Dynamically Stepping Over Obstacles by the Humanoid Robot HRP-2

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***Abstract*— Humanoid robots have the potential to navigate through complex environments such as the standard living surrounding of humans. One of the advantages is that a biped can negotiate obstacles by stepping over them, which is the topic of the work presented in this paper. The main focus of this research is to investigate stepping over large obstacles. Previous work has reported on algorithms using quasi-static balancing, which resulted in somehow unnatural slow motions. This work however is focussing on stepping over larger obstacles in a fluent dynamic motion, using stability criteria on zero moment point instead of center of gravity. All the work is formulated in function of the elaborate HRP-2 humanoid research platform.**

The strategy uses a preview controller for dynamic balancing and consists of collision free trajectory generation for feet hip. Several measures have been implemented to avoid overstretching of the knee and reduce impact at touch-down.

I. Introduction

The last two decades, substantial progress has been made in the field of legged robots. The latest developments, worldwide, show elaborate and nice hardware models featuring fully equipped humanoids. In the past, the main research effort consisted in hardware design and walking pattern generators, where as recently research centers begin to focus on more specific topics in increasing the autonomy and skills of humanoids. After all, a humanoid robot might be the future assistant for humans in the latter's own environment due to its specific layout. A lot of research is going on in a broad field of expertise, e.g. vision guided self localization [1], humanoid cognitive architectures [2] and task-oriented whole body control [3]. Another important topic, specifically related to humanoids, is the autonomy towards navigation in a complex human environment. In this framework a lot of attention goes to path planning, focussing on obstacle avoidance and goal seeking [4], [5]. These studies do incorporate the specific abilities of humanoids towards mobility, which is the use of discrete footholds and as such being able to step over obstacles. But with respect to the latter, the regarded obstacles generally are small, while actually a humanoid has the capability of negotiating larger obstacles which are often encountered in a standard human environment. Of course this requires specific strategies, which is the topic of this paper. The presented work specifically focuses on implementation on the elaborate humanoid research platform HRP-2 [6].

Previous work on stepping over large obstacles, conducted by Guan [7], investigated the feasibility of the stepping over. Hereby focusing on quasi-static stepping over procedures by keeping the projection of the global Center of Gravity (*CoG*) of the robot within the polygone of support. Since the postural stability only takes into account the *CoG*, the motion of the robot has to be slow in order not to induce substantial accelerations and as such not demanding for dynamic stability criteria, e.g. Zero Moment Point (*ZMP*).

If large obstacles are considered, this quasi-static stepping over motion has a quite unnatural resemblance due to the continuous restricting balancing of the *CoG*. Moreover, a large double support phase is required, in order to shift the *CoG* from the rear to the front during the double support phase. This implies kinematical restrictions and consequently limits the dimensions of the obstacles which can be negotiated.

On the contrary, a dynamic stepping over procedure cancels the restriction of the *CoG* balancing and allows a short double support phase. A dynamic walking pattern is characterized by postural stability on the *ZMP* criterion and allows the *CoG* to leave the supporting foot as long as the *ZMP* stays within the polygon of support. As such the *CoG* can be shifted over the obstacle during one single support phase, which in theory should allow for only using an instantaneous double support phase, if running is not regarded. This results in larger obstacle dimensions which can be negotiated.

A 2D study on stepping over large obstacles [8] proposed a preliminary collision free foot trajectory planner and pointed out some considerations concerning the dynamic influence of the stepping over on the specific dynamic pattern generator currently incorporated in the HRP-2 robot. This paper reports on a full 3D study with adapted foot, hip and body trajectories and focusses on practical implementation on the real robot. Hereby pointing out essential issues related to this practical implementation, which restricts the imposed trajectories.

II. Overall Dynamic Pattern Generator by Preview Control

The pattern generator used in this work is based on a preview control method on *ZMP*, developed by Kajita [9]. Since this method and its features are extensively used for the stepping over procedure, a short description is given here.

