Motion Planning for Humanoid Robots Stepping over Obstacles*

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***Abstract*— In this paper, we address the problem of how a humanoid robot can step over a given obstacle. Obstacle stepping-over has two aspects, namely, feasibility analysis and motion planning. The former determines whether the robot can step over the obstacle, and the latter discusses how to realize the stepping-over, if it is feasible, by trajectory planning. The paper focuses on the latter. Specifically, based on our previous analysis of feasibility, we present a novel algorithm to plan suitable trajectories for obstacle stepping-over, taking into account two basic requirements. The first requirement is to avoid any collision between the robot and the obstacle, and the second to maintain stability or balance of the robot. To meet them, we decompose the whole body motion of the robot into two parts, corresponding to the upper body motion and the lower body, respectively. We first plan collision-free trajectories of the feet and the waist for lower body motion, and then adjust upper body motion by resolved momentum control to guarantee the robot stability. This novel planning method is adaptive to obstacle sizes and hence oriented to autonomous stepping-over of humanoid robots guided by vision or other range finders. Its effectiveness is shown by simulation and experiment on our humanoid platform HRP-2.**

***Index Terms*— Humanoid robot, Motion planning, Obstacle overcoming, Collision avoidance**

I. Introduction

It is believed that humanoid robots, like human being, have better mobility for moving and dexterity for action than conventional mobile robots. This is the main motive for people to develop humanoid robots. Up to now, various humanoid robots have been developed, and fundamental issues such as system design, dynamics analysis, walking pattern planning and gait generation have been investigated extensively. Nevertheless, little work on humanoid robots walking in complex circumstances has been reported, since most of current research is based on even and clear walking environments without obstacles. Lack of this research would limit the applications of humanoid robots. Realizing this, more and more researchers begin to aim at walking in un-normal and complex environments with the assistance of vision [3], [4].

For humanoid robots to walk, an appropriate walking pattern or motion planning is of paramount importance, and therefore gait synthesis, pattern generation and motion planning have been being one of critical issues in humanoid robotics. Various methods have been proposed, some of which are based on energy consumption with the target of minimizing the energy consumed in the walking [2], [11], some on zero moment point (ZMP) where the target positions of ZMP are to be controlled [9], and some on the principle of inverted pendulum [12] or the resolved momentum control [8]. With these patterns or gaits, the robots can walk in good environments such as grounds clear of obstacles. However, since the trajectories of the robot feet are not specified directly, it is very difficult for the robots to walk in complex environments such as rough terrains and those cluttered with obstacles. Moreover, some specified positions of ZMP may not be achieved. To overcome these limitations, a walking pattern has been presented in [7], where the trajectories of the robot feet and torso were planned. With the maximum height of the lifted leg and the lifting and landing angles of the feet specified, this pattern can be used, to some extent, for the robots walking in rough terrains and overcoming relatively small obstacles. However, since the trajectories are not planned according to obstacle size, and what is more, the potential collision between the robot legs and the obstacle has not been taken into account, it is still difficult to directly use this pattern planning for humanoid robots stepping over various obstacles. In [10], an approach to path planning is presented for humanoid robots that computes dynamically-stable, collision-free trajectories from full-body posture goals. To drive the robot from the initial posture to the goal one, the configuration space of the robot is searched by utilizing Rapidly-exploring Random Trees. What is more, the planner can only handle a fixed position for either one or both feet, in other words, the support of the robot cannot be changed in the procedure. Therefore, this planning cannot be directly used in obstacle stepping-over either. A novel planning method is expected.

In this paper, we study how a humanoid robot can step over a given obstacle, if the stepping-over is feasible. As we know, for the robot to step over the obstacle, the stepping pattern is different from those in normal walking on a clear and even ground. The trajectories of the feet need to be controlled properly. Specifically, the step length should be big enough, and the feet should be lifted highly enough to negotiate the obstacle. During the stepping-over, there should not be any collision occurring between the legs and the obstacle. Another implicit requirement is that the robot should maintain its

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balance or stay dynamically stable so that the robot would not fall over in the procedure. Taking these conditions and requirements into account, we decompose the robot motion into two parts, which correspond to the lower body and upper body of the robot, respectively. Based on the results of our previous feasibility analysis [5], we propose an algorithm to generate the appropriate trajectories of the feet and that of the waist so that the robot can step over the obstacle without any collision. The motion of the upper body of the robot is controlled by resolved momentum proposed in [8] to adjust the robot CoM (center of mass) so that the robot can keep its balance stable during the stepping-over. This planning is adaptive to various sizes of obstacles and therefore it is possible for the robot to step obstacles over autonomously guided by vision or laser range finders. To verify the propose planning method, we do simulation and curry out experiment on our humanoid robot HRP-2.

