An Environmental Representation for a Legged Robot based on Visual Guidance

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Abstract. We aim to accomplish the navigation tasks for a legged robot that has multiple degrees of freedom. A legged robot has six DOFs with respect to its support plane more than a wheeled robot that has only three DOFs. Many environmental representations have been proposed for wheeled robot navigation. However, these representations are not able to be directly applicable to control the six DOFs to navigate the legged one. In order to accomplish the whole navigation task for the legged one, we propose a navigation method which consists of following three steps. First, the robot acquires a motion sequence by visually tracking the targets shown by a teacher based on its embedded gait motion realized by adaptive visual servoing. Second, it improves the acquired motion because it may include unstable motions. Finally, it abstracts the improved motion representation further into a qualitative map for navigation. In this paper, we describe about the first and the second steps and an environmental representation used in them. We apply these methods to real legged robot and show some preliminary experimental results to demonstrate the ability of reproducing the motion.

1 Introduction

One of the ultimate goals of Robotics and AI is to realize an autonomous agent which can emerge various sorts of behaviors so as to accomplish many kinds of tasks. Navigation is one of typical examples of such tasks.

Several researchers have studied about the autonomous acquisition of a navigation map. Almost all of them have constructed a 2D or 3D geometrical navigation map of the environment (Ayache and Faugeras, 1987; Elfes, 1987). Since the robots used in these studies have only two or three degrees of freedom with respect to the support plane, the translation from the map to motor commands is straightforward. However, if the robot has more DOFs, the translation becomes more complicated and therefore these maps seem difficult to be applied to robots with more DOFs.

One alternative to the autonomous acquisition of the navigation map is a reactive approach which represents the direct mapping between robot motor commands and its sensor outputs (Nakamura and Asada, 1995). Once the robot acquires the relationship, it can realize autonomous navigation in the environment based on the acquired relationship. In this approach, they could find simple and linear relationship between motor commands and sensor outputs owing to fewer (just two) DOFs of the motor commands. If the robot has more DOFs and therefore the relationship becomes more complicated and nonlinear, it seems difficult to use such a direct mapping.

In order to accomplish the autonomous navigation task in the natural environment containing a rough terrain, two or three DOFs with respect to the support plane are not sufficient.

In this paper, we propose an autonomous navigation method for legged robots with many DOFs to accomplish a whole navigation task in the natural environment. One of the most important issues to cope with controlling many DOFs in the natural environment is to embed the lower level motion controller such as a gait controller. However, still there remained a huge space to be searched. Then, basic ideas of the proposed method are (1) teaching to realize an initial mapping between its multiple DOFs of the motions and sensory data for the environment, (2) visual guidance to simplify the teaching process, and (3) the capability of self improvement of memorized motions during the teaching process. The proposed method consists of the following steps: First, the robot acquires the motion sequence of the navigation by visually tracking the targets shown by a teacher based on a periodical gait realized by adaptive visual servoing (Hosoda and Asada, 1994) (Fig.1(a)). During the teaching process, the robot acquires the environmental representation based on visual information, and it can generate the same motion sequence of the navigation (Fig.1(b)). However, the generated motion is not always optimal because the robot controller focused on only visual servoing. Then, it improves the acquired motion and its environmental representation by using its pose controller (Fig.1(c) and (d)). Finally, it abstracts its environmental representation into its own qualitative map to navigate itself.

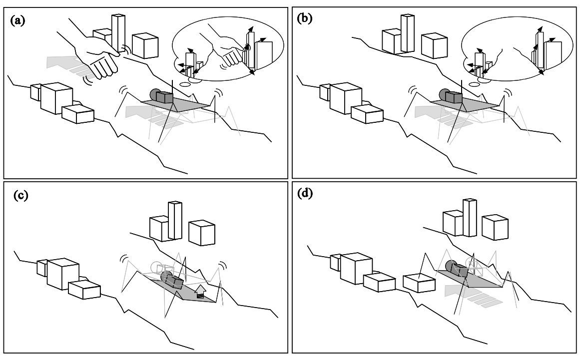

Figure 1: The navigation method for the legged robot

This paper is organized as follows. First, we explain about the legged robot and its lower level controllers that realize the periodical gait based on adaptive visual servoing. Second, we give the navigation method, especially the first and second steps in detail. Third, we describe preliminary experimental result and verify a property of motion generation. Finally, we describe our future work.

