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Control of a Quadruped Robot with Enhanced Adaptability over Unstructured Terrain

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***Abstract*— Improvement of the adaptability of a quadruped robot in rough terrain is studied in this paper. First, the position and posture of the body of the robot are adjusted to maximize the number of choices for foot placement of the next swing leg. The more choices the robot has to select the next suitable foothold, the better it will be to cope with rough terrain. Second, an effective foothold search algorithm is developed. The foothold search algorithm not only tries to find a valid foothold but also tries to maintain high adaptability of the robot. For implementing the algorithm, some new concepts such as potential swing direction, complementary kinematic margin and elliptical set of candidate footholds are also proposed. The effectiveness of this procedure in improving the adaptability of a quadruped robot moving in challenging terrain is verified in both simulation and experiment.**

I. INTRODUCTION

A legged robot has become a popular subject in robotics because of its outstanding performance in uneven terrain, where a wheeled vehicle shows poor mobility. Therefore, one of the most important characteristics of a legged robot is its adaptability to rough environment (in legged robot field, adaptability can be understood as the ability to overcome the roughness of the environment). The importance of adaptability has been the focus of several recent researches on legged robots in which the researchers have tried to let the robot challenge the more and more rough terrain [1]–[6].

However, body motion of the robot was not exploited to improve the robot's adaptability in previous work. Instead of the adaptability, body motion was used to minimize the traveled distance of the center of gravity (CoG) [2], to obtain a better stability in rough terrain [3], to have a continuous profile of velocity and acceleration [4] or to follow a planned trajectory [5]. In fact, in more challenging terrains with many bad areas for foot placement, previous work which only concentrated on finding the appropriate foothold may lose some possibility of overcoming the environment. In such terrains, the algorithms could find only some or even no points to evaluate in order to find the solution. Since the number of choices for evaluating is decreased, the chance to find a stable solution is decreased thus resulting in reduction of the adaptability of the robot. In such situations, it is necessary to find a way to increase the *not-bad* area in advance for the robot to place the next foothold before developing a foothold search algorithm. Besides, in the previous researches [1]–[6], the foothold search algorithms only find a position to place the next foothold based on the quality of the geometric conditions around that position. Actually, the quality of the position to place the next swing leg is closely related with the positions of the other legs and the posture of the robot. The selection of the next foothold based solely on geometric conditions may restrict the motion of the robot in some of the next steps, thus reducing the adaptability of the robot.

In this work, we propose an algorithm which concentrates on improving the adaptability of the quadruped robot in challenging terrain. First, an algorithm for adjusting the body of the robot to maximize the stable area for foot placement of the next swing leg is studied. With more choices for choosing a stable foothold, the robot will have a better chance to overcome the challenging environment. In addition, a foothold search algorithm that maintains a high adaptability of the quadruped robot is proposed. The algorithm will not only evaluate the geometric conditions of the terrain but also consider the relation between the foothold of the next swing leg and the positions of the other legs to find the next foothold. Recently, quadruped robot researchers tend to let their robots walk with simultaneously moving of body and swinging of leg to increase walking speed. In such a gait, the robot always tends to move its body forward, but the backward motion is restricted. In our algorithm, it is shown that a higher adaptability of the robot can be obtained by moving the body backward in many cases. Therefore, in order to achieve the highest adaptability of the robot as possible, the body motion is generated separately with the swinging of the leg in this work. Section II briefly describes the relation between the posture of a quadruped robot and foothold selection with respect to the robot's adaptability. In Section III, details on finding the location of the body which leads to the largest stable area for next placement of the swing leg are presented. Then, a foothold search algorithm is explained in Section IV. Simulations are conducted in Section V to prove the effectiveness of the proposed algorithm. Conclusion and future work are discussed in the last section.

II. Effect of Body Posture and Foothold Selection to Adaptability of Quadruped Robot

In this section, two new features of the quadruped robot that affect the adaptability of the robot are presented: body motion and foothold placement.

