Three-Dimensional Parameterised Gaits for Biped Walking

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ABSTRACT

Biped robot control techniques are usually based on the tracking of pre-computed reference trajectories. Therefore, to achieve autonomy in locomotion, it is necessary to store a set of trajectories handling all the possible situations and events the system is susceptible to encounter. This paper presents a method for the generation of walking gaits for biped robots. Theses gaits define locomotion in the three dimensional space (3D) and are parameterized with the steps characteristics. The approach we propose is based on an actuator input minimization under constraints. These constraints are linked to the gait parameters (step length, step clearance…). The method is based on a simple and intuitive reasoning, allowing the designer to define walking trajectories in a fast and easy way. We present simulation results obtained with the 15 actuated joints biped robot of INRIA called BIP.

1 INTRODUCTION

Legged locomotion main advantage is to be able to deal with different types of environments. The use of legs gives the possibility to change the configuration of the fulcrum points to stride over an obstacle, which is not possible with other mobile vehicles with wheels for instance. The ability of biped creatures to be efficient on environments made by and for humans (stairs, corridors…) has motivated the study of 2-legged robots [1][2][3][4].

Most of the control strategies of such robots are based on the tracking of predefined joint trajectories. Therefore, to achieve autonomy in locomotion, it is necessary to store a set of trajectories handling all the possible situations and events the system could ever encounter. In this paper, we consider a gait as a set of discrete postures. One important aspect when dealing with mobile robots is their autonomy and therefore their energy consumption. In human locomotion this economical aspect is also very important [5].

The minimal energy consumption gait is the passive gait where the robot is not actuated. The compass gait model [6] represents the simplest biped robot, able to walk down a slope infinitely without any actuation. The study of such a gait is motivated by the fact that a great

part of the swing phase in human locomotion is passive. Moreover, this gait is periodic and stable. So comes the idea to mimic the passive gait with active control trying to keep the periodicity and stability properties [7][8].
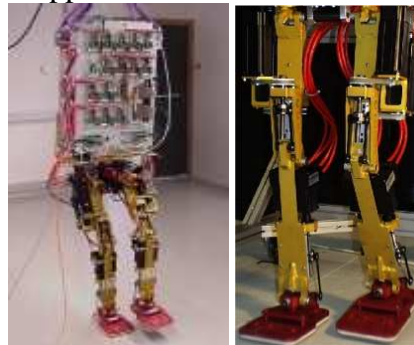
Another way to generate periodic gaits is to assume that the torques exist only around the impact [9]. Generating gaits is then to compute such torques in order to guarantee the stability and the periodicity of the gait, the major part of the movement being ballistic. This kind of strategy would be difficult to adapt to the BIP robot because of the important reduction ratios of the transmissions.

As human like gaits for anthropomorphic robots are wanted, comes the idea of human like walk learning using evolutionary optimization methods [10]. Other ways of generating gaits could be the use of optimization techniques between two known postures [11], or the simplification of the robot dynamics to get numerical solutions [12], but these strategies are not very intuitive and require a lot of calculations. Whatever the strategy or the assumptions are, stable walking is meeting objectives defining the stability of the robot [13].

Therefore, we propose to state the gait generation as a constrained optimization problem, the set of constraints defining intuitive gait objectives. This strategy allows the fast and intuitive generation of many different gaits for complex highly non-linear structures such as 3D anthropomorphic robots.

This work follows the work already done on the 2 dimensional version of the BIP robot [14].

The paper is organized as follows. In the following section, we describe the technique we use to obtain parameterized walking and transient movements for our robot. Section 3 presents the simulation results illustrating our approach.
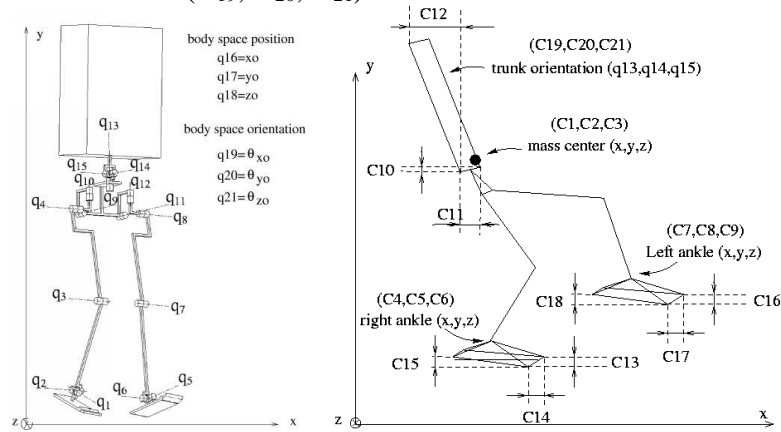

Figure 1: The robot BIP of INRIA

2 3D PARAMETRIZED GAITS GENERATION

In this paper, we consider the robot BIP of INRIA (Figure 1) composed of 15 active joints [15]. Since the robot can move in the 3D space, adding the position and orientation of the robot gives 21 degrees of freedom ($\mathbf{q_i}$) to be controlled.

