# A Tree-Climbing Robot Platform: Mechanical Concept, Control Software and Electronic Architectures

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## 1. Introduction

Robotic platforms can be used in countless applications and in the most varied branches of activities. Such results, presented over the last two decades, can be verified in Armada et al., 2003 and Virk, 2005.

It deals specifically with robots provided with legs and with the capability, or ability, to climb vertical surfaces, while many other applications/solutions can be found. As an examples: robots to climb lower parts of bridges (Abderrahim et al., 1999), to crawl inside pipes for inspection purposes (Galvez et al., 2001), implemented to perform solder inspection works in nuclear plants (White et al., 1998), to climb metallic structures for inspection purposes (Armada et al., 1990). More examples can be found in marine industry applications, such as walking robots to check internal parts solders in ship hulls, climbing robots for parts solders (Santos et al., 2000) and (Armada et al., 2005), climbing robots for paint cleaning, underwater robots for ballast tank inspection, and underwater robots for hull cleaning (Santos et al., 1997a, 1997b).

Robots were demonstrated to be the ideal option for many such applications due to the fact that the working environment is difficult to access or even hazardous or risky for human beings, such as exposure to hazardous substances or environments and risk conditions. Productivity increase and quality issues are also extremely relevant and are considered.

However, besides the varied applications and areas mentioned above, there still remains a little explored area: environmental research. As in any other area, different applications or problems can be addressed or solved with the help of a robotics platform. As an example, one can mention the tasks:

- **Gathering of Botanical Specimens**: gathering flower and plant specimen is fundamental for biodiversity studies. Several host species are found in high trees, and their collection is actually risky. Thus, this is an application where a robotics platform with tree climbing capability can be used to minimize risks for the researchers involved in this type of activity.
- **Gathering of vegetable material**: collection of vegetable material is a fundamental activity for phytochemistry. Every pharmaceutical preparation that uses as raw material plant parts such as leaves, stems, roots, flowers, and seeds, with known

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pharmacological effect is considered phytotherapic (extracts, dyes, ointments and capsules). Thus, just as in botanical collection, this is an activity that can be accomplished by a robot operating in large-sized trees, therefore minimizing risk for the humans involved in the collection.

- **Gathering of Insect Specimens**: usually, for collecting insects in higher levels, nets spread around the tree and a source of smoke below it are used. The great discussion about this technique is that one not only captures the desired insects, but one ends up killing most of the insects that inhabit that tree as well. Thus, one proposes to use a trap, positioned in the robot, containing a pheromone or equivalent substance as bait, specific for the insect species one wants to capture. One can even adapt cameras and sensors in the trap to gather images of the moment of capture. With a trap thus implemented, one reduces the negative environmental impact of the capture. Another relevant issue would be the possibility that the robot moves along the day to capture varied insect specimens at different heights in different hours, to check for variations in insect populations according to the height, and the hour of the day.
- **Climatic studies**: climatic or microclimatic studies refer to works on microenvironments in native vegetation and/or reforested areas. It is important to study the different energy flows: horizontal and vertical. The vertical directly reflects the results of solar radiation, which decisively influences the horizontal energy flows: air masses, hot and cold fronts, action centers. Solar radiation determines the whole system, and may be analyzed according to its elements: temperature, pressure, and humidity, greatly influencing biogeographic characteristics, geomorphologic and hydrologic phenomena etc. Thus, the robot can be equipped with sensors for such measures, to collect data on the desired elements.
- **Studies on biosphere/atmosphere interaction**: biosphere environments are the group of biotic or abiotic factors that interfere in the life conditions on a certain region of the biosphere. In the case of forests the aerial environment is studied, and the most important elements to consider are: light, oxygen, ice formation, winds, humidity and carbon gas. In order to register all this information, the robot can be endowed with specific sensors for each kind of required measure, to collect data regarding the elements at hand, and to provide information on them regarding both height and time variations.
- **Studies on arboreal fauna**: fauna studies are hampered by the existence of many leaves, or very dense treetops, as the lack of existing natural light hinders the observation of the species. Other usually relevant points are the difficulty to obtain a proper angle due to the great heights involved, and the very presence of human beings in that specific environment, easily detected by their movements, noise and odors. For this type of task, the robot can be fitted with cameras to capture both static and dynamic images. These can then be stored locally in some type of memory card, or transmitted via communication interface to a base station.
- **Sensors Network**: robots carrying a group of sensors and fitted with a communication interface, for instance Wi-fi or other similar technology can be dispersed in the forest to capture data regarding the ecological behavior in the area at hand. Measurements such as the ones already mentioned in climatic studies and biosphere/atmosphere interaction can be shared among robots or even retransmitted among robots to reach the base station, without the need for the researcher to “pay visits” to the reading points.