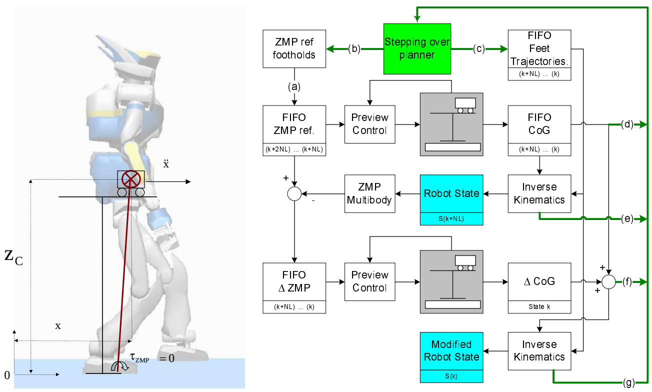


Fig. 1. The cart-table model with preview control scheme

Further detailed information can be found in the work of Kajita [9].

The equations of motion are represented by the cart-table model: the motion of the *CoG* of the robot is that of a cart moving on a horizontally positioned pedestal table with negligible mass, as depicted in Fig. 1, hereby using two cart-table representations for the horizontal motion in the sagittal (x-z) and the frontal (y-z) plane separately. The basic equations for this simplified representation, linking the *ZMP* to the *CoG*, are as follows [9]:

$$\ddot{x} = \frac{g}{z_c}(x - p_x) \tag{1a}$$

$$\ddot{y} = \frac{g}{z_c}(y - p_y) \tag{1b}$$

With x, y the moving coordinates of the *CoG*, z_c the constant height of the *CoG*, and p_x, p_y the position of the *ZMP*. If the cart is positioned near the edge of the table, the latter tends to tilt due to the small supporting area (comparable with a robot foot). But with proper accelerations, the *ZMP* can still be within the supporting area and as such the table will keep upright. This corresponds to the basic idea of dynamic walking of a humanoid, and is also of great importance for the dynamic stepping over. The *CoG* of the robot might already be over the obstacle but the robot can still be supported by the foot in front of the obstacle, which is not possible with a quasi-static motion.

The main idea of the pattern generator is to plan the motion of the *CoG*, represented by the hip motion, in function of desired *ZMP* trajectories determined by the foothold sequences. The problem is regarded as a *ZMP* servo control implementation, trying to track the *ZMP* by servo control of the horizontal acceleration. The use of preview control for solving the Eqs. (1) requires future information of the desired *ZMP* (foothold) planning. For each sample k with sample time *T*, *NL* future *ZMP* input points are stored in a fifo (first in first out) buffer and all this information contributes to the calculation of the actual position of the *CoG*.

An important parameter influencing the result is the height of the *CoG* (Z_c) which is supposed to be constant according to the cart-table model. For dynamic stepping over, the *CoG* does stay on a plane at all: firstly, due to the necessary hip height changes in order to adapt to the closed chain configuration during double support over the obstacle; and secondly large swing leg motions induce vertical as well as horizontal deviations on the *CoG* position. With respect to this issue, Kajita [9] proposes a re-feeding of the complete multi-body calculated *ZMP* trajectory into the preview control by means of taking the error between the latter and the desired *ZMP* trajectory. This error (Δ*ZMP*) is again presented as input of a second stage of preview control with the same cart-table model, resulting in deviations of the horizontal motion of the *CoG* (Δ*CoG*). The complete scheme of this implementation is given in Fig. 1, which also includes the stepping over planner, elaborated on in the next section. Thus, the complete control loop needs *2NL* future *ZMP* input points: *NL* Δ*ZMP* calculations are required to determine the final robot configuration at sample point *k*, but each of these *NL* Δ*ZMP* values are respectively derived from a calculated *CoG* value during the first preview round, which in turn needs *NL ZMP* input points. The main point is that the impact of the deviations between the multi-body model and the simplified cart-table model are cancelled by the second preview loop.

III. Foot Trajectory Planning

A. Feasibility during Double Support

A dynamic stepping over procedure has the important advantage of a short double support phase, contrary to a quasi static procedure since the *CoG* can be behind the obstacle while the supporting foot is still in front of it. This leads to a kinematical advantage concerning the feasible dimensions of the obstacle which can be negotiated.

