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Modelling and Design of a Tridimensional Compliant Leg for Bioloid Quadruped

Mafalda Couto[1,*], *Cristina P. Santos*[1] *and Jose Machado*[2]

[1] ALGORITMI Research Centre, Industrial Electronics Department, University of Minho, Guimares, Portugal
[2] CT2M Research Centre, Mechanical Engineering Department, University of Minho, Guimares, Portugal

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Abstract: In the growing field of rehabilitation robotics, the modelling of a real robot is a complex and passionate challenge. On the crossing point of mechanics, physics and computer-science, the development of a complete 3D model involves the knowledge of the different physic properties, for an accurate simulation. In this paper, it is proposed the design of an efficient three-dimensional model of the quadruped Bioloid robot setting segmented pantographic legs, in order to actively retract the quadruped legs during locomotion and minimizing large forces due to shocks, such that the robot is able to safely and dynamically interact with the user or the environment.

Keywords: 3D Modelling, Quadruped Bioloid Robot, Segmented Pantograph Leg, Compliant Joint

1 Introduction

Robotics is growing fast and in most related fields, making a significant impact on many aspects of modern life. Locomotive robots are no exception and became an attractive field of research, due to the major interest in terms of safety and effectiveness. Biomechanical models are very complex and their application in legged robots modelling, mimicking the human/animal behaviour, progresses to improve the knowledge about their mechanism features and ultimately to succeed in many significant fields, like rehabilitation [1].

The modelling and design of a robot is a complex and interesting challenge. Specifically, when considering legged locomotion, control strategies have to deal with several difficulties in which the configuration design of the legs should be able to cope with. Starting from the previously developed three-dimensional model of a Bioloid quadruped robot by Fillion-Robin [2], the main motivation of the work proposed in this paper was to improve its leg configuration design. Namely, in order to minimize large forces due to shocks and to safely interact with the user or the environment, the goal of this work is to elaborate an accurate efficient three-dimensional model of a quadruped robot with compliant legs. Focusing on the leg retraction, the design features to be implemented are essential for the performance of the quadruped leg. Therefore, taking inspiration in biology concepts, a new segmented pantographic robotic leg design with passive compliant knee joints was created using the Webots™ [3] simulation software. In order to study the behaviour of the mechanism, this configuration morphology was associated to an controller and simulation tests were performed.

In the chapter 2 the Bioloid robot as well as the platform for modelling and simulation is presented. In section 3 some biological principles adopted for the leg model are discussed; next the entire model of the leg and respective kinematic analysis is presented; further, in chapter 5 results are obtained by simulation and, finally in chapter 6 conclusions and suggestions for future works are summarized.

2 Bioloid Robot

The ROBOTIS®[4] is a well-known, specialized company developer of robotic kits with a wide set of advantageous features, thus it holds an academic interest on research in many fields, greatly due to its robustness and versatility. The kit used in this project is named Bioloid, based on the mentioned Fillion-Robins [2] model, which holds a three-dimensional model that closely resembles a real dog robot, as illustrated in Fig. 1.

* Corresponding author e-mail: mafaldacouto88@gmail.com

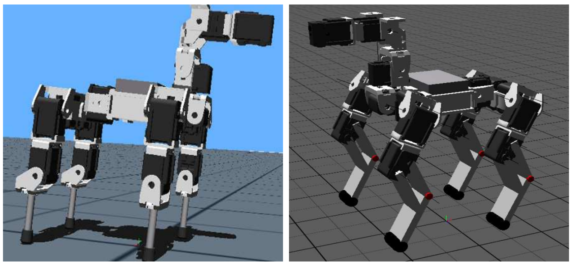

Fig. 1: Former [2] and new Bioloid robot model rendered in Webots^{TM}.

