Towards an Autonomous Small-Size Humanoid Robot: Design Issues and Control Strategies

Filipe Silva
Department of Electronics and Telecommunications
IEETA, University of Aveiro
3810-19, Aveiro, Portugal
fsilva@det.ua.pt

Vítor Santos
Department of Mechanical Engineering
TEMA, University of Aveiro
3810-193 Aveiro, Portugal
vsantos@mec.ua.pt

Abstract – **This paper presents the design considerations of a small-size humanoid robot. The design process has revealed much about the several problems, challenges and tradeoffs imposed by biped locomotion. Among them, we here focus on the control of a single leg and its behaviour when assuming a forward motion. The controller is based on simple motion goals taking into account the reaction forces between the feet and the ground. A new method is proposed which appears to be well adapted to the class of problem considered: the use of a fractional-order controller combined with a genetic algorithm for optimal tuning of the control parameters. The control algorithm is tested through several simulations and its robustness is discussed.**

Index Terms – Humanoid robot, distributed control, biped locomotion, fractional calculus, genetic algorithms.

I. Introduction

In recent years, there has been a large effort in the development of biped robot prototypes and in the control and analysis of biped gaits. From the literature, several categories of control algorithms appear, falling largely into two groups: time-dependent and time-invariant algorithms. By far, the most popular are time-dependent that involve the tracking of pre-computed trajectories [1-3]. One of the most prominent schemes used to enhance trajectory tracking controllers or to analyse their stability is the so-called Zero Moment Point (ZMP) criterion [4]. In addition to the various time-dependent trajectory tracking algorithms, there have been several other time-invariant control schemes proposed [5-6]. The results of the time-dependent schemes are impressive by inducing dynamic walking, but it is unclear how stability is achieved and how robustness or efficiency can be improved.

In order to test models related to control and autonomous navigation, a hardware platform is required, and one such platform was ultimately decided to be constructed from scratch. The design process has revealed much about the several problems, challenges and tradeoffs imposed by biped locomotion. The demands for limited costs gave rise to the selection of off-the-shelf materials and components. The main difficulties arise because bipeds are typically high DOF mechanisms with changing dynamic constraints due to foot touchdown and lift-off during the walking cycle.

The approach followed in this paper consists of studying a simple model, but keeping enough complexity to cover for two main problems associated with biped locomotion. First, the unilateral constraints during the phase of single support imposes that the ground reaction forces are kept positive at both ends of the foot (heel and foot). Second, the design of a controller that induces limit cycles.

The partial robot model adopted is a kinematics chain consisting of a planar two-DOF leg in contact with the ground (stance leg). Here, we emphasis the functional properties that emerge from the interaction between the leg and its environment. The ground reaction forces are the key element through which the control scheme is proposed to provide the required level of compliance, adaptation and dynamic stability. At the same time, a novel design procedure is developed based on two additional features: 1) the use of a fractional-order controller in the tracking of the interaction forces between the foot and the ground; and 2) the use of a genetic algorithm for optimal tuning of the control parameter. The theoretical and practical interest of these operators is nowadays well established, and its applicability to science and engineering can be considered as an emerging new topic. The authors believe this to be the first example of the use of fractional calculus to design a controller for biped locomotion.

The remainder of the paper is organised as follows. Section 2 describes briefly the humanoid platform, namely, the technological and strategic options. Section 3 focuses on the single leg reduced model and the force control algorithm. Section 4 studies the application of the fractional-order controller and their parameters' optimization by a genetic algorithm. Section 5 illustrates how the results of previous sections, when taken together, afford the tradeoffs between stability and energy efficiency. Section 6 concludes the paper and outlines the perspectives towards future research.

II. The Humanoid Platform

A. Purpose

The main goal of the project beneath this paper has been the development of a small-size humanoid platform to carry out research on control, navigation and perception on robotics in general, and also to offer opportunities for undergraduate and pos-graduate students to apply engineering methods and techniques in such an ambitious and overwhelming endeavor.

