Proceedings of 2005 5th IEEE-RAS International Conference on Humanoid Robots

Humanoid Motion Planning for Dynamic Tasks

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***Abstract*— This paper addresses an integrated humanoid motion planning scheme including both advanced algorithmic motion planning technique and dynamic pattern generator so that the humanoid robot achieve tasks including dynamic motions. A two-stage approach is proposed for this goal. First, geometric and kinematic motion planner first computes collision-free paths for the humanoid robot. Then the dynamic pattern generator provides dynamically feasible humanoid motion including both locomotion and task execution such as object transportation or manipulation. If the generated dynamic motion causes collision due to dynamic movements, the planner go back to the planning stage to remove the collision by path reshaping. This iterative planning scheme enables robust planning against variation of task dynamics. Simulation results are provided to validate the proposed planning method.**

***Index Terms*— Humanoid, Motion planning, Dynamics, Mobile manipulation**

I. Introduction

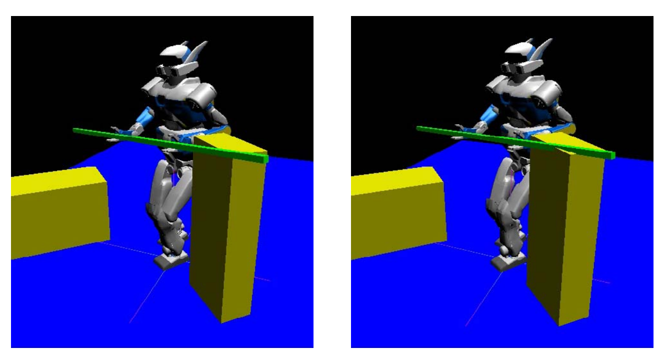
Recent rapid advancement of humanoid robot research on mechanism and control has brought great improvements in ability of their executable tasks. Not only entertainment or demonstration, they are now expected to perform a variety of tasks to assist or replace humans in environments hardly accessible to humans. For instance, we can imagine a humanoid robot transports objects or drives a machine in cluttered and dangerous construction sites.

One of the important tasks is object manipulation in complex environments. Humanoid robots have higher capacity to transport objects with irregular shapes through narrow space, rough terrain, or over obstacles compared to other types of robots. In this aspect humanoid robots can benefit from kinematic and geometric motion planning techniques that have been making remarkable progress in recent years, especially probabilistic diffusion such as rapidly-exploring random trees (RRT) [1], [2] or probabilistic sampling such as PRM approaches [3].

On the other hand, humanoids should keep dynamic balance not to fall down while walking with objects. Therefore, kinematic and geometric motion planning and dynamic task execution should be taken into account. Although there have been many work on motion planning of humanoid itself on such issues as footstep planning or pattern generation, few research has been conducted motion generation taking account of both geometric and kinematic planning and dynamics of humanoid and task. A typical dynamic task is object transportation and collision avoidance by the humanoid robot where the humanoid robot transports a long bar while keeping its balance and avoiding collision with the obstacles at the same time. According to the weight of the bar, a motion planned only at kinematic and geometric level may not be valid.

An example is given in Fig. 1. Figure 1a shows a snapshot of the motion kinematically planned to transport a light object avoiding collision with obstacles. The same motion is not valid for a heavy object as shown in Fig. 1b because the controller of the humanoid robot does not perform exactly the same kinematics due to different dynamics of the object carrying task. Path reshaping is therefore necessary by adapting the planned paths according to the task dynamics as shown in Fig. 2. In this way, the overall planning system can have enough robustness against variation of dynamic property of the task.

In this paper, we aim to provide a method of humanoid motion planning for dynamic tasks based on two-stage approach. At the first stage the kinematic and geometric motion planner generates the trajectory for both humanoid body and carried object. Then in the second stage the dynamic walking pattern generator outputs appropriate dynamically stable walking motion that allows the robot to carry the object from the trajectory given from motion planner. If the desired trajectory is not feasible, the planned motion is modified partially or entirely until dynamically feasible motion is obtained. The planning is made in a robust manner to cope with different physical parameters of the object and dynamic effect by using a dynamic pattern generator and a planner including certain clearance for collision avoidance.



