MVA2005 IAPR Conference on Machine VIsion Applications, May 16-18, 2005 Tsukuba Science City, Japan
8-24

Motion Stabilization of Biped Robot by Gaze Control

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Abstract

We present a motion stabilization system for a biped robot that makes it possible to keep relative posture and position to a moving or stationary object. Our system consists of two layers of control subsystems, gaze control system and motion control system. In order to achieve an actual motion which follows exactly a scheduled one, the biped robot gazes a target to estimate errors of robot motion and adjusts both an actual motion and the scheduled one simultaneously. The gaze control system has 2 DOF controller which uses a scheduled robot motion in the feedforward part. A periodic motion of robot body swing induced by walking is used to estimate the distance to the target by forming a motion stereo. The scheduled motion is adjusted based on an adaptive law of Model Reference Adaptive Control (MRAC).

1 Introduction

For a robot that autonomously moves in a real-world environment, vision is a source of enormous amount of useful information for planning and controlling the motion of the robot. Although several previous researches on biped walking robots did use vision for motion planning and control, its purpose was basically limited to directly measuring location of the robot using some visual landmarks. In other words, vision was used only for high-level tasks such as collision detection and path planning and never used for lower-level tasks of motion control. However, in biological systems (e.g. animals) vision and motion control appear to be deeply connected with each other. Similarly, for autonomously moving biped robots, vision could be used for primitive and basic motion control. This forms the motivation of our research.

In order to control a biped robot to realize a desired motion, firstly, the dynamics of the robot including the interaction with the environment is modeled. Secondly, based on the models developed, the motion to be realized is reduced to a time series of control data of each actuator of the robot, which we call a scheduled motion. Lastly, the scheduled motion generated is actually applied to the robot with appropriate feedback control using dynamical information about the motion of the robot that are obtained by built-in motion (and other) sensors.

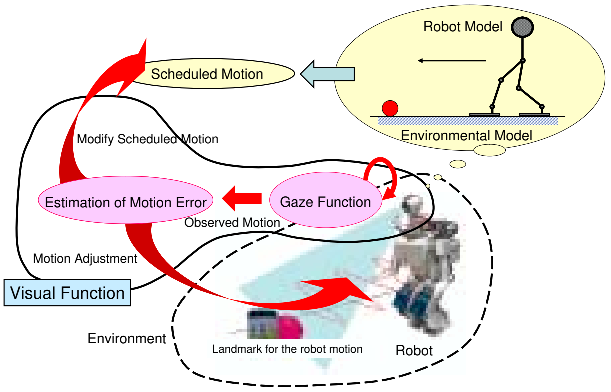

Figure 1: Basic scheme of vision-based motion stabilization

For the second one in the above three steps, i.e. creating a scheduled motion, many methods have been proposed up to date. For example, Ogino et al. [4] proposed a heuristic method for generating motion that uses a vision-based reinforcement learning. Deguchi and Nakagawa [2] proposed an active-vision-based scheme for identifying 3D environmental model. The third step, i.e. controlling the robot based on the scheduled motion, has also been studied by many researchers. For example, Kajita et al. [3] proposed a scheme called Resolved Momentum Control, which controls motion on the basis of desired total moments.

It is needless to say that the first step, developing dynamical model of the robot itself and its interaction with the environment, is also important. Accuracy of the generated model determines the success of the robot control. However, the dynamics of a biped robot is always very complicated, and, more importantly, the interaction of the robot with the environment is not only complicated but time-varying. For example, friction between the floor and the soles of the robot can change depending on the floor material. Precisely modeling them in advance is almost impossible, and thus it is inevitable that the resulting models will have some amount of inaccuracy or will have some flexibility to absorb the environmental changes. In order to deal with this modeling problem, the overall system of a biped robot is usually designed so that the scheduled motion can be flexibly modified in an online manner using some sensory information.

We use visual information for this purpose of online modification of the scheduled motion. We present a

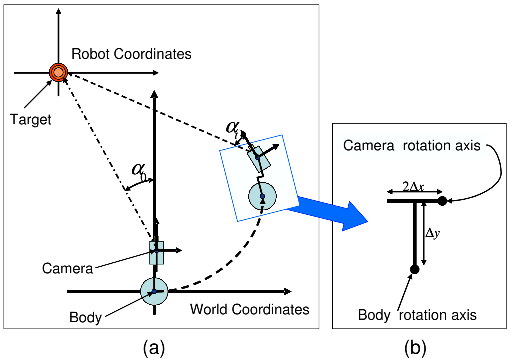

Figure 2: (a) Relationship between the target and the biped robot and (b) the offset distance between the camera rotation axis and the instantaneous center of the robot rotation

novel scheme for the problem in Fig. 1. In the scheme, motion of the robot is observed using visual information. Then it is used for controlling the robot so as to realize the scheduled motion, and, at the same time, used for modifying the scheduled motion. The scheduled motion is modified using a measure of the error between the scheduled motion and actual motion that is defined on visual sensor. Because of the structure of the scheme, vision is deeply involved in a primitive layer of robot control. The overall process is based on Model Reference Adaptive Control (MRAC), which was proposed in the field of control theory [1].