## 2. Kamanbaré platform

Purporting the main goal to climb trees for environmental research applications, to be applied in tasks such as presented above, a bioinspired robotic platform named Kamanbaré was proposed.

The project's main application is climbing trees for non-invasive search purposes, reaching points (at high altitudes) that may offer risk to humans.

The development was driven mainly to seek for robot stability and efficiency regarding the paws. The adopted line of research is an implementation inspired in nature. One must stress here that the system doesn't mimic nature, by copying an animal or insect to accomplish the desired work, but rather, a robot development project that combines the climbers' best characteristics (insects and lizards) considering the available technologies and the associated cost/benefit ratio, in other words, some parts were inspired in certain solutions found in nature, while other parts were inspired in different elements.

Ensemble stability, contact stability (paws), contact position, and contact force (pressure) were defined and used to implement the strategies and techniques for dynamic and static control of the system.

## 3. Chameleons: the biological inspiration

Differently from any other reptile or lizard, chameleons have paws that were created, or adapted, to adequately clasp the different types of branches or shrubs existing in its environment.

The chameleon paws evolved to provide them with the best possible maneuvering and grip capabilities on trees. The paws are actually forked, with three fingers on one side and two on the other. Frequently they also have powerful and sharp nails (or claws) that can grip the surface which they hold on to. This unique arrangement allows them to position their paws completely around the branches or shrubs on which they move around, giving them an amazingly strong clasping capability.

Chameleon paws have five fingers each, divided in two groups (internal and external), one side composed of three fingers while the other side has two, as seen in Fig 1. Front paws have two fingers pointing to the external side, and three towards the inner side, while rear paws are configured in an opposite arrangement, i.e., two inside fingers and three outside fingers. This provides the chameleon with the same number of fingers on each side of the branch, considering all the paws, allowing a balanced and stable clasping.

Fig. 1. Details of the chameleon paw, presenting the bifurcation and configuration of the fingers

## 4. Mechanical model

The mechanical structure of the Kamanbaré platform consists of a central rigid body with four legs, identical and symmetrically distributed. Each leg comprises three links connected by two rotating joints, and it is connected to the central body by a third rotating joint, while each joint has 1 DOF (degrees of freedom). Identical motor and reduction groups make the rotary movements. Fig. 2 shows the kinematic configuration of a leg. Each leg also has a paw, which is forked just as the chameleons, but with only two fingers, one on each side, for simplification purposes. The paw connects to the leg by a rotating joint, and also has another motor and reduction group that provides for its opening and closing movements.

As each leg has four joints, this means 4 DOF. Considering the four legs, the platform will have a total of 16 DOF. Therefore, sixteen motor and reduction groups were necessary to produce the global movements.

Fig. 2. Kinematic configuration of a leg

The main dimensions of the platform are: length of 250 mm, and width varying between 260 and 740 mm, depending on the positioning of the legs. Its height also depends on the posture and positioning of the legs, and can vary between 190 and 310 mm.

This configuration, with all the parts implemented using two different materials, aluminum and polyacetal, comprises an approximate total weight of 1.3 kg, not including the batteries. The geometric model obtained can be seen in Fig. 3. This model was used to generate the basic locomotion behavior.

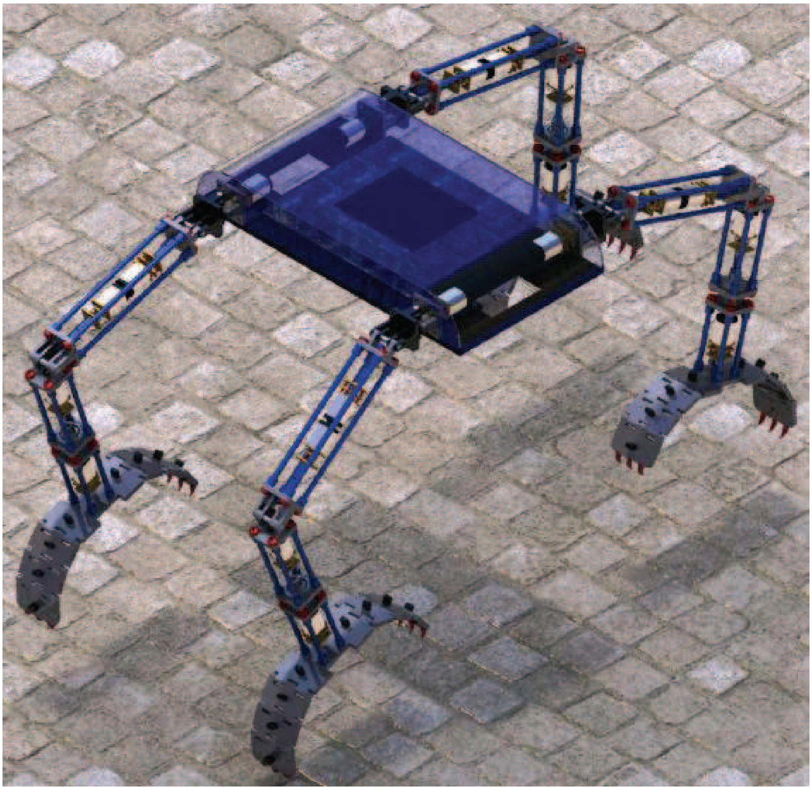

Fig. 3. Mechanical structure of the Kamanbaré platform

## 5. Control software architecture

An architecture was implemented for local control of the Kamanbaré platform. This architecture corresponds to the robot's functional organization.

