POSITIONING CONTROL OF THE LEG OF THE HUMANOID ROBOT BY LINEAR VISUAL SERVOING

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This paper presents a positioning control of the 4 d.o.f. leg of the humanoid robot by linear visual servoing. Linear visual servoing is based on the linear approximation between binocular visual space and joint space of the leg of the humanoid robot. It is very robust to calibration error, especially to camera angle errors and joint angle errors, because it uses neither camera angles nor joint angles to calculate feedback command. We obtain the linear approximation matrix of the inverse kinematics of the leg using the binocular visual space by the least squares approximation. Some experimental results are presented to demonstrate the effectiveness of the proposed method.

Keywords: Humanoid Robot; Linear Visual Servoing; Leg Positioning Control.

1. Introduction

Visual feedback is indispensable for the intelligent robots that work in dynamic changing environment. Various kinds of mechanisms of visual feedback have been proposed and they are called *visual servoing* [1234]. Mitsuda et al. proposed a simple visual servoing scheme called *linear visual servoing*[57] and showed the effectiveness in 2D positioning control. Linear visual servoing is based on the linear approximation between binocular visual space and joint space of the arm of the humanoid robot which has a similar kinematic structure to a human being. The relationship makes it possible to generate joint velocities from image data using a constant linear mapping. Linear visual servoing is very robust to calibration error, especially to camera angle errors and joint angle errors, because it uses neither camera angles nor joint angles to calculate feedback command. Hence, it is especially suitable for the humanoid robots which use *active stereo vision*[1112]. That is, it is possible to turn cameras to facilitate visual processing, even if the arm is under control by visual servoing. Furthermore, the amount of the calculation is very small compared to the conventional visual servoing schemes, because it only needs both the time-invariant constant matrix and the image coordinates of the feature points.

Although we showed that positioning control of the 3 d.o.f. leg of the humanoid robot by linear visual servoing is realizable[10] , the possibility of the 4 d.o.f. leg positioning control is not shown yet. In this paper, we propose a positioning control method of the 4 d.o.f. leg of the humanoid robot by linear visual servoing. Some experimental results are presented to demonstrate the effectiveness of the proposed method.

2. Linear Visual Servoing

2.1. *Model of the Leg-eye Coordination of the Humanoid robot*

Fig.1 shows the leg-eye coordination of the Humanoid Robot which has a similar kinematic structure to a human being. The leg consists of two links L_1, L_2 and four joints j_0, j_1, j_2, j_3. The knee joint has 1 d.o.f. and the thigh joint has 3 d.o.f. The two cameras pan and tilt independently and are mounted on a head which pan and tilt. And head is mounted on the body. We show the parameters of the leg-eye coordination of the Humanoid robot in Table 1. These parameters are defined to be proportional to those of a human being.

