Discrete Movement Control of a Bio-Inspired Multi-Legged Robot

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Discrete Movement Control of a Bio-Inspired Multi-Legged Robot

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Abstract— **Bio-inspired robots have been widely used in different scenarios and applications such as disaster environments, mining industry, environmental monitoring, among others. In this sense, the locomotion control is a paramount operation for efficient and safe navigation of bio-inspired robots. Several locomotion controllers have been proposed to address the referred problem. Most of the techniques in literature represent the locomotion control through continuous systems. However, for a well-known set of events, like the movement control adjustment in different conditions, a discrete event-based approach can result in accurate and robust locomotion control. In this paper, we propose a discrete-event representation for multi-legged robot movements through finite state machines, regarding three different locomotion gaits and rotating operations. We demonstrate with indoor real-world experiments that, the proposed discrete-event representation can successfully supports multi-legged locomotion in different gait movements.**

I. Introduction

Bio-inspiration allows the use of nature as a source of inspiration for developing new computational techniques. Besides this, it provides examples to solve numerous real-world problems, efficiently and elegantly [1].

Many relevant problems are addressed based on behaviors and mechanisms found in nature, such as: ants, birds or even the brain [2]. For example, the way ants cooperate to solve problems quickly [3]. The way birds fly in formation to optimize the aerodynamics flight [4]. The way the brain understands and learns patterns in different tasks [5].

In mobile robotics, many problems have been the focus of extensive research effort, such as localization, mapping, path planning and multi-robot cooperation. However, to solve the mentioned problems it is paramount to take into account the environment and robot properties [6].

For mobile robots, navigating in unstructured terrain is a challenging task, spatially using wheeled robots. The movement control techniques of wheeled robots are frequently based on kinematics control and its motion performance is directly affected by surface deformations. In this sense, as an alternative, bio-inspired legged robots can be applied for efficient navigation, since in nature, legged living beings can move safely in different types of terrain [7].

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Legged robots have been used in several scenarios and applications, including the use of multi-legged robots. The movement control of legged robots is directly related to natural behaviors and is commonly defined using learning methods and kinematics forces control [8]. Taking the mentioned context into account, in this paper we propose a discrete model, based on deterministic finite automates, to model the movement control of a multi-legged robot.

Our main contribution is to provide an efficient movement control of multi-legged robots through an exact and precise control, based on discrete events. Additionally, the proposed movement strategy presents a robust set of actions, allowing a safe robot motion regarding three different gait locomotion techniques.

The remainder of this paper is structured as follows. In Section II, we present a brief discussion on related works regarding movement control of multi-legged robots and correlated issues. An overview of the proposed methodology is presented in Section III. Real experiments are discussed in Section IV. Finally, in Section V we draw the conclusions and discuss paths for future investigation.

II. Related work

The movement control of mobile robots plays a fundamental role in their autonomous navigation and has been the subject of intensive investigation. Bio-inspired robots have been used in several scenarios and applications, presenting satifactory results [8][9][2].

Different types of bio-inspired robots can be found in literature. Some robotic platforms mimic animal shapes and behaviours, like snakes [5], fish [2], dogs [8] and insects [10]. A special category of bio-inspired robots regards multi-legged platforms, taking into account biped [11], quadruped [8] and hexapod [1] robots.

To extract and represent the environment around the bio-inspired robots, several sensors are used like force sensor [12], tactile sensor [13] and RGBD sensor [7]. Many challenges are related to sensing strategies and multi-legged robots like terrain classification [13], traversability mapping [14] and posture adaptation [7]. However, much effort has been invested in the locomotion problem and how to optimize this process [15], [10].

E. Ambrose et al. [15] proposed a study to assess the impact of different configurations for a biped locomotion. The authors used three different configurations, with Flat-Foot, Point-Foot and Spring-Foot. In experiments, the walking task with all three configurations was performed, using the same control methods and experimental procedures. The results demonstrate better energy performance, for point-foot configuration in different walking speeds. In walking task was used the Hybrid Control System method, for locomotion control.