The actual leg layout of HRP-2 and the closed kinematic chain during the double support phase makes this phase mainly determine the actual obstacles which can be stepped over. As such the stepping over planner starts here and calculates the step length, step height and foothold positions during the stepping over procedure. Fig. 2 shows all the essential parameters which are of concern for these calculations. The obstacle is regarded to be rectangular with certain width O_w and height O_h. For the stepping over trajectory planning a safety margin (S_w, S_h) around the obstacle is included, not only to cope with deviations on calculated kinematics due to tracking errors during the actual stepping over, but mainly regarding the uncertainty of the vision system, determining the obstacle dimensions, which will be implemented in the future.

The feasibility study is a kinematical study which calculates a collision free configuration determining step-length ($X_{a_{DS}}$) and hip-height ($Z_{h_{DS}}$), for large obstacles. The selection of these parameters starts with minimal step-length and normal walking hip-height, while piecewise increasing step-length and decreasing hip height until a collision free configuration is found. Hereby taking into account a minimum angle (q_{min}) for the knee angle (q_k) which can not be exceeded in order to avoid the singular configuration of knee overstretch.

As mentioned, the leg layout substantially limits the available space for the obstacle. And the determination of the possible configurations in this double support phase relies on collision detection between both lower legs and the obstacle. These calculations use a simplified representation of the leg layout, considering several line segments: (l_1, l_2)..(l_3, l_4) for the front side of the lower leg, and (l_5, l_6), (l_6, l_7) for the rear side. The basics of detection of a collision is performed by calculation in 2D of the intersection between two line segments which is straightforward by considering an oriented area (e.g. A_{l_1,l_2,o_1}) formed by respectively three end points involved [7]:

$$A_{l_1,l_2,o_1} = x_{l_1}(z_{l_2} - z_{o_1}) + x_{l_2}(z_{o_1} - z_{l_1}) + x_{o_1}(z_{l_1} - z_{l_2}) \quad (2)$$

No intersection occurs between line segment (l_1, l_2) and (o_1, o_2) if:

$$max(A_{l_1,l_2,o_1} A_{l_1,l_2,o_2}, A_{o_1,o_2,l_1} A_{o_1,o_2,l_2}) > 0 \quad (3)$$

The 3D collision detection will check on combinations of intersection between the line segments of the leg and rectangular planes around the obstacle formed by the respective lines (o_1, o_2)...(o_3, o_4). For this 'line by plane intersection' check, each time two projections of the points which bound the leg line segments are made in the obstacle coordinate frame (aligned with the obstacles boundaries) . The coordinates of l_i given in the local lower-leg frame $l_i^{leg} = (X_{l_i}, Y_{l_i}, Z_{l_i})$ are transformed to the waist base frame of the robot (transformation $R_{l\to b}$), depending on joint angels of the leg. Subsequently, depending on the position of the robot, these new coordinates are transformed to the world frame ($R_{b\to w}$) and depending on the orientation of the obstacle, the obstacle coordinates are related to the world frame ($R_{o\to w}$). Thus the leg segment coordinates are transformed to the obstacle frame as:

$$l_i^{obst} = R_{o\to w}^{-1} R_{b\to w} R_{l\to b}\, l_i^{leg} \quad (4)$$

So now depending if the plane to examine is parallel to the ground (XY) or standing vertically upright (YZ) the specific projections (X_{l_i}, Y_{l_i} and X_{l_i}, Z_{l_i}) or (Y_{l_i}, Z_{l_i} and X_{l_i}, Z_{l_i}) are used respectively.

