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Planning approach and local reactivity for 3D Operational space control of 3D bipedal robots with flexible feet

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***Abstract*— This paper presents an approach to control gaits of humanoid bipedal robots in operational space without reference trajectories. This control strategy is based on the planning of the sequential events during the walking process. The aim of this study is to propose a new control strategy which is more reactive, permits a precise coordination of both legs during the double stance phase and the generation of dynamic 3D walking of an anthropomorphic biped with flexible feet. Based on homogeneous transformation matrices, the control strategy integrates three aspects in one unified representation: structural parameters of the robot, measurements given by sensors, planning of the sequential events during the different stages of the walk.**

***Index Terms*—bipedal humanoid robot, flexible feet, 3D operational space control, events planning, coordination of the legs.**

I. Introduction

When developing a useful humanoid robot, one of the main problems to be solved is the stability of bipedal robots.

The robotics community has been involved in the field of modeling and control of bipeds stability for many years [1]-[8] .The main concepts used to evaluate the quality of dynamic equilibrium of walking robots and to control them are the following ones : zero-moment point principle [4] [5] [6], 3D linear inverted pendulum mode [9] , virtual intuitive model control [10] . All these approaches are aimed to measure stability of walking systems relatively to the support polygon. In a first time experiments stability was ensured with the legs only [2] [3] [9] and then, in a second time, with the trunk [5] [6]. In more advanced robots: ASIMO [11], QRIO [12], HRP-2 [13], KHR-3 (HUBO) [14], WABIAN-2LL [15], WABIAN-2 [16] and BHR-02 [17], stability control during walking is based on the well-known ZMP approach. Sabourin et al. [18] developed the robustness of the dynamic walk of a biped robot subjected to disturbing external forces by using CMAC neural networks. The implementation of a neural network in the RABBIT robot made it possible for it to walk at a given speed and to compensate external disturbances applied to the robot [19]. Renner et al. [20] proposed a method to detect instabilities that occur during omni-directional walking. The model takes the gait target vector into account. They estimate model parameters from a gait test sequence and detect deviations of the actual sensor readings from the model later on. Sentis et al. [21] describe all the components of a behavior-oriented whole-body control framework, based on task prioritization. They establish three distinct control categories: constraints (contacts, joint limits, balancing), operational tasks, and postures. Based on this framework they have built a task-oriented behavior architecture which is now being implemented in the ASIMO robot. Hyon et al. (2006) [22] proposed a passivity-based hierarchical full-body motion controller for force-controllable multi-DOF humanoid robots. The contact force closure problem is solved and transformed into the joint torques in real-time without any joint trajectory planning. They introduce gravity compensation at the lowest layer of the controller. The closed-loop system is passive with respect to additional inputs as well as external forces.

However, the framework of these approaches does not really have a unified representation, integrating the different aspects of the robots and its control: the structural parameters of the robot, the planning of the events, the measurements given by the robot sensors and the high-level control that modifies desired trajectories at each sample time. Our objective is to carry out the complementary framework of these approaches and to illustrate it for dynamic walking on a biped robot with flexible feet. A first step towards this framework was proposed in [23]. Nevertheless, there remained certain problems to be regulated which are the following: large tangential forces during double stance phase, large joint torques, sometimes weak reactivity of control strategy and weak stability in the frontal plane. The aim of this study, is to propose a new control strategy which is more reactive, permits a precise coordination of both legs during the double stance phase and the generation of dynamic 3D walking of an anthropomorphic biped with flexible feet without reference trajectories.

This paper is organized as follows: in section II, the modeling of the anthropomorphic biped is briefly presented. In section III, the planning of the walking task and the main principles used during the single support phase and the double support phase are proposed. In section IV the detailed gait planning for the four stages are described. In section V, the new control strategy based on the sequential events planning and the composition of the homogenous matrices used during the single and the double support phases are detailed. Presentation of the simulation results is given in section VI. Conclusions and further developments of this approach are finally presented.

