Gait Planning of Quadruped Walking and Climbing Robot in Convex Corner Environment

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Abstract: When a robot navigates in the real environment, it frequently meets various environments that can be expressed by simple geometrical shapes such as flat floor, uneven floor, floor with obstacles, slopes, concave or convex corners, etc. Among them, the convex corner composed of two plain surfaces is the most difficult one for the robot to negotiate. In this paper, we propose a gait planning algorithm to help the robot overcome the convex environment. The trajectory of the body is derived from the maximum distance between the edge boundary of the corner and the bottom of the robot when it travels in the convex environment. Additionally, we find the relation between kinematical structure of the robot and its ability of avoiding collision. The relation is realized by considering the workspace and the best posture of the robot in the convex structure. To provide necessary information for the algorithm, we use an IR sensor attached in the leg of the robot to perceive the convex environment. The validity of the gait planning algorithm is verified through simulations and the performance is demonstrated using a quadruped walking robot, called "MRWALLSPECT III"(Multifunctional Robot for WALL inSPECTion version 3).

Keywords: Overcoming convex corner,Walking and Climbing Robot, MRWALLSPECT III

1. Introduction

Recently, many applications require robots to perform tasks in place where workers and traditional vehicles can not reach. Among the various types of the robot, quadruped walking and climbing robots are one of the appropriate solutions for these applications because they have outstanding mobility and superior capability of adapting to the unstructured environment.

Previous researches on the walking and climbing robot have reported many achievements in design [1], [2], gait planning [3], [4], perception [5], control [6]–[9], etc. But most of these robots can travel only on the simple environment such as flat surfaces and wall and are designed for the restricted application in the determined environment. To cope with real environment, the robot should have large workspace as well as high mobility. Moreover, the advanced algorithm to generate the suitable gait is required.

The real environments are composed of primitive geometrical shape such as plain, rough terrains, concave corners, curves and convex corners. Among them, the convex corner is hard to attack, which has not been sufficiently discussed up until now.

To overcome a convex structure, the robot should avoid the collision between its bottom and the edge of the corner. To avoid such collision, the first criterion is to have a large workspace and the appropriate structure of the robot should be provided. In chapter 2, we will be studying on the collision between the robot and the corner in order to find out the optimal design of the quadruped robot that has a larger workspace and a higher adaptability level. The posture of the robot is investigated to discover the best gait of the robot in the convex environment. In the next chapter, we propose a new algorithm for overcoming the convex environment. The distance between the bottom of the robot and the boundary edge of the corner is carefully considered to determine the appropriate gait. The trajectories of the body and the position of the feet are generated based on the safe distance that the robot can keep away from the edge of the corner. When using this algorithm, the robot should have good capability of sensing the environment. In the research, we use an IR sensor attached in the leg of the robot to provide information about the corner. Chapter IV introduces the result of simulations and experiments of the quadruped walking and climbing robot, named MRWALL-SPECT III. The performance strongly shows the validity of the proposed method. Finally, we give our conclusion as well as recommendation with summary in chapter V.

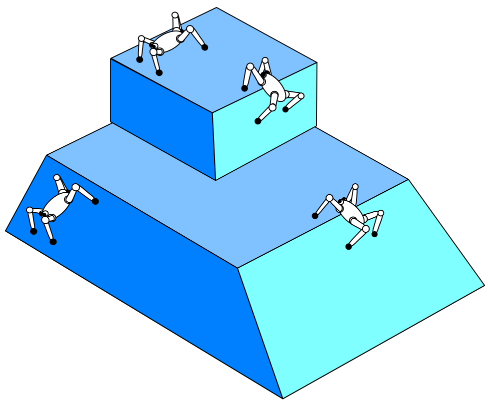

Fig. 1. Navigation in convex environment.

2. Problem statements

In this section, we study the relation between kinematical structure of the robot and its adaptability in convex environment. The issue of collision will get investigated to give understanding on the robot's capabilities.