Based on the hardware architecture to be presented in the following section, the development of the following systems was accomplished according to Fig. 4. This model is based on the architecture implemented for the MARIUS robot (Pascoal et al., 1997) and has the following main components described below.

- **Support system:** this system controls energy distribution to the platform's electronic and electromechanic hardware, and monitors energy consumption as well. This system is also responsible for the startup of other subsystems and, during operation, for detecting hardware failures, and for starting and controlling the emergency modes.
- **Actuators control system:** this system is responsible for controlling the motors, and also for controlling the movements of the legs. Information on legs positioning is received from the general control system. Data regarding joint positions, as well as the values of the electric currents involved, are sent to the general control system.
- **General control system:** this system receives trajectory reference information from the mission control system. It controls all the robot's movements, sending the necessary

commands to the actuators control system. Problems occurring in the path, such as obstacles and absence of support points for the paws, are handled in this system.

- **Mission control system:** this system is the main module, the highest hierarchical level of the platform. It is responsible for receiving commands via the communications system, and for distributing them to the systems involved. It also stores information on the general status of the platform (battery voltage, position of the legs, angles etc.) keeping them available in case the Base Station (described in the following topics) requests them. This system gathers information from the Environmental inspection system to be subsequently forwarded to the Base Station.
- **Communication system:** this system is the module responsible for the communication interfaces existing in the platform, managing communications via Wi-fi and Bluetooth, and exchanging data with the Mission control system.
- **Environmental inspection system:** this system is responsible for gathering data from the installed sensors, and for controlling any additional hardware necessary for that purpose as well. Every data acquired are sent to the Mission control system.

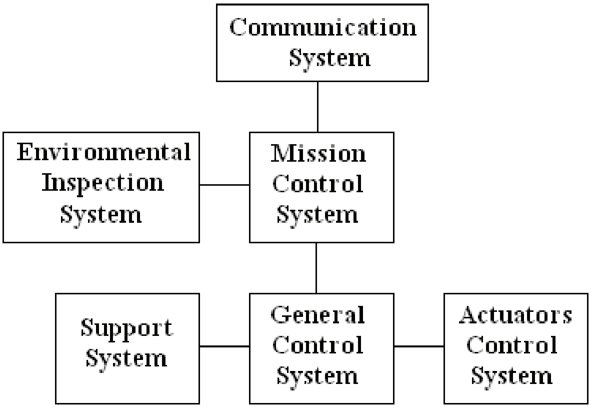

Fig. 4. Kamanbaré's Control Software Architecture

## 6. Electronic architecture

Considering the implementation of control algorithms, processing information from sensors, the necessary calculations for control and locomotion strategies, interfacing and communication with the base station, added to the need of real time control with position and force feedback, the involvement of high computing complexity was ascertained, thus requiring a processor of advanced architecture.

Eventually, it was selected then a development kit containing a processor based on the ARM9 core, and the deployment of a Linux operating system.

Other motor control boards were also developed using a Texas Instruments microcontroller of the MSP430 family and specific integrated circuits to implement the power actuation section, based on the so-called H-bridge technique.

To implement the control systems for the Kamanbaré platform, an electronic architecture was defined. Initially considering only one joint, it can be represented in Fig. 5, where the main components are seen: a DC motor, a potentiometer and a micro switch.

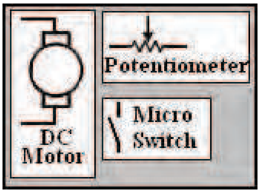

Fig. 5. Representation of a joint

Thus, for control purposes, the need of a PWM output (motor control), an analog input (potentiometer reading, indicating the joint angle), and a digital input (reading the end, or beginning, of the joint course) was ascertained.

As already mentioned, the platform has 16 DOF, corresponding to the need of sixteen copies of the joint control system described above.

As the robot has four legs, one opted for distributing the control individually to each one of them. Thus, each leg control module needs four groups as mentioned, namely, three for the joints, and one for controlling the opening and closing of the claw.

One then developed a motor control board for this specific purpose, Fig. 6, based on the MSP430F149 Texas Instruments microcontroller, and the L298 integrated circuit (H-bridge).