In what follows we will present an experimental system implementing this scheme. In the system a camera mounted on the robot whose rotation is freely controlled, is controlled so as to gaze at a particular target in the environment. This gaze control of the camera is composed of feedback control using visual information obtained from the camera itself and also feedforward control using the scheduled motion. The orientation of the camera itself, while this gaze control is being carried out, yields the relative motion of the robot to the target. The errors between the actual motion and the scheduled one are defined in terms of this orientation of the camera. Based on this framework, we stabilize motion of a biped robot.

Section 2 explains the gaze control. Section 3 presents the novel scheme for motion error estimation and its adjustment. Experimental data are shown in Section 4. Section 5 concludes this research.

2 Formulation of gaze control

In the case of gaze control that uses vision, we have to consider about large time delay, which is caused by response time of gaze mechanism, data transfer time and image processing time.

We proposed gaze control system [6] which uses a scheduled motion to compensate this time delay having 2 DOF structure.

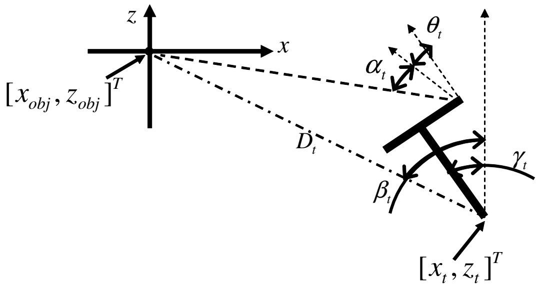

Figure 3: Definition of parameters

2.1 Feedforward control input calculation

Fig. 2 shows a situation that the robot walks on the floor and gazes a target. Relation among the robot position $[x_t, z_t]^{\mathrm{T}}$, a posture γ_t, a camera orientation θ_t and a gaze error angle from line of sight to the target α_t in Fig. 3 is given as,

$$\dot{\theta}_t = \dot{\beta}_t - \dot{\gamma}_t = \frac{-\dot{x}_t z_t + \dot{z}_t x_t}{D_t^2} - \dot{\gamma}_t. \tag{1}$$

where D_t is the distance from the robot to the target.

We are using a robot position and posture in the scheduled motion at the time of advance to compensate the time delay L instead of any prediction. In order to achive this feedforward control, its input v_t is calculated as,

$$\begin{aligned} v_t &= W^{-1}\left(\frac{-\dot{\tilde{x}}_{t+L}\tilde{z}_{t+L} + \dot{\tilde{z}}_{t+L}\tilde{x}_{t+L}}{\tilde{D}_{t+L}^2} - \dot{\tilde{\gamma}}_{t+L}\right) \\ &= F([\tilde{x}_t, \tilde{z}_t]^{\mathrm{T}}, \tilde{\gamma}_t), \end{aligned} \tag{2}$$

where $[\tilde{x}_t, \tilde{z}_t]^{\mathrm{T}}$ and $\tilde{\gamma}_t$ are the robot position and posture in the scheduled motion, $\tilde{D}_t$ is the distance from the robot to the target in the scheduled one, and $W(*)$ is a dynamical model of the gaze mechanism.

2.2 Gaze control system

Fig. 4 shows gaze control system which has a feedforward controller and a visual feedback controller. In our system, feedforward controller is able to compensate time delay. In order to reduce the gaze error angle α_t, visual feedback controller counteracts the error which is caused by difference between the actual motion and the scheduled one.

