Hybrid Structure of Reflective Gait Control and Visual Servoing for Walking

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Abstract

This paper presents a hybrid structure of reflective gait control and adaptive visual servoing [3] by which a vision guided legged robot realizes a reflective walk. The reflective gait consists of three steps: 1) select a leg to be lifted so as to increase the body stability, 2) move one of other legs to enable the selected leg lifted, and 3) move the selected leg. During these steps, adaptive visual servoing [5] generates a swaying motion of the robot so that it can stabilize the visual target at the desired position in the image. Combining the reflective gait and the swaying, the robot attempts at tracking the visual target, and as a result a reflective walk emerges. The validity of the method is shown by computer simulation and a preliminary real experiment, and future work is given.

1 Introduction

Legged locomotion has been attracting many researchers not only as a method of navigation on rough terrains but also due to its biological interests in realizing artificial systems similar to legged animals owing to many degrees of freedom. As the range of robot applications becomes wider and their task complexities becomes higher, the needs for such locomotion has been increasing since wheel based locomotion is limited to well-developed structured terrains.

Most existing methods have considered kinematics and/or dynamics of the legged robots, calculated desired trajectories of the joints, and applied internal sensory feedback so that the robot can control leg motions to follow the trajectories [1]. Therefore, these robots seems difficult to adapt themselves to changes in their environments. To cope with these changes, external sensors such as vision, tactile, and force sensors seem necessary as we can see in many living systems.

Vision is one of the most powerful external sensors to obtain the information of the changes of the environment without physical interactions. Recent progress on visual servoing techniques make it possible for robot systems to feed visual information back so as to build a closed servo loop robust against disturbance [4]. Most work has paid its attention on robot arm control, and to the best of our knowledge only Hosoda et al.[4, 5] have challenged to apply the visual servoing technique to legged robots. They pointed out the difficulty of the problems due to the differences from the conventional visual servoing on arm control, that is, the base of the robot is not fixed but movable, and the legged robot can be regarded as a closed link system. As the first step, they formulated the adaptive visual servoing for legged robots, and their robot showed swaying motion, but no walking motion yet.

There are some work to realize reflective walks for human-operated walking control [6, 2]. S. Salmi and A. Halme [6] built a motion planner to the six-legged walking robot, "MECANT", and realized a reflective walk. Their method is, however, difficult to apply to quadruped robots directly, since it is difficult to keep static stability and realize the reflective gait. H. Adachi et al. [2] realized a reflective gait for the quadruped robot by a body propulsive action and recovery ones. However, they need a strong assumption on horizontal plane terrain in order to realize stable lift-down actions. Therefore, their method seems difficult to apply to non-horizontal plane terrain.

In this paper, we propose a hybrid structure of reflective gait control and adaptive visual servoing [3] by which a vision guided quadruped robot realizes a reflective walk. The reflective gait consists of three steps: 1) select a leg to be lifted so as to increase the body stability, 2) move one of other legs to enable the selected leg lifted, and 3) move the selected leg. During these steps, adaptive visual servoing [5] generates a swaying motion of the robot so that it can stabilize the visual target at the desired position in the image. Combining the reflective gait and the swaying, the robot attempts at tracking the visual target coping with changes of the environment and the body stability, and as a result a reflective walk emerges on non-horizontal plane terrain.

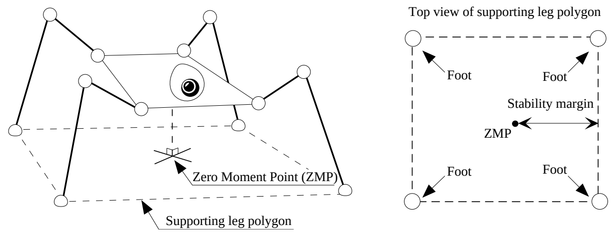
The rest of this article is structured as follows. In the next section, we explain our method for reflective walking. Then, we show the computer simulation to verify the proposed method. Finally, an overview of our real robot is shown and the future work is given.

