Studying the Effect of Different Optimization Criteria on Humanoid Walking Motions

Kai Henning Koch[1], Katja Daniela Mombaur[1], and Philipp Souères[2]

[1] IWR - University of Heidelberg - Im Neuenheimer Feld 368
69120 Heidelberg - Germany
Henning.Koch@iwr.uni-heidelberg.de, kmombaur@uni-hd.de
[2] LAAS-CRNS - 7, av du Colonel Roche - 31077 Toulouse Cedex 04 - France
philippe.soueres@laas.fr

Abstract. The generation of stable, efficient and versatile walking motions for humanoid robots is still an open field of research. Several approaches have been implemented on humanoids in the past years, but so far none has led to a walking performance that is anywhere close to humans. This may be caused by limitations of the robotic hardware, but we claim that it is also due to the methods chosen for motion generation which do not fully exploit the capabilities of the hardware. Often, several characteristics of the gait, such as foot placement or step time, are fixed in advance in a suboptimal way for the robot. In this paper we discuss the potential of our optimal control techniques based on dynamical models of the humanoid robot for the generation of improved walking motions. We apply the method to a 3D dynamic model of the humanoid robot HRP-2 with 36 DOF and 30 actuators. Robot specific stability constraints (such as ZMP constraints) can be taken into account in the optimization. We present results for five different objective functions, and evaluate the influence of free foot placement and a relaxation of ZMP constraints.

Keywords: optimal control, humanoid robot, HRP-2, simulation, walking motion.

1 Introduction

Humanoid robots are highly redundant and underactuated multibody systems with many degrees of freedom. Generating walking motions for them which are at the same time efficient, stable and versatile, is a challenging task, and the motion capabilities of today's humanoids are still far behind those of humans. We claim that this problem is not only pertaining to the present robotic hardware, but that more effort should be put into choosing and developing appropriate software and control methods that can exploit all motion capabilities of the given hardware. In this paper, we explore the use of optimal control methods for the generation of walking motions for the humanoid robot HRP-2 [11]. The use of optimization approaches can be justified in two different ways:

– Optimization is used to mimic biology: It is a common assumption that movements of humans and animals are optimal due to evolution, individual

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development and training [15]. Optimization criteria depend on the particular situation. With optimal control techniques we can generate optimal motions for robot models, optimizing important gait characteristics such as stability, efficiency, effort or speed.
– Optimization is helpful for technical reasons: it serves on the one hand to find walking solutions that are feasible (among an infinite number of infeasible solutions), and on the other hand to select from the remaining motion abundance (i.e. the still large number of feasible gaits).

The efficient optimal control approach that we are presenting in this paper allows to determine position and velocity trajectories as well as actuator inputs simultaneously in an optimal way, and does not require to prescribe any of these quantities a priori. We compare the effect of five different objective functions (minimization of torque and of joint velocities, and a maximization of walking speed, of postural stability and of efficiency). In addition, we evaluate the effect of different constraints on the motion. First optimization results for HRP-2 have been presented in [12], but the present paper provides more detailed results for all objective functions and constraints as well as a more extensive discussion of the applicability of the different numerical results to the robot. We would like to emphasize that this paper treats the problem of offline motion generation and not the online control of walking. The fact that the computations described in this paper can not be performed in real time is therefore not an issue. Online control techniques such as real time optimization or NMPC (nonlinear model predictive control) methods later have to be applied to implement the computed trajectories on the real humanoid robot.

In many humanoid robots, walking is initially planned constraining the ZMP (zero moment point) [25] to lie within a desired region. To generate feasible reference walking trajectories many authors considered the linear inverse pendulum model [10]. The mass of the pendulum is usually set at the center of mass (CoM) of the robot and restricted to move horizontally. The method was extended in [8] to generate 3D walking. Model-based reference trajectory generation is the key point in the control of many humanoid robots such as ASIMO [23], WABIAN [6], or HRP-2. A well established approach is the technique of the pattern generators [19,24]. These methods may usually perform in real-time and are convenient to parametrize but do not choose gait characteristics in an optimal way. An alternative approach is the stack of task [14,20] to compute cascaded quadratic programs to minimize slacks with respect to a growing pile of constraint sets to represent descending priority-layers. Optimization approaches have also been used to generate walking motions. Investigations of cyclic walking motions for planar bipeds based on forward and inverse dynamic models have been published by [21,5,3,1] based on direct (e.g. collocation) and indirect optimization (Pontryagin Maximum Principle) methods with minimum energy consumption criteria. Based on stability optimization Mombaur et al. ([17,18,16]) published open-loop stable walking and somersault motions of bipedal walking mechanisms. In [22] optimization has been used to generate realistic running motions of 2D and 3D anthropomorphic models.

