ROBUST OPTIMIZATION UNDER UNCERTAIN FACTORS OF ENVIRONMENT FOR SIMPLE GAIT OF BIPED ROBOTS

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Abstract

Many biped robots have sensing devices and actuators to control their body. And they can walk stably to apply pressure sensor, gyro sensor or acceleration sensor with walking control methods. If a biped robot has no sensors, it would slip or can not walk. However, it is worth pointing out, some biped robots can walk without sensors. They have only servo actuators to move their body or legs. In such a case, walking biped robots is affected environmental factors. There are restitution and friction between bottoms of its feet and floors. These affects are changed by the floor's surface or materials. And, these also depend on the location on the floor. Thus, biped robots can walk if they use the gait for them including friction and restitution coefficients as the environmental factors. In this paper, we study to optimize the gait for biped robots by using Simulated Annealing (SA), and robust optimization considered random values as floor's friction and restitution. In addition, the generated gait is simple for biped robots which have lately responding actuators or sensors. Thus, this method needs control system is very easy, and this simulation model is made by small and low cost a robot which has been selling at the hobby shops.

Keywords: Biped Robot, Gait, Simulated Annealing, Robust Optimization, Uncertain factors

Presenting Author's biography

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1 Introduction

Biped robots can walk stably by using a walking control method. One of the famous methods is ZMP [1,2,3]. A robot system calculates its center of mass based on the data of pressure sensors which equipped under the bottom of its foot, or gyro sensors in its body. This is way, robots can walk and avoid slipping. Other famous method has been applying Central Pattern Generator (CPG) [4,5]. CPG is the simulated model of the neural oscillator which animals are believed to have. It generates the rhythmical patterns to walk, swim or fly. And, it has the specific feature adapting to the environment they are in. However, their methods require some high accuracy sensors. It also needs high resolution actuators in order to control robots' body exactly.

On the other hand, there are also some robots without actuators and sensing devices, which actually can walk stably on the sloping road. It is called Passive Dynamic Walking [6,7,8]. Furthermore, some robots without sensing devices have been playing activity in "ROBO-ONE [9]" which is biped robots competition in Japan.

In this paper, we study to generate a simple and stable gait for biped robots without or unable sensors by using robust optimization.

2 Optimization of the gait for a biped robot

On the horizontal floor, its friction and restitution are not constant. Both of them depend on the kind of floors. If a biped robot without sensing devices walks on, it would slip or go to random direction. This is why we need to optimize a gait for biped robots according to floor's friction and restitution.

The process of the optimizing gait is shown in Fig. 1. First, initial design variables are optimized by using SA. Second, if it can optimize successfully, robust optimization is carried out by applying SA with environmental random factors. Uncertain design parameters are defined at the floor's friction and restitution.

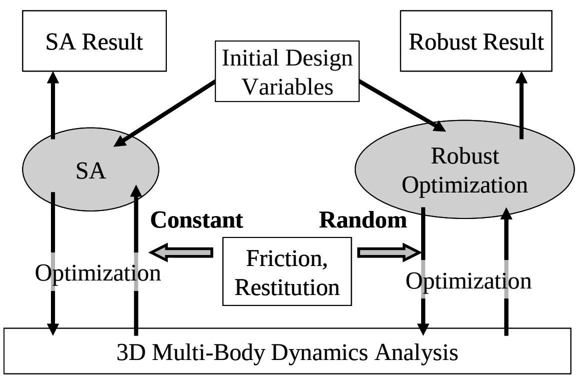

Fig. 1 Process of the optimizing gait

3 Simulation

3.1 Simulation model

The 3D model of the multi-body dynamics analysis is created based on a biped robot which has been selling at the hobby shop for the humanoid robot as shown in Fig. 2. It has 10 RC-Servo motors under the hip. This simulation uses same degrees of freedom on these joints.

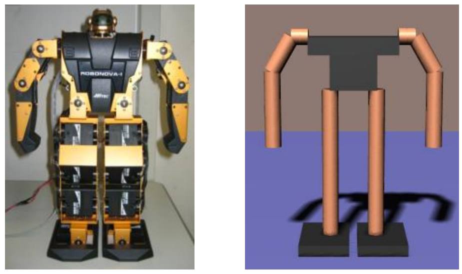

Fig. 2 Biped robot and analysis model

3.2 Definition of the gait function

The periodic function–gait function–to generate the gait for a biped robot is defined as follows:

$$GF_i(t) = a_i + b_i\cos(\omega t) + c_i\sin(\omega t) + d_i\cos(2\omega t) + e_i\sin(2\omega t), \quad (1)$$

where t is time, ω is angular velocity, a_i, b_i, c_i, d_i and e_i are coefficients to generating the gait for various waves.

