SIMULATION BASED DESIGN OPTIMIZATION FRAMEWORK FOR A GAIT PATTERN GENERATION OF A SMALL BIPED ROBOT WITH TIPTOE MECHANISM.

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ABSTRACT
The research of biped robot is still far from proposing a solution which generates a level of flexibility and reliability gait pattern that would enable practical walking on the variety of rough ground human's negotiation with ease on a regular basis.

To solve its issue, we learn from the mammal, belong to the plantigrade, on the natural world. The plantigrade, i.e., human, monkey or bear walk by adapting to a ground from a toe up to heel. From this adaptive walk, its flexibility and stability are excellent although this gait is not suitable for a quick walk.

In this study, to get flexibility and reliability of gait pattern, we introduce a tiptoe mechanism to a small biped robot through inspiration from its adaptive walk, and develop the Simulation Based Design Optimization framework (SBDO).

In this paper, the SBDO framework by approximated optimization process using Adaptive Plan system with Genetic Algorithm (APGA) is proposed. Moreover, to validate an ability of this framework, a small biped robot with tiptoe mechanism is simulated on flat ground at first trial. We discuss this validation result for estimating the SBDO framework.

Keywords: Simulation Based Design Optimization (SBDO), Tiptoe Mechanism, Adaptive Plan system with Genetic Algorithm (APGA).

1. INTRODUCTION
The research of biped robot is still far from proposing a solution which generates a level of flexibility and reliability gait pattern that would enable practical walking on the variety of rough ground human's negotiate with ease on a regular basis.

To solve its issue, we learn from the mammal, belong to the plantigrade, on the natural world. The plantigrade, i.e., human, monkey or bear walk by adapting to a ground from a toe up to heel. From this adaptive walk, its flexibility and stability are excellent although this gait is not suitable for a quick walk, to get flexibility and reliability of gait pattern, we introduce a tiptoe mechanism to a small biped robot through inspiration from its adaptive walk.

Until recently, the studies of gait analysis for walking biped robot are incessant. Zhe Tang et al. have proposed a optimization for humanoid walking based on Genetic Algorithm (GA) base optimization for humanoid walking (Zhe et al. 2006). Lingyun Hu et al. have presented bipeds gait optimization using spline function based on probability model (Lingyun et al. 2006). These studies are about gait optimization of biped robot. Furthermore, a natural human walking was proposed in tiptoe mechanism for biped robot. Y. Xiang et al. have presented optimization based dynamic human walking prediction (Xiang et al. 2007) which were studied an optimization-based approach for simulation the motion of a digital human model. A model has 55 degrees of freedom which included tiptoe joints. Nandha Handharu et al. have proposed gait pattern generation with knee stretch motion for biped robot using toe and heel joints (Nandha et al. 2008). Cheol Ki Ahn et al. have proposed development of a biped robot with toes to improve gait pattern (Cheol et al. 2003), the gait pattern of the robot with toes was compared to the robot without toes by 3D graphical simulation. Shuuji Kajita et al. have proposed zero of moment point (ZPM) based running pattern generation for a biped robot equipped with toe spring (Shuuji et al. 2007). Abovementioned research was based on flat plate.

In addition, there are some studies which related to framework for biped robot locomotion. S. Ali A. Moosavian et al. have proposed the introduction of a cartesian approach for gate planning and control of biped robots and implementation on various slopes (S. Ali A. Moosavian et al. 2007). Naoya Ito and Hasegawa Hiroshi have presented a robust optimization uncertain factors of environment for simple gait of biped robot (Naoya and Hasegawa 2007), to optimize the gait for biped robot by using Simulated Annealing (SA). The robust optimization considered random values as floor of fiction and restitution. Yu Zheng et al. have proposed a walking pattern generator for biped robots on uneven terrains (Yu et al. 2010), these approach were more general and applicable to uneven trains as compared with prior research methods based on the ZMP criterion. Abovementioned were used without toes mechanism model.

On the other hand, The Simulation Based Design (SBD) is powerful technology for improving the competitive power of products. Especially optimal design is an important technology for SBD. Therefore, authors have proposed Simulation Based Design Optimization (SBDO) in automotive design area (Hasegawa et al. 2007).