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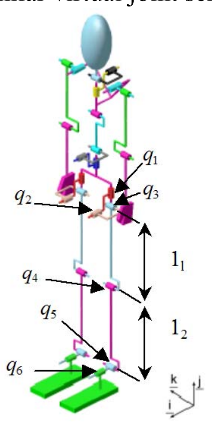
II. NUMERICAL MODEL OF THE BIPED

The biped model is made up of 25 active d.o.f. (degrees of freedom) (Fig. 1). Some passive joints are also included in the foot. The d.o.f. are distributed as shown in Fig. 1. The foot is modeled using a set made up of n right-angled parallelepipeds of decreasing volumes starting from the heel to the end of the toes [24]. These primitives are connected through rotational joints provided with torsion springs in order to model the interaction of flexible feet with the ground [24]. The adopted feet model for the study presented in this paper is made of four parts (Fig. 2). The six joint motions q_i (q_i =1,…,6) will be measured with joint sensors on the final prototype of the robot called ROBIAN. The virtual robot will, thus, be equipped with similar virtual joint sensors.



- 3 d.o.f. for the neck
- 2 × 3 d.o.f. for the two arms (2 d.o.f. for the shoulder, 1 d.o.f. for the elbow, 0 d.o.f. for the wrist)
- 4 d.o.f. for the trunk,
- 2 × 6 d.o.f. for the two legs (3 d.o.f. for the hip (spherical joint), 1 d.o.f. for the knee (rotational joint), 2 d.o.f. for the ankle (universal joint)).

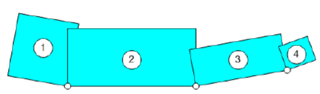


Fig. 1. Biped joints. Fig. 2. Model of the flexible feet used in simulation.

Furthermore, the real prototype will be equipped with foot sensors, gyroscope and accelerometers on the pelvis. All these sensors will be integrated into the virtual version of the simulated biped robot.

III. PRINCIPLES AND PLANNING OF THE TASK

The interest of this approach is that the set of events during walking will be sequentially defined in a planned framework with local reactivity according to current states and prescribed states of the bipedal robot.

A. *Main principles during single support phase and double support phase*

1) *Single support phase*

The single support phase starts at the end of the double stance phase when the rear foot toes leave the ground. During this phase, the stance leg has the role to control the position and the orientation of the pelvis (Fig. 3) while the swing leg aims to choose a good future contact surface for the current swing foot relatively to the current stance foot.

2) *Double support phase*

During the double support phase, the both feet are in contact with the ground. Because of the presence of a closed loop in the system (see Fig. 4), it is important to synchronize the both legs to produce the desired positions and orientations of the pelvis and to minimize opposite tangential forces applied to the ground by each foot during double stance phase. This method allows us to minimize the joint torques during this phase and to ensure the whole balance of the bipedal system.

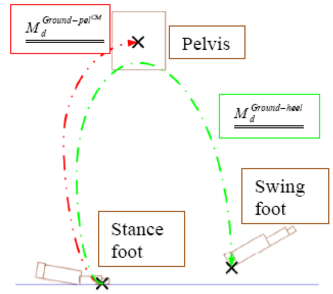


Fig. 3. Single support phase

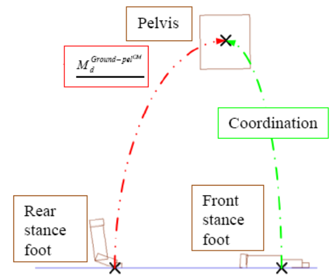


Fig. 4. Double support phase

B. *Definition and planning of the task*

The aim of the task is to perform the simulation of the transition from a standing position of the biped to the dynamic stable 3D walking. The Fig. 5 shows the four sequential stages required to carry out this task. These four stages are the following: *1. Initial condition positioning 2. Walking preparation 3. Beginning of walk 4. Stable walking*

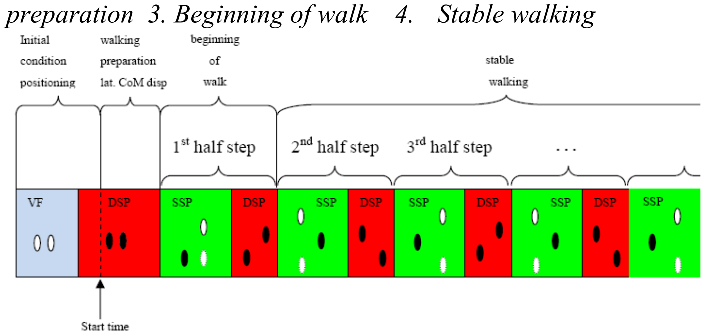


Fig. 5. Global "Walking" histogram

These four stages are detailed later. In the figures, the symbols have the following meanings:

VF → Vertical Fall DSP→Double Support Phase
SSP → Single Support Phase CoM→ Center of Mass
● → Stance Foot (or foot in contact with ground)
○ → Swing Foot (or foot without contact) just before landing
◌ → Swing Foot (or foot without contact) just after toe-off

These four histograms allow us to prepare gait planning and to prescribe all the motions for the translations and rotations of the pelvis and of the swing foot. The axis called X, Y and Z are related to the unit vectors given by Fig. 1:

Y (unit vector $\underline{j_{Abs}}$) is the vertical axis defined by gravity,

X (unit vector $\underline{i_{Abs}}$) is the longitudinal horizontal axis giving the biped robot its main displacement direction,

Z (unit vector $\underline{k_{Abs}}$) is the transversal horizontal axis.

IV. DETAILED GAIT PLANNING FOR THE FOUR STAGES

In this section, the four stages of the histogram previously presented will be detailed.

A. *Initial condition positioning*

The first stage, called "initial condition positioning" is a preliminary stage with no internal joint motions of the biped. This preliminary stage occurs before "start time" of varying controlled motions. The bipedal is stable on its both feet and is ready to initiate the walk.

B. Walking preparation (lateral displacement of the CoM)

The second stage, called "walking preparation" aims to start the internal motions of the biped and to move the CoM laterally and forward at the same time during a DSP. During this stage, the "front" stance leg (future single stance leg) and the "rear" stance leg (future swing leg) are synchronized in order to produce the six motions of the pelvis according to a frame attached to the rear stance leg on the ground. This stage is finished when a SSP begins, the bipeds enters in the beginning of the walk.

C. Beginning of walk

The third stage, called "beginning of walk" is related to the first half step of the biped and is composed by one SSP and one DSP (Fig. 6). Motion analysis shows that the established walking speed (equal here to 1.1 ms^{-1}) is reached at the end of the first half step. The observations show that, during this stage (including one SSP and one DSP), the pelvis keeps its orientation almost parallel to the ground. It implies that the prescribed rotations of the pelvis produced by the stance leg during the SSP (and by the rear stance leg during the DSP) are the following:

-rotations of the pelvis around the X-axis and the Z-axis according to the stance foot are equal to 0

-rotation around Y-axis is maintained equal to the stance foot orientation.

The translations of the pelvis produced by the stance leg during the SSP (and by the rear stance leg during the DSP) are the following:

-along X-axis, one acceleration is produced during the SSP and during the DSP according to the step length in order to reach the desired average velocity for the next half step

-along Y-axis, the pelvis height decreases during the SSP and is stabilized during the DSP

- along Z-axis, there are three phases: the first one is an external lateral translation of the CoM under the current stance foot (SSP), the second one is an internal lateral translation of the CoM under current stance foot (SSP), the third one is a lateral translation of the CoM from rear to front stance foot (DSP). The oscillation of the CoM during this stage is due to natural energetic exchanges in the frontal plane and to the required support change from one foot to the other one.

The prescribed rotations of the foot produced by the swing leg during the SSP are the following:

-Rotations around X-axis so that the foot is maintained parallel to the ground.

-Rotations around Y-axis and Z-axis in order to prepare foot landing. The rotation around Y-axis is related to the orientation (around Y-axis) of the next stance foot to propel the pelvis during the next step in the desired direction. The rotation around Z-axis is carried out in order to start foot landing with heel landing. Indeed, the angle landing between the foot and the ground has to be greater than 15 degrees.

The prescribed translations of the foot produced by the swing leg during the SSP are the following:

-Along X-axis, the foot is moved forward in the sagittal plane towards the future contact surface.

-Along Z-axis, the foot is moved laterally in the frontal plane towards the future contact surface.

Furthermore, the velocity of the swing foot along X-axis and Z-axis has to be approximately equal to zero with regard to the ground in order to minimize the interaction tangential forces with ground and to avoid horizontal sliding.

-Along Y-axis, the SSP is divided into three parts. During the first part, the height of the swing foot increases in order to carry out the toes lift-off. During the second part, the distance between the swing foot and the ground is stabilized in order to avoid a premature contact of the swing foot with the ground. During the last part, the height of the swing foot decreases in order to carry out the heel landing. Furthermore, the velocity of the swing foot along this direction at heel landing has to be approximately equal to zero with regard to the ground in order to minimize the vertical impact forces. During the DSP, the prescribed rotations and translations of the pelvis produced by the front stance leg are synchronized with the motions of the pelvis produced by the rear stance leg in order to minimize the internal joints efforts and the tangential contact forces with ground. Moreover this coordination gives good conditions for the smooth transitions towards the next SSP of the next stage "stable walking".