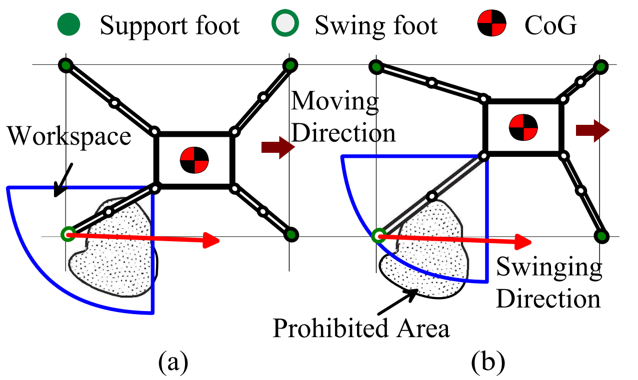

Fig. 1. Various different "reach-ability" with different positions of body.

A. Stance of quadruped robot and adaptability

With the same four foot locations, a quadruped robot can move and/or rotate its body to have different center of gravity positions and body's orientations (yaw, pitch, and roll angle). A certain combination of body position and orientation is called a stance.

In addition, the workspace of a leg of a quadruped robot is a part of a determined sphere whose center is at the scapula joint of the body of the robot. Thus, all the different stances according to the different positions of the body will give different locations of the swing leg, and thus, lead to different reach-ability (here, reach-ability is kinematical ability to reach to a point by the swing leg as the robot still maintains its stability) of stances which have the same four foot locations, as illustrated in Fig. 1. In Fig. 1 (a), with the relevant position of the CoG of the robot, the next swing leg cannot reach to the area behind the obstacle. However, when the robot moves its body to the position as shown in Fig. 1 (b), the reach-ability of the robot is improved and the next swing leg can reach to the area behind the prohibited area. At this position, the robot can avoid the prohibited area and successfully overcome the given environment, proving the enhanced adaptability of the robot.

Thus, a proper way to help a quadruped robot overcome a natural, rough environment is to find the best stance that can maximize the robot's reach-ability.

B. Foothold selection and adaptability

In rough terrain, the robot has to change its swinging direction and stroke distance continuously because of obstacles or bad geometric areas. Then, the robot may have an inconvenience set of footholds, which will limit its reach-ability. In such a case, the robot may easily meet a deadlock situation after a few steps because of its reduced step-by-step adaptability after each walking cycle. A case of an immediate deadlock situation in the next step is illustrated in Fig. 2. If the robot just swings leg 2 forward, a normal stride length from the foothold F_2 to the point F_2', the robot will meet a deadlock situation in the next step. When leg 2 is placed to F_2', the COG is locked inside *Diagonal Support Quarter (DSQ)* F_3IF_4 (the support polygon is divided into four DSQs by Diagonal Support Line I and II). The robot cannot move the CoG to DSQ F_4IF_2' to swing leg 3 because its body motion is limited by the reach-ability of leg 2 in this situation. Similarly, the robot cannot move its CoG to DSQ F_3IF_1 to swing leg 4 because of leg 1 will go out of its workspace in this situation. The robot also cannot move its CoG to DSQ F_1IF_2' to swing leg 3 or 4 due to restriction of workspace of leg 3. This leaves only leg 1 as the swing leg after leg 2 is swung. However, leg 1 is near the boundary of its workspace. Moving leg 1 forward only worsens the deadlock situation; thus, the robot is stuck in a deadlock situation. On the other hand, the robot can easily avoid this deadlock situation by placing leg 2 to the point F_2'' in the next step. In that stance, the robot is given a much larger moveable area for its CoG. By adjusting the CoG to other DSQ, the robot can swing any leg to move forward.

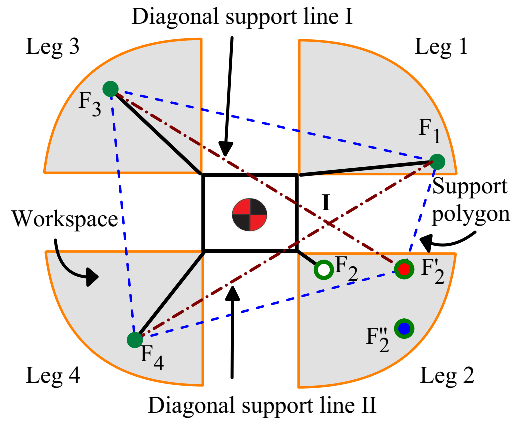

Fig. 2. Foothold selection and deadlock situation.