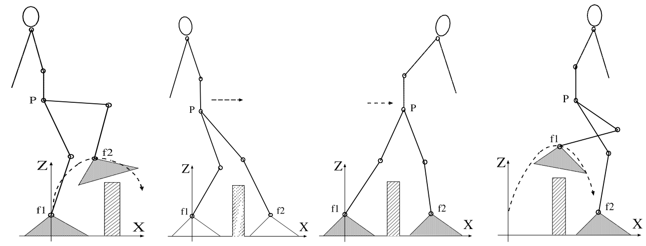
II. Stepping-over Procedure And Constraints

In this section, we briefly examine the procedure that a humanoid robot takes to step over an obstacle and the constraints that must be satisfied, for the convenience of motion planning.

It is well known that biped walking is a periodic or cyclic procedure. Each cycle consists of two phases, namely, single-support phase and double-support phase. A normal walking proceeds with these two phases taking place in turn. The procedure of obstacle stepping-over is similar. If there is an obstacle to overcome, the robot first walks to the obstacle at an appropriate position, then takes the following steps, which consists of three phases:

- Phase 1 (single-support): Supported by one leg, the robot lifts another highly enough, swings it over the obstacle and puts it down to the ground on another side of the obstacle (see Fig. 1(a));
- Phase 2 (double-support): Then the robot moves its waist forwards, transfers its center of mass (CoM) from the rear support (see Fig. 1(b)) to the front one (see Fig. 1(c));
- Phase 3 (single-support): Under the support of the front leg, the robot withdraws the rear one by lifting it highly enough, and moves it forwards, over the obstacle, and puts it down to the ground (see Fig. 1(d)).

In the whole procedure, it is obvious that two requirements or constraints must be satisfied: (a) the robot maintains stability or keeps its balance, and (b) there is no any collision between the robot (the thighs, the shank and the feet) and the obstacle. To satisfy constraint (a), the ZMP (in dynamic case) or the projection of the robot CoM (in static or quasi-static case) onto the ground must be within the convex hull of the supporting area(s). Constraint (b) is the so-called collision-free constraint. This constraint is related to the geometry and position of the object with respect to the robot, the size, shape and kinemetics of the robot legs.



(a) Phase1 (b) Phase 2 (c) Phase 2 (d) Phase 3

Fig. 1. Stepping-over procedure

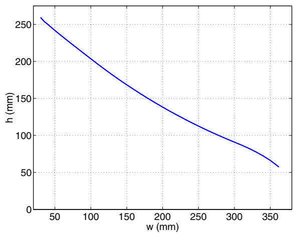
III. Review of Feasibility

In this section, we briefly review the problem of feasibility and some of the associated results. The feasibility provides us necessary and *a prior* knowledge for the humanoid robot to step over an obstacle, and the results are the base of our motion planning, as the following sections will show. For the details of stepping-over feasibility, please refer to [5].

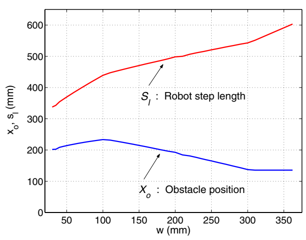
In our analysis, we take rectangular objects as typical obstacles to determine whether the robot can step over them while satisfies the two kinds of constraints mentioned above, by taking into account the geometry of the obstacle (height and depth), the sizes, shapes and kinematics of the robot legs. We use signed areas of triangles formed by three points to formulate collision-free constraints, since such signed triangular areas can completely describe the geometric relationship between three ordered points or one point and one directed line segment. The triangular area may be zero, positive or negative, reflecting the relationship between the geometric elements involved (e.g., collinearity of three points, one point is to the left or right of a directed line). Based on this fact, after abstract the obstacle and the robot legs by their topological features (vertices as points and edges as line segments), we formulate easily the collision-free constraints of two line segments.

After formulate the collision-free constraints, we then use optimization technique to cast the problem into global optimization (GO) models with nonlinear constraints. In other words, we build GO models to obtain the maximum height or depth of an obstacle that the robot can step over. In the models, the objective function is the obstacle height to be maximized, the variables include the obstacle height itself, the position of the obstacle with respect to the robot, and joint angles of the robot legs. The constraints in the models include those on joint ranges, balance and collision avoidance mentioned previously. There are different GO models for the three phases in the stepping-over procedure. These models should be integrated into one to obtain the final solution.