In this paper, to design and develop a tiptoe mechanism of a small biped robot, the SBDO framework by approximating optimization process using Adaptive Plan system with Genetic Algorithm (APGA) is proposed. Moreover, to validate an ability of this framework, a small biped robot with tiptoe mechanism is simulated on flat ground at first trial.

2. METHODOLOGY FOR GAIT OPTMIZATION

2.1. Simulation Model

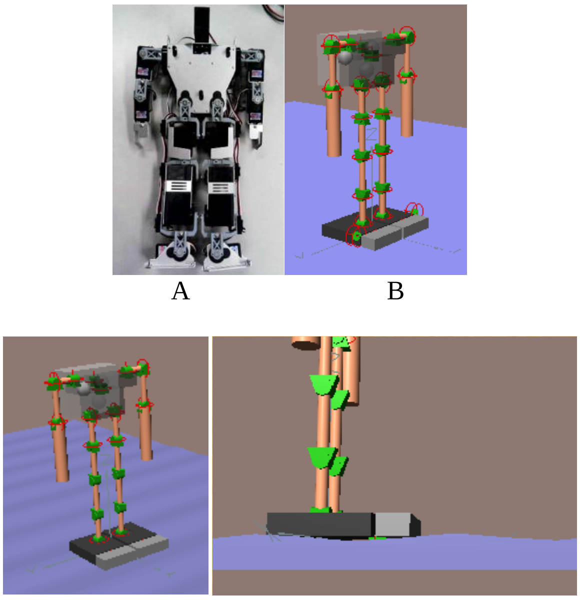

Figure 1: Model A Is KHR-2HV Robot
Model B is simulation model on flat floor
Model C is simulation model on rough floor

The optimization in this paper simulated on flat plate as friction constant by basing on KHR-2HV model. The robot is show in Figure. 1. It has 10 RC-Servo motor under the hip. The simulation uses same degree of freedom on these joints.

Several researches of toe joint utilization in bipedal locomotion have been proposed such as, 1) passive tiptoe joints in order to achieve stable foot lifting, 2) tiptoe joints that are both active and passive control both actively and passively for less energy consumption walking and 3) active tiptoe joints for stepping up stairs. In this study, to get flexibility and reliability of gait pattern, we introduce a passive tiptoe mechanism to a small biped robot is shows in Figure. 2.

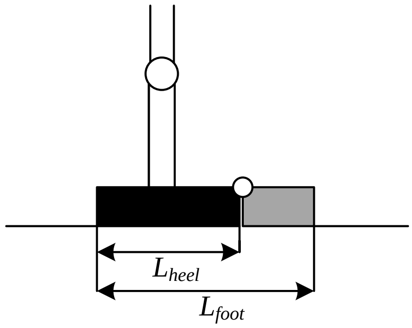

Figure 2: Model Of Robot Foot

The lengths are shown in Figure. 2, L_{foot} is length of foot defined to *92[mm]* and L_{foot} is length of heel define to *75[mm]*. The foot-heel length ratio obtaine from Eq. 1 is *1.227*, the range of ratio between from *1.196* to *1.426* (Chockalingam and Ashford 2007).

$$L_{foot-heel} = \frac{L_{foot}}{L_{heel}} \quad (1)$$

2.2. Simulation Based Design (SBD)

2.2.1. Definition of the gait function

This paper is assumed the robot walks based on the gait function. Therefore, the function is defined based on a human gait pattern that focused attention on the walk cycle. To express this periodic cycle, the function to generate the gait is defined as follows:

$$\theta_i(t) = a_i + b_i \cos(\omega t) + c_i \sin(\omega t)$$

$$+ d_i \cos(2\omega t) + e_i \sin(2\omega t) \quad (2)$$

Where t is time, ω is angular velocity, *i* is number of each joint a, *b*, *c*, *d*, and *e* are coefficients to generating the gait for various wave. The gait for biped robot is changed by operating these coefficients.

