Evolutionary Optimized Footstep Planning for Humanoid Robot

Young-Dae Hong, Ye-Hoon Kim and Jong-Hwan Kim

Abstract— **This paper proposes a novel evolutionary optimized footstep planner for humanoid robot. Firstly, a footstep planner using univector field navigation method is proposed to provide a command state (CS) which is to be the input of modifiable walking pattern generator (MWPG) at each footstep. Then the MWPG generates the associated trajectories of every leg joint of humanoid robot at each footstep to follow the inputted CS. Secondly, the step length modification method which makes the humanoid robot step over low obstacles with minimum step length is proposed. Lastly, evolutionary optimization for the univector fields is presented. The univector fields are optimized by evolutionary algorithm (EA) considering objectives in navigation of humanoid robot for efficient navigation. The effectiveness of the proposed evolutionary optimized footstep planner is demonstrated through computer simulations for the simulation model of small-sized humanoid robot, HanSaRam-VIII (HSR-VIII).**

I. INTRODUCTION

These days research on humanoid robot has made rapid progress for dexterous motions with hardware development. Various humanoid robots have demonstrated stable walking with control schemes [1]–[3]. Considering future of humanoid robot, research on navigation of humanoid robot in the environment with obstacles is now needed. In particular, footstep planning is one of key research issues in navigation.

As research on footstep planning, the algorithm which planned a sequence of footsteps by obtaining information such as shapes and locations of obstacles by using sensors was introduced [4]. Based on the obtained information, the humanoid robot determined its step length which was predefined as one of three type step lengths and its motions such as circumventing, stepping over and stepping on obstacles. However, this algorithm might lead to local loop or deadlock because it considered only local environment. Also, there was an algorithm which used A* to compute footstep sequences [5]. It predetermined stable region of robot's footprints, and then a few of foot positions were selected as a discrete set. It checked collision between the robot and obstacles by 2D polygon-polygon intersection test. By extending it, there was approach which selected foot positions autonomously using the concept of an intelligent joystick which was a simple high-level interface to control the humanoid robot [6]. Also, footstep planning using human-like strategy to select the ways for passing an obstacle such as circumventing it from right or left and stepping over it was proposed [7]. However, these researches had to precalculate the discrete set of feasible footstep positions and the associated trajectories of every leg joint for footstep transition. Also, they did not consider the objectives in navigation of humanoid robot.

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Recently, evolutionary techniques have been applied to optimize various issues of humanoid robot. Genetic programming (GP) was applied to the neural oscillator for human-like biped locomotion [8] and generation of gait trajectory for the humanoid robot based on genetic algorithm (GA) was proposed [9]. Also, evolutionary gait generators of which structure and parameters were optimized by GA were proposed [10], [11].

This paper proposes a novel evolutionary optimized footstep planner for humanoid robot. Firstly, the footstep planner using univector field navigation method [12] is proposed to provide a command state (CS) which is to be the input of modifiable walking pattern generator (MWPG) [13] at each footstep. The univector field navigation method is one of the navigation methods for mobile robot and the MWPG generates the associated trajectories of every leg joint at each footstep to follow the CS determined by the univector field navigation method. Secondly, the step length modification method to step over low obstacles with minimum step length is proposed. Lastly, evolutionary optimization for the univector fields is presented. For efficient navigation he univector fields are optimized by evolutionary algorithm (EA) considering objectives in navigation of humanoid robot such as elapsed time, safety and energy consumption including the mechanical constraint of real humanoid robot such as allowable yawing range of feet. The effectiveness of the proposed evolutionary optimized footstep planner is demonstrated through computer simulations for the simulation model of small-sized humanoid robot, HanSaRam-VIII (HSR-VIII) which is developed at the Robot Intelligence Technology (RIT) laboratory, KAIST.

This paper organized as follows. In Section II, the proposed footstep planner is presented including reviews of MWPG and univector field navigation method. Also, concept and procedure of step length modification method for stepping over low obstacles are explained. In Section III, evolutionary optimization for univector fields is investigated. Section IV presents simulation results and finally conclusions follow in Section V.

