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Efficient Locomotion Planning for a Humanoid Robot with Whole-Body Collision Avoidance Guided by Footsteps and Centroidal Sway Motion

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***Abstract*—In this paper, we propose a locomotion planning framework for a humanoid robot with an efficient footstep and whole-body collision avoidance planning, which enables the robot to traverse an unknown narrow space while utilizing its body structure like a human. The key idea of the proposed method is to reduce a large computational cost for the whole-body locomotion planning by executing global footstep planning first, which has a much smaller search space, and then performing a sequential whole-body posture planning while utilizing the resulting footsteps and a centroidal trajectory as a guide. In the global footstep planning phase, we modify bounding box of the robot based on the centroidal sway motion. This idea enables the planner to obtain appropriate footsteps for next whole-body motion planning. Then, we execute sequential whole-body collision avoidance motion planning by prioritized inverse kinematics based on the resulting footsteps and centroidal trajectory, which enables the robot to plan whole-body collision avoidance motion for each step within less than 100ms at worst. The major contribution of our paper is solving the problem of the increasing computational cost for whole-body motion planning and enabling a humanoid robot to execute adaptive locomotion planning on the spot in an unknown narrow space.**

I. Introduction

Recent research on humanoid robots aims at taking over tasks with a big burden on human workers while walking freely in a working space like a construction site. Since a humanoid robot has a body structure similar to human beings, it is especially expected to move around a narrow space utilizing the degree of freedom of its body. In order to achieve practical tasks in a narrow working space where the arrangement of obstacles is not pre-known, like a construction site or a disaster response scenario, a humanoid robot is required to measure the environment and execute locomotion planning with whole-body collision avoidance online. In the previous research on whole-body locomotion planning, methods which globally explore a sequence of collision-free postures are mainstream. However, such methods take a lot of time because of the large degree of freedom of its body structure and it is difficult for them to plan adaptive whole-body locomotion.

In this paper, we propose an efficient locomotion planning framework for a humanoid robot to move around an unknown narrow space adaptively. The key idea of the proposed method is reducing a large computational cost for a whole-body locomotion planning by executing global footstep planning first, and then performing a sequential whole-body posture planning while utilizing resulting footsteps and a centroidal trajectory as a guide. We successfully perform locomotion planning with whole-body collision avoidance within the transition time in a humanoid robot walking. Moreover, we verified the practicality of the proposed method by some simulation experiment as shown in Fig.1.

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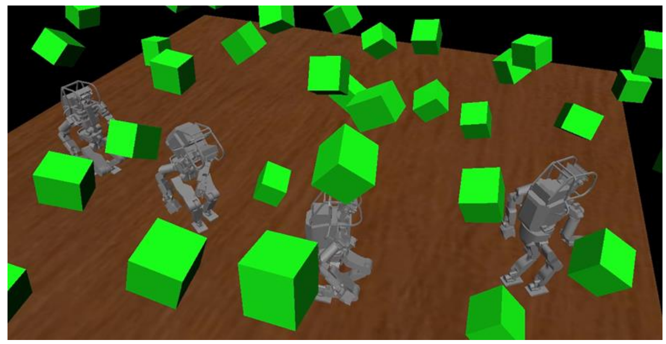

Fig. 1. An example of whole-body locomotion for a humanoid robot in a complex environment

II. Related Works and Concepts

A. Whole-body locomotion planning for a humanoid robot

Since a humanoid robot has a distinctive form of walking, the previous research on locomotion planning for a humanoid robot mainly focused on the footstep planning. The footstep planning methods can easily formulate the locomotion planning problem for a humanoid robot, having a large degree of freedom, as the exploring of sequence of foot positions and orientations, which has a 6 degree of freedom. Many efficient solutions for the footstep planning problem has been proposed, such as A* search with discretized footstep successors [1], RRT [2] and MIQCQP [3]. These footstep planning methods were integrated with environmental measurement methods and enabled humanoid robots to traverse complex terrains [4], [5].

