Gait-Behavior Optimization Considering Arm Swing and Toe Mechanism for Biped Walking on Rough Road

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Abstract—**This research implements to optimize gait behavior of a biped robot while walking on rough road. Gait pattern is produced by solving constrained optimization problem using improve self-adaptive differential evolution (ISADE) and response surface model (RSM). The foot structure of the robot adopts a toe mechanism and is generated by topology optimization in which four specific situations are considered. The optimal structure is a combination of these four results. This structure not only reduces the weight of the robot but also ensures its stable walk. In addition, while considering the human walk, we discover that arm swing motion can preclude ground reaction torque caused by leg wing, thus, we applied a mechanism to imitate arm swing motion of the humans for the robot to enhance stability. It can be said that with two applied mechanisms, the robot motion is primarily comparable to the human one. Our result is validated by dynamic simulation in Adams environment (MSC software).**

***Index Terms*—biped robot; topology; foot structure; gait pattern; arm swing.**

I. INTRODUCTION

In biped robot field, the human-like walking is always the final goal which the researchers have expected to reach. This problem still establishes one of the most challenging issues for the robot even for a locomotion on the perfectly flat surface where the robot walking is required to be stable and natural like the human beings. Through the locomotion on the rough ground, this issue becomes extremely difficult due to the various change of the terrain. The robot not only encounters the unpredicted difficulty in keeping stability but also needs to walk naturally.

Investigating the papers in this areas, we can mention some highlight researches. Firstly, it can be said that walking on uneven surfaces such as slopes and inclines have received much more attention [1], [2], [3] since it restricts the challenge of the unstable issue on the rough environment. In the same way, a number of other works study biped motion concerned with walking on level surface such as up and down stair [4], [5].

However, in the reality, the robot is intervening in many applications with the diverse terrain other than expected. Overcoming this matter, a few researches focus on a gait generation method for biped locomotion on rough ground. In detail, Sang-Ho Hyon et al. presented an adaptive control method for humanoid robot on unknown rough terrain. The adaption is achieved by an optimally-distributed anti-gravitational forces [6]. In the same way, Mitsuharu Morisawa et al. proposed a biped locomotion control for uneven terrain with narrow support region. In their work, a walking capability of the robot is enhanced by using the information of a support region [7]. In [8], Y. F. Zheng et al. proposed two new types of gaits named “step-over” and “ski-type” to overcome challenge when humanoid robot moves on uneven surfaces.

On the other hand, some researchers have realized that the conventional foot with a rigid and flat sole has sufficient support polygon area, only when the robot walks on flat ground. On rough surface, contact states often become one-point contacts or line-contacts, thus the support polygon becomes too small, center of gravity (CoG) point moves out of the support polygon, and causing the robot unstable. As a result, some previous papers have developed a new foot structure for a humanoid robot to adapt to a rough environment. For instance, to realize stability on complex ground surface, Moyuru Yamada et al. developed a biped robot with a point-contact type foot with springs. It suppresses the impact force at foot landing and provided a stable contact states on rough terrain by adapting geometrically to complex surfaces [9]. Likewise, in [10], Takumi Yokomichi proposed a new foot structure with three toes with frictional locking and unlocking mechanism to avoid the influence of reaction force on biped robot when walking on unknown rough terrain such as a craggy place.

Through consideration of current research and development results, we consider a foot structures with toe when investigating locomotion of the robot on rough ground. In toe mechanism, the passive joint using torsion spring is selected as a toe joint. This mechanism is expected to enable the robot to overcome the challenge on uneven terrain by stabilizing walking behavior as depicted in Fig. 1.

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Fig. 1 describes a working mechanism of robot's toe in motion. During walking, reaction force F_r is exerted by the ground on a foot in contact with it, this force produces an external moment acting on a robot and it makes robot unstable. By adding a toe mechanism using torsion spring, an internal moment M_{lx} is exerted to oppose the external one. Thus, stability of walking behavior is enhanced.

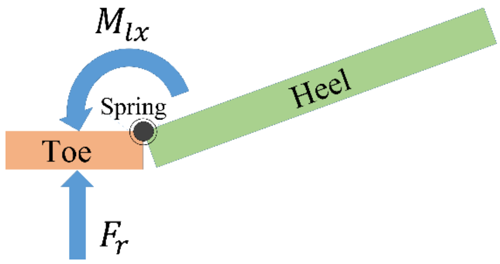

Figure 1. Reaction moment of toe mechanism.