2.2.2. Adaptation to simulation

A sampling time for the function to generate the gait is quarter a gait cycle. The generated angle data is allocated the joint for position control value. A joint will move as a constant velocity between control points. In this simulation, *1 cycle* of walking is defined *1.2 seconds*. Thus, angular velocity is give as follows:

$$\omega = \frac{2\pi}{1.2} \quad (3)$$

3 cycle 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* takes *0.2 seconds,* thus the number of total step was *240 steps*. For example, a gait pattern of a joint angle which is made by the gait function.

The position of the joint is shown in Figure. 3 In addition, because of the servomotor of the joint of the biped robot, its joint can be rotated by *60 degree* every *0.14* seconds. The rotate directions for each joint are shows in Table. 1. Gait Functions of model are defined as follows:

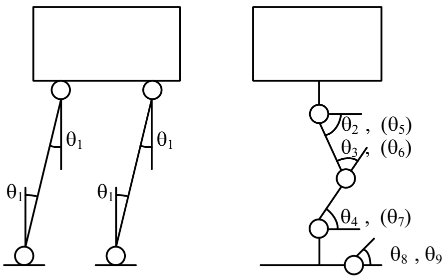

Figure 3: The Link Of Model

$$\theta_1 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ \theta_1(t) & if \quad 0 < t \leq 3.3 \end{cases}, \tag{4}$$

$$\theta_2 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ 0 & if \quad t = 0.3 \\ 30 & if \quad t = 3.3 \\ \theta_2\,(t) & if \quad t = 0 \ < t < 3.3 \end{cases}, \tag{5}$$

$$\theta_3 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ 0 & if \quad t = 0.3 \\ 60 & if \quad t = 3.3 \\ \theta_3\,(t) & if \quad t = 0 \ < t < 3.3 \end{cases}, \tag{6}$$

$$\theta_4 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ 0 & if \quad t = 0.3 \\ 30 & if \quad t = 3.3 \\ \theta_4\,(t) & if \quad t = 0 \ < t < 3.3 \end{cases}, \tag{7}$$

$$\theta_5 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ 30 & if \quad t = 0.3 \\ 0 & if \quad t = 3.3 \\ \theta_2\,(t + 0.6) & if \quad t = 0 \ < t < 3.3 \end{cases}, \tag{8}$$

$$\theta_6 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ 60 & if \quad t = 0.3 \\ 0 & if \quad t = 3.3 \\ \theta_3\,(t + 0.6) & if \quad t = 0 \ < t < 3.3 \end{cases}, \tag{9}$$

$$\theta_7 = \begin{cases} 0 & if \quad t = 0 \ or \ t > 3.3 \\ 30 & if \quad t = 0.3 \\ 0 & if \quad t = 3.3 \\ \theta_4\,(t + 0.6) & if \quad t = 0 \ < t < 3.3 \end{cases}, \tag{10}$$

$$\theta_8 = \begin{cases} 0 & if \quad t = 0 \\ 0 < \theta_8 < 30 & if \quad 0 < t' \end{cases} \tag{11}$$

$$\theta_9 = \begin{cases} 0 & if \quad t = 0 \\ 0 < \theta_9 < 30 & if \quad 0 < t' \end{cases} \tag{12}$$

In addition, minimum rotation angle use *0 degree* in this simulation. Eq. (4) - (8) defines the behavior of lifting right leg of the robot to stop its movement after *3.3 seconds*. Eq. (7) - (10) define the behavior of lifting left leg of the robot to start walking while *0* to *0.3 second*.

Table 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
θ_8	Right	Tiptoe	Backward-and-Forward
θ_9	Left	Tiptoe	Backward-and-Forward

Knee joints do not rotate to backward direction from standing. Thus, these joint are stricter rotating to minus angle as follows:

$$\theta_3 = \begin{cases} 0 & if \quad \theta_3 < 0 \\ \theta_3 & if \quad 0 \leq \theta_3 \end{cases}, \tag{13}$$

$$\theta_6 = \begin{cases} 0 & if \quad \theta_6 < 0 \\ \theta_6 & if \quad 0 \leq \theta_6 \end{cases}, \tag{14}$$

The horizontal surface is applied for the ground surface of the simulation. Moreover, for the ground surface, Friction and restitution coefficients are defined as *0.3* and *0.0*, respectively.