2.1. Collision

The robot manages the convex corner by avoiding the collision between its bottom and the edge of the corner, therefore the collision should be considered in advance. To enable this avoidance, the robot should be able to operate in a large workspace as well as have a high level of adaptability. Moreover, with a given walking and climbing robot, the ability of preventing a collision has a close link with a predetermined minimal angle of the corner that the robot can pass through. It indicates that with a corner having an angle smaller than the predetermined one, the robot cannot travel to the next surface. When the bottom of the robot collides with the edge, if the workspace of this robot intersects with both surfaces of the convex corner, it is a possible means for the robot to move on to the next surface. In contrast, if the workspace of robot does not include one of the two surfaces when the bottom contacts with the edge, the robot cannot enter the next area. Therefore, by studying the collision, we can derive more-than-one good lessons for improving the capabilities of the robot.

2.2. Solution

Because the collisions between any point of the bottom of the robot and the corner can be solved based on the same foundation, we simplify the problem by working with the middle point of the bottom. In a specific situation, the minimum angle may be obtained by applying this solution to every single point on the bottom of the robot.

When traveling in convex corner, the robot attempts to distance its bottom from the edge of the corner in order to prevent a collision. To keep the body away at that state, link 1 of the robot legs should reach its maximum possible angle while link 2 should perpendicularly contact with the terrain. In order to help understand the theory, we put H to be the distance between the bottom of the body and the boundary edge of the corner and introduce the problem in advance by Fig. 2.

Move Link 1 of all legs to the maximal possible an-

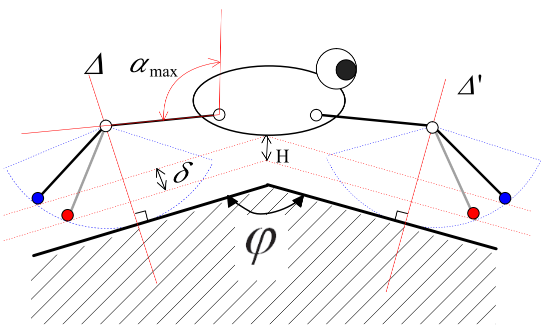

Fig. 2. Relation between high of robot and angle value of link 2.

gle then draw a line from Joint 2 perpendicularly with the surfaces of the corner. As shown in the figure, δ is the distance between the foot of arbitrary position and the foot of a position at which H = 0. However, $H = \delta/\cos(90 - \phi/2)$ so H reaches the maximal value when δ is maximized. In Fig. 2, we can easily see that δ is at its maximum when Link 2 coincides with Δ. It means that the body of the robot is furthest away from the edge when the legs are in such state.

Supported by the above theory, we find the robot's ability in the convex environment. It relates to the minimum angle of the convex corner that a given robot can pass through and this relation is shown in Fig. 3.

Geometrical model of Fig. 3 is describes in Fig. 4.

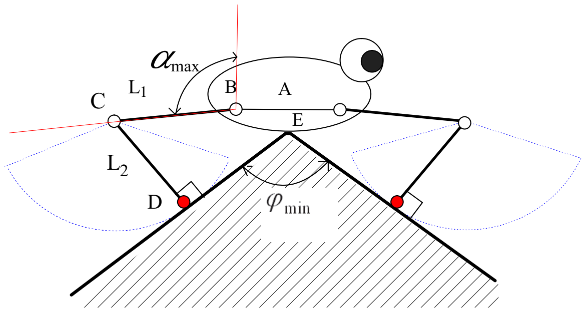

Fig. 3. Collision between robot and corner.

As shown in Fig. 4,we have equation:

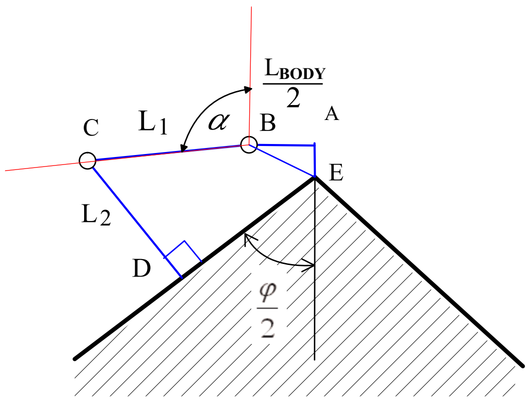

Fig. 4. Minimal angle of corner with a given robot.

