Vision-Based Servoing Control for Legged Robots

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Abstract

This paper describes a vision-based servoing control scheme for legged robots to achieve a vision-guided swaying task utilizing a visual servoing technique. According to the controller, motions of the legs are not pre-programmed by analyzing the kinematics/dynamics of the system, but are generated by the servoing scheme reactively. The vision-based servoing scheme is a hybrid one consisting of a controller to keep the distances between feet constant (a stance servoing controller), and a visual servoing controller. Some preliminary experimental results are shown to demonstrate the effectiveness of the proposed scheme.

1 Introduction

Mobile abilities are essential for robots to achieve a given task in a wide task space. Among such abilities, legged locomotion has an advantage over the others owing to its adaptivity/robustness against changes of terrain. To make use of legged locomotion, however, one has to cope with many degrees of freedom which make controlling the robot complicated. Nevertheless, a number of studies have been proposed to control such a legged robot because of its adaptivity [1].

Many studies have been made on legged robots focusing on controllers utilizing internal sensors. In the previous work, they consider kinematics and/or dynamics of the legged robot, and calculate inputs to the joints. Then, they give the calculated inputs to the joints and apply a certain internal sensor based feedback control scheme in which changes of the environment cannot be considered. To cope with such changes, external sensors play a great role.

A vision sensor is one of such external sensors to be able to make the legged robot robust against changes of the environment. Researchers engaged in vision-based legged robot control utilize the vision sensors to navigate the robots [2–4]. Behaviors of the legs are pre-programmed and visual information is used for navigating the behaviors. However, vision sensors can also be utilized for servoing the legs, that is, visual servoing. Utilizing the visual servoing scheme, one can make the robot behave reactively against disturbance and changes of the environment. Consequently, we can realize a swaying behavior of the robot reactively by showing a visual cue (see figure 1).

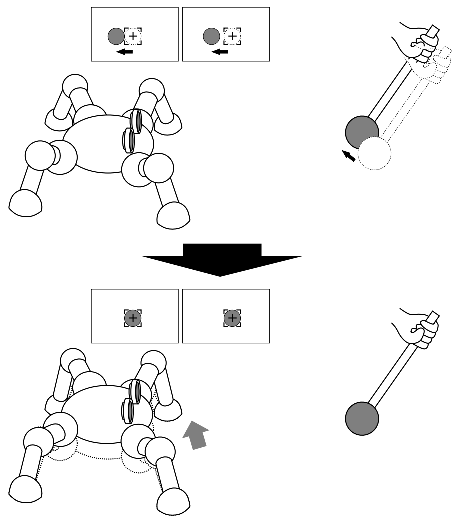

Figure 1: A visual cue can make a legged robot sway reactively utilizing visual servoing

Recently, visual servoing control has been received increasing attention in building a robust/high-response robot system [5–12]. The controller feeds the visual information back to the control inputs directly, which makes the closed loop system robust against disturbance. By applying such a visual servoing scheme to a legged robot, we can realize an adaptive/reactive swaying behavior of the robot. The resultant system is robust and adaptive against disturbance and changes of the environment. There have been many studies on visual servoing applied to manipulators, but none for legged robots to the best of our knowledge. The main difficulty to apply visual servoing to a legged robot is that the robot is not fixed on the ground unlike manipulators.

In this paper, we propose a vision-based servoing scheme for legged robots to achieve a vision-guided swaying task utilizing visual servoing. According to the proposed scheme, motions of legs are not pre-programmed by analyzing the kinematics/dynamics of the robot, but are generated by the servoing scheme re-

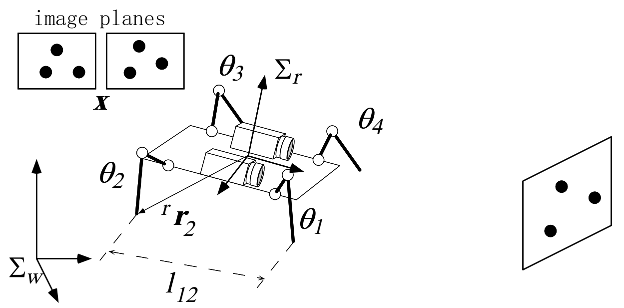

Figure 2: A legged robot with cameras gazes at a visual target

actively. The vision-based servoing scheme is a hybrid one consisting of a controller to keep the distances between feet constant (a stance servoing controller), and a visual servoing controller. Some preliminary experimental results are shown to demonstrate the effectiveness of the proposed scheme.