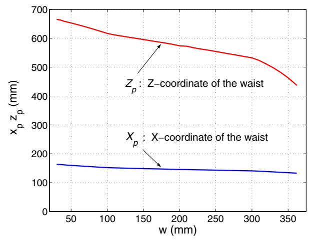
If the height (or depth) of an obstacle with the same depth (height) is less than the maximum height (accordingly depth) obtained from the integrated GO model, then the obstacle can be stepped over by the robot. For practical application, we can make a series of calculation for the maximum heights of obstacles with different depths, and then make a data base



(a) Depth $\sim$ Height



(b) Depth $\sim$ Pos. / step-length



(c) Depth $\sim$ Waist-position

Fig. 2. Mappings of stepping-over feasibility

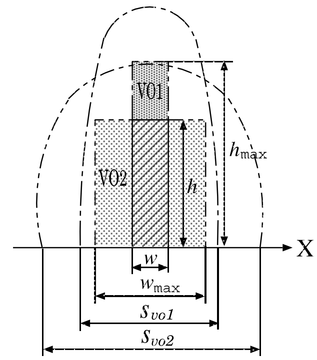


Fig. 3. Virtual obstacles and the related parameters

mapping the depth and the maximum height of the obstacle for online and real-time application. For our platform HRP-2, the mappings between the obstacle depth and the maximum height, between the depth and the robot-obstacle distance and the robot step-length, between the depth and the waist position, are shown in Fig.2 (a), (b) and (c), respectively. They will be used in motion planning in the following section.

IV. Planning of Trajectories

Based on previous feasibility analysis, we now address motion planning for obstacle stepping-over. Given an obstacle to step over, the step length of the robot should be big enough, and the feet should be lifted highly enough to surmount the obstacle. To satisfy collision-free constraint, the trajectories of both the feet and the waist must be designed properly. Once these trajectories are determined, the joint trajectories can be attained easily according to the kinematics of the legs. This is the planning of lower body motion of the robot. The motion of upper body is adjusted by resolved momentum control for the maintenance of robot balance. In the following, we only discuss trajectories in the sagittal plane. If lateral motion is involved (say, the motion of the robot waist in Phase 2), the corresponding trajectory can be determined in the same way.

A. Planning of Trajectories

1) Step Length and Obstacle Position: For a humanoid robot to step over an obstacle successfully, the step length of the robot and the distance between the robot and the obstacle should be first determined properly. And to realize autonomous stepping-over of various obstacles, these parameter should be set automatically according to the obstacle size.

The step length s_l is set the same for both legs. Its setting should be related to obstacle size. The wider the obstacle is, the bigger the step length should be. The setting of step length should also take obstacle height into account, since a bigger step length needs requires a lower waist position, which may result in the collision between the legs and the obstacle. If the obstacle height close the maximum one corresponding to the given depth (refer to Fig.2 (a)), then the step should be close the step length obtained in feasibility analysis (refer to Fig.2 (b)). Considering these points, the following is a choice:

$$s_l = (s_{vo1} + s_{vo2})/2.0, \tag{1}$$

where s_{vo1} and s_{vo2} are the two feasible step lengths for the robot to step over two "virtual obstacles" VO1 and VO2, respectively, as shown in Fig.3. VO1 is the virtual obstacle with the same depth w as the real obstacle and with the corresponding maximum height h_{max} found in feasibility analysis, and VO2 is the one with the same height h as the real obstacle and with the corresponding maximum depth found in feasibility analysis (refer to Fig.2 (a)). s_{vo1} and s_{vo2} can be obtained by looking up and interpolating the feasibility mapping (see Fig.2 (b)). Obviously, the bigger w, the bigger s_{vo1}; and the smaller h, the bigger s_{vo2}. If the height h is close to the corresponding h_{max} for a given depth, or the depth w close to its maximum w_{max} for a given height, then VO1 and VO2 is close to each other, and s_{vo1} and s_{vo2} approach each other, and hence the step length s_l calculated by (1) approaches s_{vo1}. Thus the step length set in this way is adaptive to various obstacles including VO1 and VO2. Alternatively, the step length can also be set as:

$$s_l = s_{vo1} + \lambda(s_{vo2} - s_{vo1}) \tag{2}$$

where $\lambda \in (0, 1)$ is a coefficient. For instance, we can set $\lambda = 0.1$ for HRP-2. We use (2), rather than (1), to get a smaller s_l for keeping collision avoidance and stability easily.