$$\widehat{CBE} = 270 - \alpha - \widehat{ABE} \tag{1}$$

We can calculate the following value:

$$EC = \sqrt{BC^2 + BE^2 - 2BCBE\cos\widehat{CBE}} \tag{2}$$

$$\widehat{BEC} = \arcsin\frac{BC \times \sin\widehat{CBE}}{AC} \tag{3}$$

$$\widehat{CED} = \arcsin\frac{CD}{CE} \tag{4}$$

And φ can be obtained from the below equation:

$$\varphi = 180 - \widehat{AEB} - \widehat{BEC} - \widehat{CED} \tag{5}$$

So we have:

$$\varphi = 180 - \widehat{AEB} - \arcsin\frac{BC \times \sin\widehat{CBE}}{AC} - \arcsin\frac{CD}{CE} \tag{6}$$

2.3. Advantages from the solution

From the Eq. (6), there is a derivation of certain problems that should be considered for the purpose of improving the capability and adaptability of the robot:

• - Ratio between the leg length and body length of the robot. In advance, the leg of the robot should be longer than the body of the robot.

• Working range of the leg: The legs of the robot should be designed for large workspace. They should not be restricted in a small area by another mechanism.

• The distance from the bottom of the robot to the plain that made of 4 rotational center of the link 1 of 4 legs of the robot–AE as shown in Fig. 4. The shorter that distance is, the greater the ability of the robot in the convex corner is improved.

3. Algorithm and sensor system

Based on the above analysis, we develop a gait planning algorithm to help the robot treat with the convex environment. In addition, we introduce a means of using infrared sensor to perceive precisely the convex terrain.

3.1. Gait planning algorithm

To ease up the problem, it is assumed that the direction of movements is perpendicular to the boundary of the slope. Thus, the problems in 3D environment can be treated as that of 2D environment. The gait planning is consisted of two main parts: the location of the body and the position of the feet. It is addressed how to generate appropriate trajectories of the body on the convex slope, and the method of determining the position of feet in accordance with the movement of the body.

A. Determination of body trajectory

At first, we define the safe distance for a walking and climbing robot when it travels in a convex environment. This type of environment most likely will nurture all possibilities for a collision to occur. Call the maximal distance that the robot can keep away in this situation the safe distance-H_s. With a given robot and a corner, backed by the solution that was presented in chapter 1, we can find the safe distance of a given robot in a predetermined angle of the convex corner. The body trajectory can be smoothly generated, based on the safe distance displayed in Fig. 5.

B. Determination of foot position.

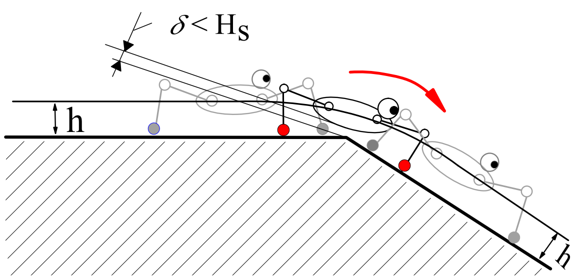

Fig. 5. Body trajectory for convex slope.

The method used for calculating the position of feet for the next step is illustrated in Fig. 6. When applying this method, we can manage the locomotion of the robot more easily and clearly. Moreover, it does not require any complex function, or equation or calculation. Position of the fore leg

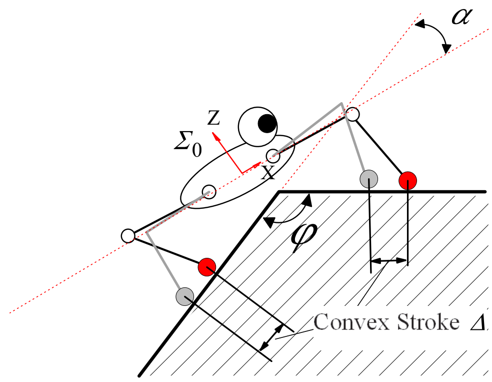

Fig. 6. Determination of foot position.

along X and Z axis is gained from the following equation:

$$NextX = Now + \Delta \times \cos(180 - \varphi - \alpha) \quad (7)$$

$$NextZ = Now - \Delta \times \sin(180 - \varphi - \alpha) \quad (8)$$

Position of foot of hind leg along X and Z axis:

$$NextX = Now + \Delta \times \cos\alpha \quad (9)$$

$$NextZ = Now + \Delta \times \sin\alpha \quad (10)$$

C. Flow chart of gait planning algorithm

The algorithm is described as shown in Fig. 7.

