance in the forward direction. This is the sixth phase shown in Fig. 4. With similar actions by all four legs, robot moves forward.

were made for a path that involved X-crawl, X-to-Y transition, Y-crawl, and Y-to-X transition.

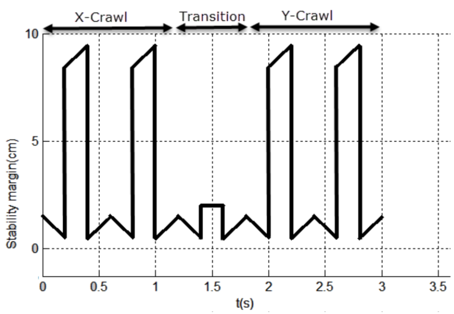

Figure 10: Stability Margin during X-Crawl, X-to-Y Transition, and Y-Crawl

Fig. 10 shows the stability margin of the robot during the complete traversal on the preplanned path. The graph clearly shows that stability margin is always positive during the crawl and transition stages.

4.2 Experimental Results

Validation of above numerical and simulation results was done using an experimental robot fully designed and developed for this purpose. The design of the robot was inspired by TITAN-VIII model of quadruped robot developed in [6]. The quadruped robot is shown in Fig. 1. The robot has a central chassis for housing control equipment and limb-lengths of 11.737cm and 12.323cm.

The static walking ability of the robot was tested on a rough surface in one direction as shown in Fig. 9. It was observed that the stability of the robot improved considerably albeit at the cost of the speed of the walk. The robot was able to walk without falling or wobbling which was observed in the conventional crawl gait. This validates the proposed change in the planning of the crawl gait.

5. CONCLUSION

Quadruped robots are intended to traverse difficult terrain for reconnaissance, surveying and other important tasks. Difficult terrain demands increased stability of the robot for successful walking as well as safety of robot. The paper successfully demonstrated the increased stability margin with the modified crawl and rotation gaits. Mathematically, we were able to demonstrate the validity of our claim of increased stability. Simulations were performed which showed the stability margin remains positive throughout the walking of the quadruped robot. Experiments performed on a model quadruped robot showed the omnidirectional static walking with more stability. However, the increase in stability also brought about decrease in speed. The paper brings into focus the future investigation into this domain - the optimization of stability vis-a-vis speed of the robot.

6. REFERENCES

[1] Rebula, J. R., Neuhaus, P. D., Bonnlander, B. V., Johnson, M. J., Pratt, J. E. (2007). A controller for the littledog quadruped walking on rough terrain. ICRA, 1467-1473.

[2] Raibert, M., Blankespoor, K., Nelson, G., Playter, R. (2008). Bigdog, the rough-terrain quadruped robot. In Proc, of the 17th World Congress, 17(1), 10822-10825.

[3] Shimoyama, I., Miura, H., Horita, M., Hattori, Y. (1991). Analysis of walk for quadruped. IROS, 1541-1544.

[4] Fukuoka, Y., Kimura, H., Cohen, A. H. (2003). Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts. The Int. J. of Robotics Research, 22(3-4), 187-202.

[5] Ijspeert, A. J. (2008). Central pattern generators for locomotion control in animals and robots: a review. Neural Networks, 21(4), 642-653.

[6] Hirose, S., Yoneda, K., Tsukagoshi, H. (1997). Titan VII: Quadruped walking and manipulating robot on a steep slope. ICRA, 1, 494-500.

[7] Ma, S., Tomiyama, T., Wada, H. (2005). Omnidirectional static walking of a quadruped robot.Transactions on Robotics, 21(2), 152-161.

[8] Lee, T. T., Shih, C. L. (1986). A study of the gait control of a quadruped walking vehicle. J. of Robotics and Automation, 2(2), 61-69.

[9] Kim, B. H. (2009). Centroid-based analysis of Quadruped-robot Walking Balance. Int. Conf. on Advanced Robotics, 1-6.

[10] McGhee, R. B., Frank, A. A. (1968). On the stability properties of quadruped creeping gaits. Mathematical Biosciences, 3, 331-351.