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Handling the Transition in the Locomotion of an Articulated Quadruped Robot by Adaptive CPG

Edgar Mario Rico Mesa, Jesus-Antonio Hernandez-Riveros

Abstract—**A control strategy based on the theory of Central Pattern Generators (CPG) implemented through recurrent neural network (RNN) for the development of trotting and walking locomotion of an articulated quadruped robot is presented in this paper. The control strategy was enriched with fuzzy logic to ensure the stability and balance of the robot in transitions among locomotion modes. The control strategy was simulated and then implemented in a prototype. The results are very promising. A quadruped robot with three joints per leg, name R4A3, was built for this purpose. The R4A3 learnt to walk by itself; for its locomotion, it is not necessary to develop the kinematic equations. A novel Nonlinear First Order Differential Equation System was developed to simulate the CPG as oscillators. The control strategy is distributed and autonomous, operating through three levels of control. Each level determines the degree of complexity of the action concerning the consequence of how it affects the entire robot. Level 1 aims to those repetitive continuous movements occurring on each joint. These movements are action primitives. Level 2 governs repetitive movements occurring on each leg. It involves the basic actions that identify the type of locomotion. Level 3 considers the recognition of the motion of the R4A3 determining its stability and balance, planning transitions between types of locomotion and avoiding overturning. With the appropriated parameterization the same Differential Equation System is used in each CPG on each level reducing the mathematical complexity to reproduce the quadruped movement resulting in a low computational cost suitable for hardware implementation.**

Index Terms—**Central Pattern Generators; Recurrent Neural Networks; Stability; Fuzzy Logic; Articulated Quadruped Robot.**

I. INTRODUCTION

HARDWARE in the first developments of robots was based on electromechanical components [1]. Robotics began a vertiginous advance from the mid-twentieth century with the development of semiconductor technology and miniaturization of electronic components [2]. New materials emerged at the end of the 20th century contributing with high strength and low weight in structural and operational elements [3]. Nowadays, in the 21st century, algorithms, methods, and techniques are getting closer to biological theories [4]. In the last decade, there has been a strong tendency to develop locomotion projects in artificial systems, such as quadruped and biped robots, using procedures inspired by theories posed by biologists [5], [6]. Theories that have been interpreted and evaluated by expert engineers in computational intelligence using mathematical tools and techniques of advanced control [7]. Central Pattern Generator (CPG) is a theory that explains the shaping of rhythmical and involuntary movements in animals [8]. This paper focuses on the application of CPG for the development of trotting and walking locomotion, and its transition, on an articulated quadruped robot. The robot, named R4A3, is a four-legged robot that has three joints per leg. The objective is to emulate the movement of a quadruped using CPG as the basis of the control architecture of the R4A3. Each joint is endowed with high torque and high precision servo motors. An electronic and control system handles the power and coding module of 12 servomotors by I2C. Additionally, I2C receives information from the three-axis acceleration detection sensors (accelerometer). The control system features are 16 analog channels, 54 digital channels, 4 UART modules, 14 PWM channels, 256k flash memory. The configuration used to represent the CPG is Recurring Neural Networks (RNN). The mathematical expression of these RNN applied in this paper is a novel Nonlinear First Order Differential Equation System (NLFODS). These RNN function as oscillators. This way, one main contribution of using CPG to reproduce the quadruped movement is its low mathematical complexity that results in a low computational cost [9]. The control architecture in this project is composed of three levels, each level has a specific function to perform. Level 1 focuses on the coordinated movements of each articulation per leg. Level 2 aims to synchronize movements of the 4 legs. Level 3 is dedicated to the stability of the robot and to determine the moment in which the transition between types of locomotion must be made. This control by levels allows autonomy in the execution of the respective functions. The commands of the higher levels are of immediate fulfillment, at the instant in which they are produced, modifying some characteristics of the current movement in execution. Transition between types of locomotion is a subject of research in robotics [10], [11]. Changes in locomotion have a high degree of complexity by requiring a multidisciplinary solution, with ingredients in mathematics, physics, control theory, mechanics and electronics. Our purpose is to emulate the behavior of living beings at the time of transitioning between different types of locomotion. This paper deals with this problem on a quadruped robot with three joints per leg. There is no necessary a previous kinematic study, but signals are sent to each joint. The locomotion is emulated using mathematical tools and computer engineering through a procedure called Adaptive CPG. This paper is organized in the following sections. Locomotion control architecture: presents the reasons for the architecture and the functions each component fulfills for a coordinate movement. Adaptive CPG for the transition in locomotion: describes the active components of the control system to realize the transition and to prevent the robot from overturning. Review of works in the transition of locomotion:

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Edgar Mario Rico Mesa is with the Centro de Tecnológia de la Manufactura Avanzada, SENA, E-Mail: emrico@sena.edu.co

Jesús-Antonio Hernández-Riveros is with the Dept. Energía Eléctrica y Automática, Universidad Nacional de Colombia sede Medellín, E-Mail: jahernan@unal.edu.co

shows works related to the problem, in the last five years. Application of the control architecture in a quadruped robot: presents the results obtained by the R4A3 in the emulation of the transition in the locomotion of a quadruped living being. Discussion: section where a comparison between the different works found in the review and the ones developed in this project is shown.

II. LOCOMOTION CONTROL ARCHITECTURE

The robot in this project for transition in locomotion is a quadruped. Each leg has three degrees of freedom (Figure 1A), whose functionality is focused on having the balance at all period of locomotion while walking or trotting, and in the transition between them. The hip corresponds to articulation 1, the knee to the 2, and the ankle to 3. Each joint has rotational movement and houses a high-torque digital servo motor (Figure 1A) with its respective controller fulfilling the function of a RNN. They are in a serial configuration since action of each actuator originates directly from the joint.

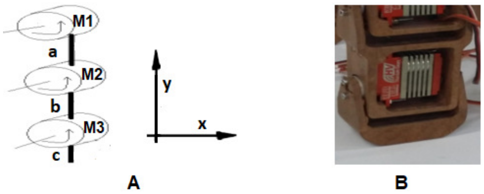

Fig. 1. Configuration of a leg. A)Leg with three joints. B) Ankle joint.

The links of the R4A3 were designed in SolidWorks and were machined in wood by a high precision CNC (Figure 2). This is a low-cost structure with acceptable mechanical conditions that allows the required locomotion tests to check the performance of algorithms during the transition between types of locomotion.

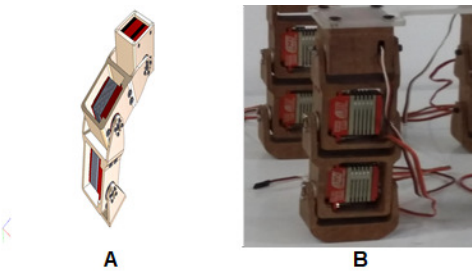

Fig. 2. Design and development of robot members.

The robot's body is based on a transparent polycarbonate sheet (4-mm thick), designed and manufactured according to the adequate elasticity and size required for the quadruped robot (Figure 3). In the implementation of the locomotion of an articulated robot is essential to define the control strategy to achieve the adequate movements of the joints and legs to get the system displacement. Here, the applied strategy is based on the theory of CPG; theory that explains the behavior of motor functions in living beings [12]. CPG theory has been used in applications of robotics [13]. It rests on the premise that the control system is distributed and autonomous [14]. This notion is developed in this paper, operating through three levels of control. Each level determines the degree of complexity of the action concerning the consequence of how it affects the entire robot. Level 1 aims to those repetitive continuous movements occurring on each joint. These movements are action primitives. Level 2 governs repetitive movements occurring on each leg. It involves the basic actions that identify the type of locomotion. Level 3 considers the recognition of the motion of the robot determining its stability and balance. It, also, controls actions to avoid overturning and plans transitions between types of locomotion, both, in time and in the way of successfully achieving a required change.