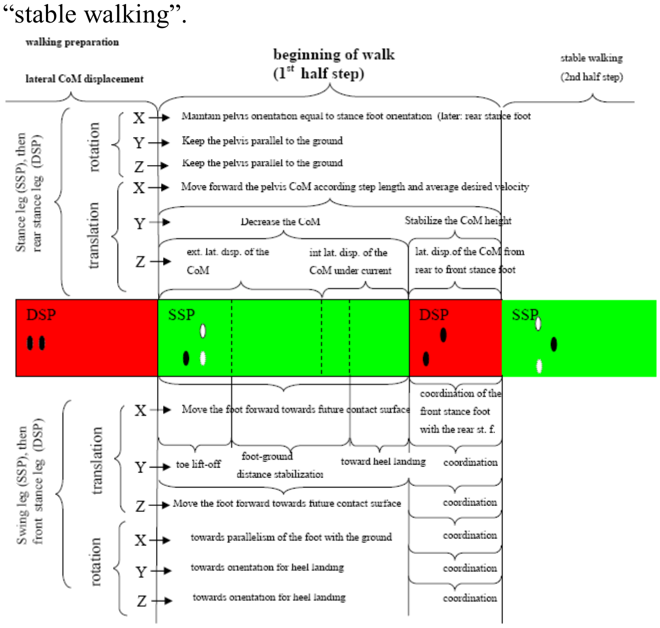


Fig. 6. "Beginning of walk" histogram

D. Stable walking

The fourth stage, called "stable walking", starts with the beginning of the second half step of the biped which is composed by one SSP and one DSP and continues as long as no external disturbances is applied to the system or no problematic event occurs. This fourth stage is composed of N identical half steps. The average walking speed is constant from one half step to another one. All the principles previously described for the prescribed motions of the third stage "beginning of walk", are similar to the fourth stage, except for the translations of the pelvis leg along X-axis and Y-axis. Indeed, along X-axis during the fourth stage, instantaneous prescribed pelvis velocity during one half step oscillates between 0.9 ms^{-1} and 1.3 ms^{-1} for an average speed equal to 1.1 ms^{-1} as measured with motion capture on a human subject.

Furthermore, the translation along Y-axis produced by the stance leg during the SSP is composed by an augmentation of the CoM height followed by a diminution of the CoM height. The four stages previously described in the gait planning have to be produced by a control strategy. This is the subject of the next section.

V. CONTROL STRATEGY

In this section, the control strategy used to apply the four stages previously described is presented.

A. *Control method*

The control method used in the operational space is decomposed into one high level control and one low level control (Fig. 7). The low level control is carried out with a PD (proportional derivative) controller and the high level control is used to perform the gait planning. Based on the previous principles, the gait planning produces feasible dynamic motions for the different parts of the biped (legs, arms, trunk and head) to obtain the vector, $\underline{V_{HM_{\text{Plan}}}}$ which is composed

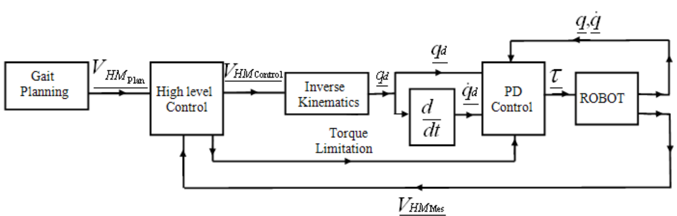


Fig. 7. Control strategy for gait planning in the operational space

of homogeneous matrices giving the position of some key points of the structure and the orientation of the frames associated with these points . For instance, $\underline{\underline{M_{\text{Plan}}^{hip^{right}-ank^{right}}}}$ and $\underline{\underline{M_{\text{Plan}}^{hip^{left}-ank^{left}}}}$ give the position of the ankle and the orientation of the feet in relation to the hip center for the right leg and the left leg, respectively (the 6 dof of the leg are used).

All these motions given by $\underline{V_{HM_{\text{Plan}}}}$ are used as desired motions imposed by the gait planning (including constraints) in the operational space.