Purchasing a commercial platform and develop research on it was not an option not only due to its prohibitive costs, but also because it would reduce the involvement at the lowest levels of machine design, which was posed as a relevant pursuit for the desired engineering approach. Moreover, the authors sought a platform with enhanced flexibility, namely at the level of system control, and not many platforms offer that level of flexibility. That was one of the relevant achievements of the project that was then based on distributed actuation and control, which on the other hand has raised new problems, and that this paper addresses further on.

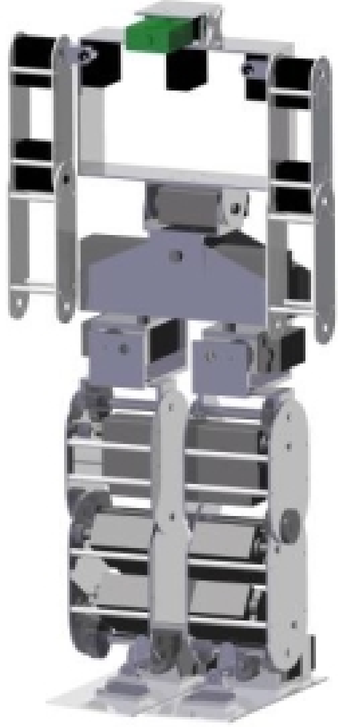


Fig. 1 - Front view of the humanoid model.

B. Mechanical Design

When conceiving a robotic platform, namely a bipedal and, latter on, a humanoid one, countless decisions have to be made. Specifications and target applications must be defined and applied to impose limits both on skills and overall objectives. Hence, the *RoboCup* framework was adopted, which has consequences on the robot dimensions and at the very high level of autonomy required; also, locomotion (walking) was elected the kernel concern in the project.

After the structure height (60 cm) and remainder body proportions, the very first issue has been the number of degrees of freedom, namely to ensure proper and versatile locomotion. Walking concerns can range from simply ensuring robust equilibrium to static walking up to, hopefully, dynamic walking for energetic efficiency.

The most versatile humanoids presented in *RoboCup*, and elsewhere, show up six DOFs per leg, namely one universal joint at the ankle, simple joint on the knee and a spherical joint on the hip, where nonetheless a simpler universal joint would still deal with many of the walking demands.

Connecting the legs to the upper structure of the abdomen was decided to be done with two DOFs mainly aiming at greater flexibility in control to balance and account for the perturbations of the Center of Mass (CoM). Arms have been so far poorly defined and the head accounts for two DOFs for vision based perception.

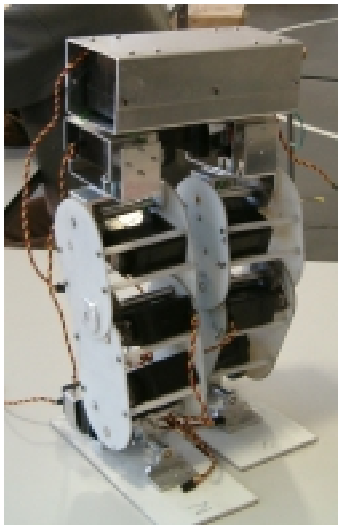


Fig. 2 - Photo with earlier implementation of the legs.

C. Actuators and Sensors

For the dimensions involved, and for good autonomy, off-the-shelf technologies for actuation give not significant alternatives other than the small servomotors, such as those from FUTABA and similar used worldwide. Therefore, HITEC servomotors were chosen. This kind of servos has the disadvantage that velocity can not be automatically controlled. That is being overcome by an algorithm based on dynamic PWM tracking using the servo own potentiometer for feedback information. Velocity is now going to be controlled in slots of 10 ms, or less if required.

As all systems intended to be autonomous, this robot has both proprioceptive and exteroceptive sensors. For now, only the former exist and the following are available: each joint position, 4 force sensors on each foot to measure reaction force from ground, accelerometers, used mainly as inclinometers, and gyro for instant angular velocity measuring. Accelerometers and gyro are of the integrated type based on MEMS technology. Force sensing was custom made using strain gauges properly calibrated and electrically conditioned.

Regarding the desired control, as explained further, it was necessary to develop a foot sensitive to reaction forces. A simple approach would be sufficient to test the system, so a device with four strain gauges was arranged near the four corners of the foot base (Fig. 3).

