Interactive walking pattern generator for mechanically coupled bipedal agents

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Abstract— **This work presents a simple 2D model for physically coupled bipedal agents (humans/humanoids) that can be used as an interactive walking pattern generator. Such a model is based on the Angular Momentum inducing inverted Pendulum (AMP) which is used in robotics to plan motion paths for biped robots and on the assumption that the coupling can be modeled as a spring-damper. The right choice of parameters allow the model to achieve stable walking gaits and coordinated foot-fall patterns are shown to occur between two humans walking together while mechanically coupled. The use of such a model as a walking pattern generator for humanoid robots allows the modulation of their stepping frequency according to the interaction with another agent. External forces applied on the robot can be mapped into the model dynamics so that it is possible to accommodate such interaction while keeping the gait coordination between the two bipedal agents. Mathematical analysis and simulation results with a humanoid robot (COMAN) are presented to show the adaptive locomotion behaviour.**

I. INTRODUCTION

HUMAN-robot interaction is difficult due to human-in-the-loop, requiring an understanding of human intentions to better control the haptic interaction while providing a safe and robust environment. Moreover if a humanoid robot is required, one should also ensure a reactive walking pattern generator under equilibrium and unknown forces. Only few works have integrated the aforementioned features to develop control strategies for human-humanoid task sharing during gait [1, 2, 3]. However none of the works have shown a clear interlimb and intersubject coordination, nor have they exploited such coordination to optimize task performances. Such aspects are interesting to investigate, in addition to the relationship between interaction forces and locomotion. In our study we will explore foot-fall pattern synchronization and entrainment between human locomotion and the haptic interaction and how such behaviour can be modeled and reproduced in a robotic scenario.

II. THE MODEL

The model realized to represent mechanically paired bipeds while walking is made up of two AMPs [4] coupled by a parallel spring and damper system. Each pendulum represents a bipedal agent while a mass in between represents the rigid coupling. Parallel spring-damper represents arms' impedance. The following main assumptions were made:

- The mass of each agent is concentrated at its Center of Mass (CoM);
- Arms effect in the coupling is represented as a spring and damper system with fixed impedance;
- No vertical displacement of the object is allowed;

From a systematic search it was possible to find regions of impedance parameters that ensure stable and synchronized foot-fall pattern between the two modeled agents even when starting from different initial velocities, as showed from humans experiment.

A. Simulation Results

Starting from the same initial condition set in the systematic search ($v_1 = 1ms$, $v_2 = 1.5ms$), an example of a stable and synchronized walking behaviour is presented in Fig.1.
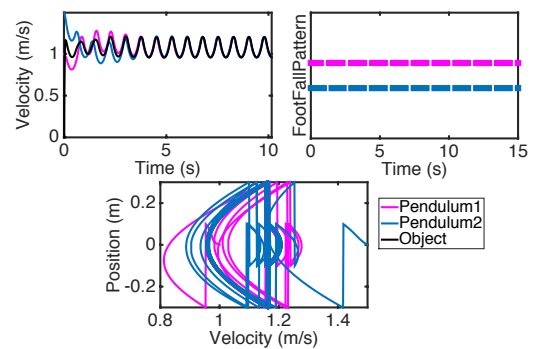

Figure 1 – Coupled AMPs Model behaviour by imposing as stiffness and damping values for the connection $\mathbf{k_1 = k_2 = 100\frac{N}{m}}$ and $\mathbf{b_1 = b_2 = 150\frac{N}{m \cdot s}}$ respectively. Initial velocity are $\mathbf{v_1 = 1\frac{m}{s}}$, $\mathbf{v_2 = 1.5\frac{m}{s}}$. The two pendulums find a stable and synchronized walking gait after few seconds of transitory state where the system loses part of its energy.

III. COUPLED AMPS MODEL AS INTERACTIVE WALKING PATTERN GENERATOR (WPG)

The presented model can be used as interactive WPG for humanoid robots that need to regulate their gait according to another operator (another humanoid robot or a human being) who is mechanically coupled to them (e.g while carrying an object). Such a coupling can be modeled as a virtual force attached to the robot's CoM (Fig.2) that varies with the interaction between the two bipedal agents and that cannot be evaluated and computed 'a priori'. It will determine in turn a modulation of the humanoid stepping frequency.
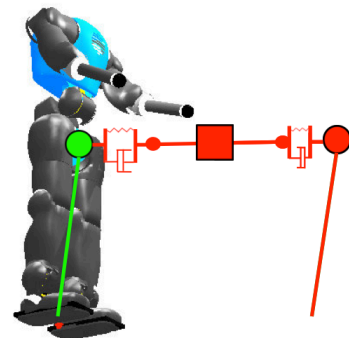