The remainder of this paper is organized as follows: In Section 2, we briefly present the dynamic models of walking motions of the humanoid robot HRP-2. In Section 3, we describe the formulation and solution of optimal control problems to generate walking motions. Section 4 presents extensive optimization results and compares different optimization criteria. We end the paper with a short summary and and outlook on the extensions of the presented research.

2 Mathematical Models of Walking Motions of the Humanoid Robot HRP-2

This section describes the 3D mathematical model of the humanoid robot HRP-2 in a form that is suitable for the use in optimal control problems. HRP-2 has 36 DOF and 30 torque actuators. We use the following assumptions for our robot model: the robot has rigid links and transmission units, the transmission ratios are sufficiently high that dynamic coupling effects of the motor inertias to the whole body structure are negligible and joint friction is not considered. The robot has flat, rubber coated feet and and an elastic 3 DOF ankle joint, but both elasticities are neglected for the present computations. HRP-2 is equipped with a stabilizer ([9]) that serves to prevent the robot from falling by compensating small modeling errors and small external perturbations. The stabilizer aims at keeping the ZMP in a stability region that is smaller than the actual support polygon. The base reference frame is fixed to the pelvis. As model coordinates we use the six coordinates of this base frame as well as the 30 internal joint angles, which would be minimal coordinates for a free-floating robot. In single and double support, the robot looses DOF, but we keep the same set of coordinates during all phases and describe their redundancy by additional algebraic constraints.

Walking motions are described as a series of alternating single and double support phases. In this study, we are only interested in symmetric and periodic gaits, and therefore we can reduce the mathematical problem formulation to one step of the gait and a subsequent mirroring of sides after which periodicity constraints are applied (see [22] for more details). The equations of motion of this multibody system result in nonlinear systems of differential algebraic equations for redundant coordinates:

$$\dot{q} = v \tag{1}$$

$$\dot{v} = a \tag{2}$$

$$\begin{pmatrix} M & G^T \\ G & 0 \end{pmatrix} \begin{pmatrix} a \\ \lambda \end{pmatrix} = \begin{pmatrix} -N + F \\ \gamma \end{pmatrix}, \tag{3}$$

also satisfying the constraints on position and velocity level $g(q) = 0$ and $\frac{\mathrm{d}g(q(t))}{\mathrm{d}t} = G\dot{q} = 0$.

In these equations, M is the symmetric positive definite mass matrix and N is the term of nonlinear effects (combining Coriolis, centrifugal and gyroscopic forces): Matrix M and vector N for the humanoid robot HRP-2 have been computed with the automatic model generator HuMAnS [26]. In equation (3), F denotes the sum of all external forces acting on the multibody system, such as gravity force, joint torques, etc. The constraint Jacobian and constraint Hessian are $G = (\partial g/\partial q)$ and $\gamma = -\left(\left(\partial G/\partial q\right)\dot{q}\right)\dot{q}$, and λ the vector of Lagrange multipliers.

Switches from one motion phase to the next do not take place at given times but depend on the position variables which can be expressed by so-called switching functions

$$s(q, v, p) = 0. \tag{4}$$

Touchdown takes place, when a foot reaches zero height, and lift-off occurs, when the vertical contact force becomes zero. The contact forces are equivalent to the negative Lagrange multipliers in eqn. (3). There can be a discontinuity of velocities at touchdown of the swing foot to he ground. The velocity after impact v_+ is then computed using the same matrices M and G as above, and the velocity before impact v_-:

$$\begin{pmatrix} M & G^T \\ G & 0 \end{pmatrix} \begin{pmatrix} v_+ \\ \Lambda \end{pmatrix} = \begin{pmatrix} Mv_- \\ 0 \end{pmatrix}. \tag{5}$$

It can be generally assumed that lift-off of the foot is smooth, i.e. there are no discontinuities. Models of the type described above - combining continuous motion phases as well as discrete “jump phases” - are often called hybrid dynamical systems.

3 Formulation and Solution of Optimal Control Problems for the Generation of Robot Walking Motions

The problem if generating optimal walking motions for HRP-2 can be formulated as a multiphase optimal control problem of the following form:

$$\min_{x(\cdot),u(\cdot)p,\bar{t}_i\in\mathcal{M}} \sum_{i=1}^{r} \int_{\bar{t}_{i-1}}^{\bar{t}_i} \Phi_i\left(x(t), u(t), p\right) dt + \Psi_i\left(\bar{t}_i, x\left(\bar{t}_i\right), p\right) \tag{6}$$

$$\text{subject to} \quad \dot{x}(t) - f_i\left(t, x(t), u(t), p\right) = 0 \quad i \in \mathcal{M} \tag{7}$$

$$x\left(\bar{t}_i^+\right) - h_i\left(x\left(\bar{t}_i^-\right)\right) = 0 \quad i \in \mathcal{M} \tag{8}$$

$$r_{eq}\left(x\left(\hat{t}_0\right), ..., x\left(\hat{t}_s\right), p\right) = 0 \tag{9}$$

$$r_{ineq}\left(x\left(\hat{t}_0\right), ..., x\left(\hat{t}_s\right), p\right) \geq 0 \tag{10}$$

$$g_i\left(x(t), u(t), p\right) \geq 0 \quad i \in \mathcal{M} \tag{11}$$

In these equations, x denote the state variables of the system, u the control variables - in this case the joint torques, p the model parameters, t the physical time. $\mathcal{M} = \{1, ..., r\}$ denotes the phase indices, with $r = 2$ for one step of a walking motion. $\bar{t}_{i-1}$ and $\bar{t}_i$ are the start and end times of phase i, respectively.