(a) Light object: no collision occurs — (b) Heavy object: collisions occur

Fig. 1. A dynamic task of object transportation by a humanoid robot

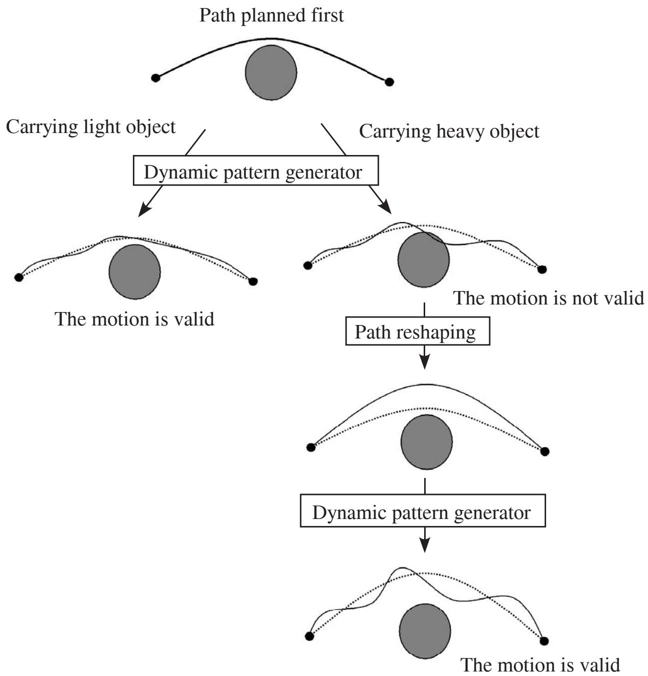


Fig. 2. Path reshaping according to task dynamics

This paper is organized as follows. After outlining related work in Section II, the two-stage approach is described in Section III. Then the motion planning and dynamics walking pattern generation are detailed in Sections IV and V before showing simulation results in Section VI. Section VII concludes the paper.

II. Related work and contribution

Motion planning is becoming a major topic in humanoid research in recent years. Kuffner et al. proposed a two-stage planning scheme to obtain dynamic motion from the motion planner using dynamic balance filter [4]. They have also been working on humanoid motion planning [5], footstep planning on rough terrain [6] and navigation in environments with movable obstacles [7]. Locomotion planning for humanoid robots to pass through narrow spaces by discretely changing the locomotion modes (such as walking, sidestepping or crawling for instance) has been investigated in [8], [9]. An integrated motion control scheme for running and walking has been proposed by Nagasaka et al.[10]. Okada et al. [11] have addressed motion planning for collision-free full body posture control by dividing the robot into movable, fixed and free limbs using RRT planner. He has also showed task-oriented motion planning [12]. Yoshida proposed humanoid motion planning based on multi-resolution DOF exploitation [13].

Now the research area of realistic animation, dynamic computation, and motion planning are getting closer. There has been advancement in integration of dynamics and motion planning [16] and digital actor animation based on motion planning technique [14].

With respect to the above related work, our contribution is to propose a whole generic integrated solution addressing both:

- the three geometric, kinematic, and dynamic issues in the same planning scheme, and
- complex tasks including simultaneous dynamic locomotion and manipulation.

The key issues are:

- to integrate task planning and dynamic simulation in the same framework, and
- to benefit from the respective advantages of diffusion and sampling path planning methods.

III. Two-stage motion planning for dynamic tasks

In spite of many related studies shown in the previous section, few work has been made on humanoid motion planning taking account of dynamic task execution. This issue will be more important when humanoid robots must execute various tasks in complex environments. We therefore propose a two-stage humanoid motion planning scheme dynamic tasks, of which a typical example of object transporting task is adopted in this paper.

The proposed planner is characterized by collision-free humanoid motion including not only dynamics of humanoid walking but also that of the tasks to be executed. In addition, the planner can guarantee a safe margin from the carried object and humanoid robot to the obstacles so that the generated plan is robust enough against dynamic motion error. Another feature is that its ability to deal with different dynamics of the tasks whose physical parameters may vary. In our transportation task, the planner is applied for motion planning of a humanoid robot carrying different weight of long bar in environments with obstacles.