Therefore, only evaluating the quality conditions of the terrain to find the next foothold is not sufficient. It cannot prevent the robot from avoiding a deadlock situation, which is one of the most serious reasons that ruin the locomotion of a quadruped robot in rough terrain.

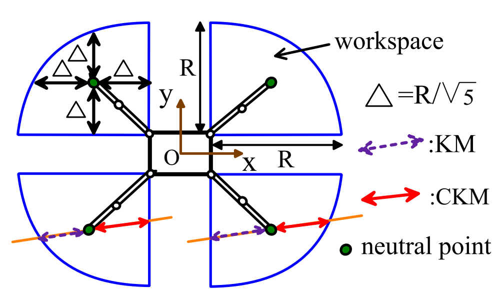

Fig. 3. Concept of the desired posture and CKM.

III. Body adjustment algorithm

To simplify the problem, we only deal with the position of the robot, not the stance of the robot (the yaw, pitch, roll angles of the body are not considered yet). Here, two questions arise, “where should the body position be moved to?” and “how do we know the best position?”.

A. Definitions and notations

1) Recovery Foothold and Recovery Swing Direction: In order to prevent from a deadlock situation, our robot was kept around a posture that had high flexibility, which is called the desired posture.

Definition 1: A *desired posture* is the posture where all the legs are at the neutral points of their workspaces and the height of the body is at a specific desired height (neutral point of a workspace is the point that the distances from it to the boundary of the workspace along *x*– and *y*–direction are same).

The concept of the desired posture is illustrated in Fig. 3. The robot always has high flexibility for changing its posture and swinging the next swing leg by controlling its legs around the neutral point of their workspace. Due to this high flexibility, the robot has a better chance to overcome the rough environment. For controlling the robot to the desired posture, *recovery foothold* and *recovery swing direction* are defined.

Definition 2: *Recovery foothold* is the foothold of the next swing leg that leads the robot to the desired posture in the next walking cycle.

Definition 3: The swing direction of the next swing leg to place the foot to the recovery foothold is called *recovery swing direction*.

2) Potential Swing Direction: The body of the robot is moved to maximize the reach-ability of the next swing leg along its swinging direction. In flat terrain, the swing direction is simply the recovery swing direction (also the main locomotion direction). However, in rough terrain, the recovery swing direction may not give a valid foothold due to an obstacle. Therefore, the quality of the recovery direction should be checked in advance. If the recovery direction is a bad solution, another direction that may give a higher possibility of finding a valid foothold should be found. Furthermore, the direction should not deviate too far from the recovery swing direction so that the posture of the robot can be maintained around the desired posture. Therefore, a potential swing direction is proposed as follows.

Definition 4: *Potential swing direction* is defined as the direction of swinging of the next leg that is nearest to the recovery swing direction (the angle made of the potential swing direction and the recovery swing direction should be minimized) and gives sufficient possibility of finding a valid foothold.

3) Complementary Kinematic Margin: In the field of legged robots, Kinematic Margin (KM) is defined as the distance that the foothold of a given leg can travel in the opposite direction of motion before reaching the boundary of the workspace [8]. In this work, since reach-ability of a swing leg is the focus, Complementary Kinematic Margin (CKM), which has the opposite meaning as Kinematic Margin, is introduced. It is defined as follows.

Definition 5: *Complementary kinematic margin* is the distance that the foothold of a given leg can travel in a given direction before reaching the boundary of the workspace.

Fig. 3 illustrates the concept of both KM and CKM. As shown in the figure, CKM exactly represents the reach-ability of a leg of the robot at that stance.