2 Walking based on a reflective gait and a visual tracking

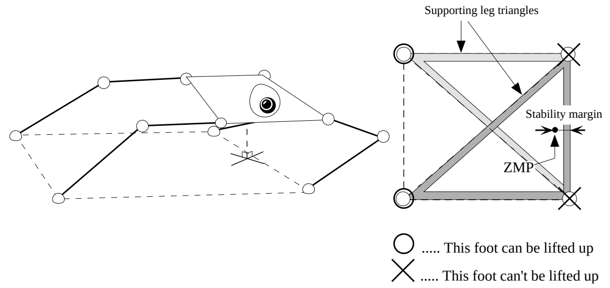
In this section, we describe an outline of our method which is explained by adopting a four-legged robot in illustrations for the readers' understanding. The stability of the robot generally can be represented by the distances between the zero moment point (here after, ZMP) and sides of the supporting leg polygon. As far as ZMP is inside of the polygon, the robot is stable (see Figure 1(a)). We use a stability margin, which is the shortest distance between ZMP and a side of the supporting leg polygon, as a measure of the stability (see Figure 1).

The reflective gait control plays a role of maintaining the stability of the robot. For example, if the stability margin becomes small as shown in Figure 1(b), the robot has to lift a leg up and move it, which we call a "target leg" in the following, to increase the margin. In Figure 1(b), candidates of the target leg are indicated as "×". They can not be lifted up because ZMP is always inside two supporting leg triangles including the both target legs. In such a case, therefore, the reflective gait control lifts one of the other legs so as to make the target leg to be lifted (see Figure 2(a)), and moves the target leg to increase the stability margin (see Figure 2).

On the other hand, the visual servoing plays a role of stabilizing a visual target at the desired position in the image. According to the target motion, the robot shows swaying motions attempting at tracking the target (see Figure 3(a)). However, if it goes on swaying, the robot falls down. Then, we combine the reflective gait control with the visual servoing and realize visual target tracking. Consequently, a reflective walk emerges (see Figure 3(b)).



(a) a stable pose



(b) an unstable pose

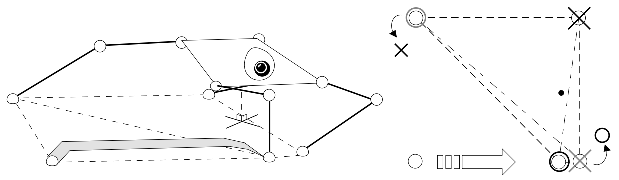
Figure 1: The relationship between the stability margin and the feet

2.1 Reflective gait

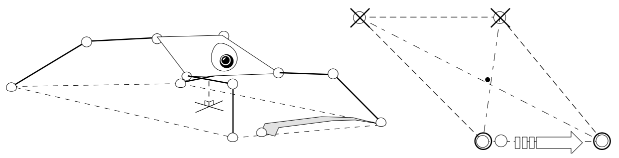
In this subsection, we describe the reflective gait control in detail. We propose a gait measure to select a leg for the gait. The measure of leg(i) is defined as

$$I_i = (\text{Distance}) + \alpha\,(\text{Manipulability})\,, \tag{1}$$

where Distance, α and Manipulability denote a distance between the foot(i) and ZMP, an appropriate constant, and the manipulability measure [7] of the foot(i), respectively. For example, in Figure 4, the candidates for the target leg are leg(A) and leg(C). As the first step of the reflective gait control, the robot calculates the gait measures of the candidates, I_A and I_C. If I_A is smaller than I_C, then it selects leg(A) as a target leg. Next, it moves another leg, leg(B), to enable the target leg, leg(A), lifted. Finally, it increases the stability margin by moving the target leg (A). Using this simple algorithm, it can realize a reflective gait.