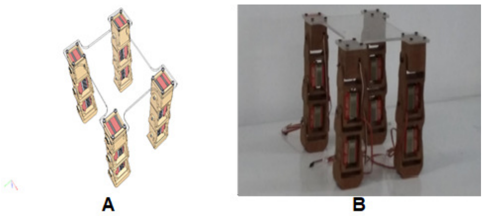

Fig. 3. Robot structure. A)Design. B)Mounting.

A. *Level 1 - Movement Coordination:*

This layer corresponds to the action in each of the three joints composing each leg of the robot. Its function is to develop the repetitive movements of each joint. Each joint has a recurrent neuronal network of 4 neurons bidirectionally connected. Figure 4 shows the assignment of the neuron responsible for activating the movement of a specific joint in a leg.

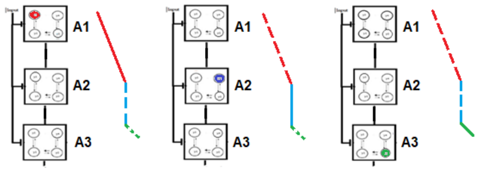

Fig. 4. Configuration of the Recurrent Neural Network (RNN) in joints of the leg: In solid line is the active articulation.

For the configuration of the RNN for each joint, a new system of 4 non-linear first-order differential equations was yielded, as observed in equations 1, 2, 3 and 4. Of these equations, Equation 2 represents the time-out.

$$\tau_1 \frac{dy_1}{dt} = -y_1 + \frac{A(k1 - Dy_2)^2}{(k1 + Dy_2)^2 + (k1 - Dy_1)^2} \tag{1}$$

$$\tau_2 \frac{dy_2}{dt} = -y_2 + \frac{A(K2 - Dy_1)^2}{(k2 + Dy_2)^2 + (k2 - Dy_3)^2} \tag{2}$$

$$\tau_3 \frac{dy_3}{dt} = -y_3 + \frac{A(K2 - Dy_2)^2}{(k2 + Dy_3)^2 + (k2 - Dy_4)^2} \tag{3}$$

$$\tau_4 \frac{dy_4}{dt} = -y_4 + \frac{A(B - Cy_3)^2}{(B + Cy_3)^2 + (B - Cy_4)^2} \tag{4}$$

The terms or parameters of the equations 1, 2, 3, 4 are described below:
τ is the time constant (periodicity of the signal).
A constant is an amplitude signal.
k1, k2, B constants are operation reference applied to the summed signal.

D, C constants are a multiplying factor feedback signal. Figure 5 shows the signals (y1, y2, y3, y4) produced by each neuron (N1, N2, N3, N4) as oscillators for the development of the movement expected by the leg. The moment in which each joint executes the action shown. The signal Y2 is dead time, in the beginning, before the execution of the movement of the leg joints. The signal Y1 activates the motion of the hip (A1). The signal Y4 activates the motion knee (A2). The signal Y3 activates the motion ankle (A3).

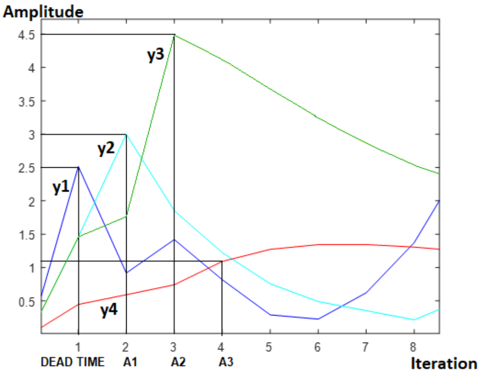

Fig. 5. Signals from a RNN of 4 neurons.

B. *Level 2 - Locomotion Synchronization:*

This layer executes the movement of each leg. The function of this level is the realization of a type of locomotion. The arrangement of each neuron as an oscillator observes in Figure 6A. In Figure 6B presents the RNN of 4 neurons (N1, N2, N3, N4). The signals produced (y1, y2, y3, y4)conform the activation commands to the correspondent leg (L3, L4, L1, L2) of the quadruped robot. The mathematical scheme of the recurrent neural network for each of the four legs has the same structure of the four nonlinear first order differential equations (1), (2), (3), (4), with a different parametrization set.

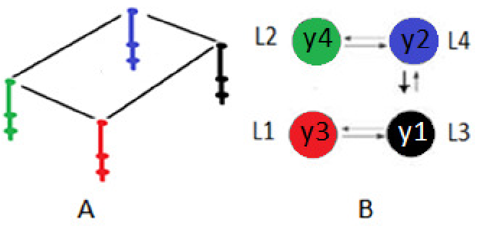

Fig. 6. Recurrent neural network configuration for the 4 legs. A) Command handling at the robot's feet. B) Recurrent neural network structure.

Figure 7 shows the control signals for the operation of each leg. Each neuron produces an oscillatory signal delayed with respect to the other signals produced by the other neurons.

C. *Level 3 - Locomotion Planning:*

This layer is focused on learning locomotion and the use of reflex actions to avoid overturning situations. This layer determines the transitions between types of locomotion. In addition, it applies fuzzy logic on the CPG at times of instability and imbalance.

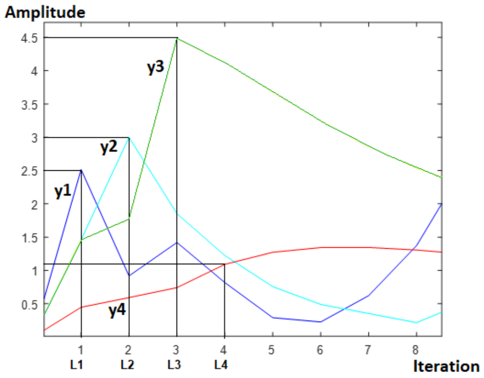

Fig. 7. Control signals from the RNN for the operation of each leg.

For the configuration of the RNN for the transition, another novel system of two nonlinear first-order differential equations is used, as observed in equations (5) and (6).

$$\tau_1 \frac{dy_1}{dt} = -y_1 + \frac{A(K1 - Dy_2)^2}{(k1 + Dy_2)^2 + (k1 - Dy_1)^2} \tag{5}$$

$$\tau_2 \frac{dy_2}{dt} = -y_2 + \frac{A(B - Cy_1)^2}{(B + Cy_1)^2 + (B - Cy_2)^2} \tag{6}$$

The terms or parameters of the equations 5 and 6 are described below:
τ is the time constant (periodicity of the signal).
A constant is an amplitude signal.
k1, B constants are operation reference applied to the summed signal.
D, C constants are a multiplying factor feedback signal. Figure 8 shows the scheme of a RNN applied for level three. The mathematical representation is a system of two nonlinear first-order differential equations. The produced signals are commands of modification of the locomotion to avoid overturning situations. Figure 9 shows that, unlike the first two levels, handling cyclic signals, at level 3 transient signals are used, because locomotion changes or leg movement corrections should be made at any time by sending commands to all legs simultaneously.

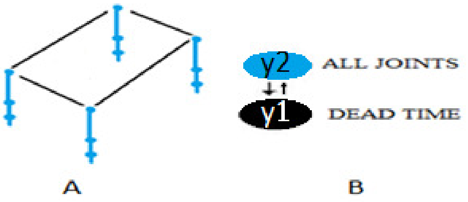

Fig. 8. Configuration of RNN of 2 neurons for the transition in locomotion. A) Handling commands to the robot's legs. B) Recurrent neural network structure.

