Unified Strategy for Quadruped Walking Robot in Unstructured Environment

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Abstract: An unstructured environment requires a robot to possess outstanding mobility and advanced control algorithms since there exist complicated configurations such as obstacle, uneven surface, etc. Especially, when a quadruped robot walks in these environments, obstacles in the walking route will obstruct the walking or may give rise to a serious trouble. In this paper, we introduce a strategy for the stable walking in unstructured environment. The proposed strategy consists of two control algorithms. One is a collision–free algorithm to avoid obstacles and the other is an algorithm to overcome any obstacle. These are based on the obstacle detection method and a shape reconstruction algorithm, Which algorithms are described in detail. In addition, the validity of these algorithms have been demonstrated through experiments using a quadruped walking robot called "MRWALLSPECT III(*Multifunctional Robot for Wall inSPECTion version 3*)".

Keywords: Unstructured Environment, Quadruped Walking Robot, MRWALLSPECT

1. Introduction

Recently, in the field of robotics a lot of progress has been made and many things considered to be impossible previously are going to be performed by robots. In a near future, robots are sure to be used as substitutes of the human for many tasks in our daily life. In order to replace the human, a robot should have several special abilities such as the high intellectual power to cope with arbitrary situations, mobility or adaptability to travel in the environment and dexterity to manipulate objects. Among theses requirements, the legged system have been considered as the solution to improve the mobility of robot. So, many researchers have been performed on various walking robots such as biped, quadruped, hexapod robot, etc. Especially, the quadruped walking robot is expected to apply in industrial facilities because they have an outstanding mobility and the potential capability to adapt in uneven terrain. Though many people recognized the mobility advantage of legged locomotion systems, it was difficult to develop a suitable walking robot which can be used in unstructured environment. Because the environment in which a walking robot is expected to locomote is composed of complicated configurations such as obstacle, uneven surface, etc. To develop a walking robot which can locomote in unstructured environment may not be easily accomplished but classification of unstructured environment and development of gait control algorithm will give us good inspirations of design and deserve to refer to. In fact several studies have been reported on the classification and quantitative description of configuration of an unstructured environment[1]. And some researchers have proposed some criteria which can be applied to the design of walking robot[2][3]. Moreover, the other researchers proposed various gait control algorithms to overcome unknown environments[4][5]. In spite of these many results, there are no example of the walking robot which can be used in the industrial fields. Among reasons, a major cause is that robot has not the ability to adapt in unknown environment. To obtain the enough ability, the detection algorithm and gait control algorithm are considered at once. So, in this paper, we propose a control method to improve the adaptability of robot in unknown environment. We performed the obstacle detection using two degree of freedom(abbreviated as DOF) infrared sensor. And then, we can get some important data such as height and width of obstacle. These data will be used to determine the gait control algorithm as *"overcoming"* or *"avoidance"*.

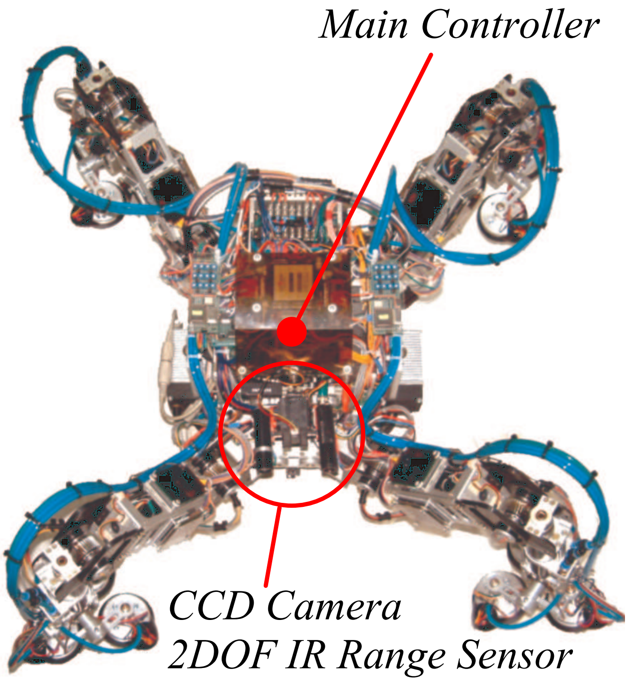

Fig. 1. MRWALLSPECT III

This paper is organized as follows. In the next section, we will describe the quadruped walking robot called MRWALLSPECT III. A gait control algorithm to overcome and to avoid any obstacle is presented in section 3. And the obstacle detection method and shape reconstruction algorithm are