Since the rear leg is most likely to collide with the obstacle, due to the knee which is directed towards the obstacle, the heel of the front foot behind the obstacle is positioned near the safety boundary around the obstacle at point o_4. Thus, once the step-length is calculated, both foothold positions of front and rear foot are determined. Now there is one important parameter which resides in the calculations of the feasible step-length. The kinematical calculation of the closed loop formed by the two legs involves the horizontal hip distance $X_{h_{DS}}$ in the sagittal plane (and $Y_{h_{DS}}$ in the frontal plane), which in fact is determined by the dynamic pattern generator. But the pattern generator on the contrary first needs the input of *ZMP* trajectories and foothold positions. Therefor the calculation of the step-length ($X_{a_{DS}}$), and consequently foothold position, by the stepping over planner uses a parameter (δ_{DS}) which

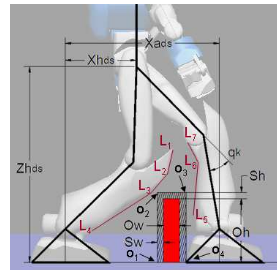


Fig. 2. Double support phase feasibility

determines the position of the hip during double support in function of the step-length:

$$X_{h_{DS}} = \delta_{DS} X_{a_{DS}} \quad (5)$$

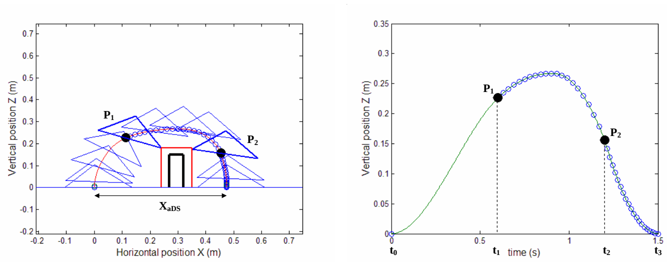
The value of this parameter originates from a look-up table containing an estimate for different step-lengths created by the pattern generator, for which a specific step-time has to be chosen. For the Y direction in the frontal plane, generally $Y_{h_{DS}} = 0$ if the left and right foot are positioned symmetric with respect to the center waist frame. The height of the hip of course is determined by the feasibility selection itself.

In summary, as a result of the feasibility calculation, first of all can be decided if a specific obstacle can be negotiated by stepping over or not. And in case the answer is positive, the footholds and consequently the desired *ZMP* course can be determined. This is indicated by the flow line (*b*) in the general scheme of Fig. 1. The next step is to plan the foot trajectories during the step over procedure.

B. Spline Foot Trajectories

Contrary to regular walking the stepping over of large obstacles requires more information to be used for the design of the foot trajectories, in order not to collide with the obstacle. Therefore Clamped Cubic Splines (CCS), for the 3 translations (X,Y,Z) and yaw rotation ω of the foot (ccw+ angle between horizontal and foot sole), are chosen over the more traditional polynomials because these tend to oscillate when different control points are chosen. Clamped Cubic Splines are constructed of piecewise third-order polynomials which pass through a set of control points with a chosen start and end velocity. These boundary values on the velocity are chosen zero to avoid impacts at touch-down and have a smooth transition at lift-off.

For the following discussion on the trajectory design, it is assumed that the feet are oriented orthogonal with respect to the obstacle, which is actually the situation depicted in Fig. 2. The more general case only involves some extra straightforward geometrical calculations. The trajectories are calculated for the point on the sole right beneath the ankle point. Two intermediate control points P1 and P2 are selected to construct the foot trajectories. For most cases the Y coordinate (horizontal frontal plane axis) of the feet is kept constant, so the focus is set on the sagital horizontal X and vertical Z coordinate. The two intermediate control points P_1 and P_2



(a) Foot trajectory XZ plane (b) Foot trajectory Z

Fig. 3. Spline Foot trajectory construction

are depicted in boldface in Fig. 3, and are determined such that the tip of the foot coincide with point o_2 of the obstacle and the ankle of the foot with point o_3 respectively. When the rotation of the foot for the two instants are chosen (ω_1, ω_2)to prevent self collision of the leg and the foot, the horizontal X and vertical Z coordinates with respect to the stance foot in front of the obstacle are calculated as follows:

$$X_{P_1} = X_{a_{DS}} - d^X_{ah} - 2S_w - O_w - d^X_{at}cos(\omega_1) \quad (6a)$$
$$Z_{P_1} = O_h + S_h - d^X_{at}sin(\omega_1) \quad (6b)$$
$$X_{P_2} = X_{a_{DS}} - d^X_{ah} + d^X_{ah}cos(\omega_2) \quad (6c)$$
$$Z_{P_2} = O_h + S_h + d^X_{ah}sin(\omega_2) \quad (6d)$$

with d^X_{ah} and d^X_{at} the horizontal distances (foot on the ground) between ankle and heel and ankle and tip respectively and $X_{a_{DS}}$ calculated by the feasibility study.