After the step length is specified, the distance between the robot and the obstacle is then set as:

$$x_o = d_1 + (s_l - w - d_1 - d_2)(1 + r_h)/2.0, \tag{3}$$

where w is the obstacle depth, d_1 and d_2 are the lengths of the toe and the heel from the the ankle, respectively (refer to

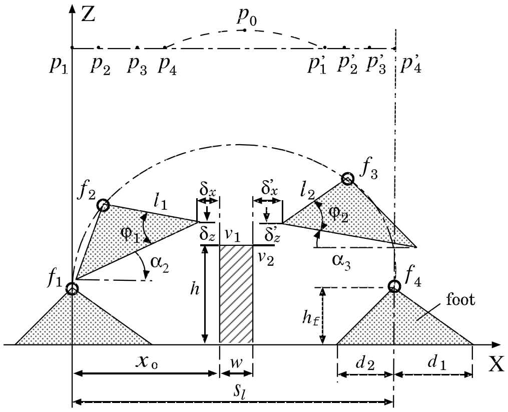


Fig. 4. Parameters for stepping-over (side view)

Fig. 4), and r_h is the ratio of obstacle height to the maximum height, $r_h = h/h_{max}$. Formula (3) for obstacle position is based on the fact found in the feasibility analysis that, in the stepping-over of an obstacle like VO1 or VO2, the obstacle is not at middle of the front and rear feet in Phase 2. For VO1 or VO2, r_h is equal to 1.0, and hence the position x_o computed by (3) equals $s_l - w - d_2$, which is consistent with the value gotten in feasibility analysis.

2) Foot Trajectories: Suppose that the two feet do 2-D or planar motion during the obstacle stepping-over procedure, i.e., the front and rear foot moves in sagittal plane in Phase 1 and 3, respectively. Then the trajectories of the feet can be described by planar curves. We specify four points (path control points) for each foot, and then use third- and fourth-order polynomials to generate the trajectories.

Once the step length and the obstacle position are determined, the first and last path points (end points), f_1 and f_4 in Fig.4, are then set. If the ground under these points are even and horizontal, then their coordinates are $(0, h_f)$ and (s_l, h_f), respectively, where h_f is foot height (the distance from the ankle joint to the sole). Since we set the same step length for the two feet, the end points are the same for their trajectories. Now we have two more points, f_2 and f_3, to set for the trajectory. In the setting of them, the potential collision between the feet and the obstacle must be taken into account. For better avoidance of collision, we also control the orientation of the feet during the stepping-over. Here the foot orientation is defined as the sole angle $\alpha(t)$ with respect to the ground, whose positive direction is defined as clockwise (for example, in Fig. 4, α_2 is negative while α_3 is positive). Suppose, corresponding to the four path control points f_i, the foot orientation is α_i $(i = 1, 2, 3, 4)$. Without loss of generality, and if the ground is flat and horizontal, we have $\alpha_1 = \alpha_4 = 0$. To specify α_2 and α_3, the ankle joint limits must be considered. Their determination depends on not only ankle joint positions but also the shank orientation. First, suppose the foot positions f_2 and f_3 are:

$$(x_o - d_1, h + h_f), \quad (x_o + w + d_2, h + h_f),$$

respectively. According to them and the corresponding waist positions (determined in next subsection), the minimum sole orientation α_2^{min} of the ankle joint at f_2 and the maximum α_3^{max} at f_3 can be trivially calculated by the inverse kinematics of the leg. Then α_2 and α_3 can be specified as

$$\alpha_2 = r_h \alpha_2^{min}, \quad \alpha_3 = r_h \alpha_3^{max}.$$

When the obstacle height is relatively small with respect to the maximum height, the sole angle can also be small, hence the height ratio r_h is used here as a coefficient.

Once α_2 and α_3 are specified, the positions of $f_2(x_2, z_2)$ and $f_3(x_3, z_3)$ can be computed as (refer to Fig.4):

$$f_2: \begin{cases} x_2 = x_o - l_1 cos(\varphi_1 + \alpha_2) - \delta_x \\ z_2 = h + l_1 sin(\varphi_1 + \alpha_2) + \delta_z \end{cases},$$

$$f_3: \begin{cases} x_3 = x_o + w + l_2 cos(\varphi_2 - \alpha_3) + \delta_x' \\ z_3 = h + l_2 sin(\varphi_2 - \alpha_3) + \delta_z' \end{cases},$$

where l_1 and l_2 are the lengths from the ankle joint to the toe and the heel, φ_1 and φ_2 are the angles of the toe and the heel, respectively, which depend on only the geometry of the feet. δ_x, δ_z and δ_x', δ_z' are margins to determine the distances between the toe and the heel and obstacle vertices (all are positive here), for avoidance of collision.