3.3 Adaptation to the simulation

A sampling time for the function to generate the gait is quarter of a gait cycle. And the generated angle data is allocated a joint for position control value. A joint will move as a constant velocity between control points. In this simulation, one cycle of walking is defined 1.2 seconds. Thus, angular velocity is given as

$$\omega = \frac{2\pi}{1.2}. \quad (2)$$

3 cycles of walking time is 3.6 seconds. And the total time is 4.8 seconds taking 1.2 seconds in order to check after walking stability. In this simulation, 1 step is 0.02 seconds, thus the number of total steps is 240 steps.

Rotative directions for each joint are shown in Tab. 1. θ_1 is rotating side-to-side, From θ_2 to θ_7, these parameters are rotating backward-and-forward. Position of joints which equipped on the biped robot are shown in Fig. 3. Gait functions are substituted as follows:

$$\theta_1 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ GF_1(t) & otherwise \end{cases}, \quad (3)$$

$$\theta_2 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ 30 & if\ t = 3.3 \\ GF_2(t) & otherwise \end{cases}, \quad (4)$$

$$\theta_3 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ 60 & if\ t = 3.3 \\ GF_3(t) & otherwise \end{cases}, \quad (5)$$

$$\theta_4 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ 30 & if\ t = 3.3 \\ GF_4(t) & otherwise \end{cases}, \quad (6)$$

$$\theta_5 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ 30 & if\ t = 0.3 \\ GF_2(t+0.6) & otherwise \end{cases}, \quad (7)$$

$$\theta_6 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ 60 & if\ t = 0.3 \\ GF_3(t+0.6) & otherwise \end{cases}, \quad (8)$$

$$\theta_7 = \begin{cases} 0 & if\ t \le 0, t > 3.3 \\ 30 & if\ t = 0.3 \\ GF_4(t+0.6) & otherwise \end{cases}. \quad (9)$$

In addition, minimum rotation angle uses 0.1 [deg] in this simulation. Eq. (4)-(6) define the behavior of lifting right leg of the robot to stop its movement after 3.3 seconds. Eq. (7)-(9) define the behavior of lifting the left leg of the robot to start walking while 0 to 0.3 seconds. Knee joints do not rotate to backward direction from standing. Thus, these joints are restricted rotating to minus angle as follows:

$$\theta_3 = \begin{cases} 0 & if\ \theta_3 < 0 \\ \theta_3 & otherwise \end{cases}, \quad (10)$$

$$\theta_6 = \begin{cases} 0 & if\ \theta_6 < 0 \\ \theta_6 & otherwise \end{cases}. \quad (11)$$

Tab. 1 Parameter and rotative direction

Parameter	Leg	Joint	Rotative Direction
θ_1	Both	Hip and Ankle	Side-to-Side
θ_2	Right	Hip	Backward-and-Forward
θ_3	Right	Knee	Backward-and-Forward
θ_4	Right	Ankle	Backward-and-Forward
θ_5	Left	Hip	Backward-and-Forward
θ_6	Left	Knee	Backward-and-Forward
θ_7	Left	Ankle	Backward-and-Forward

Furthermore, environmental factors for the biped robot walking are given as follows:

$$\mathrm{U} = [\mu_1, \mu_2], \quad (12)$$

$$\mu_i = 0.1\ (i = 1,2), \quad (13)$$

where μ_1 is friction coefficient, μ_2 is restitution coefficient on the floor.

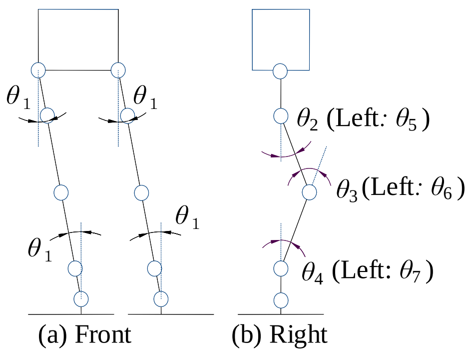

Fig. 3 Link model of the biped robot

3.4 Formulations for the determinate optimization

In the determinate optimization by using SA, design variable vectors, an objective function, a penalty function and constraint functions are defined as shown from Eq. (14) to Eq. (20).