2.2.3. Formulation of the optimization

In the determinate optimization by using APGA, design variable vectors, an objective function, a penalty function and constraints are defined as shown from Eq. (15) to Eq. (21).

Design variable vector (DVs):

$$X_i = [a_i, b_i, c_i, d_i, e_i]; \qquad (i = 1, 2,3,4) \tag{15}$$

$X_{all} = [X_1, X_2, X_3, X_4]$,

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:

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

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

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

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

The objective function is minimized. In Eq. (16) Y_d denote the distance between centers of the biped robot model as shown in Figure. 4. The penalty coefficient is the value of $\gamma = 1.0$. The penalty function includes four constraint functions. In Eq. (18) g_1 and X_d are the distances at the side under ±*30 [mm]*. In Eq. (19) g_2 and R_d is the angle to the direction under ±*5 degree*. In Eq. (20) g_3 and Z_h are the heights from the ground to the hip part. It is over *200[mm]* to check to slipping at the end of the simulation. In Eq. (21) N_s is the number of steps should be *240* to indicate the success of the simulation

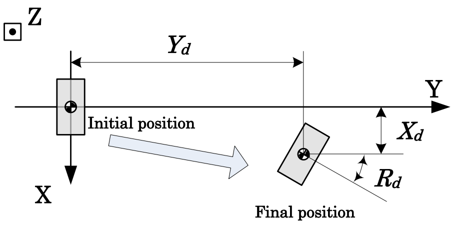

Figure 4: Overview Of The Simulation

Figure. 5 shows the approximated optimization process by following steps.

1. Initial design is initialized by specifying the simple Analysis.
2. For making a response surface model (RSM), X_{all} to generate the angle of each joint is defined. Moreover, random sampling is performed to get results of simulation.
3. Random sampling and then simulated to obtain the results for making the RSM.
4. Using APGA for optimization, the design variables were optimized by APGA based on RSM.
5. The design variables from APGA in step 4. are used to verify the result by simulation.
6. Verification process is conducted to check the convergence of the solutions. If the convergence is achieved, the optimal design will be stopped. Otherwise, the repetition of this process from step 3. will be carried out.

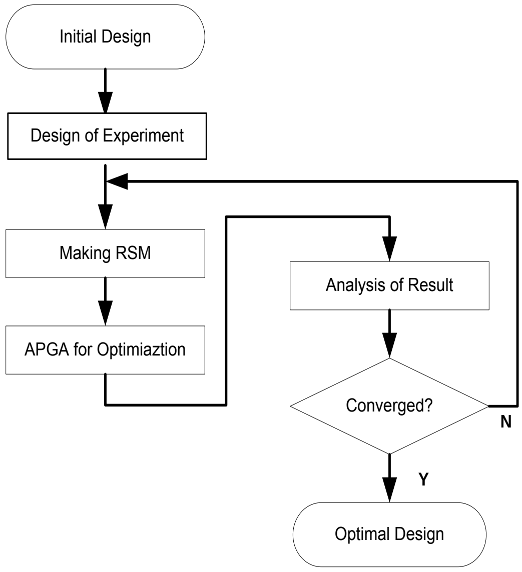

Figure 5: Approximated Optimization Process

2.2.4. Response Surface Model (RSM)

In the optimization process of gait pattern for the robot is used a lot of calculation times. A large portion of this cost can be avoided using RSM by approximating the more cost analysis. Therefore, various optimization problems with this cost are applied by this method. In the paper used Response Surface Model (RSM) of 3rd orders (Cubic polynomial) to approximate response of an actual analysis code. A number of exact analyses using the simulation code(s) have to be performed initially to construct a model with a set of analyzed design point can be used. The 3rd order (Cubic) model is represented by a polynomial of the follows:

$$\tilde{F}(x) = a_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_{i_i}^2 \sum_{ij\,(i<j)} c_{ij}\, x_i x_j + \sum_{i=1}^{N} d_i x_{i_i}^3 \quad (22)$$

Where:
N is number of model inputs or number of variable
X_i is the set of model inputs
a, b, c, d, e are the polynomial coefficients

The number of sampling for initialization equaled to the number of polynomial coefficients which for a cubic polynomial is:

$$\frac{(N+1)(N+2)}{2} + N \quad (23)$$

The number of sampling is calculated using the equation Eq. (23) and N =20 (number of design variables), and is obtained as 215 of data for the calculation of all polynomial coefficients.