The Clamped Cubic splines are constructed for the X and Z direction and the yaw rotation ω in function of time, as such that the selected coordinates of P_1 and P_2 are accompanied by appropriate time instants t_1 and t_2, and two position and additional speed conditions at lift-off t_0 and at touch-down t_3. Thus with this structure the following data set is presented for the spline construction:

$$X_f : [(t_0, 0)\,;\,(t_1, X_{P_1})\,;\,(t_2, X_{P_2})\,;\,(t_3, X_{a_{DS}})] \quad (7a)$$
$$Z_f : [(t_0, 0)\,;\,(t_1, Z_{P_1})\,;\,(t_2, Z_{P_2})\,;\,(t_3, 0)] \quad (7b)$$
$$\omega_f : [(t_0, 0)\,;\,(t_1, \omega_1)\,;\,(t_2, \omega_2)\,;\,(t_3, 0)] \quad (7c)$$

One interesting feature using splines is the possibility to add extra intermediate points easily by expanding the data series (7) in order to force the function to pass through these points and mold the trajectory at will depending on the specific needs. This e.g. is performed for the Z coordinate of the first foot stepping over the obstacle, as depicted in Fig. 3b. The first trajectory on the interval [t_0,t_1] is untouched, but both trajectories on [t_1,t_2] and [t_2,t_3] have extra data points. The first adapted interval is modified with extra points to limit the height to which the standard spline would direct the swing foot, comparable to the use of regular polynomials on this specific interval. The second adapted interval is modified to adjust the speed conditions at touch-down. Although, the Clamped Cubic spline function ensures zero velocity at touch-down, it does not specify the acceleration in this point. Now in a real application, the desired trajectory of the foot is not tracked perfectly due to e.g. compliance in the foot, tracking limitation and additional stabilizing control loops. Therefore the time instant of impact is not exact the one predicted by the pattern generator and as such the speed is not necessarily zero at touch-down, which of course increases impact. For regular walking this is not an issue but for a dynamic movement such as stepping over large obstacles, the touch-down condition should be smoothed.

The distance between the extra intermediate points on the interval [t_2,t_3] is made variable by a weight function based on a speed profile. A speed value at start and end are chosen: v_s and v_e, and if the number of extra intermediate points is n, the discrete speed weight function $V_w(i)$ to set the distance between the intermediate points is created as follows:

$$V_d(i) = (v_e - v_s)\,\frac{i}{n} + v_s \qquad i : [1 : n] \quad (8a)$$
$$V_w(i) = \frac{V_d(i)}{\sum_{i=1}^{i=n} V_d(i)} \qquad i : [1 : n] \quad (8b)$$
$$|Z_i - Z_{i-1}| = V_w(i)|Z_n - Z_0| \qquad i : [1 : n] \quad (8c)$$

$V_d(i)$ (8a) is a linear distribution of the speed over the time interval, but this can be any function. For the last time interval [t_2,t_3] e.g. the begin and end speed are:

$$v_s = \frac{-Z_{P_2}}{t_3 - t_2} \quad ; \quad v_e = 0 \quad (9)$$

This construction leads to the smooth profile at touch-down, as can be seen on Fig. 3b. For the time interval [t_1,t_2] a central control point in the middle of this interval is added to set the maximum height that the foot is allowed to swing. Subsequently two analogous constructions (8) are used to set all the intermediate points on [t_1,t_2].