Figure 3 describes the outline of the two-stage motion planning for dynamic tasks.

The motion planning part takes care of geometric and kinematic motion in a given environment. We assume that the environment is known beforehand. Given the desired start and goal position with environment model and planning parameters, the motion planner first outputs the robot trajectory (x, y, θ) in two dimensions as well as the motion of the carried object that determines upper body motion $\boldsymbol{q_u}$ through inverse kinematics [14]. The walking pattern generator accepts those commands with walking parameters such as step length and speed and generates dynamically-stable walking pattern as all the joint angles $\boldsymbol{q}$ with position and orientation (X, R) of base reference coordinate at the robot's waist.

The generated dynamic motion is checked by the collision checker. If collision or possible collision is detected, the motion planner modifies the previous motion it planned last time. The modification is applied partially or entirely to the trajectory according to the detected collision. This two-stage loop is repeated until a feasible dynamic motion is obtained. The following two sections present details of each part of the planner.

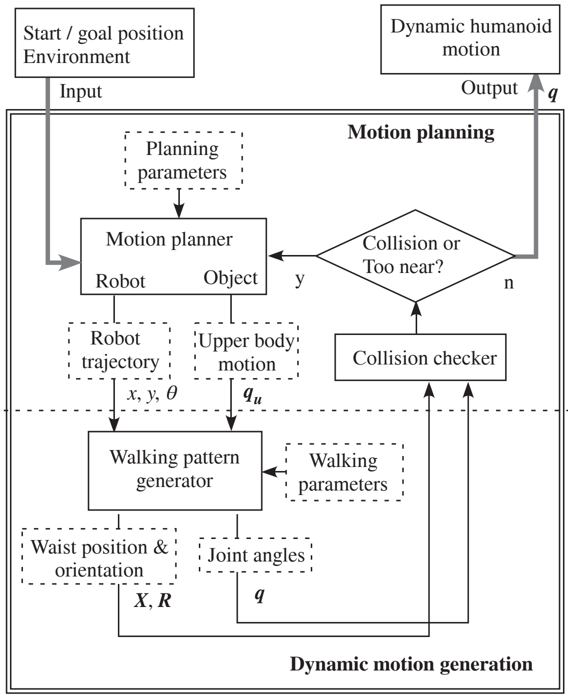


Fig. 3. Two-stage motion planning scheme

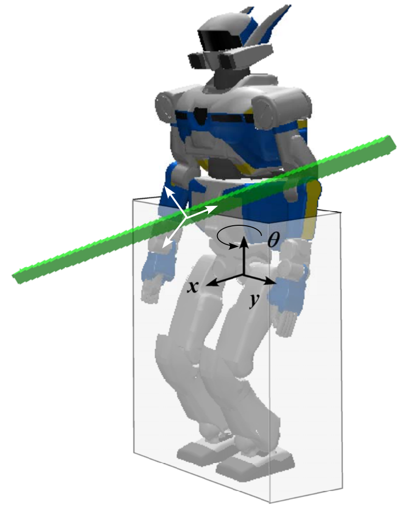


Fig. 4. Humanoid modeled by rectangle box with a bar

IV. Motion Planning for Task Execution by Humanoid

This section addresses the algorithmic issues dealing with geometric constraints (3D obstacle avoidance) and kinematic constraints (object manipulation). The objective is to plan collision-free admissible paths allowing the humanoid to perform simultaneously walking and object manipulation. The paths should be robust enough to guaranty their dynamic execution.

The global scheme is based on two motion planners benefiting from the respective advantages of both sampling and diffusion probabilistic approaches. The first one plans a global path while the second one is dedicated to path re-shaping.