Design variable vectors:

$$\mathbf{x}_i = [a_i, b_i, c_i, d_i, e_i]\ (i=1, 2, 3, 4), \quad (14)$$

$$\mathbf{x}_{All} = [\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4]. \quad (15)$$

Objective function:

$$F = -Y_d + \gamma P \rightarrow Min. \quad (16)$$

Penalty function:

$$P = \sum_{j=1}^{3} \max(g_j, 0) + h_1. \quad (17)$$

Constraint functions:

$$g_1 = \begin{cases} 30.0 - X_d \le 0 & if\ \ X_d > 0 \\ 30.0 + X_d \le 0 & otherwise \end{cases}, \quad (18)$$

$$g_2 = \begin{cases} 5.0 - R_d \le 0 & if\ R_d > 0 \\ 5.0 + R_d \le 0 & otherwise \end{cases}, \quad (19)$$

$$g_3 = 200.0 - Z_h \le 0, \quad (20)$$

$$h_1 = 240 - N_s = 0. \quad (21)$$

The objective function is minimized. In Eq. (15), Y_d denotes the distance between centers of the biped robot model as shown in Fig. 4. The penalty coefficient is the value of γ = 1.0. The penalty function includes four constraint functions. In Eq. (17), g_1 is X_d which denotes the distance at the side under +/-30[mm]. In Eq. (18), g_2 is R_d which denotes the angle to the direction under +/- 5[deg]. In Eq. (19), g_3 is Z_h which denotes the height from the ground to the hip part. It is over 200.0[mm] to check slipping at the end of the simulation. In Eq. (20), N_s denotes the number of steps should be 240 to indicate the success of the simulation.

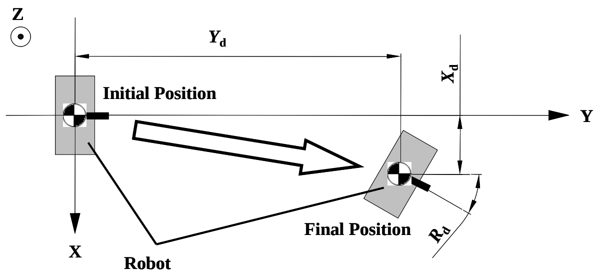

Fig. 4 Overview of the simulation

3.5 Ranges of design variables and initial values

Only $GF_1(t)$ generates the wave to shake the robot's body to the side. Thus, $GF_1(t)$ is defined again as follows:

$$GF_1(t) = a_1 + c_1 \sin(\omega t)\,. \tag{22}$$

And, ranges of design variables are defined as follows:

$$-5.0 \le a_1 \le 5.0\,, \tag{23}$$

$$5.0 \le c_1 \le 10.0\,. \tag{24}$$

Other ranges of design variables are defined as follows:

$$\mathrm{x}_{UB} = \begin{cases} 1.5 \cdot \mathrm{x}_{Init.} & if\ \mathrm{x}_{Init.} > 0 \\ 0 & otherwise \end{cases}, \tag{25}$$

$$\mathrm{x}_{LB} = \begin{cases} 0 & if\ \mathrm{x}_{Init.} > 0 \\ 1.5 \cdot \mathrm{x}_{Init.} & otherwise \end{cases}, \tag{26}$$

where $\mathbf{x}_{UB}$ and $\mathbf{x}_{LB}$ denote upper and lower boundary of design variable vectors, respectively. In Eq. (25) and (26), $\mathbf{x}_{Init}$ denotes initial design variables which are shown in Tab. 2. It is made by waveforms of human walking [10].