Without loss of generality it is assumed that $\bar{t}_0 = 0$ holds. With $x(\bar{t}_i^-)$ and $x(\bar{t}_i^+)$ we express a state x evaluated at time $\bar{t}_i$ just before or after a discontinuity.

The system dynamics during each phase is described by the corresponding set of DAEs (1) - (3) . The optimal control problem only "sees" the differential part of the variables and the equations which are considered as constraint of the optimal control problem , and the algebraic part is solved implicitly to determine a in the right hand side of (2). The objective function (6) can consist of continuous integral Lagrange-type functions Φ_i as well as end-value dependent Mayer-type functions Ψ_i. The purpose of this paper is to compare the effect of different objectives on the gait which will be further detailed below in section 4.1. Eqn. (8) describes state discontinuities between continuous motion phases: these include potential velocity discontinuities at impact, but also the discontinuity coming from the shift of sides after the end of the step. Eqn. (9) summarizes all pointwise coupled and decoupled equality constraints of the problem such as periodicity constraints, phase switching conditions, and the invariants resulting from index reduction of the DAE. (10) and (11) are pointwise as well as continuous inequality constraints, e.g. bounds on all optimization variables or foot clearance constraints or ZMP stability constraints, see below.

The multi-phase optimal control problem is solved with the powerful optimal control software MUSCOD II developed in Heidelberg. It is based on early works of [2] and was implemented by [13]. The approach applies the direct multiple shooting method to transform the infinite dimensional optimal control problem to a finite dimensional optimization problem. Controls are discretized by means of functions with local support (all computations in this paper are based on piecewise linear support functions). Multiple shooting is then used to parameterize the state variables of the system. Multiple shooting essentially transforms a boundary value problem into a set of initial value problems with continuity conditions. For structural reasons, multiple shooting and control grid are chosen identically. This finally results in a large but highly structured nonlinear programming problem that may efficiently be solved by a tailored sequential quadratic programming method. The integration of the system dynamics and the computation of the derivatives of the trajectories is performed by powerful integrators with sensitivity generation capabilities. As all optimization methods, also the direct multiple shooting approach needs initial values for all optimization variables (in this case for discretized controls, phase times and state variables at the multiple shooting nodes). The higher the quality of these values the better is generally the convergence of the algorithm. For the computations presented in this paper we have taken initial values from physically feasible and stable gaits from a preview control pattern generator (see [7]) since this motion was available to us. Note however that this motion is quite different from the motions that are finally produced by the optimization (see the next section). It is not necessary that the initial values are all feasible; also simpler ways of initialization (like an interpolation of state variables between initial and final point) might in principle be used.

4 Optimization Results

4.1 Overview of Computations

In this section, we compare optimization results for walking for the following objective functions:

– a minimization of joint torques squared (which penalizes actuator torques which are the control inputs for the optimal control problem - no matter if they are used for dynamic or static purpose. This objective generally produces smooth controls with little oscillations):

$$\min \Phi_{\text{torques}} = \int_0^T \sum_{j=1}^{N} (\omega_j u_j)^2 \, dt \tag{12}$$

– a maximization of average forward velocity (since humanoid robots still move very slowly compared to humans, we want to investigate the potential limits of HRP-2):

$$\max \Psi_{\text{forw Vel.}} = \frac{l_{\text{Step}}}{T} \tag{13}$$

– a maximization of postural stability (penalizing the deviation of the local center of pressure p_{COP_e} from a reference point under the sole of the foot p_{Centr_e}, see [3] for further discussion):

$$\min \Phi_{\text{post stab}} = \int_0^T \sum_{e=\{Lf,Rf\}} (p_{COP_e} - p_{Centr_e})^2 \, dt \tag{14}$$

– a maximization of efficiency of the gait which can also be expressed as a minimization of the cost of transport [4] or the mechanical power output over a step [3]:

$$\min \Phi_{\text{eff}} = \int_0^T \sum_{j=1}^{N} \frac{|\dot{q}_j u_j|}{l_{step}} dt \tag{15}$$

– a minimization of joint velocities (angular rates) squared which aims at reducing the angular motions as much as possible while still maintaining some form of gait):

$$\min \Phi_{\text{joint vel}} = \int_0^T \sum_{j=1}^{N} (\omega_j \dot{q}_j)^2 \, dt \tag{16}$$

For all five objective functions above, we have investigated the following variations of the constraints set:

– with and without constraint on the ZMP, restricting it to stay within a small circle below the center of the foot during single support and in a tube connecting the two foot centers during double support.
– for the ZMP constrained case: leaving the foot placement free, or constraining the step length and step width to the values of the initial walking solution

Overall, this results in 15 different objective function - constraint combinations.