Biomechanical locomotion studies [15] developed in various breeds of dogs were used as a seed for the construction of trotting and walking locomotion patterns for the first two hierarchical levels. The capacities established in the robot hardware were based on the operating frequency of each leg, the positioning angles of each joint in the legs, the

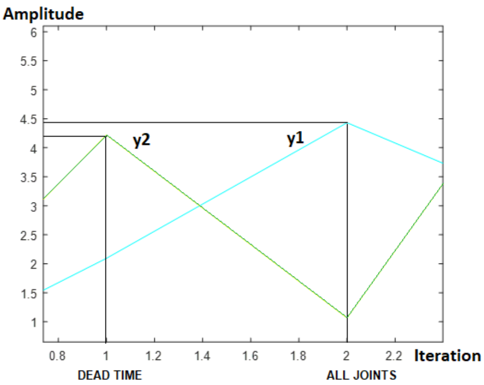

Fig. 9. Signals from the RNN of 2 neurons.

locomotion sequence, residence times in both the support phase and the air phase, among others (see Table I and Table II). These data were driven by the codes incorporated in the recurrent neural networks (RNN).

TABLE I
OPERATION PARAMETERS FOR THE R4A3.

Characteristic	Walk	Trot
Locomotion operating frequency	1 Hz	4 Hz
Frequency of operation of each leg in locomotion	0.25 Hz	2 Hz
Locomotion sequence	One leg at a time in the aerial phase	Alternate front - rear legs in support or aerial phase
Time spent in support phase by leg	3.75 s	0.25 s
Time spent in the air phase by leg	0.25 s	0.25 s
Ankle angle range	[130,160]	[110, 170]
Knee angle range	[110,150]	[90, 150]
Hip angle range	[70, 130]	[70, 140]

At level three, a diffuse CPG was developed based on the observations, findings, and descriptions obtained in biomechanical studies [16] on walking-trotting transitions, allowing:

- Organize the slopes and geometric shapes of the fuzzy sets for fuzzification and defuzzification.
- Build the antecedents and consequents of the rules.
- Apply relevant operations for the inference machine to activate rules.

Those criteria are based on situations that occurred with different breeds of dogs that are applied and adapted for the quadruped robot, considering its technological limitations.

The control architecture is expressed as a block diagram in Figure 10. Sub-diagram 1 corresponds to the coordination of joint movements for a leg. Sub-diagram 2 to synchronization of the four legs, and sub-diagram 3 to locomotion planning based on equilibrium.

III. ADAPTIVE CPG FOR THE TRANSITION IN LOCOMOTION.

To pass from one type of locomotion to another, a special control protocol named Adaptive CPG was proposed. This protocol allows to make the best decision without hindering the movement of the robotic system R4A3 during the transition, according to the following items:

TABLE II
TRANSITION PARAMETERS FOR THE R4A3.

Characteristic	Observation: Transition walk–trot	Observation: Transition Trot–Walk
Frequency used	1-4 Hz	4-2-1 Hz
Specific leg movements	Immediate change of locomotion	Change of locomotion in an operation cycle
Overturning situations	No	No
Support phase residence time by leg	3.75-0.25s	0.25-3.75 s
Aerial phase residence time by leg	0.25-0.25 s	0.25-0.25 s

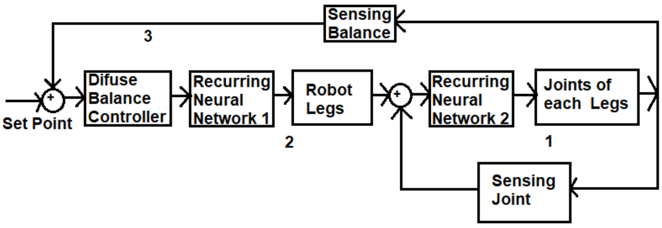

Fig. 10. Block diagram of the control system.

A. *Transition Commands.*

The robot R4A3 has a decentralized control system composed of 12 controllers (local RNN) governing the movement of the joints in each leg. Its function is to coordinate the movements of the joints. There is also a controller (central RNN) that rules the actions between the legs. Its function is to synchronize the movements of the legs. The central RNN is responsible for initiating the transition process through an encrypted command sent to all local RNN.

B. *Sensing the spatial position of the robot's body.*

The following alternatives were defined to establish the position of the robot: a) Each local RNN corresponding to the ankle of each leg of the robot are connected to a force sensor (at the hip of each leg). The force is measured at the time of the transition and transmitted through a specific protocol between the local networks to the central RNN. b) The central RNN is connected to an acceleration measurement system in the three coordinate axes that senses at the time of the transition between types of locomotion.

C. *Joint position sensing.*

Each joint store the information regarding the actual position of the servomotor during the transition in locomotion.

D. *Stability calculation.*

The computation of the level of stability of the robot has the following alternatives: a) The action performed at the time of obtaining the force per leg contacting the surface. b) The acceleration in the three axes in the central neural network. This information is transmitted to all local neural networks that are related in the tendency to instability.

E. *Position error calculation.*

This error is the magnitude obtained through the subtraction operation between the current position and the new locomotion.

F. Execution of the fuzzy control algorithm.

The fuzzy control system has as input information about the position of the leg that can cause the overturn the angle of the hip (Figure 11). This joint moves the entire leg and affects the acceleration on the Y-axis. The X-axis has not joints. Each input has three fuzzy sets. A set of rules (Table III), to be followed by the fuzzy control system, has been constructed based on the input and output variables that describe the robot's behavior in a possible overturn. Fuzzification obtains the input weight of the variables. Therefore, the inference machine determines the rules that are activated. Equation 7 obtains the weight of the output variable (position).

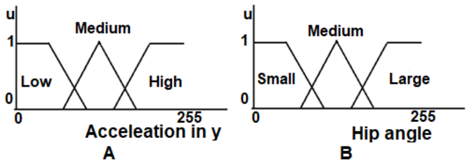

Fig. 11. Fuzzification of the input. A) Acceleration input on Y axis. B) Hip Angle input.

$$U_s = Max(Min(U_{ay}, U_{ha})) \tag{7}$$

TABLE III
SET OF RULES FOR OVERTURNING.

Rules		Hip angle		
		Small	Medium	Large
Acceleratión y axis	Low	Hold	Hold	Hold
	Medium	Increase	Increase	Decrease
	High	Increase	Decrease	Decrease

The value obtained when applying the inference operations is brought to the defuzzification module consisting of three fuzzy sets (Figure 12) that convert this information into an output data or command (angle). The angle variable corresponds to the new position that the hip joint of the leg will adopt in the transition process. It should be noted that the geometric shapes of the assemblies and their respective slopes of both fuzzification and defuzzification must be determined according to the operating range of each joint between the two types of locomotion. The output data is obtained calculating the centroid with equation 8.

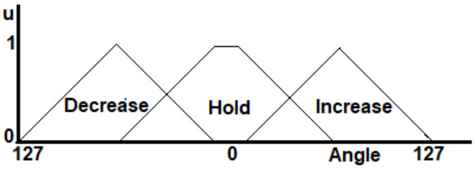

Fig. 12. Defuzzification of the angle variable.

$$Centroid = \frac{\sum_{i=0}^{n} f(x)_i x_i}{\sum_{i=0}^{n} f(x)_i} \tag{8}$$

G. Application of the new articulation position.

Each local RNN adopt the new angle for the new position of the servomotor in the respective joint.

IV. REVIEW OF WORKS IN TRANSITION OF LOCOMOTION.

In the search for publications related to the issue of transition in quadruped robot locomotion, in the last four years, the following results were obtained through sources from Asia, Europe, and America: [9], [13], [14] Proposes a quadruped robot with three joints per leg. The locomotion used is walking. The control algorithm is recurrent neural networks. [17] Proposes a model for the transition between gait and high-speed gallop. The proposal is verified with 2D simulations and 3D hardware experiments. [18] Proposes a deformable robot with spherical balancing. The robot reproduces the locomotion of the quadruped walk achieving energy savings on flat surfaces. [19] Presents a comparison between an open-loop controller based on phase oscillators with the Tegotae controller. The Tegotae algorithm presents a good behavior with the spontaneous locomotion transition. [20] Shows a controller formed with coupled oscillators using a CPG structure with a symmetric network for adaptive locomotion developed for robots with legs. Natural locomotion patterns must generate stability in the displacement of the quadruped robot. [21] Proposes a path planning method for a quadruped robot. Robot's movement coordination bases on the limbs that are in the support phase during locomotion. [22] Presents a work that uses CPG for the coordination of the legs in the transition process. The robot has communication between all parts of the system. [23] Proposes a simple CPG-based model for joint movement complemented by the head movement for the spontaneous transition of locomotion at high speed in quadrupeds. [24] Presents a CPG model-based in rhythmic signals. The modulation of the signals allows the transition between slow and fast locomotion. The model simulates the locomotion of a quadruped robot. [25] Describes a quasi-static transition control method. This model shows sudden and discrete changes in locomotion transition patterns as a function of speed. The transition patterns are defined according to the position of the current legs and the new positions of the legs. [26] Describes a method to generate different trajectories of the legs for different types of locomotion. The trajectories simulate the locomotion. The method describes through a set of parameters the typical movements of animals during locomotion. [27] Proposes a semi-passive walking robot. The robot is controlled by two microcontrollers, (the main microcontroller handles the front legs and the secondary microcontroller manipulates the rear legs). The control is developed with an "on-off" control algorithm. Each leg has a motor on the hip, an electromagnet on the knee, and a fixed support point (it has no joint).