II. FOOTSTEP PLANNING FOR HUMANOID ROBOT

This section presents the proposed footstep planner for the humanoid robot which is based on the MWPG [13] and the univector field navigation method [12]. The MWPG and the univector field navigation method are briefly summarized in the following. Also, while the humanoid robot moves towards a destination, it can step over low obstacles. In order to solve this situation effectively, the method which modify the step length to step over low obstacles with the minimum step length is proposed.

A. Modifiable Walking Pattern Generator (MWPG)

In the conventional 3-D linear inverted pendulum mode (3D-LIPM) method, only the homogeneous solutions of the 3D-LIPM dynamic equation were used as the zero moment point (ZMP) variation was not considered [14]. The MWPG extended it by allowing the ZMP variation while in the single support phase such that the particular solutions were also employed and more extensive and unrestricted walking patterns could be generated [13]. The homogeneous and particular solutions of the 3D-LIPM dynamic equation are as follows:
Sagittal motion:

$$\begin{bmatrix} x_f \\ v_f T_c \end{bmatrix} = \begin{bmatrix} C(T) & S(T) \\ S(T) & C(T) \end{bmatrix} \begin{bmatrix} x_i \\ v_i T_c \end{bmatrix} - \frac{1}{T_c} \begin{bmatrix} \int_0^T S(t)\bar{p}(t)dt \\ \int_0^T C(t)\bar{p}(t)dt \end{bmatrix} \tag{1}$$

Lateral motion:

$$\begin{bmatrix} y_f \\ w_f T_c \end{bmatrix} = \begin{bmatrix} C(T) & S(T) \\ S(T) & C(T) \end{bmatrix} \begin{bmatrix} y_i \\ w_i T_c \end{bmatrix} - \frac{1}{T_c} \begin{bmatrix} \int_0^T S(t)\bar{q}(t)dt \\ \int_0^T C(t)\bar{q}(t)dt \end{bmatrix} \tag{2}$$

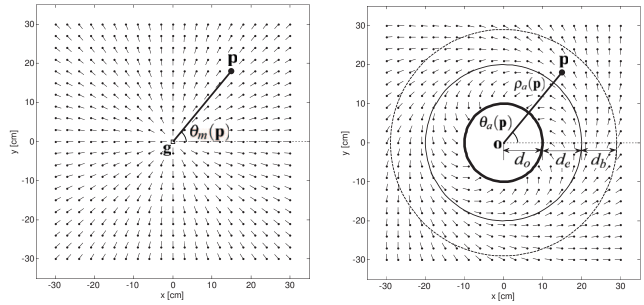
where $(x_i,\ v_i)/(x_f,\ v_f)$ and $(y_i,\ w_i)/(y_f,\ w_f)$ represent the initial/final position and velocity of center of mass (CM) in the sagittal and lateral planes, respectively. $S(t)$ and $C(t)$ are defined as $\sinh(t/T_c)$ and $\cosh(t/T_c)$ with time constant $T_c = \sqrt{Z_c/g}$, respectively. The functions $p(t)$ and $q(t)$ are ZMP trajectories for the sagittal and lateral planes, respectively. $\bar{p}(t) = p(T-t)$ and $\bar{q}(t) = q(T-t)$.

Subsequently, it is possible to change the CM position and velocity independently throughout the single support phase by setting $p(t)$ and $q(t)$. It means that the MWPG enables the humanoid robot to change both sagittal and lateral step lengths, the period of the walking pattern and directions of feet. As the inputs of MWPG, command state (CS) is defined as follows:

***Definition** 1:* Command State (CS)
$c \equiv [F_l \quad F_r \quad S_l \quad S_r \quad T_{sl} \quad T_{sr} \quad T_{dl} \quad T_{dr} \quad \theta_l \quad \theta_r]^T$
where
$F_{l/r}$: sagittal step length of left/right leg from supporting leg,
$S_{l/r}$: lateral step length of left/right leg from supporting leg,
$T_{sl/r}$: single support time,
$T_{dl/r}$: double support time,
$\theta_{l/r}$: direction of left/right foot.
Thus, based on the CS, the CM trajectories is derived from (1) and (2), and then trajectories of every joint of humanoid robot are calculated by inverse kinematics for the CS.