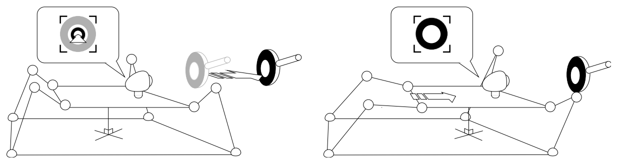


(a) Step1: Making the leg a lifted leg

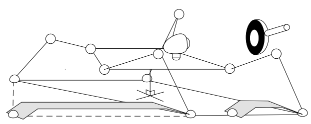


(b) Step2: Moving the lifted leg

Figure 2: The reflective gait



(a) Swaying based on visual servoing



(b) Reflective walking

Figure 3: The reflective walk

2.2 Swaying based on visual tracking[5]

We apply the adaptive visual servoing to the legged robot in order to track visual targets. As a result, the robot realizes swaying. We introduce the swaying controller, briefly.

Let Σ_R, $\boldsymbol{p}$, $\boldsymbol{r}_i$ and $\boldsymbol{l}$ denote a robot coordinate frame fixed to the robot body, a position vector of a camera attached to the robot with respect to Σ_R, the i-th foot position vector w. r. t. Σ_R and a stance vector consists of distances between feet, respectively(see Figure 5). Defining $\boldsymbol{r}$ by

$$\boldsymbol{r} \triangleq \left[\boldsymbol{r}_1^T \boldsymbol{r}_2^T \cdots \boldsymbol{r}_n^T\right]^T \quad , \tag{2}$$

we can obtain two velocity relations,

$$\begin{aligned} \dot{\boldsymbol{l}} &= \boldsymbol{J}_{lr}\dot{\boldsymbol{r}} \quad , &(3)\\ \dot{\boldsymbol{p}} &= \boldsymbol{J}_{pr}\dot{\boldsymbol{r}} \quad , &(4)\end{aligned}$$

where $\boldsymbol{J}_{lr} = \partial \boldsymbol{l}/\partial \boldsymbol{r}^T$ and $\boldsymbol{J}_{pr} = \partial \boldsymbol{p}/\partial \boldsymbol{r}^T$, respectively.

Let a vector of the image features be $\boldsymbol{x}$. Assume that the visual target is moving so slowly that one can neglect the velocity of the target comparing to the velocity of the robot. If the feet of the robot are fixed on the ground, we can obtain a velocity relation,

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{xp}\dot{\boldsymbol{p}} = \boldsymbol{J}_{xp}\boldsymbol{J}_{pr}^{+}\dot{\boldsymbol{r}} = \boldsymbol{J}_{xr}\dot{\boldsymbol{r}}. \tag{5}$$

From eq.(3),(5), visual servoing controller ,which makes the image feature vector $\boldsymbol{x}$ converge to a given desired trajectory $\boldsymbol{x}_d$, under a control of the feet distance vector $\boldsymbol{l}$ constant to fix the feet on the ground, can be derived as

$$\begin{aligned} \boldsymbol{u}_r \;=\; & \boldsymbol{J}_{lr}^{+}\boldsymbol{K}_l\left(\boldsymbol{l}_d - \boldsymbol{l}\right) \\ & + \left(\boldsymbol{I} - \boldsymbol{J}_{lr}^{+}\boldsymbol{J}_{lr}\right)\left\{\boldsymbol{J}_{xr}\left(\boldsymbol{I} - \boldsymbol{J}_{lr}^{+}\boldsymbol{J}_{lr}\right)\right\}^{+} \\ & \left\{\boldsymbol{K}_x\left(\boldsymbol{x}_d - \boldsymbol{x}\right) - \boldsymbol{J}_{xr}\boldsymbol{J}_{lr}^{+}\boldsymbol{K}_l\left(\boldsymbol{l}_d - \boldsymbol{l}\right)\right\}, \end{aligned} \tag{6}$$

where $\boldsymbol{u}_r$, $\boldsymbol{K}_l$ and $\boldsymbol{K}_x$ denote a control input vector and gain matrices, respectively.