2 Vision-based servoing scheme for legged robots

2.1 How to apply visual servoing to legged robots

On applications of visual servoing, there are a number of studies on controlling manipulators, but there is no study on controlling legged robots to the best of our knowledge. One of the main difficulties to apply visual servoing to legged robots is that they are not fixed on the ground, whereas manipulators are fixed. If the position of a foot of the robot moves with respect to the ground by gaits and/or slips while a visual servoing scheme is applied, one needs to observe the amount of gaits/slips and needs to re-calculate the Jacobian matrix which describes the relation between the velocity of the robot with respect to the ground and the velocities of the joints.

To cope with the problem, we propose a hybrid controller consisting of a stance servoing controller to keep the distances between the feet constant and a visual servoing controller to chase the visual target. As far as distances between the feet are constant, the legged robot is supposed to be fixed on the ground, and we can apply a visual servoing scheme without re-calculating the Jacobian matrix. In the following, first we introduce a stance servoing scheme to keep the distances between the feet constant, and then visual servoing under the condition that the robot is fixed on the ground.

2.2 Stance servoing scheme

In figure 2 we show an n-legged robot chasing a visual target. Assume that each foot contacts with the ground at a point with friction. Let Σ_w and Σ_r be a world coordinate frame fixed on the ground and a robot coordinate frame fixed to the robot body, respectively. A vector from the origin of Σ_r to the i-th foot with respect to Σ_r, ${}^r\boldsymbol{r}_i$ $(i = 1, \cdots, n)$, is a function of the joint angle vector of the i-th leg, $\boldsymbol{\theta}_i$:

$$ {}^r\boldsymbol{r}_i = {}^r\boldsymbol{r}_i(\boldsymbol{\theta}_i). \tag{1} $$

Differentiating eq.(1), we can get a velocity relation between the joint velocity $\dot{\boldsymbol{\theta}} = [\dot{\boldsymbol{\theta}}_1^T \cdots \dot{\boldsymbol{\theta}}_n^T]^T$ and ${}^r\dot{\boldsymbol{r}} = [{}^r\dot{\boldsymbol{r}}_1{}^T \cdots {}^r\dot{\boldsymbol{r}}_n{}^T]^T$,

$$ {}^r\dot{\boldsymbol{r}} = \boldsymbol{J}_{r\theta}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}, \tag{2} $$

where $\boldsymbol{J}_{r\theta} = \partial^r\boldsymbol{r}/\partial\boldsymbol{\theta}^T$. Assume that each leg has sufficient degrees of freedom for positioning each foot, and the Jacobian matrix $\boldsymbol{J}_{r\theta}$ becomes invertible without losing generality (If a leg has more than 4 d.o.f., all we have to do is to find a certain subtask to deal with the redundancy). Let a stance vector $\boldsymbol{l} \triangleq [l_{12} \cdots l_{n-1n}]^T \in \Re^{{}_nC_2}$ denote a collection vector of distances between feet,

$$ \boldsymbol{l} = \begin{bmatrix} \| {}^r\boldsymbol{r}_1 - {}^r\boldsymbol{r}_2 \| \\ \vdots \\ \| {}^r\boldsymbol{r}_{n-1} - {}^r\boldsymbol{r}_n \| \end{bmatrix}. \tag{3} $$

Differentiating eq.(3), we get a velocity relation

$$ \dot{\boldsymbol{l}} = \boldsymbol{J}_{lr}({}^r\boldsymbol{r}){}^r\dot{\boldsymbol{r}}, \tag{4} $$

where $\boldsymbol{J}_{lr} = \partial\boldsymbol{l}/\partial^r\boldsymbol{r}^T$. From eqs.(2) and (4), a feedback controller for joint velocities to keep the stance vector $\boldsymbol{l}$ as a constant desired vector $\boldsymbol{l}_d$ can be derived as