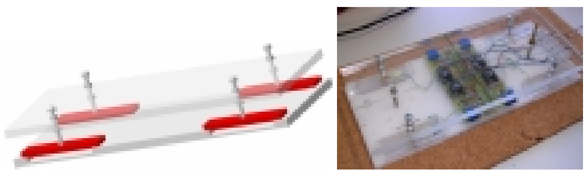


Fig. 3 - Sensitive foot base. Model and real device.

D. Computing System

One of the major challenges of the project was to conceive and implement a distributed control system. To allow for short and possibly longer term developments, the platform was given a network of controllers connected by a CAN bus in a master-multi slave arrangement. The master unit performs no device low-level control but dispatches orders and collects information to be exchanged with a central system that currently is still located on an external computer.

Each slave controller can control up to three joints. Each controller is made of a PIC device with its own program made up of local low-level actuator control, but with the possibility for joint group control, such as an entire foot up to the knee. In summary, each unit can control up to 3 motors and monitor several local sensors (up to 16 in current configuration).

This possibility of local units with their own control ability allows for more elaborate control strategies, since they can either simply accept directives from upstream controllers, implement their own control decisions, or a combination of both. This ability releases the higher level control units from the burden of being aware of every and all details of control and perception (PID, PWM, sensor processing, etc.). The control strategy detailed further on this paper is one example of the local control power that this architecture can allow.

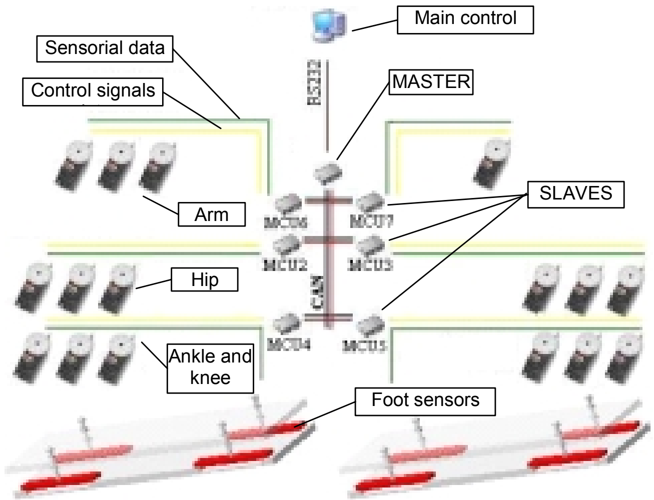


Fig. 4 – Distributed control system.

E. Motion Planning and Control Approach

The major problems associated with bipedal systems are the high-order, highly coupled nonlinear dynamics and the discrete changes in the dynamics due to the nature of the walking gait. The difficult relation between planning and stability has justified a new line of thought where the skill of locomotion emerges from the physical interaction between the machine and the environment itself [7-9]. In this line of thought, the interaction forces are the key element through which new control strategies are proposed to provide the required level of adaptation and stability.

According to this principle, it is convenient that the controller may establish the relation between the desired mobility (at the hip) and the postural stability (at the ground). In this context, it is up to the degrees of freedom nearest to the ground – ankle and knee – to assure the mobility and stability of the system, and to the degrees of freedom more distant from the ground – hip and trunk – the main role of compensation.

To put a bipedal robot on the road demands a lot of control at various levels. The simpler approach is first to define a very elementary locomotion principle – static walking. Here, the CoM is always above the support base, ensuring the balance and, thus, preventing falling over. A step towards dynamic balance must be more exigent, requiring the implementation of more robust procedures. Focusing on the reaction forces, a control scheme with application in both static and dynamic walking is proposed.

III. LEG-FOOT SYSTEM'S CONTROL

This section describes the control strategies applied to a simplified mathematical model used in simulation. In general, the study of simple models tends to give better insight into the underlying mechanics of complicated systems.

A. A Simple Model

The robot model is a kinematics chain consisting of a planar two-DOF leg in contact with the ground. It is assumed the existence of two actuators (ankle and knee) and two contact points where the force sensors are inserted (see Fig. 5). The contact of the foot with the constraint surface is modelled through a linear spring-damper system in the horizontal and vertical directions. Further, the friction is assumed to be large enough to avoid any foot's slippage.

