Interactive control of a semi-autonomous avatar in Virtual Reality: Balance and Locomotion of a 3D Bipedal Model

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Abstract

Virtual Humans (VH) are used in the manufacturing field as a tool for design, maintenance studies, operator training or ergonomics studies. Nowadays, VH are animated by replicating the movement of an operator, using an optical motion-capture system, for example Vicon or Kinect. Those methods do not consider the feasibility of the task (torque limitations, obstacle avoidance, step irregularity) nor the optimisation of the task (adapted posture, torque reduction). The objective of this thesis is to develop a new control approach which will have to replicate the user's movement (head, waist and arm positions), to maintain a sensation of immersion, and respects some physical constraints (balance, obstacles, weight) to maintain a physically realistic behaviour. The first necessary steps of this approach are balance and locomotion control of the VH.

I. INTRODUCTION

Assuming that the upper body of the VH is following the user via motion capture, the problem is to properly control the lower body in an autonomous way. In order to maintain balance of the system and to follow the movement of the user, the lower body is represented with a reduced model. The models often used in robotics are the linear inverse pendulum (LIPM) [1], the cart table [2], and more recently the inverse pendulum model (IPM) [3]. Since human operator center of mass (CoM) heigh can vary, we choose the IPM. We consider that way the variation of the CoM but we assume that there is no angular-momentum variation around the center of mass. We also assume for locomotion that the position of the waist and of the CoM remain identical.

In the robotics field, the IPM and LIPM stability is assured by the control of the CoM or of the Zero Moment Point (ZMP) above its feet. For our approach, we have decided to inverse the input and output of the control, and keep the same dynamics of the system. We present this strategy in two parts:

- Dynamics of the Inverted Pendulum Model:
  Explanation and Optimisation to calculate the dynamics of the system.
- Application of the stable dynamics to the VH:
  We keep the optimized dynamics, previously explained, to control the positions of the legs.

II. DYNAMICS OF THE INVERTED PENDULUM MODEL

The general dynamics equation of the IPM can be expressed as below:

$$\ddot{c}(t) = \lambda(t)(c(t) - r(t)) + g \tag{1}$$

where $\boldsymbol{c}$ is the CoM, $\boldsymbol{g}$ is the gravity vector and the two control inputs of the system are the CoP $\boldsymbol{r}$ and the stiffness $\boldsymbol{\lambda}$.

A natural choice of the IPM state consists of its CoM position and velocity $[\boldsymbol{c}, \dot{\boldsymbol{c}}]$. We can rewrite the IPM second order equation equivalently as a linear time-variant state function:

$$\begin{bmatrix} \dot{c} \\ \ddot{c} \end{bmatrix} = \begin{bmatrix} 0 & I \\ \lambda I & 0 \end{bmatrix} \begin{bmatrix} c \\ \dot{c} \end{bmatrix} + \begin{bmatrix} 0 \\ g - \lambda r \end{bmatrix} \tag{2}$$

In the document [4], the state of the system is rewritten to separate its convergent and divergent part. Then they find a solution for $\boldsymbol{\lambda}$ and $\boldsymbol{r}$ so that $\boldsymbol{c}$ stay stable and convergent at any time.

We assume that the stiffness is non-negative and that the CoP position is included inside the contact area of the VH. It means that the VH isn't running nor falling.

The trajectory of the CoP is given by the following function:

$$r(s) = r_f + (r_i - r_f)f(s\omega) \tag{3}$$

With $\boldsymbol{s}$ the timeless variable so that when
$\boldsymbol{s = 1 \Leftrightarrow t = t_i}$ and $\boldsymbol{s = 0 \Leftrightarrow t = t_f}$.
That way we can work with any interval of time.
$\boldsymbol{r_i}$ and $\boldsymbol{r_f}$ are the initial and final CoP positions.
$\boldsymbol{\omega}$ is a damping parameter calculated by the QP
$\boldsymbol{f()}$ a function that define the transition from $\boldsymbol{r_i}$ to $\boldsymbol{r_f}$. This function is defined as:

$$f(s\omega) = (\frac{s\omega}{\omega_i})^{\frac{\alpha}{1-\alpha}} \tag{4}$$

Where $\boldsymbol{\alpha} \in [\boldsymbol{0}, \boldsymbol{1}[$ is a variable that needs to be tuned in during the simulation to match the evolution of the CoP.