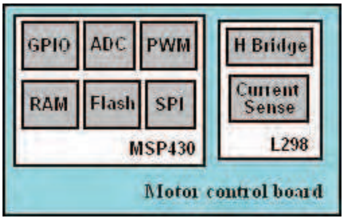

Fig. 6. Motor control board diagram

Due to the control complexity existing in a robotics platform, it was necessary to adopt a main board where the highest hierarchical level control activities were executed.

As a solution for the main board, the model selected was the TS-7250 by Technologic Systems. It was selected because it's compact, contains different standard interfaces, and is based on the EP9302 Cirrus Logic processor, with an ARM9 core, Fig. 7. The EP9302 implements an advanced processor core: 200 MHz ARM920T with support for a memory management unit (MMU). This ensemble allows the use of a high-level operating system, in this case Linux. The ARM920T core has a 32-bit architecture with a 5-stage pipeline, offering high performance and low energy consumption levels. With a 200 MHz clock, the TS-7250 module offers a performance approximately twice as fast as other boards based on 586-core processors.

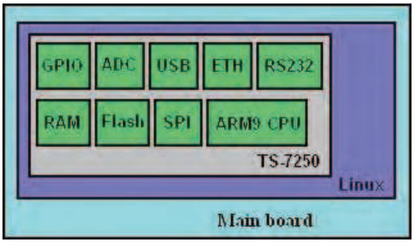

Fig. 7. Main board diagram

Thus, the general electronic architecture for the Kamanbaré platform was deployed according to the diagram in Fig. 8.

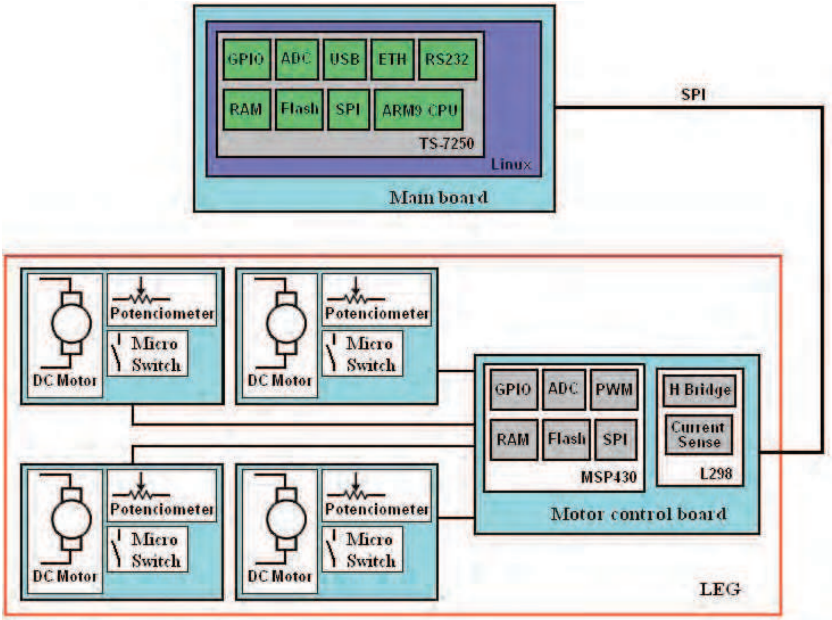

Fig. 8. Electronic architecture of the Kamanbaré platform

## 7. Simulink models

Simulink® and SimMechanicsTM software use a block diagram approach to model control systems around mechanical devices and simulate their dynamics. With CAD (Computer-aided design) translation, it was possible to combine the power of CAD and SimMechanics software. The translator transforms geometric CAD assemblies into Simulink blocks.

The CAD model of the Kamanbaré robotic platform, described in the section 2 – Mechanical Model, was designed using Soliworks.

Thus a Kamanbaré model was generated using the SolidWorks-to-SimMechanics translator.

This translation process is based on two major steps: to export the CAD assembly into a physical modeling XML format file and to import the generated XML file into a Sim Mechanics model in Simulink.

For the translation procedure, some configurations like the name of the joints and legs were adopted as well the desired movement direction and the gravitational acceleration direction of influence, as demonstrated in Fig. 9.

The resultant model obtained for the Kamanbaré platform is depicted in the next in Fig. 10. For a better understanding and visualization the legs were represented as model blocks.

Due the fact that all four legs are identical, one detailed leg model block, the Front Left Leg, is described in Fig. 11.

A signal builder was also implemented with the main function of gait generation, here providing the correct angle references for all joints as function of time, Fig. 12.