$$ \boldsymbol{u} = \boldsymbol{J}_{r\theta}{}^{-1}\{\boldsymbol{J}_{lr}{}^{+}\boldsymbol{K}_l(\boldsymbol{l}_d - \boldsymbol{l}) + \boldsymbol{n}(\boldsymbol{J}_{lr})\}, \tag{5} $$

where $\boldsymbol{J}_{lr}{}^{+}$ and $\boldsymbol{n}(\boldsymbol{J}_{lr})$ denote a pseudo inverse matrix and a null space vector of a matrix $\boldsymbol{J}_{lr}$, respectively. The matrix $\boldsymbol{K}_l \in \Re^{{}_nC_2 \times {}_nC_2}$ is a gain matrix. Because the desired vector of this controller can be the initial distance vector, one needs not to know the shape of the ground nor to sense gait/slip displacement as far as all the legs of the robot keep touch with the ground at the initial configuration. Utilizing the null space $\boldsymbol{n}(\boldsymbol{J}_{lr})$, a visual servoing controller can be applied.

2.3 Visual servoing controller

From the cameras attached on the robot body, one can get some quantities of image features such as position, line length, contour length, and/or area of certain image patterns. Let the image feature vector be $\boldsymbol{x} \in \Re^m$. Assume that the target is moving so slowly that one can neglect the velocity of the target comparing to the velocity of the robot. If the stance servoing scheme (5) keeps stance constant, the image feature vector is a function of the foot position vector w. r. t. Σ_r,

$$\boldsymbol{x} = \boldsymbol{x}({}^r\boldsymbol{r}). \tag{6}$$

Differentiating eq.(6), we can get

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{xr}{}^r\dot{\boldsymbol{r}}, \tag{7}$$

where $\boldsymbol{J}_{xr} = \partial\boldsymbol{x}/\partial{}^r\boldsymbol{r}^T$. Note that more than four legs are redundant for determining the relative position/orientation of Σ_r with respect to Σ_w, therefore the matrix $\boldsymbol{J}_{xr}$ is not identical.

To deal with the description redundancy of $\boldsymbol{J}_{xr}$, we decide to use a matrix to minimize the variation of ${}^r\boldsymbol{r}$. If the stance vector $\boldsymbol{l}$ is constant, ${}^r\boldsymbol{r}$ is a function of $\boldsymbol{x}$

$${}^r\dot{\boldsymbol{r}} = \boldsymbol{J}_{rx}\dot{\boldsymbol{x}}, \tag{8}$$

in which $\boldsymbol{J}_{rx}$ is identical. A description of $\boldsymbol{J}_{xr}$ which minimize the variation of ${}^r\boldsymbol{r}$ is therefore obtained as

$$\boldsymbol{J}_{xr} = \boldsymbol{J}_{rx}{}^+. \tag{9}$$

2.4 Hybrid servoing scheme of stance servoing and visual servoing

From eqs.(5) and (7), we propose a hybrid controller to keep feet distances and to make the image features converge to the desired ones,

$$\begin{aligned}\boldsymbol{u} \;=\;& \boldsymbol{J}_{r\theta}{}^{-1}[\boldsymbol{J}_{lr}{}^+\boldsymbol{K}_l(\boldsymbol{l}_d - \boldsymbol{l}) \\ & +(\boldsymbol{I}_{3n} - \boldsymbol{J}_{lr}{}^+\boldsymbol{J}_{lr})\{(\boldsymbol{I}_{3n} - \boldsymbol{J}_{lr}{}^+\boldsymbol{J}_{lr})\boldsymbol{J}_{rx}{}^+\}^+ \\ & \{\boldsymbol{K}_i(\boldsymbol{x}_d - \boldsymbol{x}) - \boldsymbol{J}_{rx}{}^+\boldsymbol{J}_{lr}{}^+\boldsymbol{K}_l(\boldsymbol{l}_d - \boldsymbol{l})\}],\end{aligned} \tag{10}$$

where $\boldsymbol{I}_{3n}$, $\boldsymbol{K}_i$, and $\boldsymbol{x}_d$ denote a $3n \times 3n$ identity matrix, $m \times m$ gain matrix, and a given desired vector of the image features, respectively. This controller changes the attitude of the legged robot so as to visually track the target. Therefore, by applying this controller to a legged robot, one can achieve a swaying behavior by moving the target.