However, the whole-body locomotion planning considering collision avoidance and dynamics for walking is necessary for a humanoid robot to traverse freely in an unknown narrow space like a construction site. As a whole-body locomotion planning strategy, there is a method which uses previously defining action primitives. Kanehiro et al. [6] proposed a whole-body locomotion framework for a humanoid robot to traverse a narrow space, which selects an appropriate one from the pre-defined motion primitives based on the size of the passable area obtained by environmental measurements. Many posture exploring strategies based on random sampling have been proposed as global whole-body motion planning methods. Harada et al. [7] achieved for a humanoid robot to walk through a gate by generating walking pattern first and searching for the collision avoidance attitude by SBL only for the part where collision with the environment was assumed to occur. Recently, some motion planning methods based on optimization with kinematics and dynamics constraints have been proposed, which can generate whole-body motion sequence considering collision avoidance and environmental contact. Dai et al. [8] generate collision avoidance motion like passing through a gate and environmental contact motion like climbing monkey bars by formulating a whole-body motion planning for a humanoid robot as a nonlinear trajectory optimization problem. Although these whole-body motion planning methods are expected to greatly expand the range of work for a humanoid robot, there is a problem that the large degree of freedom of its body structure expands the search space for the motion planning exponentially.

B. Problems of whole-body locomotion planning

In order to perform adaptive locomotion planning based on environmental measurements online, it is one of the major challenges to suppress computational costs for a whole-body motion planning, which increases with the degrees of freedom. In the previous works, computational costs of a whole-body motion planning were reduced by limiting the search space by some reasonable assumptions. Shimizu et al. [9] reduced the computational time in a complex environment by estimating a passable area in the walking trajectory from a variable size bounding box and by planning collision avoidance postures based on RRT only in narrow spaces. Grey et al. [10] proposed Randomized Possibility Graph, which represents the possible path of the robot considering necessary and sufficient conditions for locomotion. They achieved to plan whole-body postures for locomotion in a semi-unstructured environment reducing large number of computational time using it as a guide for Random-MMP. However, whole-body motion planning still requires a large computational costs and it is challenging to make adaptive whole-body locomotion postures on the spot. Hildebrandt et al. [11] achieved vision-based navigation of a humanoid robot in an unknown environment by combining a 2D mobile platform path planner and A*-based footstep planner. Although their method mainly focused on 2D footstep planning, their idea of utilizing a low dimensional pre-planning result as a guide for a detailed planner succeeded to reduce a large amount of computational effort and enabled a robot to execute feasible steps in real-time.

Moreover, another challenge in locomotion planning for a humanoid robot is to integrate generated whole-body motion and walking control considering dynamics. Nishi et al. [12] proposed a whole-body locomotion posture planning strategy based on RRT and post-processing techniques, which solved

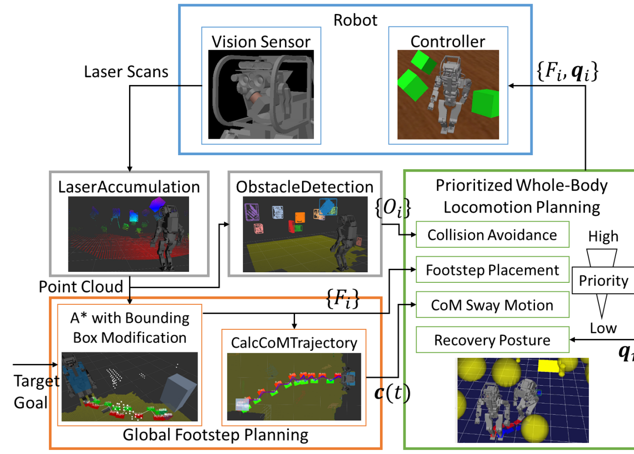

Fig. 2. The overview of the proposed locomotion framework with whole-body obstacle avoidance for a humanoid robot

the problem of the jaggy and detouring trajectory by NURBS interpolation and re-timing for dynamical constraints. Dalibard et al. [13] proposed a method for planning collision-free whole-body walking motions for a humanoid robot, which generated collision-free postures by randomized algorithm first and then transformed them into dynamically balanced trajectories by modifying a step length and frequency based on the small-space controllability theory. In general, these integration strategies for whole-body motions and a walking controller apply smoothing or interpolation process to the generated whole-body motions considering dynamics, which increase the computational costs of the locomotion planning.