Despite the good characteristics of the former Bioloid model, several aspects can be improved. From the previous quadruped configuration model, some main characteristics were maintained. First of all, the leg has the same degrees of freedom (DoF), where each leg is able to move in three axes: hip joint can be actuated for pitch and roll and the knee joint can also be actuated for the pitch angle variation, thereby the motion generation takes place only for the sagittal plane. Secondly, it should be emphasized that the configuration of the leg was only changed after the knee joint extension, maintaining the trunk, head and upper parts of the limbs as the original model.

The robot design aims for the development of an accurate leg model both efficient and robust for a quadruped robot. The Webots^{TM} [3] simulator software was used to the render the 3D model, reproducing accurate properties of robots and environment. This platform is based on a robust and powerful physics engine, Open Dynamics Engine (ODE) and is responsible for performing all modelling and simulation tasks.

3 Bio-Inspired Design

Over the years, the study of human and animal locomotion has witnessed a significant increase of interest due to its desirable structural properties such as adaptability and robustness. Although many challenges remain, inspired by biology, some principles of locomotion for the efficient design and control of walking machines can be extracted (surveyed in Fig. 2):

– The limbs of mammals are almost trisegmented shaped and present the same configuration in terms of functionality, both in fore and hind-limb. The triple linkage of the leg shows a higher effective energetic and mechanical advantage.
– The progression is mainly due to the displacement of the proximal segment (scapula or femur) being the leg drive.
– Two segments (first and third femur/foot) operate almost parallel during retraction of the limb, similarly to a closed loop pantograph, insuring that instability does not occur.

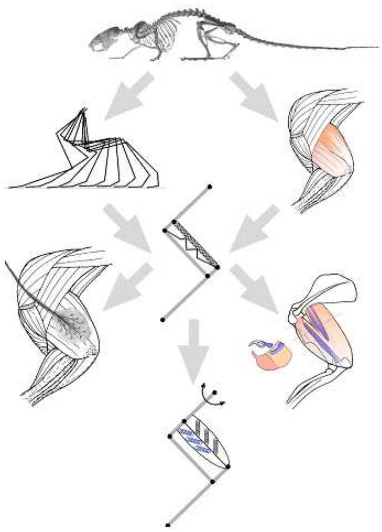

Fig. 2: The pantograph coupled with a spring-mass system can close resemble the skeletal muscles together with the tendons [6]

Also, limb compliance is a main principle for small mammals, helping in the animals selfstabilization in presence of external disturbances [5][6]

Cheetah [7], later on named Oncilla, is a robot developed by BioRob that features a lightweight mammal-like threesegmented pantographic legs with compliance from bio-inspiration in domestic cats (*Felis catus*), proving to be an interesting case study.

3.1 Pantographic Configuration

Taking into account the previously mentioned work principles, considering the configuration design for the new leg, a three segmented pantographic model is adopted. For the leg characterization (Fig. 3), it can be distinguished, for the hind limb: a hip joint (point B) and thigh (l_3); a knee joint (CDEF apparatus) and shank (l_2, l_4), and a foot (l_1). For the robots front limb the same relative segmentation is done.

The pantographic behavior concerns the synchronous movement of the knee joint of the trisegmented leg and is responsible for its extension and retraction during locomotion. The pantograph holds the connection between proximal and distal limb segment, where the first and third segments operate in matched motion (l_1 and l_3, e.g. thigh and foot). The inner angles are always equal, constantly providing parallelism between the two leg segments [8]. This mechanism assembly only one DoF influences the leg length [7] [5].

3.2 Model Actuation

Research in legged locomotion is evolving and new technologies are being exploited worldwide with the aim of improving actuator performance, regarding a safe human-robot interaction, reducing large shock-forces and improving energy-efficient locomotion. Internal elastic elements provides the ability to store and release energy reducing power consumption of walking robots and helps to make a segmented leg safer and more robust when faced with disturbances [9] [10].