This spline structure is a very flexible tool, allowing to shift the intermediate points easily when necessary, while still ensuring a continuous trajectory. And this becomes important when dealing with large obstacles, after all the control points P_1 and P_2 are determined as such that there is no collision with the obstacle, but nothing ensures that the complex leg movement in total does not touch the obstacle. Especially the rear leg for which the knee is bending towards the obstacle during the stepping over. For these situations an online collision free trajectory adapter is required which will shift the data points of the spline construction. This topic is beyond the scope of this paper and has been discussed in a previous publication [8].

IV. Complete Leg Motion

The feasibility study discussed in section III-A selected a collision free combination of the step-length and hip-height for the short double support phase over the obstacle. The calculation of the step-length allows for the planning of foothold sequence and the construction of the foot spline trajectories. The hip-height selection demands for a planning of the vertical hip motion, which has to be changed (in general lowered) from the normal walking height to the one ($Z_{h_{DS}}$) at double support over the obstacle. During the step over of the first leg, the hip is lowered such that it reaches $Z_{h_{DS}}$, subsequently it is raised again during the second step. Both these motions are achieved by regular 3^{th} order polynomials which include boundary conditions at position and velocity level.

To clear more space during the double support over the obstacle and consequently allow for larger obstacles to be stepped over, the waist of the robot is rotated. The HRP-2 robot includes 2 extra degrees of freedom (yaw and pitch) between the waist and upper-body such that the upper-body and head (with vision system) is oriented towards walking direction. This motion is achieved with an analogous polynomial structure as for the vertical hip motion.

The desired footholds are presented for the *ZMP* reference FIFO (link (a) and (b) in Fig. 1) of the preview control, such that the horizontal and vertical hip motion can be calculated by the dynamic pattern generator. On the other hand the planned spline functions allow to fill the FIFO foot buffers (link (c) in Fig. 1) and, including the vertical hip motion, inverse kinematics are performed to determine the complete leg motion. As such the correcting second preview loop can be completed and the final robot state determined for each sampling time. The graphs in Fig. 4 show *ZMP* and *CoG* planning in both X and Y direction, and foot trajectories in X and Z direction with respect to time for stepping over an obstacle of 15 cm height and 5 cm width (18 height and 11 width including safety boundaries). The graphs show both desired *ZMP* and complete multi-body *ZMP*, clearly showing the robustness of the pattern generator due to the second correcting preview loop. A difference between desired *ZMP* and actual *ZMP* can be witnessed on the graphs for the Y direction during the stepping over, due to the large leg swing motions, but the deviations don't jeopardize the stability since the *ZMP* is still far away from the foot boundaries. The double support of the stepping over is situated between 5 and 6 s.

For normal walking the step length is 0.23 m while the stepping over demands a step length of 0.48 m. Thus for the stepping over almost doubled distance has to be travelled by the legs, therefore the step time of the stepping over is increased. The timing for the step sequence is 0.78 s single support and 0.02 s double support for the normal steps and 1.5 s, 0.04 s respective phase times for the stepping over itself and the preceding and succeeding steps. The step time may not be set too high otherwise the motion will become more and more static, causing the hip to stay for a long time above the stance foot and inducing overstretch.

It is mainly during the lowering of the first leg over the obstacle from point P_2 to touch-down that overstretch of the swing leg knee occurs due to the hip motion which is not evolved far enough to the front. To cope with the overstretch problem a combination of several modifications is implemented. First the desired *ZMP* is moved to the middle of the foot instead of under the ankle point. Secondly, the rotation of the upper-body and arms is used to shift the hip more to the front. By imposing a backwards motion of the upper-body (arms), the second preview loop (which includes