2 A Legged Robot

We use a following quadruped robot as a legged robot (Fig.2) which has:

- four legs, each of which has three DOFs,
- twelve joint angle sensors and a gravity sensor, and
- one uncalibrated TV camera and four foot touch sensors.

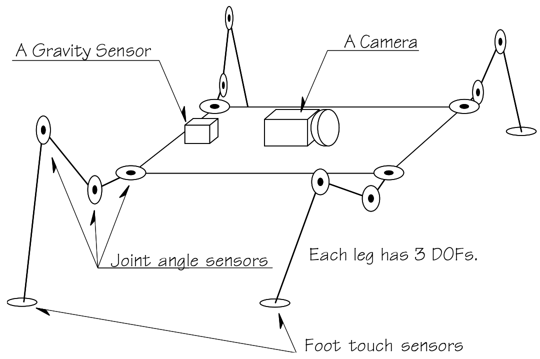

Figure 2: The robot construction

2.1 Embedded lower level controllers

We design two controllers to accomplish a walking task based on visual target tracking. They are swaying and lifted leg controllers.

A. Swaying controller

Swaying behavior can be seen as a result of visual servoing. This behavior can be realized by applying the adaptive visual servoing method (Hosoda and Asada, 1994). The following is a brief explanation of this method.

Let $\boldsymbol{\theta} \in \Re^{12}$ and $\boldsymbol{x} \in \Re^{n}$ denote the joint angle vector and the coordinates of the image feature points, respectively. A velocity relationship between $\boldsymbol{\theta}$ and $\boldsymbol{x}$ is given by,

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{J}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}, \\ \boldsymbol{J}(\boldsymbol{\theta}) &= \partial \boldsymbol{x} / \partial \boldsymbol{\theta}^{T} \in \Re^{n \times 12}, \end{aligned} \tag{1}$$

where $\boldsymbol{J}(\boldsymbol{\theta})$ is a Jacobian matrix that denotes the relation between time-derivatives of features and joint angles. If $\boldsymbol{J}$ can be estimated in real-time, the robot can track the visual features' movement adaptively.

As far as sampling rate ΔT is short enough so as to regard $\boldsymbol{J}$ constant during ΔT, we can discretize eq.(1) as

$$\boldsymbol{x}(k+1) = \boldsymbol{x}(k) + \boldsymbol{J}(k)\boldsymbol{u}(k), \tag{2}$$

where $\boldsymbol{u} = \Delta T\dot{\boldsymbol{\theta}}$.

Applying the least mean square method, we can estimate the i-th row vector $\boldsymbol{j}_i$ of the Jacobian $\boldsymbol{J}$ that satisfies eq.(2) as

$$\{\widehat{\boldsymbol{j}}_i(k+1) - \widehat{\boldsymbol{j}}_i(k)\} = \frac{\{\boldsymbol{x}(k+1) - \boldsymbol{x}(k) - \widehat{\boldsymbol{J}}(k)\boldsymbol{u}(k)\}_i}{\rho_i + \boldsymbol{u}(k)^T \boldsymbol{W}_{(i,k)}\boldsymbol{u}(k)} \boldsymbol{W}_{(i,k)}\boldsymbol{u}(k), \quad (3)$$

where $\boldsymbol{W}_{(i,k)} \in \Re^{12\times 12}$ and ρ_i is a covariance matrix and a forgetting factor, respectively.

One of the most desirable feature of this method is that it does not need a priori knowledge on the kinematic structure of the whole system. Therefore, we need not calibrate the TV camera of the robot beforehand.

B. Lifted leg controller

Since the legged robot can be regarded as a closed loop linkage system, the legs each of which has three DOFs can control six DOFs of its body with respect to the support plane. Therefore, we can use three of them as supporting legs for standing and controlling the attitude of the robot, and the remaining as a lifted leg for realizing a gait.