3 Experiments

To show the effectiveness of the proposed servoing controller, some preliminary experimental results are shown in this section.

3.1 Experimental equipment

In figure 3, a legged robot TITAN–VIII and its controller used for experiments are shown. The quadruped walking robot TITAN–VIII was developed by Tokyo Institute of Technology [13] whose size was about 0.5(W)× 0.6(D)× 0.4(H)[m], and whose weight was about 25[kg]. The walking robot was equipped with stereo cameras whose baseline was 0.1[m]. Video signals from two cameras (EVI–330, Sony Corp.) were sent to a scan-line converter (Sony Corp.) in which the two signals were pasted on an image. Size of each image was 256[pixel] × 256[pixel].

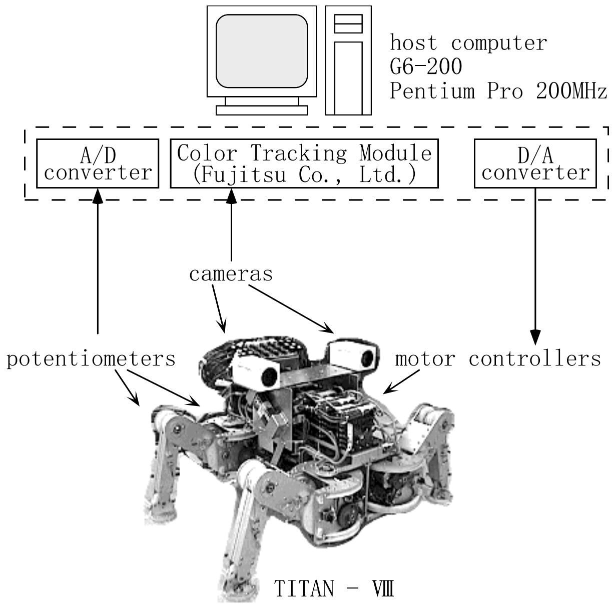

Figure 3: Experimental equipment

The output image was sent to a tracking unit equipped with a high-speed correlation processor (Fujitsu Corp.) whose image size was 512[pixel] × 512[pixel]. Before starting an experiment, we gave 16×16 certain images (called reference images) to be tracked. During the experiment the unit fed coordinates where the correlation coefficient (it used a SAD (Sum of Absolute Difference) measure) was the smallest with respect to the reference images to the host computer G6–200 (Gateway2000 Corp. CPU:Pentium Pro 200MHz) in real–time (33[ms]). Coordinates of three corresponding points were sent to the host, that is $\boldsymbol{x} \in \Re^{12}$.

Each joint of the walking robot was equipped with a potentiometer to observe the joint angle. The joint angle was sent to the computer via an A/D converter board. The computer calculated the desired joint velocities according to the proposed method and sent commands to velocity controllers of joints via a D/A converter board. A manipulator was used to move a visual target. The visual target was a picture pasted at the tip of the manipulator (see figures 5 and 7). Distance between the target and the robot was 1.0[m].

3.2 Experimental results

Two experimental results are shown in this paper. First, the visual target was moved vertically so that a vertical swaying behavior was realized. Second, the

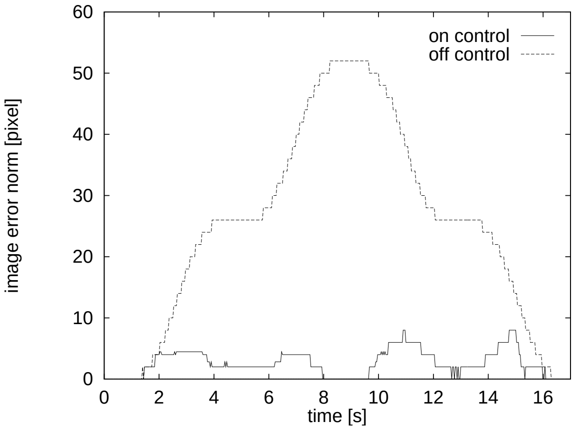

Figure 4: Error norm of one point in the left image plane from its desired point (vertical swaying)