The CoP is then calculated with an equation with a similar form of a capture point:

$$r_i^{xy} = \frac{1}{1-\alpha}[c_i^{xy} + \frac{\dot{c}_i^{xy}}{\omega_i} - \alpha r_f^{xy}] \tag{5}$$

This way, $\boldsymbol{\omega}$ and $\boldsymbol{\lambda}$ are calculated in order to maintains the dynamics of the system stable and convergent.

III. APPLICATION OF THE STABLE DYNAMIC TO THE VH

Initially, once $\boldsymbol{\omega}$ and $\boldsymbol{\lambda}$ are computed, $\boldsymbol{r_i}$ is computed with equation (5), $\ddot{\boldsymbol{c}}_i$ is computed with equation (1) and integrated to finally get the desired CoM for the next step of time.

But since the position and acceleration of the CoM are already known in virtual reality, what we need is to inverse (1) and

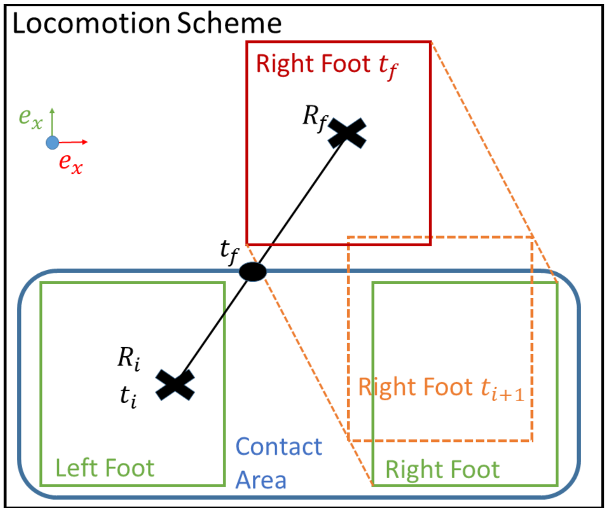

Fig. 1: time-varying CoP trajectory. Future variations of the center of pressure is calculated to force the VH to adapt the position of its legs.

(5) to obtain desired positions for the feet.
That way equation (1) becomes:

$$r(t) = c(t) + \frac{(g - \ddot{c}(t))}{\lambda(t)} \tag{6}$$

And equation (5) becomes:

$$r_f^{xy} = r_i^{xy}(1 - \frac{1}{\alpha}) + \frac{c_i^{xy}}{\alpha} + \frac{\dot{c}_i^{xy}}{\alpha\omega_i} \tag{7}$$

Finally, with $\boldsymbol{r_f}$ we can predict if the system is stable and otherwise, with (4), we know when and where to move the contact area to maintain balance of the VH. Those parameters are the indications we will have as input of our locomotion algorithm that will calculate the trajectory of our feet.

This way we can define a trajectory for the feet with a polynomial function that respect the final position $\boldsymbol{r_f}$ and the final time $\boldsymbol{t_f}$ which correspond at the moment the CoP leave the Contact Area. At each iteration, those parameters vary until $\boldsymbol{t_i}$ converge to $\boldsymbol{t_f}$ and the trajectory $\boldsymbol{R_i}$ to $\boldsymbol{R_f}$ is include inside the Contact Area. If $\boldsymbol{r_f}$ is already inside of the Contact Area, the feet will stay in their initials positions
Those feet positions will then be respected through the inverse dynamics model of the system and later in the thesis, in another QP, for the task prioritization.

IV. Perspectives

We have seen in this document how to benefit of the tools and strategy employed in the Humanoid Robotics field in a Virtual Reality application. We will need in the future to implement and test this dynamic to test its robustness, to test different strategies to define the more adequate $\boldsymbol{\alpha}$ and finally, define the sensation of immersion of the operator.

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