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presented in Section 4. Section 5 introduces several simulations and experimental results, and we conclude with summary in Section 6.

2. MRWALLSPECT III

To verify the proposed strategy, we used a quadruped robot called MRWALLSPECT III as shown in Fig. 1. MRWALLSPECT III had been developed for walking and climbing in three dimensional unstructured environment. But, in this work, we regards MRWALLSPECT III as a general quadruped robot for the proof of the proposed gait control algorithm. This robot has four legs with three–DOFs active joints and a passive ankle joint for each leg. The active joints are actuated by three geared DC motors, respectively. The ankle joint of the robot that is a passive spherical joint. 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) is ported as the operating system. The other controller is used to drive the two–DOF scanning module consisted a CCD camera and a infrared sensor. Motors in the scanning module are driven by 50Hz PWM signal generated by FPGA(EPM7128SLC84-15). The visual information of the camera module is transferred to the operator via RF(radio frequency) transmission unit. The power of the robot is supplied with a tether cable, although all the other communication is transmitted through wireless LAN. In the open space, it can be controlled far from 300 meters away.

3. Unified Gait Control Algorithm

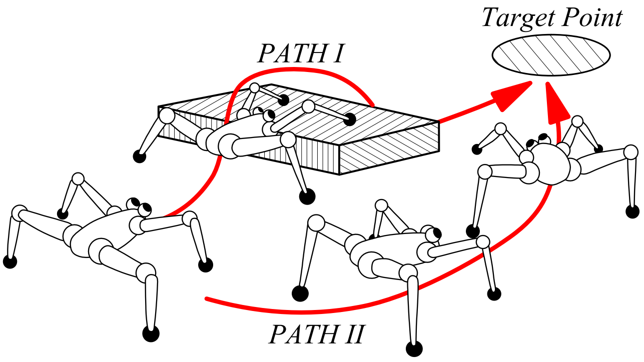


Fig. 2. Motivation

If a quadruped robot walks in unknown environment, scattered obstacles in walking route will obstruct the walking or may give rise to a serious trouble. So, the discriminative gait controls are required for the stable walking in this environment. For example, as shown Fig. 2, when robot reaches the obstacle, a suitable gait should be determined by the operator or itself. In this case, there is two gait. One is a gait to go over the obstacle through *PATH I*, the other is a gait to avoid the obstacle through *PATH II*.

In this section, we will introduce the strategy to determine the discriminative gait controls as overcoming or avoidance algorithm. This strategy is composed of three major parts such as an obstacle detection method, a algorithm to overcome obstacle and avoidance obstacle.

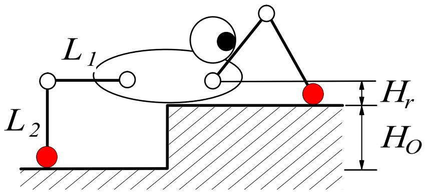


Fig. 3. Discrimination of environment

From Fig. 3, we assume that H_o is the height of the step, H_r is the height between the bottom of robot body and the first joint, and the length of thigh L_1 and tibia L_2 of legs are equal to L. Then, we can discriminate between an obstacle and a wall according to

1. $H_o < L - H_r$: the step is considered as an obstacle that the robot can go over.
2. $H_o \geq L - H_r$: the step is regarded as a kind of wall to climb on.