In the controller (6), we can obtain the Jacobian matrix $\boldsymbol{J}_{lr}$ from kinematic parameters of the robot. But, since the matrix $\boldsymbol{J}_{xr}$ consists not only of the kinematic parameters that are known, but also of intrinsic and extrinsic camera parameters and of the parameters of the environment, we need to estimate the matrix $\widehat{\boldsymbol{J}}_{xr}$ that satisfies eq.(5) by correcting $\boldsymbol{r}$ and $\boldsymbol{x}$. We utilize a least squares method to identify the non-linear system in the discrete time domain:

$$\begin{aligned} &\{\widehat{\boldsymbol{j}}_i(k+1) - \widehat{\boldsymbol{j}}_i(k)\} = \\ &\frac{\{\boldsymbol{x}(k+1) - \boldsymbol{x}(k) - \widehat{\boldsymbol{J}}_{xr}(k)\boldsymbol{u}_r(k)\}_i}{\rho_i + \boldsymbol{u}_r(k)^T\boldsymbol{W}_{(i,k)}\boldsymbol{u}_r(k)}\boldsymbol{W}_{(i,k)}\boldsymbol{u}_r(k) \end{aligned} \tag{7}$$

where $\widehat{\boldsymbol{J}}_{xr}(k)$, $\widehat{\boldsymbol{j}}_i(k)$, $\boldsymbol{u}(k)(=T\dot{\boldsymbol{r}})$, ρ_i and $\boldsymbol{W}_i(k)$ denote a constant Jacobian matrix, its the i-th row vector, a control input vector in the k-th step during sampling rate T, an appropriate positive constant and a weighting matrix, respectively. Using the estimated matrix $\widehat{\boldsymbol{J}}_{xr}$, we can rewrite the controller (6) as

$$\boldsymbol{u}_r \;=\; \boldsymbol{J}_{lr}^{+}\boldsymbol{K}_l\left(\boldsymbol{l}_d - \boldsymbol{l}\right)$$

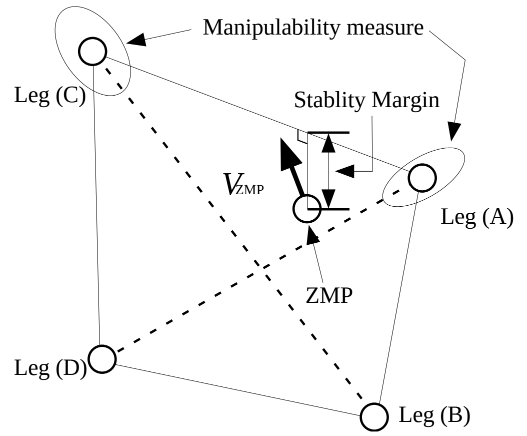


Figure 4: Stability margin

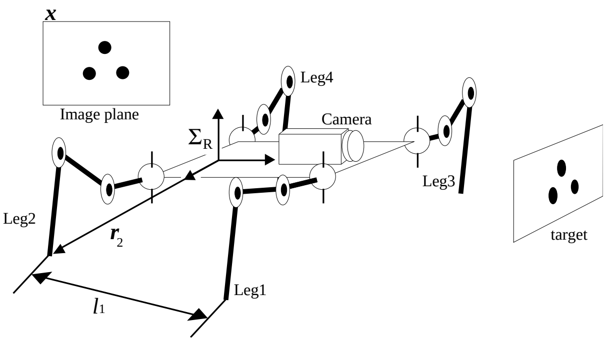


Figure 5: Robot system

$$+\left(\boldsymbol{I}-\boldsymbol{J}_{lr}^{+}\boldsymbol{J}_{lr}\right)\{\widehat{\boldsymbol{J}}_{xr}\left(\boldsymbol{I}-\boldsymbol{J}_{lr}^{+}\boldsymbol{J}_{lr}\right)\}^{+}$$
$$\{\boldsymbol{K}_x\left(\boldsymbol{x}_d-\boldsymbol{x}\right)-\widehat{\boldsymbol{J}}_{xr}\boldsymbol{J}_{lr}^{+}\boldsymbol{K}_l\left(\boldsymbol{l}_d-\boldsymbol{l}\right)\}. \quad (8)$$

2.3 Hybrid controller

We propose a hybrid controller which consists of the reflective gait controller and visual servoing (see Figure 6). By utilizing the hybrid controller, the robot attempts at tracking the visual target, and as a result a reflective walk emerges.

