Smooth Collision Avoidance: Practical Issues in Dynamic Humanoid Motion

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***Abstract*— In this paper we address smooth and collision-free whole-body motion planning for humanoid robots. A two-stage iterative planning framework is introduced where geometric motion planner and dynamic pattern generator interacts by exchanging the trajectory, to obtain 3D whole-body dynamic motions simultaneous tasks including locomotion, in complex environments. We propose a practical method for smooth motion reshaping to avoid collisions in generated dynamic motion. Based on motion editing techniques in computer graphics animation, smooth collision-avoiding motion is generated through trajectory deformation. The validity of the proposed reshaping method is verified by computer simulations and experiments using humanoid platform HRP-2.**

I. INTRODUCTION

Humanoid robots are expected to perform complicated tasks thanks to their high mobility and many degrees of freedom including legs and arms. Their anthropomorphic configuration gives another advantage that they can easily adapt to machines or environments designed for humans.

Recent progress in hardware accelerates diverse research in humanoid robots. Various types of tasks have been performed: manipulation [1], [2], [3], navigation in dynamic environments [4], [5], or serving tasks [6], [7].

One of the key issues to fully exploit the capacity of humanoid robots is to develop a methodology that enables them to explore and execute various dynamic tasks, requiring dynamic and smooth whole-body motion including collision avoidance and locomotion, like an object carrying task as shown in Fig. 1.

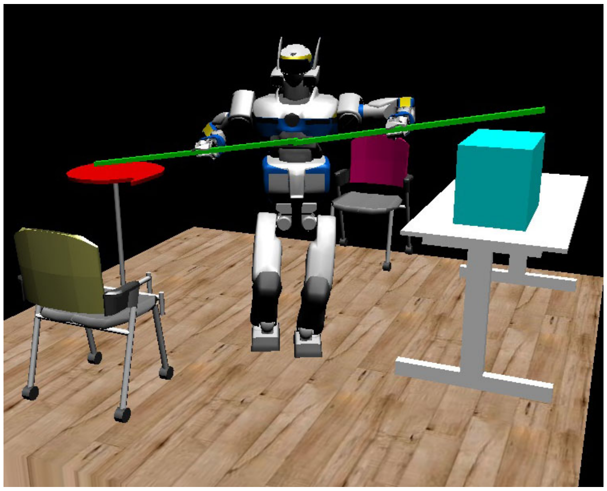

Fig. 1. A 3D collision-free whole-body motion including task and locomotion

In the field of motion planning, recent advancement in probabilistic methods has greatly improved planning of the three-dimensional (3D) motion of mechanism including complicated geometry and many degrees of freedom (e.g. [25]). However, most of those methods are based on geometric and kinematic planning in configuration space whereas dynamic control is required for humanoid motion planning in workspace to execute tasks by keeping its balance.

Concerning control issues of humanoid robots, stable motion pattern can be generated efficiently thanks to the progress in biped locomotion control theory, basically based on ZMP (zero moment point [8]) control [9], [10]. In other studies [11], a powerful controller has been developed that generates whole-body dynamic motion in a reactive manner.

Planning of 3D humanoid motion for tasks in complex environments must definitely benefit from those two domains. Indeed, integration of dynamics into geometric and kinematic motion planner is a challenging topic.

As the first step to this goal, we proposed a two-stage planning framework [12] based on the geometrical and kinematic planning technique whose output is validated by dynamic motion pattern generator. Using proposed planning framework, we could obtain 3D whole-body humanoid motions for execution of dynamic task in complex environment, which remains a difficult problem without integration of motion planning and dynamic control.

However, the generated motion was not smooth enough and neither verified by experiments. It was because path "reshaping", which modifies a colliding motion path into collision-free one, is based on a biased randomized planning method. Random sampling for each colliding configuration in the path results in lack of smoothness. In this paper, we apply a method based on a motion editing method in graphics animation (see [13] for survey). By using this method in workspace for path

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*This research was conducted in LAAS-CNRS and experimented in AIST.

reshaping, this allows the planner to generate smoother path by deforming a segment of path, not each configuration. Through an illustrative example of a dynamic task of carrying a bar in an environment with obstacles, the generated path is verified through simulations and experiments.

This paper is organized as follows. Section II provides related work and highlights the contribution. After briefly outlining the proposed two-stage planning framework in section III, the improved reshaping method is presented in section IV. Simulation and experimental results are shown in section V.

II. RELATED WORK

Humanoid motion planning is becoming a hot topic since it faces complexity of planning and dynamic control at the same time.