B. Univector Field Navigation Method

As the navigation method for mobile robot, potential field method has been studied, which is able to control the robot in real time because it is very simple [15]–[17]. However, the robot is tend to navigate with oscillations if an obstacle is big. Also, this method employed an attractive force from the desired position and a repulsive force from the obstacle may result in inefficient trajectories. Accordingly, the univector field navigation method was designed for mobile robot to enhance performances [12]. Using this method, the robot can navigate rapidly to the desired position without oscillation and unintended inefficient motions. In this paper, the univector field navigation method is adopted for humanoid robot.



(a) (b)

Fig. 1. Univector field. (a) Move-to-goal univector field. (b) Avoid-obstacle univector field.

The univector field navigation method employs move-to-goal univector field (MUF) and avoid-obstacle univector field (AUF). The former is to lead a robot move to a goal and the latter is for obstacle avoidance. MUF at position $\mathbf{p}$ is generated by the attractive univector field as shown in Fig. 1(a) and defined as follows:

$$\mathbf{u}_{muf}(\mathbf{p}) = [-\cos\theta_m(\mathbf{p}) \ \ -\sin\theta_m(\mathbf{p})]^T \tag{3}$$

where $\theta_m(\mathbf{p})$ is the angle from x-axis of a destination $\mathbf{g}$ to the robot position $\mathbf{p}$. In the figure, the dots and the lines mean the positions of robots and their move-to-goal univectors, respectively. AUF is designed by the hyperbolic spiral univector field $\phi_h(\mathbf{p})$ at position $\mathbf{p}$ (Fig. 1(b)), which is defined as

$$\mathbf{u}_{auf}(\mathbf{p}) = \begin{cases} [\cos\phi_h(\mathbf{p}) \ \ \sin\phi_h(\mathbf{p})]^T & \text{if } d_o < \rho_a(\mathbf{p}) \le d_o \\ & +d_e + d_b \text{ and the} \\ & \text{robot dose not pass} \\ & \text{by an obstacle} \\ [0 \ 0]^T & \text{otherwise} \end{cases} \tag{4}$$

with

$$\phi_h(\mathbf{p}) = \begin{cases} \theta_a(\mathbf{p}) \pm \frac{\pi}{2}(2 - \frac{d_o+d_e+K_r}{\rho_a(\mathbf{p})+K_r}) & \text{if } d_o + d_e \le \rho_a(\mathbf{p}) \\ \theta_a(\mathbf{p}) \pm \frac{\pi}{2}\sqrt{\frac{\rho_a(\mathbf{p})-d_o}{d_e}} & \text{if } d_o \le \rho_a(\mathbf{p}) < d_o + d_e \end{cases}$$

where $\rho_a(\mathbf{p})$ is the distance between position $\mathbf{p}$ and a center of obstacle $\mathbf{o}$. In the figure, d_o is the radius of an obstacle denoted by thick circle, d_e is the predefined radius which decides the size of spiral denoted by thin circle and d_b is the size of the boundary of AUF denoted by dotted circle. AUF is generated when position $\mathbf{p}$ is within the boundary of AUF. Also, if the robot passes by the obstacle already,

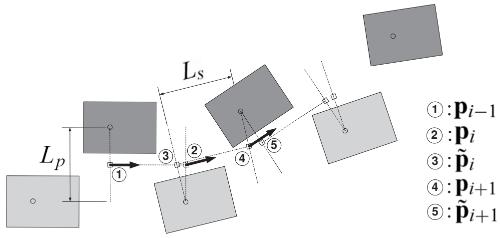


Fig. 2. Procedure of footstep planning.

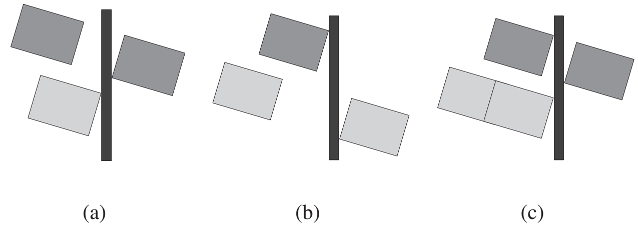


Fig. 3. Concept of step length modification method.

