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Locomotion Planning of Humanoid Robots to Pass through Narrow Spaces

Fumio KANEHIRO Hirohisa HIRUKAWA Kenji KANEKO Shuuji KAJITA
Kiyoshi FUJIWARA Kensuke HARADA Kazuhito YOKOI
National Institute of Advanced Industrial Science and Technology(AIST),
Tsukuba Central 2, 1-1-1 Umezono, Tukuba, Ibaraki, 305-8568 JAPAN
{f-kanehiro,hiro.hirukawa,k.kaneko,s.kajita,
k-fujiwara,kensuke.harada,kazuhito.yokoi}@aist.go.jp

Abstract— **This paper studies locomotion planning of humanoid robots to pass through narrow spaces. Humanoid robots can alter the style of the locomotion while wheeled robots can not. The proposed method generates a 3D local map from visual information and plans the appropriate locomotion based on the map from biped walking with the variable height and the width and from crawling.**

I. Introduction

With the advance of humanoid researches in recent years, several humanoid robots including ASIMO[1], SDR-4X[2], Johnnie[3] can walk stably. They can walk on the flat floor, on rough terrain with small gaps and climb stairs under an assumption that a 3D map is given beforehand.

Another advantage of humanoid robots over wheeled robots is that they can move around in the various environment like shown in Fig.1. They can select a locomotion style which is appropriate to the environment using many degree of freedom. For example, they can stride over holes, step over obstacles, walk sideways to get through a narrow space and crawl on hands and knees to pass a small gate.

To make full use of this advantage, humanoid robots must observe the environment by themselves, select an appropriate locomotion style and execute it. The propose method generates a 3D local map from visual information and plans the appropriate locomotion based on the map from biped walking with the variable height and the width and from crawling.

This paper is organized follows. Section 2 surveys related works on the locomotion planning in the complex environment. Section 3 describes how to make a 3D local map from visual information. Section 4 explains how to select an appropriate locomotion style using the map. Section 5 presents a simulation result. Section 6 concludes this paper.

II. Related works

Major differences between locomotion of humanoid robots and wheeled robots are (1)humanoid robots can switch locomotion style (walk sideways, crawl and so on) according to the environment and (2) a biped locomotion is described not by a continuous trajectory but by a sequence of footsteps.

Considering the background, researches on humanoid locomotion in the complex environment can be classified into two categories. One is on a footstep planning of a biped locomotion, and another is on a selection of locomotion styles including a biped locomotion and crawling.