Besides, on the course of human walking, the leg swing results in an angular momentum that is balanced by the ground reaction moments on the stance foot. Swinging arms create an angular momentum which arises due to the inertial effects of arm swing motion about the vertical axis of the torso in the opposing direction of lower limb rotation, reducing the total angular momentum of the body as shown in Fig. 2.

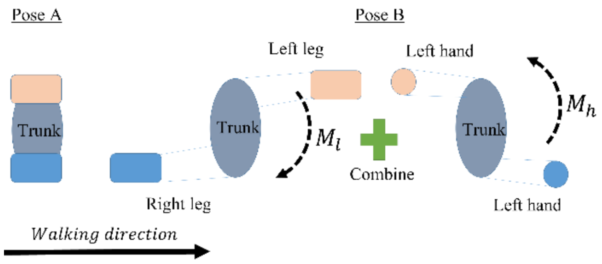

Figure 2. Arm swing moment opposes ground reaction moment.

As can be seen that for moving from pose A to pose B, clockwise moment M_l is required. Simultaneously, the external counter-clockwise moment is also exerted by the ground to counter the motion of leg swing. Meanwhile, because the arms rotate in opposing directions about the lateral axis (axis passing through the shoulders). Thus, the reaction moment from the arms to the trunk precludes ground reaction torque [11]. With mentioned advantage, F. Naoki's research has proposed and modeled an arm swing mechanism using Adams [12], our research applies this model for walking on rough road.

Finally, to generate gait pattern for the robot, the approximated optimization method using improve self-adaptive differential evolution (ISADE) and response surface model (RSM) is applied. This approach considers gait generation as an optimization problem with constraints, where constraint function is to ensure the stability of the robot during locomotion. We confirmed the success of this research through dynamic simulation of the walking process in Adams software environment.

The rest of this paper is organized into five sections. Section 2 describes the approach to build the foot structure of the humanoid robot. Section 3 presents the improvement of upper body structure. The principle of gait pattern generation is in Section 4. Section 5 describes the simulation model. The results of the simulation are depicted in Section 6. Finally, Section 7 includes some brief conclusions and future works.

II. Topology-Based Foot Structure

This study applies the result of K. Daichi's research [13] by considering some situations with different forces as described in Fig. 3 and Table I, where the point related to the ankle position of the robot is fixed and the ground reaction forces only act on the supporting point 1, 2 and 3. Since the weight of the robot is 1.5kg, the maximum ground reaction force set to each supporting point is 15N such as case 1, 3 and 4. In case 2, the ground reaction force is equally distributed in three supporting points. To solve this topology optimization problem, the algorithm proposed by Liu and Tovar [14] is applied.

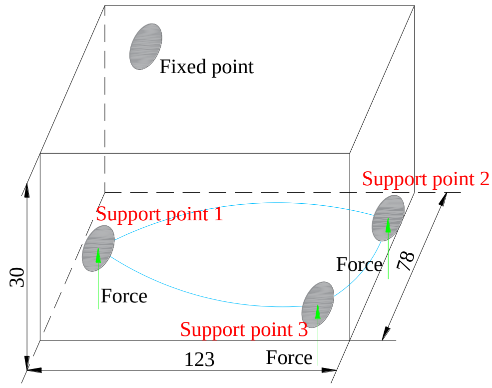

Figure 3. Design space for topology problem [13].

TABLE I. Force Distribution

Case	*Force 1[N]*	*Force 2[N]*	*Force 3[N]*
1	15	0	0
2	5	5	5
3	0	15	0
4	0	0	15

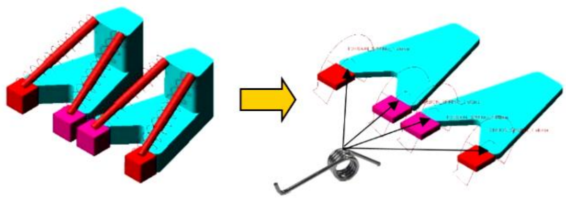

Figure 4. Optimal foot structure.

However, in order to reduce the complexity of foot structure because the subject is a small humanoid robot, linear springs are replaced by torsion springs as shown in Fig. 4. Optimal foot structure in detail is described in Fig. 5. With this topology foot structure, the unnecessary areas are removed, and thus, the weight of the foot is reduced.