3. ADAPTIVE PLAN SYSTEM WITH GENETIC ALGORITHM (APGA)

APGA has been proposed to solve the multi-peak optimization problems with multi dimensions. The proposed algorithm is a stochastic global search heuristics in which EAs based approaches are combined with local search method. APGA uses the Adaptive Plan (AP) to control its optimization process for the local search process. APGA differs in handing design variable vectors (DVs) from genetic algorithm (GA) encode DVs into genes, and handle them through GA operator. However, APGA encodes control variable vectors (CVs) of AP, which searches to local minima, into its genes. CVs decide on global behavior of AP, and DVs are handled by AP in the optimization process of APGA. APGA has been confirmed to improve the calculation cost and the stability of convergence towards the optimal solution.

3.1. Formulation of the simple APGA

APGA is developed for overcoming the difficulty in controlling switching, choosing and steering a combination of global and local search method. On the other hand, Natural and artificial system adapt the behavior of themselves to the changing global and social environments over generations. These systems have been defined as an Adaptive System (AS) by Honlland (Honlland 1992), and AS has an adaptive plan (AP) which decides on its behavior through response to environment (ENV).

APGA is introduced its concept to new evolution algorithm (EA) strategy for multi-peak optimization problems. Hence, this study considers a global search method as AS, a local search method as AP and an optimization space of DVs as ENV, respectively. The conceptual strategy of APGA is show in Figure. 6. APGA differs in handing DVs from general EAs based on GAs to overcome these difficult problems. EAs generally encode DVs into genes of chromosome, and them through GA operator. However, APGA separates DVs of global search and local search methods completely. It encodes control variable vector (CVs) of AP, which searches to local minima into its genes on AS. CVs decide on a global behavior of AP, and DVs are handled by AP in the optimization process of APGA. The generation process of DVs is show in Figure. 7. This process generates a new DVs X_{t+1} from current search point X_t according to the following formula:

$$X_{t+1} = X_t + AP(C_t, R_t), \quad (24)$$

Where *AP()*, *C*, *R* and t denote a function of *AP*,*CVs*, *response value (RVs)* and generation, respectively. AS is controlled by the behavior of *AP()* via feedback loop of fitness value *f* or from a function of problem (*ENV*) during the global search process. Moreover, *C* can be renewed by estimating *f* by suing the GA operators within this process, and their trends are believed to make optimal behaviors like a cooling temperature of Simulate Annealing (SA).

3.2. Adaptive plan (AP): Sensitivity plan

In this paper, the plan introduces a DV generation formula using a sensitivity analysis, which is effective in the convex function problem as a heuristic rule, because a multi-peak problem is combined of convex functions. This plan uses the following equation.

$$AP(C_t, R_t) = -\,Scale \cdot SP \cdot sign(\nabla R_t) \quad (25)$$
$$SP = 2C_t - 1,\ 0.0 \le c_{i,j} \le 1.0, \quad (26)$$

Where scale and ∇R are denoted the scale factor and sensitivity of the *RVs*, respectively. A step size *SP* is defined by *CVs* for controlling a global behavior to prevent it from falling into the local optimum. $C = [c_{i,j}, \ldots, c_{i,p}]$ is used by Eq. (26) so that it can change the direction to improve or worsen the objective function, and *C* is encoded into a chromosome. In addition, *i*, *j*, and *p* are the individual number, design variable number, and its size.