A. *Task planning*

As task planning is concerned, the objective is to compute a motion plan guarantying collision-freeness for both the robot and the object. We use here a functional decomposition of the robot body already experienced in motion planning for virtual mannequins [14]. At this level the robot is modeled as a geometric parallelepiped bounding box (see Fig. 4). Only that box and the object to be manipulated are considered with respect to collision avoidance. The configuration space to be searched is then 9-dimensionated (3 dimensions for the box, 6 dimensions for the object). To explore such a space we use a sampling approach as in [14].

The novelty here is to consider an additional constraint for the locomotion of the humanoid. We want the robot walking in a "natural" manner: it should walk sideway only if it is necessary. This constraint is taken into account by considering two different steering methods (or local methods) to build the roadmap. The first one is based on the use of the Dubins curves (Dubins curves are sequences of straight line segments and arcs of a circle [15]) that enable to account the nonholonomic nature of the "natural" forward motions: the humanoid direction should be tangent to its path. The second one corresponds to a holonomic mode where the humanoid is considered as an omni-directional system (ODS mode). The steering method here consists in computing a straight line segment between two configurations of the robot.

The roadmap is then built in two steps. In the first step only the Dubins curves are used. After this step, the current roadmap is enriched to improve covering and connectiveness by using the holonomic mode. In such a way nonholonomic (natural) paths are privileged.

As the object is concerned, the configurations are randomly chosen under two constraints: collision-freeness and reachability by the humanoid hands.

At this stage the method provides a path in a 9-dimensionated space. The complementary configurations (DOFs) of the arms are computed by using inverse kinematics (see [14] for details).

B. *Path reshaping*

Our general scheme consists in giving the task plan as an input of pattern generator in charge to animate the degrees of freedom of the legs and to account for the weight of the manipulated object. The output of the pattern generator is then a whole body motion. Such a motion is then checked with respect to collision-freeness. Indeed, after the dynamic simulation phase, the motion may include oscillations which cannot be taken into account at the task planning stage. If the resulting motion is not collision-free, then the path computed at the first stage should be reshaped. Path reshaping consists in isolating the parts of the motion plan that need to be improved and adapted with respect to the environment. Such situations correspond to configurations very close to the obstacles.

For path reshaping we need another type of motion planning algorithm that allows to control the clearance to the obstacles. We use the diffusion probabilistic method introduced in [17]. This method is a multi-stage refinement method capable to iteratively reshape a potentially colliding path into a collision-free one. The approach has been successfully applied to highly constrained spaces as they appear in mechanical assembly framework. The method is based on clearance and penetration control of the path. An initial (possibly colliding) path being given, the path is decomposed into a sequence of admissible sub-paths. Then the diffusion algorithm is applied to connect the end-points of the sub-paths on the basis of a decreasing value of the penetration and an increasing value of the clearance. If the process does not converge towards a collision-free path after some stages, then the initial roadmap is updated and a new plan is computed.

V. Dynamic walking pattern generator

The walking pattern generator is based on preview control of zero moment point (ZMP) proposed by Kajita et. al [19] Based on preview control of ZMP position and invert pendulum, this method enables to generate biped walking motion for arbitrary foot placements. More precisely, the pattern generator accepts the foot placement or movement of body base (pelvis) with other fixed parameters such as footstep length or double/single support ratio, etc. As a result, the whole joint commands $\boldsymbol{q}$ with the position and orientation X, R of the base reference at the robot's waist are generated for humanoid body to satisfy the desired motion for every sampling time (5 [ms]). Although it is not used in this work, but the pattern generator can provide walking patterns for stairs. In our case, we use body base input composed of line segments (ODS mode) and arcs of a circle (arc mode) to execute Dubins curves.

Since the pattern generator takes account of dynamically stable walking pattern based on ZMP, we can specify the upper body motion while walking. Then the mixed whole-body motion for desired upper body movement and walking motion is computed. We utilize this feature to obtain combined motion of walking and collision-free motion derived by the motion planner part.

VI. Results

We have conducted several simulations using a HRP-2 humanoid platform [20]. HRP-2 has 30 degrees of freedom with 1.54 [m] in height and 58 [kg] in weight. Wrists and ankles are equipped with force sensors.