4.2 Comparison of All Objectives and Constraint Combinations

Figure 1 shows bar plots of different gait characteristics for all optimization criteria and constraint combinations. The top left plot shows the optimal step length and step width for the different criteria. Trivially these quantities remain unchanged with respect to the initial value for the optimization runs with fixed foot position. However, they change - in some cases significantly - for the other five computations. Step width is in all cases chosen smaller than the original $0.144m$, for the maximization of efficiency it is even reduced to $0.016m$. Step length increases in three cases and is reduced in two. Compared to the original step length of $0.152m$, the longest step length occurred for a maximization of

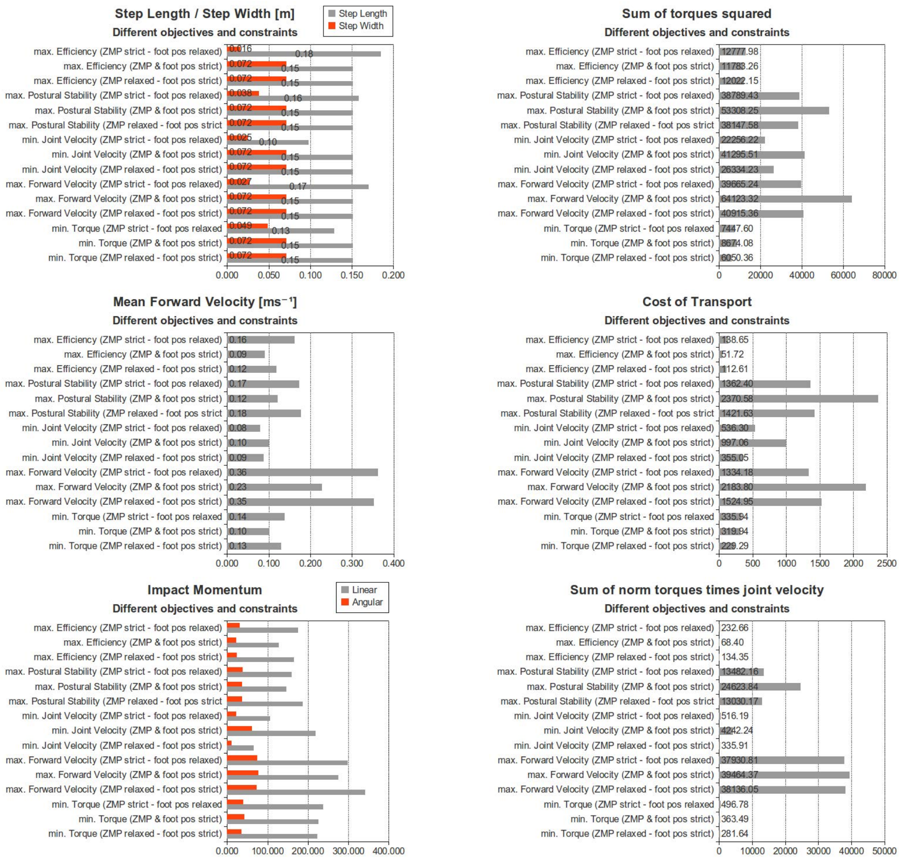

Fig. 1. Different gait characteristics compared for all optimization criteria and constraint combinations. Left column: step length/ width, average forward velocity and linear as well as angular impact momentum at touchdown. Right column shows different cost measures for these different solutions: sum of torques squared, cost of transport, and absolute mechanical energy (sum of torques along angles).

