Emergence of Quadruped Walk by a Combination of Reflexes

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Abstract

Several behaviors of living things seem to be consequences of combinations of simple reflexes. By this hypothesis, emergence of walk of a quadruped robot is demonstrated by a combination of two reflexes in this paper. One reflex is to move its body according to movement of a target object which the robot gaze at, a vision-cued swaying reflex. The other is a gait reflex, a gait of a free leg so as not to make the robot fall down. As a consequence of these reflexes, the quadruped robot can walk according to the movement of the target object.

1. Introduction

Among mobile abilities of robots, legged locomotion has an advantage to the others owing to its adaptivity/robustness against changes of terrain. There have been numerous studies on legged locomotion in robotics [1] to utilize this advantage. Another reason why legged locomotion receives the attention is that most of natural living things such as human, animals, and insects utilize the ability.

Most common way to realize walking of a legged robot is (1) designing a trajectory of each leg considering kinematics and dynamics of the robot in assumed/estimated terrain, and (2) applying a control scheme to make each leg track the trajectory. Since it is necessary to know the shape of the ground and kinematic/dynamic parameters of the robot beforehand, the resultant robot system cannot be adaptive against changes of environment. There are several attempts (for example [2]) to make the robot adaptive by using external sensors such as cameras, which still lack for a quick response since they need to reconstruct the shape of the ground by the external sensor signal.

Let us consider walking of an infant leaded by his/her mother. The mother may show her hand to the infant, and the infant tries to chase the hand. It does not seem to be true that the infant reconstructs geometry of the ground, calculates desired trajectories, and moves legs. He/she may have primal reflexes such as not to lose balance, to keep the image of the hand constant, and so forth. Following this consideration, we come to the idea that the robot can also be controlled by several reflexes.

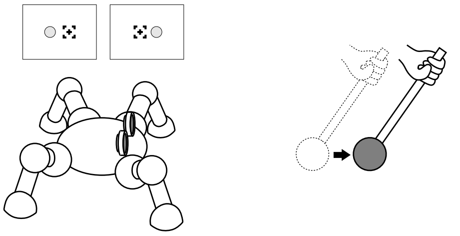
In the field of biology and physiology, they assume that several purposive behaviors emerge by combinations of elemental reflexes. Although the reflex of natural creatures should be different from that of artifacts, we can still learn how to construct a behavior of a robot. It may be designed by a combination of elements each of which does not exactly correspond to a behavior. If the element acts in a reactive manner without considering heavy reconstruction, we can call it a reflex of a robot.

The aim of this paper is emergence of walking by a combination of such artificial reflexes. We introduce two relfexes, a vision-cued swaying reflex and a gait reflex. The vision-cued reflex is realized by an adaptive visual servoing controller [3]. The gait reflex is realized by a lifted leg controller that generates a reflective gait which consists of three steps: (1) selecting a leg to be lifted so as to increase the body stability, (2) shifting (lift up, move, and down) one of other legs to enable the selected leg lifted, and (3) shifting the selected leg.

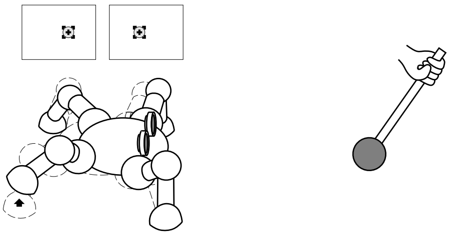
In the rest of this article, we first discuss on emergence of walking by the vision-cued reflex and the gait reflex. Then, an adaptive visual servoing controller and a lifted leg controller are proposed to realize the vision-cued reflex and the gait reflex, respectively. To realize these reflexes simultaneously, a hybrid controller is derived consisting of these controllers. Finally, we show experimental results in a real environment to demonstrate that the proposed combination of reflexes can emgerge quadruped walking.

2. Emergence of Walking

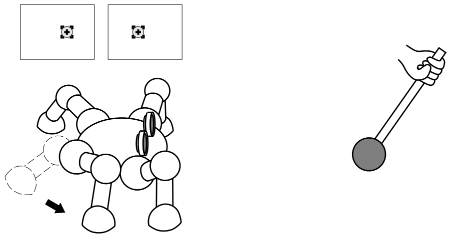
In this paper, we are going to deal with a quadruped robot that has camera(s) on it (Figure 1). The robot is gazing at a visual target and trying to keep observed



(a) When the visual taget moves,



(b) the vision-cued reflex makes the robot sway, and



(c) finally, the gait reflex makes another step.