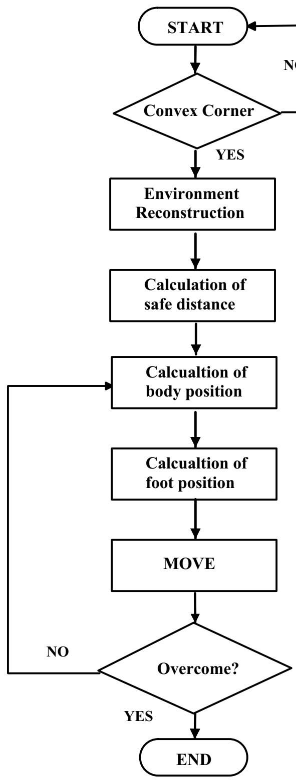

Fig. 7. Flow chart of gait planning algorithm.

3.2. Sensor system

To generate an appropriate gait, the robot should know well about the environment that it is walking on. Normally, the construction of the environment can be acquired by using the sensory system. But in the case of convex corners, it is difficult for the robot to have sufficient information upon the two surfaces of the corner. Therefore, the robot appears to lack of essential information to generate an appropriate locomotion for overcoming the convex corner.

To solve this problem, we use an IR sensor attached

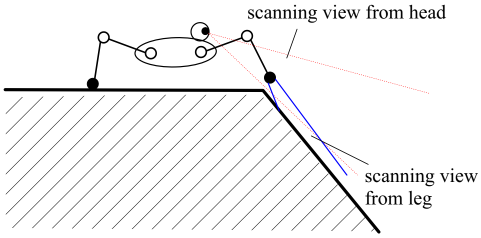

Fig. 8. Effectiveness of sensor attached in leg.

to the leg of the robot. With the leg's flexibility, the robot can scan the next surface of the corner after completing movements in the first surface. We use the SHARP-GP2D12 IR sensor to measure the distance from the leg of the robot to the next surface of the corner. Data that has been collected during the scan helps the robot gain the compatible locomotion to approach the area of the convex corner that this robot wants to access.

As shown in Fig. 9, the convex angle γ can be de-

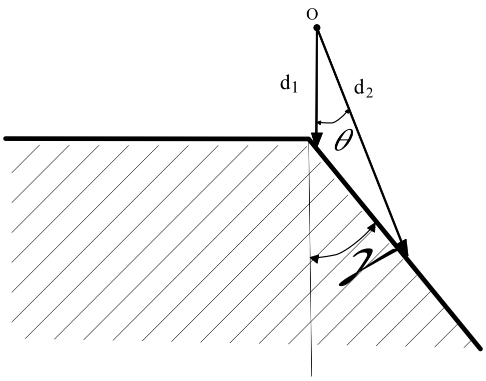

Fig. 9. Determination of concave angle.

termined as follow.

$$\gamma = \arcsin \frac{d_2 \sin\theta}{\sqrt{d_1^2 + d_2^2 - 2d_1 d_2 \cos\theta}} \tag{11}$$

4. Simulations and Experiments

In this chapter, the proposed algorithms have been validated by simulations and experiments using a walking and climbing robot, called MRWALLSPECT III. The robot reshapes the construction of environment by using an infrared sensor attached on its head[11].