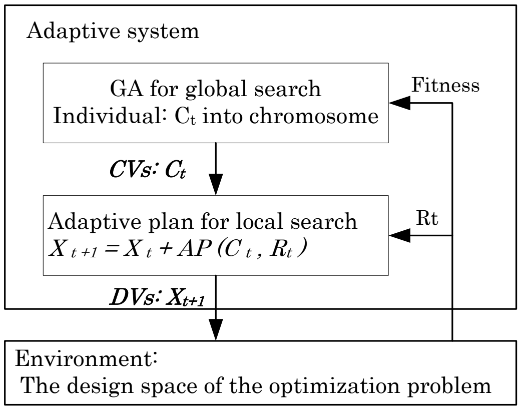

Figure 6: Conceptual Strategy Of APGA

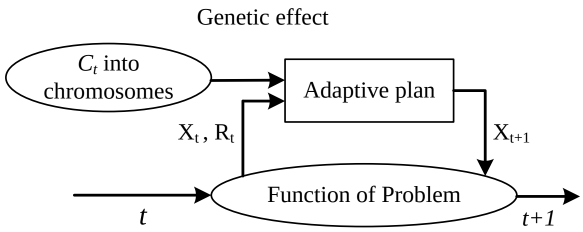

Figure 7: Generation process of DVs

3.3. Ingenuities for DVs and CVs

3.3.1. Handing of significant figures

In the optimal design of the product design, dimension of products can be mainly dealt with as DVs. These are always assigned dimensional accuracies on a mechanical drawing. Therefore, a value of DVs is done well to use a number of significant figures of assigned dimensional accuracy in its drawing in the optimal process. In APGA, a number of significant figures of DVs are defined, and DVs truncated to it within optimal process.

3.3.2. Handling of DVs's out of range

DVs are renewed by AP, and when their values exceed the range of them, returns by Eq. (27) into the range of them.

$$\left.\begin{array}{llll} if & X_t < X^{LB} & then & X_i = X^{LB} \\ if & X_t < X^{UB} & then & X_i = X^{UB} \end{array}\right\} \quad (27)$$

3.3.3. Coding into chromosome for CVs

This 10 bit string with two values *0* and *1* represents a real value of CVs by using procedure of Figure. 8. In addition, Figure. 8. shows DVs and CVs of two dimensional cases.

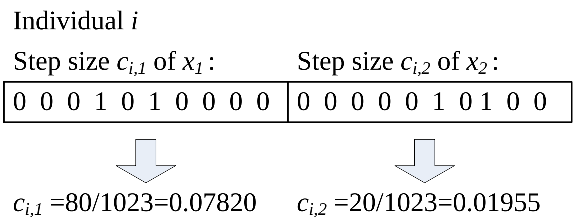

Figure 8: Encoding Into Genes

3.4. GA operators

3.4.1. Selection

Selection is performed using tournament strategy to keep a diverseness of individuals at early generations. The tournament size of *2* is used.

3.4.2. Elite strategy

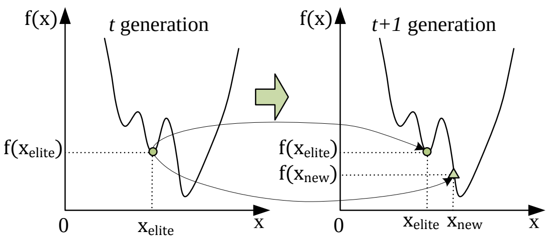

Figure 8: Elite Strategy

An elite strategy, where the best individual survives in the next generation, is adopted during each generation process. It is necessary to assume that the best individual, i.e., as for the elite individual, generates two global behaviors of AP by updating DVs with AP, not GA. Therefore, its strategy replicates the best individual to two elite individuals, and keeps them to the next generation. As shown in Figure. 8, DVs of one of them (▲ Symbol) is renewed by AP, and its CVs which are coded into chromosome are not changed by GA operators. Another one (• Symbol) means that both DVs and CVs are not renewed, and are kept to next generation as an elite individual at the same search point.

3.4.3. Crossover and mutation

In order to pick up the values of each CV, a single point crossover is used for string of each CV. This can be considered to be a uniform crossover for the string of chromosome as show in Figure. 9. The mutation is adapted for string of each CV, and its method reverses the 1 bit in its string.