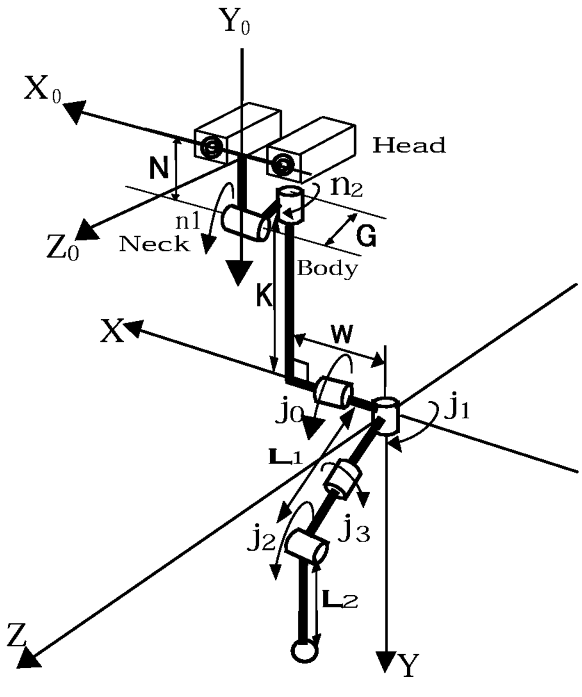


Fig. 1. Model of the leg-eye coordination of the humanoid robot

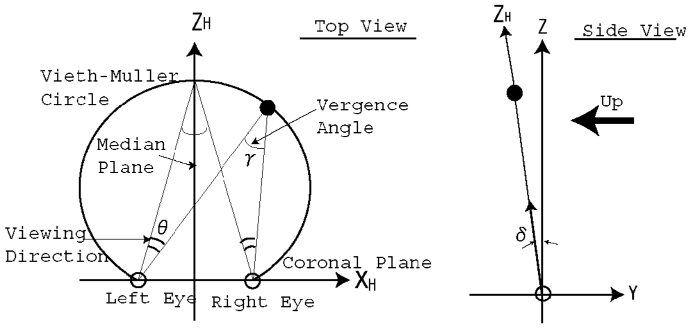


Fig. 2. Binocular visual space

Table 1. Parameters of the model

Link Length	$L_1 = 450, \ L_2 = 710$
Body Length	$k = 780$
Camera Position	W=310
Baseline Length/2	E=50
Neck Length	N=165, G=60

2.2. *Binocular Visual Space*

The binocular visual space is defined as the vergence angle γ and the viewing directions θ, δ(see Fig.2). This space has been employed by psychologists and physiologists as a model of binocularly-perceived space. The binocular visual coordinate of a fixation point is described as

$$\mathbf{V} = \begin{bmatrix} \gamma \\ \theta \\ \delta \end{bmatrix} = \begin{bmatrix} \alpha_L - \alpha_R \\ (\alpha_L + \alpha_R)/2 \\ \alpha_D \end{bmatrix}, \tag{1}$$

where α_L, α_R and α_D are the camera angles.

The binocular visual space has a close relation to the camera image. We show the stereo camera geometry in Fig.3.

The coordinates of a feature point projected on the camera image planes are transformed into binocular visual coordinates by

$$\mathbf{V} = \begin{bmatrix} \alpha_L - \alpha_R \\ (\alpha_L + \alpha_R)/2 \\ \alpha_D \end{bmatrix} + \begin{bmatrix} (X^L - X^R)/f \\ (X^L + X^R)/2f \\ (Y^L + Y^R)/2f \end{bmatrix}, \tag{2}$$

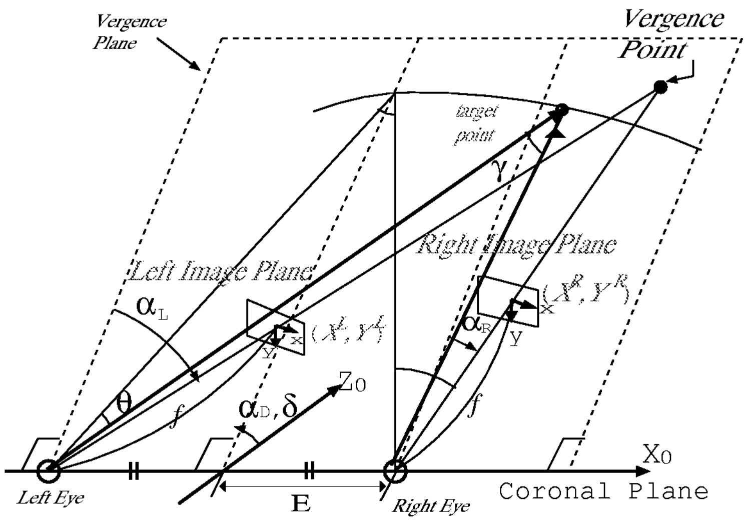


Fig. 3. Model of the active stereo cameras

where (X^L, Y^L) and (X^R, Y^R) are the coordinates of a feature point in the left and right image respectively. Note that we use the approximation such as $\tan^{-1}(X^{L,R}/f) \simeq X^{L,R}/f$. This approximation is available around the fixation point. Camera angles and image data are transformed into binocular visual coordinates.