efficiency with $0.185m$ and the shortest for the minimization of joint velocities with $0.098m$. The middle left plot in figure 1 shows the average walking speed resulting from the different optimization criteria. The gait used for initialization had a walking speed of $0.178m/s$[1] As one could expect, the highest walking speeds result when precisely this quantity is maximized, i.e. when optimizing the second criterion listed in section 4.1. For this objective and free foot placement but constrained ZMP, the walking speed can be increased to $0.363m/s$, i.e. $1.31km/h$ which represents an increase by a factor of 2.03, even further than for an unconstrained ZMP but a fixed foot position ($0.352m/s$). With both constraints, the same criterion only leads to $0.228m/s$. For all objective functions, except for the minimum joint velocity criterion, the relaxation of any of the constraints leads to an increased average walking speed. The bottom left plot shows the linear and angular impact momentum for all 15 cases. A high impact momentum is undesirable since it results in a loss of energy and, in particular in the case of a humanoid robot, produces a high risk a destabilization. Both linear and angular impact momentum were particularly high for the maximum average velocity criterion, no matter if ZMP or foot position are constrained or relaxed. This makes the maximum velocity solution less interesting than it seemed above, and this criterion might only be useful for the real robot if additional constraints on the size of the impact are taken into account. The smallest impact momenta occur for the minimum joint velocity criterion and a relaxed ZMP, followed by the same criterion with relaxed foot position. Minimum torque, maximum efficiency and maximum postural stability result in medium size impacts which however also might have to be reduced for an implementation on the real robot. The right column of figure 1 presents different measures for the cost of the different walking motions, namely the sum of torques squared (which corresponds to the electric power consumed by the motors), the cost of transport as defined above, as well as the absolute mechanical energy (sum of absolute values of torques integrated over joint angles). Even though they have quantitatively different results, all three measures show the same tendencies: maximum velocity and maximum postural stability lead to quite costly solutions while minimum joint torques and maximization of efficiency lead to rather cheap solutions in terms of all three measures.

4.3 Further Analysis of Optimization Results for Constrained ZMP and Free Foot Placement

In the following, we will discuss the optimization results for free foot placement and constrained ZMP in more detail, since this combination of constraints seems to be the most interesting for HRP-2. Figure 2 shows snapshot sequences of the optimal walking cycles for all five criteria.

Figure 3 shows the trajectories of position (top row) and orientation (bottom row) variables of the pelvis for all five objective functions (see color code explained in the first plot) over a walking cycle of two steps. In all plots the

[1] For comparison purposes: the regular walking speed of humans is about $1.3-1.4m/s$.

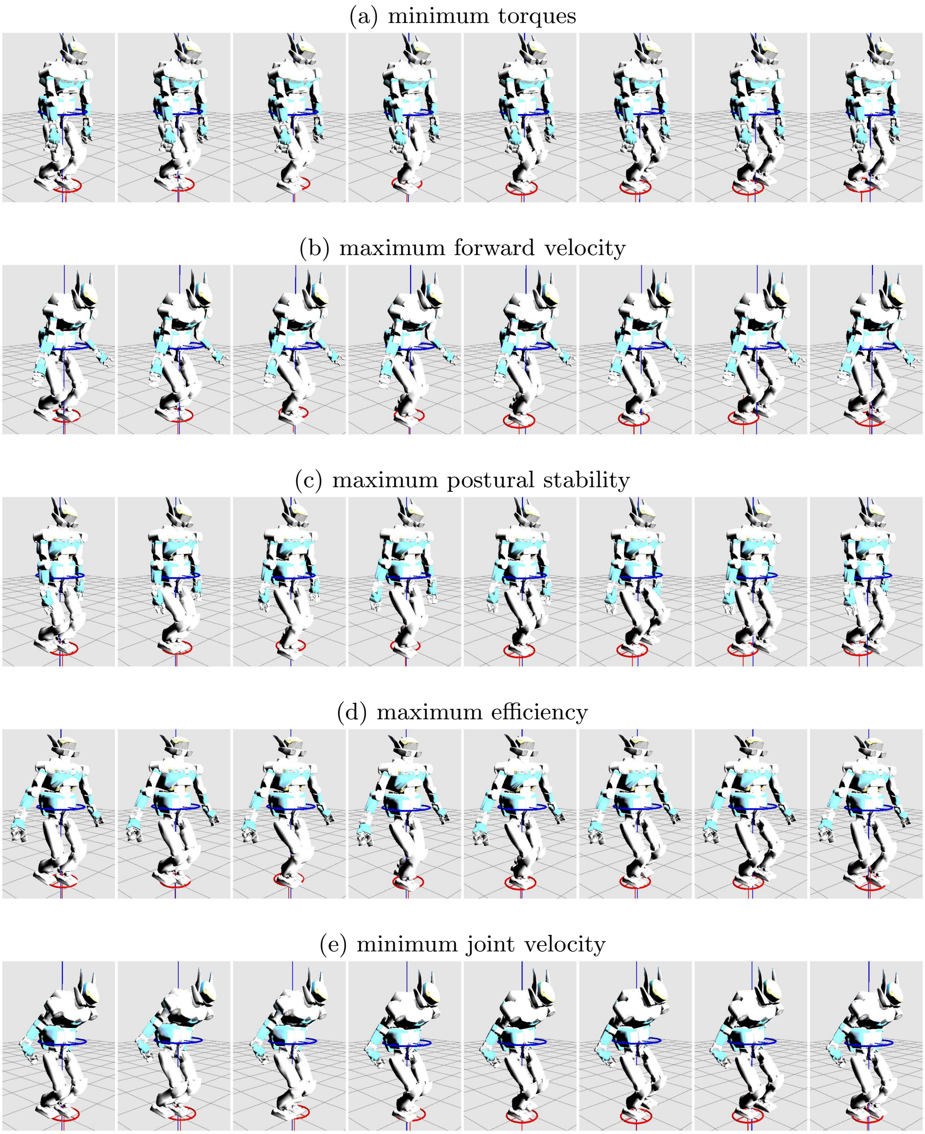

Fig. 2. Walking sequences for HRP-2 with free foot placement and constrained ZMP for different objective functions (center of circle on the floor represents ZMP, center of circle near pelvis shows CoM)