B. Algorithm

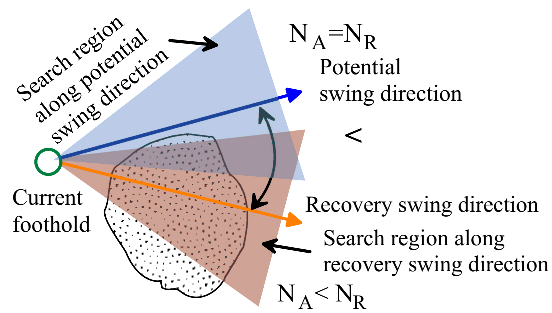

Fig. 4. Varying the search area to find the potential swing direction.

1) Determination of recovery foothold and recovery direction: To easily determine the recovery foothold in each step, the robot is allowed to start moving into the desired posture. Thus, the desired recovery foothold of the next swing leg is simply determined by adding a normal stroke length to the current foothold along the moving direction. In rough terrain, there may be an error between the recovery foothold and the real foothold due to obstacles. The error is recorded and will be compensated in calculating the recovery foothold of the next step to make the robot move back to the desired posture. The recovery swing direction is simply the direction from the current foothold to the recovery foothold.

2) Determination of potential swing direction: Terrain Evaluation: First, a terrain scorer is executed to pre-evaluate the quality of each cell of the given terrain when the robot is setup. The terrain cells are classified into acceptable cells and unacceptable cells. An acceptable cell is a cell which is not near the boundary of any obstacle, not inside a hole and not on a hard slope surface.

Checking whether the recovery foothold is an acceptable cell or not: If the recovery foothold is on an acceptable cell, the potential swing direction is the same as the recovery swing direction. If the recovery foothold is an unacceptable cell, the robot should check the possibility of finding a valid foothold around the recovery foothold.

Checking possibility of finding a valid foothold along recovery swing direction: The possibility of finding a valid foothold is represented by the number of acceptable cells inside a triangular region around the search direction, which called the search region, as illustrated in Fig. 4. If the number of the acceptable cells inside the search region N_A in the recovery direction is bigger than required minimum number of acceptable cells N_R, the potential swing direction becomes the same as the recovery swing direction. If the possibility of finding a valid foothold around the recovery swing direction is small ($N_A < N_R$), the robot has to find another swing direction that will give sufficient possibility of finding a valid foothold – potential swing direction.

Varying recovery swing direction to find the potential swing direction: When $N_A < N_R$, the robot varies the search region step by step around the recovery swing direction until $N_A \geq N_R$. To keep the potential swing direction near the recovery direction, the search angle β (made of the potential swing direction and the recovery direction) is limited from $-\alpha$ to α where α is maximum angle of search. If the robot cannot find any solution around the recovery swing direction (N_A is always smaller than N_R), it means that there is a large obstacle in front of the robot. In that case, the robot just chooses the recovery swing direction as the potential swing direction. Lastly, the robot may be able to overcome that big obstacle by adjusting the body to a suitable position to yield a long stride.

Fig. 4 illustrates the concept of finding potential swing direction. The side of the search region, value of N_R and α depend on the configuration of the robot and the given rough environment and the rate of the successful tests using those values. For example, if the rate that a specific robot can overcome a given environment is very low with a small value of N_R, it is recommended to increase the value of N_R until the successful rate is sufficient.

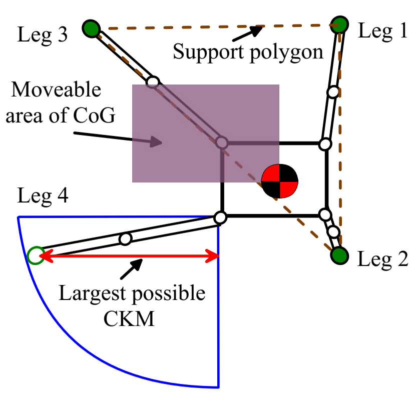

Fig. 5. The position of CoG for maximum reach-ability of leg 4 .