2.3. *Linear Approximation of the Inverse Kinematics with 3 D.O.F. Leg*

At first, we explain about 3 d.o.f. leg positioning control by setting $j_3 = 0$. Fig.4 and Fig.5 show the joint space of the 3 d.o.f. leg projected onto Cartesian space and binocular visual space respectively when neck angle $n_1 = n_2 = 0$. These figures indicate that the joint space projected onto binocular visual space is more linear than that onto Cartesian space.

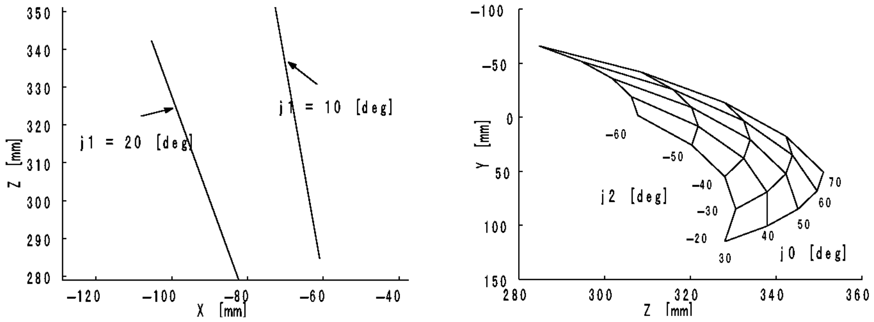
We linearize the transformation between binocular visual space and joint space using the least-squares approximation in space defined as $-20[\text{deg}] \leq j_0 \leq 20[\text{deg}], 20[\text{deg}] \leq j_1 \leq 60[\text{deg}], 60[\text{deg}] \leq j_2 \leq 100[\text{deg}]$.

Then the transformation from binocular visual space to joint space is given by

$$\boldsymbol{j} = \boldsymbol{RV} + \boldsymbol{C}, \tag{3}$$

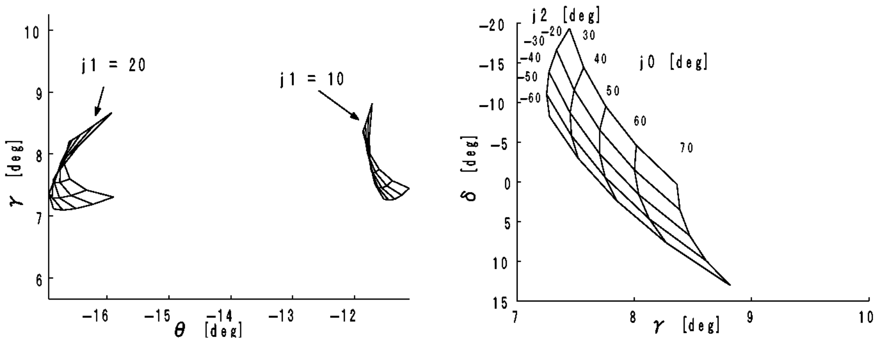
where $\boldsymbol{V} = (\gamma, \theta, \delta)^T$ and $\boldsymbol{j} = (j_0, j_1, j_2)^T, \mathbf{R} : matrix(3X3), \mathbf{C} : vector(3X1)$.

The least-squares approximation using binocular visual space results in



a)$X - Z(j_0 = 0[deg])$ b)$Z - Y$

Fig. 4. Joint space projected onto Cartesian space



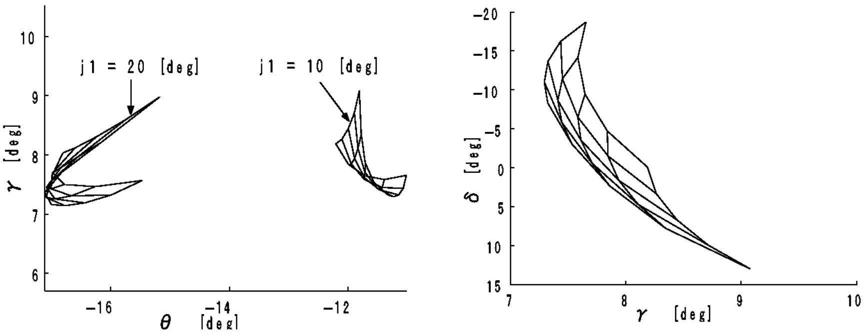
a)$\theta - \gamma(j_0 = 0[deg])$ b)$\gamma - \delta$