A. Outline of MRWALLSPECT III

As shown in Fig. 10, MRWALLSPECT III had been developed for walking and climbing in a three–dimensional

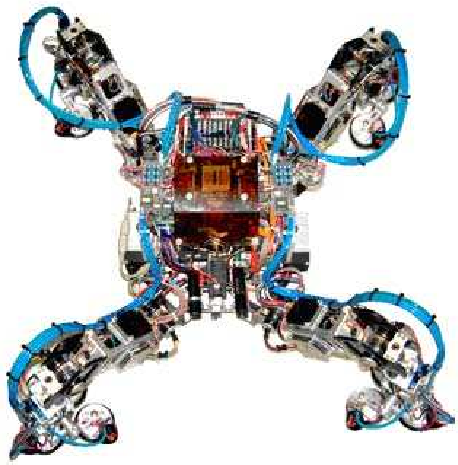

Fig. 10. MRWALLSPECT III.

unstructured environment. The robot has four legs with three–DOF active joints and a passive ankle joint for each leg. The active joints are actuated by geared DC motors, respectively. Three suction pads are attached symmetrically on each ankle. Thus, a total of twelve suction pads are used for adhesion to the wall. Vacuum for suction is generated by four vacuum pumps connected in parallel. Also, the robot can make a smooth transition from adhesion to detachment by using two–way–three–port–valves, which prevents the vacuum from being locked down.

MRWALLSPECT III contains two controllers. One is an embedded controller using a single board computer(Pentium-III 850MHz with IDE type flash disk, several DIO channels, DA channels, and wireless LAN module), and RTLinux(real time linux 2.2.14) is ported as the operating system. The other controller is used to drive the two-DOF scanning module, composed of a CCD camera and a infrared sensor. Motors in the scanning module are driven by a 50Hz PWM signal generated by FPGA(EPM7128SLC84-15). The RF(radio frequency) transmission unit transfers the visual information from the camera module to the operator. The power for the robot is supplied through a tether cable, although all the other communication are transmitted through a wireless LAN. In open space, it can be controlled from as far as 300 meters away.

B. Simulations

The proposed algorithm was tested by simulation with parameters of the MRWALLSPECT III. The simulation has been carried out for two cases. One is for climbing up the hill with a slope of 35 degrees and the other one is for strolling down the hill. In both cases, convex transition gaits are performed sequentially. Figs 11 and 12 show the convex transition of climbing up hill. In Side 3 of Fig. 11, we can see that there is a safe distance between the bottom of the body and the boundary edge corner. Consequently, it can be concluded that the bottom of the body and the boundary edge of convex slope do not collide with each other by applying the proposed algorithm.

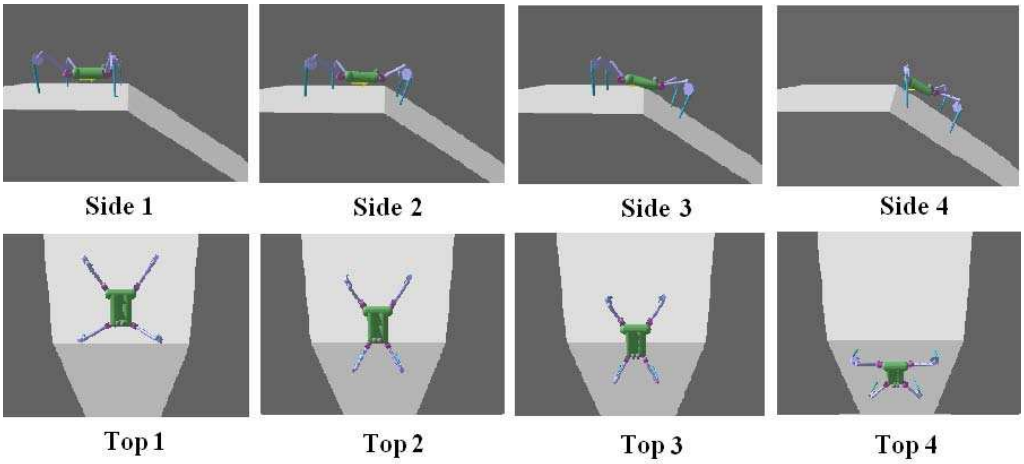

Fig. 11. Go down convex slope.