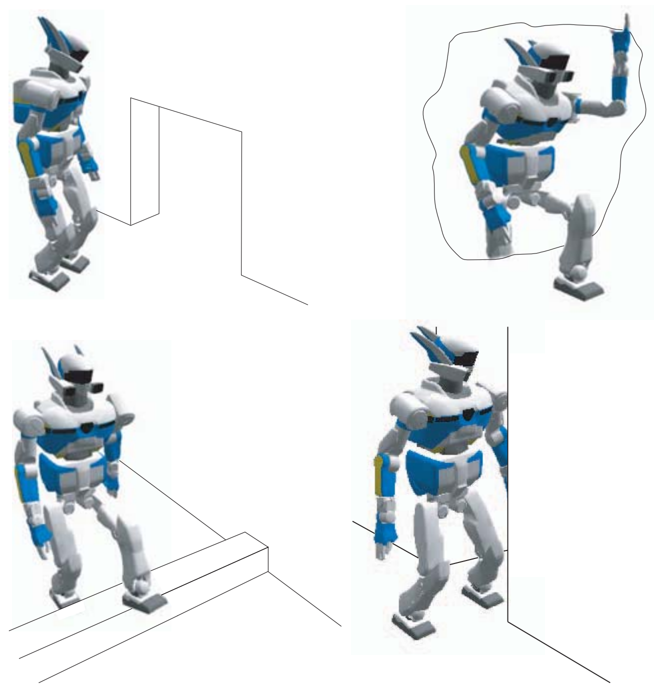

Fig. 1. Various locomotion styles

There is several researches on a footstep planning. Kuffner et al. proposed a planner which finds a sequence of footsteps which do not collide with obstacles on the floor[4]. Kagami et al. presented an experiment that a humanoid robot detects obstacles using visual information and plans footsteps using Kuffner's planner[5], [6]. Chestnutt et al. developed a planner which includes several evaluation functions and as a result, it outputs footsteps which means stepping over motion if it is evaluated better than avoiding motion[7]. Seara et al. are working on a gaze control when a robot observing the environment to make footsteps[8], [9], [10].

On the other hand, there is a few researches on locomotion switching. Shiller et al. developed a planner which finds a sequence of locomotion styles using a 3D global map[11]. Fujimoto et al. presented an experiment that a humanoid robot detects a obstacle region using points specified by an operator

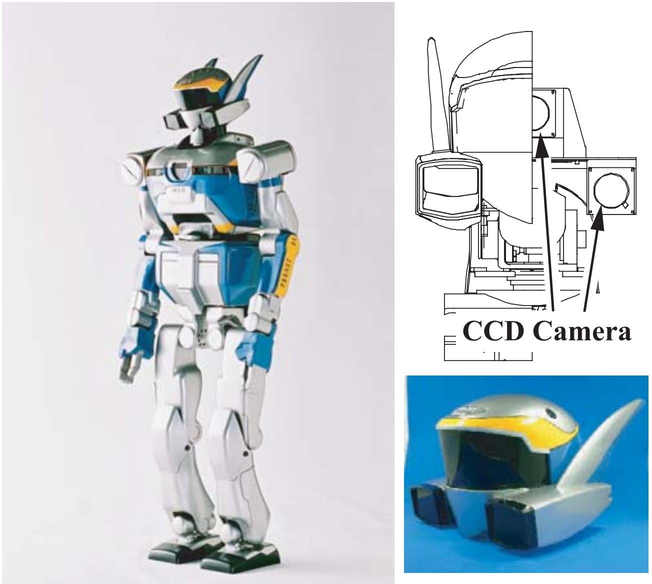

Fig. 2. The exterior of HRP-2 and a camera system

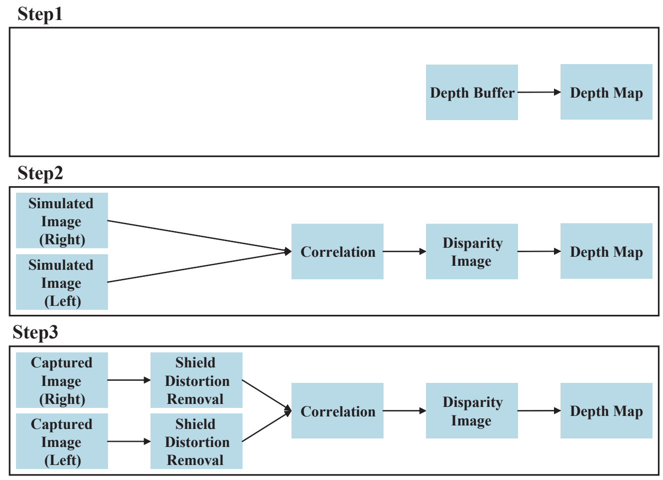

Fig. 3. 3 steps for a 3D local map generation

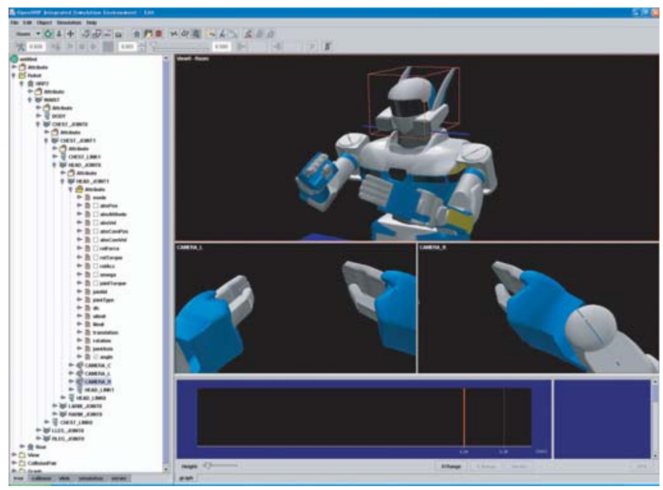

Fig. 4. OpenHRP

and selects a locomotion style[12].