3 Simulation

We verify effectiveness of the proposed method by computer simulation. In [5], the swaying motion based on adaptive visual servoing has been already verified

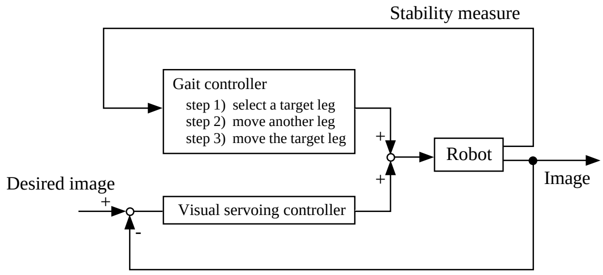


Figure 6: Hybrid controller

by applying them to a real quadruped robot. Therefore, we are focusing on the changing step motion and simulate the robot motion by giving the desired velocity of the robot ($\boldsymbol{v}_{zmp}$).

In the simulation, we assume that the robot has four legs, each of which has three degrees of freedom. It also has a TV camera, twelve joint angle sensors, four force sensors attached to each foot.

We gave the robot four $\boldsymbol{v}_{zmp}$s, $[50.0\ \ 50.0\ \ 0.0]^T$, $[0.0\ \ -50.0\ \ 0.0]^T$, $[50.0\ \ 0.0\ \ 0.0]^T$, $[0.0\ \ 50.0\ \ 0.0]^T$. The unit of $\boldsymbol{v}_{zmp}$ is [cm/sec]. Results of the simulation are shown in Figures 7 and 8. The sampling rates in Figures 7 and 8 are 100 [msec] and 10 [msec], respectively.

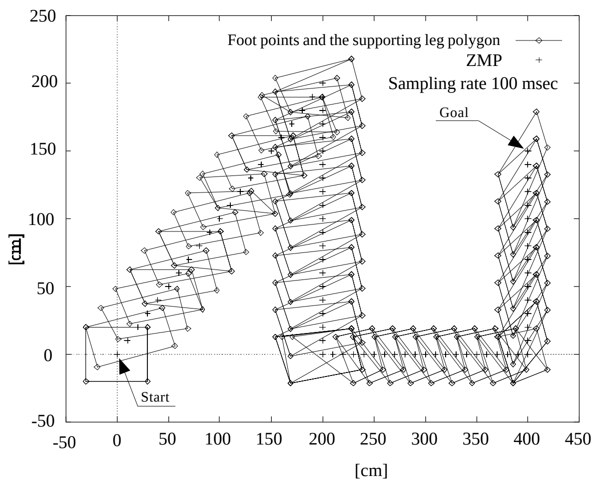


Figure 7: Simulated motion along random value of $\boldsymbol{v}_{zmp}$

It is clear in Figure 7 that the robot realizes the reflective gait which achieve the given $\boldsymbol{v}_{zmp}$ in realtime. Also we can see that its motion converge to a peri-

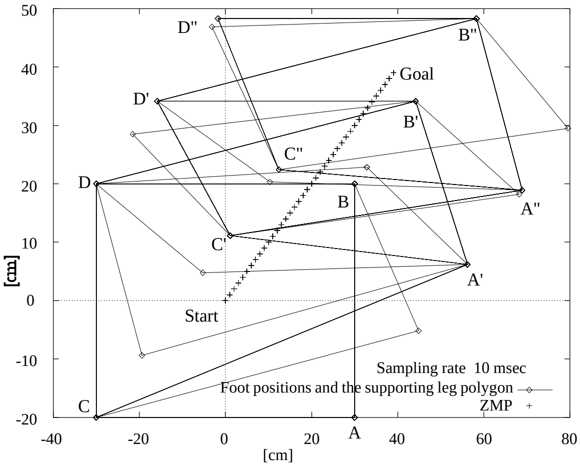


Figure 8: Reflective gait motion (magnifyed graph of Figure 7)

