Embedded System for Quadruped Robot in Mammalian Configuration

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***Abstract*—The robots with legs have a better performance than the terrestrial mobile robots for some applications, the development of quadruped robots has increased in the last years mainly with the mammalian configuration due to the velocity of displacement and for the implementation of new control strategies that improve its stability. However, it is necessary to integrate embedded systems into the quadruped robot design to increase the overall performance. The proposal research presents the development of an integrated system composed of a quadruped robot in mammalian configuration and an embedded system with a concurrent methodology that ensures harmonic integration. The system was tested under real environments, on flat, sandy, and rocky terrains. The experimental results were analyzed with Kinovea software, obtaining a maximum velocity in the flat terrain with 0.43m/s, 0.2m/s in sandy terrain, and 0.345 m/s in rocky. Finally, an embedded system is a factor key to improving the quadruped robot's performance because it allows for modification of the behavior through the implementation of unconventional control strategies, to make the robot smaller, and it is possible to integrate tools of IoT that are necessary for the new applications.**

***Index Terms*—Embedded systems, mammalian configuration, quadruped robot, walking trajectory**

I. INTRODUCTION

The design of robots with limbs has had accelerated growth in recent years due to the advantages they offer in comparison with other configurations such as wheeled robots or caterpillar mechanisms [1], including a better ability to avoid obstacles, better performance on irregular terrains, and improvement of efficiency and mobility, among others. Quadruped robots are the most prominent among robots with limbs, they are divided into two configurations [2]: mammalian and extended. The extended configuration has better stability and reduces implementation complexity due to it performing a static walk. However, mammal-type robots have become popular due to their speed of advancement and the implementation of new control proposals, increasing robustness and walking capacity on irregular terrains. Additionally, quadruped robots in a mammalian configuration are characterized by having their legs stretched vertically. Examples are the Boston Dynamics "Spot" robot [3] and the MIT Cheetah robot [4]. Quadruped robots require more complex systems, that collaborate harmoniously to obtain adequate walking results. In [5] a robot is presented that proposes the implementation of an embedded system, a behavior planner, motion control strategies, and a structural system composed of four limbs with DC motors. Another proposal is presented in [6], where three servomotors per limb are used in an open loop, it includes orientation modules based on an Inertial Measurement Unit (IMU) located at the center of the robot's body, a planner, and control and interface devices. Therefore, quadruped robots require an embedded system that allows combining hardware and software to improve the robot's performance. In other words, the embedded system must be integrated into the robot to enhance the control actions, internal communication with peripherals, and data management. The design and integration of a system embedded in a quadruped robot in mammalian configuration is proposed, conformed by the Central Processing Unit that performs the gait control action based on the generated trajectories and the IMU measurements, constructing the movement instructions based on the characteristics of the terrain, which are communicated to the limbs of the robot from the Bus Interface Controller. Additionally, experimental tests of the integrated robot were carried out on three different terrains (flat, sandy, and rocky), obtaining adequate results according to the forward speeds and stability. Finally, the proposal opens the way for new research to improve the performance of quadruped robots based on embedded systems, integrating new technology, trajectory control strategies, and energy management strategies, among others. The work is organized as follows. In Section II, the methodology used for the development of the integrated system is described. Section III describes the system definition, including the quadruped robot, the embedded system and the system integration. The system is tested under real conditions, the experimental results are presented in Section IV. Finally, Section V concludes the proposal.

II. METHODOLOGY

Embedded systems must integrate with host systems to best perform functions for specific tasks harmoniously. In particular, the embedded system must increase the performance of the quadruped robot in a diverse sense, such as enhancing gait, forward speed, information processing, and communication between devices efficiently, among others. To solve this challenge, the methodology defined in [7], called the V-model, is used throughout the development process. The methodology seeks to integrate and combine different disciplines, such as mechanics, electronics, control theory, and computer science to improve the overall performance of the systems. In addition, it allows the development of more complex systems from an innovative approach, and the constant validation and verification process ensures compliance with the functionality and performance of the integrated systems. The V-model is grouped into three sequential and two simultaneous stages, the specific description can be found in [7].

III. SYSTEM DEFINITION

Fig. 1 shows the proposed architecture of the embedded system, where the quadruped robot is the host system of the embedded system. Both are described below.

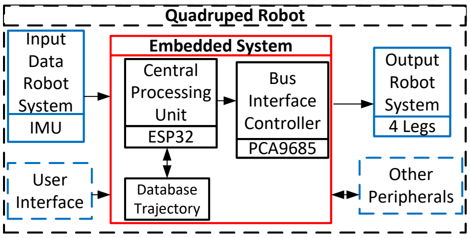


Fig. 1: Embedded system architecture for quadruped robot.