III. 3D LOCAL MAP GENERATION

A. Humanoid robot:HRP-2

Figure 2 shows a humanoid robot HRP-2[13]. HRP-2 is developed for a cooperative work with a human in the open-air[14] by one of application investigation groups of HRP(Humanoid Robotics Project)[15]. It has almost same size as a human, 154[cm] height and 58[kg] weight.

HRP-2 has a stereo vision system composed of three cameras(Fig.2 upper right). Two horizontal cameras are separated by 144[mm], and the third camera is 70[mm] upper than them. Three cameras system is adopt since it is difficult for stereo vision composed of two cameras to detect the horizontal line. Relatively short focus lens is used whose standoff is from 0.5[m] to 4[m]. The camera's shutter speed is controllable by a computer to adapt various lighting condition. The image processing is based on VVV System[16]. VVV consists of several image processing modules, 3D shape model reconstruction, an object recognition, an object tracking and so on.

Through a plastic shield in front of the cameras (Fig.2 lower right), the object image is distorted. It is practically difficult to model the shield shape and the position of the camera correctly. So a conversion table between a distorted image to a image without the shield is made using a calibration board. Lens distortion is also corrected using the same method. As a result, the distortion is reduced within 0.2 pixel.

B. 3D Local Map Generation using View Simulator

As mentioned in the previous subsection, a 3D local map generation on the real robot requires to remove distortions caused by a shield and a lens. In this research, therefore, the map generation is realized in three steps as shown in Fig.3.

In the first and second steps, a view simulator which is a part of OpenHRP[17] is used and in the final step a real robot is used. Figure 4 shows a snapshot of a graphical user interface of OpenHRP.

In the first step, a depth buffer which is generated in the view simulation of the robot is used to make the map instead of a disparity image which can be generated by a stereo image processing. In the second step, a disparity image is generated by processing simulated views and it is used to make the map. In the final step, the distortion is removed from captured real views and its result is passed to software developed in the second step.

In this paper, the first step is described in detail. The depth buffer includes Z values in the raster coordinates at each pixel that ranges from 0.0 to 1.0. $Z = 0.0$ corresponds to the near clip distance, and $Z = 1.0$ the far clip one. And if Z value is 1.0 it means far clip distance. 3D coordinates (x, y, z) for a pixel(i, j) in the depth buffer can be calculated by