3 Vision based motion stabilization

3.1 Relation between motion error and camera orientation error

A geometric relation between motion error and camera orientation error is given as,

$$\Delta\theta_t = \tan^{-1}\left(\frac{\tilde{x}_t\Delta l_z - \tilde{z}_t\Delta l_x}{\tilde{z}_t(\tilde{z}_t + \Delta l_z) + \tilde{x}_t(\tilde{x}_t + \Delta l_x)}\right) - \Delta\gamma_t$$

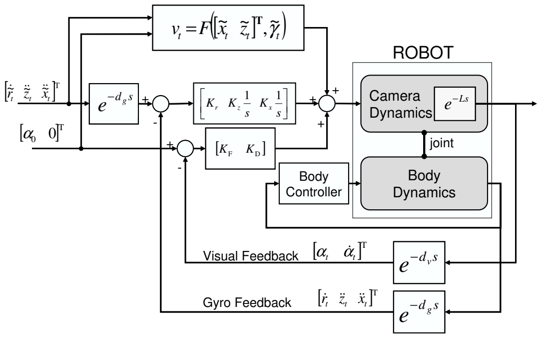

Figure 4: Block diagram of gaze control system which has a Feedback and a Feedforward Controller

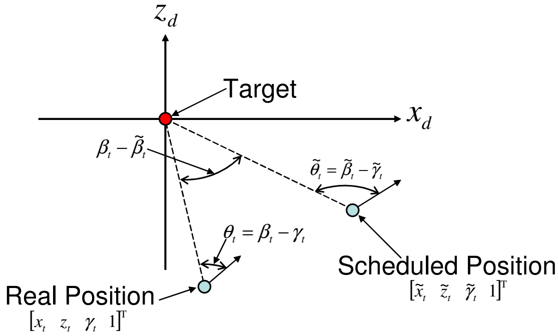

Figure 5: Relations between real and scheduled robot positions at time t

$$= \quad (\beta_t - \tilde{\beta}_t) - \Delta\gamma_t \qquad (3)$$

where $\Delta\theta_t$ is a difference between actual camera orientation and modeled one and, Δl_x and Δl_z are position errors of x and z direction, respectively, and $\Delta\gamma_t$ is a posture error.

3.2 Motion error estimation from camera orientation

By using a periodic motion such as body swing induced by walking, moving distance error Δl_x, Δl_z and motion direction errors $\Delta\gamma_t$ can be estimated from camera orientation error $\Delta\theta_t$. Switching the supporting leg causes Δl_x and Δl_z and we assume that Δl_x and Δl_z are constant value at every step.

Integration of the term $\beta_t - \tilde{\beta}_t$ in eq. (3) through one cycle time is approximately represented as

$$\int_{-\frac{\pi}{\omega}}^{\frac{\pi}{\omega}} \tan(\beta_t - \tilde{\beta}_t)dt = \int_{-\frac{\pi}{\omega}}^{\frac{\pi}{\omega}} \frac{(\tilde{x}_0 \Delta l_z - \tilde{z}_0 \Delta l_x)}{\tilde{D}_t^2} dt \qquad (4)$$

where $\tilde{x}_0$ and $\tilde{z}_0$ are an initial robot position in the scheduled motion.

By selecting the coordinates that $\tilde{x}_0 = 0$ and $\tilde{\gamma}_0 = 0$ are satisfied, Δl_x corresponds to the error of a lateral direction and Δl_z corresponds to that of a sagittal direction. Because the scheduled motion is a periodic and a symmetric motion, Δl_x is canceled through one cycle of motion such as two steps of walk and, eq. (4) corresponds to 0. Therefore, we can consider that eq. (3) consists of two functions: the first term of right hand side of eq. (3) is the function that the average is 0 and its change is periodically and, the second is the offset of the oscillation. These properties about eq. (3) allow us to estimate Δl_z and $\Delta\gamma_t$ on the condition that Δl_x is 0 and, redefine Δl_z as Δl_t. Moving distance error Δl_t and motion direction error $\Delta\gamma_t$ are estimated as

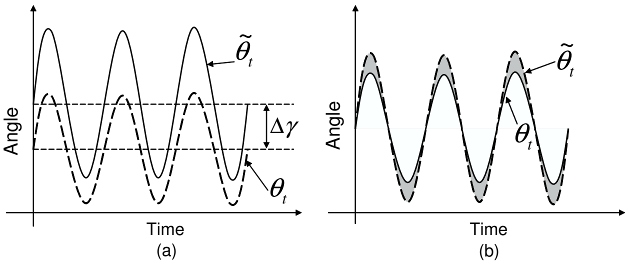

Figure 6: (a)Offset distance between $\tilde{\theta}_t$ and θ_t and (b) distance error component of $\Delta\theta_t$