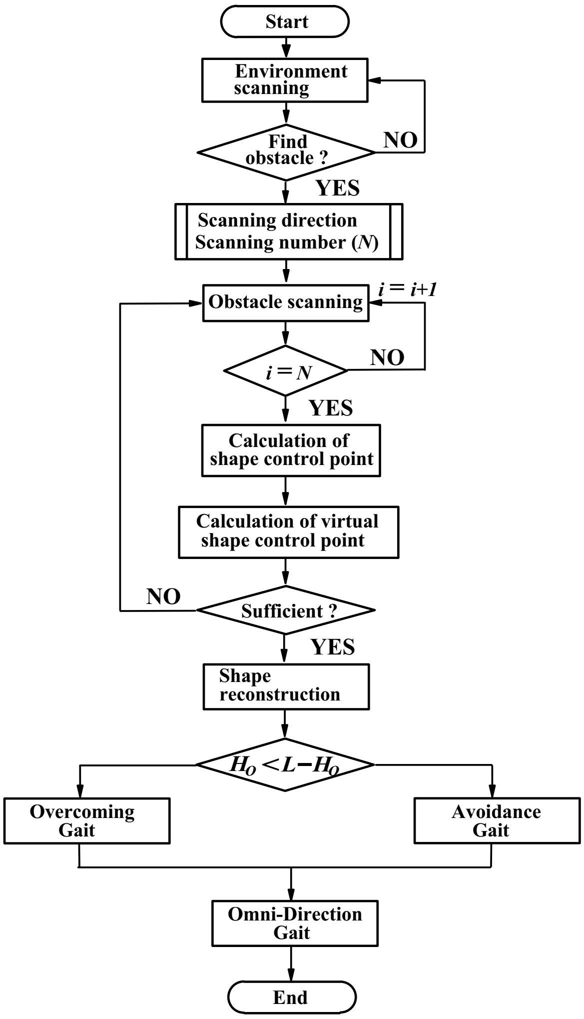


Fig. 4. The flowchart for the differential gait control

Depending on this discrimination, the patterns of locomotion is changed. For example, in case of $H_o < L - H_r$ the obstacle overcoming gait is used, and the other case the gait control should be changed to the obstacle avoidance gait.

The flowchart for the discriminative gait control algorithm is shown in Fig. 4. In this algorithm, the object detection algorithm is base on the shape reconstruction algorithm. At following sections, we will describe the detail explanation about these algorithms.

4. Shape Reconstruction

Up to now much attention has been paid to sensing the shape of object or the environment with the active or passive sensing method. Visual sensing is considered as one of the ways, but it may not be suitable for robot system since that is required too much calculation power as well as conditions. Though tactile or force/torque sensor can be used easily for sensing, this is not a desirable way because it is contact sensing. In this section, we will propose a suitable method to sensing the shape of object or the environment with infrared sensor. Our shape reconstruction algorithm is based on the calculation of any surface on Euclidean 3-space $\mathbf{R^3}$[6].

4.1. Mathematical Background

In order to help the understanding of the proposed algorithm in advance some basic concepts in differential geometry are introduced[6]

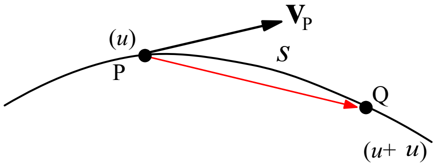


Fig. 5. Approximated tangent vector

Theorem 1: In the Fig. 5, if β is a regular curve on Euclidean 3-space $\mathbf{R^3}$ and Δu has very small value, Eq. (1)and (2) are valid, clearly.

$$\|\mathbf{PQ}\| \simeq \Delta S \tag{1}$$

$$\mathbf{v}_p \simeq \frac{\mathbf{PQ}}{\|\mathbf{PQ}\|} \tag{2}$$

where, ΔS means the segment length of curve β and $\mathbf{v}_p$ is a unit tangent vector on point P.