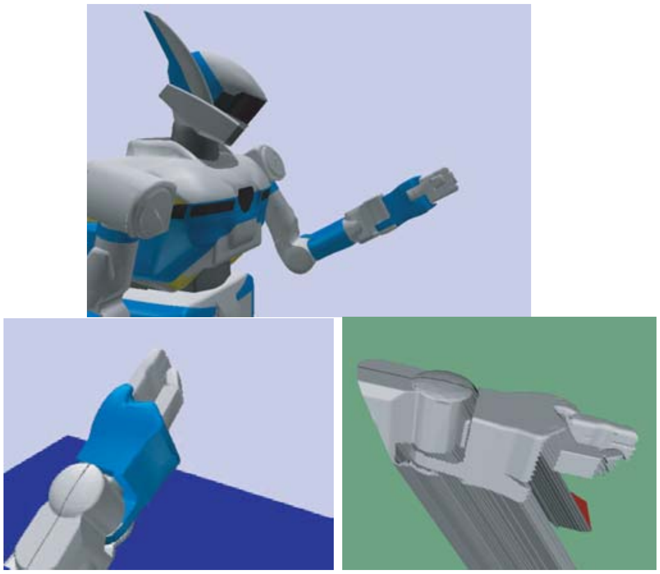

Fig. 5. An example of a 3D local map generation

$$Z_s = \frac{W}{2 \times tan(\theta/2)}, \quad (1)$$

$$z = \frac{Z_f \times Z_n}{Z \times (Z_f - Z_n) - Z_f}, \quad (2)$$

$$x = \frac{(j - W/2) \times Z}{Z_s}, \quad (3)$$

$$y = \frac{(i - H/2) \times Z}{Z_s}, \quad (4)$$

where W, H, θ, Z_n, Z_f and Z denote the width of the simulated view, the height of the simulated view, the horizontal field of view, the near clip distance, a far clip distance and Z value for pixel(i, j) respectively.

Figure 5 shows an example of the map generation mentioned above. The upper picture shows an external view, and the lower ones show a simulated view and a generated map. In the example, W, H, Z_n, Z_f and θ are set to 320, 240, 0.1[m], 10.0[m] and 45[deg] respectively.

IV. Locomotion planning

A. Locomotion styles

Five locomotion styles can be chosen according to the 3D local map. Figure 6 shows basic postures of them. From the left, crawling locomotion(*Crawl*), biped locomotion with squatting posture(*Squat*), biped locomotion sideways(*Side*), biped locomotion with twisting its waist joint(*Twist*) and ordinary biped locomotion(*Normal*).

The biped locomotion is generated by a biped walking pattern generator based on a preview control of the Zero-Moment Point [18]. The generator can output the walking

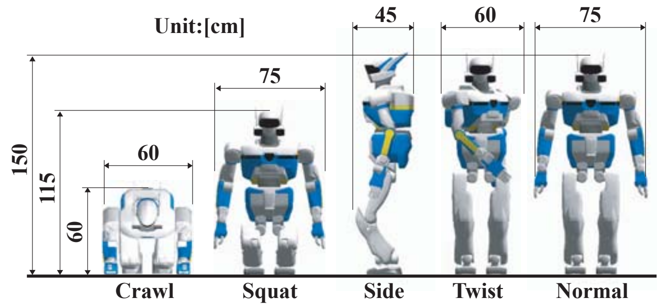

Fig. 6. Locomotion postures

pattern with a specified height z_c of the center of the mass of the robot, i.e.

$$\ddot{y} = \frac{g}{z_c}(y - p_y), \quad (5)$$

$$\ddot{x} = \frac{g}{z_c}(x - p_x). \quad (6)$$

where (x, y) denotes the trajectory of the center of the mass projected on the horizontal plane, g the gravity acceleration and (p_x, p_y) that of the ZMP. *Squat* can be generated by specifying z_c to be a lower value.

The robot must lie down to switch from a biped walking to *Crawl* and get up from *Crawl* to the walking. The transition between *Squat* style and *Crawl* one needs a dynamic balance control[19] given by

$$\Delta P = P_d(t_i) - P(t_i), \quad (7)$$

$$\tilde{\theta}_{hip}(t_i) = k_1 \Delta P(t_i) + k_2 \tilde{\theta}_{hip}(t_{i-1}), \quad (8)$$

where $P_d(t_i)$ is the desired position of the ZMP of the robot at the i-th sampling time t_i, $P(t)$ the actual position of ZMP that is computed from the outputs of the force sensors at the ankles, k_1 and k_2 are the gains of the feedback, and $\tilde{\theta}_{hip}$ is the compensation angle that is added to the hip pitch joints and subtracted from the ankle pitch joints.

B. Selection of a locomotion style

A locomotion method is selected by the following steps.

1) Remove locomotion styles which are not suitable to the current environment
2) In the case several locomotion styles are admissible, they are scored by an evaluation function.

These steps are described as follows.