For the Bioloid quadruped locomotion, each leg features tri-segmented pantograph together with two actuated joints per leg (in Fig. 3, point B is hip-pitch and point E is knee-pitch). The proximal actuator placed at the hip joint, is responsible for leg protraction and retraction, providing to the robot the main locomotion and displacement. The second actuator controls the apparatus at the mid-joint, extending and contracting the pantograph (Fig. 4), having the main role in the retraction and extension of the leg. Therefore, this joint will also hold a passive compliant mechanism, responsible for shock absorption during stance phase of the cycle. Consists in a virtual linear rotation spring-damp system added at the knee joint level (point D in Fig. 3) [5] [7].

In addition to the configuration design, also the controllers actuation principle of the robot will held some feature settings. Following the concepts from animal behavior the operation modes towards the pantographic compliant mechanism can be established for the locomotion control:

– Actuated position joint (Fig. 4.a): The servomotor is on, reducing the diagonal of the parallelogram at the shank, contracting the leg actively. The motor at the knee joint only actuates to retract the leg during flight phase.
– Resting position joint (Fig. 4.b): If there is no action of the servomotor, and no action on the distal segment, then the spring extends the leg towards its equilibrium position and it is ready to become gravity loaded at touchdown.
– Joint under external forces (Fig. 4.c): The servomotor is off and the system is characterized by the compliant mechanism which in case of external interaction (e.g. the ground) is actively compressed. The equilibrium is obtained by the spring, counter-acting the gravity force due to the weight of the robot [5].

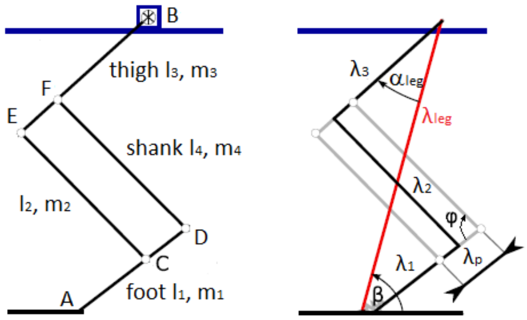

Fig. 3: Sideview of the pantographic leg for the Bioloid. Illustration of the three-segmentation (l_i), angles and normalized lenghts (λ_i) of the limb. The virtual telescopic leg is represented by the line $|AB|$.

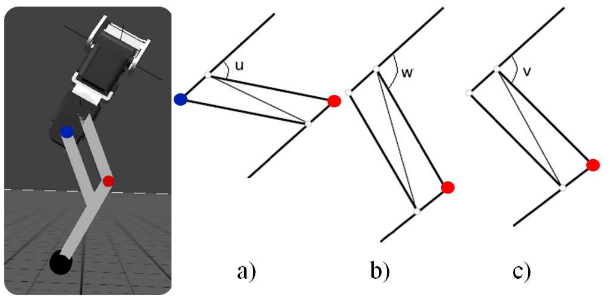

Fig. 4: Diagram of the pantographic leg operation (u<v<w) [7].

4 Leg Modelling

4.1 Segmentation

Considering the previews insights, the design of the new Bioloid robot leg may be developed. In Fig. 3 it is possible to observe the relation between the segment relative and absolute lengths. The subtraction of the relative distance between shank segments l_2 and l_4, called $\lambda_p/2$ in terms of λ_1 and λ_3, is due to the fact that studies on relative segment lengths do not consider pantographic legs specifically, but rather work with only the middle segment, simplifying the kinematic study. This subtraction gives the mid-point between linkages, considering leg segment l_2 as the mid segment and neglecting segment l_4, or the other way around.