To define a smooth curve to pass through four path control points, we use three piecewise polynomials for three segments:

$$F_i(t) = a_i + b_i t + c_i t^2 + d_i t^3 + e_i t^4, \quad (i = 1, 2, 3), \qquad (4)$$

where $t \in [0, 1]$ is a normalized parameter for time. The function $F_i(t)$ may be $x_i(t), z_i(t)$ or $\alpha_i(t)$, the X and Z coordinates of path points or the corresponding sole orientation. To get the parameters a_i, b_i, c_i, d_i and e_i for the polynomials, boundary conditions include: (a) the curve is continuous at the interior control points, (b) it is also smooth at these points, i.e., the first derivatives of adjacent segments at these points are equal, (c) the second derivatives also match at the interior control points, and (d) the first derivatives at end-points (f_1 and f_4, or α_1 and α_4) be zero, (e) the second derivatives at end-points be also zero. Under these boundary conditions, the curve would be very smooth. To get the parameters from the 14 boundary conditions in total, we let the second polynomial to be of third order, or equivalently $e_2 = 0$, then the parameters can be easily and uniquely obtained [1]. The curve consists of two fourth-order polynomials and one third-order polynomial:

$$\begin{cases} F_1(t) = a_1 + b_1 t + c_1 t^2 + d_1 t^3 + e_1 t^4 \\ F_2(t) = a_2 + b_2 t + c_2 t^2 + d_2 t^3 \\ F_3(t) = a_3 + b_3 t + c_3 t^2 + d_3 t^3 + e_3 t^4 \end{cases}$$

3) Waist Trajectory: Waist position of the robot is also important in the procedure of obstacle stepping-over. If the waist is too high, then the robot may not put its leg down to the ground on another side of the obstacle with the desired step length; if the waist is too low, then it is likely that the legs collide with the obstacle. Therefore the trajectory of the waist need also to be planned carefully.

For simplicity, it is often desired that the motion of robot waist is kept on a plane parallel to the ground. In other words, if possible, the height of the waist is kept constantly, as shown by the line p_1p_4' in Fig. 4. Suppose that, at the beginning the waist point (the original of the robot base frame) is vertically over the ankle joint of the supporting foot (p_1 in Fig.4), and at the end of stepping-over (also end of Phase 3), it is vertically over the ankle joint of another supporting foot (p_4' in Fig.4). In Phase 1, when lifts its front foot from f_1 to f_2, f_3 and f_4, the robot moves its waist only in X direction from p_1 to p_2, p_3 and p_4 correspondingly; in Phase 3, it moves the waist only in X direction from p_1' to p_4' when withdraw the rear leg from f_1 to f_4; and in Phase 2, it moves the waist in both X and Y directions from p_4 to p_1'.

Waist path points p_2 and p_3 can be set so that the rates between the lengths of line segments p_1p_2, p_2p_3 and p_3p_4 are equal to those between f_1f_2, f_2f_3 and f_3f_4. Waist path points $p_1', \cdots, p_4'$ in Phase 3 can be set in a similar way.

The waist position $p_4(x_{p_4}, z_{p_4})$ is initially set as

$$x_{p_4} = (x_{vo_1} + x_{vo_2})/2.0, \quad z_{p_4} = (z_{vo_1} + z_{vo_2})/2.0, \qquad (5)$$

respectively, where x_{vo_1} and x_{vo_2} are X-positions of the waist at the end of Phase 1 for the robot to step over the two "virtual obstacles" VO1 and VO2 mentioned above, and z_{vo_1} and z_{vo_2} are the corresponding waist heights. These parameters can be obtained by feasibility analysis (see Fig.2(c)). Although (x_{vo_1}, z_{vo_1}) and (x_{vo_2}, z_{vo_2}) are feasible waist position for the robot to step over VO1 and VO2, here we still check the feasibility of waist position by examining the inverse kinematics of the two legs when the robot waist is at p_4 and the two feet are at f_1 and f_4, respectively, and by checking the collision between the obstacle and the two legs. If the inverse kinematics is not satisfied, then the waist height is reduced by a suitable amount and check again until a satisfied height is found. Inverse kinematics check is also performed in Phase 3 when the waist is at p_1' and the rear foot and front foot are at f_1 and f_4 respectively.

Collision detection is performed in the planning, especially at these path points of the waist and the feet, using the method of signed triangular area proposed in [6]. As mentioned before, for simplicity, collision detection is performed in sagittal plane, and to do so, all checking points are projected onto this plane. If collision is detected at some path points of the waist and the feet, then the step length is reduced by a suitable amount, and the waist height is set again in the way mentioned above. If the robot waist is set to move little in Phase 1 and 3, i.e., the distances p_1p_4 and $p_1'p_4'$ are small, then the corresponding waist height would also be smaller to reach the step length set previously, and as a result, the legs may collide with the obstacle in Phase 2 if the waist height is kept constantly. In that case, the waist should be increased in the middle of Phase 2, that is, one more path point (p_0 in Fig.4) should be added at the middle of p_4p_1', and its height is determined according to the leg inverse kinematics and collision detection. After it is set, the wait trajectory can be generated in a way similar to that for foot trajectories.