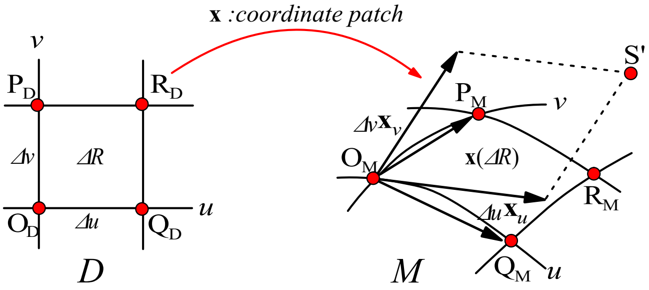


Fig. 6. Integration of surface with coordinate patch

Theorem 2: As shown in Fig. 6, To discover a proper definition of area in $\mathbf{R^3}$, generally, a coordinate patch is performed as $\mathbf{x}$: $D \to M$. Let ΔR be a small coordinate rectangle in D with side Δu and Δv. Now, $\mathbf{x}$ distorts ΔR into a small curved region $\mathbf{x}(\Delta R)$ in M, marked off by four segments of parameter curves. If the segment from $\mathbf{x}(u, v)$ to $\mathbf{x}(u + \Delta u, v)$ is linearly approximated by the vector $\Delta u\mathbf{x}_u$ evaluated at (u, v), and the segment from $\mathbf{x}(u, v)$ to $\mathbf{x}(u, v + \Delta v)$ is approximated by $\Delta v\mathbf{x}_v$. Thus the region $\mathbf{x}(\Delta R)$ is approximated by the parallelogram in the tangent plane at $\mathbf{x}(u, v)$ as Eq. (3).

$$\|\Delta u\mathbf{x}_u \times \Delta v\mathbf{x}_v\| = \|\mathbf{x}_u \times \mathbf{x}_v\|\Delta u\Delta v \tag{3}$$

where, $\mathbf{x}_u$ and $\mathbf{x}_v$ are unit tangent vectors at point O_M in direction u and v, respectively.

If Δu and Δv have a small value, we can find Eqs. (4) and (5) using **Theorem 1**.

$$\mathbf{x}_u \simeq \frac{\mathbf{O}_M\mathbf{Q}_M}{\|\mathbf{O}_M\mathbf{Q}_M\|} \tag{4}$$

$$\mathbf{x}_v \simeq \frac{\mathbf{O}_M\mathbf{P}_M}{\|\mathbf{O}_M\mathbf{P}_M\|} \tag{5}$$

Substituting Eqs. (4) and (5) for Eq.(3), we obtain Eq. (6).

$$\|\Delta u\mathbf{x}_u \times \mathbf{\Delta v x}_v\| = \|\mathbf{O}_M\mathbf{P}_M \times \mathbf{O}_M\mathbf{R}_M\| \tag{6}$$

From Eq. (6), we can find that the parallelogram in the tangent plane coincide with the parallelogram formed by four points on any surface. Consequently, in Euclidean 3-space $\mathbf{R^3}$, if three points on any surface are determined, another point is derived by using parallelism theorem. Also, if the local area composed by four points is very small, the fourth point derived from three points is located on this surface.

4.2. Shape Reconstruction Algorithm

In this paragraph, an algorithm is proposed to derive the shape reconstruction of object or environment by using two–DOF infrared sensor.

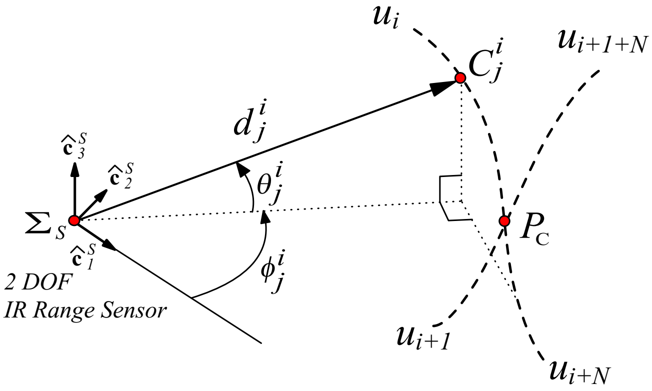


Fig. 7. Relationship between sensor and shape control points

In the Euclidean 3-space $\mathbf{R^3}$, To obtain curves which can be expressive of the shape of obstacle, N times sweeping are executed with a range sensor($N \geq 2$). In this time, all curves must pass through $\mathbf{P}_C$ called *common position* formed by sweeping. Then the i th curve is divided into two curves as u_i and u_{i+N}, respectively. These curves are called *shape curve*. If there exists a large number of points which depend on the sampling frequency of a range sensor and these points compose u_i, then these points are called *shape control point*.