From small mammal biology, an energetically advantageous approach was considered, which introduces equal segment lengths for the limb linkages, improving the working range and acceleration properties, guaranteeing the mechanical strength [7] [11]. Analytically, the normalized lengths of the limb are:

$$\lambda_1 = \lambda_2 = \lambda_3 = \frac{1}{3} \qquad (1)$$

From the relative dimensions of the three segments, the absolute segment lengths are able to be deduced. The relation between the segment lengths relative to the maximum leg length is defined as:

$$\lambda_1 = \frac{l_1}{l_1 + l_2 + l_3} - \frac{\lambda_p}{2} \qquad (2)$$

$$\lambda_2 = \frac{l_2}{l_1 + l_2 + l_3} \quad (3)$$

$$\lambda_3 = \frac{l_3}{l_1 + l_2 + l_3} - \frac{\lambda_p}{2} \quad (4)$$

$$\lambda_p = \frac{l_p}{l_1 + l_2 + l_3} \quad (5)$$

The basis of the new linkage measurements definition was the thigh segment length from the original Bioloid robot (illustrated as |BE| in Fig. 3), *i.e.* the measurement of the length between the axis at the hip joint and the axis at the knee joint corresponds to the l_3 segment length (l_3=0,083m).

4.2 Models Kinematic Analysis

For the structural and actuation setups a kinematic analysis of the leg is carried out and limitative parameters for the joints configuration and spring-damp coupled system are assessed for a desired retraction.

The virtual leg (see Fig. 3) is a telescopic leg with equivalent properties to the pantograph leg in terms of the leg force. The definition of the leg length can be expressed relatively to a complete extension of the limb. For this model the total leg length was settled, $L_T = l_1 + l_2 + l_3 = 0.21m$. The respective relative leg length $\lambda_{leg} = |AB| / (l_1 + l_2 + l_3 - l_p)$ can be expressed in function of the inner pantograph angle φ (angle between segments l_1/l_4 and l_3/l_2) and the relative leg segment lengths:

$$\lambda_{leg} = \sqrt{(\lambda_2 \sin\varphi)^2 + (\lambda_1 - \lambda_2 \cos\varphi + \lambda_3)^2} \quad (6)$$

The angle between the virtual leg and the thigh segment l_3, α_{leg}, is given by:

$$\sin\alpha_{leg} = \frac{(\lambda_2 \sin\varphi)}{\lambda_{leg}} \quad (7)$$

A simple model for running with compliant legs is the spring-mass model, also known as spring-loaded inverted pendulum (SLIP) by Seyfarth in [11], illustrated in Fig. 5. In the SLIP model, the body is represented by a point mass m, and the axial leg operation during the stance phase is approximated by a linear spring of constant stiffness k_{leg} and length L_0 when fully extended. The leg touches the ground with angle of attack β_0. This virtual leg is massless and it has no moment of inertia. Effects of friction or other non-conservative forces are neglected. Therefore the system is energy conservative.

Every stance phase begins with the touchdown of the leg and afterwards the leg suffers a maximal compression represented by ΔL, which is the difference between the length of the illustrated dashed leg spring and the maximally compressed leg ($\Delta L = L_0 - L$). The study of this variation allows assessing the force and spring constant in play:

$$F_{leg} = \frac{k_{leg}}{(L_0 - L)} [N] \quad (8)$$

To setup the locomotion movement some limitative requirements were considered and three relevant instants of the step cycle were identified: touchdown (td), stance (st) and swing (sw) (Fig. 6).

Following the procedure from Rutishauser [7] a leg angle of φ (td) $=130^o$ at touchdown is assumed (knee angle behavior illustrated in Fig. 6). From the previous analysis, the relative leg length at touchdown may be determined, $\lambda_{leg}(td)=0.917$.

The peak of force in the leg spring occurs at the middle of the stance phase when the leg spring is vertical oriented and thus corresponds to the peak vertical ground reaction force [11][12]. At this point the angle of attack β is of 90^o and the maximum leg length compression is expected to occur. The work presented by Farley [12]

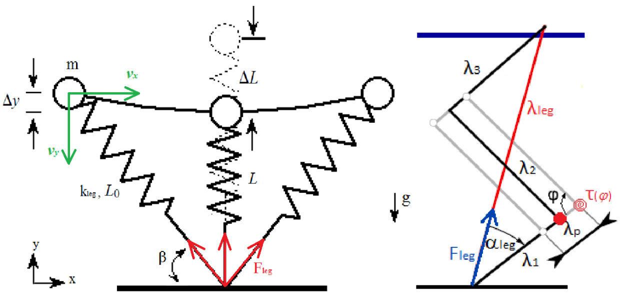

Fig. 5: Variation on the virtual SLIP leg model during step cycle (left to right) [5] [12]. Resulting forces applied at the knee joint system.