Whether a locomotion style is admissible is decided by whether there is collision between the map and the sweeping volume of the robot body while moving. If the collision is detected the locomotion style can not be used. In this paper, a precise sweeping volume is not used and the robot is approximated by a box.

The sizes of the bounding boxes are shown in Fig.6, but its body swings right and left to keep balance when the robot moves. As a result, the sizes of the boxes must be enlarged. In addition, a map includes errors due to the noise on sensor signals and the modeling errors. Taking account of these

TABLE I

LOCOMOTION METHODS

	Width[m]	Height[m]	Velocity[km/h]
Normal	0.95	1.55	1.35
Twist	0.75	1.55	1.35
Side	0.55	1.55	0.23
Squat	0.95	1.15	0.45
Crawl	0.75	0.65	1.08

TABLE II

THE TIME REQUIRED BY TRANSITIONS(UNIT:[S])

	Normal	Twist	Side	Squat	Crawl
Normal	0	1.0	9.7	2.3	28.4
Twist	1.0	0	10.7	2.3	28.4
Side	9.7	10.7	0	12.0	38.1
Squat	2.3	2.3	12.0	0	30.4
Crawl	19.2	19.2	28.9	21.2	0

elements, the sizes of the bounding boxes for the locomotion styles are decided as shown in Table I, and the depth of the box is decided as 1.7[m] considering the field of view and the distance which is required to stop the current locomotion and to transit to a new locomotion.

The function evaluates the following criteria.

- Moving speed
- Time required to switch locomotion
- Load on the robot hardware(current, heat and so on)

If the global map of the environment is known a priori, it is possible to plan an optimal sequence of the locomotion which minimizes the time required to get to the goal using the moving speeds and the transition time. However, in this paper, it is assumed that the environment is unknown, and therefore the criteria mentions above are adopted.

Using these criteria, the evaluation value is calculated by

$$f_{total} = w_{vel} \times f_{vel} - w_{trans} \times f_{trans} - w_{load} \times f_{load} \quad (9)$$

Where ,f and w denote an evaluation value and a weight respectively, and the subscripts, $vel, trans, load$ correspond to the criteria. The moving speeds of the locomotion are shown in Fig.6 and the transition time in Table II.

V. PRELIMINARY SIMULATION AND EXPERIMENT

A. Simulation

In order to confirm that the 3D local map generation and the locomotion planning, a preliminary simulation is done in the environment shown in Fig.7. In the environment there are gates which have openings as shown in Table III and 10[cm] thickness. These six gates are set every five meters on a line. The admissible locomotion to get through those gates are shown in Table III. The robot stands on a position three meters away from the first gate at the initial state. After the simulation starts, the robot moves forward using *Normal* looking ahead and switches the locomotion if necessary. When the locomotion is switched to *Side* or *Crawl*, HRP-2 can not observe moving direction because of a restriction of joint movable ranges. Therefore, after switching those locomotion and moving forward two meters, the locomotion method is switched to *Normal* automatically. When the robot comes close to an opening, the robot can not see the gate and may miss the gate. Therefore, after switching to another locomotion style and before moving two meters forward, locomotion which has a larger box size than the current one is not selected.

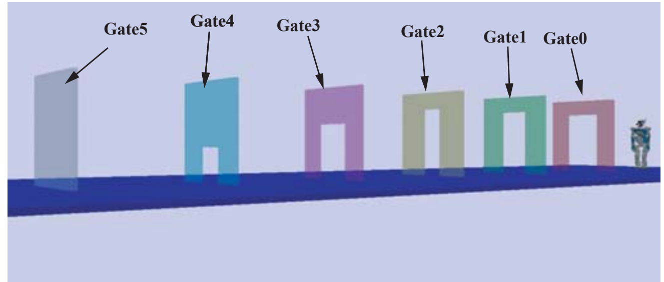

Fig. 7. Simulation world

TABLE III

THE SIZE OF OPENINGS AND AVAILABLE LOCOMOTION METHODS(UNIT:[M])