Fig. 5. Joint space projected onto binocular visual space

$$\boldsymbol{R} = \begin{pmatrix} -1.432 & -0.148 & -1.144 \\ -9.234 & -2.207 & 0.303 \\ 16.888 & 1.678 & -0.439 \end{pmatrix}, \tag{4}$$

$$\boldsymbol{C} = \begin{bmatrix} 3.086 \\ 162.869 \\ -99.663 \end{bmatrix}. \tag{5}$$

Fig.6 shows the joint space obtained by linear approximation.



a) $\theta - \gamma (j_0 = 0[deg])$ b) $\gamma - \delta$

Fig. 6. Joint space obtained by linear approximation

2.4. *Linear Visual Servoing*

The linear visual servoing using binocular visual space is given by

$$\begin{aligned}
\boldsymbol{u} &= -\lambda \boldsymbol{R}(\boldsymbol{V} - \boldsymbol{V_d}), \\
&= -\lambda \boldsymbol{R} \begin{bmatrix} \{(X^L - X^R) - (X_d^L - X_d^R)\}/f \\ \{(X^L + X^R) - (X_d^L + X_d^R)\}/2f \\ \{(Y^L + Y^R) - (Y_d^L + Y_d^R)\}/2f \end{bmatrix}, \\
&= -\lambda \boldsymbol{R}\boldsymbol{T}(\boldsymbol{I} - \boldsymbol{I_d}), \qquad (6) \\
\boldsymbol{T} &= \begin{pmatrix} 1/f & -1/f & 0 & 0 \\ 1/2f & 1/2f & 0 & 0 \\ 0 & 0 & 1/2f & 1/2f \end{pmatrix}, \\
\boldsymbol{I} &= (X^L, X^R, Y^L, Y^R)^T, \\
\boldsymbol{I_d} &= (X_d^L, X_d^R, Y_d^L, Y_d^R)^T,
\end{aligned}$$

where $\boldsymbol{u}$ are control signals to joint velocity controllers, $\boldsymbol{V}$ is the binocular visual coordinates of the end tip of the leg, $\boldsymbol{V_d}$ is the binocular visual coordinates of a target and λ is a scalar gain, $\boldsymbol{R}$ is the linear approximation matrix of the inverse kinematics obtained in the previous section.

Linear visual servoing is very robust to calibration error, especially to camera angle errors and joint angle errors, because the control law includes neither camera angles nor joint angles. Furthermore, the amount of the calculation is very small compared to the conventional visual servoing schemes.

3. Linear Visual Servoing of the 4 D.O.F. Leg

3.1. *Linear Approximation of the Inverse Kinematics of the 4 D.O.F. Leg*

In this section, we consider that the humanoid robot has 4 d.o.f. leg whose joint angles are j_0, j_1, j_2, j_3. At first, we obtain the linear approximation matrix of the inverse kinematics of the 4 d.o.f. leg. In this section, we use the Spherical coordinate system (r,ϕ, φ) to describe the region of linear approximation. Fig.7 and Table 2 show the region of linear approximation.We linearize the transformation between binocular visual space and joint space by the least-squares approximation using every 10[deg] nodal point of the region shown in Table 2. We locate the end tip of the leg to this nodal point and varies j_3 from $0[deg]$ to $70[deg]$. Then we obtain the joint angles j_0, j_1, j_2 based on the inverse kinematics. We obtain the linear approximation matrix by the similar way as shown in the previous section. Fig.8,Fig.9,Fig.10 shows the varies of the j_0,j_1,j_2 element of the linear approximation matrix to j_3 respecitely. In these figures, A_i, B_i, C_i and $D_i(i = 0, 1, 2)$ denotes the coefficients of j_0, j_1, j_2 and constant term respectively. As can be seen from these figures, the linear approximation matrix has a strong non-linearity to the joint angle j_3.