M. Thor and P. Manoonpong [10] presented an online learning mechanism that can automatically generate a proper walking frequency for energy-efficient hexapod locomotion. The authors modulate the Central Pattern Generation (CPG) frequency through a neural CPG network, it ensures that the CPG frequency matches the robot performance, thereby utilizing its full potential. In experiments, from different parameters the locomotion frequency is adapted, improving the locomotion performance. The authors investigate the relationship between distributed learning and decentralized control policies, for the locomotion of articulated robots in challenging environments. To this end, individual agents are defined to independently control portions of the robot's body. A shape-based movement control is used for locomotion task. Experiments were carried out in unstructured environments, using a snake and a hexapod robot. The results show that the proposed approach can be adapted to many different types of articulated robots by controlling some of their independent parts in a distributed manner, and the decentralized policy can be trained with high sample efficiency.

B. Tam et al. [9] proposed a robot controller capable of generating gaits and poses for multi-legged robots, both simulated and with real hardware implementations. For movement control was used a kinematic model, regarding the Denavit-Hartenberg (DH) parameters. In experiments, were evaluated the energetic performance of several legs, kinematic arrangements and different locomotion speeds. The results show that the mammalian configuration offers lower power consumption across a range of step frequencies; with the insectoid configuration providing performance advantages at higher body velocities and increased stability at low step frequencies.

X. A. Wu et al. [13] proposed an approach to adapt the hexapod robot gait based on the terrain classification of outdoor environments. For the terrain classification was used a tactile sensor to extract the ground features and the Support Vector Machine (SVM) as supervised classification model. To define the gait to be used for each terrain category, was proposed a Finite State Machine (FSM). In the FSM, from the classified terrain and the set of states and transitions, the adequate gait was applied in locomotion process. In experiments were evaluated the robot speed and the cost of transport, regarding a fast walk-gait and the proposed adaptive walk-gait. The results show that the proposed adaptive gait approach, with FSM, achieved better running performance.

G. C. Kang and Y. Lee [16] presented a Deep Reinforcement Learning (DRL) method for learning a Finite State Machine (FSM) based policy in a motion-free manner (without the use of any motion data). The FSM controls a simulated character to produce a gait as specified by the desired gait parameters. To this end, the FSM represents a set of states and actions needed to achieve the desired locomotion steps. The results show that the learning process achieved accurate movement estimations, resulting in an efficient locomotion process.

The locomotion problem for bio-inspired robots is a challenging task. Several approaches have been proposed to tackle the referred task efficiently. However, for multi-legged robots, especially hexapods, the learning process can lead to unstable and impracticable movements. On the other hand, FSM-based approaches can efficiently represent a set of states and actions, allowing an accurate control movement of multi-legged robots.

In some approaches mentioned before, learning techniques are used to learn an FSM to define the movement control of multi-legged robots, resulting in unrealistic and awkward gaits. In contrast to the aforementioned works, we use a discrete event system to overcome the referred problems, achieving robust movements.

III. Methodology

A. Theoretical formalization

The problem we tackled can be summarized as follows: given a hexapod robot with 18 degrees of freedom. Our main goal is to model the leg movements of a hexapod through discrete events for 3 different gait movements: $i)$ tripod; $ii)$ wave; and $iii)$ ripple.

B. Bio-inspired Discrete Event System

Bio-inspired robots have been frequently used in different applications since its provide appropriate skills for specific activities and interacting with real-world environments. Real-world applications commonly are depicted as: $i)$ Continuous systems (CS), in which the system state is changed continuously over time; or $ii)$ Discrete-event systems (DES), in which the system state is changed every time an event occurs, in irregular and unknown time [17].

In this paper, we propose a discrete-event representation for multi-legged robot movements through finite state machines. To this end, we have defined a set of discrete events, corresponding to the multi-legged movements, regarding three different locomotion gaits and rotating operations. In Table I, is presented the main events for a multi-legged robot locomotion.

TABLE I: Discrete events for a multi-legged robot locomotion.