The second vector introduced in Fig. 8 is $\underline{V_{HM\text{Mes}}}$. This vector is composed of a set of homogeneous matrices expressed in the operational space and resulting from the sensors of the robot. All the data contained in this vector are the results of measurements. They give for instance the measured position and orientation of the pelvis relatively to the ground, of the swing foot relatively to the pelvis and of the swing foot relatively to the ground. The third vector lately introduced into Fig. 8 is the vector $\underline{V_{HM\text{Control}}}$ which is a composition of the vectors $\underline{V_{HM_{\text{Plan}}}}$ and $\underline{V_{HM\text{Mes}}}$. The vector $\underline{V_{HM\text{Control}}}$ always includes homogeneous matrices expressing the position and the orientation of one link (or joint) in relation to another link (or joint) in the operational space. For instance, this may concern the swing foot (or ankle position and orientation) in relation to the hip of the swing leg or the hip of the stance leg in relation to the stance foot. The vector $\underline{V_{HM\text{Control}}}$ is the input of the inverse kinematics of all the parts of the biped robot. It can be directly performed with the actuators of these parts. The vector of the desired joint motions $\underline{q_d}$ in Fig. 8 is thus obtained with inverse kinematics of the legs of the biped. The vector of the desired joint velocities $\underline{\dot{q}_d}$ is computed by numerical derivation of $\underline{q_d}$. All the joints are controlled by a simple PD control. The torques vector applied to the robot joints is written:

$$\underline{\tau}=\underline{\underline{K_p}}\left(\underline{q_d}-\underline{q}\right)+\underline{\underline{K_v}}\left(\underline{\dot{q}_d}-\underline{\dot{q}}\right) \quad (1)$$

where $\underline{q}$ and $\underline{\dot{q}}$ are the vector of measured joint positions and velocities, respectively, and $\underline{\underline{K_p}}$ and $\underline{\underline{K_v}}$ are the diagonal gain matrices for positions and velocities, respectively. Furthermore, a constraint of torque limitation is applied on each joint of the robot.

B. *Main frames and points used in the control method*

Three key points and their respective attached frames will be used in the control strategy. These frames are related to the locomotive part of the biped and are called: R_{gr} , $R_{PelvisCM}$, R_{heel} .

1) *Position and definition of the reference frame* R_{gr}

The element of the stance foot which has the smaller displacements is composed by the toes. Thus, the point which will be chosen as reference point is situated at the middle of the edge of the fourth element of the propelling foot.

2) *Position and definition of the frame* $R_{PelvisCM}$

The origin $O_{PelvisCM}$ of the frame $R_{PelvisCM}$ will be placed on the gravity center of the biped pelvis with the three axis parallel to R_{gr} in an initial configuration when the robot stands on its two

3) *Position and definition of the frame* R_{heel}

The part of the swing foot coming into contact in first with the ground is the heel of the swing foot. The point located in the middle on the posterior edge of the first segment of the foot called O_{heel} (associated to the frame R_{heel}) will be thus chosen as a key point to control with the swing leg to prepare the double support phase.

C. *Details of the control strategy*

In order to improve the results obtained in [23], we propose to treat the double and single stance phases separately.

1) *Single support phase*

During the single support phase, the stance leg is used to control the pelvis according to the stance foot on the ground (Fig. 3), ie to control the position and orientation of the frame $R_{PelvisCM}$ with regard to the frame R_{gr} . The swing leg is used to control the heel of the swing foot according to the stance foot on the ground (Fig. 3), ie to control the position and orientation of the frame R_{heel} with regard to the frame R_{gr} . The aim is thus to produce the adequate homogeneous matrices $\underline{\underline{M_{\text{control}}^{pel_d^{hip\_sta}-ank^{sta}}}}$ and $\underline{\underline{M_{\text{control}}^{pel^{hip\_sw}-ank_d^{sw}}}}$ used to control $R_{PelvisCM}$ and R_{heel} with regard to the frame R_{gr} .

a) Stance leg

The aim is to produce the matrix $\underline{\underline{M_{control}^{pel_d^{hip\_sta}-ank^{sta}}}}$ to control the pelvis with the stance leg by introducing on one hand some measurements given by the sensors (joint sensors and pelvis sensors) and on the other hand, the desired motions of the pelvis according to the ground. The composition for the matrix $\underline{\underline{M_{control}^{pel_d^{hip\_sta}-ank^{sta}}}}$ can thus be written as follows (see Fig. 3):

$$\begin{aligned}\underline{\underline{M_{control}^{pel_d^{hip\_sta}-ank^{sta}}}} &= \underline{\underline{M_{struct}^{pel_d^{hip\_sta}-pel_d^{CM}}}} \cdot \left(\underline{\underline{M_d^{Ground-pel_d^{CM}}}}\right)^{-1} \\ &\cdot \underline{\underline{M_{mes}^{Ground-pel^{CM}}}} \; \underline{\underline{M_{struct}^{pel^{CM}-pel^{hip\_sta}}}} \cdot \underline{\underline{M_{mes}^{pel^{hip\_sta}-ank^{sta}}}}\end{aligned} \tag{2}$$