Figure 1: Legged robot walking emerges by tracking a visual target.

target images constant. Therefore, the robot will sway according to the movement of the target (Figure 1(a)). This is a vision-cued reflex built in the robot.

The robot also has force sensors at its feet. By these force sensors, the robot can observe the ZMP (zero moment point) which is used to calculate a stability measure. Yet another reflex of the robot is a gait reflex by utilizing this stability measure. When the stability is small (Figure 1(b)), the robot will make steps to enlarge it (Figure 1(c)).

Because of a combination of these two reflexes, the robot will sway when the movement of the target is small, and it will walk when the movement is large. Note that these reflexes do not necessarily corresponds to *a behavior*. We do not explicitly program walking of a quadruped, but it emgerges as a consequence of two reflexes.

3. Vision-cued Swaying Reflex

To realize vision-cued swaying according to the movement of the target, we apply visual servoing [4, 5]. The visual servoing controller feeds the visual information back to control inputs directly, which makes the robot response quick and robust. There have been many studies on visual servoing applied to manipulators, but only one for legged robots [6] to the best of our knowledge. In the paper, to apply visual servoing to a legged robot, stance servoing control is introduced.

Another difficulty to apply visual servoing to the legged robot is that the relation between change of features in the image plane and joint displacement is unknown when the geometry of the terrain is unknown. To estimate the relation, we have to use an on-line estimator [3, 7].

In this section, we quickly introduce adaptive visual servoing control for legged robots to realize a vision-cued swaying reflex, consisting of a stance servoing controller, an on-line estimator, and a visual servoing controller.

3.1. Stance servoing control

First, we introduce the stance servoing controller to keep distances between feet constant. Let ${}^R\boldsymbol{r}_i$ be a position vector of the foot i with respect to the robot coordinate frame Σ_R fixed to the robot body. Since a stance vector $\boldsymbol{l}$, a correction vector of distance between feet, is a function of ${}^R\boldsymbol{r}_i$, we can derive a velocity relation:

$$\dot{\boldsymbol{l}} = \boldsymbol{J}_{lr}\, {}^R\dot{\boldsymbol{r}}, \tag{1}$$

where ${}^R\boldsymbol{r} = [{}^R\boldsymbol{r}_1{}^T\ {}^R\boldsymbol{r}_2{}^T\ \cdots\ {}^R\boldsymbol{r}_2{}^T]^T$, and $\boldsymbol{J}_{lr} = \partial\boldsymbol{l}/\partial\, {}^R\boldsymbol{r}^T$. From eq.(1), we can obtain a stance servoing controller:

$$\boldsymbol{u} = \boldsymbol{J}_{lr}{}^{+}\boldsymbol{K}_l(\boldsymbol{l}_d - \boldsymbol{l}) + (\boldsymbol{I} - \boldsymbol{J}_{lr}{}^{+}\boldsymbol{J}_{lr})\boldsymbol{k}_l, \tag{2}$$

where $\boldsymbol{J}_{lr}{}^{+}$, $\boldsymbol{l}_d$, $\boldsymbol{K}_l$, and $\boldsymbol{k}_l$ denote the pseudo-inverse matrix of $\boldsymbol{J}_{lr}$, the desired stance vector, a gain matrix, and an arbitrary vector that describes redundancy, respectively. Utilizing the second term on the right hand side, we can apply servoing control.

3.2. Visual servoing control

From the camera(s) attached to the robot body, one can get some image features such as position, line length, contour length, and/or area of certain image patterns. Let a vector of the image features be $\boldsymbol{x}$. 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 controller (2) keeps the feet distances constant, the image feature vector $\boldsymbol{x}$ is a function of ${}^R\boldsymbol{r}$,

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{xr}{}^R\dot{\boldsymbol{r}}, \qquad (3)$$

where $\boldsymbol{J}_{xr} = \partial\boldsymbol{x}/\partial^R\boldsymbol{r}^T$.