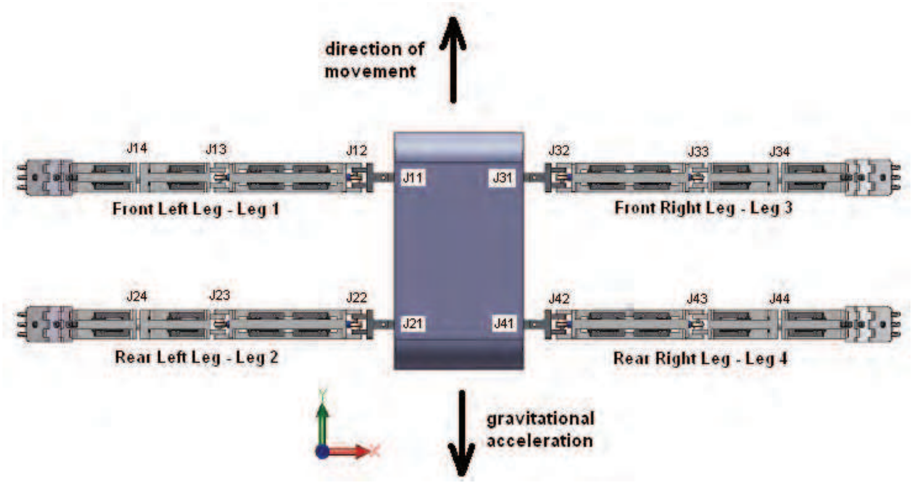

Fig. 9. Kamanbaré's configuration of joints: top view

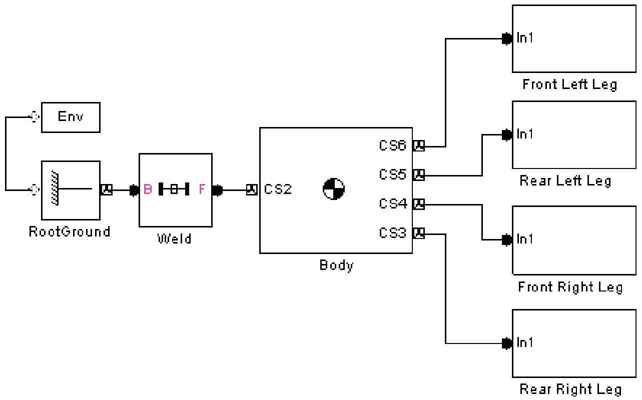

Fig. 10. Kamanbaré's Simulink model

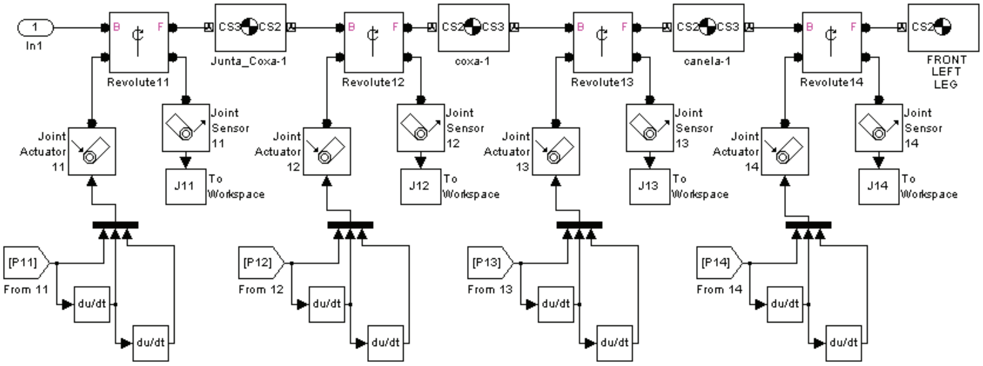

Fig. 11. Front Left Leg model

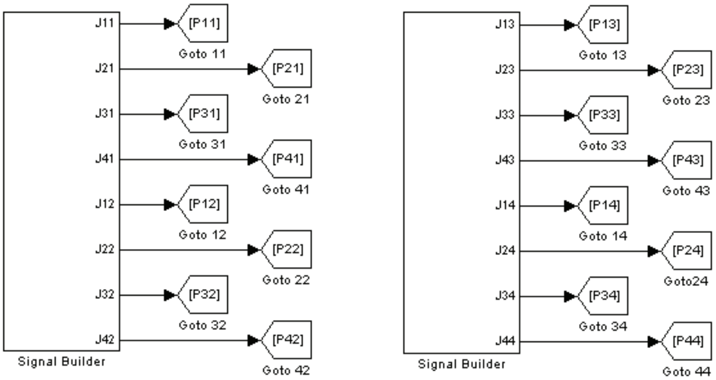

Fig. 12. Gait generator model

## 8. Gait generation

Gait generation is the formulation and selection of a sequence of coordinated leg and body motions that propel the robot along a desired path.

Free gaits are gaits in which any leg is permitted to move at any time. Fixed, or regular, gaits are those in which a specific pattern of leg movement is imposed. All animals locomote with fixed gaits. A tenet of behavioral systems is that the emulation of animal behavior, hence fixed gaits, is sufficient.