Kuffner et al. proposed a various types of humanoid motion planner [14], [15], [16], [17] such as balancing, footstep planning and navigation displacing movable obstacles. Locomotion planning for humanoid robots to pass through narrow spaces by changing the locomotion modes has been investigated in [18], [19]. Okada et al. addressed motion planning for collision-free whole-body posture control [20] by dividing the robot into movable, fixed and free limbs using RRT planner. He has also showed task-oriented motion planning [21]. Yoshida proposed humanoid motion planning based on multi-level DOF exploitation [22].

Sentis et al. developed a hierarchical controller that synthesizes whole-body motion based on prioritized behavioral primitives including postures and other tasks in a reactive manner [11].

In the domain of computer graphics, motion editing is an active area of research. Gleicher classified various constraint-based methods that take account of spatial and temporal constraints, which often corresponds to the problems of inverse kinematics and filtering respectively [13]. Especially for graphic animation of digital actors, recent development in randomized motion planning is now actively investigated [23], [25].

The two-stage approach [12] we have proposed attempts to have both advantages of motion planning technique and dynamic controller.

The main contribution of our approach is to cover both manipulation and locomotion tasks in a single unified framework. While dynamic motions are addressed in [15] either for locomotion (foot step planning) or for manipulation from a fixed foot position, such a whole-body task combination is absent. On the other side, the whole-body dynamical system framework proposed in [11] does not address locomotion issues.

From a more technical point of view, the contribution of this paper with respect to our previous work [12] lies in its performance improvement and experimental verification of planned motions. Inspired from motion editing in computer graphics animation, we introduce a smooth reshaping method in workspace while the previous method has a drawback of sharp changes of velocity due to randomized search. The feasibility of the generated collision-avoidance motion has been verified using the hardware humanoid platform HRP-2.

III. TWO-STAGE PLANNING METHOD

In this section we will outline the two-stage planning method we have proposed [12] illustrated in Fig. 2. At the first stage of motion planning (upper part in Fig. 2), the geometric and kinematic motion planner takes charge of generating collision-free walking path described by the position and orientation ($\boldsymbol{X}$, $\boldsymbol{\Theta}$) of the waist for a bounding box approximating the humanoid robot, as well as the upper body motion expressed by joint angles ($\boldsymbol{q_u}$) to achieve desired tasks. Here we assume that robot moves on a flat plane with obstacles. Then at the second stage, those outputs is given to the dynamic pattern generator [9] (lower part in Fig. 2) of humanoid robots to transform the input planar path into a dynamically executable motion described by waist position and orientation ($\boldsymbol{X_d}$, $\boldsymbol{\Theta_d}$) and joint angles of whole body ($\boldsymbol{q}$) at sampling time of 5[ms] by taking account of dynamic balance based on ZMP. However, the generated dynamic motion often differs from the geometrically and kinematically planned path, which may cause unpredicted collision. Then the planner goes back to the first stage to "reshape" the previous path based on randomized method to avoid possible collision. This refining process is repeated until the planner obtains a collision-free and dynamically stable 3D whole-body motion to realize locomotion and task execution. If no solution is found, then a new walking plan is searched.

The proposed method is characterized by integration of motion planner and dynamic pattern generator to deal with 3D whole-body motion to achieve collision avoidance, task execution and locomotion at the same time.

We assume that the geometric and physical information of

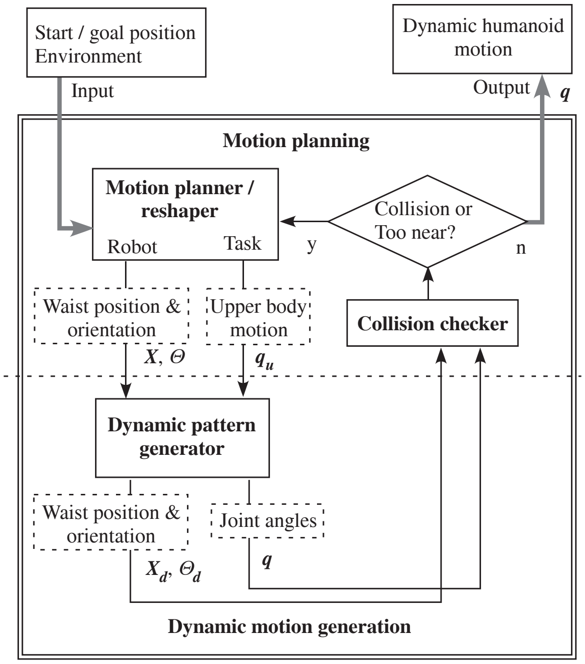


Fig. 2. Two-stage motion planning framework

environment or object is known beforehand to plan the robot's motion prior to task execution. In the next section we address the improvement of quality of reshaped motion.