The robot selects one of its four legs as a lifted leg based on easiness defined by manipulability measure (Yoshikawa, 1990). Then, the robot controls the selected leg according to the pre-defined simple trajectory. By iterating this process, a gait motion is realized.

3 The navigation method

The proposed method of the navigation for the legged robot consists of following three steps:

(i) acquire a motion sequence of the navigation by visually tracking the targets shown by a teacher,

(ii) improve the acquired motion by using its pose controller, and

(iii) acquire its own qualitative map to navigate itself by improving its motion and abstracting its environmental representation.

3.1 Acquiring and improving the motion sequence

(i) **Vision guided navigation and acquisition of initial environmental representation**

First, a teacher shows visual targets to the robot as a guide of navigation, and moves them from an initial position to a goal one (figure 1(a),(b)). If the robot can take an adaptive gait based on embedded lower level controllers, it can successfully navigate along the desired path by following the visual targets. During its motion, the robot collects a sequence of motion data and changes of positions of visual features in the environment as the initial environmental representation.

(ii) **Improvement of motion**

To navigate in the environment, the robot does not need to realize completely the same motion in the teaching process. It might be able to improve the motion of the robot so that it can achieve the goal robustly (figure 1(c),(d)).

In this step, we embed a new lower level controller that maintains its initial pose. After the first teaching step, the robot can find some locations where its motion becomes unstable. It improves these motions through the following two steps. First, it expands the target zones of the positions of the feature points at these locations in the representation. Next, it moves to these locations and stabilizes the motion by the hybrid controller for pose maintaining and visual servoing..

4 Experiments

4.1 Experimental systems

Figure 3 shows a system configuration of the experiments. We used TITAN VIII (4 legs, 12 DOFs) (Arikawa and Hirose, 1996) as a legged robot. As a vision system, it has a color CCD camera EVI-330 (Sony), and a host computer Gateway2000 G6-200 (CPU:Intel Pentium Pro 200MHz)

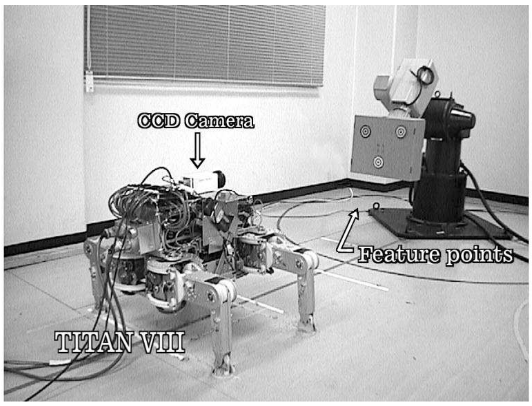

Figure 3: Experimental systems

has a tracking unit Tracking Vision (Fujitsu) equipped with a high-speed correlation processor (Inaba et al., 1993).

Video images captured by the camera on the robot and its joint angles are sent to the host computer. The system tracks the visual targets by using the tracking unit, calculates control signals for the robot, and sends them to the robot.

4.2 Experimental results

In the experiment, we have not implemented the gait motion controller but realized only the swaying controller. Therefore, the environmental representation consists of only the time series data of the positions of the visual features. We verify the capability of motion reproduction here.

(i) **Vision guided action generation**

We showed the robot three visual feature points which are pictures pasted at the tip of a manipulator, and the robot generated swaying motion according to the motion of these visual targets. While moving, the robot tracks and memorizes three positions of other visual feature points fixed to the environment as sequential data.

Here, we specified the all initial positions of visual feature points. First, we moved three of them horizontally, and next, we moved them vertically. The table1 shows the parameters of these horizontally and vertically motions in detail.

time [sec]	4	5	4	5	4	5	4
Horizontal motion	⇐	·	⇒	·	⇒	·	⇐
Vertical motion	⇑	·	⇓	·	⇓	·	⇑

leftward 0.2[m]	:	⇐
rightward 0.2[m]	:	⇒
upward 0.2[m]	:	⇑
downward 0.2[m]	:	⇓
staying	:	·

Table 1: The motions of the visual targets

(ii) **Action generation based on environmental representation**

The robot generated the desired trajectory of the feature points fixed to the static environment based on the environmental representation obtained in (i), and realized the same swaying motion. In this step, the visual targets used in the first step have not been shown.