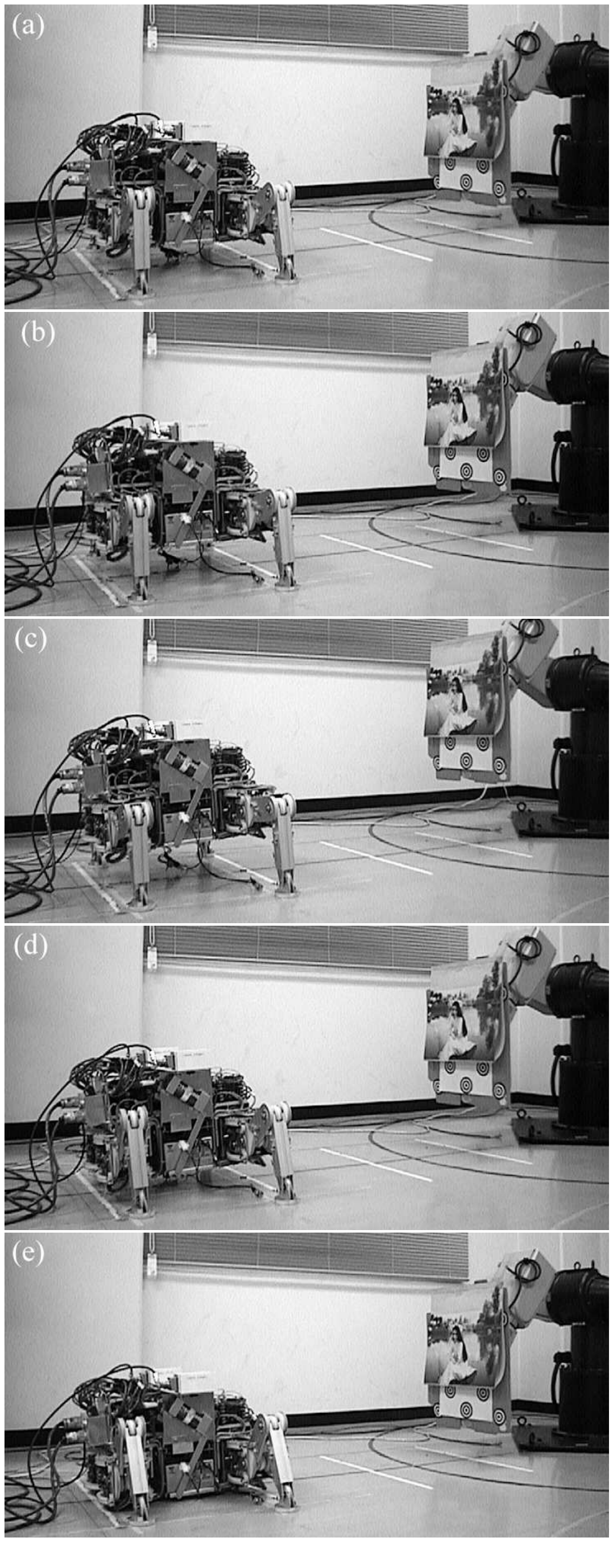

Figure 5: A realized vertical swaying motion

visual target was moved horizontally so that a horizontal swaying behavior was realized.

Vertical swaying of the robot. In figure 5, realized vertical motions of the robot are shown. The initial posture of the robot is shown in figure 5(a). The target moved 0.07[m] upward in 1[s], stayed 1[s] (b), moved 0.07[m] upward in 1[s], stayed 1[s](c), moved 0.07[m] downward in 1[s], stayed 1[s](d), and moved 0.07[m] downward in 1[s]. The final posture is shown in (e). We can find that the robot sway upward and downward according to the motion of the visual target. The error norm of a coordinate from its desired in the image plane is shown in figure 4. We can also see the error norm without the proposed scheme in the figure.

Horizontal swaying of the robot. In figure 7, realized horizontal motions of the robot are shown. The initial posture of the robot is shown in figure 7(a). The target moved 0.07[m] leftward in 1[s], stayed 1[s] (b), moved 0.07[m] rightward in 1[s], stayed 1[s](c), moved 0.07[m] rightward in 1[s], stayed 1[s](d), and moved 0.07[m] leftward in 1[s]. The final posture is shown in (e). We can find that the robot sway leftward and rightward according to the motion of the visual target. The error norm of a coordinate from its desired in the image plane is shown in figure 6. We also see the error norm without the proposed scheme in the figure.