Event	Event description
e	Centering Legs
o	Turn off robot actuators
t	Tripod gait
w	Wave gait
r	Ripple gait
s_l	Spin left
s_r	Spin right

C. FSM-based Control

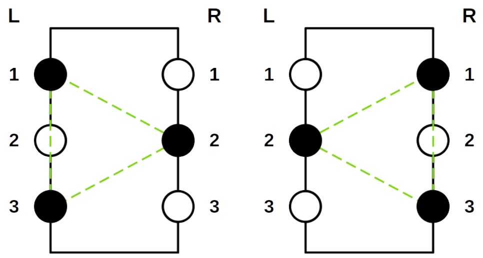
Discrete-event based approaches for robot locomotion improve the performance in terms of reaction, adaptability, flexibility and robustness, resulting in complex controls and stable movements [16]. In this paper we propose a finite state machine-based approach. The proposed FSM is defined by the sextuple bellow:

$$FSM = \{\Sigma, \Gamma, S, s_0, \delta, \omega\}, \tag{1}$$

where, Σ corresponds to the set of events or alphabet. Γ corresponds to the output alphabet. S is a finite non-empty set of states. s_0 is the initial state, an element of S. δ is the state-transition function: $\delta : S \times \Sigma \rightarrow S$. ω is the output function, i.e. it is the set of all events that can occur in a given state.

For each tackled locomotion gait we define the respective behavior and the proposed FSM.

1) Tripod gait: In Tripod gait, the legs move three to three and can move at higher speeds. For each tripod, the legs are raised, moved back and forth together, and lowered. Since three legs are always in contact with the ground at all times, this type of gait is statically and dynamically stable. Figure 1 shows the leg's behavior in tripod gait. In Figure 1 the black circles represent the raised legs and the white circles represent the lowered legs.



(a) Left movement (b) Right movement

Fig. 1: Tripod gait behavior. In Figs. 1a and 1b the three black circles are raised, moved forward and lowered, meanwhile the white circles are on the ground.

From the presented behavior for tripod gait, we have defined the parameters below to represent the robot locomotion through the proposed finite state machine in Figure 2.

$S = \{q_0, q_1, q_2\}$;
$\Sigma = \{e, t, o\}$;
$s_0 = \{q_0\}$;
$\Gamma = \{q_0\}$;
$\delta(q_0, e) = q_1$, $\delta(q_1, o) = q_0$, $\delta(q_1, t) = q_2$, $\delta(q_2, e) = q_1$, $\delta(q_2, t) = q_2$;
$\omega(q_0) = \{e\}$, $\omega(q_1) = \{o, t\}$, $\omega(q_2) = \{e, t\}$.

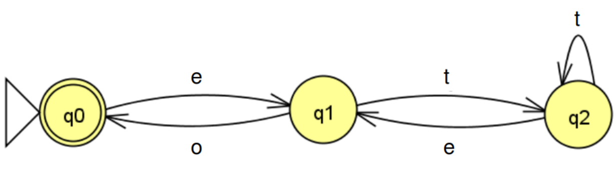
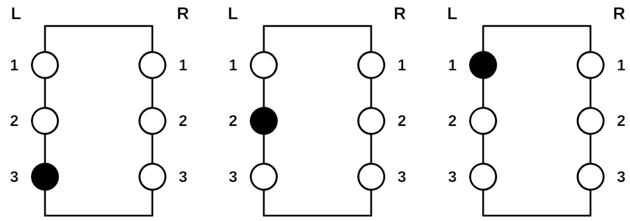


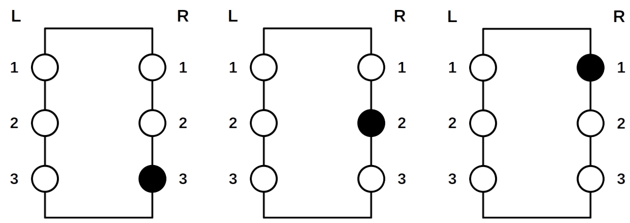
Fig. 2: Proposed FSM-based movement control for tripod gait. In this FSM, the legs are centered and after the tripod gait is run.

2) Wave gait: In Wave gait, only one leg leaves ground contact at a given time. All the legs on one side move forward, starting with the rear leg and following the leg's sequence, presented in Figure 3. Since only one leg is raised at a time, with the other five legs on the ground, the robot is always in a highly stable posture.