An image from a camera on the robot is shown in figure 4. Experimental results are presented in figures 5, 6, 7, and 8. In figure 4, the feature

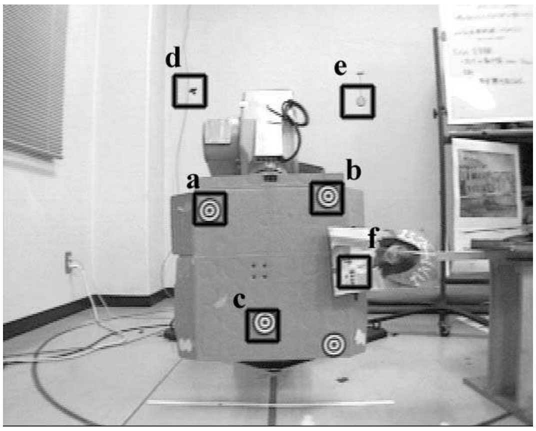

Figure 4: Feature points in the Image

points mentioned above are shown as centers of six squares. The three squares (a, b and c) are pasted at the tip of manipulator, and the others (d, e and f) are fixed to static objects. A pair of the time series data of the positions of the feature points along x-axis in the image plane at the horizontal motions are shown in figure 5. And a pair of the time series data of the positions of the feature points along y-axis in the image plane at the vertical motions are shown in figure 6. In figure 7 and 8, the realized swaying motions of the robot are shown. The vision guided swaying motions are shown in figure 7(a) and 8(a). The swaying motions based on memorized data are shown in figure 7(b) and 8(b). As these figures indicate, the same motions can be realized without visual targets for teaching.

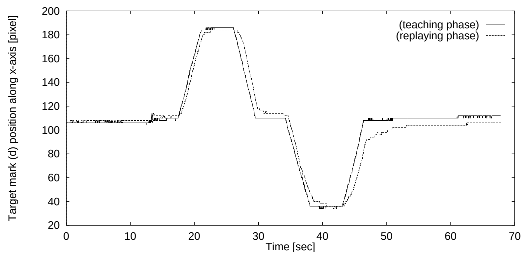

Figure 5: Feature point position at the horizontal motions

5 Conclusion

We have proposed the navigation method for the legged robot which has multiple DOFs. By using

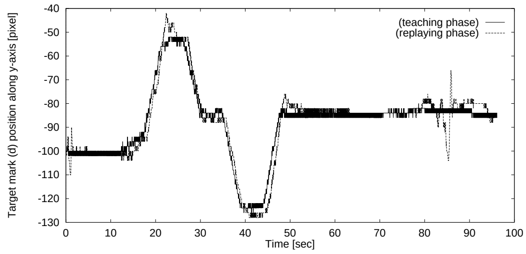

Figure 6: Feature point position at the vertical motions

this method, the robots which can take a gait based on visual guidance can realize the navigation task.

We have shown only the preliminary experiments with only the swaying motion. In the workshop, we will be able to show more results with not only swaying but also gait motions.