By utilizing null space of eq.(2), we can derive an adaptive visual servoing controller for a legged robot,

$$\begin{aligned} \boldsymbol{u} &= \boldsymbol{J}_{lr}{}^+\boldsymbol{K}_l(\boldsymbol{l}_d - \boldsymbol{l}) \\ &\quad +(\boldsymbol{I} - \boldsymbol{J}_{lr}{}^+\boldsymbol{J}_{lr})\left\{\boldsymbol{J}_{xr}(\boldsymbol{I} - \boldsymbol{J}_{lr}{}^+\boldsymbol{J}_{lr})\right\}^+ \\ &\quad \left\{\boldsymbol{K}_x(\boldsymbol{x}_d - \boldsymbol{x}) - \boldsymbol{J}_{xr}\boldsymbol{J}_{lr}{}^+\boldsymbol{K}_l(\boldsymbol{l}_d - \boldsymbol{l})\right\}, \qquad (4) \end{aligned}$$

where $\boldsymbol{K}_x$ denote a gain matrix for visual servoing.

3.3. On-line estimator

The Jacobian matrix $\boldsymbol{J}_{xr}$ is a function not only of intrinsic camera parameters but also of position/orientation of the visual target w. r. t. Σ_R, and of geometry of the terrain. Since the legged robot is moving in unknown terrain and the position of target is also unknown, the robot must estimate $\boldsymbol{J}_{xr}$ on-line.

We can derive an on-line estimator to identify a nonlinear system in the discrete time domain [3],

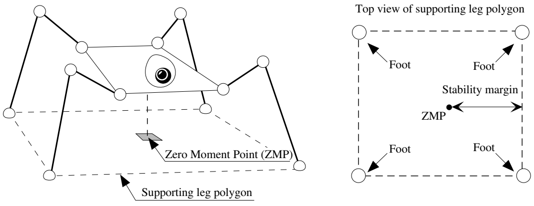
$$\begin{aligned} \widehat{\boldsymbol{J}}_{xr}(k) &= \widehat{\boldsymbol{J}}_{xr}(k-1) \\ &\quad +\{\Delta\boldsymbol{x}(k) - \widehat{\boldsymbol{J}}_{xr}(k-1)\Delta\boldsymbol{u}(k)\} \\ &\quad \frac{\Delta\boldsymbol{u}(k)^T\boldsymbol{W}(k-1)}{\rho + \Delta\boldsymbol{u}(k)^T\boldsymbol{W}(k-1)\Delta\boldsymbol{u}(k)}, \qquad (5) \end{aligned}$$

where $\widehat{\boldsymbol{J}}_{xr}(k)$, $\boldsymbol{u}(k)(= T\dot{\boldsymbol{\theta}})$, ρ, and $\boldsymbol{W}(k)$ denote a constant Jacobian matrix, a control input vector in the k-th step during sampling rate T, an appropriate positive constant and a weighting matrix, respectively. In a case that $\boldsymbol{W}$ is a covariance matrix and that ρ_i is in the range $0 < \rho \leq 1$, the proposed estimator is a well-known weighted recursive least squares estimator [8].

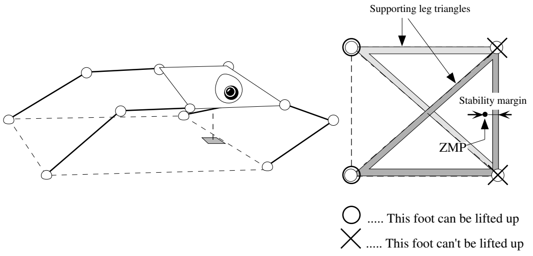
By using estimated $\widehat{\boldsymbol{J}}_{xr}$ instead of $\boldsymbol{J}_{xr}$ in the visual servoing controller (4), we can realize a vision-cued reflex of the legged robot.

4. Gait Reflex to Increase Body Stability

To realize a gait reflex, we proposed a gait stategy based on a body stability measure calculated from the ZMP.



(a) a stable pose



(b) an unstable pose

Figure 2: The stability margin is the shortest distance between the ZMP and a side of the supporting leg polygon. If the margin is large, the robot is stable, otherwise it is unstable.

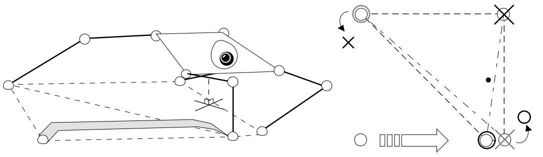
4.1. The reflective gait procedure

We adopt a stability margin [9], the shortest distance between the ZMP and a side of the supporting leg polygon (the boudaries of the support pattern), as a stability measure of the legged robot (see Figure 2). As the robot sways the body, the margin becomes small as shown in Figure 2(b). To recover the stability, the robot has to move one of legs indicated as "×" in the figure so as to increase the margin. However, both legs can not be lifted up immediately because they are included in two supporing triangles where the ZMP is inside. To lift up one of the legs (which we call *target leg* in the following), therefore, one of the others indicated as "○" has to be moved as shown in Figure 3. This is a *reactive gait* procedure since it is reactive to the movement of the ZMP.