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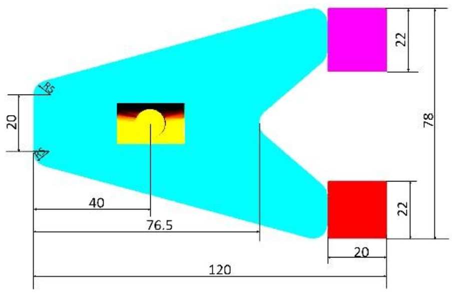


Figure 5. Design of optimal foot structure.

III. Arm Swing And Backbone Mechanism

A. Arm Swing Mechanism

To learn from arm swing behavior of the humans, F. Naoki's research [12] proposed an arm swing mechanism for the biped robot as depicted in Fig. 6. Its principle is similar to a four-bar linkage. The motion of the shoulder joint is provided by the actuator of the contralateral hip pitch joint through two linear springs with damper. Our work applies this structure with transmission ratio of 1.67. The stiffness and damping coefficient are set to 0.8 (N/mm) and 0.008 (N.s/mm), respectively.

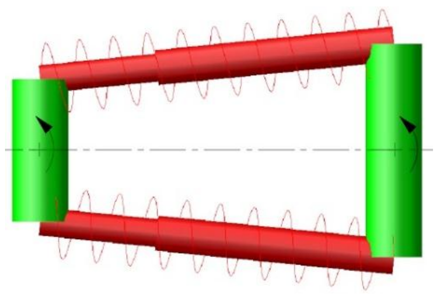
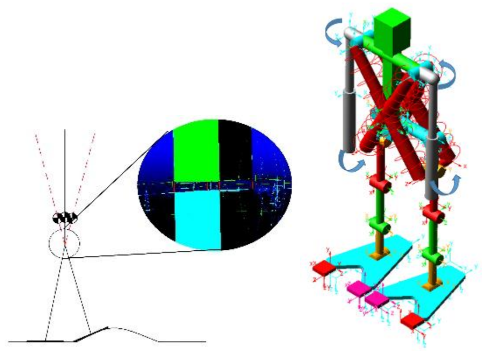


Figure 6. Arm swing principle of the robot.

B. Backbone Structure

The humans' backbone is a complex and functionally significant segment of the human body. Providing the mechanical linkage between the upper and lower extremities, the spine enables motion in all three planes. In humans' walking, the vertebrae flexibly move to maintain the CoM to drop into the support polygon, specially while walking on the rough environment. Thus, the spine has an important role in preserving the humans from falling down.

By above mentioned advantage, F. Naoki [12] introduced a backbone structure using 8 linear springs to constrain the segments of the spine. Based on this idea, we design a simple one consisting of a passive 3-DoF joint and 4 linear springs. When overcoming the obstacles in corrugated ground, the robot's CoM have a trend to move out the polygon support. The spinal motion of the robot keeps CoM point inside the polygon support by moving forward as described in Fig. 7a. Backbone structure combining with arm swinging mechanism performs upper-body moving behavior as depicted in Fig. 7b. It is expected to have a positive effect on locomotion of this robot while walking on high rough level ground.



(a) (b)

Figure 7. Backbone mechanism: (a) Backbone structure; and (b) Upper-body moving behavior.

The stiffness and damping coefficient of all four linear springs are 3.5 (N/mm) and 0.05 (N. s/mm), respectively. This mechanism is applied for the robot performance on ground with 10mm-high waves only.

IV. Gait Pattern Generation

A. Definition of Joint Angle

In this study, the paper focus on the lower body with 10 controlled DoFs. The joint angles are defined as depicted in Fig. 8 and these specifications are described in Table II.

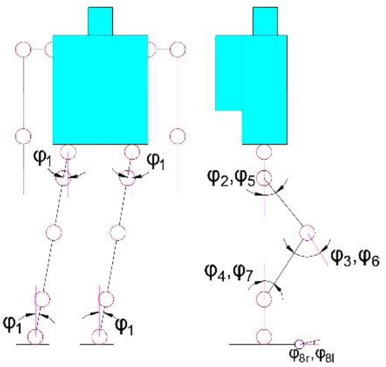


Figure 8. Robot linkage model.