In the present study, we consider a simplified model that comprises a maximum height of $L = 33cm$ and a total mass of $M = 5kg$ (see Table I). Thus, the upper body and the swing leg masses are incorporated into the model.

Table I – Robot and environment parameters.

Robot Link	Mass (kg)	Length		Spring-damper model	
		l_i (m)	r_i (m)	K_x (N/m)	B_x (Ns/m^2)
Thigh	4.0	0.165	0.09	50.0×10^3	1000.0
Shank	0.6	0.165	0.12	K_y (N/m)	B_y (Ns/m^2)
Foot	0.4	0.12	0.04	200.0×10^3	250.0

Restricting attention to the sagittal plane is reasonable since its dynamics is almost decoupled from those in the frontal plane. Therefore, it is expected that a control algorithm to stabilise walking in the sagittal plane may be coupled with an algorithm to stabilise motions in the frontal plane.

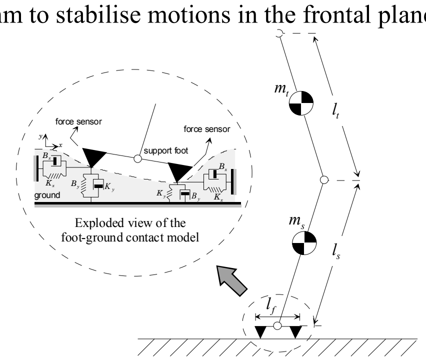


Fig. 5 – Planar 2-dof foot-leg model and constraint surface.

B. Goal-Oriented Force Interaction Control (GO-FIC)

In light of the above settings, the essence of locomotion is to transport the upper body from an initial position to a desired one throughout the action of the lower limb. Conceptually, this goal requires the consideration of two problems: postural stability and contact with the ground. In fact, the rotational equilibrium of the foot is the major factor of postural instability in legged robots.

The proposed control algorithm is based on simple motion goals taking into account the reaction forces between the feet and the ground (Fig. 6). In other words, the stance leg "feels" the forces while the controller distributes them as driving torques that regulate the desired motion of the upper body.

The relevant aspects of the GO-FIC are the minimal dependence on planned variables and the consideration of the unilateral constraints that severely limits the amount of torque that may be supplied at the stance ankle. Constrained forces at the foot are controlled such that stable contact is preserved between the foot and the ground (avoiding foot roll-over):

$$f_{heel} > 0 \text{ and } f_{toe} > 0 \qquad (1)$$

where f_{heel} and f_{toe} are the normal ground reaction forces at the extremities of the foot.

In this line of thought, the control scheme enables the active steer in face of changing conditions (*e.g.*, environment or load) by combining both force feedback with online pattern-modifications. The two variables to be controlled are the normal reaction forces across the heel and at the toe, $f_{n,heel}$ and $f_{n,toe}$, respectively. The reference signals are generated automatically in result of demands (motion goals) imposed to the upper body section. These are the variables that some force control law must follow. The force errors measured in each extremity of the foot can be transformed into joint torques by using the transpose of the Jacobian matrices. A more detailed explanation of the GO-FIC can be found elsewhere [10].

IV. FRACTIONAL-ORDER CONTROLLER

Fractional calculus is a collection of relatively little-known mathematical results concerning the generalization of the ordinary differentiation and integration to non-integer (arbitrary) order. While the subject dates back to the origins of calculus, they have until recently found little application as a scientific and engineering tool. This situation is beginning to change and there are a growing number of research areas which employ fractional calculus, such as biology, electronics, signal processing, modelling and control theory. For a historical survey the reader may consult the books of Oldham and Spanier or Miller and Ross [11-12].

Next, we give an overview of the fundamentals of fractional calculus and its application in control [13]. Based on these results, we present a non-integer order controller and its tuning by a genetic algorithm.

A. Problem Formulation

One of the several definitions of non-integer order derivatives is due to the work of Grünwald and Letnikoff:

$$D^{\alpha} f(t) = \lim_{k=0} \frac{1}{h^{\alpha}} \sum_{k=0}^{+\infty} \frac{(-1)^k \Gamma(\alpha+1) f(t-kh)}{\Gamma(k+1)\Gamma(\alpha-k+1)}, \alpha \in \Re \qquad (2)$$

where $\Gamma(v)$ is the gamma function.