Then the inverse kinematics of the 4 d.o.f. leg is given by

$$j' = \mathbf{R}(j_3)V + \mathbf{C}(j_3), \tag{7}$$

where

$$\boldsymbol{R(j_3)} = \begin{pmatrix} A_0 & B_0 & C_0 \\ A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \end{pmatrix}, \tag{8}$$

$$\boldsymbol{C(j_3)} = \begin{bmatrix} D_0 \\ D_1 \\ D_2 \end{bmatrix}. \tag{9}$$

Table 2. Approximation range

$110.0^o \le R \le 210.0^o$
$70^o \le \phi \le 140^o$
$35^o \le \psi \le 90^o$

3.2. *Linear Visual Servoing of the 4 D.O.F. Leg*

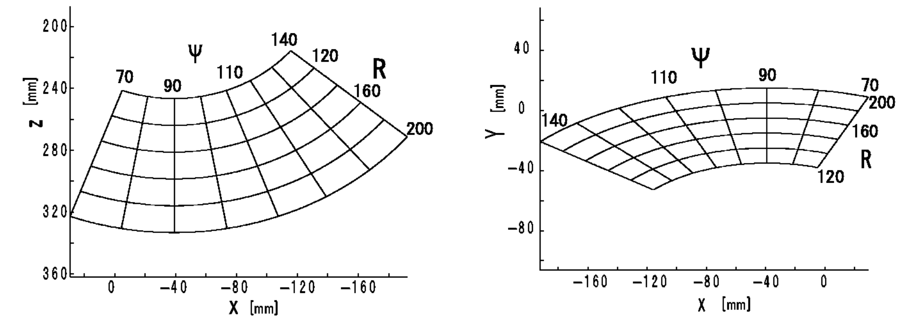
When j_3 is constant, linear visual servoing of the 4 d.o.f. leg is given by

$$u = -\lambda \mathbf{R}(j_3)(V - V_{\mathbf{d}}). \tag{10}$$

4. Experiment

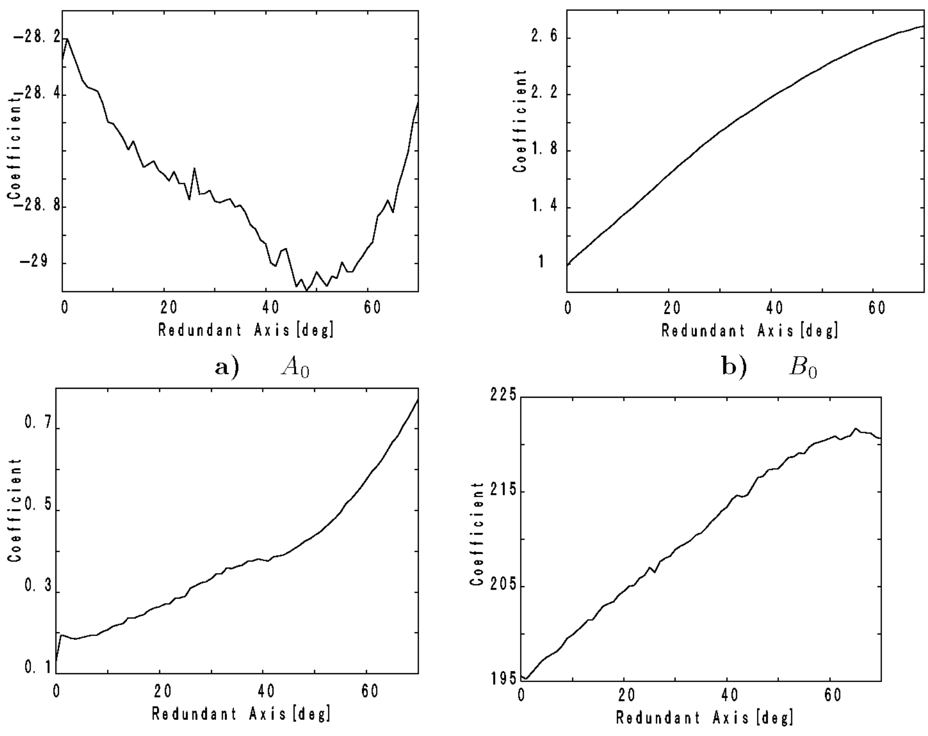
4.1. *Experimental System*

Fig.11 shows the experimental system. We used HOAP-1(Fujitsu) as a humanoid robot. The stereo cameras(Daiwa Industry) are mounted on a neck which pan and