Up to now, just a basic gait was implemented based on the biological inspiration cited before: the chameleon, Fig. 13.

Fig. 13. Biological inspiration for the gait implemented for initial simulations

The gait shown in Fig. 14 represents the variations of the joint angles as function of the time for all the four legs for a movement on a vertical and plane surface.

For a better understanding while analyzing the Fig. 14 a visit on Fig. 9 will help the identification of the names adopted here. Just for clarification, the configuration adopted follows:

- Front Left Leg: Leg 1 with the joints J11, J12, J13 and J14;

- Rear Left Leg: Leg 2 with the joints J21, J22, J23 and J24;
- Front Right Leg: Leg 3 with the joints J31, J32, J33 and J34;
- Rear Right Leg: Leg 4 with the joints J41, J42, J43 and J44.

As explained before, this is a basic gait and it was generated manually observing the chameleon model of movement.

No kind of gait optimization was implemented. The idea here is to have a basic gait to start simulations in order to obtain some results like mechanical interferences between legs while moving and necessary torques for the desired movement.

Gait optimizations in order to obtain a smooth movement as well as the better use of the energy, or energy saving, while moving the joints will be studied and presented on future works.

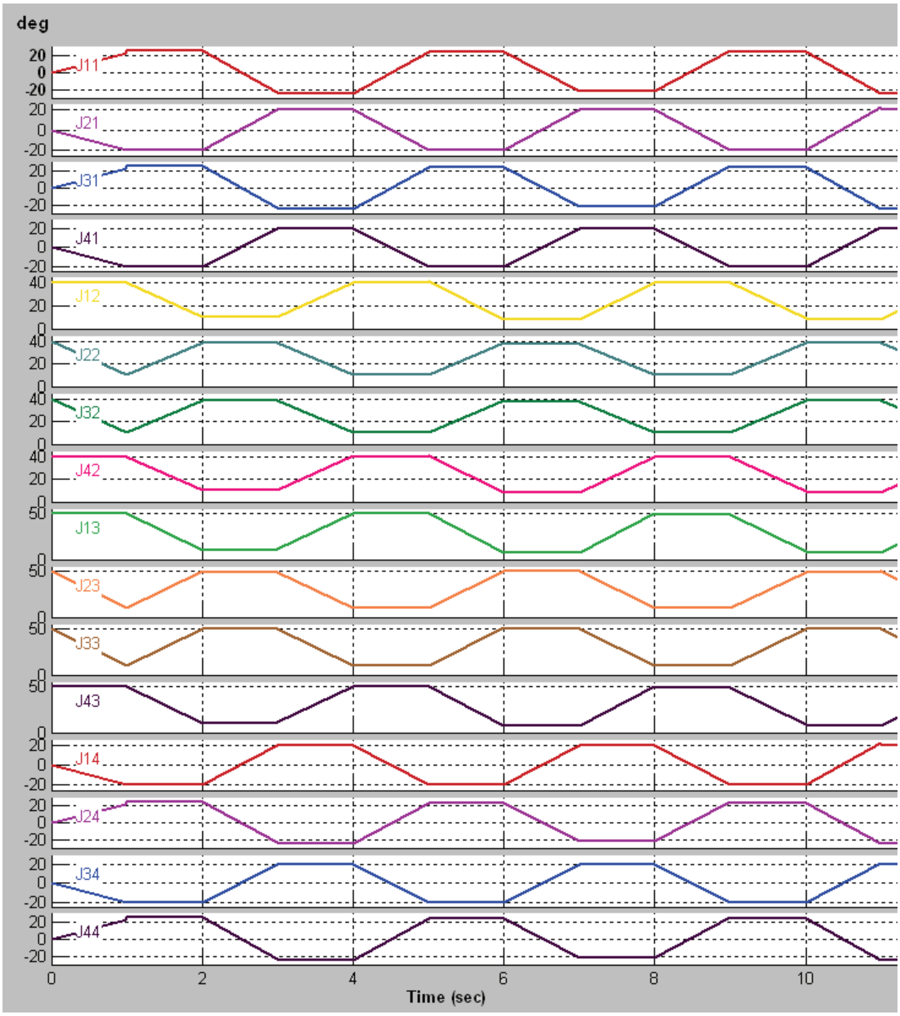

Fig. 14. Gait diagrams corresponding as joint angles positions

## 9. Simulation results

Regarding the movement generation, or gait, only the simplest way was initially implemented, i.e., the robot follows a straight path at the highest speed allowed by the surface (no waiting time will be introduced, besides those produced by the legs when searching for support points).
The proposed realistic and practical SimMechanics model is further employed to simulate the designed controller which is implemented using Simulink, in this case just a gait generator.
As first result obtained are the models machines presented in Fig. 15 and Fig. 16. These models are quite interesting and useful while running simulations for the reason that all joints and legs movements can be observed.