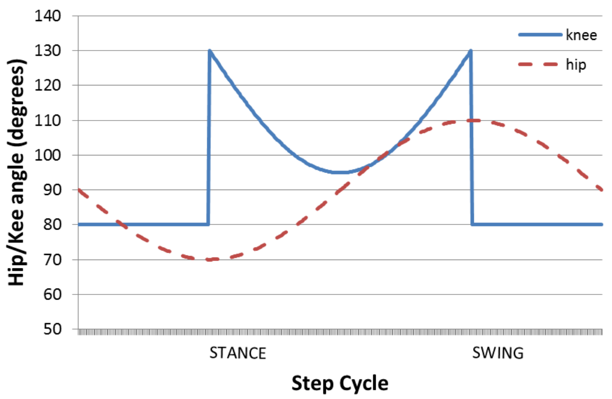

Fig. 6: Trajectory expected for the hip (dashed line - β_{attack}) and knee (continuous line - φ) angles during the step cycle with 16% stance retraction.

illustrates that the compression of the spring (ΔL) at this point is about 16% of leg length in dogs during trot speed locomotion. Based on this reference compression ($\Delta L(st)= 0.16L_0$) and the corresponding leg force $F_{leg}(st)$ of the pantographic leg model, the reference stiffness can be defined using (8). Thus, a φ angle variation of 35^o and a $\lambda_{leg}(st)= 0.770$ are expected.

In order to dimension the compliant parts of the leg it is important to estimate a limit the retraction during stance. From Farley [12], considering the dog movement, the maximal leg retraction is limited by the geometry of the system, where the joint at point D (Fig. 3) must not touch the ground, which would imply $\beta_{attack}=\alpha_{leg}$. Therefore the β_{attack} was estimated 70^o (see Fig. 6) with an amplitude of 40^o till liftoff. The maximal spring contraction occurs during the swing phase, where the motor actively retracts the leg. Assuming a retraction exceeding by one fourth the initial equilibrium condition is sufficient to do the legs flight, the φ $(sw)=80^o$ and $\lambda_{leg}(sw)= 0.688$.

As mentioned, the initial robot posture and assemblage, both trunk and head, were not changed. On the other hand, the new components require an estimation of their mass keeping in mind the goal of a functional robust performance and ensuring the cohesion and stability of the structure. In locomotion at least two limbs are in contact with the ground at the same time. The mean maximum mass estimation is $m_{MAX} = m_T/2$ for each leg [12].

To generate compliant forces in the segmented leg it was considered a torsional spring of stiffness k and damper with constant c at the inter-segmental joint, focused at point D (see Figs. 3 and 4). For a spring-damp-mass model with angular joint φ, the equivalent global equation of motion can be described by:

$$I\frac{d^2\varphi}{dt^2}+c\frac{d\varphi}{dt}+k\varphi=\tau(\varphi) \tag{9}$$

where I is moment of inertia and τ is the systems torque. The spring stiffness k works storing the elastic energy opposing the load force, the damper c acts opposing the vibratory motion, on the other hand the inertia factor I is neglected because the system is energy conservative. The resulting legs knee torque is:

$$\tau(\varphi)=k\Delta\varphi+c\Delta\dot{\varphi} \tag{10}$$

where the desired 16% leg retraction entails a angle variation $\Delta\varphi$. By setting the application of a spring-damp system equal to the leg force due to the weight during locomotion results in an equilibrium of forces (see Fig. 5), given by:

$$F_{leg}\sin\alpha_{leg}=\frac{\tau(\varphi)}{(l_{\lambda 1}+l_{\lambda p}/2)} \tag{11}$$

5 Experimental Simulation

At this point the model configuration is assembled in Webots™. As in Santos & Matos [13], a network of Central Pattern Generators (CPGs), dynamically generated oscillatory signals to control the locomotion copying the rhythmic neural activity.