Tab. 2 Initial design variable vectors

Function	a_i	b_i	c_i	d_i	e_i
GF_1	0.0	0.0	10.0	0.0	0.0
GF_2	4.6	24.0	-10.2	-0.6	-0.2
GF_3	24.2	-3.5	-16.9	-17.6	-0.9
GF_4	-9.4	-3.0	7.5	11.4	0.9

3.6 Formulations for the robust optimization

The robust optimization uses design variable vectors and these ranges of determinative optimization. And, other equals are defined as follows:

Objective function:

$$F = -f(\mu_{Y_d}, \sigma_{Y_d}) + \gamma P \rightarrow Min, \tag{27}$$

$$f(\mu_{Y_d}, \sigma_{Y_d}) = \frac{Weight_{Y_d}}{Scale_{Y_d}} \mu_{Y_d} + \frac{Weight_{Y_d}}{Scale_{Y_d}} \sigma_{Y_d}^2\,. \tag{28}$$

Penalty function:

$$P = \sum_{j=1}^{3} \max(g_j, 0)\,. \tag{29}$$

Constraint functions:

$$g_1 = \begin{cases} 30.0 - (\mu_{X_d} + 3\sigma_{X_d}) \le 0 & if\ \mu_{X_d} + 3\sigma_{X_d} > 0 \\ 30.0 + (\mu_{X_d} + 3\sigma_{X_d}) \le 0 & otherwise \end{cases}, \tag{30}$$

$$g_2 = \begin{cases} 5.0 - (\mu_{R_d} + 3\sigma_{R_d}) \le 0 & if\ \mu_{R_d} + 3\sigma_{R_d} > 0 \\ 5.0 + (\mu_{R_d} + 3\sigma_{R_d}) \le 0 & otherwise \end{cases}, \tag{31}$$

$$g_3 = 200.0 - (\mu_{Z_d} + 3\sigma_{Z_d}) \le 0\,. \tag{32}$$

From Eq (26) to Eq. (31), the values of μ and σ denote the mean value and the standard deviation, respectively. In Eq. (27), *Weight* and *Scale* factors use 1.0. In robust optimization, uncertain design parameters are friction and restitution coefficients on the floor. These probability density functions are normal distribution. These mean values use Eq. (12). And, standard deviations (Std. Dev.) use as follows:

$$ó = [\sigma_1, \sigma_2] \tag{33}$$

$$\sigma_i = 0.01\ (i = 1,2)\,, \tag{34}$$

where σ_1 is friction, σ_2 is restitution. The robust optimization method is applied SA and robust estimation uses the Sensitivity-Based Variability Estimation based on the first order Taylor's expansion [11,12] as follows:

$$Out = Out(\mathrm{x}_{All}, \mathrm{U}) + \frac{dOut}{d\mathrm{U}} \Delta \mathrm{U}\,, \tag{35}$$

$$\mu_{Out} = Out(\mathrm{x}_{All}, \mathrm{U})$$

Std. Dev. of *Out* is given as follows:

$$\sigma_{Out} = \sqrt{\sum_{j=1}^{2} \left(\frac{\partial Out}{\partial u_j} \right)^2 \sigma_j^{\,2}}\,, \tag{36}$$

where *Out* is output responses. The mean value of *Out* calculated by the uncertain design parameters which are friction and restitution.

4 Results of the simulation

4.1 Results of the determinate optimization

The number of iteration is 500 times as the optimization method of SA. Results of feasible solution are shown in Tab. 3. At first, initial values as shown tab. 2, the robot cannot walk. However, in the case of 223 times, it can walk and distance is 20.4[mm]. Maximum distance is 123.5[mm] in the case of 483 times. For the further discussion, the case of 223 times and 483 times are defined as SA-223 and SA-483. As for comparing SA-483 with SA-223, the distance of SA-483 is 6 times longer. Thus, SA-483 is optimal solution. In this time, design variable vectors are shown in Tab. 4.

Tab. 3 Feasible results

Run	Y_d	X_d	R_d	Z_h	N_s	Feasibility
223	20.4	-4.5	4.2	215.9	240	Feasible
228	24.4	-0.8	0.2	215.9	240	Feasible
240	35.8	-9.8	-2.7	215.9	240	Feasible
250	47.1	11.3	4.0	215.9	240	Feasible
307	62.5	9.6	-4.0	215.9	240	Feasible
429	67.0	-0.9	-2.2	215.9	240	Feasible
440	72.3	0.7	-0.9	215.9	240	Feasible
446	84.2	-2.6	-4.0	215.9	240	Feasible
453	85.7	-3.9	-3.5	215.9	240	Feasible
456	89.5	-3.8	4.9	215.9	240	Feasible
483	123.5	-24.6	2.4	215.9	240	Feasible