A. Quadruped Robot

According to Fig. 1, the quadruped robot is integrated into four systems. The Input Data Robot System has the orientation feedback function through an single IMU device model MPU6050 that is located in the center of the cuadruped body, which provides the angles concerning the turns yaw $+x$ $(\quad)$ and pitch $+y$ (θ), the data provided will allow the robot's orientation to be corrected, additionally, this component comes with libraries that facilitate its application, and for measurement of the angle, a ”complementary filter” was used [8]. The User interface allows the user to interact with the robot, a mobile application was developed with the MIT App Inventor program which allows defining parameters such as trajectory, type of terrain, and speeds, among others. Subsequently, the instructions are transmitted via Bluetooth communication to the Embedded System. The Output Robot System is made up of four limbs, each one has two model 2000 Dual Mode servomotors, with a maximum torque of 1.06Nm and a voltage range of 4.8V to 7.4V, with maximum no-load speeds of 145RPM. Each limb has a four-bar mechanism to transmit movement during walking. On the other hand, more devices can be incorporated into the integrated system for performance improvement through the peripherals and the communication protocols of the embedded system.

B. Embedded System

The embedded system performs the functions of receiving input signals, processing information, adjusting trajectories for walking, calculating inverse kinematics, establishing communication between the various devices, and transmitting the movement sequence to the robot limbs.

1) **Database trajectory generation**: To generate the walk, a reference trajectory is necessary, which is the pattern that the limbs must follow and the synchronization sequence of all the limbs. Once the reference trajectory is defined, it is assigned to one of the extremities, and a percentage of the difference between each extremity is defined considering the stability in walking. The main limb constructs the sequence: the front left leg, a phase shift of 50% is assigned concerning the rear left limb. On the other hand, the same trajectories are used for the right side, the trajectory of the front right limb will be the same as those of the rear left leg, considering the gap between all of them for the gait to be carried out. The trajectories were simulated in Matlab® R2023a Academic version where the values presented in [9] were assigned, modifications were made to contract or expand the trajectory, obtaining a data matrix with the reference trajectory for each limb.
2) **Central Processing Unit**: This device interprets the angular values measured by the robot's IMU to correct the trajectories and receives instructions from the user via Bluetooth connection. Additionally, the Central Processing Unit (CPU) performs inverse kinematics calculations based on the following expressions:

$$q_3 = atan2(\quad \sqrt{1 \quad D_1^2}, D_1) \tag{1}$$

$$q_2 = atan2(S, r_2) \quad atan2(L_4 \quad \mathrm{S}_3, L_3 + L_4 \quad \mathrm{C}_3) \tag{2}$$

$$Z_c = Z_e \quad \frac{L_a \quad \sin\theta}{2} \tag{3}$$

where q_i for $i = 1,2$ are the articular joints of the arm and forearm, respectively. L_2, L_3, L_4 are longitudes of the leg, S is Z_c, D_1 is $\cos q_3$, Z_e is the initial height of the robot before of orientation change, θ is the angle of yaw or pitch orientation, L_a is the width or length of the robot in function of the type of turn roll or pitch respectively, and C_3 and S_3 are $\cos q_3$ and $\sin q_3$, respectively (see Fig. 5.d). For more detail, the complete development of inverse kinematics is presented in [9]. The equation (3) represents the inverse kinematics of body orientation, which is obtained from [9]. For the analyses, the values of $L_1 = 0.0215$m and $L_2 = 0.0422$m for the shoulder, $L_3 = 0.13$m for the arm, $L_4 = 0.12$m for the forearm, $L_a = 0.099$m for yaw angle and $L_a = 0.26$m for pitch angle are considered. The trajectory at the end of the leg is defined by the pair (X_c, Y_c), which represents the point in space that the robot want to reach (see Fig. 3). Finally, an ESP32 DevKitC V4 board is selected as the CPU, it is based on an ESP32-D0WD core with a 32-bit Tensilica LX6 dual-core, 240MHz frequency with WiFi and Bluetooth communication, which facilitates the possibility of connecting new peripherals to the robot through the embedded system, also, the ESP32 serves as an RTOS that control the management of hardware resources and determines the order of task execution.

3) **Bus Interface Controller**: This device receives instructions from the CPU and transmits them to the robot's servomotors through a 16-channel PCA9685 board, sending the eight PWM signals via the I2C communication protocol.