AUF of the obstacle does not influence the navigation of the robot. $\theta_a(\mathbf{p})$ is the angle from x-axis of a center of obstacle $\mathbf{o}$ to position $\mathbf{p}$ and the signs $\pm$ represent the direction of navigation, where $-$ is when the robot moves clockwise and $+$ counter clockwise. K_r is an adjustable parameter. If K_r becomes larger, the maximal value of curvature derivative decreases and the contour of spiral becomes smoother.

The total univector field which determines the moving direction of the robot at position $\mathbf{p}$ is obtained by adding MUF with AUFs and its normalization, which is defined as

$$\mathbf{u}_{uf}(\mathbf{p}) = \frac{\bar{\mathbf{u}}_{uf}(\mathbf{p})}{\mid \bar{\mathbf{u}}_{uf}(\mathbf{p}) \mid} \quad (5)$$

with

$$\bar{\mathbf{u}}_{uf}(\mathbf{p}) = \mathbf{u}_{muf}(\mathbf{p}) + \sum_{i=1}^{n} \mathbf{u}_{auf_i}(\mathbf{p})$$

where n is the total number of obstacles.

C. Procedure of Footstep Planning

The proposed footstep planner provides a CS which means position and direction of footprint of humanoid robot. Then the MWPG generates the associated trajectories of every leg joint to follow the CS. In Fig. 2, L_s and L_p are the normal sagittal and lateral step lengths of the humanoid robot in footstep planning, respectively. These are predefined as the values within the maximum step lengths caused by hardware limitation. Single/double support times are also predefined and the direction of the foot at every footstep is determined by the univector field navigation method. For footstep planning, the middle point between two feet is defined as a base position as shown in Fig 2, and then the moving direction of the foot is taken as that of this position. The procedure of footstep planning is summarized as follows:

1) The univector $\mathbf{u}_{uf}(\mathbf{p}_i)$ at the base position of i-th footstep $\mathbf{p}_i$, $i = 0, 1, 2, ...$, is calculated by (5) with $\mathbf{p}_0 = (L_s, \frac{L_p}{2})$. Then the direction of the foot $\theta_{l/r}$ of the CS is set as the angle of the calculated $\mathbf{u}_{uf}(\mathbf{p}_i)$.
2) The determined CS is inputted to the MWPG, and then the humanoid robot follows the CS by placing the foot in the direction of $\mathbf{u}_{uf}(\mathbf{p}_i)$ at the position which is on the line perpendicular to the direction of the foot at previous footstep, $\mathbf{u}_{uf}(\mathbf{p}_{i-1})$ and $\frac{L_p}{2}$ distant from the base position $\mathbf{p}_i$.
3) The position $\mathbf{p}_i$ is modified to the position $\tilde{\mathbf{p}}_i$ which is on the line perpendicular to the direction of the foot, $\mathbf{u}_{uf}(\mathbf{p}_i)$ and $\frac{L_p}{2}$ distant from the center of the foot.
4) Using the univector $\mathbf{u}_{uf}(\mathbf{p}_i)$, the base position of the next footstep, $\mathbf{p}_{i+1}$ is calculated as follows:

$$\mathbf{p}_{i+1} = \tilde{\mathbf{p}}_i + L_s \mathbf{u}_{uf}(\mathbf{p}_i). \quad (6)$$

5) The univector $\mathbf{u}_{uf}(\mathbf{p}_{i+1})$ is calculated and the CS is inputted to the MWPG. Also, the humanoid robot follows the CS by placing the foot in the direction of $\mathbf{u}_{uf}(\mathbf{p}_{i+1})$ and the position $\mathbf{p}_{i+1}$ is modified to the position $\tilde{\mathbf{p}}_{i+1}$.
6) 1)$\sim$5) steps are repeated until the humanoid robot arrives at a destination.

In summary, if the sequence of footsteps to arrive at a destination is planned by the proposed footstep planner, the humanoid robot follows the planned sequence of footsteps by the MWPG. After all, the proposed footstep planner plans the sequence of footsteps without precalculating the discrete set of feasible footstep positions and the associated trajectories of every leg joint for footstep transition.

D. Step Length Modification Method for Stepping over Obstacle

1) Concept: While the humanoid robot moves towards a destination, it can step over low obstacles. This is the main difference from the path planning for mobile robot which tries to find a detour route to circumvent the obstacle instead of stepping over it. In this section, the concept of step length modification method for stepping over low obstacles is described.