3) Determination of next body position: After obtaining the potential swing direction, the robot scans all the possible positions of the CoG (with the same four footholds) that are stable when the next leg is swung (the CoG is inside the supporting polygon when the next swing leg is swinging). The position of the CoG that has the largest CKM along the potential swing direction will have the maximal number of acceptable cells inside the search region. If many positions of CoG have the same largest CKM, the position with the shortest moving distance is the best position. Fig. 5 shows the position of the CoG that has maximum reach-ability for the next swing leg. The sequence of the CoG position search algorithm is presented in Fig. 7.

IV. Foot Placement Algorithm

The foothold search algorithm should be able to find a valid foothold for the next swing leg. It also should maintain the posture of the robot around the desired posture to allow the robot to have high adaptability. In addition, the algorithm must be able to perform real time calculation. To cope with these requirements, *potential foothold* and a *set of potential footholds* are proposed.

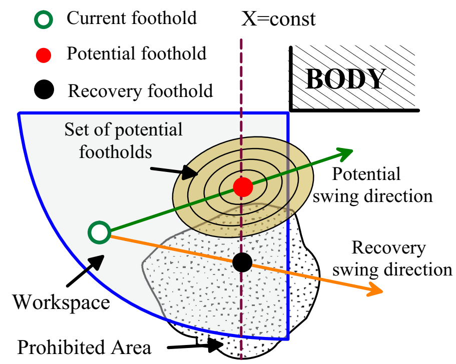

Fig. 6. The potential foothold and the elliptical set of candidate footholds.

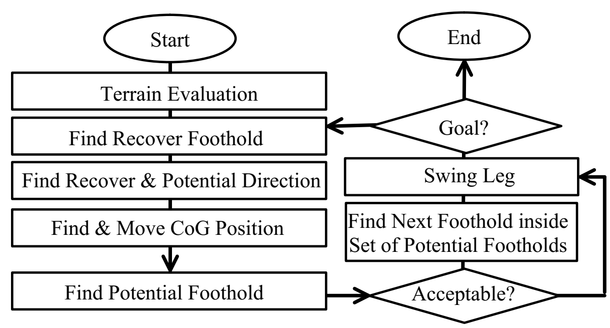

Fig. 7. Flowchart of the proposed algorithms.

A. Potential Foothold and Set of Potential Footholds

Definition 6: the *potential foothold* is the foothold that has the highest possibility to be chosen as the next leg placement.

Definition 7: In this work, a *set of potential footholds* is defined as an elliptic region whose center is the potential foothold. The shape of the set is an ellipse instead of a circle because a deviation along the swing direction does not affect to the main locomotion direction as oppose to deviation perpendicular to the swing direction does. For simplicity, the aspect ratio of the height and width of the ellipse is determined to be equal to 1:2. The concept of the set of potential footholds is depicted in Fig. 6.

B. Algorithm

1) Determination of the potential foothold: The error between the desired posture and the current posture occurs mainly along the moving direction because the robot swings its leg along the moving direction to move forward. Therefore, the potential foothold is determined as the projection of the recovery foothold to the potential swing line along the direction that is perpendicular to the moving direction as shown in Fig. 6 This method of determining the potential foothold ensures the smallest error between the current posture and the desired posture along the moving direction.

2) Finding the next foothold inside the set of potential footholds: To save calculation time, the robot finds the next foothold inside the set of potential foothold in advance. The robot checks the quality of a foothold that is inside the set of potential foothold against three features. First, the foothold must be inside the workspace. Second, the foothold must be in an acceptable cell. The foothold that satisfies these two features and has the shortest distance to the potential foothold will be chosen as the next foothold. If the robot cannot find any valid foothold inside the set of potential footholds, it extends the search outside the set. However, since the potential swing direction ensures a high possibility of finding a valid foothold in most of the cases, such an extension search is rarely needed. The whole sequence of the foothold search algorithm is shown in Fig. 7.

V. RESULTS

A. Outline of MRWALLSPECT IV robot

In this section, the effectiveness of the proposed algorithm is verified through the walking performances of a quadruped robot named MRWALLSPECT IV (MR4). The robot was upgraded from MRWALLSPECT III robot [9]. The main controller of MR4 is a single board computer (Pentium III 900MHz) using RTLinux (version 2.4.22) as the operating system. Fourteen local control units control the motion of the legs and send all the sensed information to the main controller by using CAN protocol (up to 1MB baudrate). The length of its leg is 550 (mm) with 226 (mm) of thigh and 226 (mm) of tibia. The length of its body is 226 (mm).