Focusing on the mathematical evaluation developed for the leg an energy advantageous approach was considered. Therefore, for the evaluation of the variation of the knee angle during motion, were considered five spring constant values [0.5; 1.0; 1.5; 2.0; 2.5] *N.m/rad*;

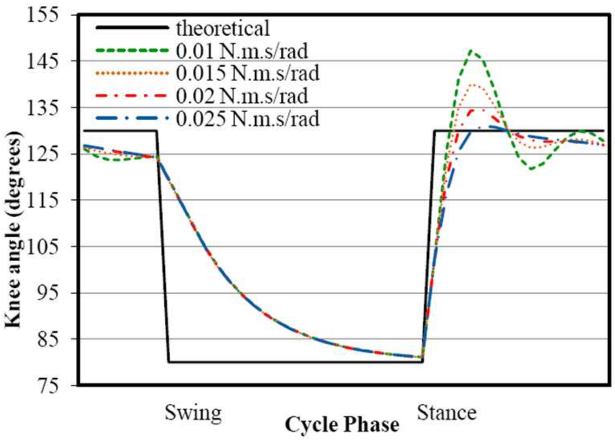

Fig. 7: Simulation trajectory of the theoretical (continuous line) and tested knee angles during the step cycle with spring constant of 1.0 N.m/rad for different damping constant values.

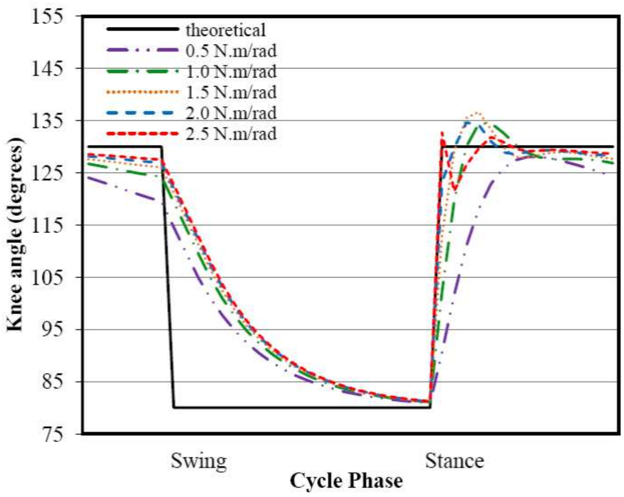

Fig. 8: Simulation trajectory of the theoretical (continuous line) and tested knee angles during the step cycle with damping constant of 0.02 N.m.s/rad for different spring constant values.

and four co-working damping coefficients [0.01; 0.015; 0.02; 0.025] *N.m.s/rad*. For the study of the synchronized behavior of the spring-damp model coupled with the controller, the floor contact was not considered, thus the external forces were excluded and focus was given to the evaluation of the angles progression. Two specific cases were considered to study the compliant leg performance, first the spring constant was fixed to 1.0 *N.m/rad* (Fig. 7) and second the damping constant was set to 0.02 *N.m.s/rad* (Fig. 8).

Thus, the robot is tested assessing the angles activity during simulation (Fig. 1). With regard to the controlling of the joints motion, the hip joint performs a continuous and active motion during the simulation with amplitude of 20^o as commanded. Differently from the hip, in the knee compliant joint it is expected a nonlinear behavior (see Figs. 6, 7 and 8). During swing phase the servomotor actuation is on, it can be observed in the several tested simulations that the expected 50^o angle variation is not instantaneous. The focus of the knee angle performance is the stance phase, which corresponds to the point when the model acts passively and the forces perform self-sufficiently.