Analyzing the review of literature, it can be say: The work [17] focuses on the modeling and simulation of a quadruped robot with 2 joints per leg in gait mode and its transition between walking and galloping. It states that the travel speed is a function of the type of locomotion, as an energy-saving factor that must be taken into account in the design of a quadruped system. [18] and [27] describe quadruped robot structures, focusing on the locomotion of the walk. In [18], a spherical robot with a deformation mechanism allows the development of the walk. Therefore, in flat terrain, its structural form is quadruped with two joints per leg while in irregular environments its structural form is spherical. [27] proposes a structure of a semi-passive robot used on descent slopes to perform locomotion, adding a second joint through an electromagnet in the knee for locomotion in flat terrain. The action of the legs is based on the movement of the simple pendulum. This mechanical conception of [18] and [27] allows handling low energy costs. In [19] and [20], there is a quadruped robot with two joints per leg having a feedback force by limb used to determine, at all times, the relationship of forces in the robot. In [19], the control system consists of phase oscillators based on the Tegotae model that acts on the two joints of each of the legs, while [20] uses a CPG architecture with four Hopf oscillators that govern the two joints of each of the legs. Both works seek to develop the locomotion of walking and jogging and the transition between them. In [21], a simulated reptile robotic system in the type of trot locomotion is presented with satisfactory results in the movements executed in a displacement similar to the Gecko reptile. The control algorithm is based on a defined function, composed of oscillators of phase. In [22], a quadruped robot of a one joint per leg was proposed. Its locomotion control is performed with CPG based on phase oscillators with feedback force sensor on each leg. Another algorithm is responsible for generating the walk, trot, and gallop patterns and transitions between types of locomotion. In [23], a quadruped robot with two joints per leg (rotary actuator and linear actuator) with a control algorithm based on a CPG proposes a phase oscillator simulating the locomotion of the rotary gallop and its transitions between medium and high speeds. In [24], there is a quadruped robot with two joints per leg with a CPG control system based on Hopf oscillator. It simulates three types of locomotion (walking, trotting, and galloping) and their transitions. In [25], a work was published with a quadruped robot with two joints per leg, simulated the locomotion of walking and trotting and its transition and staged by a real robot to perform the walk. Its control system bases on predetermined movements of a robot in quasi-static equilibrium. In [26], a quadruped robot with 3 joints per leg simulates using as a control system a CPG based on a state machine, the locomotion of walking, trotting and low-speed movements and its possible transitions. The objective of this work is to determine, in those types of locomotion and their transitions, the foot's trajectory. After detailing the different works carried out in the last 5 years, it has been found that although there are advances in terms of the transition between types of locomotion, CPG with traditional oscillators have been applied mostly to solve the problem for quadrupeds of two degrees of freedom by leg, both, some in simulation [17], [21], [24], [25] and others in real systems [18], [19], [20], [27]. A special case is [22], because there is a real system with locomotion in walking, trotting and galloping and its transitions, but it only has one joint per leg. While in [23], the gallop locomotion is developed and speed transitions in the same type of locomotion are solved. Also, [26] presents a work of locomotion in walking and trotting and its transitions, the controller bases on a state machine with a quadruped robot of three joints per leg in simulation. However, it is focused on the trajectory of the foot during locomotion and only show results of the behavior of the foot. In [9], [13], [14] the development of tools and modules that were consolidated to perform the locomotion of a quadruped robot is described for the construction of the basic CPG control architecture. In these works, there is a new conception of oscillators on recurrent neural networks for 2, 3, 4, 5 and 6 neurons and the coding of control data in the new recurrent neural networks. Those components are the basis of the project described in this paper. In the work proposed in this paper, both the simulation and the real assembly shows a three-joint per leg quadruped robot with equilibrium feedback. Its control system is a new one based on CPG with recurrent neural networks, per articulation and in the central nervous system. The communication between joints is physical and bidirectional, also with CPG. This approach based on a set of signals, delayed among them, and relays makes not necessary to know a priori the kinematic equations of the joints and legs.

V. APPLICATION OF THE CPG CONTROL ARCHITECTURE IN A QUADRUPED ROBOT.

It is fundamental to validate the operation of the proposed controller. Therefore, the simulation and emulation of the quadruped robot in locomotion is presented below.

A. Locomotion simulation in the R4A3 robot.

The projection criterion of the center of gravity proposed by McGhee and Frank [28] was used for the robot locomotion. This criterion establishes that ideally a walking machine has the characteristic of being in a statically stable state (equilibrium), if the horizontal projection of its Center of Gravity (CoG) is within its support polygon. Therefore, the static stability margin is the shortest distance between a side of the polygon and the CoG (Figure 13).

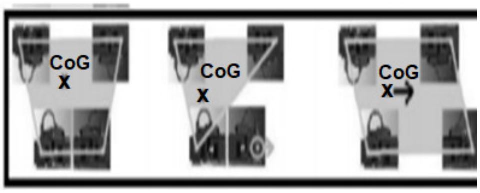

Fig. 13. Static equilibrium of a quadruped robot.

Additionally, the Zero-Point criterion proposed by Vukobratovic [29], which has been used in trotting machines, was also considered. For each leg in the phase of support the center of mass, the moment of rotational inertia, the angular acceleration, and the acceleration in the three coordinate axes are calculated. These data, introduced in equations 8 and 9, correspond to the inertial zero point (ZMP) in Figure 14 [30].

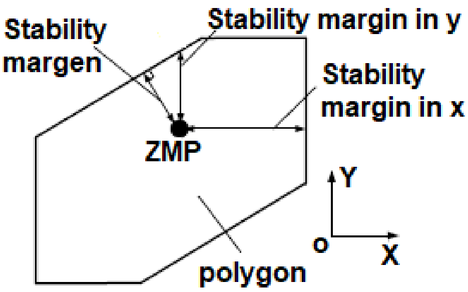

Fig. 14. Dynamic Balance on a quadruped robot.

$$x_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i\ddot{x}_i z_i - \sum_{i=1}^{n}(\ddot{\omega}_i I_i)}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \quad (9)$$

$$y_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i\ddot{y}_i z_i - \sum_{i=1}^{n}(\ddot{\omega}_i I_i)}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \quad (10)$$

1) Walking Locomotion: In the locomotion of the walk, three movements related to the different joints of the legs are executed. Only one step is executed in the air phase. The coordinates required by articulation to execute the sequence are shown in Table IV. Taking into account the matrix (Table IV) of the triad of positions (hip, knee and ankle), the simulation of the locomotion of the walk has been implemented in the quadruped robot. Figure 15 shows the position of legs and its support polygon, in which 3 frames stand out (15B, 15C, 15D), moving one of its legs between support phase and air phase, this movement facilitates the advance of the robot.

TABLE IV
JOINT POSITION AND LEG END IN WALKING.