One disadvantage of the wave gait is that this gait can not be accelerated too much. In higher acceleration, the suspension phases will be shorter, and the leg movements will overlap, leading the structure to a partial collapse. In Figure 3, the black circles represent the raised legs and the white circles represent the lowered legs.



(a) Step 1 (b) Step 2 (c) Step 3



(d) Step 4 (e) Step 5 (f) Step 6

Fig. 3: Wave gait behavior. Figs. 3a-3f represent every leg movement in wave gait. For each step, the black circle is raised, moved forward and lowered, while the white circles are on the ground.

From the presented behavior for wave gait, we have defined the parameters below to represent the robot locomotion through the proposed finite state machine in Figure 4.

$S = \{q_0, q_1, q_2\}$;
$\Sigma = \{e, w, o\}$;
$s_0 = \{q_0\}$;
$\Gamma = \{q_0\}$;
$\delta(q_0, e) = q_1$, $\delta(q_1, o) = q_0$, $\delta(q_1, w) = q_2$, $\delta(q_2, e) = q_1$, $\delta(q_2, w) = q_2$;
$\omega(q_0) = \{e\}$, $\omega(q_1) = \{o, w\}$, $\omega(q_2) = \{e, w\}$.

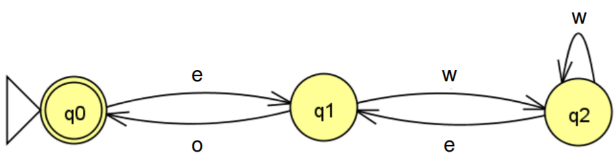
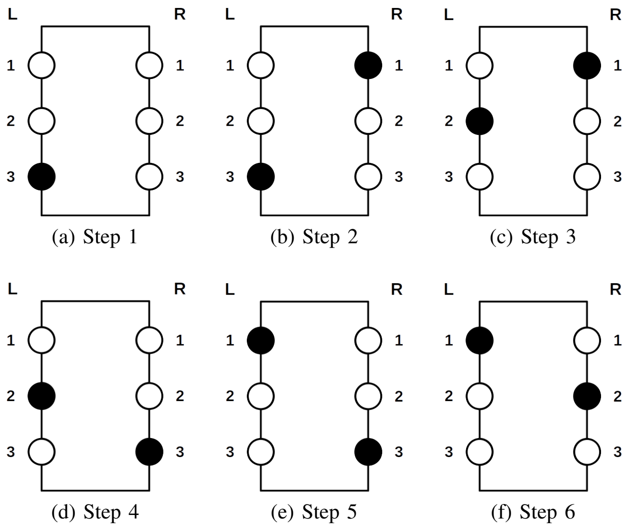


Fig. 4: Proposed FSM-based movement control for wave gait. In this FSM, the legs are centered and after the wave gait is run.

3) Ripple gait: In Ripple gait on each robot side, a local wave comprising non-overlapping elevation phases is performed and the two opposite side waves are precisely 180 degrees out of phase with each other. Figure 5 shows the leg's behavior in ripple gait. In Figure 5, the black circles represent the raised legs and the white circles represent the lowered legs.



(a) Step 1 (b) Step 2 (c) Step 3

(d) Step 4 (e) Step 5 (f) Step 6

Fig. 5: Ripple gait behavior. Figs. 5a-5f represent every leg movement in ripple gait. For each step, the black circle is raised, moved forward and lowered, while the white circles are on the ground.

From the presented behavior for ripple gait, we have defined the parameters below to represent the robot locomotion through the proposed finite state machine in Figure 6.

$S = \{q_0, q_1, q_2\}$;
$\Sigma = \{e, r, o\}$;
$s_0 = \{q_0\}$;
$\Gamma = \{q_0\}$;
$\delta(q_0, e) = q_1$, $\delta(q_1, o) = q_0$, $\delta(q_1, r) = q_2$, $\delta(q_2, e) = q_1$, $\delta(q_2, r) = q_2$;
$\omega(q_0) = \{e\}$, $\omega(q_1) = \{o, r\}$, $\omega(q_2) = \{e, r\}$.