We have conducted simulations in an environment shown in Fig 5. This complicated working scene is constructed as a combined VRML file and is used both in the humanoid robot simulation environment (OpenHRP [1]) and in the environment for path planning (KineoWorks [2]).

Fig. 5. Humanoid robot in the office environment. Initial position (center) and goal (lower).

In the KineoWorks environment we calculate collision-free motion of the robot with an object. In the OpenHRP environment we check dynamic behavior of the robot (feasibility of the calculated kinematic paths).

In the current implementation of the two-stage motion planning algorithms with robot dynamics we exchange the data between OpenHRP and KineoWorks using the files. Two converters for the files to provide OpenHRP → KineoWorks and KineoWorks → OpenHRP data format translation have been developed. Also a program for automatic generation of the execution script for robot Walking Pattern Generator has been written. As the next step we are going to realize all data transfers between OpenHRP and KineoWorks using CORBA mechanisms — the basis of OpenHRP software organization.

In the first series of the experiments we investigated the influence of the robot dynamics to the calculated kinematic path for the robot without the object. The path has been calculated in KineoWorks to displace the robot from initial to goal position (Fig. 5).

The main difficulty consists in high complexity of the environment. Robot should pass narrow places (left-part side of the images on Figs. 5a and 5b). To provide this we have calculated the sidestepping walking patterns. In spite of the fact that these paths were collision-free on the kinematics level, while verifying them in OpenHRP with dynamical simulation some of the paths were not feasible anymore (Fig. 6). Iterative adaptation of the kinematic paths taking into account robot dynamics allowed the robot to pass narrow places without collisions (Fig. 7).

Robot walking while carrying the large and heavy object in hands is a much more complicated task. We have demonstrated its feasibility for this particular case.

Figures 8 - 11 show several simulation results[3] obtained

[1]OpenHRP is a virtual humanoid robot platform [21] with a compatible humanoid robot (http://www.is.aist.go.jp/humanoid/) and HRP-2 control software on OpenHRP is commercialized by GeneralRobotix (http://www.generalrobotix.com).

[2]KineoWorks is a software development kit dedicated to motion planning and marketed by Kineo CAM (http://www.kineocam.com). It is built from probabilistic motion planning approaches presented in [22].

[3]The simulation movies are found at http://www.laas.fr/˜cesteves/dynamic-motion-humanoid.html

Fig. 6. Collisions generate forces (reaction forces are visualized) and the robot falls (in this example, even if other solutions with higher clearance are possible, we force the robot to enter the narrow passage for path reshaping evaluation purpose).

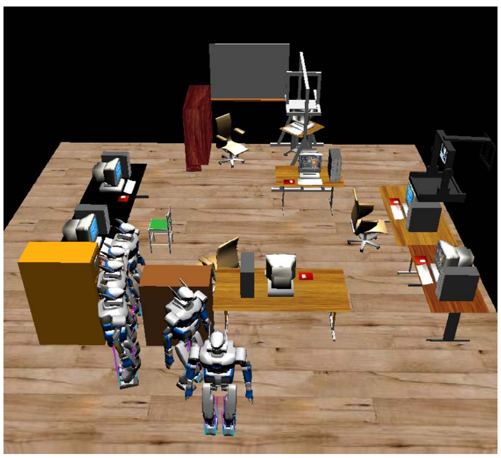


Fig. 7. Robot going through narrow space

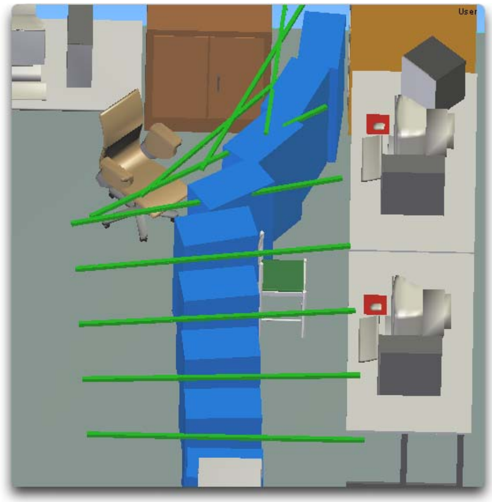


Fig. 8. Kinematically planned collision-free path for a bar carrying task by going through narrow space. The box models the humanoid robot body with a bar in the reachable area of arms