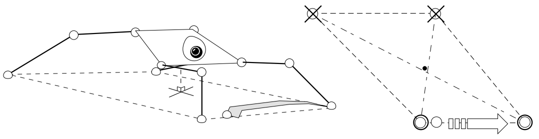
4.2. Lifted leg control algorithm

We can realize the reflective gait by a simple algorithm as follows. The positions of the lifted legs fall into two cases with respect to the relationship between the supporting legs and v_{zmp}, the velocity of ZMP (see Figure 4): a hind leg case and a fore leg one.

The hind leg case (Figure 4(a): The lifted leg is the diagonal leg of leg(A) or leg(B).) The robot

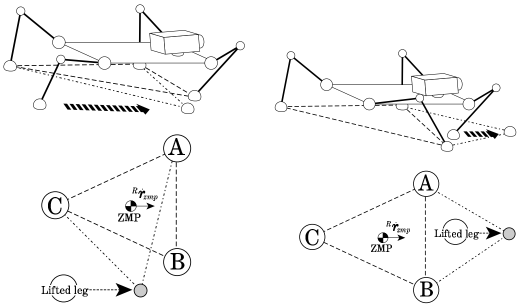


(a) To lift the target leg (right below “×”), the robot have to move one of the others to make the target leg out of one of supporting triangles.



(b) After moving the leg, the target leg can be lifted up since it is no more inside the supporting triangle.

Figure 3: The procedure of the reflective gait



(a) a hind leg case (a) a fore leg case

Figure 4: Supporting leg triangles and a lifted leg

moves the lifted leg to keep ZMP inside the next supporting leg triangle which consists of leg(A) (or leg(B)), leg(C), and the lifted leg. Subsequently, leg(B) (or leg(A)) becomes the lifted leg.

The fore leg case (Figure 4(b): The lifted leg is the diagonal leg of leg (C).) The robot moves the lifted leg to appropriate position in front of it, but does not touch down yet. If the ZMP moves into the next supporting leg triangle which consists of leg(A), leg(B), and the lifted leg, then it is naturally touched down, and subsequently leg(C) becomes the lifted leg.

5. Experiments

We apply the proposed two controllers to a real quadruped robot to realize two reflexes. Emergence of walking is demonstrated in this section.

5.1. A quadruped for experiements

In Figure 5, a legged robot TITAN-VIII [10] and its controller used for the experiment are shown. The legged robot is equipped with one CCD camera (EVI-310, SONY). The image from the camera is sent to a tracking unit (TRV-CPD6, Fujitsu) equipped with a high-speed correlation processor [11]. Before starting an experiment, we give three 16[pixel] × 16[pixel] patterns (called reference patterns) to be tracked. During the experiment the unit feeds coordinates where the correlation coefficient is the highest with respect to the reference patterns to the host computer G6-200 (Gateway2000, CPU:Intel Pentium Pro 200MHz) through a PCI-bus link in real-time (33[ms]).

Each joint of the legged robot is equipped with a potentiometer to observe its angle. Each foot is also equipped with a force sensor to observe its foot force and to estimate the ZMP. The observed joint angles and the foot forces are sent to the computer through an A/D converter board (RIF-01, Fujitsu). The computer calculates the desired joint velocities and sends the commands to the velocity controllers of joints through a D/A converter board (RIF-01, Fujitsu). A hand cart is used as a visual target on which 3 target marks are drawn.

5.2. Experimental results

An example of emerged walking is shown in Figure 6. At t=2.0[s], the cart began to move rightward. The robot was initially supported by right-fore-leg (RF), left-fore-leg (LF), and left-hind-leg (LH). The initial lifted leg was right-hind-leg (RH). The robot was swinging its body as the target motion and switched the lifted leg from RH to LF at t=14.0[s], which was the fore leg case. Subsequently, it switched the lifted leg from LF to RF (the hind leg case) at t=23.0[s], from RF to LH (the fore leg case) at t=32.0[s], from LH to LF (the hind leg case) at t=39.0[s]. In Figure 6, we can see how the legged robot behaved reflectively to track the visual target.