The forward and backward step lengths from a supporting leg of humanoid robot are restricted due to hardware limitation. If the obstacle is wider in width than the maximum step length of humanoid robot, it is not able to step over the obstacle. Thus the humanoid robot has to step over the obstacle with the shortest possible step length in order to step over the widest possible obstacle. The step length is determined by which leg is a supporting leg when it steps over the obstacle. Fig. 3(a) is the situation when the right foot comes close to the obstacle earlier than the left foot. In this case, the robot can step over the obstacle with the minimum step length by setting the right leg as a supporting leg. On the other hand, the step length of the right leg is not minimum in Fig. 3(b) when the left foot approaches the obstacle closely

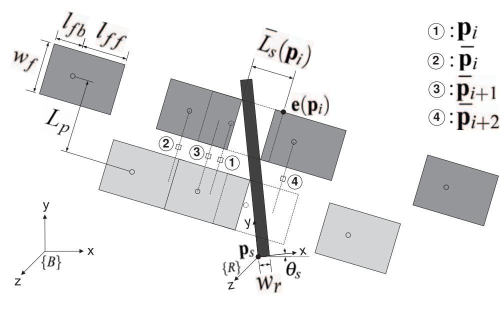


Fig. 4. Procedure of step length modification method.

than the other one and the left leg is a supporting leg. In order to step over the obstacle with the minimum step length in this case, the right leg and the left leg have to be a supporting leg and a swing leg, respectively. Thus one more step is needed before stepping over the obstacle as shown in Fig. 3(c). The right leg is appropriate as a supporting leg when the robot steps over the obstacle diagonally to its right side as shown in Fig. 3(c). If the robot steps over the obstacle diagonally to its left side, the left leg is appropriate as a supporting leg for the minimum step length.

2) Procedure: In this section, the procedure of the step length modification method is illustrated by the situation of the Fig. 4. In the proposed footstep planner, if the height of the obstacle is lower than the maximum height of the swing leg of humanoid robot, the obstacle does not generate AUF. Thus the robot does not avoid the obstacle. The shape of feet is assumed as rectangular. The procedure is as follows:

1) The left foot overlaps the obstacle at the position $\mathbf{p}_i$.
2) The position $\mathbf{p}_i$ is modified to the position $\bar{\mathbf{p}}_i$ at which the left foot is in front of the obstacle and does not overlap the obstacle using the foot's edge position $\mathbf{e}(\mathbf{p}_i)$, which is calculated as

$$\mathbf{e}(\mathbf{p}_i) = \mathbf{p}_i + \begin{bmatrix} \cos \mid \theta_u(\mathbf{p}_i) \mid & \sin \mid \theta_u(\mathbf{p}_i) \mid \\ \sin \mid \theta_u(\mathbf{p}_i) \mid & \cos \mid \theta_u(\mathbf{p}_i) \mid \end{bmatrix} \begin{bmatrix} l_{ff} \\ \frac{L_p + w_f}{2} \end{bmatrix} \tag{7}$$

where $\theta_u(\mathbf{p}_i)$ is the angle of the univector $\mathbf{u}_{uf}(\mathbf{p}_i)$. l_{ff} and w_f represent foot front length and foot width, respectively as shown in Fig 4. In order to modify the position $\mathbf{p}_i$, $\mathbf{p}_i$ and $\mathbf{e}(\mathbf{p}_i)$ are changed to the positions in the coordinate frame $\{R\}$, which is rotated about $\hat{z}$ by the obstacle rotation angle θ_s and translated by the obstacle position vector $\mathbf{p}_s$ relative to the base coordinate frame $\{B\}$. The changed positions ${}^R\mathbf{p}_i$ and ${}^R\mathbf{e}(\mathbf{p}_i)$ are given as

$$\begin{bmatrix} {}^R\mathbf{p}_i \\ 1 \end{bmatrix} = {}^R_B T \begin{bmatrix} \mathbf{p}_i \\ 1 \end{bmatrix}, \quad \begin{bmatrix} {}^R\mathbf{e}(\mathbf{p}_i) \\ 1 \end{bmatrix} = {}^R_B T \begin{bmatrix} \mathbf{e}(\mathbf{p}_i) \\ 1 \end{bmatrix} \tag{8}$$