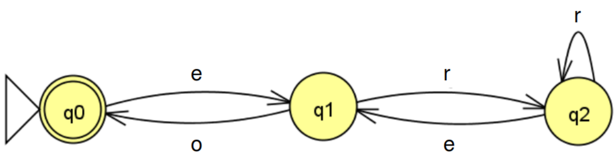
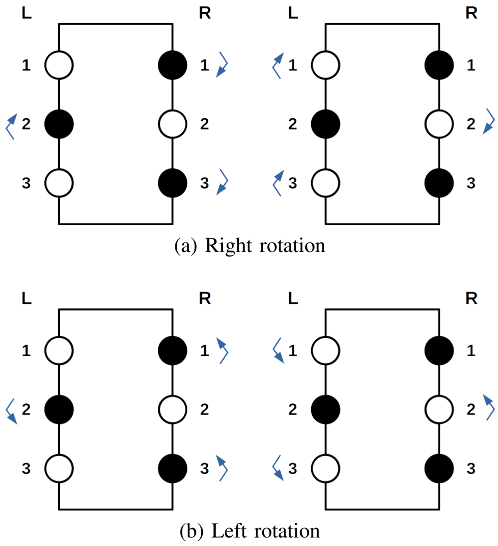


Fig. 6: Proposed FSM-based movement control for ripple gait. In this FSM, the legs are centered and after the ripple gait is run.

4) Robot spin (Right and Left): The robot rotating movements are based on the locomotion of an insect and applies the tripod gait movement. In this movement, three legs are suspended in a triangular shape and the other three legs support the robot. The rotating movement is completed in two cycles: $i)$ First, the two legs, on the right side, are suspended and perform the backward movement. The suspended leg, on the left side, performs the opposite movement; and $ii)$ Finally, the two lowered legs, on the left side, perform the forward movement and the lowered leg, on the right side, performs the opposite movement, thus rotating the robot's body to the right side. The same procedure occurs for the left side rotation, but with mirrored behavior. Figure 7 shows the leg's behavior in robot spin, for right and left side, respectively. In Figure 7, the black circles represent the raised legs and the white circles represent the lowered legs.



(a) Right rotation

(b) Left rotation

Fig. 7: Robot spin movements. Figs. 7a and 7b represent the right and left rotation movements, respectively.

From the presented behaviors for robot rotation, we have defined the parameters below to represent the robot right rotation through the proposed FSM in Figure 8.

$S = \{q_0, q_1, q_2\}$;
$\Sigma = \{e, s_r, o\}$;
$s_0 = \{q_0\}$;
$\Gamma = \{q_0\}$;
$\delta(q_0, e) = q_1$, $\delta(q_1, o) = q_0$, $\delta(q_1, s_r) = q_2$, $\delta(q_2, e) = q_1$, $\delta(q_2, s_r) = q_2$;
$\omega(q_0) = \{e\}$, $\omega(q_1) = \{o, s_r\}$, $\omega(q_2) = \{e, s_r\}$.

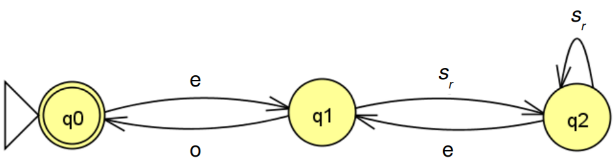


Fig. 8: Proposed FSM-based movement control for right rotation movement.

From the presented behaviors for robot rotation, we have defined the parameters below to represent the robot left rotation through the proposed FSM in Figure 9.

$S = \{q_0, q_1, q_2\}$;
$\Sigma = \{e, s_l, o\}$;
$s_0 = \{q_0\}$;
$\Gamma = \{q_0\}$;
$\delta(q_0, e) = q_1$, $\delta(q_1, o) = q_0$, $\delta(q_1, s_l) = q_2$, $\delta(q_2, e) = q_1$, $\delta(q_2, s_l) = q_2$;
$\omega(q_0) = \{e\}$, $\omega(q_1) = \{o, s_l\}$, $\omega(q_2) = \{e, s_l\}$.