The measurements obtained by the pelvis sensors (gyroscope and accelerometers) are included in the matrix $\underline{\underline{M_{mes}^{Ground-pel^{CM}}}}$ (position and rotation of the pelvis with regard to the ground). The measurements obtained by the joint sensors are used to build the matrix $\underline{\underline{M_{mes}^{pel^{hip\_sta}-ank^{sta}}}}$ which is a composition of the 6 elementary homogeneous matrices from the hip to the ankle. The two matrices $\underline{\underline{M_{struct}^{pel_d^{hip\_sta}-pel_d^{CM}}}}$ and $\underline{\underline{M_{struct}^{pel^{CM}-pel^{hip\_sta}}}}$ are known matrices where all the coefficients are constant because they are related to the invariant part of the biped structure (the two frames are attached to the same body: the pelvis). They give the position and the orientation of the frame attached to the pelvis and placed in the hip center of the stance leg with regard to the frame attached to the pelvis and placed in the center of mass. Finally the matrix $\underline{\underline{M_d^{Ground-pel_d^{CM}}}}$ represents the desired position and orientation of the pelvis according to the frame attached to the stance foot on the ground. This matrix is produced by gait planning.

b) Swing leg

The aim is to produce the homogeneous matrix $\underline{\underline{M_{\mathrm{control}}^{pel^{hip\_sw}-ank_d^{sw}}}}$ to control the heel with the swing leg by taking into account the real motions of the pelvis produced by the stance leg. Furthermore, we have to introduce the measurements of the joint sensors of the swing leg, some measurements given by the pelvis sensors and the desired motions of the swing heel according to a frame attached to the stance foot on the ground. The composition for the matrix $\underline{\underline{M_{\mathrm{control}}^{pel^{hip\_sw}-ank_d^{sw}}}}$ can thus be written as follows (see Fig. 3):

$$\begin{aligned}\underline{\underline{M_{control}^{pel_d^{hip\_sw}-ank^{sw}}}} &= \underline{\underline{M_{struct}^{pel_d^{hip\_sw}-pel_d^{CM}}}} \cdot \left(\underline{\underline{M_{mes}^{Ground-pel^{CM}}}}\right)^{-1} \\ &\cdot \underline{\underline{M_d^{Ground-heel^{sw}}}} \cdot \underline{\underline{M_{mes}^{heel^{sw}-ank^{sw}}}}\end{aligned} \tag{3}$$

$\underline{\underline{M_{struct}^{pel_d^{hip\_sw}-pel_d^{CM}}}}$ is a matrix with constant structural coefficients

$\underline{\underline{M_{mes}^{Ground-pel^{CM}}}}$ includes the measurements obtained by the pelvis sensors (gyroscope and accelerometers) and is a function of the real motions produced by the stance leg.

$\underline{\underline{M_{mes}^{heel^{sw}-ank^{sw}}}}$ includes the measurements obtained by the ankle joint sensor and the local inverse kinematics of the foot

$\underline{\underline{M_d^{Ground-heel^{sw}}}}$ represents the desired position and orientation of the heel of the swing leg according to the frame attached to the stance foot on the ground. This matrix is produced by gait planning.

2) Double support phase

During the double support phase, the both legs are used. They are called the rear stance leg (future swing leg) and the front stance leg (which was the swing leg just before the double support phase). The both legs are synchronized in the operational space to control the pelvis according to the frame attached to the heel of the rear stance leg on the ground (Fig. 4), that is to say the position and orientation of the frame $R_{PelvisCM}$ with regard to the frame R_{gr}. The aim is thus to include the homogeneous matrix $\underline{\underline{M_d^{Ground-pel^{CM}}}}$ in the expressions of $\underline{\underline{M_{control}^{pel_d^{hip\_Rsta}-ank^{Rsta}}}}$ and of $\underline{\underline{M_{control}^{pel_d^{hip\_Fsta}-ank^{Fsta}}}}$. (exponents R for rear and F for front). For the rear stance leg, we have the same expression as in the equation (2):

$$\underline{\underline{M_{control}^{pel_d^{hip\_Rsta}-ank^{Rsta}}}} = \underline{\underline{M_{control}^{pel_d^{hip\_sta}-ank^{sta}}}} \tag{4}$$