This point can be expressed in $\sum_S$ as the position vector $\mathbf{C}^{(i,o)}_{(m,o)}$(where, it is the m th point of u_i). Also, if u_i and u_{i+1} are selected, one local area $M_{(i,i+1)}$ called *fanwise surface* is determined.

The relationship between the range sensor and *shape curves* in Fig. 7. In Fig. 7, θ^i_j and ϕ^i_j represent angles of sweeping of the range sensor. d^i_j denotes the distance from the origin of $\sum_S$ to point $C^{(i,0)}_{(m,0)}$.

Then we can express *Shape control point* such as

$$\mathbf{C}^{(i,o)}_{(m,o)} = [x^i_m \quad y^i_m \quad z^i_m]^T \tag{7}$$

where,

$$\begin{aligned} x^i_m &= d^i_m \cos\phi^i_m \cos\theta^i_m \\ y^i_m &= d^i_m \sin\phi^i_m \cos\theta^i_m \\ z^i_m &= d^i_m \sin\theta^i_m \end{aligned}$$

If three points which locate on surface S in $\mathbf{R^3}$ are selected, we can generate two vectors connected with two points, respectively. And then we can determine the fourth point $\mathbf{C^{(i,i+1)}_{(m,n)}}$ called *virtual shape control point* with the parallelism theorem. Of course, in **Theorem 1** and **2**, we confirmed that this point is located on surface S. Thus, the relationship between $\mathbf{C}^{(i,o)}_{(m,o)}$ and $\mathbf{C}^{(i,i+1)}_{(m,n)}$ is presented as Eq. 8. The local area $M_{(i,i+1)}$ is a set composed of $\mathbf{C}^{(i,o)}_{(m,o)}$ and $\mathbf{C}^{(i,i+1)}_{(m,n)}$, and a surface S is a set composed of $M_{(i,i+1)}$, respectively. Therefore, we can reconstruct the shape of object with this relationship. Fig. 8 shows the outline of the proposed algorithm.

$$\mathbf{C}^{(i,i+1)}_{(m,n)} = \mathbf{C}^{(i,i+1)}_{(m-1,n)} + \mathbf{C}^{(i,i+1)}_{(m,n-1)} - \mathbf{C}^{(i,i+1)}_{(m-1,n-1)} \tag{8}$$

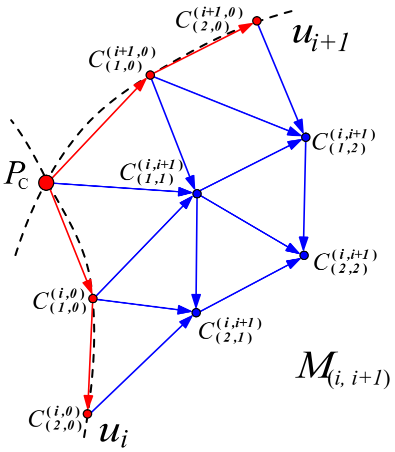
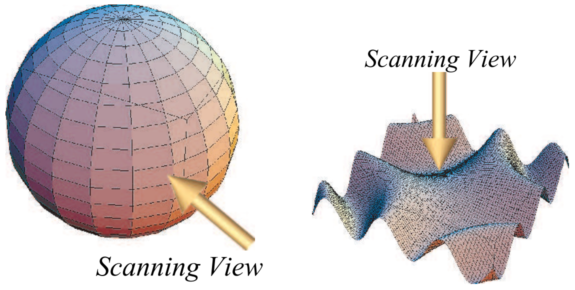