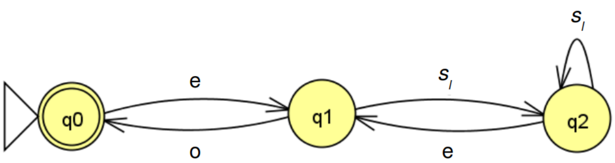


Fig. 9: Proposed FSM-based movement control for left rotation movement.

IV. Experiments

Experiments were carried out using a bio-inspired robotic platform with 6 legs, that is a hexapod, in indoor scenarios. The robot was equipped with a Wifi ESP8266 NodeMCU, a Servo Driver 18 Channels PCA9685 and 18 Micro Servo Motors 9g MG90S, resulting in a robot with 18 degrees of freedom. Additionally, experiments were run using a laptop with Intel® Core^{TM} i7-5500U CPU and 8 GB of memory (Fig. 10).

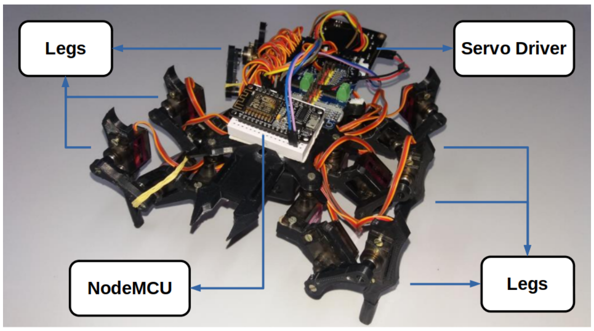


Fig. 10: Bio-inspired robotic platform used in the experiments.

A. Multi-gait discrete event control

As first result obtained is presented the multi-gait FSM-based locomotion control, combining the individual proposed movement controls. The parameters below represent the robot locomotion through the proposed finite state machine for 3 different gaits and 2 rotation movements, as we can see in Figure 11.

$S = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6\}$;
$\Sigma = \{e, t, w, r, s_r, s_l, o\}$;
$s_0 = \{q_0\}$;
$\Gamma = \{q_0\}$;
$\delta(q_0, e) = q_1$, $\delta(q_1, o) = q_0$, $\delta(q_1, t) = q_2$, $\delta(q_2, e) = q_1$, $\delta(q_2, t) = q_2$, $\delta(q_1, w) = q_3$, $\delta(q_3, e) = q_1$, $\delta(q_3, w) = q_3$, $\delta(q_1, r) = q_4$, $\delta(q_4, e) = q_1$, $\delta(q_4, r) = q_4$, $\delta(q_1, s_l) = q_5$, $\delta(q_5, e) = q_1$, $\delta(q_5, s_l) = q_5$, $\delta(q_1, s_r) = q_6$, $\delta(q_6, e) = q_1$, $\delta(q_6, s_r) = q_6$;
$\omega(q_0) = \{e\}$, $\omega(q_1) = \{o, t, w, r, s_l, s_r\}$, $\omega(q_2) = \{e, t\}$, $\omega(q_3) = \{e, w\}$, $\omega(q_4) = \{e, r\}$, $\omega(q_5) = \{e, s_l\}$, $\omega(q_6) = \{e, s_r\}$.