Coordinate	Hip	Knee	Ankle	Tiptoe
X	0	-212.1199e-003	-57.5228e-003	48.9859e-018
Y	0	252.7947e-003	657.4885e-003	800.0000e-003
X	0	-212.1199e-003	-57.5228e-003	48.9859e-018
Y	0	252.7947e-003	657.4885e-003	800.0000e-003
X	0	-212.1199e-003	-57.5228e-003	48.9859e-018
Y	0	252.7947e-003	657.4885e-003	800.0000e-003
X	0	20.2067e-018	424.2398e-003	565.6854e-003
Y	0	330.0000e-003	505.5893e-003	565.6854e-003
X	0	20.2067e-018	80.4338e-003	111.3385e-003
Y	0	330.0000e-003	655.0805e-003	792.2145e-003

2) Trotting Locomotion: Two frames were defined for the development of trotting that must be executed by the robot's legs, of which, one is made in the support phase and the other in the aerial phase. The coordinates required by articulations to execute the sequence is in Table V.

TABLE V
JOINT POSITION AND LEG END IN TROTTING.

Coordinate	Hip	Knee	Ankle	Tiptoe
X	0	0	0.4242	0.5657
Y	0	0.3300	0.5056	0.5657
X	0	-0.2121	-0.0575	0
Y	0	0.2528	0.6575	0.8000

Taking into account Table V, which represents the angles of the hip, knee and ankle, the simulation of the trot locomotion for the quadruped robot (Figure 16) was made, observing that the crossed legs remain simultaneously both in the support phase or in the air phase.

Note that the operating frequencies for each type of locomotion are different. The frequency of locomotion for the walk is 1 Hertz. The frequency for the trot is 4 Hertz.

B. Simulation of the transition between types of locomotion.

The strategy to perform the transition was based on a project of the biomechanics of dogs in locomotion with 25 different races [15]. Therefore, in the development of the transition in the locomotion, the operating frequency has been defined between 1 and 4 hertz. The way of operating the transition has been defined considering the stability of the robotic system.

1) From walking to trotting: This transition begins from the moment one of the front legs starts the balancing phase. Immediately, the rear leg also starts the balancing phase and the operating frequency increases from 1 to 4 hertz. It is important to indicate that while the legs that are in the swinging phase follow the trotting movements, the legs that are in the support phase follow the movements of the walk. This process takes at most two frames of advance in the displacement of the quadruped robot. The sequence of the simulation of the transition locomotion is in Figure 17.

2) From trotting to walking: The transition begins from the moment when the rear and front alternate legs will enter the support phase. At that moment, the rear alternating leg that is in the balancing phase passes to the support phase and the operating frequency 4 to 2 hertz. This process lasts at most two cycles or steps of advance in the displacement of the quadruped robot. In the first cycle the trotting is continued lowering the operating frequency to 2 Hz, and in the second cycle it is operated in 1 Hz walk. The sequence of the simulation of this transition locomotion is presented in Figure 18.

Note that the transition actives the diffuse CPG only in the case where the robot tends to lose stability during its movement.

C. Locomotion emulation in the R4A3 robot

A performance electronic card with a power module for servo motor control and an I2C communication module for receiving information from an accelerometer (Figure 19). were used to verify the simulation in a real system emulating the locomotion of an articulated quadruped robot.

The performance card having the CPG has been formed by virtual functions representing the main function for the central nervous system and specific functions for the management of each real joint (Figure 20).

The performing of the robot to experiment the locomotion in walking, trotting and its transition starts from the frames developed in the simulation fitting the signals applied to the servomotors. It is important to indicate that the selected servomotors are digital ones with high torque position control.

1) Walking Locomotion: In the locomotion process during the walking, one leg of the R4A3 is in the aerial phase and the other three legs in the support phase maintaining the stability of the robot with a center of gravity immersed in the polygon formed by them, guaranteeing the balance in static mode, and with a slow advance of approximately 0.1 cm (Figure 21).

2) Locomotion Walking - Trotting Transition: The locomotion process during the transition is performed at the end of a complete cycle of walking. Immediately, a pair of diagonal legs of the robot are taken to the air phase without losing the stability of the robot within zero point of inertia immersed in the polygon formed by the robot body and legs in support phase, guaranteeing balance in dynamical mode and with a slow advance of approximately 0.15 cm (Figure 22).

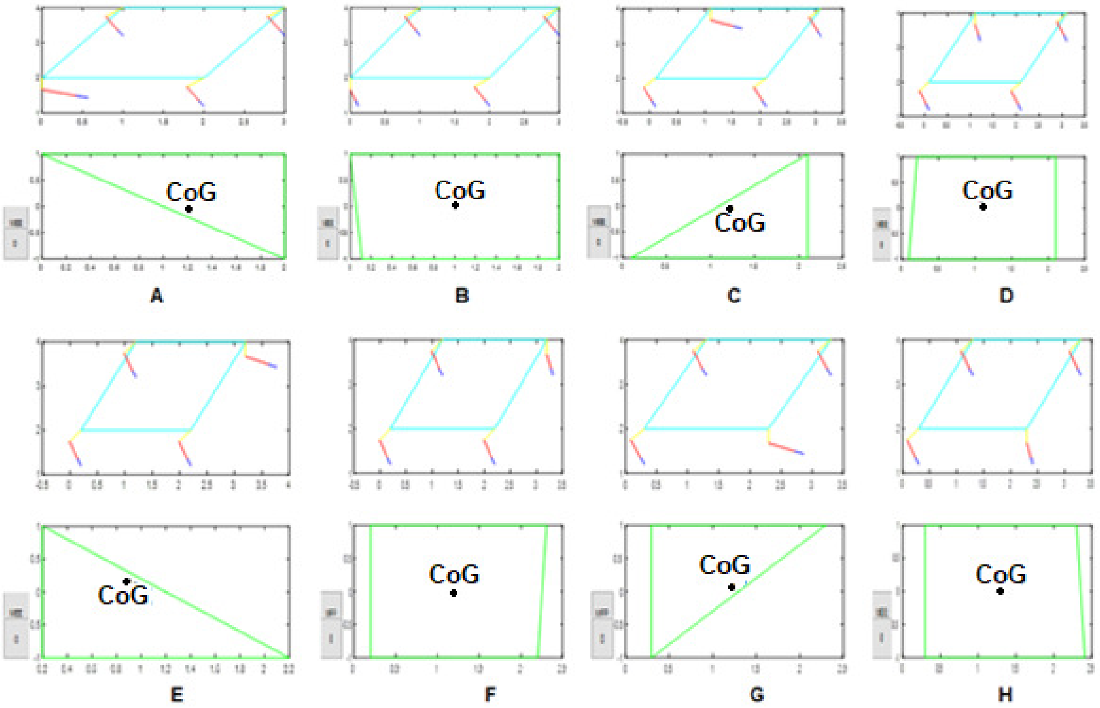

Fig. 15. Walk locomotion sequence.

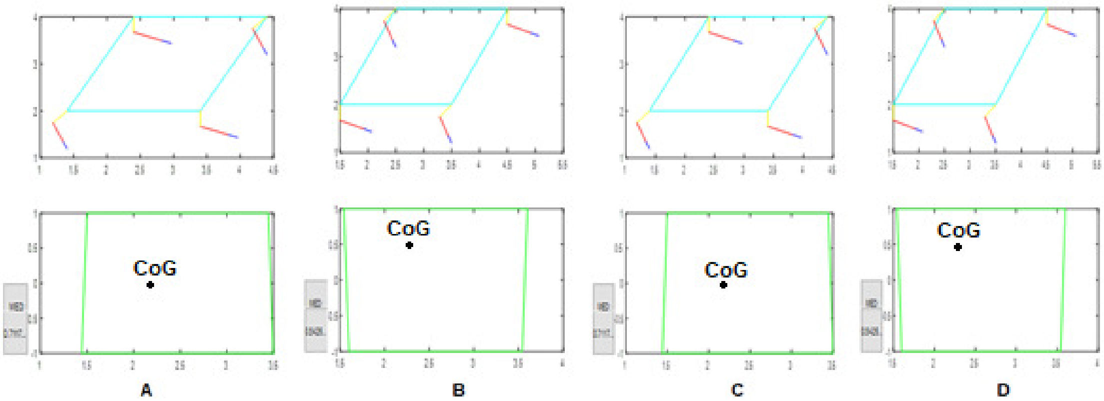

Fig. 16. Trot locomotion sequence.