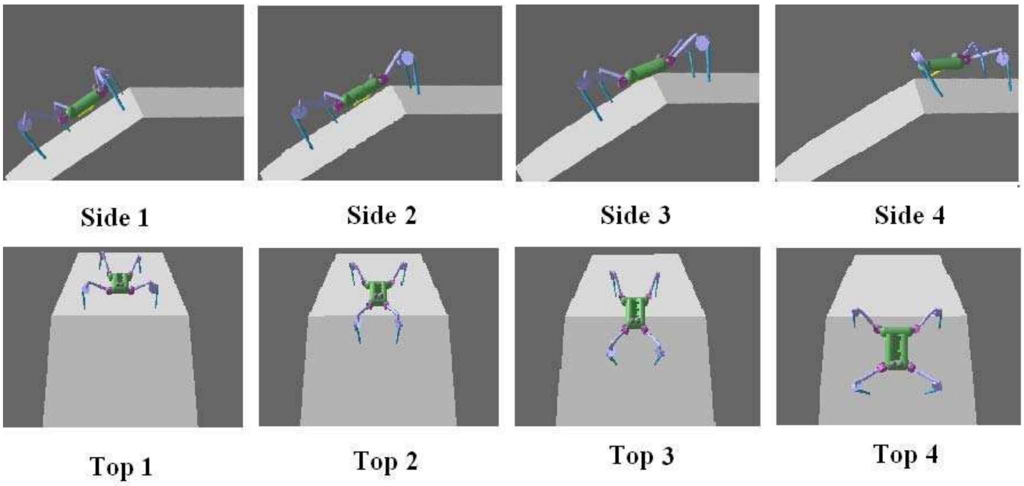

Fig. 12. Go up convex slope.

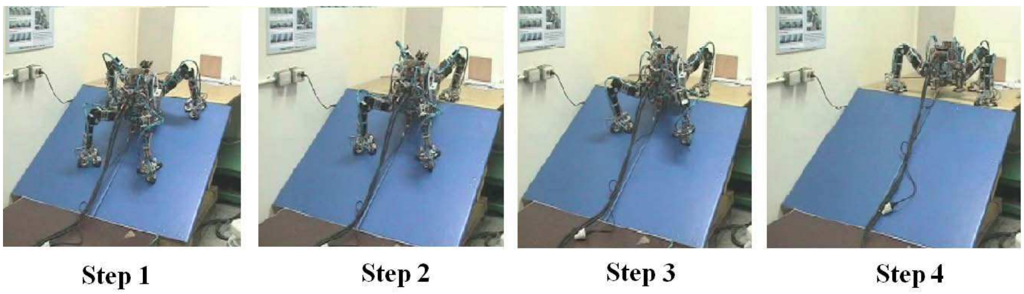

Fig. 13. Overcome the convex corner from beside view.

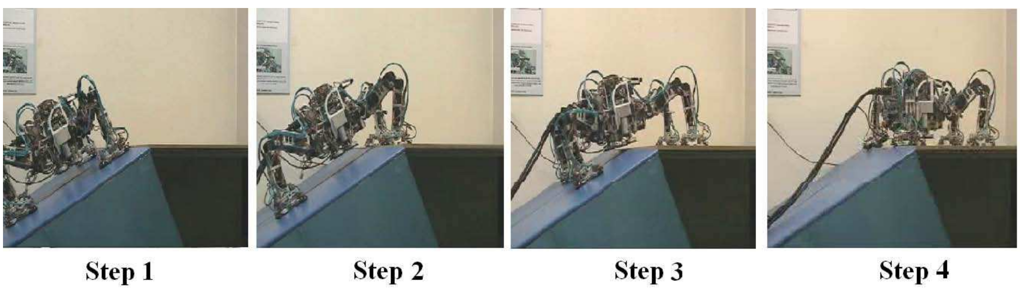

Fig. 14. Overcome the convex corner from side view.

C. Experiments

In the experiments, the validity of the proposed algorithms has been demonstrated by the MRWALLSPECT III [13]. . Climbing over a slope with convex corner was tested as shown in Fig. 13 and Fig. 14. When the robot moves up or down on the slope, the tumbling of the robot and slipping of the legs should be avoided. However, in the case of the walking robot with suction pads, these problems may be neglected because there always are adhesive forces between the ground and the legs. The step 1 of Fig. 13 shows the approach phase for the transition gait in the slope.