From the evaluation of the performances of the different spring-damp coupled coefficients (see Figs. 7 and 8), results show that the robots leg behaved better when the spring values are around *2.0-2.5 N.m/rad* and corresponding *0.002 N.m.s/rad* of damping constant. The increasing of spring constant values forces the introduction of greater damping constant values, due to the fact that the high spring constants present larger vibration forces to be suppressed. Summarizing the spring has the function of extending the leg and maintaining its length during the stance phase, while the damp component plays a role in the avoidance of oscillations by reducing the vibration at the joint.

6 Conclusions

In summary, a new design of the Bioloid quadruped robot leg model was developed taking inspiration from nature in order to perform a stable locomotion. After the configuration of the three-segmented pantographic leg, a compliant system introducing a simple virtual torsional spring-damping was designed and simulation tests were performed in Webots^{TM} simulation software with a control system based on CPGs allowing a harmonic and rhythmic locomotion.

At the spring-damping models it was applied a close range of values and evaluated the outcome behavior during leg motion. The experiments were carried out without the floor contact excluding the influence of external forces and the legs synchronized performance was able to be assessed. Future work may be carried out, testing the ground contact influence, in which the control system must be calibrated to adopt a different gates and velocity locomotion patterns. Another major improvement to address is the implementation of feedback sensors promoting the interaction between the environment and the machine through obstacle and ground force detection.

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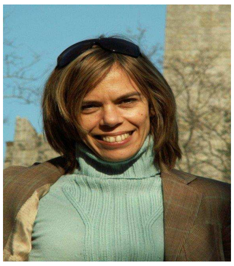
Mafalda Couto has graduated in MSc in Biomedical Engineering at the University of Minho, with expertise in the field of Biomaterials, Biomechanics and Rehabilitation in 2011. During a semester worked at the CSIC - Consejo Superior de Investigaciones Cientficas, Grupo de Bioingeniera Instituto de Automtica Industrial at Madrid, through ERASMUS exchange program. Since 2012, she is a working at the Life and Health Sciences Research Institute (ICVS), School of Health Sciences, in a research and development investigation project of the study of the evolution and outcome of the rib cage structures in pectus excavatum correction procedure using finite element simulation.



Cristina P. Santos received the B.S. degree in Industrial Electronics, the M.Sc degree in Robotics, and the Ph.D. degree in Robotics in the field of Nonlinear dynamics, all from University of Minho, Guimaraes, Portugal, in 1994, 1998 and 2003 respectively. The PhD was also in collaboration wht the CNRS-CNRC Marseille, France. She is working since 1996 as an Auxiliar Professor at the University of Minho, Industrial Electronics Department, Portugal. Her research focus on the extension of the use of the dynamical systems theory to the achievement of more complex behavior for robots: generate locomotion for multi-dof robots; achieve cooperativity among multi-robots and learning. Recently her reserach interests focus on methods to characterize human motion, and designing robots and robot controllers for rehabilitation of patients suffering from motor problems. She has authored/co-authored more than 40 research papers, published in international journals or presented at international conferences.

Jose Machado received his PhD degree in Mechanical Engineering Automation, from University of Minho, Portugal (and, in simultaneous, in cole Normale Superieure de Cachan, France) in 2006. He is Assistant Professor at Mechanical Engineering Department of University of Minho. He has authored, or co-authored, more than 100 refereed journal and conference proceeding papers. He has coordinated several Research Projects on Mechatronics and Automation domains and his main interests are related with design and analysis of dependable controllers for obtaining dependable mechatronic systems. He is a frequent paper reviewer for several journals, including Journal of Process Control, Control Engineering Practice, IEEE Transactions on Control Systems Technology, IEEE Transactions on Industrial Informatics, International Journal of Advanced Robotic Systems and Applied Mathematical Modeling. He is a member of IEEE and member of IFAC organizations.