Describing movements for the robot in the configuration space is not intuitive. We therefore introduce an output space in which one can more easily handle the displacements of the robot (Figure 2). In this output space, the degrees of freedom ($\mathbf{C_i}$) have been defined to represent useful aspects when defining a posture:

- position of the center of mass: 3 dof (C_1, C_2, C_3)
- position of right and left ankles: 6 dof (C_4, C_5, C_6) and (C_7, C_8, C_9)

- lumbar movements abduction/adduction and trunk rotation: 3 dof (C_{10}, C_{11}, C_{12})
- orientation of the feet: 6 dof (C_{13}, C_{14}, C_{15}) and (C_{16}, C_{17}, C_{18})
- orientation of the trunk: 3 dof (C_{19}, C_{20}, C_{21})

Figure 2: configuration space (left) and output space (right)

Our technique is based on an optimal algorithm, which computes the robot joints positions that minimize a quadratic objective function of the actuators inputs under specified constraints. The problem is to solve

$$\min{}_q J(q) = \frac{1}{2} U(q)^T U(q)$$

subject to:

$$q_{min} \leq q \leq q_{max} \tag{1}$$
$$g_j(C) \leq 0 \qquad j = 1...n_g$$
$$h_j(C) = 0 \qquad j = 1...n_h$$

where U is the vector of the 15 actuators inputs corresponding to the torques needed for maintaining the posture (i.e. gravity compensation). The first set of constraints corresponds to the joint limits, the other sets are inequalities (g_j) and equalities (h_j) to be defined by the designer (keeping feet on the ground, CoM trajectory, …). The trajectories are then checked out to verify the feasibility of the movements in terms of actuators saturations ($U_{min} \leq U \leq U_{max}$).

The constraints describe the movements the robot has to achieve. Two conditions have to be fulfilled: maintaining the equilibrium of the robot and moving forward. In this paper, we consider static stability, which is guaranteed by keeping the projection of the body center of mass (CoM), within the support base (convex hull of support points). The forward progression is obtained when the CoM moves forward. These two conditions define a first set of constraints. Adding a second set of constraints gives the possibility to handle different gaits, allowing the robot to avoid collision with obstacles for example.

Walking is a cyclic activity where the feet have symmetric roles. One step corresponds to 2 phases: single support and double support (Figure 3). The step starts from a given posture and ends when the symmetrical configuration is achieved (symmetric step).

2.1 Initial posture

The initial posture is the ending posture of a double support phase. It precedes the first posture in single support. The initial posture must consequently respect several constraints:
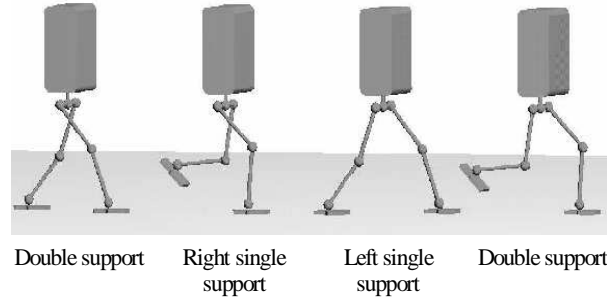- the two feet are on the ground

- the future free foot is half the step length behind the future stance foot in order to realize a symmetric step
- the CoM projection is on the future stance foot in order to guarantee static stability when the other foot will left. We choose to put the CoM right behind the ankle, between the soil internal and external borders.

This set of constraints is expressed in the output space as equality constraints:
- position of the ankles (6 constraints)
- orientation of the feet (6 constraints)
- position of the projection of the CoM (2 constraints)

The optimization algorithm presented previously is then applied to compute an optimal initial posture.

Double support   Right single support   Left single support   Double support

Figure 3: walking phases

2.2 Single support phase

Single support phase must lead to a symmetric configuration of the initial posture. A special care about CoM projection must be taken in order to guarantee the static stability.

Since the torques needed for maintaining the posture are minimized, specifying only a forward movement for the flying foot will lead to a double support posture. We therefore have to define a trajectory in the sagittal plane for the free foot. So, the set of equality constraints we define to get a single support phase is:

- position of the support ankle and orientation of the support foot in order to avoid translation and rotation of the foot (6 constraints)
- orientation of the flying foot in order to avoid rotation of the foot (3 constraints)
- trajectory of the flying foot
  - ankle position constraint to keep the movements in the sagittal plane (1 constraint)
  - ankle positions constraints in the sagittal plane to get a forward movement following a defined trajectory (2 constraints)

$$flying\_ankle_{c_x} = flying\_ankle_{p_x} + \delta_{foot} \qquad (2)$$

  where index c is related to the current posture and index p to the previous one. δ_{foot} is the forward progression of the flying foot (along x axis).

$$flying\_ankle_y = f(flying\_ankle_x) \qquad (3)$$

  where function f is a 4th order polynomial function (Figure 4) depending on the height (*step_height*) and length (*step_length*) of the desired step.