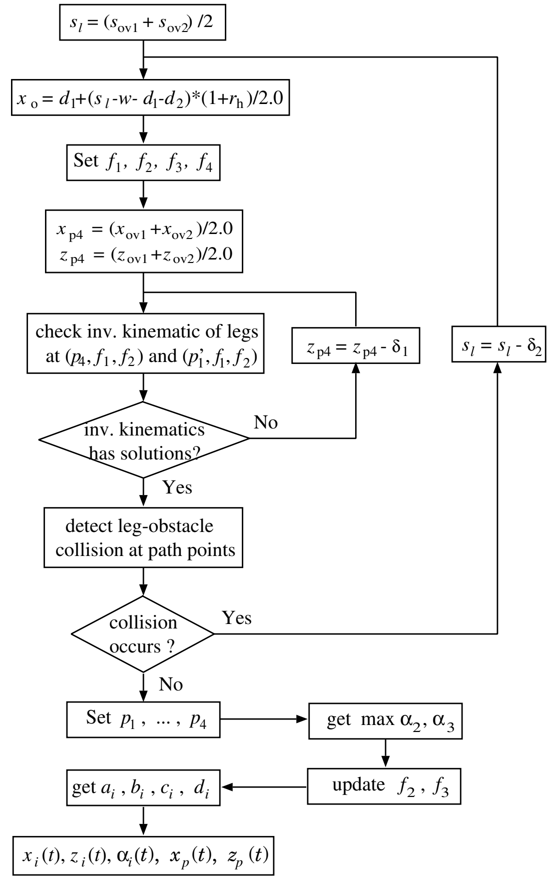


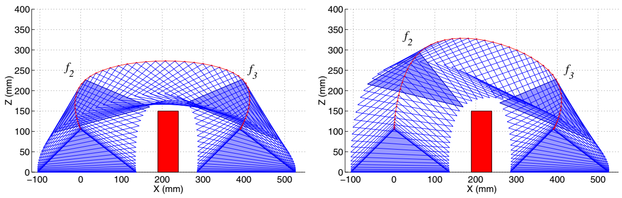
Fig. 5. The algorithm for trajectory planning

In summary, the algorithm for trajectory planning can be depicted by the block diagram shown in Fig.5.

After the trajectories of the feet and the waist have been generated, the motion of the leg joints can be easily obtained by the kinematics of the legs.

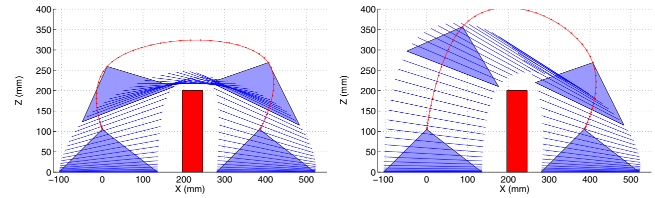
B. Upper-body Motion and Balance Maintenance

As mentioned previously, collision avoidance and robot stability must be satisfied in the whole stepping-over procedure. While the former is met by the planning of foot trajectories and waist trajectory in the preceding section, the latter can be controlled by the resolved momentum. It is well known that, for a humanoid robot to walk stably, the ZMP must be within the convex hull of the supporting area(s). The ZMP depends on the masses and inertia of the robot links, the robot configuration (position and orientation of the links) and the robot motion (velocity and acceleration of the links). In our planning for obstacle stepping-over, though the lower body of the robot is controlled to realize the desired trajectories under the constraints of collision avoidance, the upper body (including the chest, the head and the two arms) is free and can be used to adjust the ZMP or CoM to keep the robot balance. In this way, we decompose the robot motion into two parts



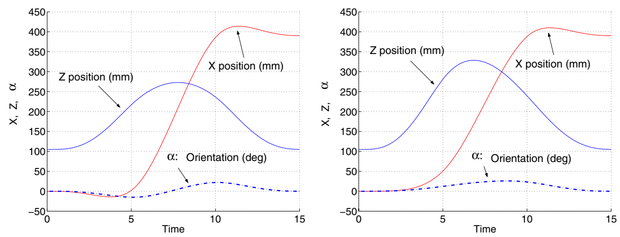
(a) Front foot (in Phase 1) (b) Rear foot (in Phase 3)

Fig. 6. Foot trajectories in X-Z plane



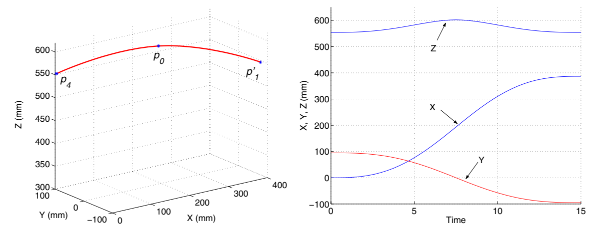
(a) Front foot (in Phase 1) (b) Rear foot (in Phase 3)