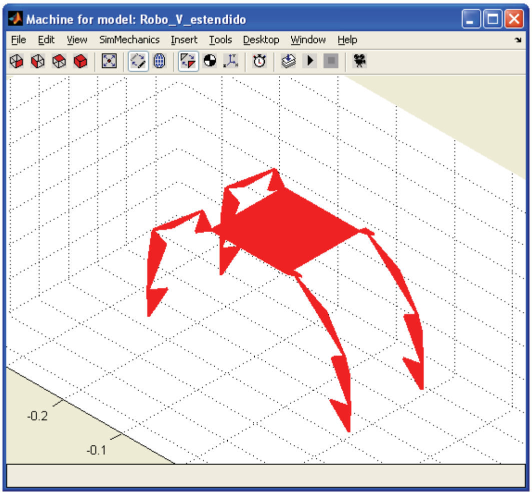

Fig. 15. Kamanbaré's model machine in convex hulls view mode

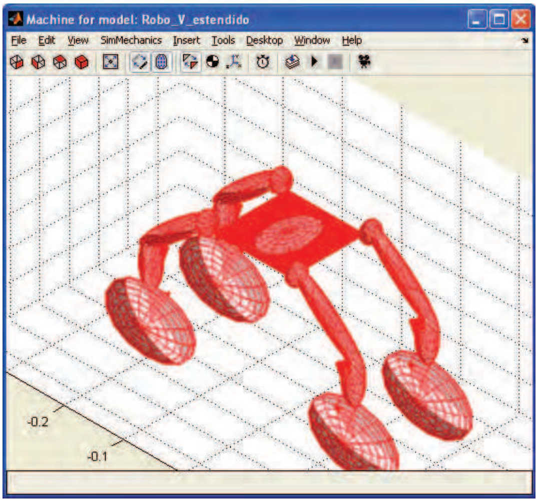

Fig. 16. Kamanbaré's model machine in convex hulls + ellipsoids view mode

As explained before, both the body movement and the foot trajectories are given, as well the joint angles of the legs, as a gait. Using these inputs and running simulations in an inverse dynamics option, all the joint torques can be determined.