a)Flont View b)Upper View

Fig. 7. Linear Approximation region (Spherical Coordinate System)



a) A_0 b) B_0 c) C_0 c) D_0

Fig. 8. Approximation Coefficient change A_0, B_0, C_0, D_0

tilt by two stepping motors(Japan Pulse motor). We attached a yellow marker at the end tip of the leg and a red object to simplify image processing. The stereo images are converted in an image using a picture division equipment(Video Device) and input to IP5000(Hitachi). The stereo images are binarized by each color and

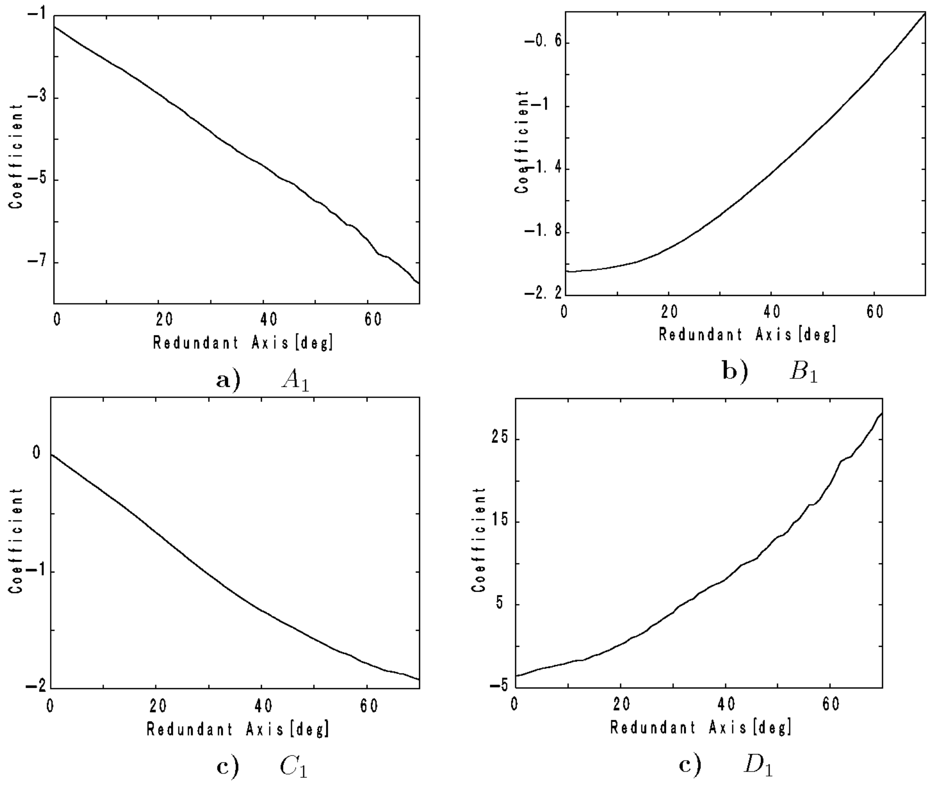


Fig. 9. Approximation Coefficient change A_1, B_1, C_1, D_1

the gravity centers are calculated to obtain the image coordinates of both the end tip of the leg and a target. Then the feedback commands are calculated and sent to HOPA-1 using USB. In this experiment, we used $\lambda = 150$ and the sampling time is $33[ms]$.