Gate	Width	Height	
0	1.0	1.6	All
1	0.8	1.6	Twist, Side and Crawl
2	0.6	1.6	Side
3	1.0	1.2	Squat and Crawl
4	0.8	0.7	Crawl
5	0	0	None

Moving speeds shown in Fig.I are used as f_{vel} and transition time shown in Table II are used as f_{trans}. f_{load} for *Squat* is set to 1.0 and for others to 0.0. This is because *Squat* posture needs high torque at the knee joints. w_{vel}, w_{trans} and w_{load} are set to 2, 1 and 3 respectively. Snapshots while the simulation and a result of locomotion planning are shown in Fig.8 and Fig.9 respectively.

B. Experiment

We did the corresponding experiment to the simulation and confirmed the locomotion styles can be executed on the real robot. Figure 10 shows selected snapshots of the experiment. In the experiment visual information was not used and the locomotion styles were selected in turn.

VI. CONCLUSIONS

In this paper, we proposed a method which generates a 3D local map from visual information and plans the appropriate locomotion based on the map from biped walking with the variable height and the width and from crawling, and confirmed it by the gate passing simulation. The proposed method is summarized as follows.

- A 3D local map is generated from the depth buffer which is generated in the view simulation of the robot

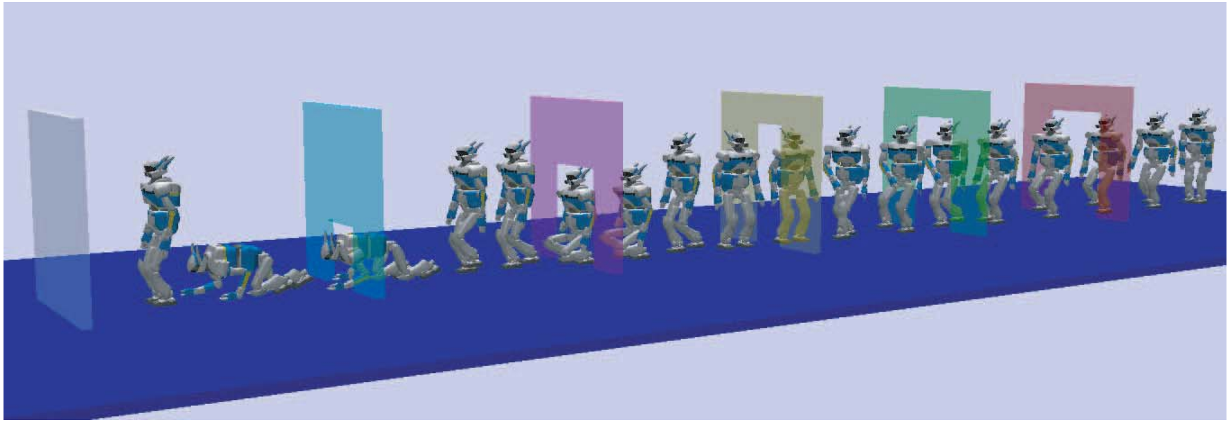

Fig. 8. Snapshots of the passing gates simulation

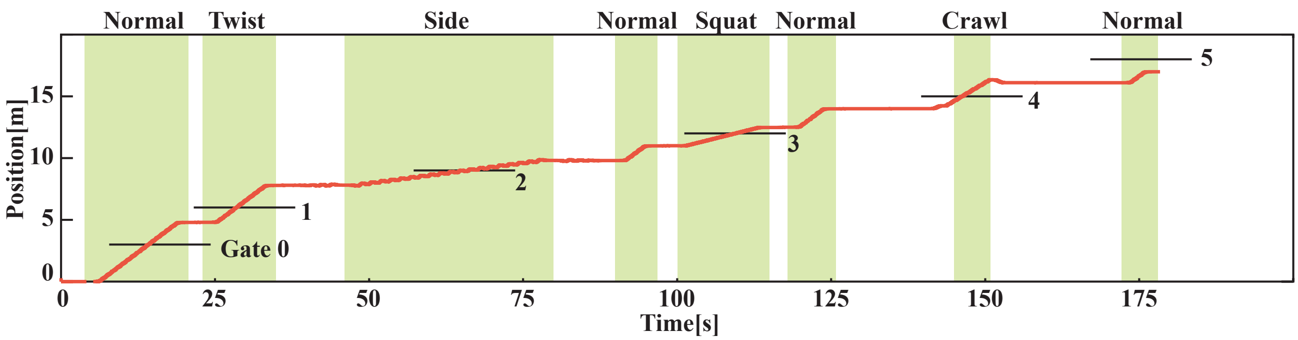

Fig. 9. Simulation result(robot position and locomotion methods)

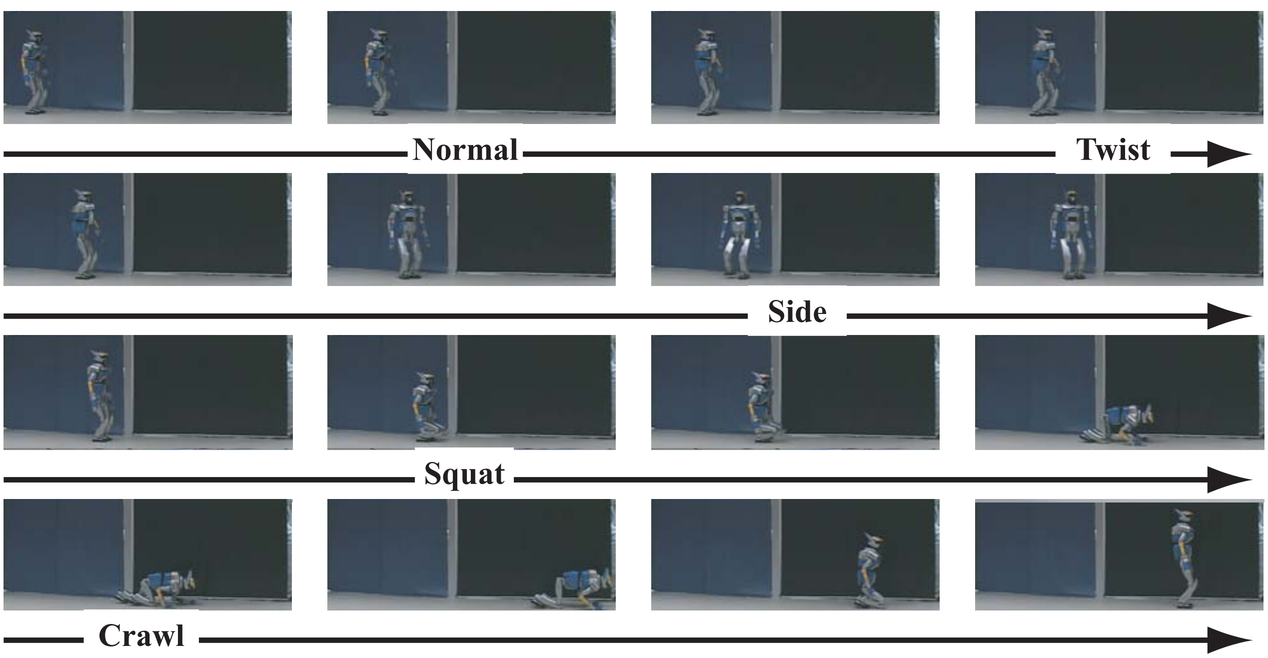

Fig. 10. Preliminary experimental result

- Using the map, inadmissible locomotion are removed and an appropriate locomotion is selected using the evaluation function.

Through these steps, the robot could pass gates which have various sizes in the simulation world.

The future works include

- the map generation by a stereo vision,
- the unification of the local maps into the global map,
- usage a precise sweeping volume instead of that of the box,
- on-side generation of a locomotion style to be applicable to the obtained environment.

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