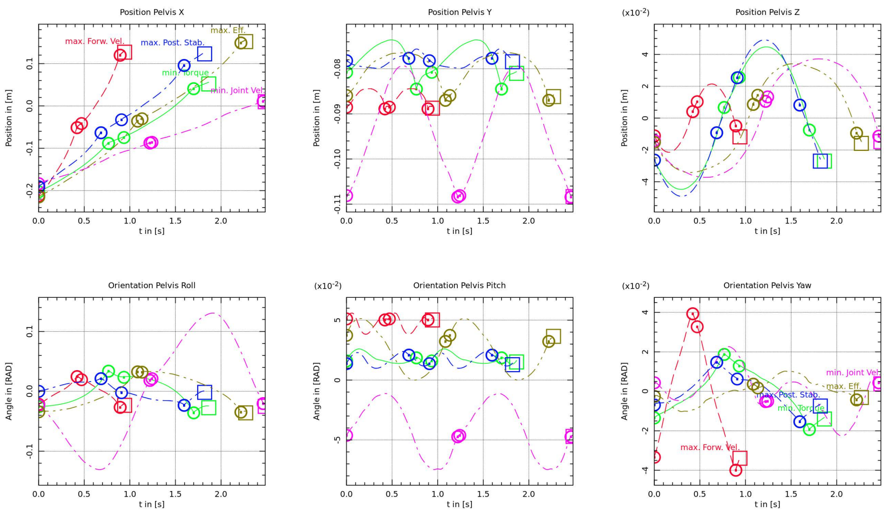

Fig. 3. Pelvis trajectories over a full gait cycle (two steps) for the five different objective functions with constrained ZMP and free foot placement. Top: pelvis position trajectories in forward, vertical and sideward direction. Bottom: pelvis roll, pitch and yaw angles. The gait cycle starts with the single support on the left leg, followed by double support, single support with the right leg and then double support phase (circles denote ends of phase, squares the end of the cycle).

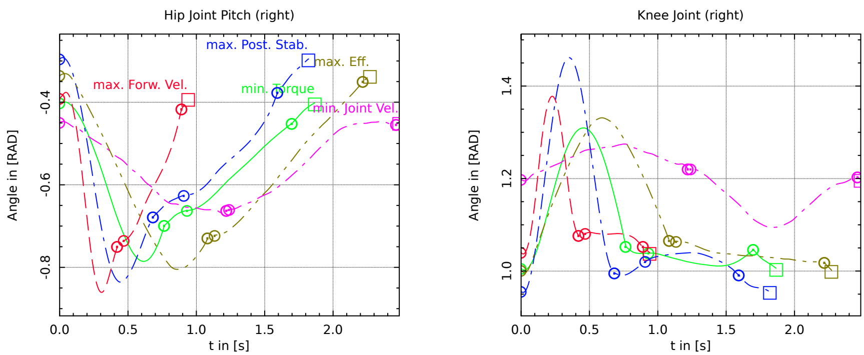

Fig. 4. Sagittal plane hip and knee angle trajectories of one leg over a full gait cycle (two steps) for the five different objective functions with constrained ZMP and free foot placement. The gait cycle for this leg starts with the swing phase, followed by double support, single support and then double support phase (circles denote ends of phase, squares the end of the cycle).

different step durations resulting from the different objectives become obvious. The top left plot describes the forward motion of the pelvis which differs significantly for the different objectives (also compare discussion about step lengths and average velocities above). The second plot in the top row shows the vertical motion of the pelvis, clearly depicting in all cases the two vertical oscillations over the two steps. The height variations of the pelvis are quite small (smaller than 1 cm) for all objective functions except for the minimum joint velocity criterion, where the variation is around 3 cm despite the small steps. This is due to the very small range of motion of the hip and the knee angles caused by this criterion which induces a high stiffness in the joints. The third plot shows the sideward motion of the pelvis. Note that this time there is only one oscillation since the periodic cycle for orthogonal gait oscillations is two steps and not one, as for the vertical motion. The variations in sideward directions lie between 4 cm - for the maximum speed criterion - and 10 cm - for the maximum postural stability criterion. The lower row in figure 3 presents the roll, pitch and yaw angles of the pelvis. Especially noteworthy is the high amplitude of the roll angle for the minimum joint velocity criterion which again is caused by the fact that the criterion stiffens the legs. This criterion also leads to a significantly reduced pitch angle, i.e. the pelvis is turned backwards. In all other cases, the pelvis is bent slightly forward. For the yaw angle, in particular the maximum speed velocity stands out with much larger amplitudes than the other criteria, which is caused by the large steps performed in this mode of motion.