- position of the projection of the CoM to get a forward movement along a straight line (2 constraints)

$$CoM_{c_x} = CoM_{p_x} + \frac{\delta_{feet}}{step\_length} \Delta_{CoM} \qquad (4)$$

$$CoM_{c_y} = CoM_{p_y} \tag{5}$$

where Δ_{CoM} defines the entire step forward movement of the CoM. Δ_{CoM} must be well defined to prevent from the projection of the CoM going out of the support base.

14 on 21 constraints have been defined and since the objective function does not include the dynamic of the robot we have to add a 15th constraint as inequality to avoid large movements on the dof we did not constrained yet. We define a vector T composed of the 6 dof we did not consider and define the inequality constraint

$$(T_c - T_p)^T (T_c - T_p) \le \delta_{free} \tag{6}$$

where T_c is the vector of the current position, T_p the vector of the previous position and δ_{free} a threshold defined to limit movements between two postures.

The single support phase, as we defined it, is parameterized by the step length and height, the forward progression of the free foot and the entire step forward progression of the CoM.

2.3 Double support phase
In this phase, the CoM projection moves from one foot to the other. Our symmetric definition of step imposes that the ending posture in this phase is the symmetric one of the initial posture of the single support phase. This gives a posture to converge to. We also want to move smoothly the weight to the next support leg, so we define a trajectory for the projection of the CoM. We define the following set of equality constraints:
- positions and orientations of the feet in order to avoid translations and rotations of the feet (12 constraints)
- position of the projection of the CoM to get a smooth weight transfer from on feet to the other (2 equations)

$$CoM_{c_x} = CoM_{p_x} + \frac{\delta_{CoM_x}}{nb\_samples} \tag{7}$$

where δ_{CoM_x} is the CoM progression in the x direction between the initial posture of the double support phase and the posture to reach.

$$CoM_y = f'(CoM_x) \tag{8}$$

where f' is a 3rd order polynomial function (Figure 4).

The CoM movement is defined as a linear progression between the initial posture and the posture to reach sampled in *nb_samples* postures. The double support phase is therefore parameterized by the trajectory of the CoM, the degree of sampling *nb_samples* and the posture to reach at the end of the phase.
In this phase, the feet positions and orientations stay still, remaining a few dof to act on in order to move the CoM. As in single support phase, we introduce a constraint on the trunk rotation to prevent from large movements of the unconstrained dof.

$$\alpha_{trunc_c} = \alpha_{trunc_p} + \frac{\delta_{\alpha_{trunk}}}{nb\_samples} \tag{9}$$

2.4 Transient gait

To define transient gait, the set of constraint is identical to the one used in symmetric gaits. Only the gait parameters have to be adjusted. In single support phase, the polynomial trajectory of the flying foot is not centered on the stance foot anymore. This trajectory is generated by starting from a double support posture and giving a step length parameter corresponding to
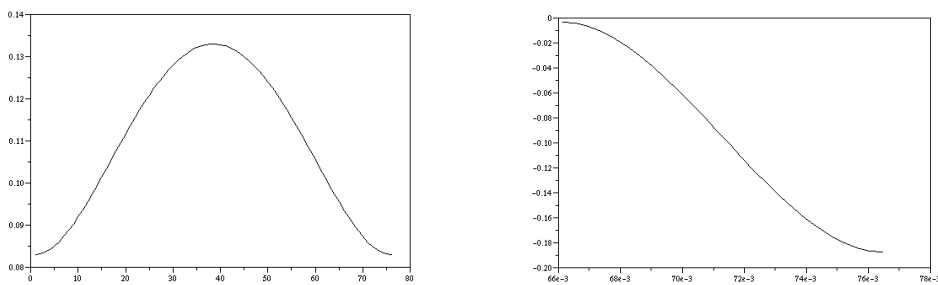
$$\frac{1}{2} \text{ previous step length} + \frac{1}{2} \text{ new step length}$$
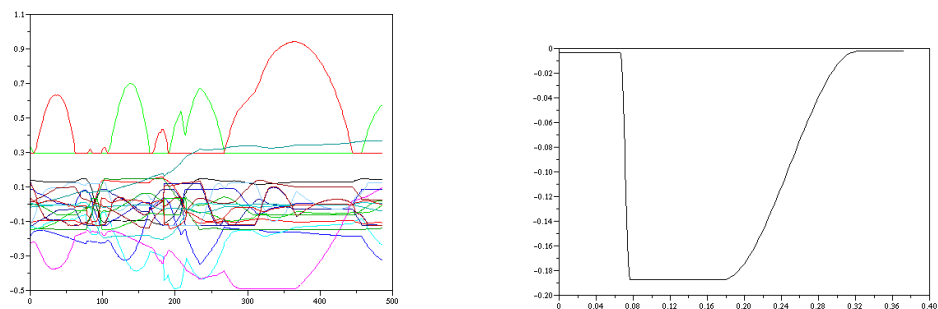
3 SIMULATION RESULTS