We can find that the proposed scheme can track the target well from these results. We also observed the distance between feet, and found that the changes of the distance were remarkably small.

Forward and Backward swaying motions were also tested. Unfortunately, the forward and backward swaying was not realized well. The reason for this is not hard to see: it was that the size of the image planes was so small that the robot could not observe

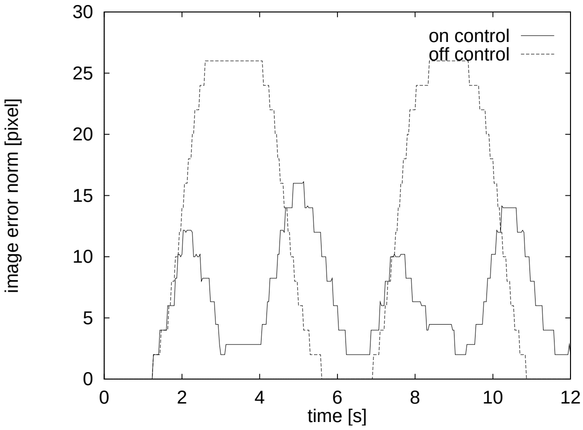

Figure 6: Error norm of one point in the left image plane from its desired point (horizontal swaying)

motions of the visual target along forward/backward axis.

4 Summary and discussions

In this paper, we have proposed a new vision-guided control scheme for legged robots not only from the standpoint of legged robot control, but also of visual servoing. From the standpoint of legged robot control, we have proposed to utilize visual information for servoing the legs. Utilizing the visual servoing technique, one can make the robot behave reactively against disturbance and changes of the environment. Consequently, we can realize a swaying behavior of the robot reactively by showing a visual cue. On the other hand, from the standpoint of visual servoing, this paper has shown a method how to apply the visual servoing technique to a legged robot which is not fixed on the ground unlike manipulators. We have utilized the redundancy which a legged robot essentially has so as to apply the visual servoing technique.

If the robot has more than four legs, the Jacobian matrix describing the relation between the foot position with respect to the robot frame and image features is no more identical because the closed linkage system is redundant as shown in eq.(7). In this paper, we have proposed to use a description (9), which may not be an optimum solution. How to treat this kind of redundancy seems one of the issues interesting and important.

In this paper, the robot and the environment are well-calibrated. It is not so difficult to calibrate the robot and the environment, when the robot does not walk but only sways, because one need not to estimate the terrain. But, when the robot walks around in an unknown environment chasing the visual cue, which may be the final goal of the study, the robot must