with

$${}^R_B T = {}^R_B R \begin{bmatrix} \mathbf{I} & -\mathbf{p}_s \\ 0\ 0 & 1 \end{bmatrix},$$

$${}^R_B R = \begin{bmatrix} \cos\theta_s & \sin\theta_s & 0 \\ -\sin\theta_s & \cos\theta_s & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Thus, the modified position in the coordinate frame $\{R\}$, ${}^R\bar{\mathbf{p}}_i$ is calculated as

$${}^R\bar{\mathbf{p}}_i = {}^R\mathbf{p}_i + \begin{bmatrix} -1 & \tan(\mid \theta_s - \theta_u \mid) \end{bmatrix} {}^R\mathbf{e}(\mathbf{p}_i). \tag{9}$$

Eventually, the modified position in the base coordinate frame $\{B\}$, $\bar{\mathbf{p}}_i$ can be written as

$$\begin{bmatrix} \bar{\mathbf{p}}_i \\ 1 \end{bmatrix} = {}^R_B R^T \begin{bmatrix} \mathbf{I} & \mathbf{p}_s \\ 0\ 0 & 1 \end{bmatrix} \begin{bmatrix} {}^R\bar{\mathbf{p}}_i \\ 1 \end{bmatrix}. \tag{10}$$

3) The step length of the robot is modified to $\bar{L}_s(\mathbf{p}_i)$, which is calculated as

$$\bar{L}_s(\mathbf{p}_i) = L_s - \parallel {}^R\bar{\mathbf{p}}_i - {}^R\mathbf{p}_i \parallel . \tag{11}$$

4) The right foot overlaps the obstacle, and then the position and the step length of the right leg are modified to the position $\bar{\mathbf{p}}_{i+1} = [\bar{x}_{i+1}\ \bar{y}_{i+1}]^T$ and $\bar{L}_s(\mathbf{p}_{i+1})$ in a similar manner to the case of the left leg, respectively.
5) The position ${}^R\bar{\mathbf{p}}_{i+2} = [{}^R\bar{x}_{i+2}\ {}^R\bar{y}_{i+2}]^T$ at which the left foot is in the rear of the obstacle in the coordinate frame $\{R\}$ is obtained to step over the obstacle as follows:

$$\begin{aligned} {}^R\bar{x}_{i+2} &= w_r + l_{fb}\cos \mid \theta_s - \theta_u \mid \\ &\quad - (\tfrac{L_p - w_f}{2}) \sin \mid \theta_s - \theta_u \mid, \\ {}^R\bar{y}_{i+2} &= {}^R\bar{y}_{i+1} - ({}^R\bar{x}_{i+2} - {}^R\bar{x}_{i+1}) \tan \mid \theta_s - \theta_u \mid \end{aligned} \tag{12}$$

where w_r and l_{fb} are the obstacle width and the foot back length, respectively. Subsequently, $\bar{\mathbf{p}}_{i+2}$ can be written as

$$\begin{bmatrix} \bar{\mathbf{p}}_{i+2} \\ 1 \end{bmatrix} = {}^R_B R^T \begin{bmatrix} \mathbf{I} & \mathbf{p}_s \\ 0\ 0 & 1 \end{bmatrix} \begin{bmatrix} {}^R\bar{\mathbf{p}}_{i+2} \\ 1 \end{bmatrix}. \tag{13}$$

6) The step length of the left leg for traversing over the obstacle, $\bar{L}_s(\mathbf{p}_{i+2})$ is calculated as

$$\bar{L}_s(\mathbf{p}_{i+2}) = \frac{{}^R\bar{x}_{i+2} - {}^R\bar{x}_{i+1}}{\cos \mid \theta_s - \theta_u \mid}. \tag{14}$$

III. Evolutionary Optimization for Univector Fields

This section presents evolutionary optimization for univector fields. In the navigation of the humanoid robot, The key objectives are the shortest elapsed time to get to a destination, safety without obstacle collision and less energy consumption. For the first objective, the total number of footsteps during the navigation should be minimized. For the second, the distance between the robot and obstacles should be kept maximized to avoid the obstacle collision while walking. The moving direction difference of the robot at every footstep should not exceed the allowable yawing range such that the total amount of yawing angles should be minimized to meet the last one. To satisfy these objectives, evolutionary optimization approach is introduced to obtain nondominated solutions of the univector fields.