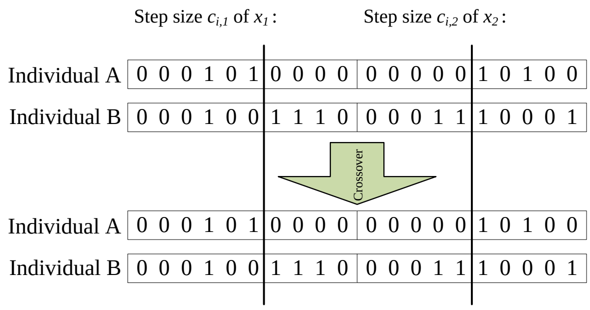

Figure 9: Example Of Crossover

3.4.4. Recombination of gene

At following conditions, the genetic information on chromosome of individual is recombined by a uniform random function.

- One fitness value occupies 80% of the fitness of all individuals.
- One chromosome occupies 80% of the population.

If this manipulation is applied for general GAs, improved chromosome which DVs have been encoded into is broken down. However, in APGA, genetic information is only CVs to make a decision of a decision of a behavior of AP. Therefore, to prevent from falling into a local optima, and to get out from the condition converged with a local optimal search process can recalculate by recombination gene of CVs into chromosome. This strategy is believed to make behavior like a reannealing of SA.

4. RESULTS OF THE SIMULAION

4.1. Results of the simulation on flat plate

The simulation model of small biped robot with passive tiptoe mechanism simulated by using APGA method, it can walk on flat ground (FG). The results are shown in Table 2. We set the number of iterations to 500. Maximum distance is *116[mm]*, distance side (X_d) is *24.8[mm]* in the case of *24 time*.

In the rough ground (RG), the results are not satisfactory because robots cannot walk or can walk but falls down. As a result, we cannot make RSM for using

APGA method. The rough ground will be study in the further. However, the trajectory of the robot's Center of mass (CoM) that can walk shown in Figure. 10.

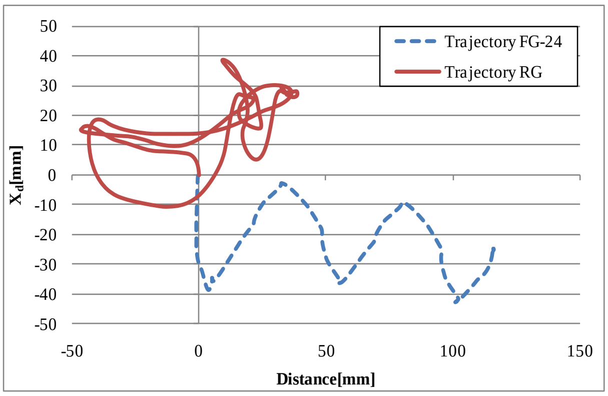

Figure 10: Center Of Mass (CoM) Trajectories Of The Robot Simulation.

The trajectory of the robot's CoM is compared FG-24 with RG as shown in Figure. 10. In RG, trajectory is small and walking is awkward. The other side, the trajectory of FG-24 is larger and similar to human walking trajectory (Gait Analysis Based on Joint Moment 1997). Therefore, we expect this biped robot will be able to walk in rough ground similar to a human walking.

Table 2: The Simulation Results

No. Iteration	X	Y	R_d	Z	N_s
4	-22.7	120.2	7.0	244.0	240.0
7	-28.8	114.9	9.1	244.0	240.0
11	-27.9	119.4	10.6	244.0	240.0
14	-24.5	119.1	5.9	244.0	240.0
16	-20.6	119.5	5.4	244.0	240.0
18	-22.7	121.1	6.1	244.0	240.0
20	-22.4	122.5	7.1	244.0	240.0
22	-24.9	119.0	5.9	244.0	240.0
23	-24.9	119.0	5.9	244.0	240.0
24	**-24.8**	**116.0**	**4.8**	**244.0**	**240.0**
25	19.5	121.8	7.2	244.0	240.0

Waveforms of the gait functions assigned to joints are compared FG4, FG24 and RG as shown in Figure. 11-14. The widely of waveform of less changed, and in $\theta_1(t)$ (hip and ankle joints, rotating side to side) and $\theta_4(t)$ that similar to cosine function.