C. System Integration

The integration process begins with the modifications of the hardware devices, which allows them to be physically communicated and assembled. Subsequently, software integration is carried out, where communication and behavior tests are carried out between the embedded system and the quadruped robot for walking validation. Fig. 2 shows the integrated system and its main components, including the quadruped robot and the embedded system. On the other hand, Fig. 4 shows the proposed behavior control strategy, it begins with the input of information given by the user, the measurements carried out by the IMU and the generated Database, and then the Processing for the adjustment and calculation of the angles of each extremity are implemented with the embedded system. The verification of the trajectories at the end of the legs was carried out with a simulation in Matlab® R2023a Academic version, where the trajectories are plotted (see Fig. 3). Also, a multi-body simulation is carried out to validate the walk-in conditions similar to real ones, the CoppeliaSim Edu software is used to evaluate its behavior, which allows simulating inverse kinematics, sensors, and trajectory planning. Finally, the first robot design included a battery 7.4V@10Ah. However, during testing the battery became an inconvenient because it needed to be recharged frequently. Therefore, we decided to supply power externally using wires, which distribute energy to the power stage and a LM2596 step-down regulator.

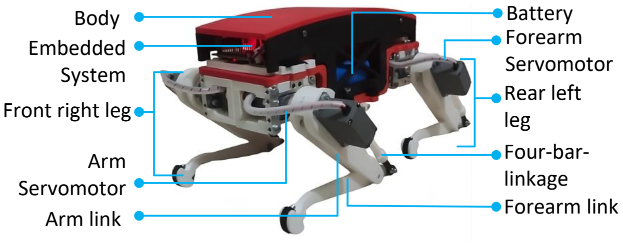


Fig. 2: Integrated system.

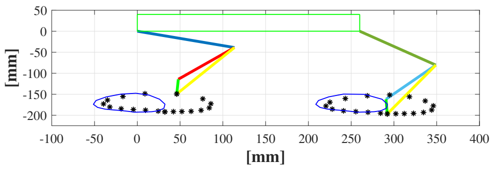


Fig. 3: Simulation of the walking of the quadruped robot in right lateral view, where the blue line represents the original trajectory and the black points the modified one.

IV. EXPERIMENTAL RESULTS

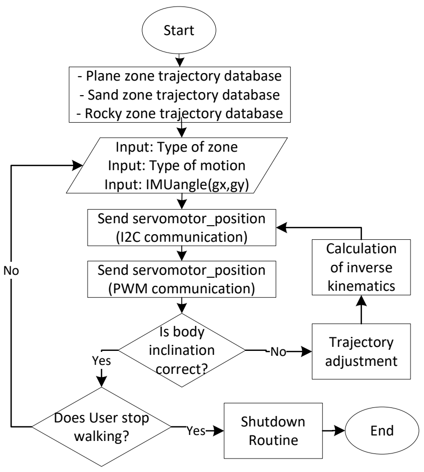
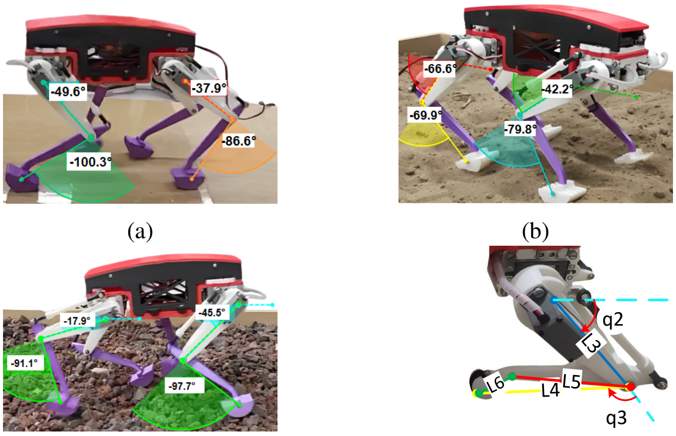


Fig. 4: Operation flow chart of the integrated system.

A. Experimental setup

The integrated system was tested under real operating conditions, three different terrains were defined: flat, sandy, and rocky. The distance was 1.5m for each type of terrain with a width of 1m. To verify the trajectory tracking controlled by the embedded system, videos of the experimental tests were made and analyzed using the Kinovea software to define the angles of the extremities, the real forward speeds, and the body inclination for each type of terrain.



(a) (b)

(c) (d)

Fig. 5: Analysis of gait in real on different terrains: a) flat, b) sandy, and c) rocky. d) Lateral view of the arm and forearm for inverse kinematics calculation.