C. Efficient whole-body locomotion planning guided by footsteps and centroidal motion

Based on the above discussion, we propose an efficient locomotion planning framework for a humanoid robot with whole-body collision avoidance. The overview of the proposed framework is shown in Fig.2. At first, we execute the global footstep planning, which has much smaller search space and thus requires much less computational cost than the whole-body motion planning. In this phase, we consider centroidal sway motion and modify bounding box of the robot based on its maximum amplitude. This enables the planner to exclude footstep candidates which may cause collision with the environment during walking and obtain appropriate footsteps for the next whole-body motion planning. Then, we execute sequential whole-body collision avoidance motion planning by prioritized quadratic programming utilizing the resulting footsteps and centroidal trajectory as the guide. This motion planning requires much less computational cost than global whole-body motion planning, and enables a humanoid robot to execute adaptive locomotion planning on the spot in an unknown narrow space. The major contribution of our paper is solving the problem of the increasing computational cost due to the degree of freedom of a humanoid robot and a smoothing or interpolation process for dynamic walking, by planning global footstep placement and centroidal trajectory first and using them as a guide for sequential whole-body collision avoidance planning.

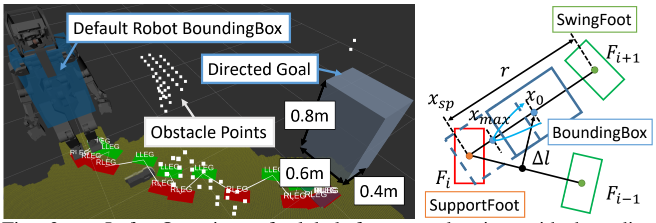

Fig. 3. Left: Overview of global footstep planning with bounding box collision check, Right: Bounding box modification strategy based on approximate sway amplitude

III. Global Footstep Planning

A. Global A* footstep planning with collision avoidance

In this paper, we execute global footstep planning by perception based locomotion system [14], which integrates A* based footstep planning algorithm [15] and environmental measurements from laser scans. For global footstep planning, a method of approximating the robot to a bounding box and checking collision with the environmental model is common [16]. However, there is a problem of how to define the size of robot's bounding box. A possible strategy is to define the robot's bounding box which can approximate its entire body with a certain margin [3], [16], but this makes planning footsteps for passing through a complicated narrow space difficult, where a robot is required to perform whole-body collision avoidance. Another effective strategy is defining bounding boxes of different sizes and planning collision free path using them properly according to the passable regions [9], [10]. However, using the partial bounding box of a robot in a narrow space increases the possibility of collision with the environment due to centroidal sway motion during walking. In general, some strategies for suppressing sway motion [13], or making a stride small [17] are effective for collision avoidance in a narrow space.

In this paper, we define a default bounding box for the trunk and thigh links, as shown on the left of Fig.3. Then, we introduce a new strategy to modify the size of the bounding box based on a sway motion. This method enables the planner to estimate collision with the environment and obtain appropriate footsteps for the next sequential whole-body collision avoidance planning.

B. Bounding box modification based on sway motion

An overview of the proposed bounding box modification strategy is shown on the right of Fig.3. In the footstep planning process based on A*, we need a collision avoidance strategy which can estimate collisions during walking without prospective footsteps, which have not planned yet. Therefore, we assume a scenario where the center of gravity modeled by a linear inverted pendulum oscillates on a straight line connecting the centers of the candidate support foot F_i and swing foot F_{i+1}. In the following descriptions, we define the center of the swing leg on this straight line as the origin, the center of the support leg as $x_{sp} = r$ and the initial position of the linear inverted pendulum as the center of the both footsteps $x_0 = \frac{r}{2}$.

We assume that a robot walks at a constant velocity v_c and define transition time of the swing foot as (1) using the travel distance of the center of the both foot Δl.

$$T = \frac{\Delta l}{v_c} \tag{1}$$

We also define the lower limit of transition time T_{min} considering a walking performance of a robot. This means that the target speed is reduced when the stride Δl is small. In this paper, we use $v_c = 0.2$m/s and $T_{min} = 0.8$s. The time constant of the oscillation can be described as $T_c = \sqrt{\frac{z_c}{g}}$ using the height of CoM z_c and gravitational acceleration g. Based on the dynamics of a linear inverted pendulum [18], the position $x(t)$ and velocity $\dot{x}(t)$ of the centroid at a time t can be described as (2) with $C(t) = \cosh(\frac{t}{T_c})$ and $S(t) = \sinh(\frac{t}{T_c})$.