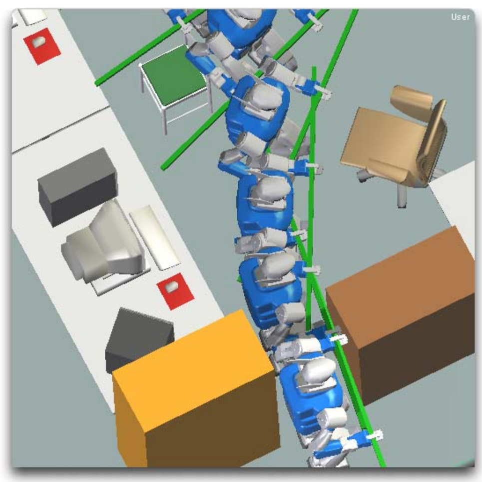


Fig. 9. Generated dynamic path for the light object. No collision occurs.

from the integrated motion planner shown in Fig. 3.

In Fig. 8, a collision-free initial path is planned by the motion planner in the kinematic level. In this stage the path is generated on the kinematic and geometrical basis to go through a narrow passage. Then in the dynamic motion generation level the path is transformed into humanoid motion by the dynamic pattern generator. The same initial path is applied to two bars of same geometry but with different mass.

While the task is the same in geometrical and kinematic sense, the same plan computed at the kinematic level produces two different motions when considering dynamics. Figure 9 shows the case of light-weight bar. Since the effect of dynamic task to the robot body motion is small, the robot can carry the bar without collision. In this case there is no need for reshaping the generated dynamic path.

In contrast, collision between the robot and the obstacle occurs as shown Fig. 10 since the dynamics of the task influences the robot dynamics more significantly. In this case, the path must be reshaped to avoid this collision caused by the dynamics of the task. Although only the path of the robot could be changed, it may lead to collision between the object (or arms) and the obstacle in front. The path reshaping is therefore performed by modifying both the path of the robot body and the arms (Fig. 11). As can be seen, the robot motion is modified to avoid the collision both for the robot and the bar. With the above simulation results, the proposed planning scheme has been validated.

VII. Conclusions

In this paper we presented an integrated motion method for a humanoid robot performing dynamic tasks. We have demonstrated through simulations that it is truly possible to take both the advantages of modern algorithmic path planning techniques and complex dynamic pattern generator to address motion planning for dynamic tasks.

In our current implementation we did not include full exploitation of other parts of body, for example, including ducking motion to go underneath obstacles. However, this

Fig. 10. Generated dynamic path for the heavy object. Collision occurs due to larger effect of task dynamics at the last position (colored red).

Fig. 11. Reshaped path for the heavy object to avoid collisions. The movement of the carried bar and the arms is modified.

problem is only related to the planning stage. Any motion planner capable to address whole body motions or different behaviors may be integrated to the general scheme we propose.

Future work includes experiments using the platform HRP-2. We are quite confident about the experiments using hardware since OpenHRP is a highly realistic software platform and it has binary compatibility of controller between the simulated and the real robot to facilitate the experiments.

The more challenging issue is to enhance the proposed planner to accomplish better integration the whole dynamic within the planning. The idea is to use the dynamic pattern generator as a "steering method" for probabilistic path planning algorithm. This will reduce the reshaping processes in planning. However, since the dynamic pattern generator is currently computationally expensive, taking several seconds, such integration appears challenging. This will require profound investigation for efficient dynamic simulation techniques.

Acknowledgments

We would like to express our sincere thankfulness to Dr. Shuuji Kajita, Humanoid Research Group, AIST, for his instructive advice on humanoid dynamic pattern generator and E. Ferré from Kineo CAM for his technical support on KineoWorks. Part of this work is supported by the IST-2001-39250 MOVIE project from the European Community. C. Esteves is supported by the Mexican Conacyt program.

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