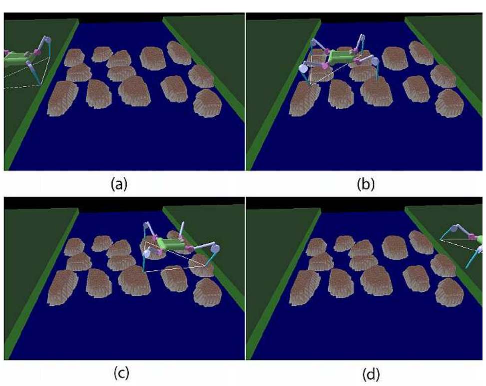

Fig. 8. MR4 is crossing a stream containing some rocks. It is a hard mission because distances between the rocks are large. The robot cannot place its legs on the slope surface or edge of the rocks as well as the water.

B. Simulations

In the simulations, the robot had to cross over a stream containing only some rocks. The distances between any two rocks were quite large and varied from 180 (mm) to 280 (mm), nearly half the length of the robot's leg. A terrain scorer was executed to classify the map into acceptable cells

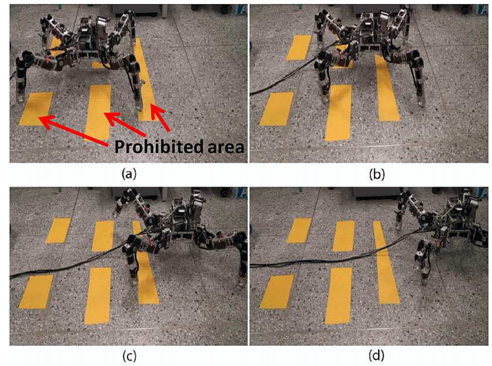

Fig. 9. MR4 robot is passing through a real environment containing several prohibited area. The robot must travel over all the prohibited areas without placing its foot on them.

and unacceptable cells. The calculation time takes around one minute depending on the complexity of the terrain. The robot could place its foot only on the acceptable cells (flat surface of the rocks), not on the unacceptable cells (edge and slope surface of the rock, the water surface). The sequence of the MR4 robot crossing through the stream is shown in Fig. 8. This could be done by proficiently controlled the robot's body to the position that gave the largest reach-ability for the next swing leg, as it was illustrated in the figure. The body was always inside the white triangular support polygon and the reach-ability of the swing leg at that stance was very large. In addition, the robot had to avoid a deadlock situation, which commonly occurs in such an environment. However, since the foothold search algorithm considered the positions of the other legs carefully, the robot was able to always maintain its high adaptability posture as shown in the figure. Step by step, the robot traversed from its initial position to the desired target in the opposite shore of the stream.

C. Experiments

Due to the limitation of time, there is a gap between the simulation and the experiment. The real environment contained five large size prohibited areas, which were represented by the polygons as shown in Fig. 9 (a). The largest prohibited area was up to 180 (mm) in length. The polygons are irregular in shape and placed confusingly on the terrain. Except the given map, the robot was fully automated and walked in the environment without any intervention from human. As shown in Fig. 9, the robot did not place its legs inside the prohibited areas through the travel. The robot always maintained a high reach-ability for the next swing leg by moving its body effectively. As shown in the figure, the robot overcame all the large size prohibited areas by properly adjusting the body position and placing the swing leg. Even when several prohibited areas were placed quite near each other and continuously, the robot was not confronted with a deadlock situation because it kept its posture around the desired posture of high adaptability. When the robot successfully passed over all the prohibited areas, it recovered to the desired posture as shown in Fig. 9 (d).