$$\begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix} = \begin{bmatrix} C(t) & T_c S(t) \\ T_c^{-1} S(t) & C(t) \end{bmatrix} \begin{bmatrix} x_0 \\ v_0 \end{bmatrix} + \begin{bmatrix} 1 - C(t) \\ -T_c^{-1} S(t) \end{bmatrix} x_{sp} \tag{2}$$

Assuming that the centroid goes towards x_{sp} and back to x_0 in the transition time T, the time t_m when the the sway motion reaches its peak x_{max} can be estimated as $t_m = \frac{T}{2}$. We can also calculate the initial velocity of the centroid $v_0 = \dot{x}(0) = -\dot{x}(T)$ as (3) by solving (2) for the velocity at the time $t = T$.

$$v_0 = \frac{(x_{sp} - x_0)S(T)}{T_c\{1 + C(T)\}} \tag{3}$$

Finally, we can obtain the amplitude of the sway motion as (4), which is the position of the centroid at the time t_m, using (2) and (3).

$$x_{max} = C(t_m)\frac{r}{2} + T_c S(t_m) v_0 + \{1 - C(t_m)\} r \tag{4}$$

We expand the both sides of the bounding box put on the center of candidate footsteps in the direction of the straight line connecting them by $\Delta x = x_{max} - x_0$. This process means that we assume Δx as the approximate amplitude of the sway motion when a robot stands on F_i and F_{i+1}, and exclude candidate footsteps which may cause collision with the environment by the approximated sway motion in the footstep planning process.

IV. Sequential Whole-Body Motion Planning

A. Motion planning by prioritized inverse kinematics

In order to plan whole-body collision avoidance motions based on the resulting footsteps, we introduce prioritized linear quadratic programming formulation [19]. This method solves (5) hierarchically based on the priorities $k \in \{0, 1, \ldots, N\}$ under an equality constraints $A_k \boldsymbol{x} = \boldsymbol{b}_k$ and an inequality constraints $C_k \boldsymbol{x} \leq \boldsymbol{d}_k$ for decision variables $\boldsymbol{x} \in \mathbb{R}^n$ with an initial solution space $S_0 \in \mathbb{R}^n$ and a slack variable ω.

$$S_{k+1} = \underset{x \in S_k}{\operatorname{argmin}} \frac{1}{2}\|A_k \boldsymbol{x} - \boldsymbol{b}_k\|^2 + \frac{1}{2}\|\omega\|^2$$
$$\text{with} \quad C_k \boldsymbol{x} - \omega \leq \boldsymbol{d}_k, \omega \in \mathbb{R}_+^m \tag{5}$$

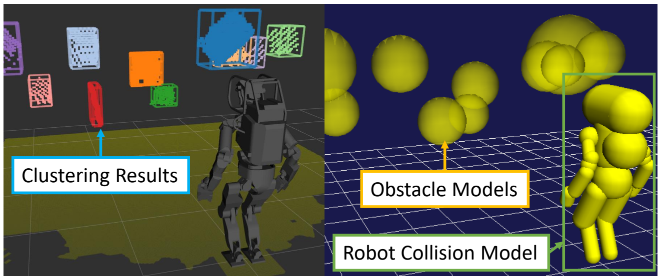

Fig. 4. The example of the obstacle detection in a simulation world; Left: Result of euclidean cluster extraction, Right: Generated collision models

In this paper, we use the joint velocity of a robot $\dot{\boldsymbol{q}}$ as the decision variable and consider constraints for the collision avoidance, foot placement, centroidal trajectory and recovery posture. These constraints are updated each time the supporting leg of the robot changes during walking. We define the priority of the collision avoidance constraint and foot placement constraint as 0, centroidal trajectory constraint as 1 and recovery posture constraint as 2 and solve (5) for $\dot{\boldsymbol{q}}$ with constraints from smaller priority values using QLD algorithm [20]. We also use constraints for joint angle limitation and joint velocity limitation with the priority 0, but do not explain their details. In this paper, we use sampling time $\Delta t = 0.02$s.