Fig. 8. Foot trajectories for obstacle with height of 200 mm



(a) Components of front foot (b) Components of rear foot

Fig. 7. Components of trajectory with time



(a) Trajectory in 3-D space (b) Components with time

Fig. 9. Waist trajectory

corresponding to the lower body and upper body of the robot to satisfy the two conditions mentioned above. At the current stage of our research, we control the CoM of the robot so that it is always within the convex hull of the supporting area(s) to maintain robot balance. Since the linear momentum P depends on the time derivative of CoM position r through the total mass m as $P = m\dot{r}$, the position of CoM can be controlled by manipulating the linear momentum as $P = km(\tilde{r} - r)$, where the tilde denotes the reference value, and k is the gain of the control scheme. Using this equation we are able to calculate the desired linear momentum P to control the robot CoM. We achieve this desired linear momentum by generating upper body motion of the robot using the resolved momentum control scheme presented in [9]. In our system, these values are controlled automatically during the stepping-over. Note that the robot balance can always be realized in our case, since the trajectory planning for the lower body motion is based on our previous feasibility analysis in which the constraint on robot balance has already been taken into account.

V. Simulation and Experiment

To verify the proposed planning method, we do some simulation and perform experiment in this section. These simulation and experiment are curried out on the same platform, the humanoid robot HRP-2.

A. Basic Results

We use a box with depth of $50mm$ and height of $150mm$ as the obstacle. From previous feasibility analysis, we know that this obstacle can be stepped over by HRP-2, since its height is less than the corresponding maximum height $242.1mm$.

The trajectories and orientations of the two feet in X-Z plane are shown in Fig.6, where the shaded blue triangles indicate the foot configurations at four path control points, and the shaded red rectangle represents the obstacle. It can be seen that the feet surmount the obstacle without any collision. While the orientation angle of the front foot first becomes negative (ankle pitches in negative direction) and then positive, that of the rear foot are constantly positive (though the ankle pitches in negative direction) because of the limit of ankle pitch in negative direction. Fig.7 shows the components of the trajectories with time, from which the good smoothness of the curves are seen. For comparison, Fig.8 show the foot trajectories of the feet for obstacle with height of $200mm$, where the line segments indicate the sole at different path points. These figures show the wide adaptation of the planning method to different obstacles.

Fig.10, Fig.11 and Fig.12 show some snapshots of the robot in the experiment. From these results, we see that the upper body of the robot also has its own motion (mainly that of the chest) by the RMC to keep the balance of the robot.

B. Discussion

In our simulation without dynamic stability, the robot can step over the obstacle with the constant waist height of $590\ mm$ during the procedure. However, in the experiment, the actual waist height in Phase 1 and 3 is reduced to about $540\ mm$. This is because, to keep the dynamic balance more easily with our current RMC, the waist moves little during these single-support phases. As stated before, the less the waist moves forward, the lower the waist height should

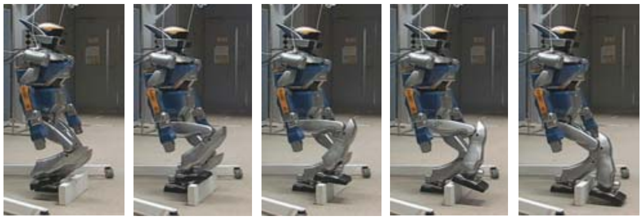


Fig. 10. Experiment of obstacle stepping-over (Phase 1)

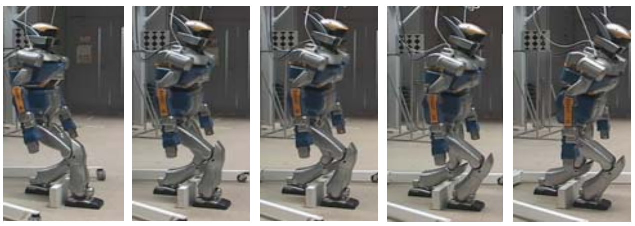


Fig. 11. Experiment of obstacle stepping-over (Phase 2)