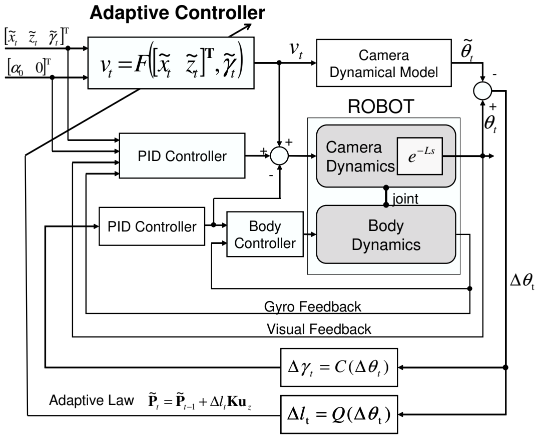

Figure 7: Motion stabilization system based on the gaze control

$$\begin{aligned} \Delta\gamma_t &= -\frac{1}{t}\int_0^t \Delta\theta_s ds \\ &= C(\Delta\theta_t), \qquad (5) \\ \Delta l_t &= \frac{1}{t}\int_0^t \left(\Delta\theta_v - \frac{1}{v}\int_0^v \Delta\theta_u du\right) dv \\ &= Q(\Delta\theta_t), \qquad (6) \end{aligned}$$

where eq. (5) corresponds to the offset in Fig. 6 (a) and, eq. (6) corresponds to the average of shaded area in Fig. 6 (b).

3.3 Construction of motion stabilization system

Fig. 7 is a block diagram of our motion stabilization system that uses vision. This system is designed on the basis of gaze control system, which has feed-forward controller and visual feedback controller. In our proposed system, firstly, $\tilde{\theta}_t$ is calculated by feed-forward control input v_t and a dynamics of the gaze mechanism. Secondly, Δl_t and $\Delta\gamma_t$ is estimated by eq. (5) and eq. (6). Lastly, motion direction in actual motion and moving distance in scheduled motion is adjusted on the basis of $\Delta\gamma_t$ and Δl_t. This system is Model Reference Adaptive Control System which uses the scheduled motion as the reference model.

4 Simulation experiment

4.1 Experimental setting

In order to examine an effectivity of our motion stabilization system, we have simulated the following two situations:

- the robot steps on the spot and stabilizes its motion to the stationary target,
- the robot walks to the moving target and adjusts the walking direction and the scheduled motion to keep the target in the front of the robot.

4.2 Experimental results

Fig. 8 shows results of an estimated distance which is used to adjust the scheduled motion. The right hand side of the graph indicates the true distance between the robot and the target. In every case, the estimated distance converges to a constant value such that $\Delta\theta_t$ converges to 0. The robot could keep the target in the front of the robot in all simulation time. Actually, the estimation error is proportional to the distance between the robot and the target. Because $\Delta\theta_t$ becomes smaller with increasing the distance to the target, the distance error hardly affects a motion stabilization when the robot distances oneself from the target.

Fig. 9 shows a result of the robot trajectory under motion stabilization. The robot was able to adjust adaptively its walking direction and keep the target in the front of the robot, and the estimated distance converges to a constant value such that $\Delta\theta_t$ converges to 0.

5 Conclusion

In this paper we have presented a scheme for motion control of biped robots that is based on active vision to modify scheduled motions. We have shown effectiveness of the scheme through several experiments.

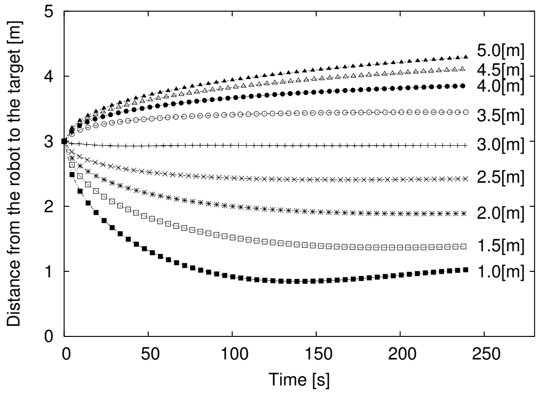

Figure 8: Estimation of distance from the robot to the target.

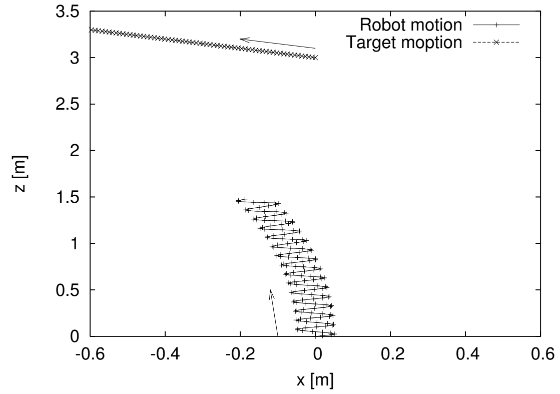

Figure 9: Robot motion and target motion from top view

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