B. Collision avoidance constraints

1) Definition of collision models: In the proposed framework, the collision model of the environment is obtained from the environmental measurements as shown in Fig.4. We extract obstacle clusters by Euclidean Cluster Extraction from the environmental point cloud, which is generated by accumulating the laser scans. In order to get continuous joint velocity solution in the collision avoidance constraint, collision models are approximated as a sphere or a capsule shape, in which two spheres are connected by cylinders. We calculate bounding box of the obtained obstacle clusters and approximate them as a capsule shape if one side is longer than the sum of other two sides, otherwise as a sphere shape. The collision model for the links of a robot is also approximated by the pre-defined spheres or a capsule shape.

2) Distance constraints for collision avoidance: We introduce the inequality constraints for collision avoidance proposed by Kanehiro et al. [21]. First, we estimate closest points $\boldsymbol{p}_1^j, \boldsymbol{p}_2^j$ for the target collision pair $(O_1, O_2)_j$ and calculate the shortest distance of them $d_j = \|\boldsymbol{p}_1^j - \boldsymbol{p}_2^j\|$. We consider the distance constraints for this pair when the shortest distance d_j is smaller than the influence distance d_i, which is a pre-defined threshold. The velocity of $\boldsymbol{p}_1$ can be calculated as (6) using the jacobian $J_j(\boldsymbol{q}, \boldsymbol{p}_1)$ for O_1.

$$\dot{\boldsymbol{p}}_1^j = J_j(\boldsymbol{q}, \boldsymbol{p}_1)\dot{\boldsymbol{q}} \tag{6}$$

Then, we can define the collision avoidance constraint as (7), which is an inequality constraint for the closest distance direction $\boldsymbol{n} = \frac{\boldsymbol{p}_1^j - \boldsymbol{p}_2^j}{d_j}$ component of relative velocity of $\boldsymbol{p}_1^j$ from $\boldsymbol{p}_2^j$. We define ξ as a coefficient to define convergence speed and d_s as a security distance, which represents minimum allowable distance of the collision pair. In this paper, we use $d_i = 0.2$, $d_s = 0.01$ and $\xi = 0.0075$.

$$\boldsymbol{n}^T\{J_j(\boldsymbol{q}, \boldsymbol{p}_1^j) - J_j(\boldsymbol{q}, \boldsymbol{p}_2^j)\}\dot{\boldsymbol{q}} \geq -\xi \frac{d_j - d_s}{d_i - d_s} \tag{7}$$

C. Locomotion constraints

Based on the resulting footsteps F_i obtained from Section III, we can define the constraints for a trajectory of a swing foot, support foot and dynamic centroidal trajectory.

1) Foot placement constraints: We define the equality constraints for the support and swing foot placements as (8) and (9) using their jacobian $J_{support}$ and J_{swing}. We use the approximated trajectory of swing foot $F_{sw}(t)$ in order to avoid self-collisions of a robot during walking.

$$J_{support}\dot{\boldsymbol{q}} = \boldsymbol{0} \tag{8}$$

$$J_{swing}\dot{\boldsymbol{q}} = \dot{F}_{sw}(t) \tag{9}$$

2) Centroidal trajectory constraints: We calculate the target ZMP trajectory $\boldsymbol{p}_{zmp}(t)$ by interpolating the center of resulting footsteps linearly. Then, we can obtain the target centroidal trajectory $\boldsymbol{c}(t)$ based on the preview control [22] with an appropriate preview time Δt_p. Therefore, we can define the equality constraint for the centroidal trajectory as (10) using CoG jacobian J_G. In this constraint, we only consider horizontal centroidal trajectory. We defined the preview time $\Delta t_p = 2.0$s in this paper.

$$J_G\dot{\boldsymbol{q}} = \dot{\boldsymbol{c}}(t) \tag{10}$$

D. Recovery posture constraints

We define the equality constraint for a robot to recover the default posture $\boldsymbol{q}_{ref}$ in a collision-free space with the lowest priority. However, it is necessary to suppress the large joint velocity that occurs from trying to recover the default posture as the robot transitions into an obstacle-free region. Then, we define a positive gain for difference of joint angles k_r (< 1.0) and overwrite the target joint angles for recovery motion as (11). In this paper, we defined $k_r = 0.3$.

$$\bar{\boldsymbol{q}}_{ref} = \boldsymbol{q} + k_r(\boldsymbol{q}_{ref} - \boldsymbol{q}) \tag{11}$$