Figure 4 shows the trajectories of the hip and knee angles in the sagittal plane for all five objective functions. The plot shows a whole walking cycle for one leg starting with the swing phase, followed by double support, then single support and again double support phase. Both angles are bent much more than in human walking motions and lead to the characteristic half-sitting position of humanoid robots. As we have shown in [12], this position is caused by the ZMP constraint, and a relaxation of this constraint results in a straightening of the legs and an increase of the pelvis height. As mentioned above, the oscillations linked to the minimum joint velocity criterion are very small for both knee and hip angle such that the leg angles are nearly constant over the full cycle. The shapes of the hip angle trajectories are very similar for the other four criteria, the only difference is the total duration of the cycle which results in more or less stretched angle trajectories. The same is true for the knee angle with slightly more pronounced differences in the amplitudes: the maximum postural stability criterion leads to the largest knee angle amplitude and the maximum efficiency criterion leads to the smallest one (but still much bigger than the minimum joint velocity knee amplitude).

We also found it interesting to analyze the different motions of the swing foot that are induced by the different optimization criteria. Figure 5 shows the sole center position trajectories as well as roll, pitch and yaw angles of the swing foot over one step. In addition to the foot step locations, the foot motion during swing is prescribed by some pattern generators, but in the optimal control approach, the foot trajectories can be freely determined along with the whole body motion. Appropriate constraints in the optimal control problem formulation avoid any penetration

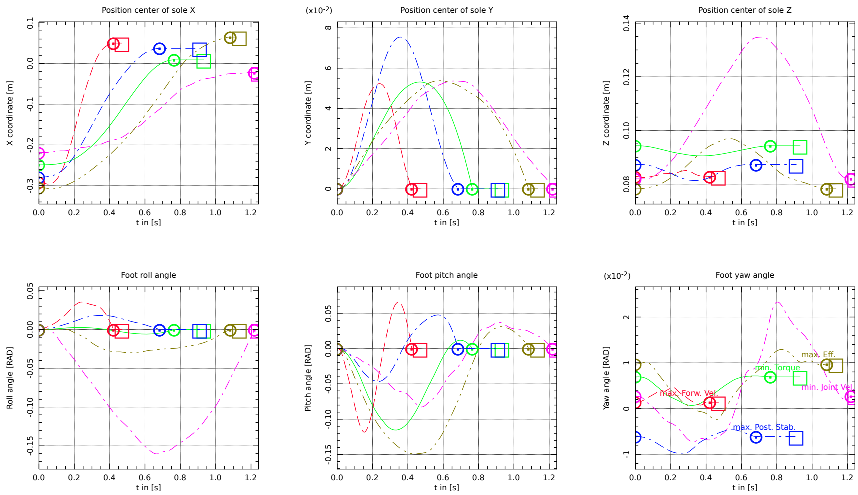

Fig. 5. Swing foot trajectories over one step (swing phase and double support phase) for the five different objective functions with constrained ZMP and free foot placement. Top: foot sole center position trajectories in forward, vertical and sideward direction. Bottom: foot roll, pitch and yaw angles (circles denote ends of phase, squares the end of the cycle. Same color code as in previous figures is used for the objective functions).

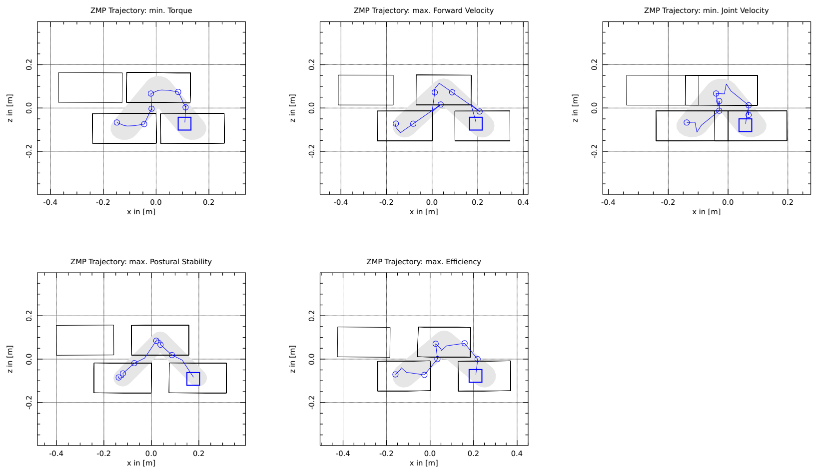

Fig. 6. ZMP paths over a full gait cycle (two steps) for the five different objective functions with constrained ZMP and free foot placement. Grey areas show the ZMP constraints.