IV. SMOOTH MOTION RESHAPING

As stated in previous sections, a collision-free path issued from the motion planning stage, will not always result in a collision-free trajectory after dynamic pattern generation is performed. For instance, in our manipulation example, unexpected collisions might arise by the influence of the weight of the carried object into the robot's dynamics. If the variation of the motion is small enough, those collisions will be with the humanoid's upper body or the carried object. In such a case, we can assume that local reshaping of the trajectory will suffice to avoid the obstacles without replanning the whole nominal trajectory.

In [12], a biased random sampling method was proposed for this reshaping. In this method, when a collision is found, a new random collision-free configuration near the colliding one is first generated, and then an inverse kinematics (IK) solver is applied to ensure the end-effector's geometric constraints. Although collision-free motions can be generated using this method, lack of smoothness in velocity profile might cause instability or unnecessary oscillation when it is executed by the humanoid robot. In this work, we propose a reshaping method that accounts for the smoothness of the motion when avoiding the obstacles.

The reshaping procedure is performed in two steps illustrated in Fig. 3 as detailed later:

1) A smooth trajectory to be followed by the end-effector is specified in the task space and resampled at each sampling time (5[ms]) to enforce temporal constraints (Fig. 3(a)-(c)).
2) An inverse kinematics solver is used to attain the specified end-effector's motions enforcing geometric constraints (Fig. 3(d)).

We account for motion continuity at both steps.

A. Smooth Task Specification

The output of a dynamic simulation of the planned trajectory is a sequence of robot's configurations uniformly sampled each 5[ms], which is the control sampling rate of the robot. With this output, the colliding portions of his trajectory can be reshaped using the motion editing techniques that enforce spatial and temporal constraints usually employed in computer animation [13]. Our reshaping method is inspired on the motion editing step described in [25].

First, the limits u_1 and u_2 of the colliding portion of the trajectory are identified. Then, a configuration that is free of collisions and that satisfies the task specification is found by randomly sampling the task space and solving the inverse kinematics problem to verify the constraints. This procedure is done in either case, when the object or when the robot's upper body are colliding. The new collision-free portion of the trajectory has to be smoothly attained with velocity constraints v_{ref}. For this, the reshaping limits are redefined by adding the number of samples ns_{before} and ns_{after} needed to smoothly anticipate the new configuration and regain the original trajectory. The anticipation time (resp. regaining time) is computed given the distance between the robot's last collision-free configuration and the new configuration between u_1 and u_2 as well as with v_{ref}. As the sampling rate is known, the number of frames needed before u_1 (resp. after