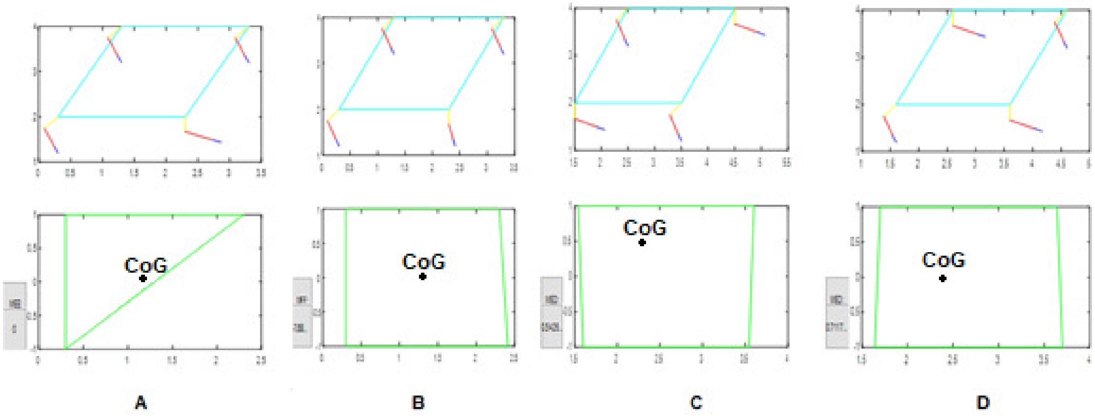

Fig. 17. Locomotion Walking – Trotting sequence.

3) Trotting Locomotion: In the locomotion process during trotting, each pair of diagonal legs of the robot are carried to the aerial phase maintaining the stability of the robot within zero point of inertia immersed in the polygon formed by the body of the robot and the legs in the support phase, guaranteeing the balance in dynamical mode and a slow advance of approximately 0.2 cm (Figure 23).

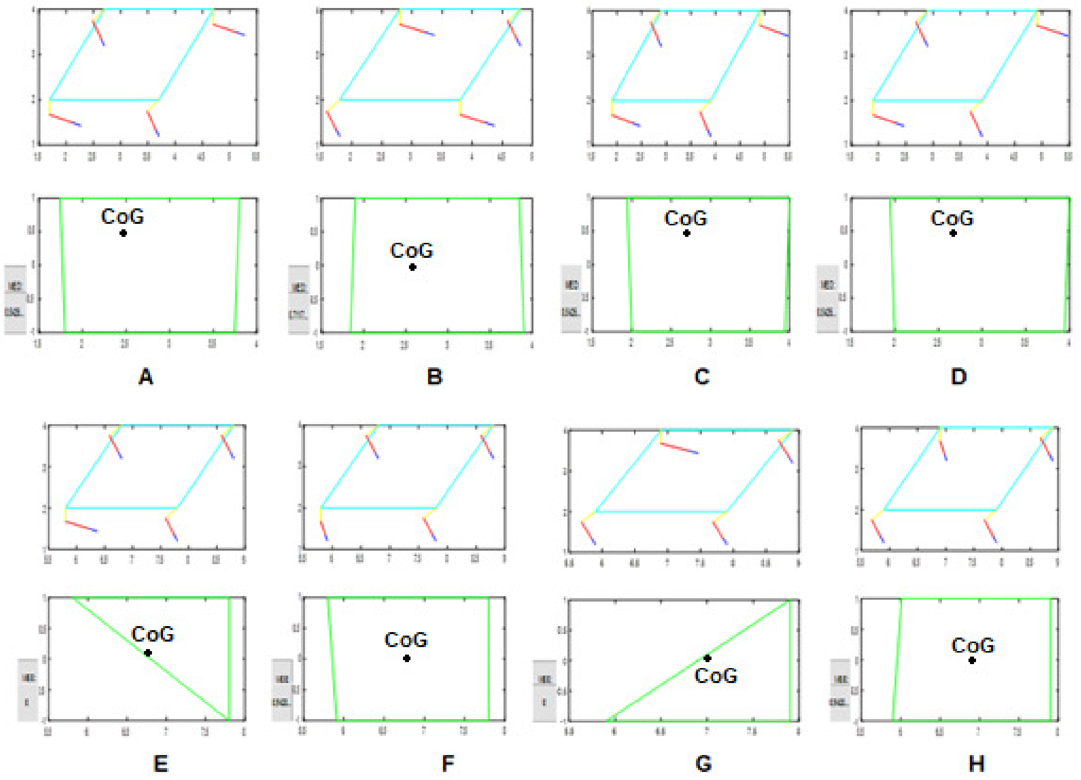

Fig. 18. Locomotion Trotting – Walking sequence.

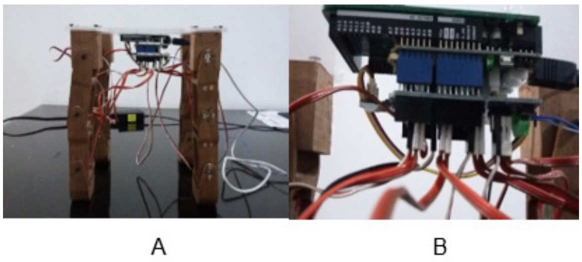

Fig. 19. Performance system and its power modules and I2C. A) View of the robot and the performance system. B) Close view of the performance system immersed in the robot.

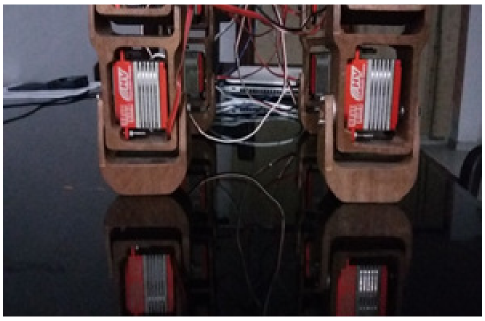

Fig. 20. R4A3 robot joint.

4) Locomotion Trotting - Walking Transition: The process of locomotion during this transition is performed at the end of a complete cycle of the trotting. Immediately, only one of the front legs of the robot is carried to the aerial phase without losing the stability of the robot maintaining the center of gravity immersed in the polygon formed by the legs in support phase, guaranteeing the balance in static mode and with a slow advance of approximately 0.15 cm (Figure 24).

Next, a series of results of both simulation and emulation of the quadruped robot in the locomotion of walking, trotting and its transition using the proposed control architecture is presented in Table VI and Table VII. According to Table VII, the simulation data of displacement and the step frequency are ideal values. The stability bases on the criteria set out in [28] and [30] whose values correspond to a margin of static stability (MSS) or dynamic stability margin (MDS) depending on the type of locomotion (Walking or Trotting). From the simulation data, the implementation of the control system emulation in a real articulated quadruped robot implements an initial seed, with some changes in its process of improvement. The frequency of passage was reduced by 25 percent to avoid a structural collapse of the robot, but the

TABLE VI
ACCELERATION DATA IN X, Y, Z OF THE ROBOT BODY DURING EMULATION OF LOCOMOTION.