Tab. 4 Design variable vectors of best feasible

Function	a_i	b_i	c_i	d_i	e_i
GF_1	0.9	0.0	7.4	0.0	0.0
GF_2	2.1	3.3	-14.1	-0.7	-0.3
GF_3	4.9	-2.2	-0.5	-9.8	-1.2
GF_4	-0.4	-1.2	10.8	6.3	0.1

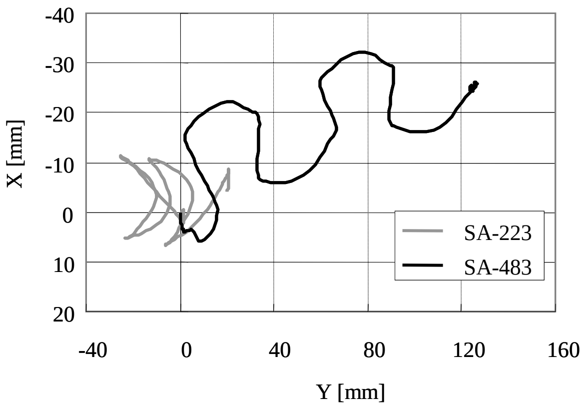

Fig. 5 Trajectory of the robot's center of mass

The trajectory of the robot's center of mass is compared SA-483 with SA-223 as shown in Fig. 4. In SA-223, trajectory is small and walking awkwardly. However, in SA-483, trajectory is larger than SA-223. And it is similar to human walking trajectory[10].