In this paper, the parameters d_e, d_b, K_r and the signs $\pm$ in AUF of each obstacle are optimized by EA based on the environment information such as the position and velocity of obstacles and the position of a destination. In general, EAs which are a repeated process of reproduction, evaluation and selection were proposed as an optimization method [19]. A population of each generation is improved and only superior individuals are survived. The evaluation function is defined as

$$f = k_s n + f_c(\mathbf{p}_i) + f_a(\mathbf{p}_i) \tag{15}$$

where k_s is the scaling factor for the total number of footsteps n. The first term in the evaluation function makes the robot arrive at a target point with the minimum number of footsteps.

The second term $f_c(\mathbf{p}_i)$ for safety without obstacle collision, is defined by assuming the cylindrical body shape, as follow:

$$f_c(\mathbf{p}_i) = \frac{k_{c1} - \sum_{i=0}^{n} \Delta d(\mathbf{p}_i)}{k_{c2}} \tag{16}$$

with

$$\Delta d(\mathbf{p}_i) = \begin{cases} C_p & \text{if the robot collides with an obstacle} \\ \rho_a(\mathbf{p}_i) - (d_r + d_o) & \text{otherwise} \end{cases}$$

where k_{c1} and k_{c2} are the scaling factors and d_r is the radius of the robot's body, $d_r + d_o$ is the distance from the center of the robot to the center of an obstacle and $\Delta d(\mathbf{p}_i)$ is the difference between $d_r + d_o$ and the distance from the position $\mathbf{p}_i$ to the obstacle position $\rho_a(\mathbf{p}_i)$. If a robot collides with an obstacle, the penalty value, C_p is given to $\Delta d(\mathbf{p}_i)$.

The last term for the minimum energy consumption, the following evaluation function is defined:

$$f_a(\mathbf{p}_i) = k_a \sum_{i=1}^{n} \Delta\theta_u(\mathbf{p}_i) \tag{17}$$

with

$$\Delta\theta_u(\mathbf{p}_i) = \begin{cases} A_p & \text{if the robot exceeds allowable yawing range} \\ |\ \theta_u(\mathbf{p}_i) - \theta_u(\mathbf{p}_{i-1})\ | & \text{otherwise} \end{cases}$$

where k_a is the scaling factor and $\Delta\theta_u(\mathbf{p}_i)$ is the difference of the moving direction of the humanoid robot between the position $\mathbf{p}_i$ and the position at previous footstep $\mathbf{p}_{i-1}$. If it exceeds the allowable yawing range, a penalty value, A_p is assigned.

IV. SIMULATIONS

To verify the performance of the proposed evolutionary footstep planner, computer simulation was carried out. Firstly, the univector fields were optimized by the EA in the environment with a variety of obstacles. Secondly, using the optimized univector fields, the sequence of footsteps was planned. Finally, walking simulation for the simulation model of small-sized humanoid robot, HanSaRam-VIII (HSR-VIII) was carried out.

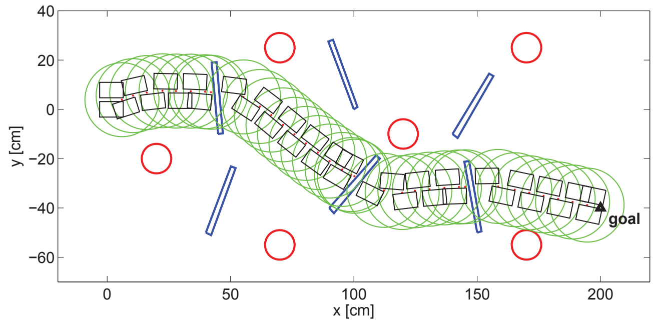


Fig. 5. Sequences of planned footsteps.