For the front stance leg (which was the swing leg just before the double contact phase), the composition for the matrix $\underline{\underline{M_{control}^{pel_d^{hip\_Fsta}-ank^{Fsta}}}}$ is written as follows:

$$\begin{aligned}\underline{\underline{M_{control}^{pel_d^{hip\_Fsta}-ank^{Fsta}}}} &= \underline{\underline{M_{struct}^{pel_d^{hip\_Fsta}-pel_d^{CM}}}} \cdot \underline{\underline{M_{struct}^{pel_d^{CM}-pel_d^{hip\_Rsta}}}} \\ &.\underline{\underline{M_{control}^{pel_d^{hip\_Rsta}-ank^{Rsta}}}} . \underline{\underline{M_{mes}^{ank^{Rsta}-fc^{Rsta}}}} . \underline{\underline{M_{mes}^{fc^{Rsta}-fc^{Fsta}}}} . \underline{\underline{M_{mes}^{fc^{Fsta}-ank^{Fsta}}}}\end{aligned} \tag{5}$$

Where $\underline{\underline{M_{struct}^{pel_d^{hip\_Fsta}-pel_d^{CM}}}}$ and $\underline{\underline{M_{struct}^{pel_d^{CM}-pel_d^{hip\_Rsta}}}}$ have constant coefficients.

The interest to include the control matrix of the rear stance leg $\underline{\underline{M_{control}^{pel_d^{hip\_Rsta}-ank^{Rsta}}}}$ is to take into account the reactivity of this leg during the double support phase in order to reduce contact tangential force on the ground. In the three matrices $\underline{\underline{M_{mes}^{ank^{Rsta}-fc^{Rsta}}}}$, $\underline{\underline{M_{mes}^{fc^{Rsta}-fc^{Fsta}}}}$ and $\underline{\underline{M_{mes}^{fc^{Fsta}-ank^{Fsta}}}}$,the symbols fc^{Rsta} and fc^{Fsta} represent the center of pressure of the rear stance leg and of the front stance leg respectively. These two points are computed at each sampling time step during the simulation.

VI. Simulation results

The simulation of the biped dynamic behavior is carried out using the Adams software. Fig. 8 shows some snapshots of the simulation of the dynamic behavior in the sagittal and frontal planes respectively. One of the key points of the approach as in [23] is that it is elaborated independently of the flexion of the toes of the feet, which allow us to exploit this flexibility without its disadvantages.

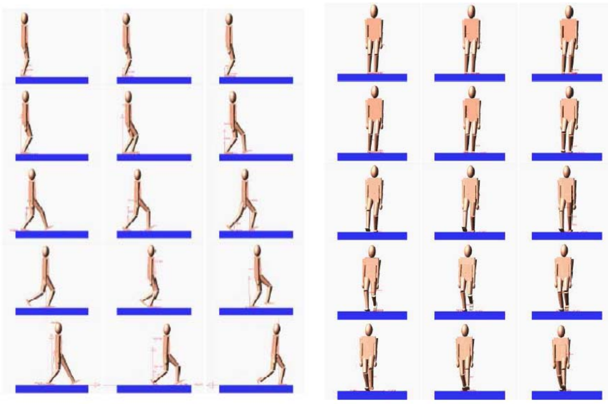


Fig. 8. Snapshots of the simulation during one half-step

VII. CONCLUSIONS AND FUTURE WORK

The five essential contributions of the approach with regard to the study presented in [23] are the following: the reference gaits based on motion capture are replaced by gait planning, the locomotion constraints are directly included in gait planning, the double and single stance phases are treated separately, the two legs are synchronized all the time (during the single and the double support phase), the homogeneous task matrices are defined relatively to a frame attached to the stance foot instead of a global absolute frame, which allows us to update all the data and the events planning at each new step. The interest of this approach is that the set of events during walking will be sequentially defined in a planned framework with local reactivity according to current states and prescribed states of the bipedal robot. One major interest of the method is that all errors in the operational space that are expressed in the joint space are measured by the sensors and taken into account at each time instant to modify desired trajectories before low-level control.

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