In order to compute a non-integer order derivative of a sampled signal, definition (2) is approximated such that the total sum is truncated after a finite number of terms and the time-step h is approximated by the sampling time T ($t = nT$):

$$D^{\alpha} f(t) \approx \frac{1}{T^{\alpha}} \sum_{k=0}^{n} \zeta_k^{\alpha} f(t-kT) \qquad (3)$$

where the coefficients ζ_k^n can be calculated iteratively using the expression:

$$\zeta_0^{\alpha} = 1 \mapsto \zeta_k^{\alpha} = \left(1 - \frac{\alpha+1}{k}\right) \zeta_{k-1}^{\alpha}, k = 1,2,3,\cdots \qquad (4)$$

The central contribution of this paper emerges when answering two questions. The first is related with the basic control actions: why not to extend them in a continuous way? The central idea behind the use of a fractional PID controller is illustrated in Fig. 7. Most of the time-dependent algorithms involve the tracking of pre-computed trajectories using a PID control law (or a particular case). In this study, the control laws are designed independently: 1) a fractional order controller is selected for the inner control loop (force feedback); and 2) the position control law for the outer control loops consists of a PD law whose parameters are selected by trial-and-error.

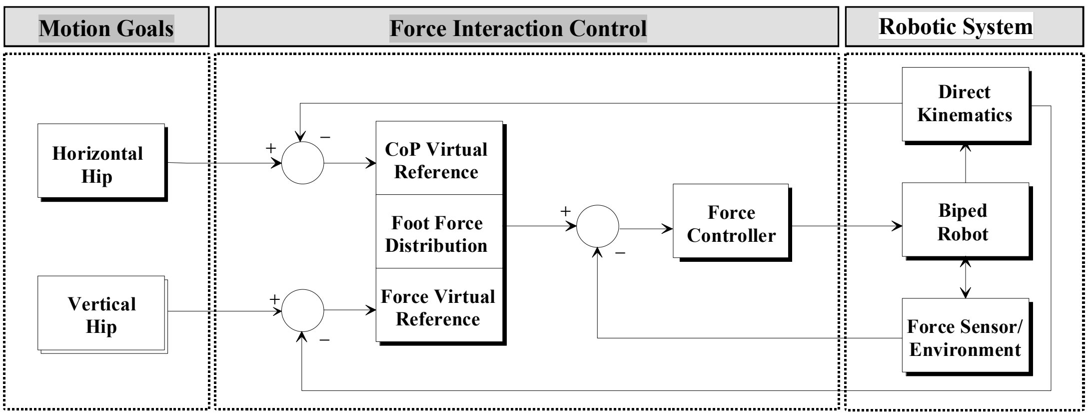


Fig. 6 - Blocks diagram of the Goal-Oriented Force Interaction Control (GO-FIC).

Here, the objective is to apply fractional order control to enhance the performance of the force feedback control system. The transfer function of the $P^{\alpha}I^{\lambda}D^{\mu}$ is given by:

$$H(s) = K_{\alpha}s^{\alpha} + K_{\lambda}s^{\lambda} + K_{\mu}s^{\mu} \quad (5)$$

where the pair (K_i, i) represents the control gain and the non-integer order. Thus, the design procedure involves the parameters of a fractional controller with three terms:

$$C_P = \left[(K_{\lambda}, \lambda) \ (K_{\alpha}, \alpha) \ (K_{\mu}, \mu) \right] \quad (6)$$

Given the additional fit parameter remains, the second question remains: how to select the scheme and the parameters of the controller? Fractional order controllers often achieve better performance and robustness results when compared with conventional ones. However, the selection and tuning of the parameters (*i.e.*, control gains and non-integer orders) is not always straightforward. In this paper, a genetic algorithm was preferred over other randomized search methods.

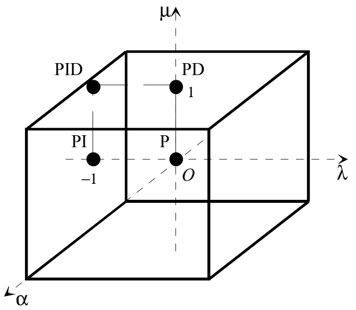


Fig. 7 Generalisation of a PID controller.