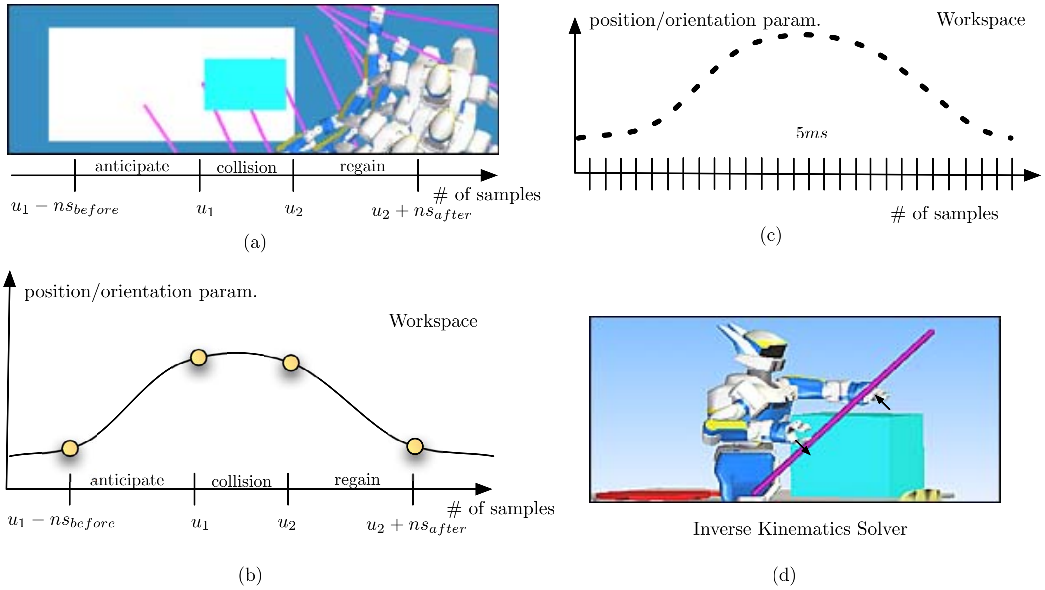


Fig. 3. (a) The reshaping limits are set by identifying the anticipating, colliding and regaining times. (b) Smooth motion is specified in the task space by interpolating the bar's configuration at key frames. (c) The bar's motion is resampled at 5[ms] to replace its original motion. (d) New constraints are enforced by using a whole-body IK solver.

u_2) to obtain a smooth motion can easily be obtained. The trajectory is then reshaped from $u_1 - ns_{before}$ to $u_2 + ns_{after}$ as illustrated in Fig. 3(b).

Then, in order to obtain a smooth motion for the end-effector's task, an interpolation of the object's configurations at $P(u_1 - ns_{before})$, $P(u_1)$, $P(u_2)$ and $P(u_2 + ns_{after})$ (Fig. 3(b)) is performed. We use well-known interpolation techniques such as cubic spline interpolation. In order to respect time constraints, the time at which each of the specified configurations should be reached is specified along with position when fitting the curve [26]. Finally, the curve is resampled to get the new object's configuration at each 5[ms] (Fig. 3(c)).

B. Whole-body smooth collision avoidance

The result of the previous stage is the reshaped motion for the task specification synchronized with the lower body motion along the original path. The last step (illustrated in Fig. 3(d)) is performed to ensure the geometric constraints and continuity of the upper body along the new reshaped trajectory.

In our algorithm, an inverse kinematics solver should be used to satisfy the end-effectors' constraints at each sample of the trajectory. We work under the assumption that the displacement achieved in the 5[ms] between samples is small enough to use (1) to relate the robot's posture variation $\dot{\boldsymbol{q}}$ to the change on the configuration $\dot{\boldsymbol{r}}_i$ of the link i using Jacobian matrix J_i.

$$\dot{\boldsymbol{r}}_i = J_i \dot{\boldsymbol{q}} \tag{1}$$

As we are dealing with a mechanism that is redundant with respect to the number of imposed tasks, we use (2) to solve the IK problem for the task with first priority:

$$\dot{\boldsymbol{q}}_1 = J_1^{\#} \dot{\boldsymbol{r}}_1 + (I - J_1^{\#} J_1)\boldsymbol{y_1} \tag{2}$$

where $J_1^{\#}$ is the pseudo-inverse of the Jacobian matrix, I is the identity matrix and $\boldsymbol{y}$ is an arbitrary optimization vector.

Our IK solver considers two geometric task, which are the position and orientation constraints imposed on each hand by the object's motion. In this case, the IK solver attempts to achieve the second task in the null space of the first task using the following formula.

$$\begin{aligned} \dot{\boldsymbol{q}}_2 \;=\; & \dot{\boldsymbol{q}}_1 + \hat{\boldsymbol{J}}_2^{\#}(\dot{\boldsymbol{r}}_2 - \boldsymbol{J}_2\dot{\boldsymbol{q}}_1) \\ & +(\boldsymbol{I}_n - \boldsymbol{J}_1^{\#}\boldsymbol{J}_1)(\boldsymbol{I}_n - \hat{\boldsymbol{J}}_2^{\#}\hat{\boldsymbol{J}}_2)\boldsymbol{y}_2 \\ \text{where} \quad & \hat{\boldsymbol{J}}_2 \equiv \boldsymbol{J}_2(\boldsymbol{I}_n - \boldsymbol{J}_1^{\#}\boldsymbol{J}_1) \end{aligned} \tag{3}$$

where $\boldsymbol{y}_2$ is an arbitrary vector [27].

The reference velocity v_{ref} for the end-effector is taken into account as in [28]. Joint limits and priority levels can be treated as in the iterative algorithm proposed in [24].