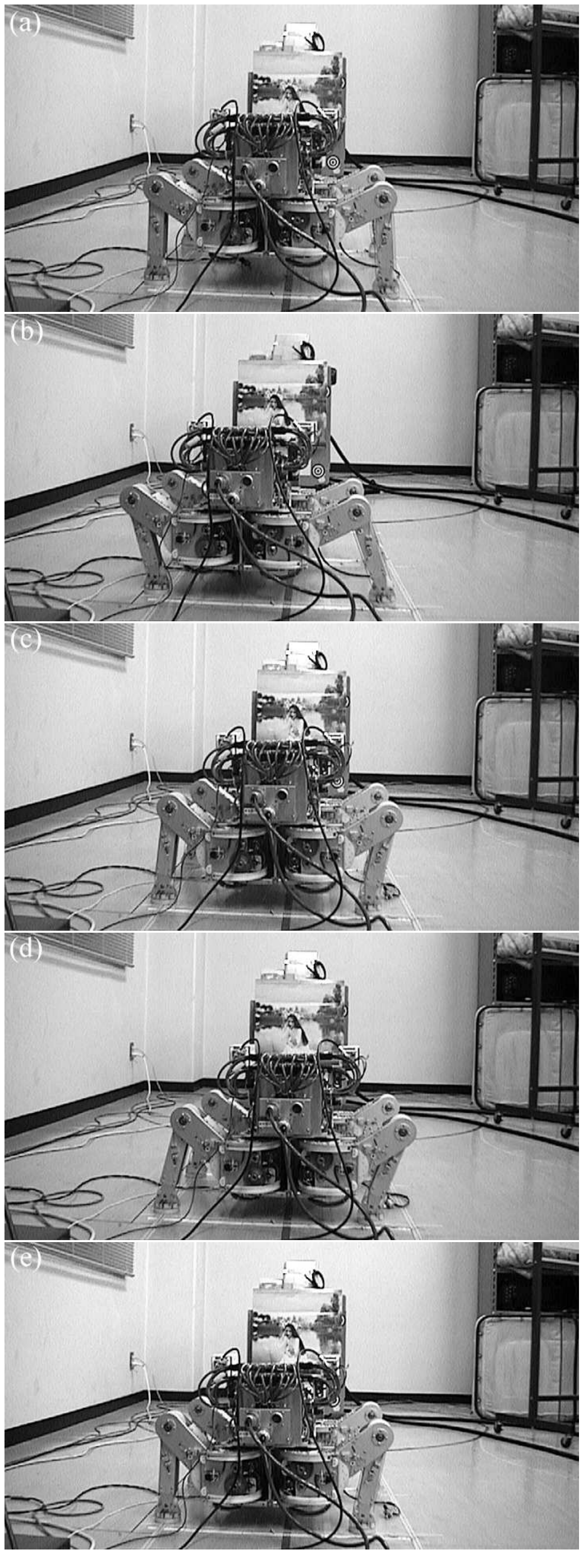

Figure 7: A realized horizontal swaying motion

estimate the environment on-line. We are now considering to apply adaptive visual servoing [12] to the legged robot.

To realize a gate, we must consider how to determine the swing leg and where to move the swing leg. The proposed scheme can make a legged robot sway tracking the target, but cannot make it walk yet. Therefore the movable range of the robot is limited. We are now strongly interested if the movement limit of the robot emerge a leg swing or not. We wonder if the visual sensors are sufficient, or additional external sensors must be required. Now, we are attacking these issues.

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References

[1] M. H. Raibert et al. Special issue on legged locomotion. *Int. J. of Robotics Research*, 3(2), 1984.

[2] E. Krotkov and R. Hoffman. Terrain mapping for a walking planetary rover. *IEEE Tras. on Robotics and Automation*, 10(6):728–739, 1994.

[3] M. Inaba, F. Kanehiro, S. Kagami, and H Inoue. Two-armed bipedal robot that can walk, roll over and stand up. In *Proc. of the 1995 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 297–302, 1995.

[4] D. J. Pack. Perception-based control for a quadruped walking robot. In *Proc. of IEEE Int. Conf. on Robotics and Automation*, pages 2994–3001, 1996.

[5] P. I. Corke. Visual control of robot manipulators – a review. In *Visual Servoing*, pages 1–31. World Scientific, 1993.

[6] L. E. Weiss, A. C. Sanderson, and C. P. Neuman. Dynamic sensor-based control of robots with visual feedback. *IEEE J. of Robotics and Automation*, RA-3(5):404–417, 1987.

[7] J. T. Feddema and C. S. G. Lee. Adaptive image feature prediction and control for visual tracking with a hand-eye coordinated camera. *IEEE Trans. on System, Man, and Cybernetics*, 20(5):1172–1183, 1990.

[8] K. Hashimoto, T. Kimoto, T. Ebine, and H. Kimura. Manipulator control with image-based visual servo. In *Proc. of IEEE Int. Conf. on Robotics and Automation*, pages 2267–2272, 1991.

[9] W. Jang and Z. Bien. Feature-based visual servoing of an eye-in-hand robot with improved tracking performance. In *Proc. of IEEE Int. Conf. on Robotics and Automation*, pages 2254–2260, 1991.

[10] N. Maru, H. Kase, et al. Manipulator control by visual servoing with the stereo vision. In *Proc. of the 1993 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 1865–1870, 1993.

[11] N. P. Papanikolopoulos and P. K. Khosla. Adaptive robotic visual tracking: Theory and experiments. *IEEE Trans. on Automatic Control*, 38(3):429–445, 1993.

[12] K. Hosoda and M. Asada. Versatile visual servoing without knowledge of true jacobian. In *Proc. of the 1994 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 186–193, 1994.

[13] K. Arikawa and S. Hirose. Development of quadruped walking robot TITAN–VIII. In *Proc. of the 1996 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 208–214, 1996.