of the foot into the ground and even prevent sliding contact before touchdown by guaranteeing a sufficient ground clearance. The maximum postural stability criterion leads to the swing foot trajectory with the highest lift (8cm), and the minimum joint velocity with the largest sideward variation of the foot (5cm). Changes of foot angles are generally not big over the swing phase with the highest roll and yaw angle variations again for the minimum joint velocity criterion, and the highest pitch angle variation for the maximum efficiency criterion.

Finally, we present the ZMP paths in the horizontal plane for all five criteria over a cycle of two steps. Grey tubes indicate the areas in which the ZMP is allowed to move for stable motions. In all five cases, suitable constraints force the ZMP to remain inside these areas during the optimal control problem solution. In four cases the ZMP moves to or along the boundaries of these stable areas. The constraints are quite expensive to satisfy, and the ZMP would move outside as soon as this constraint would be relaxed. The only exception is the postural stability criterion. This criterion punishes the ZMP moving away from the centers of these areas, and if this punishment is hard enough, it is not necessary to additionally formulate the corresponding constraint. The minimum torque criterion and the maximum postural stability criterion produce quite smooth ZMP paths while they are more "cracked" for the other criteria.

5 Conclusion and Perspectives

In this paper, we have presented solutions of optimal control problems for the generation of walking motions for the humanoid robot HRP-2. Five different objective functions have been evaluated as well as the effect of ZMP and foot placement constraints.

A free foot placement appears to be desirable in all cases investigated. Defining the foot placement a priori in some heuristic way reduces the gait variety considerably and decreases the optimization potential. The only reason to constrain foot positioning is an environment where only limited footholds are available such as walking on step stone bridges, but on even terrain with obstacles the foot positions should be chosen freely in an optimal way according to the chosen optimization criterion. Relaxing ZMP constraints has demonstrated some interesting perspectives - such as the possibility to walk in a more upright way than current humanoids do, but it is certainly not an option when generating motions for the real HRP-2 robot. It might become interesting again when applying this approach to a new robot generation or another humanoid model.

The minimization of joint velocities does not appear to be a useful criterion. Even though it may intuitively seem stabilizing to avoid unnecessary joint motions, the objective leads to very stiff, non-smooth and unnatural motions with high oscillations in the pelvis height and roll angle and the foot sidewards motion as well a backward inclination of the pelvis. We also do not consider the maximization of postural stability to be suitable for the generation of better humanoid walking motions. Postural stability in terms of the ZMP criterion is already considered in the constraints which could be made stricter if ever necessary. Maximizing postural stability results in extremely costly solutions - in particular compared to the slow walking velocities it exhibits, and we do not see the immediate advantage to be so far off the stability boundaries when shifting closer to the already very conservative boundaries would result in faster of more efficient motions.

The maximization of average walking velocity is certainly interesting if the limitations of a robot are to be evaluated. Coming closer to the role model of human walking also implies that humanoids have to become considerably faster that they are at the moment. The computed increase of walking speed by a factor of a little more than 2 with respect to the reference solution may not be reachable in reality since the associated impacts are too big for HRP-2. We therefore propose to add constraints reducing the impact to below the accepted threshold for all optimization runs maximizing walking velocity. This should then still lead to an increase of speed, but less significant than the one reported here.

The minimization of joint actuator torques and the maximization of walking efficiency also seem to be promising objective functions which are associated with low "energetic" costs (in all measures investigated). The minimization of torques leads to smoother motions while the maximization of efficiency leads to faster motions with higher speeds. These motions are characterized by smaller impacts than the maximum velocity solution, but it might still be too much for the real robot and appropriate constraints should be added.

Humans typically apply not a single optimization criterion but weighted combinations of several - in many cases contradicting - criteria which we would also recommend for robots. Interesting combinations that we will investigate in the near future are minimization of joint torques & maximization of efficiency, minimization of joint torques & minimization of time to target (i.e. maximization of walking speed), maximization of velocity & minimization of impacts, minimization of joint torques & minimization of impact for a given velocity, all combined with ZMP and impact constraints and with free foot placement.

We also would like to mention that one obvious difficulty of computed periodic motion is to reproduce the desired starting values of the periodic cycle for all position and velocity variables on the real robot. In order to tackle this difficulty we have developed a procedure that can generate - for every optimal periodic cycle that is of interest for the robot - a starting step (or more precisely 1.5 starting steps) that bring the robot from its regular half-sitting rest position onto the periodic cycle. In the same way, stopping motions are computed that take the robot out of the periodic cycle and bring it to its rest position.

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