V. SIMULATION AND EXPERIMENTS

We have conducted simulations and experiments of the proposed humanoid motion planner using simulator OpenHRP [29] and hardware humanoid platform HRP-2 [30]. HRP-2 has 30 degrees of freedom with 1.54[m] in height and 58[kg] in weight. This robot has two chest joints for pitch and yaw rotation, which extends the motion capability including lying down on the floor and standing up. It can carry load up to 2[kg] at each hands. In the following, we took an example of a task carrying a bar in an environment populated by obstacles. The length, diameter and weight of the bar is 1.8[m], 2.4[cm] and 0.5[kg] respectively. The reference velocity v_{ref} in workspace is 0.3[m/s] and 30[deg/s] for translation and rotation.

A. Simulation results

A 3D Collision-free whole-body motion of the humanoid robot is generated based on the proposed planning method. In this simulation, the task of humanoid robot is to carry a bar from a position to another in an environment of a flat plane with obstacles. Fig. 4 shows the top view of the environment with the initial and goal position and orientation (x, y, θ) on the plane, and planned walking path composed of line segments and arcs (dotted line) through the narrow passage. Two high poles are set near the goal with the distance shorter than the bar length. The robot holds the bar at the height of 0.85[m] at initial the configuration and should lift the bar to avoid the collision with the box on the table whose highest position is 1.05[m].

Snapshots of simulation are shown in Fig. 5 where collision avoidance with several obstacles is smoothly done using the whole-body motions. Note that the humanoid robot fully exploits the whole upper-body including chest joints to pass through between pole obstacles in Fig. 5(d), (e). As can be seen, a 3D collision-free whole-body motion for locomotion and task execution can be generated by using the proposed planning framework.

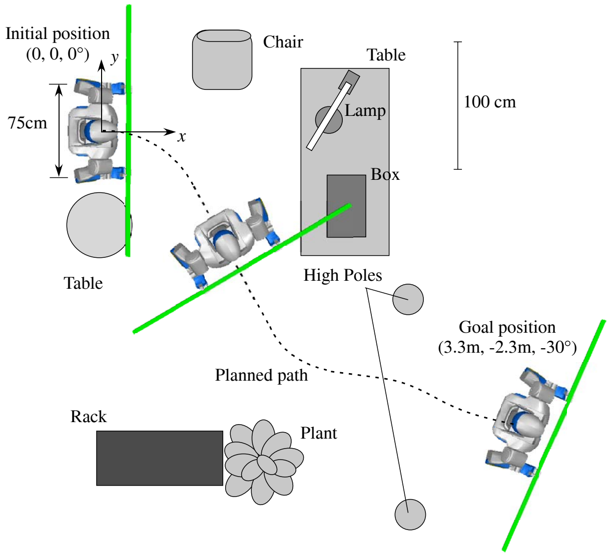
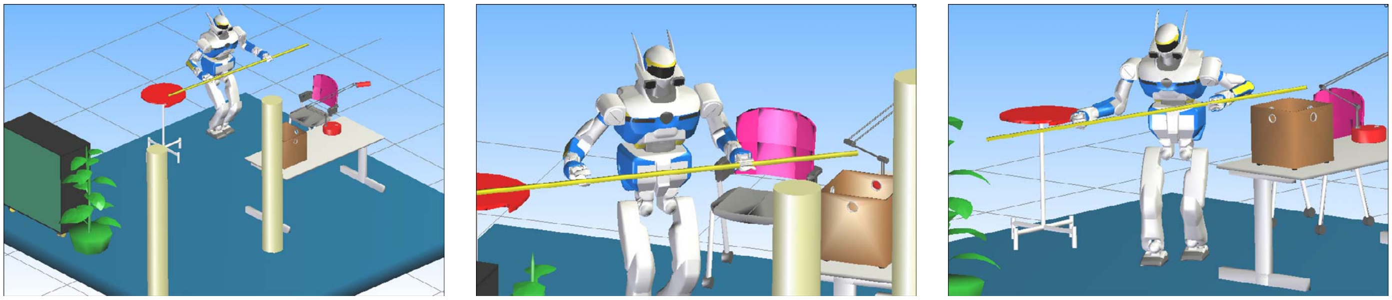
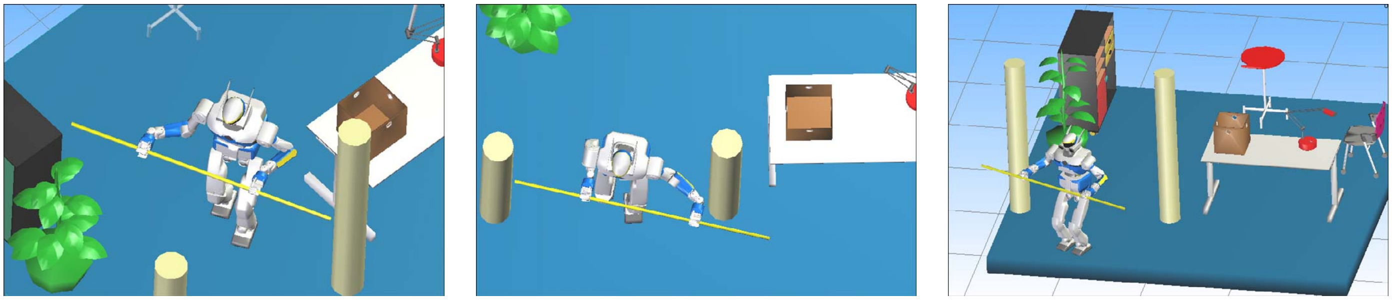