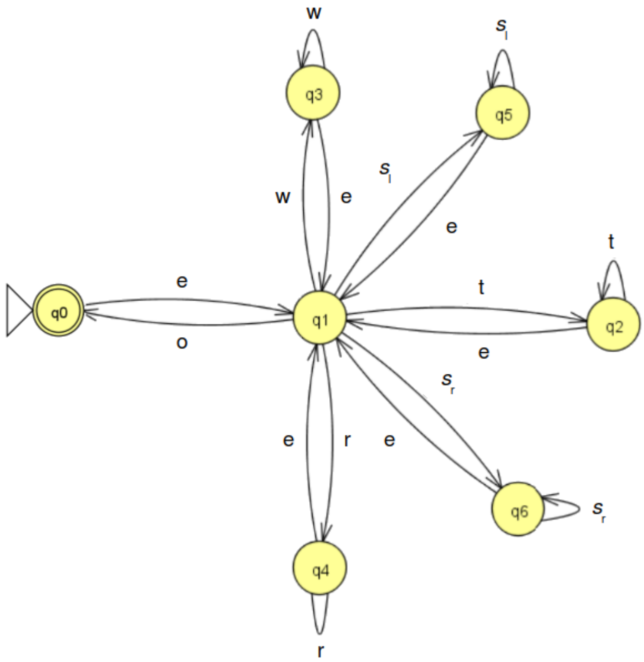


Fig. 11: Multi-gait control for multi-legged robots through discrete-events representation.

From the multi-gait control we also highlight, as complementary result, the developed robotic system to multi-legged control, as can be seen in Figure 12. In the presented interface, sets of operations can be added, run and paused. Additionally, motion parameters can be adjusted, like angle range for each servo motor and delay for movement execution.

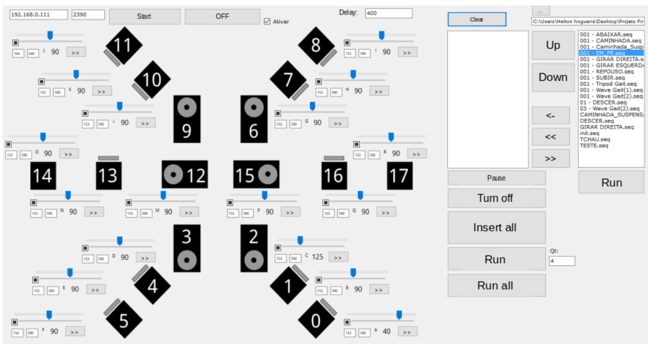


Fig. 12: Multi-legged robot system for locomotion control.

B. FSM-based control validation

In this section we validate our FSM-based control for multi-legged robots. To this end, the robot must come out of the rest state, stabilize the legs and perform a total of

10 complete gait cycles. At the end of the running stage, the robot must stabilize the legs again and return to the rest position.

The mentioned evaluation was applied to tripod, wave and ripple movement gaits and after the assessment we observed that the finite state machine reached the expected behaviors for all gaits and cycles. In this experiment we show the effectiveness of the proposed discrete-event representation for multi-legged robot movements through finite state machines, which suggests a satisfactory performance in real-applications.

C. Gait movement speed assessment

In this section we present the obtained results regarding the use of different movement gaits in multi-legged robots locomotion, and its speed relation. We performed experiments with the 3 different gaits: tripod, wave and ripple. In this experiment we compare the navigation times, for a given number of cycles, taking into account the three gaits mentioned above. For this, we compare the average times for each gait, for 10 complete cycles.

The average times are presented in Table II, using different gaits, regarding the same environment and moved distance. Table II shows that tripod gait navigates faster than other locomotion gaits. However, we observed in this experiment that although tripod gait is the fastest, it is not the most stable movement gait, through this experiment. The wave gait showed higher stability during locomotion. Thereby, it is possible to define the proper locomotion gait depending on the stability needed.

TABLE II: Time analysis regarding different gaits locomotion.

	Tripod gait	**Wave gait**	**Ripple gait**
Average time (s)	14.37	33.53	31.60

V. Conclusion and future work

Mobile robots well adapted to locomotion in structured and unstructured environments have been standing out with the improvement of service and intervention modeling. In this sense, many proposals of control architectures for mobile robots have emerged, providing them autonomy and the ability to plan tasks and reactions to events.

In this paper, we address the motion control problem of a bio-inspired multi-legged robot through a discrete event-based approach. In the experiments, we showed that the proposed approach based on discrete event representation using finite state machines is able for real-world applications, regarding indoor scenarios. Furthermore, it was showed that the FSM-based control can be successfully used to simultaneously represent different gait movements. Finally, the experiments also show the relationship between the gait movement and stability behavior.

As future work, we intend to investigate and propose strategies to classify different levels of terrain roughness, using multi-legged robots. Additionally, we intend to investigate and propose approaches to adjust the locomotion gait according to the terrain features and stability needed.

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