B. Optimization of the Control Parameters

Genetic algorithms are adaptive methods which may be used to solve search and optimisation problems. By mimicking the principles of natural selection, genetic algorithms are able to evolve solutions towards an optimal one. Although the optimal is not guaranteed, the genetic algorithm is a stochastic search procedure that, usually, generates good results.

The genetic algorithm maintains a population of candidate solutions (the individuals). Individuals are evaluated and fitness values are assigned based on the relative performance. They are then given a chance to reproduce, *i.e.*, replicating themselves a number of times. The offspring produced are modified by means of mutation and/or recombination operators before they are evaluated and reinserted in the population. This is repeated until some condition is satisfied.

The outline of the specific genetic algorithm is as follows:

1) **[Start]** Generate a random population of 100 suitable solutions (chromosomes):
   - The gains K_{λ}, K_{α} and K_{μ} are uniformly distributed in the range [0, 5000].
   - The non-integer orders λ, α and μ are uniformly distributed in the range [-2, 2].
   - These values are codified directly into real numbers (value encoding).
2) **[Simulation]** Simulate the control for all chromosomes in the population using the fractional controller.
3) **[Fitness]** Select and evaluate the fitness function for each chromosome. The steady-state performance is evaluated by computing the mean square tracking errors of the interaction forces (adding the two components).
4) **[New population]** Create a new population by repeating the following steps:
   - **[Selection]** Select the 5 best parent chromosomes according to their fitness. These solutions are copied without changes to the new population (elitism).
   - **[Crossover]** One-third of the remaining individuals are replaced by cross over the parents: two random parents are chosen and an arithmetic mean operation is performed to make a new offspring.
   - **[Mutation]** One-third of the remaining individuals are replaced by mutate the parents: one random parent is chosen and to selected values is added a small number to make a new offspring.
   - **[Spontaneous generation]** One-third of the remaining individuals are replaced by new randomly generated ones (such as in step 1).
5) **[Loop]** If this is the 500^{th} iteration or the best solution does not improve in the last 10 iterations, **stop the algorithm**, else, **go to step 2**.