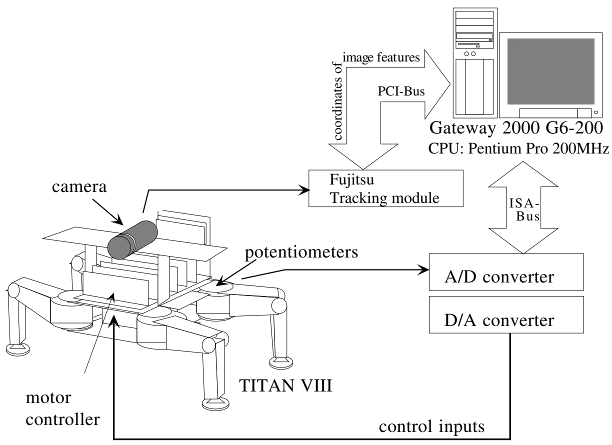


Figure 9: Experimental system with the real robot

odic gait when $\boldsymbol{v}_{zmp}$ is constant for a while. Figure 8 shows a part of the enlarged graph of Figure 7. In this figure, its gait is as follows, like a crawl gait, $A \to A'$, $B \to B'$, $C \to C'$, $D \to D'$, $A' \to A''$, $B' \to B''$, $C' \to C''$, $D' \to D''$ ($A, \cdots, D''$ are feet positions of it).

4 Future work

We showed that utilizing the hybrid control of the reflective gait control and adaptive visual servoing, the legged robot can realize the reflective walk. We verified the reflective gait control by computer simulation and showed its validity.

In this paper, we showed our method with quadruped robot. However, the method itself is not limited to it if selection criteria for one leg which assists the target leg motion is made clear. This is now under the investigation.

We are preparing the experiment with a real legged robot (see Figures 9 and 10). We will achieve the wide navigation for the legged robots.

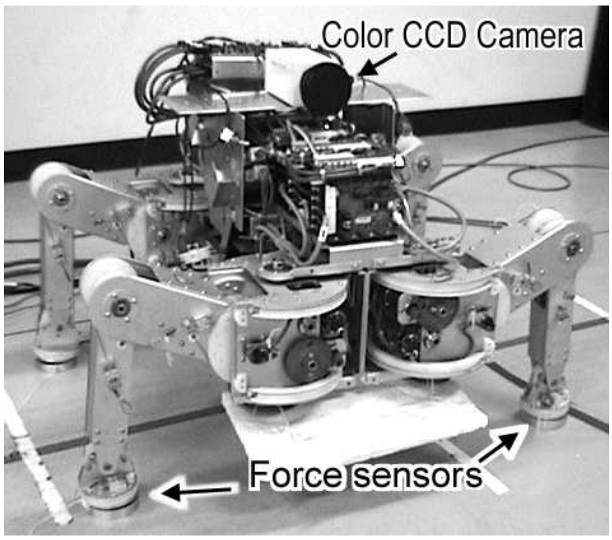


Figure 10: The vision guided quadruped robot

References

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

[2] H.Adachi, N. Koyachi, T. Arai, and Y. Shinohara. Human-operated walking control of a quadrupted by event-driven method. In *Proc. of the 1997 IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems*, pages 260–265, 1997.

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

[4] K. Hosoda, M. Kamado, and M. Asada. Vision-based servoing control for legged robots. In *Proc. of IEEE Int. Conf. on Robotics and Automation*, pages 3154–3159, 1997.

[5] K. Hosoda, T. Miyashita, S. Takeuchi, and M. Asada. Adaptive visual servoing for legged robots -vision-cued swaying of legged robots in unknown environments-. In *Proc. of the 1997 IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems*, pages 778–784, 1997.

[6] Sami Salmi and Aarne Halme. Implementing and testing a reasoning-based free gait algorithm in the six-legged walking machine, mecant. In *Proc. of International Conference on Intelligent Autonomous Vehicles '95*, pages ?–?, 1995.

[7] T. Yoshikawa. *Foundations of Robotics – Analysis and Control –*. The MIT Press, 1990.