TABLE II. Range of Joint Angle

Angle	*Leg*	*Joint*	*Value (°)*
φ_1	Both	Hip & ankle	-15° to 15°
φ_2	Right	Hip	-50° to 50°
φ_3	Right	Knee	0° to 60°
φ_4	Right	Ankle	-50° to 50°
φ_5	Left	Hip	-50° to 50°
φ_6	Left	Knee	0° to 60°
φ_7	Left	Ankle	-50° to 50°
φ_{8r}	Right	Proximal phalanx	0° to 30°
φ_{8l}	Left	Proximal phalanx	0° to 30°

B. Gait Function

Based on the human walking pattern as depicted in [15], this study assumed the robot control data was generated by the gait function as trigonometric function shown in Equation 1. By changing *a*, *b*, *c*, *d* coefficients,

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the gait functions will be created to allocate to each joint of the biped robot.

$$\varphi_i\ (t) = a_i + b_i.cos(\omega t) + c_i.sin(\omega t) + b_i.cos(\omega t). \quad (1)$$

Where φ_i is the angle of i joint; *a*; *b*; *c*; *d* are coefficients; *t* is the time, and ω is the angular velocity. By changing *a*; *b*; *c*; *d* coefficients, the gait function will be created to allocate to each joint of the robot. In toe mechanism, due to considering a reduction in energy consumption of the robot, the passive joint is selected as a toe joint. Consequently, φ_{8r} and φ_{8l} have a value in the range from 0^o to 30^o. Their values depend on the robot geometric posture as well as an impact force when the robot performs its motion. In motion, one cycle is set up to 1.2 seconds. Thus, the angular velocity is determined by below calculation.

$$\omega = \frac{2\Pi}{1.2} = 5.236$$

C. Optimization Procedure

Design variable vector, objective function, constraint function and penalty function are defined as described in (2 – 7).

Design variables (DVs):

$$x = [a_i,\ b_i,\ c_i,\ d_i],\ i = 1 \div 4. \quad (2)$$

Range of design variables is predefined as in Table III.

TABLE III. RANGE OF JOINT ANGLE

Design variables	*Lower boundary*	*Upper boundary*
a_1	0	0.006
b_1	0	0.1
c_1	0	0.002
d_1	-0.01	0
a_2	0	0.08
b_2	0	0.4
c_2	0	0.001
d_2	0	0.02
a_3	0	0.8
b_3	0	0.08
c_3	-0.4	0
d_3	-0.2	0
a_4	-0.4	0
b_4	0	0.3
c_4	0	0.2
d_4	0	0.1

Constraint functions:

$$g_1(x) = 20 - |X_f| \geq 0. \quad (3)$$

$$g_2(x) = 5 - |R_f| \geq 0. \quad (4)$$

Penalty function:

$$P(x) = \sum_{i=1}^{2} min[g_i(x), 0]^2. \quad (5)$$

Objective function:

$$f(x) = - Z_f \rightarrow min. \quad (6)$$

Modified objective function:

$$F(x) = - Z_f + \gamma.P \rightarrow min. \quad (7)$$

where X_f, Z_f, and R_f are respectively lateral distance, walking distance, and angle of rotation at the final position of the robot. The restrictions of X_f distance and R_f angle as shown in (3) and (4) guarantee that the biped robot can walk straight. γ is a penalty coefficient set to 1000. The optimization process to generate a gait pattern for the robot is depicted in Fig. 9.

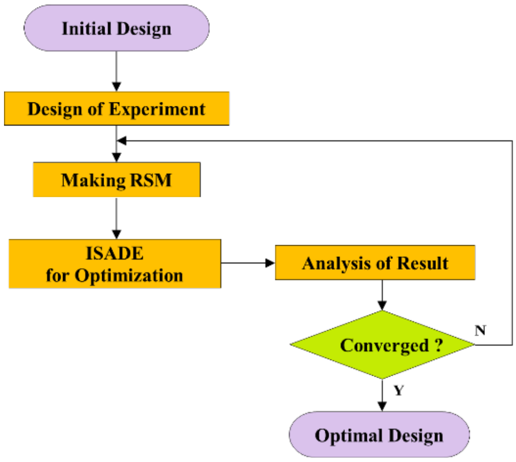

Figure 9. Overview of optimization process.

Combination of ISADE and RSM

- Initial design is implemented by trial and error method.
- Simulation samples are simulated on Adams.
- Making the RSM.
- The design variables are optimized by ISADE algorithm based on RSM.
- The design variables from step 4 are used to check constraint functions again through the simulation.
- The convergence is checked. If this is achieved, the optimal process will be terminated. Oppositely, the repetition will begin from step 3.

V. SIMULATION MODEL

A. Subject

The subject based on the KHR-3HV robot of Kondo Kagaku Company which is the third generation of a humanoid robot developed by this company. The KHR-3HV robot has the weight of 1.5kg, the height of 401.05mm. From the real robot, the paper built the simulation model in Adams environment as shown in Fig. 10.