Walking			Walking to Troting		
X	Y	Z	X	Y	Z
40	-20	263	32	-30	245
36	-21	246	-17	-2	279
38	-21	246	36	-9	243
43	-1	244	3	11	266
40	-14	253	17	-32	258
43	1	248	21	9	267
Troting			**Troting to Walking**		
X	Y	Z	X	Y	Z
31	-25	256	23	13	248
16	-5	252	2	28	247
16	-28	245	10	17	263
12	-28	265	29	22	257
21	-39	275	23	3	255
19	-34	254	2	-13	246

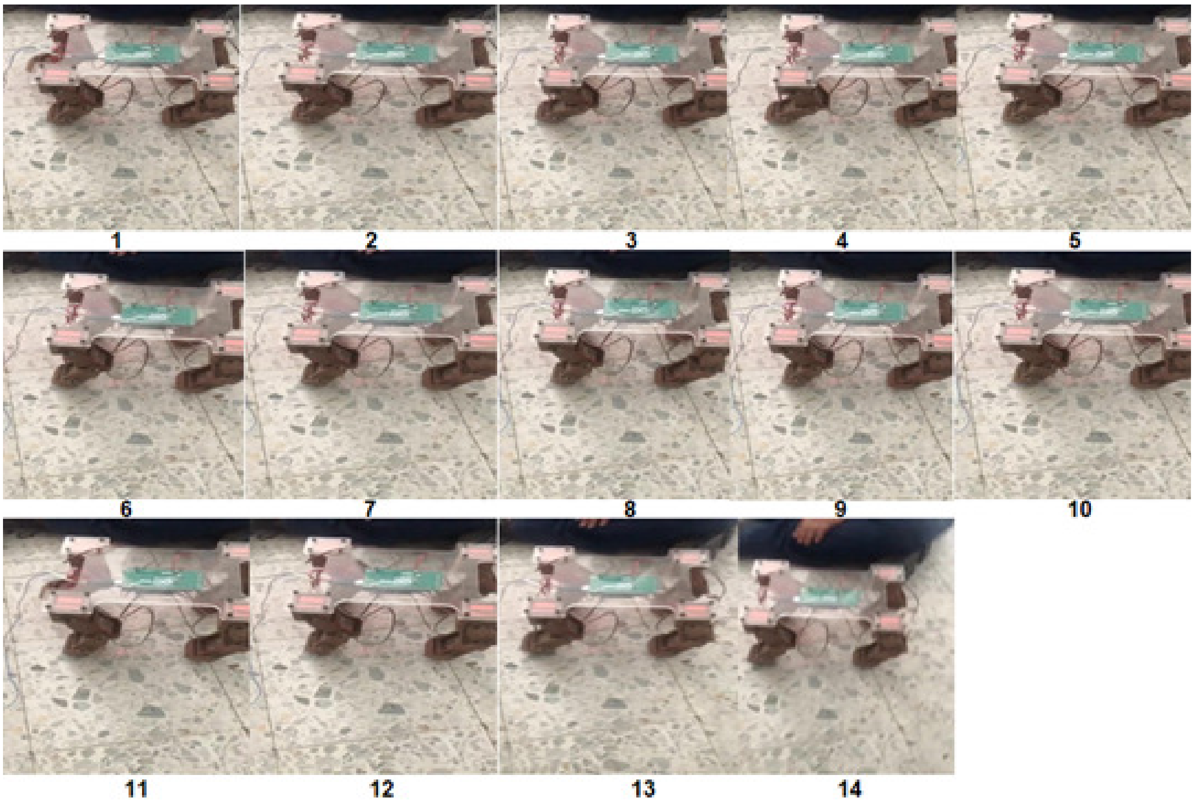

Fig. 21. Locomotion Sequence Walking.

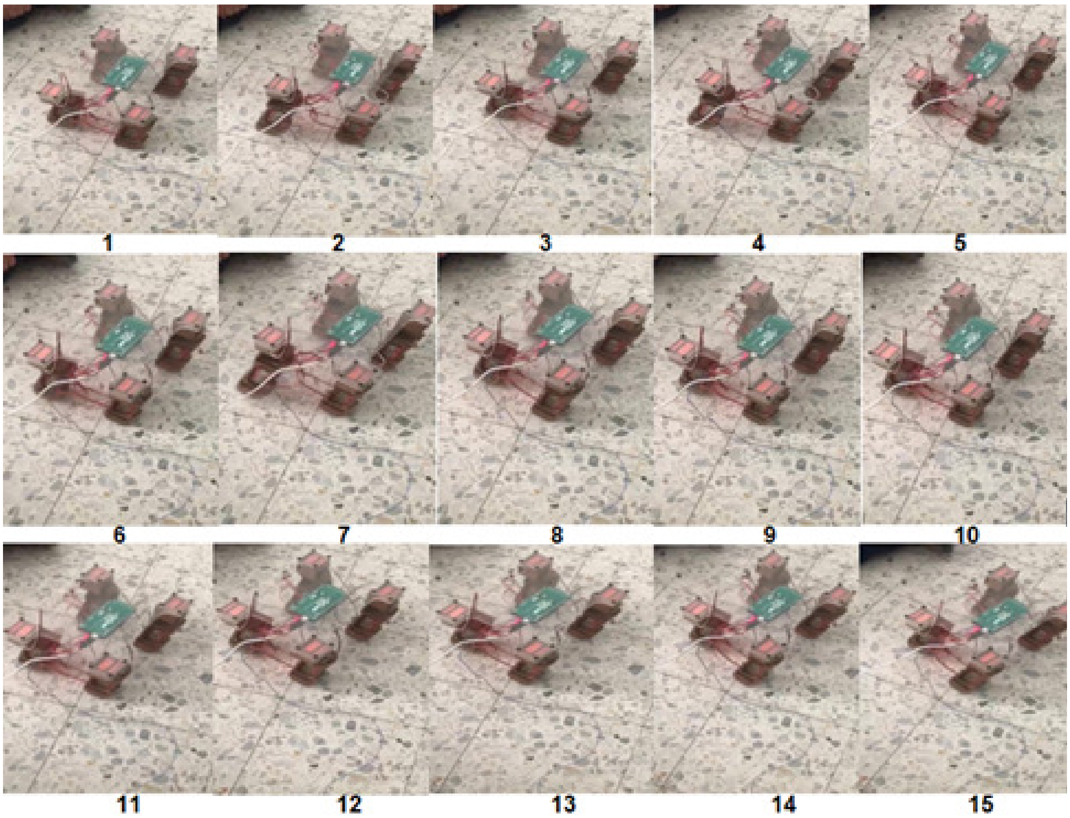

Fig. 22. Locomotion Sequence Walking - Trotting Transition.

execution of the expected locomotion types was guaranteed and the extent of its displacement reduced by 50 percent due to the low friction between the surfaces of the floor contact and the robot legs. In terms of stability, an accelerometer was used to detect the spatial position of the robot evaluating and monitoring the inclination of the robot to determine the