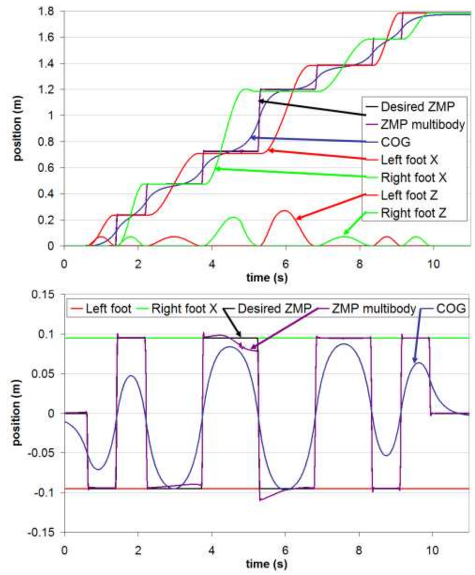


Fig. 4. *ZMP*, *Cog* and foot motion for stepping over an obstacle of 15 cm height and 5 cm width (18 height and 11 width including safety boundaries)

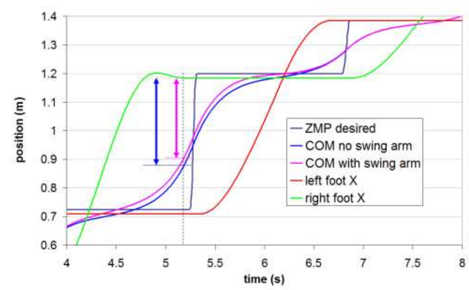


Fig. 5. Effect Induced of *CoG*-shift by Upper-body Motion

complete upper-body motion) will try to keep the *ZMP* in the desired position by shifting the *CoG* more to the front. This can be witnessed on the graph in Fig. 5 which depicts the *ZMP* and foot motion for the X direction during the stepping over and two situation of the *CoG* planning, with and without *CoG* shift for the upper-body motion. This *CoG* shift is achieved by moving the arms to the back with an analogous polynomial planning as for the vertical hip motion. Note that a small difference between foot and hip induces large differences on the knee angle in the near stretched position, so a small extra movement of the hip towards the front is sufficient to avoid overstretch. Of course the hip can not be directed forward too much since in that case the rear leg reaches the stretched position. In general the complete stepping over required fine tuning of several parameters and some online adaptation of trajectories. That is why in figure 1 the feedback loops ((d). . . (g)) to the step over planner are drawn. Part of the feedback for the online collision free trajectory planner has been explained in [8] but for this paper and the current experimental implementation these feedbacks are not yet used. And some rules for proper parameter selection still

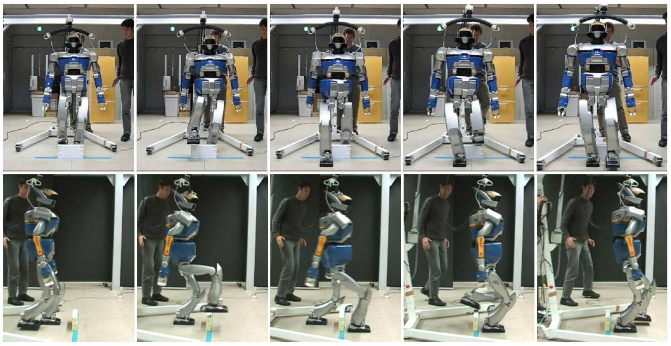


Fig. 6. Photograph sequence of HRP-2 stepping over an obstacle of 15 cm height and 5 cm width (18 height and 11 width including safety boundaries). The images are taken every 0.64 s

have to be developed.

V. Experimental Results

Fig. 6 shows a photograph sequence of HRP-2 stepping over an obstacle of 15 cm height and 5 cm width corresponding the motion discussed in the previous section, including an arm motion to the back. On the accompanying video several motions over different obstacles are presented. But the obstacle limit for real experiments so far is 15 cm mainly due to the following reasons.

An important influencing factor is the presence of the extra stabilizing control loop [10]. The preview pattern generator takes into account the complete multi-body model of the robot but does not include model parameter errors, the compliance of the feet, extra external perturbations, etc.... Therefore the stabilizer acts on the posture of the robot trying to match the real measured *ZMP* with the desired one. This feedback loop controls hip motions and consequently the stance leg configuration, but it also adapts the swing leg according to the changing hip. Consequently, even if near overstretch situations are carefully avoided by the step over planner, the stabilizer tends to induce again overstretch, mainly because the performance of the feedback control is poor in near stretched positions. Therefore the step over planner needs to apply more severe boundaries to avoid overstretch. Another issue is the speed and torque limitation of the motors, which reduces the tracking performance of some specific motions. For stepping over an obstacle of 20 cm this limitation was reached.