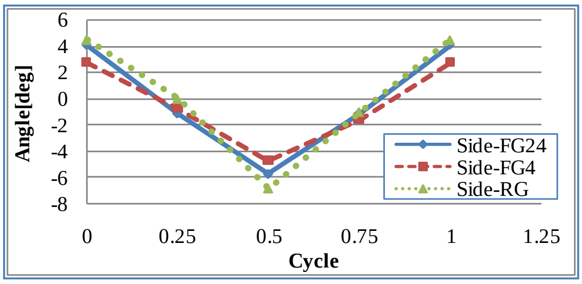

Figure 11: A Cycle Of Gait Function $\theta_1(t)$ @ (Hip And Ankle, Side To Side)

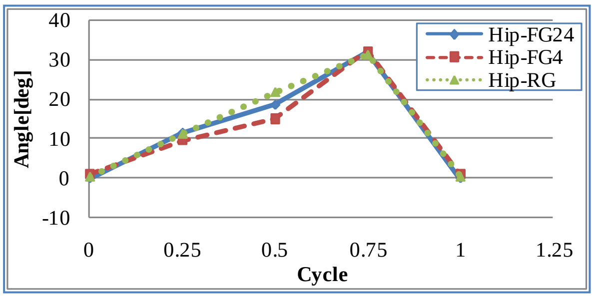

Figure 12: A Cycle Of Gait Function $\theta_2(t)$ @ (Right Hip)

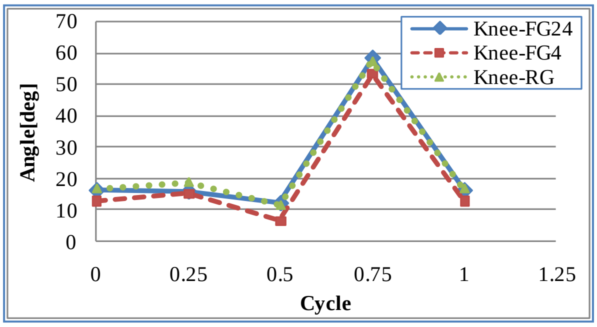

Figure 13: A Cycle Of Gait Function $\theta_3(t)$ @ (Right Knee)

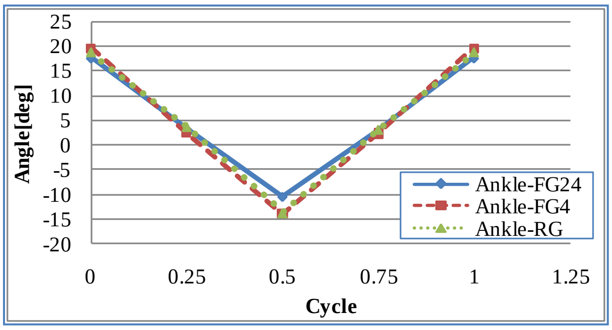

Figure 14: A Cycle Of Gait Function $\theta_4(t)$ @ (Right Ankle)

5. CONCLUSION

We discussed a SBDO framework by approximated optimization process using APGA. The simulation of robot with tiptoe can walk and obtained a good gait pattern on flat ground. The RSM is created it can reduce scope of the problems, solves problems quickly and effectively. However, it is difficult to design and make the RSM to cover all problems. This is seen as a simulation on rough ground. This is an important problem which must be resolved and studied further.

The APGA is another tool to ultimate effectiveness to find the optimal solution. In this paper, the gait patterns generated by APGA converge fast and accurately. Regularly, it depends on the accuracy in the design of the experiment.

As our next target, we will resolve in simulation framework such as on rough ground. Finally, real small biped robot walking will be test as an experiment.

ACKNOWLEDGMENTS

This work was supported by Shibaura Institute of Technology Japan Scholarship. I would like to extend my heartfelt thanks to the Shibaura Institute of Technology, Professor. Hiroshi Hasegawa and everyone for their suggest and help in making this paper.

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