4.2. *Experimental Results*

Fig.12 shows 3D trajectories of the end tip of the leg when the redundant axis $j_3 = 0$. From this figure, we can see that linear visual servoing of 3 d.o.f. leg is realized. Fig.13 and Fig.14 show 3D trajectories of the end tip of the leg when the redundant axis $j_3 = 30$ and $j_3 = 60$ respectively. From these figures, we can see that linear visual servoing of 4 d.o.f. leg is also realized.

5. Conclusion

This paper has presented a positioning control method of the 4 d.o.f. leg of the humanoid robot by *linear visual servoing.* Linear visual servoing is based on the linear approximation between binocular visual space and joint space of the leg of

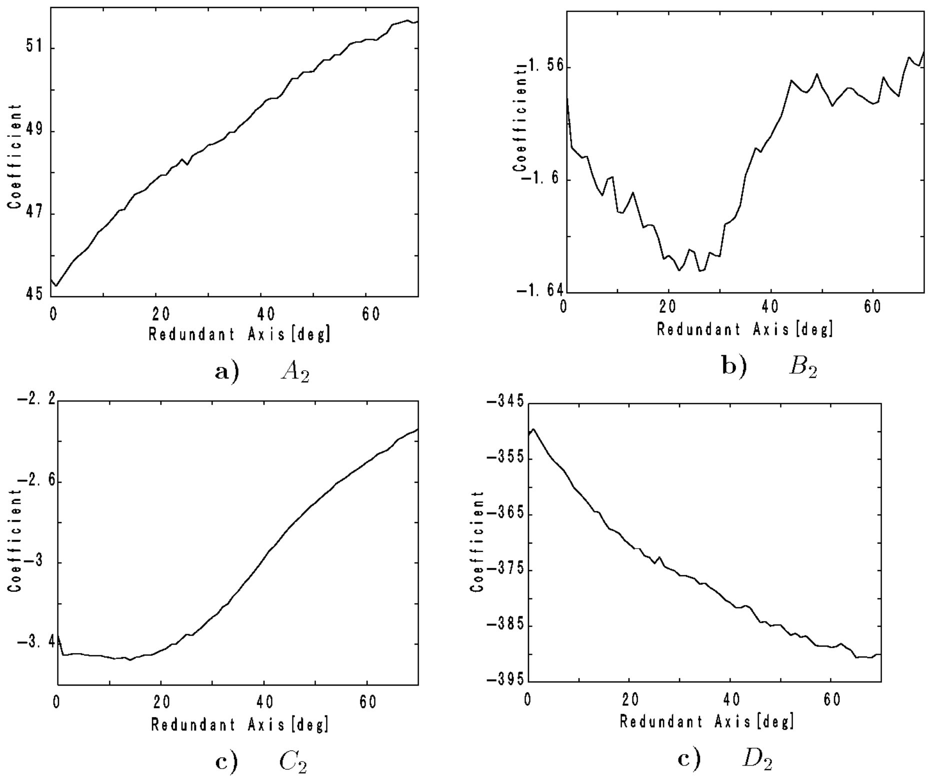


Fig. 10. Approximation Coefficient change A_2, B_2, C_2, D_2

the humanoid robot. It is very robust to calibration error, especially to camera angle errors and joint angle errors, because it uses neither camera angels nor joint angles to calculate feedback command. We have shown some experimental results to demonstrate the effectiveness of the proposed method. In this paper, we did not describe how to control redundant axis j_3. We are now investigating how to control j_3.

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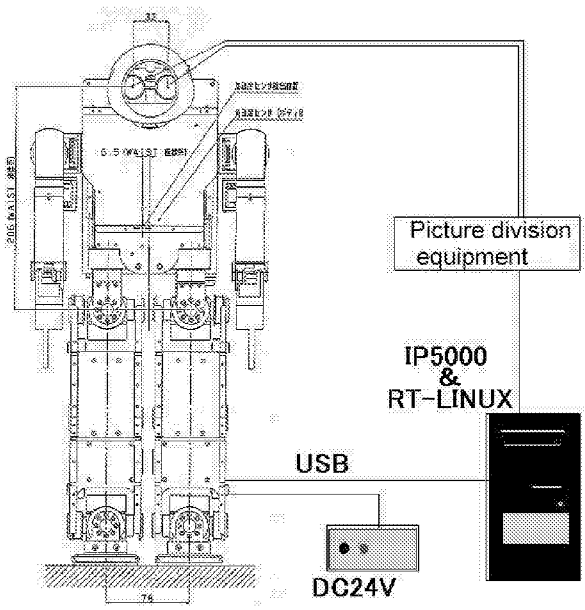