The robot is considered in two configurations: In the first configuration, arm wing mechanism is applied only. In the second configuration, both arm wing mechanism and backbone structure are applied.

B. Rough Road

The surface designed for robot walking performance consists of two parts: Flat surface and rough surface, the length of corrugated segment is 120mm and it has one positive and one negative wave with the height of 6 and 10mm for each situation as depicted in Fig. 11.

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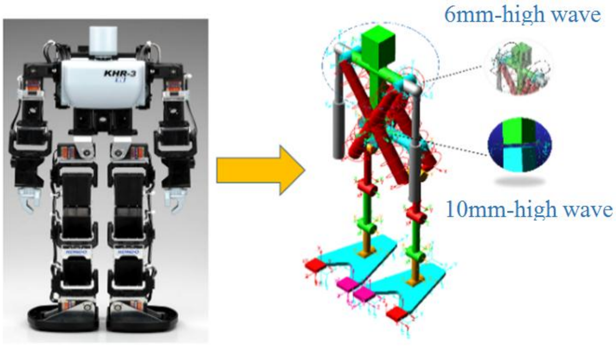


Figure 10. Real robot and proposed model.

Situation	*h (mm)*	*L (mm)*
No.1	6	120
No.2	10	120

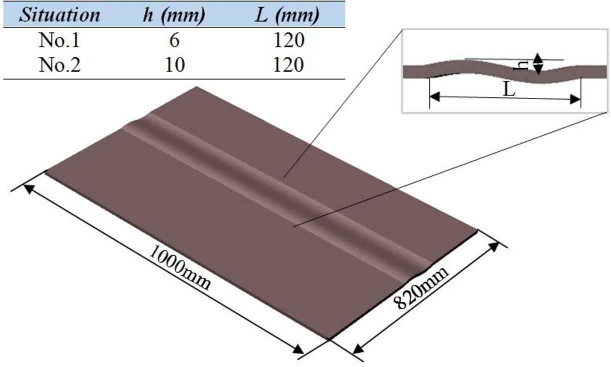


Figure 11. Testing surface.

VI. Simulation Result

In this simulation, the robot motion is considered in five cycles. One cycle is set up to 1.2 seconds. Thus, seven cycles spend on 8.4 seconds. Next, 1.2 seconds is used for checking robot stability. In this simulation, one step takes 0.02 second, so the total number of steps is 480. With 6mm-high wave ground, optimization procedure is implemented to find out the optimal value for design variables. With 10mm-high wave ground, the RSM and optimization process are not applied because I cannot collect enough number of samples for making RSM. The values of design variables on rough ground for both situations are presented in Table IV and the result of simulation is shown in Figure 12.

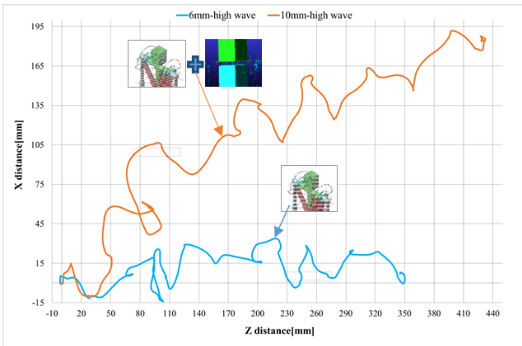
The result show that the robot walks well and has a good performance on ground with 6mm-high waves. However, when I increase the height of wave, robot cannot overcome obstacles and fall down. For the second configuration, the robot can overcome 10mm-high waves, however, it still has some limitations. The lateral distance is unexpectedly big which means the robot does not walk in straight line and the angle of rotation is big as well.

The walking behavior of the robot in the first situation is depicted in Fig. 13. As can be seen that, for overcoming the obstacles on the terrain, the robot performs bending behavior of the toe which enhances the contacting points and enable the robot to walk steadily.

Waveform of gait function for both situations is depicted in Fig. 14.

TABLE IV. Value for Design Variables on Rough Ground

i	*Design variables for 6mm-high wave ground*			
	a_i	b_i	c_i	d_i
1	0.003	0.043	0.001	-0.007
2	0.043	0.204	0.001	0.012
3	0.313	0.032	-0.164	-0.129
4	-0.206	0.129	0.106	0.069
i	*Design variables for 10mm-high wave ground*			
1	0.003	0.045	0.001	-0.007
2	0.041	0.210	0.001	0.013
3	0.414	0.039	-0.189	-0.111
4	-0.245	0.146	0.103	0.049



Situation	*Walking distance (mm)*	*Lateral distance (mm)*	*Angle of rotation (°)*
6mm-high wave	346.31	7.77	6.47
10mm-high wave	429.92	184.7	8.46

Figure 12. Simulation result.