B. Results

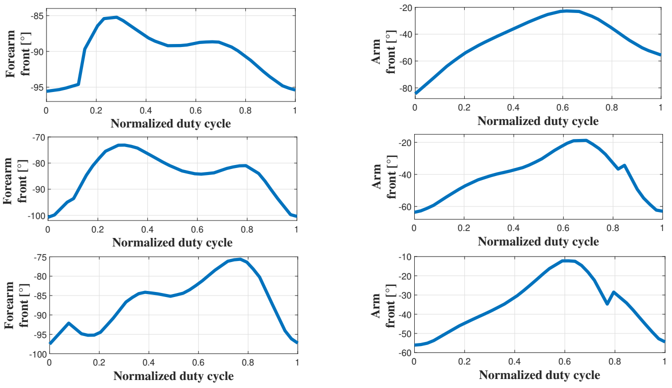
Fig. 5 shows the values obtained with the analysis in Kinovea software in different terrains for the arm and forearm of the right front limb. On flat terrain, it is observed that the change in angles is smoother because there are no irregularities in the terrain that the robot must correct while moving. On the other hand, it can be seen that the forearm on the rocky surface has to adjust the angles drastically due to the disturbance caused by the irregularity of the terrain, generating instability of the robot but compensated by the control strategy by the embedded system. In sandy terrain, the robot maintains intermediate intervals of the angles relative to the other two terrains due to the effect of sinking and getting stuck in the sand. Table I summarizes the results obtained from the movement analysis, showing the minimum and maximum values of the arm and forearm in each terrain and the average forward speed. It is observed that on flat terrain the arm reaches values of 84.4° and 100.5° for the forearm on sandy terrain. On the other hand, the maximum angle values for the arm are -12.2° in rocky terrain and 73.1° in sandy terrain. Fig. 6 shows the graphs of the angles obtained from the forearm of the right front limb during the operating cycle, where operating cycle is the range from the one position of the leg until the leg return at the same point. Finally, based on the results obtained, the average speed of the robot is determined, the highest is 0.43m/s on flat terrain and the lowest on sandy terrain with a value of 0.20m/s.

TABLE I: Summarized results of experimental tests.

Terrain	**Min. forearm angle [°]**	**Max. forearm angle [°]**	**Min. arm angle [°]**	**Max. arm angle [°]**	**Speed [m/s]**
Flat	-95.6	-85.2	-84.4	-22.7	0.43
Sandy	-100.5	-73.1	-63.6	-18.8	0.20
Rocky	-97.5	-75.6	-56.1	-12.2	0.345

V. CONCLUSIONS AND FUTURE WORK

In the present work, an integrated system of a mammal-type quadruped robot controlled by an embedded system is developed and implemented, which allows acquiring signals, communicating with the user, generating and correcting the tracking of the walking trajectory, and communicating with the robot actuators. Experimental tests were carried out in real operating conditions, on flat, sandy, and rocky terrain, the embedded system allowed the robot to modify its gait and adjust the parameters for the different terrains. Average forward speeds of 0.43 m/s on flat terrain, 0.345 m/s on rocky terrain, and 0.2 m/s on sandy terrain were achieved. Of the embedded system, it is important to highlight that the Central Processing Unit has a fundamental role in controlling the behavior of the integrated system, it requires adequate speed and processing capacity that allows testing various control strategies, having multiple communication protocols that facilitate integration with the host system, and consider the number of inputs-outputs so that the embedded system can expand. It can be concluded that the integration of the embedded system allows the orientation of the robot and the movement of the limbs to be regulated efficiently. In addition, the used methodology allows the harmonic integration of the quadruped robot and the embedded system. Finally, as future work, the embedded system allows for the incorporation of new peripherals for better environment recognition, and the implementation of unconventional control strategies for increasing the system intelligence through supervised or unsupervised learning. Also, the connectivity characteristics can be used to develop an IoT platform that monitors the system's behavior, generates instructions, and builds databases that increase the independence of the robot.



(a) (b)

Fig. 6: Graphs of the experimental results of front right leg in a) forearm and b) arm.

ACKNOWLEDGMENT

This research was partially supported by the Instituto Politécnico Nacional - Secretaría de Investigación y Posgrado under grants SIP-20240618 and SIP-20241103, and the Consejo Nacional de Humanidades, Ciencias y Tecnologías (Conahcyt) under grant Ciencia de Frontera 2023 (CF-2023-I-1635). In addition, the authors express special gratitude to Jonas S. Uriostegui-Reyna and Julio C. Ordaz-Dehesa for their contribution to the development and experimental tests of the quadruped robot.

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