Fig. 11. Experimental system

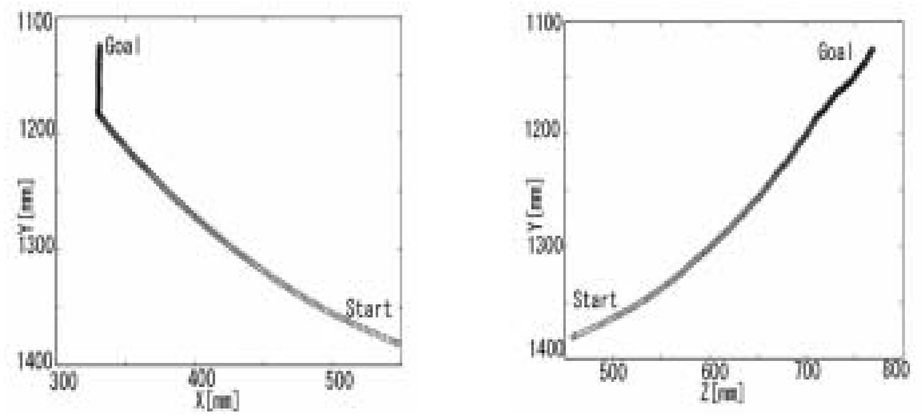

Fig. 12. Trajectories of the end tip of the leg($j_3 = 0$)

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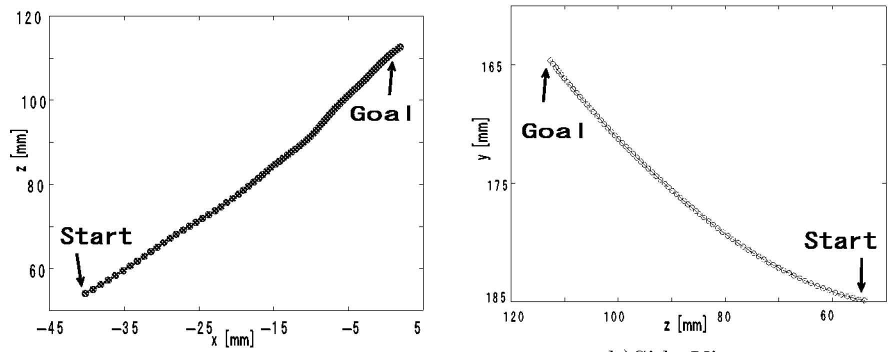
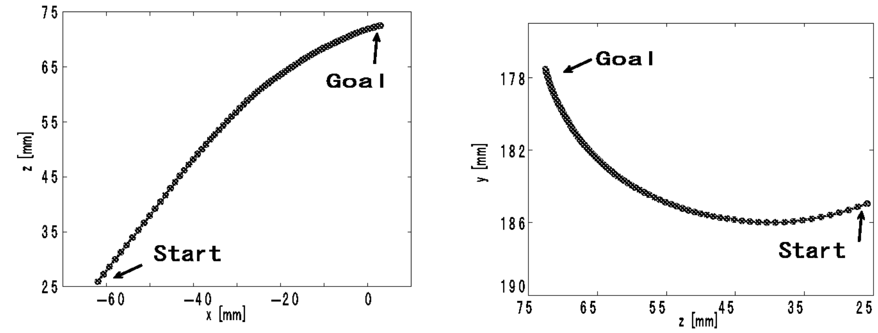


a)Upper view b)Side View

Fig. 13. Trajectories of the end tip of the leg(j_3 = 30[deg])



a)Upper view b)Side View

Fig. 14. Trajectories of the end tip of the leg(j_3 = 60[deg])

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