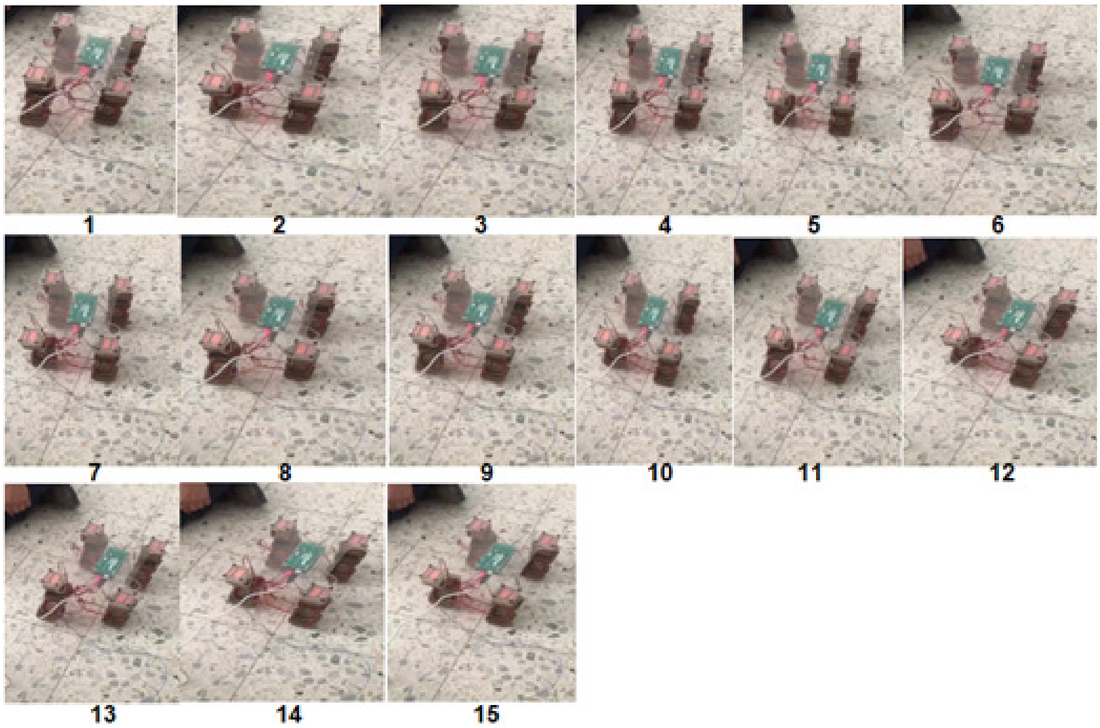

Fig. 23. Locomotion Sequence Trotting.

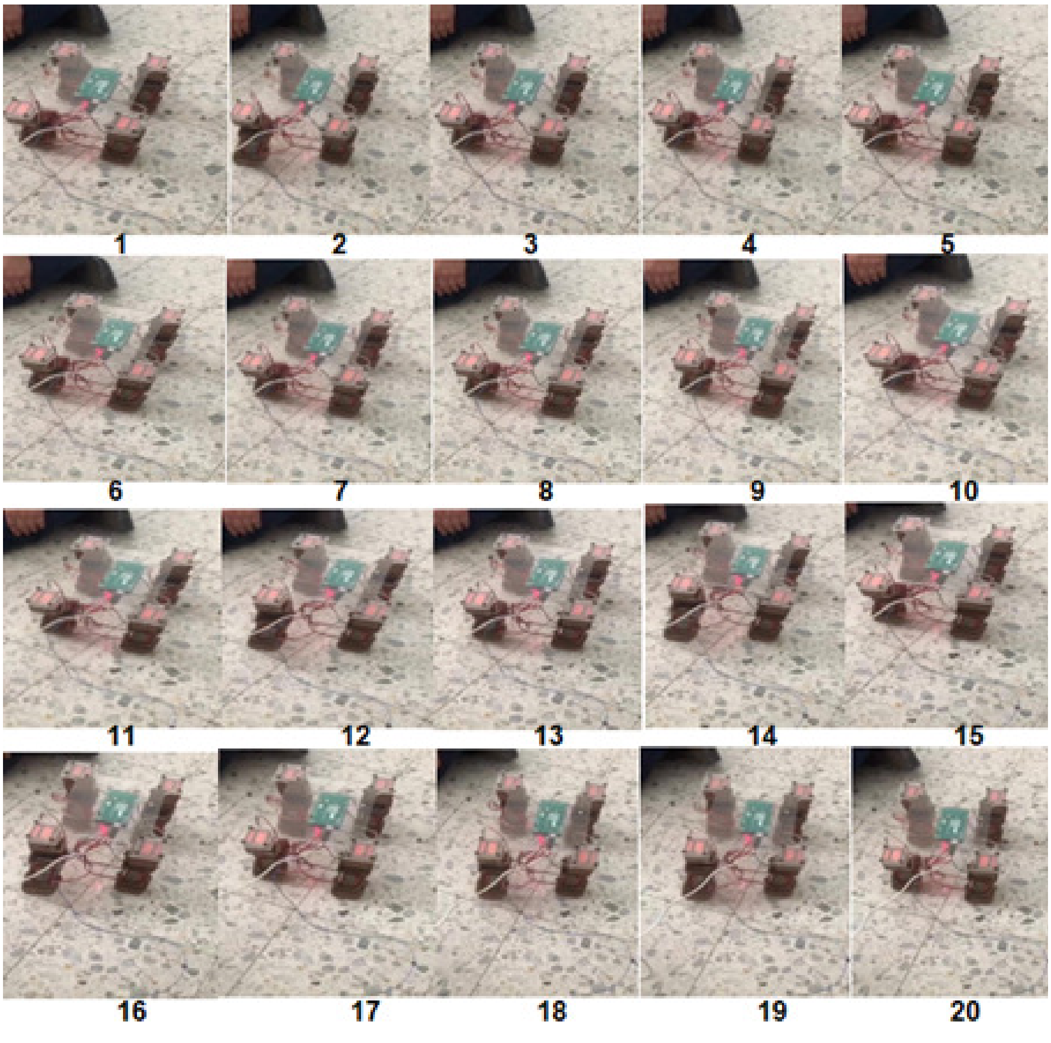

Fig. 24. Locomotion Sequence Trotting - Walking Transition.

imminence of overturning (see Table VI), which did not happen at any time since the changes in the X - Y axes were minimum as they did not exceed 10 percent of the maximum acceleration value (1023). Therefore, it performs the same stability analysis exercise according to [28] and [30] presenting a similar behavior to that in the simulation.

TABLE VII
ROBOT BEHAVIOR.

Advance(cm)	Stability	Freq(Hz)	Locomotion	Type
0.1	MSS→0	1	Walk	Simulation
0.05	MSS→0	1.1	Walk	Emulation
0.15	MSD→0.5	4	W→T	Simulation
0.05	MSD→1	4.1	W→T	Emulation
0.2	MSD→0.8	4	Trot	Simulation
0.1	MSD→1	4.25	Trot	Emulation
0.15	MSS→0	2	T→W	Simulation
0.05	MSS→0	2.2	T→W	Emulation

VI. CONCLUSION

A quadruped robot with three joints per leg, name R4A3, was developed for the locomotion of walking and trotting and the transition between them. The implemented stability measurements on the robot allowed to guarantee, at all times, static and dynamic equilibrium in the displacement, both in the simulation and emulation transitions of the robot without any type of rollover threat. This is observed when checking the stability margin (MS) of the robot between zero and one, which is interpreted as the ZMP or CoG located inside the stability polygon.

A distributed and autonomous control strategy, operating through three levels of control, was proposed to coordinate the movements of each leg of the R4A3 and the whole displacement of the robot. Recurring Neural Networks were used to represent the CPG. For that, a novel Nonlinear First Order Differential Equation System was developed to simulate the CPG as oscillators.

The two first levels of the control strategy are dedicated to the execution of the locomotion for each leg and the handling of all the legs, respectively. The third level is intended on planning and learning of the new movements required before new challenges. The whole control strategy is very successful during the transition between two types of locomotion, using a diffuse CPG that allows to give an approximate and fast solution avoiding a possible overturn due to loss of balance of the robot.

The literature found in the last 5 years has reported the evolution in the research process of the scientific community in locomotion of quadruped robots and especially on the transition in locomotion. However, the review showed that the published information is scarce in the specific characteristics of the developed robotic system (number of joints, type of controller, size of the controller, computational cost) in this project.

Usually, the communication between recurrent neural networks from a robot is complex. However, in this project, it is versatile due to the connection and the operation protocol array between all the local CPG operating points (joints) and the global planning CPG constituting the control architecture proposal.

It is important to indicate that the proposed CPG algorithms are of low computational cost. Therefore, control devices (microcontrollers) do not require high performance characteristics, even basic 8-bit microcontrollers can be used with satisfactory results. The essential characteristic of the CPG strategy is of distributed control whose joint operation of the different controllers or processors is carried out in parallel, emulating the Pipeline processing architecture. The control strategy based on the theory of Central Pattern Generators (CPG) implemented through recurrent neural networks (RNN) for the development of trotting and walking locomotion of an articulated quadruped robot is cost suitable for hardware implementation.

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