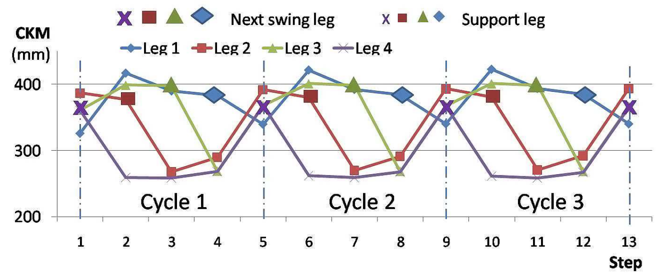

Fig. 10. CKM of foot when the robot is walking in a flat terrain.

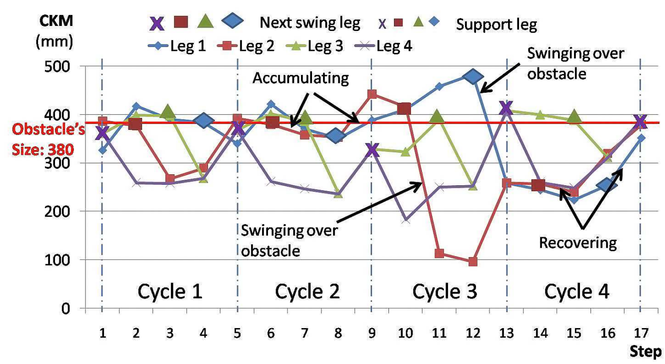

Fig. 11. CKM of foot when the robot is swinging its fore legs over a 380 (mm) large size obstacle.

Fig. 10 shows the benefit of using the body adjusting algorithm. In Fig. 10, the CKMs of all legs at the moment before swinging the next swing leg were plotted. We can see that the robot always had a high reach-ability for the next swing leg. As shown in the figure, the CKM of the next swing leg was around 360(mm); nearly 65 percentage of the leg's length. We also can verify that the desired posture is the posture that has the highest adaptability by plotting CKMs of all legs. In our tests, we saw that any posture, which is not the desired posture, will have the CKM (or reach-ability) of one of the swing legs smaller than 360 (mm).

Fig. 11 gives an illustration on the effectiveness of the foothold search algorithm. The figure shows CKM of all legs when the robot was swinging its fore legs over a 380 (mm) length obstacle; 70 percentage of the leg's length. When the robot was far from the obstacle (cycle 1), the CKM of all legs was almost the same with the CKMs of Fig. 10. However, when the robot approached the obstacle (cycle 2), the algorithm selected the footholds how to accumulate the CKMs of the fore legs. In cycle 3, where CKMs of both fore legs were bigger than the size of the obstacle, the robot swung its fore legs over the obstacle. In cycle 4, the robot decided the footholds of the fore legs how to recover to the desired posture. The robot will recover to the desired posture after cycle 5.

With the notation of the potential swing direction, the number of choices for choosing the next foothold is ensured to be big enough. Therefore, the next foothold was always found inside the set of potential footholds in all of our tests. It helps to reduce search time significantly thus ensuring the realtime requirement.

VI. Conclusion

In this work, we presented an algorithm to improve the adaptability of a quadruped robot in a challenging environment. Before swinging the next leg, the body of the robot was controlled to maximize the reach-ability of the next swing leg. In addition, the posture of the robot was always maintained around the desired posture that gives a high adaptability by choosing the foot placement of the next swing leg with consideration of the positions of the other legs. Except the time for scoring the terrain cells, the algorithm runs very fast in real-time since it is purely geometrical calculation. Using the proposed methods, the quadruped robot did have a high adaptability in rough terrain. The result showed that the size of the obstacle that the robot can overcome was up to 70 percentage of its leg's length.

Since CKM exactly represents the reach-ability of the next swing leg, it may be a useful tool for studying other problems of a walking robot, like Stability Margin (SM), duty factor or Kinematic Margin (KM). In addition, the theories and verification were presented with a quadruped robot that has a sprawl posture. However, the robot with a upright posture can use the same theories with minor modifications.

Up to now, we have only dealt with the 2D position of the CoG. Optimizing the 3D stance of a quadruped robot promises a much better performance in rough terrain.

VII. Acknowledgements

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