In this case, the convex angle measured was approximately 35 degrees. And, the step 2 and step 3 describe the transition in the convex corner. In the last step, the robot climbs over the slope with plain surfaces using the proposed gait.

5. Conclusion

In this paper, we have solved problems that a walking and climbing robot would encounter with when operating in a convex environment. First of all, the collision between the bottom of the robot and the boundary edge of the corner was considered carefully. The consideration helps us improve the workspace as well as the adaptability level of a quadruped walking and climbing robot. Secondly, we proposed a gait planning algorithm for the same robot to compromise with the convex environment. We also used an IR sensor attached in the leg of the robot to conscientiously perceive the convex corner. Through the simulations and the experiments, the validity of the above methods has been proved.

Acknowledgments

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References

[1] S. Hirose, "A Study of Design and Control of a Quadruped Walking Vehicle", The International Journal of Robotics Research vol. 1 no. 4, pp. 289-323, 1986

[2] B.L Luk, A.A Collie, V Piifort, G.S Virk "Robug 111: A Tele-operated Climbing and Walkiing Robot", UKACC International Conference on CONTROL 96,2-5 September 1996, Conference Publication No. 427, IEE 1996

[3] Juan Carlos Grieco", Manuel Prieto, Manuel Armada, Pablo Gonzalez de Santos"A six-legged climbing robot for high payloads" Proceedings of the 1998 IEEE International Conference on Control Applications Trieste, Italy 1-4 September 1998

[4] S. Hirose, Y. Fukukda, H. Kikuchi, "The gait control system of a quadruped walking vehicle", Advanced Robotics vol. 1 no. 4, pp. 289-323, 1986

[5] Satoshi KAGAMI, Kei OKADA, Mitsutaka KABASAWA, Yoshio MATSUMOTO, Atsushi KONNO, Masayuki INABA, Hirochika INOUE, "A Vision-based Legged Robot as a Research Platform",

[6] Taehun Kang, Hyungseuk Kim, Taeyoung Son and Hyoukryeol Choi, "Design of Quadruped Walking and Climbing Robot", Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 619-624, 2003

[7] S. Hirose, A. Nagakubo, R. Toyama, "Machine That Can Walk and Climb on Floors, Walls and Ceilings", Proceedings of the 1991 IEEE International Conference on Robotics and Automation, pp. 753-758, 1991

[8] B. L. Luk, A. A. Collie and J. Billingsley, "ROBUG II : an Intelligent Wall Climbing Robot", Proceedings of the 1991 IEEE International Conference on Robotics and Automation, pp. 2342-2347, 1991

[9] A. Nagakubo, S. Hirose, "Walking and Running of the Quadruped Wall-Climbing Robot", Proceedings of the 1994 IEEE International Conference on Robotics and Automation, pp. 1005-1012, 1994

[10] H. R. Choi, J. H. Kim and S. R. Oh, "Probing the curvature of a convex object via discrete active touch", Advanced Robotics, vol.13, no.4, pp. 381-399, 1999.

[11] T. H. Kang, H. S. Kim and H. R. Choi,"Realtime Perception with Infrared Scanner for Navigation of Quadruped Walking and Climbing Robot ", Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2550 2555, 2004

[12] H. S. Kim, T. H. Kang, V. G. Loc, and H. R. Choi "Gait Planning of Quadruped Walking and Climbing Robot for Locomotion in 3D Environment ", Proc. of IEEE International Conference of Robotics and Automation, 2005

[13] Junmin Pan and Junshi Cheng, "Study of Quadruped Walking Robot Climbing and Walking Down Slope", Proceeding of IEEE/RSJ International Workshop on Intelligent Robots and System, pp. 1531- 1534, 1991

[14] Hideyuki Tsukagoshi, Shigeo Hirose and Kan Yoneda, "Maneuvering Operations of the Quadruped Walking Robot on the Slope", Proceeding of IEEE/RSJ International Workshop on Intelligent Robots and System, pp. 863-869, 1996