A. Univector Field Optimization by Evolutionary Algorithm (EA)

The univector fields were optimized in the environment with six high circular obstacles and six low rectangular obstacles. the radius and height of circular obstacles are 6.0 cm and 30.0 cm, respectively and the width, length and height of rectangular obstacles are 2.0 cm, 30.0 cm and 2.0 cm, respectively. The maximum sagittal step length and the pelvis length of HSR-VIII are 12.0 cm and 7.8 cm, respectively. Thus L_s and L_p were set as 6.0 cm and 7.8 cm, respectively and l_{ff}, l_{fb} and w_f are 6.50 cm, 3.02 cm and 6.25 cm, respectively. The radius of the robot's body including the margin (2.0 cm) was set as 15.0 cm and the allowable yawing ranges are from $-20.0°$ to $35.0°$ for a left leg and from $-35.0°$ to $20.\circ$ for a right leg. There are four parameters for each circular obstacle and no parameter for rectangular obstacle since it does not generate AUF. Thus total twenty four parameters had to be optimized. For EA, Gaussian mutation which is commonly used in EAs was used [20]. The selection scheme was rank-based selection and the number of parents and offsprings were set to 10 and 100, respectively was used. The scaling factor k_s, k_{c1}, k_{c2} and k_a were taken as 1, 20000, 200 and 20 respectively. The penalty values C_p and A_p were taken as $-\infty$ cm and $+\infty$ rad, respectively.

B. Footstep Planning Result

This section describes sequences of footsteps planned by the optimized univector fields in Fig. 5. As shown the figure, the robot successfully arrived at a destination without obstacle collision in the shortest time. Also, the robot stepped over obstacles with minimum step length by means of adjusting the step length and the supporting leg.

C. Walking Simulation Result

This section presents walking simulation of sequences of footsteps generated by the optimized univector fields. The walking simulation environment was exactly the same as that for the above simulation. Walking simulations were carried out by using the simulation model of HSR-VIII which was modeled by Webot which is the 3D robotics simulation software and enable users conduct the physical and dynamical simulation [18]. HSR-VIII is a small-sized humanoid

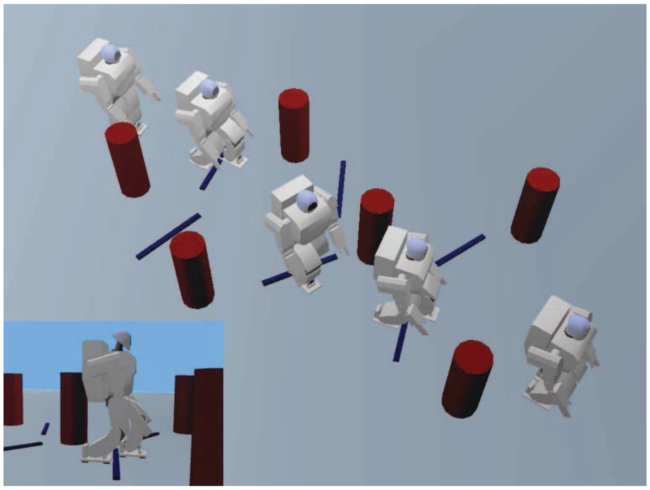


Fig. 6. Walking simulation result.

robot that has been continuously undergoing redesign and development in Robot Intelligence Technology (RIT) Lab, KAIST. Its height and weight are 52.8 cm and 5.5 kg, respectively. It has 26 DOFs which consists of 12 DC motors with harmonic drives for reduction gears in the lower body and 14 RC servo motors in the upper body.

The robot walked on the same footstep sequences as Fig. 5 avoiding and stepping over obstacles as shown in Fig 6.

V. CONCLUSION

In this paper, an evolutionary optimized footstep planner was proposed. The proposed footstep planner provided a CS, which is the input of MWPG and means the position and direction of footprint of humanoid robot, using the univector field navigation method. Then the MWPG enabled the humanoid robot to follow the planned footstep by generating the associated trajectories of every leg joint at each footstep. After all, the proposed footstep planner planed the sequence of footsteps without precalculating the discrete set of feasible footstep positions and the associated trajectories of every leg joint for footstep transition. Also, the step length modification method was proposed to step over low obstacles with minimum step length. Besides, the univector fields were optimized by using EA to arrive at a destination efficiently. In order to demonstrate the performance of the proposed evolutionary optimized footstep planner, computer simulations were carried out by the small-sized humanoid robot, HSR-VIII.

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