Finally, we define the equality constraint for the recovery motion as (12) using the trajectory of reference joint angles $\bar{\boldsymbol{q}}_{traj}(t)$, which can be obtained by interpolating the target joint angels $\bar{\boldsymbol{q}}_{ref}$ based on Hoffarbib algorithm with the transition time T_i.

$$\dot{\boldsymbol{q}} = \dot{\bar{\boldsymbol{q}}}_{traj}(t) \tag{12}$$

V. Experimental Evaluation

We applied the proposed locomotion planning framework to a humanoid robot in Choreonoid [23] and evaluated its performance and computational time in some complex environments with a dynamics simulation and stabilizing control [24]. The following simulation experiments are executed in a desktop computer with Intel(R) Xeon(R) CPU E5-1680 v4.

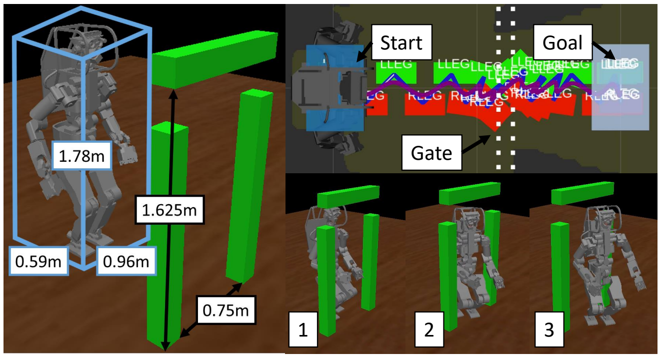

Fig. 5. Whole-body locomotion planning in passing a gate scenario. Left: experimental setup and an entire size of a robot in a default posture (this size is only for information and not used in footstep planning). Upper right: footstep planning result with bounding box modification, Lower right: Resulting whole-body locomotion sequence for passing a gate.

A. Narrow space locomotion planning in passing a gate

We performed a locomotion planning experiment for a humanoid robot to pass through a narrow gate. The experimental setup is shown on the left of Fig.5. The proposed framework successfully planned appropriate footsteps shown on the upper right of Fig.5. and generated whole-body collision avoidance motions as shown on the lower right of Fig.5 utilizing the resulting footsteps as a guide. TABLE I indicates the computational times when the proposed framework performed locomotion planning for the same environment five times. It can be seen that the motion planning time per step was 82ms at worst, which is much smaller than the transition time for a step during walking. Moreover, the total computational time of footstep and motion planning was 5.90s on average, which is about three times as fast as the state-of-art method in a similar situation [10].

TABLE I
EVALUATION OF COMPUTATIONAL TIME IN PASSING GATE SCENARIO

Trial		1	2	3	4	5	Avg
Footstep Plan [s]		4.12	4.33	4.33	4.59	3.96	4.30
Motion Plan [s]		1.51	1.61	1.67	1.57	1.52	1.59
Total Plan [s]		5.63	5.94	6.00	6.16	5.48	5.90
Motion/Step [ms]	Avg	58	56	60	56	59	58
	Max	76	76	82	78	75	77

We also evaluated the success rate of the whole-body locomotion planning in passing a gate scenario. The planned motions were regarded as valid when they satisfied constraints of 0 priority, which were described in Section IV, and the difference between the target and planned ZMP was less than a threshold as a rough indication of the feasibility. In this evaluation, we experimentally defined this threshold as 0.3m. The success rate of the proposed locomotion planner was 26 of 30 trials (86.7%). On the other hands, the success rate was dropped to 18 of 30 trials (60 %) when the bounding box modification strategy was not introduced.

B. Traversing among randomly generated obstacles

We conducted a locomotion experiment for a humanoid robot to traverse an environment with randomly arranged obstacles. The experimental setup is shown on the upper of Fig.6. In this experiment, a humanoid robot had to traverse