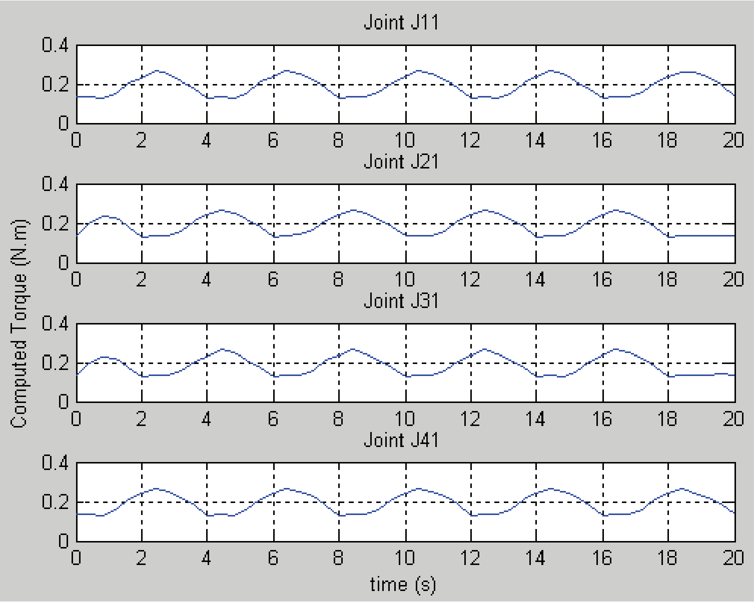

Fig. 17. Computed torques for the group of joints 1

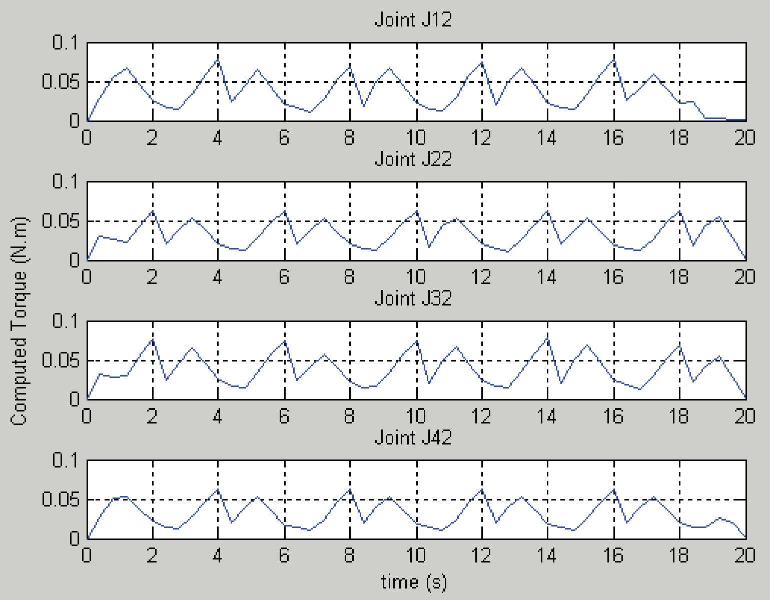

Fig. 18. Computed torques for the group of joints 2

The results presented in the following figures are the necessary torque to produce the desired movement, or gait, presented in Fig. 14. The torques are grouped by the function, i.e, torques for the joints with the same functionality, or the same mechanical position and configuration, for legs 1, 2, 3 and 4.

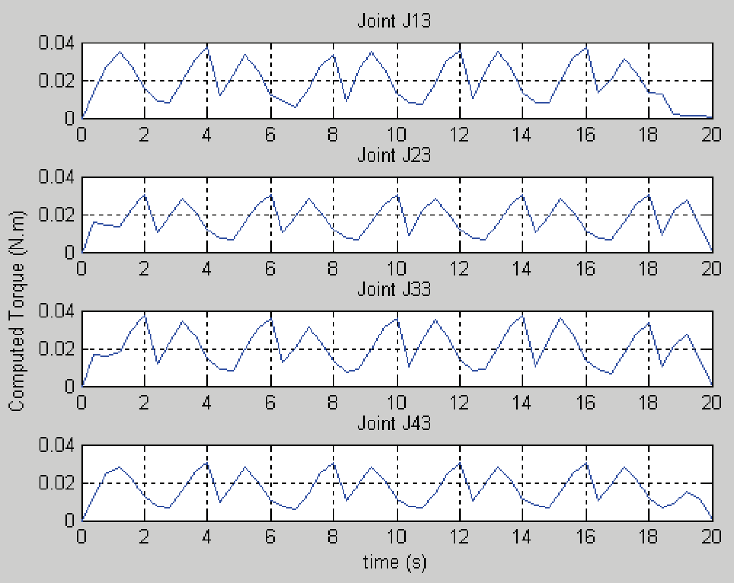

Fig. 19. Computed torques for the group of joints 3

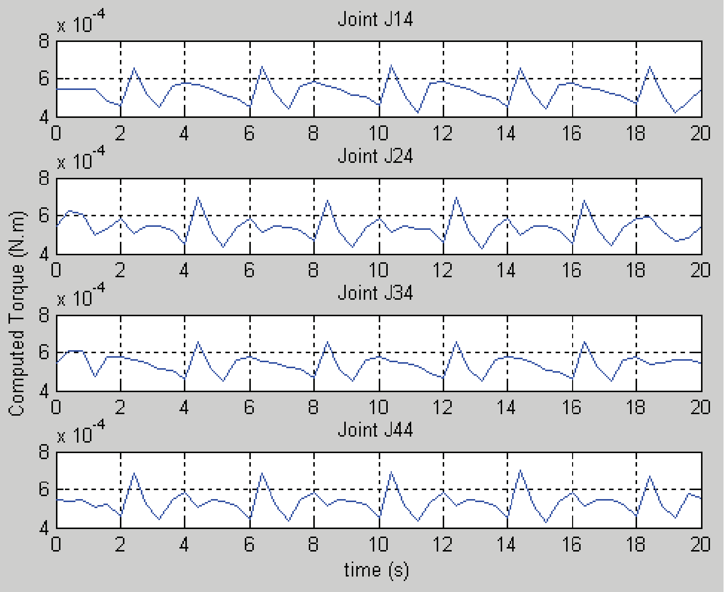

Fig. 20. Computed torques for the group of joints 4

## 10. Conclusion

This work presented the Kamanbaré robot, which is a four-legged bionspired platform with the main purpose of climbing trees, for environmental research applications. The mechanical and electronics structure, and the software architecture, were presented as well a Simulink mechanical model and simulations results.

Based on its special design, this platform offers the possibility of investigating reptile-like walking and climbing.

As a control approach, just a gait generator based on the chameleon mode of movement was presented, but it was demonstrated that is sufficient to obtain results on legs movement interference and realistic torque estimates.

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The book presents an excellent overview of the recent developments in the different areas of Robotics, Automation and Control. Through its 24 chapters, this book presents topics related to control and robot design; it also introduces new mathematical tools and techniques devoted to improve the system modeling and control. An important point is the use of rational agents and heuristic techniques to cope with the computational complexity required for controlling complex systems. Through this book, we also find navigation and vision algorithms, automatic handwritten comprehension and speech recognition systems that will be included in the next generation of productive systems developed by man.

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