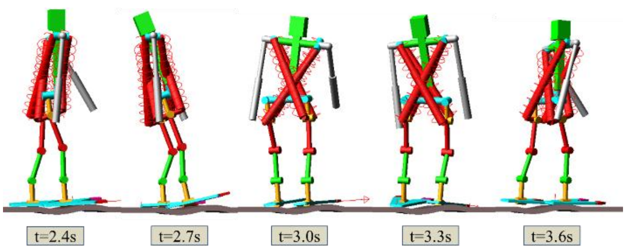
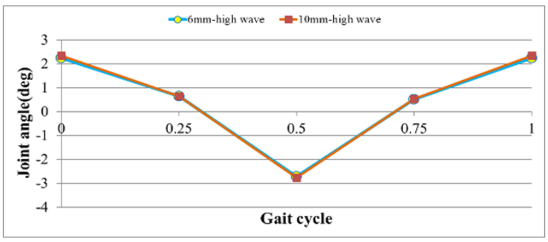
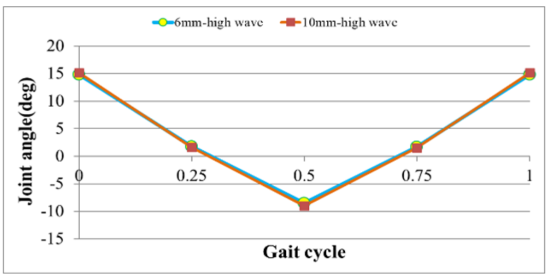


Figure 13. Robot walking behavior on rough road.



(a)



(b)

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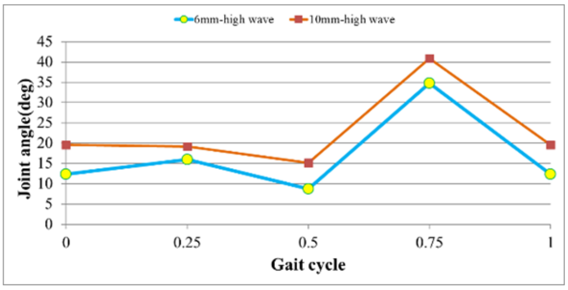

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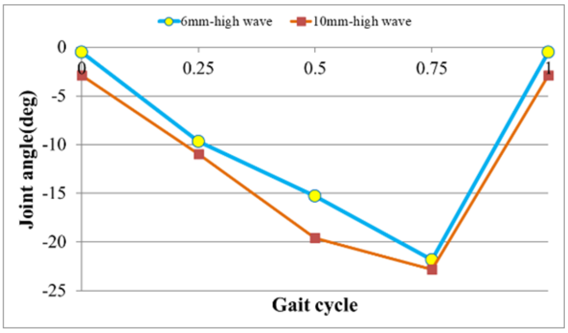

(d)

Figure 14. Waveform of the gait function for walking on rough ground: (a) Hip and ankle roll joint angle; (b) Hip pitch joint angle; (c) Knee pitch joint angle; and (d) Ankle pitch joint angle.

VII. Conclusion

This paper is to study on walking behavior of the small biped robot on rough road considering a topology-based foot structure. This structure is a combination of the optimal results when solving four topology problems in which the impact forces is considered in different situations. The optimal design helps reduce the weight of the robot by removing the unnecessary areas of the foot during walking. In addition, this paper also applies the arm swing mechanism to enable the robot to walk naturally and steadily. A gait control data is generated by solving the optimization problem with constraints. ISADE algorithm is applied to find out design variables, the objective and constraint function are approximated by RSM. The result is validated through dynamic simulation in Adams environment. We confirmed that with the optimal foot structure, our robot walks stably and steadily on the 6mm-high wave ground. However, this research still has a limitation when considering locomotion of the robot on 10mm-high wave ground and needs to be improved in the future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Van-Tinh Nguyen designed the methodology, simulated the robot in Adams environment. Hiroshi Hasegawa evaluated and commented on the methodology. Ngoc-Tam Bui reviewed and edited the manuscript. All authors contributed to the preparation of the manuscript; all authors had approved the final version.

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