6. Conclusion and Disscussions

Emergence of walk of a quadruped has been demonstrated by a combination of two reflexes in this paper. As a consequence of these reflexes, the real quadruped walked to track the moving target. We expect that this way of building a robot may be adaptive to changes

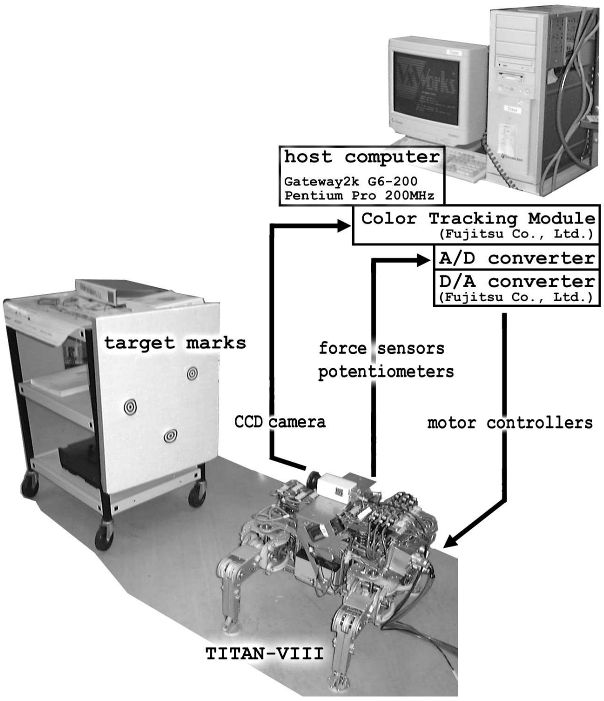
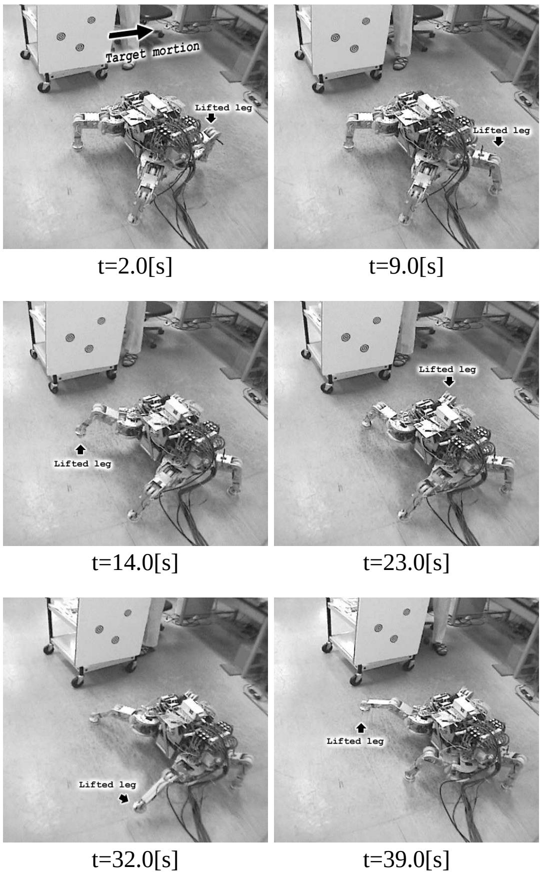


Figure 5: An experimental system: A quadruped “TITAN-VIII” and its controller used for the experiments.



t=2.0[s] t=9.0[s]

t=14.0[s] t=23.0[s]

t=32.0[s] t=39.0[s]

Figure 6: An experimental result: The legged robot walks reflectively to follow the movement of the target.

of the environment, and that an unexpected behavior emerges as a consequence of a combination of reflexes, the robot body, and the environment.

The hypothesis, several purposive behaviors emerge by combinations of elemental reflexes, must be demonstrated by more variety of tasks and robots. We have demonstrated a case of an arm and a case of a hand with several reflexes in other papers[12, 13]. However, still more examples are needed.

A robot, as a universal machine, ought to have adaptivity, ability to estimate appropriate control parameters and/or structure to achieve a given task in an environment. So as to have such adaptivity against changes of task and environment, a robot needs to have larger number of actuators and more variety of sensors. Such many degrees of freedom are expected to be controlled easily by the proposed method.

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