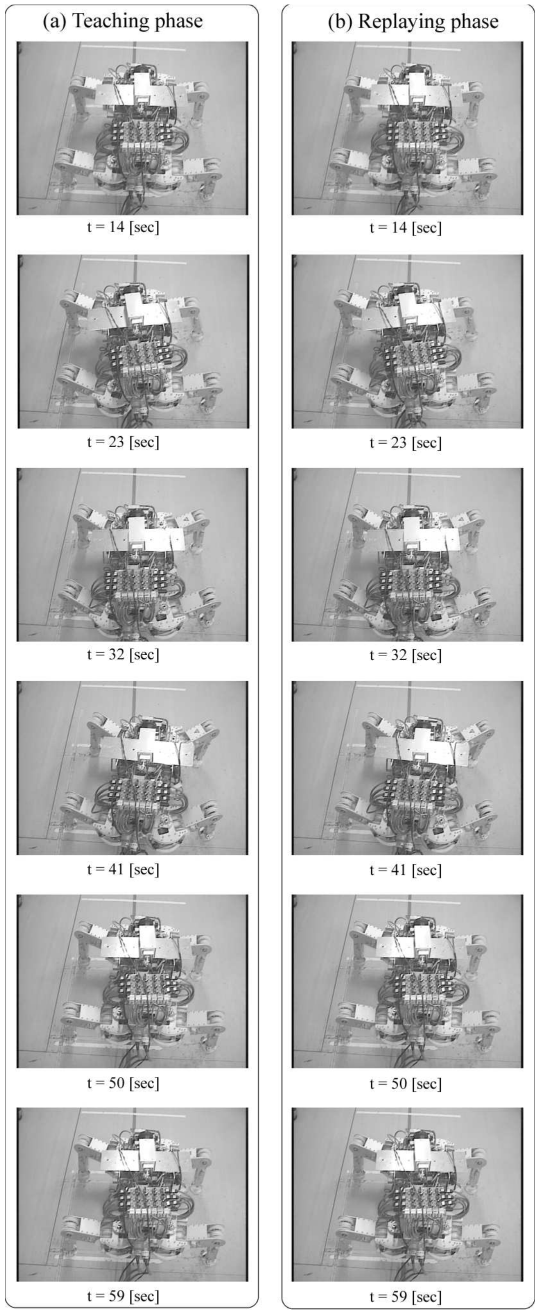

Figure 7: Robot movements at the horizontal motions

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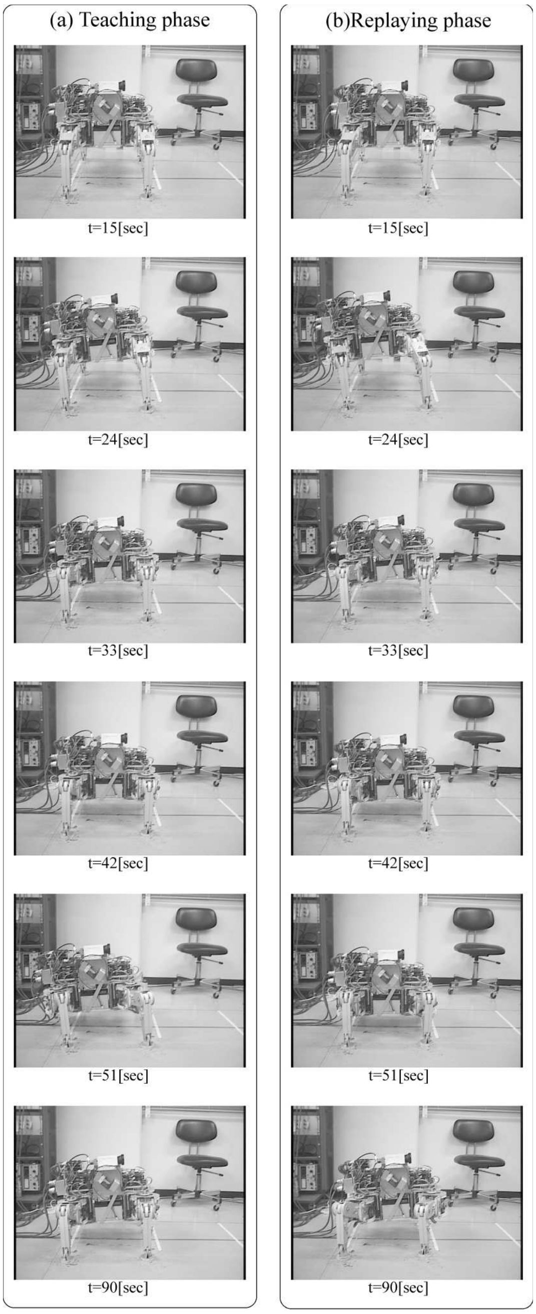

Figure 8: Robot movements at the vertical motions