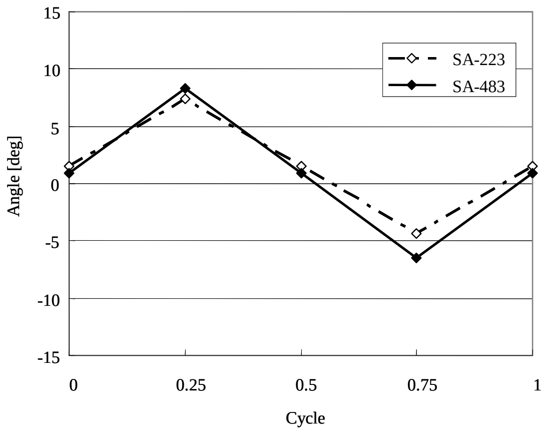

Fig. 6 A cycle of gait function $GF_1(t)$

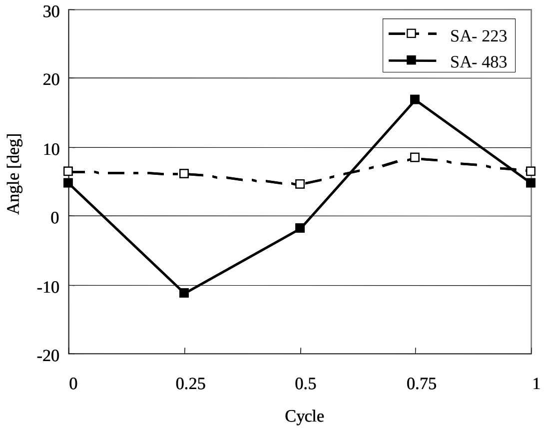

Fig. 7 A cycle of gait function $GF_2(t)$

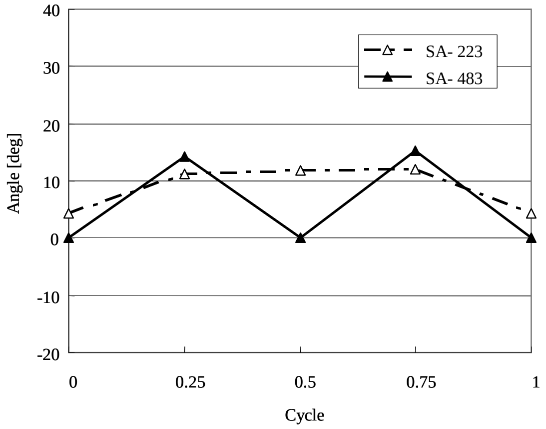

Fig. 8 A cycle of gait function $GF_3(t)$

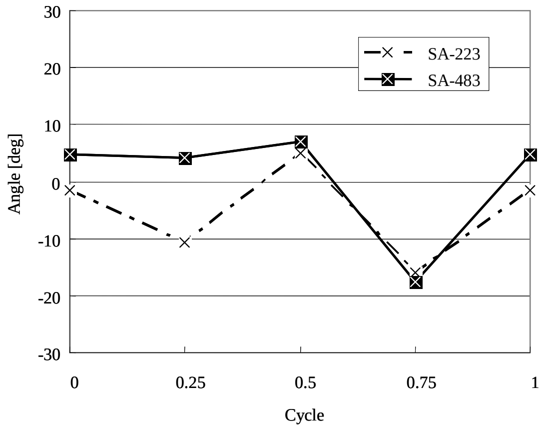

Fig. 9 A cycle of gait function $GF_4(t)$

Waveforms of the gait functions assigned to joints are compared SA-483 with SA-223 as shown in Fig. 6 to Fig. 9.In Fig. 6, the large difference is not found in waveforms as hip and ankle joints rotating side-to-side. It is considered that $GF_1(t)$ is similar to sin function. Then, wave shape changes small. In Fig. 7, waveforms of hip joints change to move the leg widely. In Fig. 8 and Fig. 9, waveforms change widely. However, waveform of SA-483 is similar to human's waveform when people walk [10]. Thus, determinate optimization elicits the simple gait to fit the biped robot. And, the gait is similar to human gait [10].

4.2 Results of robust optimization

The number of total iteration for robust optimization is 1200 times. Results for feasible solution–mean value and Std. Dev. of Y_d–are shown in Tab. 5. Mean values and 3σ values for X_d and R_d are shown in Tab. 6.

Tab. 5 Mean values and Std. Dev. of Y_d

Run	Mean of *Y*d	Std. Dev. of Yd
24	33.3	0.3
147	39.1	2.5
150	48.2	1.9
249	50.4	2.2
390	69.6	2.4
393	71.5	3.6
738	78.1	3.8

Tab. 6 Mean values and 3σ values for X_d and R_d

Run	Mean of X_d	3σ of X_d	Mean of R_d	3σ of R_d
24	9.7	2.9	1.3	1.6
147	1.9	8.8	-1.3	2.0
150	10.8	7.0	-0.3	2.4
249	14.9	3.7	0.7	2.1
390	12.0	5.8	3.7	0.8
393	9.3	3.6	0.8	1.2
738	3.7	1.4	0.6	0.8

These graphs as shown in Fig. 10 to Fig. 12 are resulted from Tab. 5 and Tab. 6. In Fig. 10, Std. Dev. of Y_d has been increasing step by step. Instead, 3σ values of X_d and R_d have been decreasing toward the axis of zero, in Fig. 11 and Fig. 12. The optimal solution is reached at 738 times. Thus, the simple gait provides the stable walking by using robust optimization.

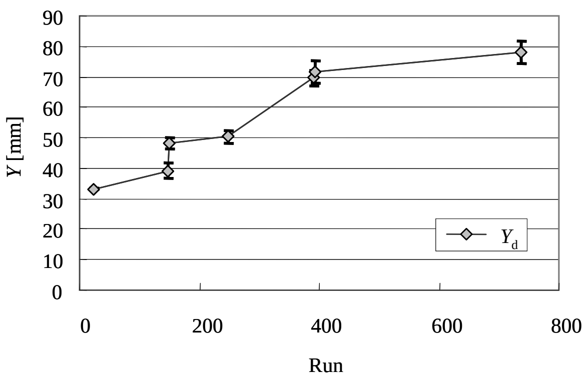

Fig. 10 Mean values of Y_d with Std. Dev.

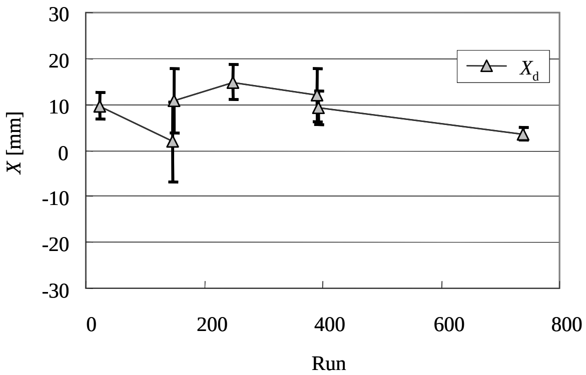

Fig. 11 Mean values of X_d with 3σ values.