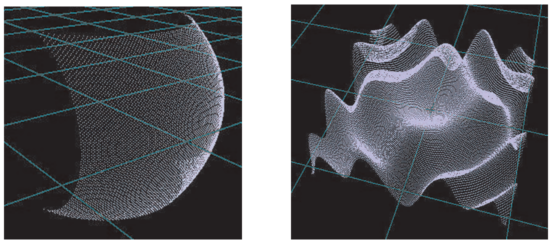
Fig. 8. Reconstruction of the local area

4.3. Evaluation of the Shape Reconstruction Algorithm

[Simulation] The performances of the proposed algorithm have been evaluated through several preliminary simulations. For simulations we selected geometrical models such as a sphere and a winding surface as shown Fig. 9 (a) and (b). In the simulation, we determined two curves as scanning curves. Also, three hundred *shape control points* and four *shape curves* are obtained, respectively. Results of these simulations are shown Fig. 9 (c) and (d).



(a) Sphere model (b) Surface model



(c) Simulation (d) Simulation

Fig. 9. Simulations of the shape reconstruction algorithm

[Experiments] We carried out experiments to evaluate a propose algorithm with actual system. To obtain *shape control points*, two times sweeping was executed. So, we could get eighteen *shape control points* and sixty three *virtual shape control points*. Fig. 10 shows results.

5. Simulations and Experiments

As shown Fig. 12, Algorithms presented in this work have been proved through simulations. These confirmed algorithms are applied to the actual robot system with MRWALLSPECT III. Fig. 13(a) shows the obstacle overcoming gait. A height of obstacle measured with two–DOF infrared range sensor is about $150mm$. In this case, MRWALLSPECT III can go over this obstacle because the attainable height of this robot is $L - H_r = 160mm$. When the height of obstacle is higher than $160mm$, MRWALLSPECT III should avoid the obstacle based on omni–directional gait[7], as shown Fig. 13(b).

6. Conclusion and Discussion

In this paper, we proposed a control method to improve the adaptability of robot in unknown environment. To obtain the information of obstacle, two–DOF infrared sensor is applied. The proposed gait control algorithm are composed of a collision–free algorithm to avoid obstacles and an algorithm for overcoming, and additional algorithms are presented such as an obstacle detection a shape reconstruction algorithm. In addition, the validity of these algorithms have been demonstrated through experiments using a quadruped

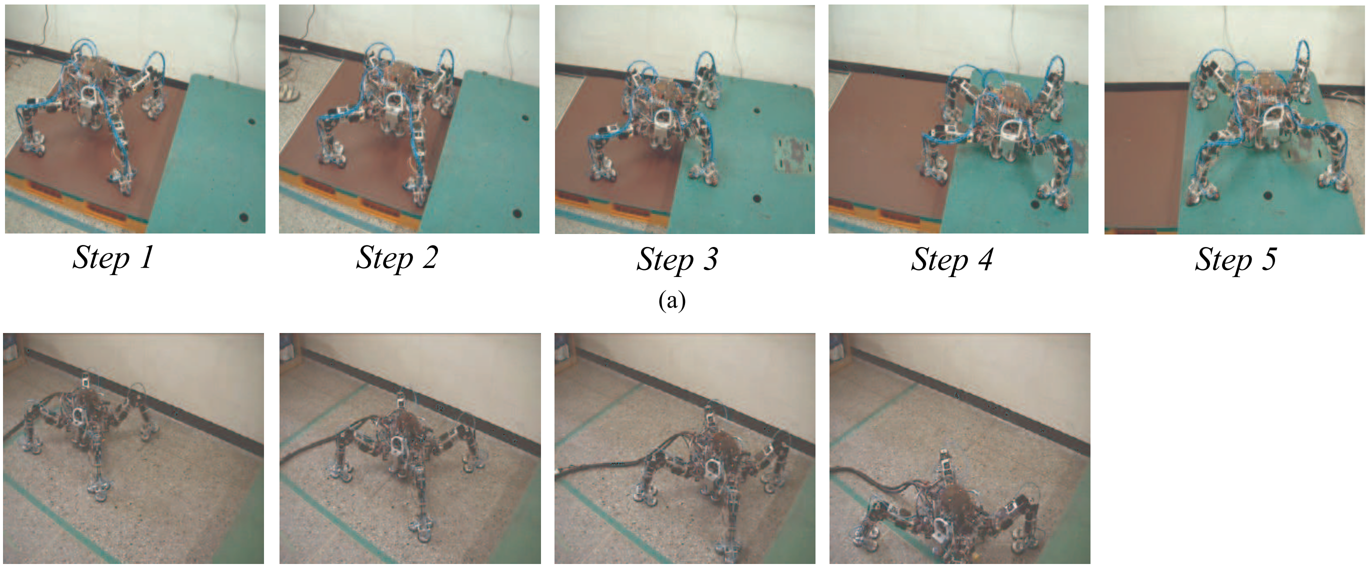
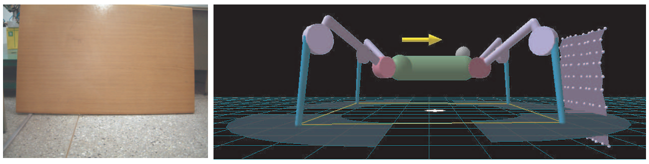
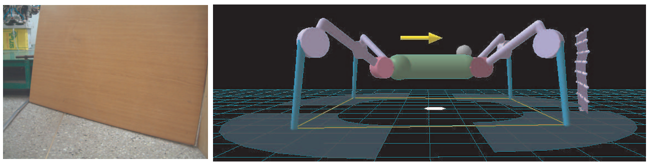