VI. Conclusions and Future Work

This paper reports on dynamic stepping over large obstacles by the humanoid robot HRP-2. It reports on the specific trajectory planning for feet, hip and upper-body motion while making use of a powerful and robust preview pattern generator developed by Kajita [9].

Although, in dynamic simulation (OpenHRP) stepping over an obstacle with 20 cm height and 5 cm width (23 height and 11 width including safety boundaries) was achieved, the current experimental status reaches approximately 15 cm height. In view of this, one has to realize that an obstacle of 20 cm height for a robot with stretched ankle to hip length of 30 cm is comparable to an obstacle with height 30 cm for a human.

In the near future, some fine tuning of the trajectories will be performed to overcome some of the limitations imposed by the real experiments in order to step over higher obstacles. Moreover, the collision free online trajectory adapter for large obstacles, discussed in previous work, will be implemented. And, an automatic selection procedure for some essential parameters will be investigated. Subsequently, the vision system to detect obstacle dimensions and position will be integrated.

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References

[1] S. Thompson and S. Kagami, "Humanoid robot localisation using stereo vision," in *Proc. IEEE International Conference on Humanoid Robots*, (Tsukuba, Japan), pp. 19–25, IEEE, 2005.

[2] C. Burghart, R. Mikut, R. Stiefelhagen, T. Asfour, H. Holzapfel, P. Steinhaus, and R. Dillmann, "A cognitive architecture for a humanoid robot: A first approach," in *Proc. IEEE International Conference on Humanoid Robots*, (Tsukuba, Japan), pp. 357–362, IEEE, December 2005.

[3] N. Ee Sian, K. Yokoi, S. Kajita, and K. Tanie, "A stable foot teleoperation method for humanoid robots," in *Proc. IEEE International Conference on Robotics and Automation*, (New Orleans, USA), pp. 1065 – 1070, April 2004.

[4] R. Cupec, and G. schmidt "An Aproach to Environment Modelling for Biped Walking Robots" in *Proc. IRS/RSJ International Conference on Intelligent Robots and Systems.*, (Alberta, Canada), IEEE, August 2005.

[5] P. Michel, J. Chestnutt, J. Kuffner, and T. Kanade, "Vision-guided humanoid footstep planning for dynamic environments," in *Proc. IEEE International Conference on Humanoid Robots*, (Tsukuba, Japan), pp. 13–18, December 2005.

[6] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozumi, "Humanoid robot HRP-2," in *Proceedings of the IEEE International Conference on Robotics and Automation*, (New Orleans, USA), pp. 1083–1090, 2004.

[7] Y. Guan, K. Yokoi, and K. Tanie, "Feasibility: Can humanoid robots overcome given obstacles?," in *Proc. IEEE International Conference on Robotics and Automation*, (Barcelona, Spain), pp. 1066–1071, IEEE, April 2005.

[8] B. Verrelst, K. Yokoi, O. Stasse, H., Arisumi and B., Vanderborght "Mobility of Humanoid Robots: Stepping Over Large Obstacles Dynamically" in *Proc. IEEE International Conference on Mechatronics and Automation*, (Henan, Luoyang, China), IEEE, June 2006.

[9] S. Kajita, K. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, "Biped walking pattern generation by using preview control of zero-moment point," in *Proc. IEEE International Conference on Robotics and Automation*, (Taipei, Taiwan), pp. 1620–1626, IEEE, 2003.

[10] K. Yokoi, F. Kanehiro, K. Kaneko, K. Fujiwara, S. Kajita, and H. Hirukawa, "A honda humanoid robot controlled by AIST software," in *Proceedings of the IEEE/RAS International Conference on Humanoid Robots*, (Tokyo, Japan), pp. 259–264, 2001.