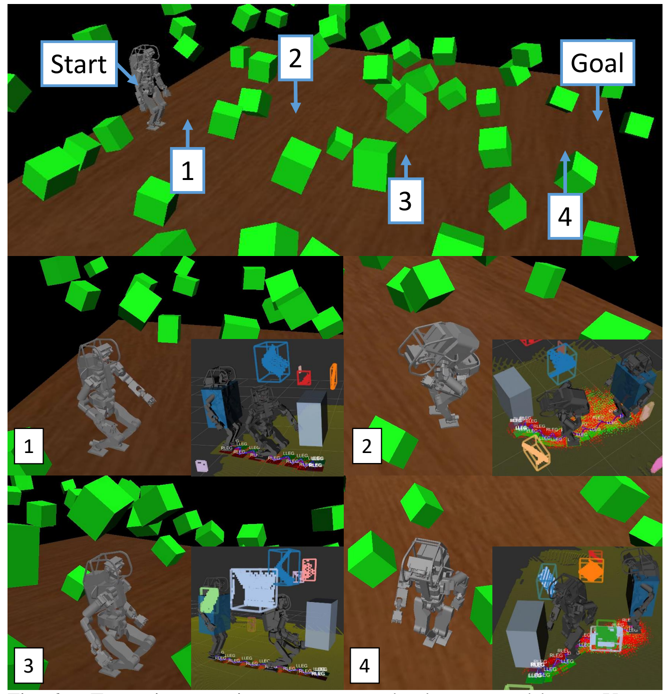

Fig. 6. Traversing experiment among randomly generated boxes. Upper: experimental setup of a simulation environment, Lower: sequence of a robot traversing the narrow space at each phase in the above with proposed planner and stabilizing control. the lower right is screen shots of the proposed locomotion planning result.

a complex environment from the start to the goal with the proposed locomotion planning. The locomotion planning was executed in the four places shown in Fig.6. The target goal was directed by an operator in each phase. The result of traversing motion is shown on the lower of Fig.6 and the average computational times for 5 trials are shown in TABLE II for each phase. It can be seen that the proposed locomotion planner can generate whole-body collision avoidance motion for each step within 73ms at worst, even in a complex narrow space. The total computational time was 23.65s for about 8.0m traversal, which is more than ten times faster than previous method in a similar situation [13].

TABLE II
EVALUATION OF COMPUTATIONAL TIME IN TRAVERSING AMONG RANDOMLY GENERATED OBSTACLES SCENARIO (AVG. OF 5 TRIALS)

Phase		1	2	3	4	Total
Footstep Plan [s]		0.12	13.56	0.075	5.95	19.71
Motion Plan [s]		0.80	1.18	0.83	1.14	3.94
Total Plan [s]		0.92	14.74	0.91	7.09	23.65
Motion/Step [ms]	Avg	50	50	52	52	51
	Max	62	67	67	73	73

VI. DISCUSSION

A. Existence of the feasible motion in the planned footsteps

It is not guaranteed that the whole-body collision avoidance planning can be solved with the resulting footsteps. Moreover, the sequential whole-body motion planning may not reach the ideal collision avoidance posture depending on the previous solution. In this sense, it can be said that the proposed method does not ensure the completeness nor optimality. However, we concluded that it was practically sub-optimal based on the experimental results shown in

Section V. Currently, we try to introduce a method to globally replan foot placements when there is no solution of whole-body motion planning for current guiding footsteps.

B. Effect of the bounding box modification

Because the proposed whole-body motion planner does not consider the dynamics of a robot, the sequential whole-body motion planner tends to cause a sudden change of resulting posture when a robot is approaching to and departing from an obstacle. This problem results in an overaction and a large deviation between the target and planned ZMP trajectory, which affects the feasibility of resulting motion. The bounding box modification strategy enables a footstep planner to secure a sufficient margin for whole-body collision avoidance, and thus reduces these overactions as shown in Section V. We would also consider the dynamics in whole-body locomotion planning for more stable collision avoidance motion in future work.

VII. Conclusion

In this paper, we proposed an efficient locomotion planning framework for a humanoid robot in order to solve the problem of increasing computational cost, which is caused by its large degree of freedom, and a smoothing or interpolation process. The proposed method reduced a large computational cost by executing global footstep planning first with the bounding box modification strategy based on the centroidal sway motion, and then performing a sequential whole-body posture planning while utilizing resulting footsteps and a centroidal trajectory as a guide. This strategy enables a simulated humanoid robot to execute whole-body locomotion on the spot in an unknown narrow space for each step within 82ms at worst, which is three to ten times as fast as existing methods. From above results, we concluded that the proposed framework contributes to improving the adaptive locomotion capability of a humanoid robot.

Acknowledgments

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