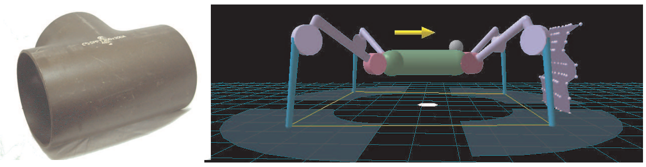
Fig. 13. Experiments for evaluation of the algorithm



(a) Vertical plane surface



(b) Askew plane surface



(c) 8 inch pipe

Fig. 10. Experiments with actual objects

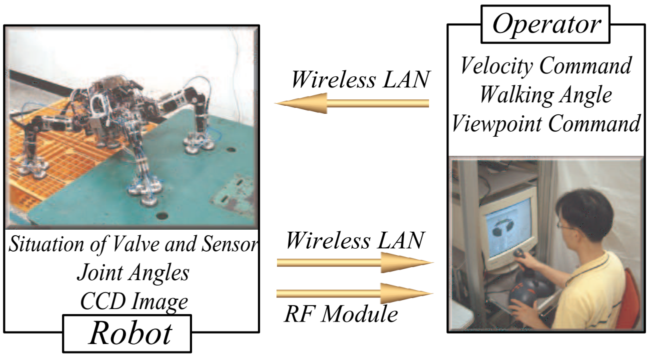


Fig. 11. System setup

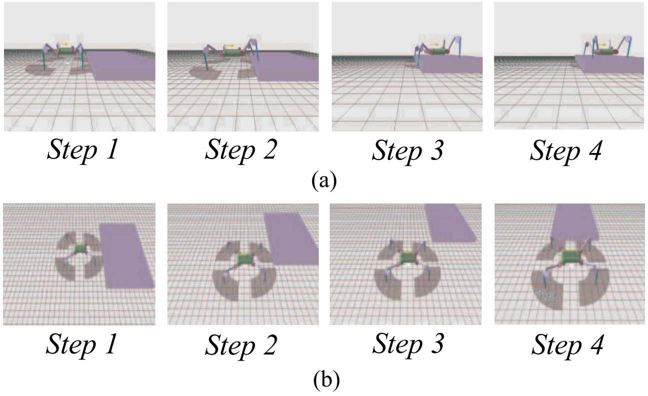


Fig. 12. Simulation

walking robot called MRWALLSPECT III.

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