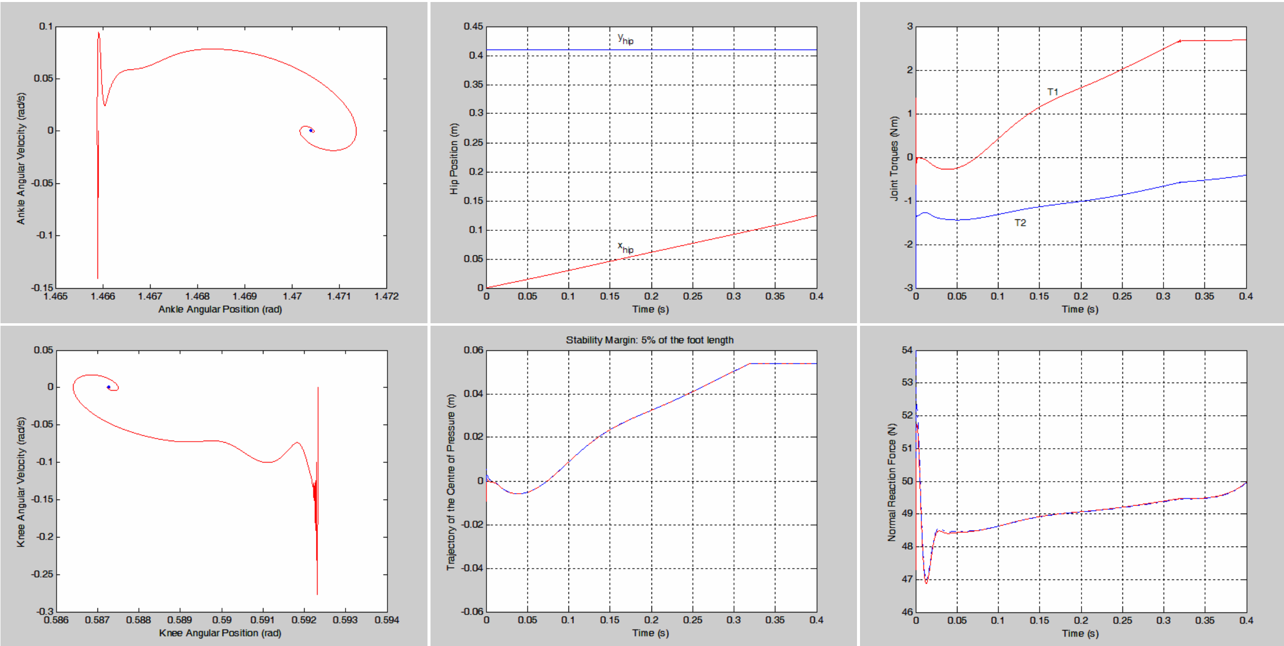
V. Simulation Results

In order to verify the effectiveness of the proposed controller, several simulations are carried out addressing the problem of steady-state locomotion. The motion planning is accomplished by prescribing the Cartesian trajectories of the hip. At the same time, the optimization algorithm produces optimal solutions for the following special cases: an integer-order PI controller, a fractional-order controller with two terms $P^{\alpha}I^{\lambda}$ and a fractional $P^{\alpha}I^{\lambda}D^{\mu}$ controller.

The same control algorithm is used to explore the progression phase of the locomotion process by focusing here on the single support phase, while ignoring the impact and the transfer of support. Thus, the next simulations are carried out assuming a constant hip height of $H_h = 0.31m$, a step length of $S_l = 0.12m$ (the same initial state) and a constant forward velocity of $V_f = 0.3ms^{-1}$. Roughly speaking, we emphasise steady-state locomotion subject to initial transients.

Table II shows the performance of the best controllers found by the genetic algorithm. From the results, a few remarks ought to be made. First, the improvements are clear when evolving from the integer-order PI to the fractional PID controller. Second, an attempt to reduce the overshoot or the settling time implies an increase of the force tracking errors, and vice-versa. At this stage, it was decided to adopt the control parameters obtained using just the force errors (an evaluation of the transient performance is also necessary).

In this context, the simulation results are illustrated in Fig. 8. The force controller is effective to generate the desired hip motion, while the COP remains inside the support covered by the stance foot (Fig. 8-*b*). At the same time, the temporal evolution of the torques reveals the reduced value for the



(*a*) (*b*) (*c*)

Fig. 8 – Phase plane: (*a*) ankle joint (up) and knee joint (down). Temporal evolution of the: (*b*) horizontal and vertical hip Cartesian position (up) and joint torques (down); (*c*) real vs. desired centre of pressure (up) and real vs. desired normal ground reaction force (down).

ankle joint (Fig. 8-*c*). These charts show how the adaptation between mobility and stability is achieved: it is necessary to sacrifice the mobility goals (*i.e.*, the step length) to assure the dynamic stability.

Table II – Control parameters optimised by GA.

	K_λ	λ	K_α	α	K_μ	μ	Force Errors (N)
PI	3000.0	**<u>-1.0</u>**	-	-	17.5	**<u>0.0</u>**	0.53
$P^\alpha I^\lambda$	4200.0	-1.02	-	-	200.0	-0.4	0.41
$P^\alpha I^\lambda D^\mu$	2500.0	-1.04	580.0	-0.61	50.0	-0.2	0.32

VI. Conclusions

This paper has described the design issues and the control strategies towards the development of a small-size humanoid robot. The design considerations that governed this project are related with both the distributed control system and the relevance of the interaction forces. The results suggest the following major comments. First, the GO-FIC is well adapted to achieve foot stability, force compliance and different motion goals. Second, the application of a fractional-order controller in the tracking of the interaction forces increases the system's performance. Third, the use of a genetic algorithm helps to find an adequate selection of the control parameters.

Besides the obvious necessary extension to the physical robot, there are a number of issues to be investigated. Ongoing research focuses the main directions: *i*) to extend this study to the lateral motion; *ii*) to study the complete robot model, incorporating the trunk and swing leg; and *iii*) to address the challenging issues of impact and smooth transfer of support.

In this sense, it seems essential to combine the force control techniques with more advanced algorithms such as adaptive and learning strategies.

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