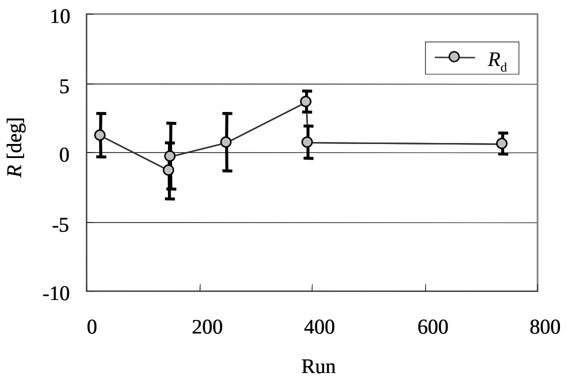

Fig. 12 Mean values of R_d with 3σ values.

Tab. 7 Mean values and 3σ values for X_d and R_d

Function	a_i	b_i	c_i	d_i	e_i
GF_1	2.2	0.0	1.0	0.0	0.0
GF_2	3.8	4.4	-11.4	-0.6	0.1
GF_3	1.8	-5.2	-19.5	-24.8	-0.2
GF_4	-7.9	-3.1	0.3	0.2	1.0

The design variable vectors of the optimal slution are gotten at 738 times, and these are shown in Tab. 7. The robust optimal solution is defined as RO-738 for the discussion. The waveforms to compare RO-738 with SA-483 are shown in Fig. 13 to Fig. 16.

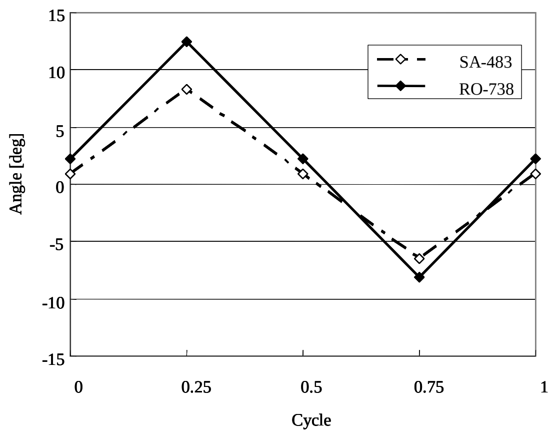

Fig. 13 A cycle of gait function GF_1(t) (SA and RO)

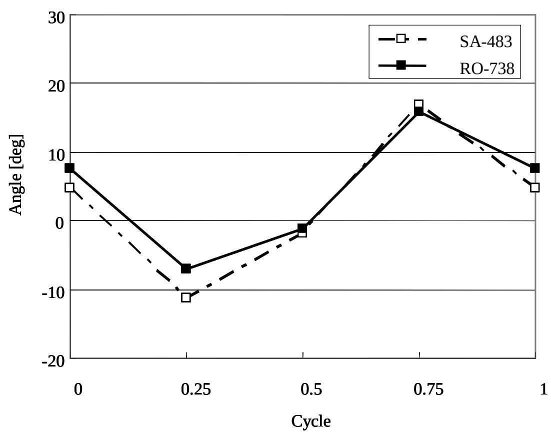

Fig. 14 A cycle of gait function GF_2(t) (SA and RO)

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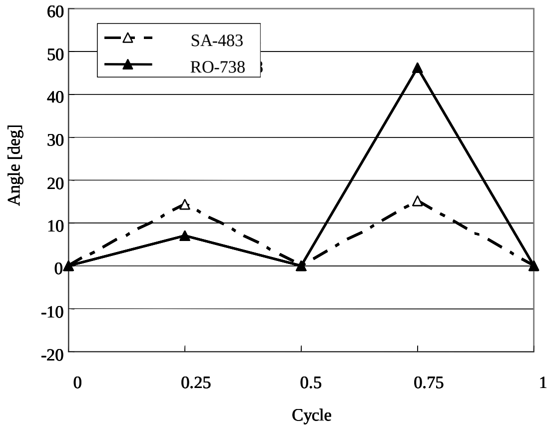