BIP dynamic model is used for the simulation. The optimization problem is solved using the *CFSQP* [18] routines.

We can see the flying ankle and the CoM trajectories (Figure 5) for a gait with the following parameters (Figure 6):
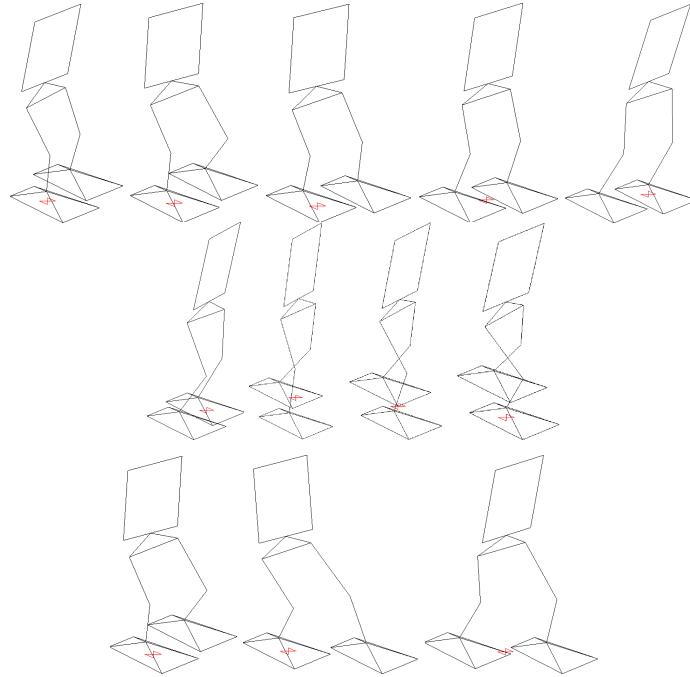
- First step is generated with step_length = 15cm, step_height = 5cm , δ_{foot} = 2mm, Δ_{CoM} = 6.5cm, δ_{free} = 1e-5 in single support phase (Figure 4) and nb_samples = 25 in double support phase.
- Transient gait is generated with step_length = 32.5cm, step_height = 6cm , δ_{foot} = 4.0625mm, Δ_{CoM} = 10cm, δ_{free} = 1e-5
- Final step is generated with step_length = 50cm, step_height = 10cm , δ_{foot} = 2mm, Δ_{CoM} = 5cm, δ_{free} = 1e-5

Figure 4: Trajectory of the flying ankle in the sagittal plane (left) and trajectory of the projection of the Center of Mass (right) during the right single support phase of a 15cm length and 5cm clearance step.

Figure 5: Joint angles and projection of the CoM trajectory for a 15 cm length and 5 cm clearance step , link with a transient gait to a 50 cm length and 10 cm clearance step

Figure 6: Postures generated during a 15 cm length and 5 cm clearance step (top), link with a transient gait (middle) to a 50 cm length and 10 cm clearance step (bottom).

The unusual postures at the end of the figure are due to the static stability constraint : the trunk has to stay behind in order to keep the CoM projection in the support base.

4 CONCLUSION & PERSPECTIVES

We presented a method to generate 3D parameterized gaits for the 21 dof BIP robot. These gaits, or discrete trajectories, are defined by a set of optimal postures. The gait generation problem is defined as a constrained optimization problem, minimizing a quadratic function of the actuators inputs. An initial posture and an appropriate set of constraints defining the movement suffice to generate a gait trajectory statically stable.

The set of 3D constraints defined in this paper can be used in others formulations in order to get statically stable gaits. The control problem can be formulated in minimizing the torques or the acceleration (as they are linked by the dynamic model) submitted to the same constraints. This formulation would allow us to suppress the additional constraints introduced to deal with the non-inclusion of the dynamic model of the robot into our objective. Moreover, as we aim at specifying the minimum gait parameters, introducing Model Predictive Control could allows us to replace trajectories (CoM, flying ankle) by bounds on these degrees of freedom. This work has already been tackled on a 2D robot model [16][16]

Finally, this whole work must lead to a real time implementation of this strategy on the real robot.

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