Fig. 4. Top view of the simulation environment



(a) Initial configuration (b) Avoiding lamp (c) Lifting the bar to avoid box



(d),(e) Avoiding collision with poles using a motion including the chest (f) Final configuration

Fig. 5. Simulation results of 3D whole-body collision avoidance

B. *Experimental results*

We have conducted an experiment of the same bar-carrying task in an environment with fewer obstacles. The motion planned by the proposed method is executed by the robot hardware. After start walking, robot lifts the bar to move it by avoiding the collision with the box on the table (Fig.6(b)-(d)). The bar is lowered to the initial height after collision avoidance (Fig. 6(e),(f)) to reach the goal position. The task was successfully achieved in this way by the dynamic motion of hardware platform, which verifies the validity of the planned motion.

The movies of simulations and experiments are available on our web site `http://www.laas.fr/~cesteves/iros2006` .

VI. CONCLUSION

This paper presented a smooth collision avoidance method for dynamic motion of humanoid robot. A two-stage planning method is adopted to generate 3D whole-body humanoid motion for stable locomotion and task execution, by integrating geometric and kinematic motion planner and dynamic pattern generator. Smooth reshaping of humanoid trajectory was realized by applying a motion editing method often utilized in computer graphics animation. If the generated dynamic motion has collisions with obstacles, the planner finds collision-free positions for task execution and interpolates smoothly from the nominal trajectory. We have shown the proposed method gave smoother motion and validated its effectiveness by simulations and experiments.

Future improvements include refinement of the algorithm for more reactive implementation. The computation time is about one minute in total for planning and dynamic motion generation. We will address this issue by deeply integrating the dynamic pattern generator in planning. One of the possibilities is the usage of efficient generalized inverse dynamics [11] whereas our method is based on generalized inverse kinematics. To apply this work to our purpose, dynamically-stable locomotion generation and 3D motion generation in complex environment must be considered. Relaxing the assumption of completely known environment is also an important issue by usage of real sensor input such as visual information to recognize the environment.

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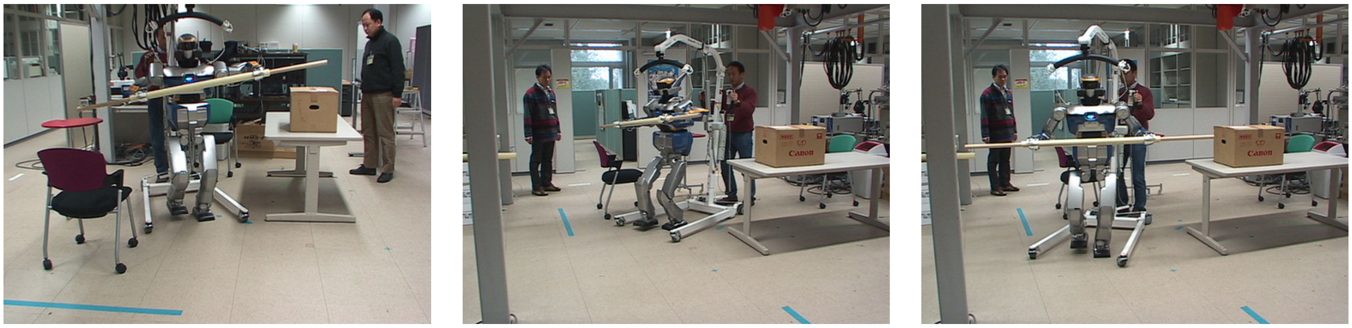
(a) Initial configuration (b) Start walking (c) Start lifting the bar



(d) The bar passes above the obstacle (e) Lowering the bar after avoiding collision (f) Going to final position

Fig. 6. Experiment of planned bar-carrying task

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