Fig. 15 A cycle of gait function GF_3(t) (SA and RO)

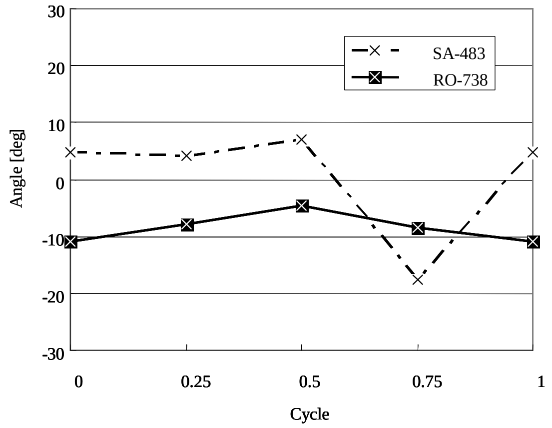

Fig. 16 A cycle of gait function GF_4(t) (SA and RO)

In Fig. 13 and Fig. 14, their waveforms are about the same. In Fig. 15 and Fig. 16, they are not similar to the result of SA-483. And, the knee and ankle joint are changed as shown in Fig. 17. In SA-483, the robot straightens its legs approximately when it walks. And, its walking style is similar to the pendulum. Thus, distance is longer than RO-738. However, the robot is influenced at the friction and restitution. In RO-738, the robot bends its legs moderately and lifts its feet to move as parallel at the floor. Thus, the walking robustness has been increased, though the distance is decreased.

5 Conclusions

Many research for biped robots have been studied. In this paper, we recognize importance of friction and restitution between the biped robot and the floor for stably walking. And we find out some knowledge in this study.

1) The biped robot cannot walk by using the simple gait for initial variables. However, it can walk by using determinate optimization.

2) Robust optimization could get the good gait, if floor's friction and restitution are varied. Especially, after the walking, the distance toward both the side and the rotative directions are decreased in comparison to determinate optimal solution. Thus, it could be considered that this result is advance to walk straight.

3) It has been confirmed that robust optimized gait does not need pressure, gyro or acceleration sensors to walk on the horizontal floor. And, it does not require the short sampling time or high accurate actuators for controlling joints of the biped robot.

Finally, this study has the plan to experiment the real biped robot walking which is applied the gait robust optimized.

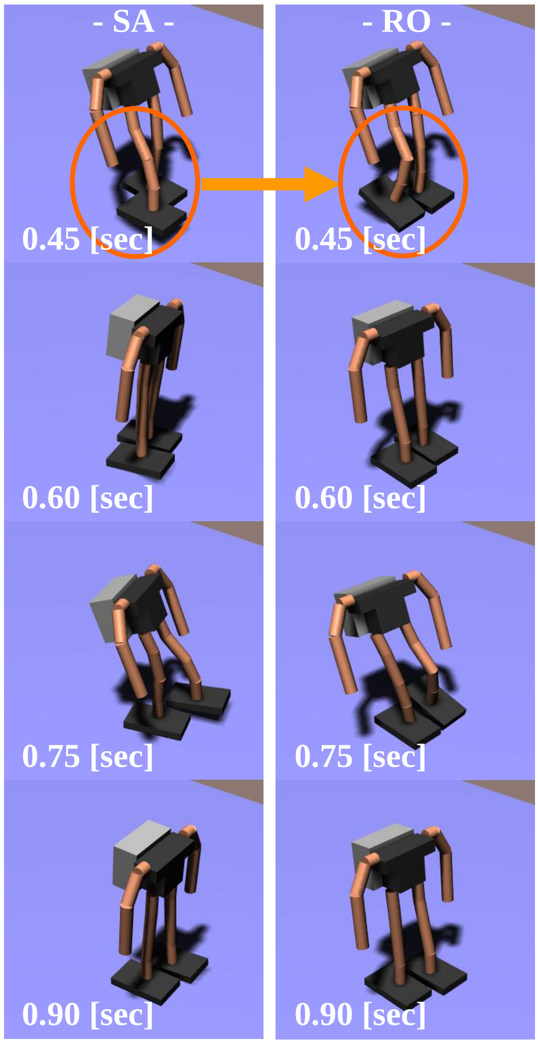

Fig. 17 Comparing knee and ankle joint

6 Acknowledgement

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