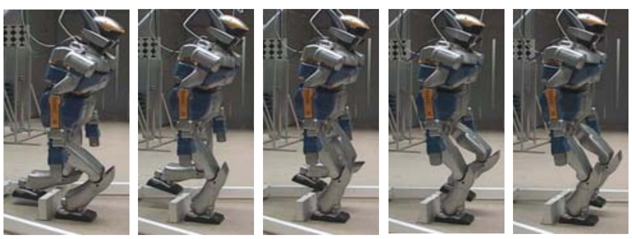


Fig. 12. Experiment of obstacle stepping-over (Phase 3)

be, for the validity of the inverse kinematics of the legs at the beginning and end stages in Phase 2. In addition, HRP-2 control system has a stabilizer, which may adjust to some extent the robot motion and in turn effects the original trajectory implementation. Especially when the lifted front leg touches the ground and hence a vibration is given rise, the stabilizer will take a bigger effect. Therefore for conservative safety, at this moment we let the robot waist moves forwards little, and as a result its height is a little bit smaller than the original one. To avoid collision between the shank and the obstacle, the height is then increased at the middle of Phase 2, as shown in Fig.9. Each component of the waist trajectory, $x(t), y(t)$ or $z(t)$, is defined by three control points (two end-points and the middle point), and consists of two fourth-order polynomials. It can be seen that the trajectory is very smooth.

HRP-2 is a humanoid robot with relative small sizes of the soles. The mass of upper body takes a rate of 72% of the total mass. To control the dynamic stability of the robot is really challenging. We are improving the RMC so that the robot CoM and ZMP can vary in a bigger range and hence the robot can move its waist forward more in obstacle stepping-over.

VI. Conclusions

Aiming at the task that the humanoid robots walk in complex environments cluttered with obstacles, we have addressed the problem of obstacle stepping-over. In this paper, we have taken motion planning of the robot as our target, focusing on the planning of foot trajectories and waist trajectory, based on the results of feasibility analysis in our previous research. A novel algorithm has been proposed to get parameters for trajectory planning, according to obstacle size, and then to generate the trajectories automatically. The algorithm has been designed for the adaptation to obstacles with different sizes. Two basic conditions, collision avoidance and robot balance, have been taken into account in the whole stepping-over procedure. To do so, the motion of the robot is decomposed into two parts. The motion of the lower body of the robot is controlled to realize the desired collision-free trajectories, and the motion of upper body is controlled by the resolved momentum control method to compensate the robot CoM and further to adjust ZMP for the robot dynamic stability during the stepping-over. The effectiveness of the presented planning method has been verified by simulation and experiment curried out on our humanoid platform HRP-2.

References

[1] R. Bartels, J. Beatty, and *et al*. *An Introducation to Splines for Use in Computer Graphics and Geometric Modelling*. Morgan Kaufmann, 1998.

[2] P. Channon, S. Hopkins, and D. Phan. Derivation of optimal walking motions for a biped walking robot. *Robotica*, 10(2):165–172, 1992.

[3] J. Chestnutt, J. Kuffner, K. Nishiwaki, and S. Kagami. Planning biped navigation strategies in complex environments. In *IEEE-RAS Int. Conf. on Humanoid Robots*, 2003.

[4] R. Cupec, O. Lorch, and G. Schmidt. Vision-guided humanoid walking – concepts and experiments. In *12th Intl. Workshop on Robotics in Alpe-Adria-Danube Region*, 2003.

[5] Y. Guan, K. Yokoi, and K. Tanie. Feasibility: Can humanoid robots overcome given obstacles? In *IEEE Int. Conf. on Robotics and Automation*, 2005.

[6] Y. Guan and H. Zhang. Kinematic graspability of a 2d multifingered hand. In *IEEE Int. Conf. on Robotics and Automation*, pages 3591–3596, 2000.

[7] Q. Huang, K. Yokoi, S. Kajita, and *et al*. Planning walking patterns for a biped robot. *IEEE Transactions on Robotics and Automation*, 17(3):280–288, 2001.

[8] S. Kajita, F. Kanehiro, and *et al*. Resolved momentum control: Humanoid motion planning based on the linear and anular momentum. In *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 1644–1650, 2003.

[9] S. Kajita, F. Kanehiro, K. Kaneko, and *et al*. Biped walking pattern generation by using preview control of zero-monment point. In *IEEE Int. Conf. on Robotics and Automation*, pages 1620–1626, 2003.

[10] J. Kuffner, S. Kagami, K. Nishiwaki, and *et al*. Dynamically-stable motion planning for humanoid robots. *The Journal of Autonomous Robots*, 12(1):105–118, 2002.

[11] L. Roussel, C. Canudas de wit, and A. Goswami. Generation of energy optimal complete gait cycles for biped robots. In *IEEE Int. Conf. on Robotics and Automation*, pages 2036–2041, 1998.

[12] T. Sugihara, Y. Nakamura, and H. Inoue. Realtime humanoid motion generation through zmp manipulation based on inverted pendulum control. In *IEEE Int. Conf. on Robotics and Automation*, pages 1404–1409, 2002.