Figure 2 –Coupled AMPs model applied to the simulated COMAN. One pendulum (red) is used as virtual agent to realize the interaction. The other pendulum (green) is used to generate cartesian references.
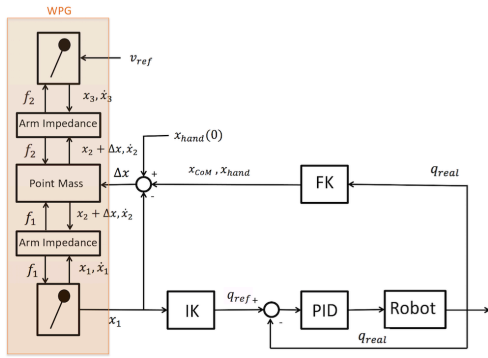
Figure 3- Overall control architecture is presented. The orange square identifies the interactive WPG. It takes a a reference velocity, when needed, and a feedback error related to the tracking of the CoM position and the hands' displacement. Cartesian references are sent to the inverse kinematics (IK) block in order to compute the corresponding desired joint angles. A PID controller is then used to determine the tracking of such desired joint positons by the robot. An error feedback (Δx) is sent back to the WPG. It is used to evaluate the displacement between the desired CoM trajectory and the real one, and also to take into account external forces applied on the robot.

Such architecture has been realized to control one simulated humanoid robot (COMAN) while mechanically coupled with a virtual agent (Fig.2, red pendulum). Such virtual agent can be used to set a reference velocity for the 'tracked' pendulum (Fig.2, green pendulum) or just to recreate a variable interaction by setting different initial conditions for the two modeled pendulums.

A. Simulation Result

The presented model has been applied as an interactive WPG for a simulated humanoid robot (COMAN) using Webots environment. As simulation result we report the effect of external perturbations applied on the simulated humanoid robot. While the simulated COMAN was walking, external forces were applied at the level of the left hand (Fig. 5). Such forces, due to the architecture in Fig. 3, were mapped as forces on the point mass caused variation in the model behaviour (CoM displacement) and, in turn, in the stepping frequency of the simulated robot. Such a variations are evident in Fig. 4 where the pendulums' and robot's CoM are reported (first and second plots from top).
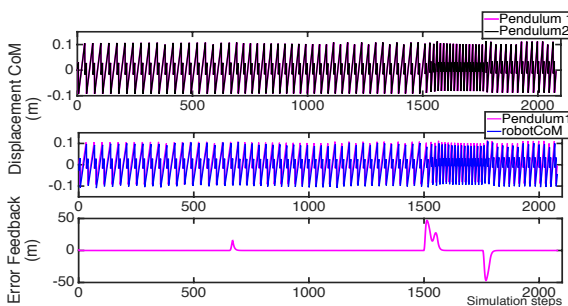

Figure 4 - Tracking results of the robot CoM position (second plot from the top, blue curve) with respect to the reference given by one pendulum (second plot from the top, magenta curve) are presented together with the error feedback (third plot from the top). Moreover, the first plot shows how the Pendulums' CoM motion are always coordinate (because of the same initial conditions and thanks to the right choice of parameters).
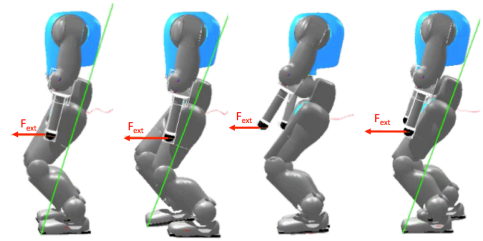

Figure 5 – Snapshots of simulation results, Case II. The simulated COMAN robot is perturbed by an external force applied by the operator and such a force is mapped into the model dynamics causing a modulation of stepping frequency.

IV. CONCLUSION

Human-robot and robot-robot interaction researches are currently lacking for walking-related tasks, such as inter-limb coordination (humanoids' arms motion and walking) and inter-subject synchronization. In this work we mainly focused on this latter aspect of the bipedal interaction, proposing a simple 2D model that can be used to describe and explain intersubject walking coordination according to the right modulation of arms' impedance. Such a simple model can be used as walking pattern generator for humanoid robots in several situation (stand-alone, human-robot interaction, robot-robot interaction). External forces are easily mapped directly into the model as part of the dynamic equations. This latter point allow the overall system to naturally react to the interaction force, mantaining a coordinated behaviour. Even if the presented work is just a first step of solving the complex problem of coordination and interaction control between bipedal agents while walking, the results obtained and also the similarities with humans' behaviour are promising. The addition of the 3D complexity to the model and a deeper evaluation of the role of sensory feedback to determine interlimb coordination in humans may, in the next future, add a more natural and robust behaviour to the robotic controller itself.

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