Study of the locomotion of a hexapod using CoppeliaSim and ROS

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***Abstract*—Generating adaptive locomotion has seen a growing interest for the design of hexapods due to improving the autonomy of these robots, allowing them to execute tasks in more demanding environments. Data from the robot's surrounding must be acquired and processed to adjust the locomotion, and aid with the actuation of the six limbs. This paper aims at using force sensors placed on the feet of a hexapod to control the changes of the gait phase of each limb. These sensors also assist in the search of new footholds when no contact forces are established with the ground. The system is tested in a smooth irregular terrain with obstacles, steps, and ramps, using CoppeliaSim and ROS (Robot Operating System), to dynamically evaluate the behavior of the hexapod.**

Keywords—Hexapod, CoppeliaSim, ROS, Adaptive gait, Robotics

I. Introduction

Hexapods are mobile ground robots commonly designed for cargo transportation, surveillance, rescue, and exploration missions, due to their static stability [1]. To execute such tasks, these systems must autonomously navigate across unstructured environments, by adjusting the actuation of their six legs to the topology of the terrain and the detected obstacles. Amongst the state-of-the-art solutions for kinematic and dynamic-based controllers, a common approach is estimating the contact forces between the feet and the ground to determine when the transition between the swing and the stance phases should occur. For instance, [2] used data regarding the torque generated by each actuator of the legs to estimate the contact forces of the robot for this purpose, while [3] inferred when the transition between the phases of the gait should occur through the information gathered by force sensors placed on the feet. Likewise, the method proposed in [4] also considers the usage of force sensors, but added a foothold search algorithm which was activated when the sensors of the feet could not detect any contact force, which provides a higher adaptability to uneven terrains, in comparison to the other described methods.

During the design of a robot for complex environments, it is important to study the feasibility of its controller and verify the generated response to external disturbances, before testing it in real conditions. CoppeliaSim can be used to obtain an estimation of the dynamic interactions of a system and estimate the possible failures of the hexapod during navigation. This software allows the evaluation of not only the motion generated but also of the torque required by the actuators and of the interaction forces [5, 6]. Moreover, it also provides an insight into the controllers behavior. Despite that, few pieces of research studied the locomotion of hexapods in this software. [7] analyzed the procedure to simulate a hexapod walking across ramps and soft terrain in CoppeliaSim, but only discussed the translation of the body under these circumstances. On the contrary, [8] used this software to analyze the feasibility of a foothold planner for a hexapod that navigated across uneven ground.

By taking advantage of the features of CoppeliaSim, this paper studies the locomotion of the hexapod ATHENA (All-Terrain Hexapod for Environment Navigation Adaptability) in a smooth irregular terrain. To overcome obstacles and adapt its motion, this robot contains an adaptive kinematic-based control system which uses the inputs provided by the force sensors placed on its feet to change the phase of the gait, similarly to [3, 4]. Since the controller is not embedded in the simulation, a ROS framework with customized topics is implemented to establish the communication between them and resemble the transition of the simulation to the real world once the algorithm is ready to be implemented on the physical robot. The objective is to study the feasibility of this control system and evaluate if it is sufficient to traverse complex environments. This paper is organized as follows. Section II describes the kinematic model of ATHENA, and Section III presents the adaptive system designed to control its locomotion. Section IV provides an insight into the setup of the simulation in CoppeliaSim and the ROS framework, and discusses the results obtained in the experiments that were carried out. Section V presents the conclusions and future work.

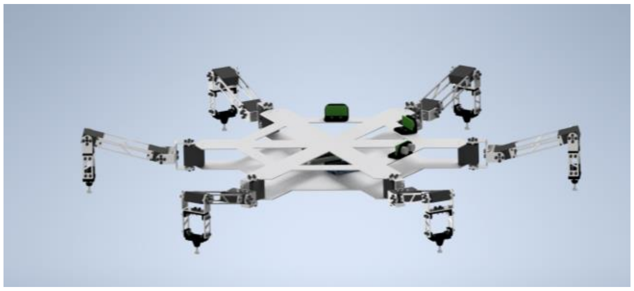

Fig. 1. The 3D model of ATHENA

TABLE I. DIMENSIONS AND MASSES OF THE COMPONENTS OF ATHENA

Component	Dimension (m)	Mass (kg)
Body	0.2710	1.7262
Coxa	0.0538	0.0220
Femur	0.1500	0.1399
Tibia	0.1088	0.0378

II. KINEMATICS OF THE ROBOT'S 3D MODEL

This paper studies the hexapod ATHENA which is presented in Fig. 1, which aims to autonomously navigate across complex environments for exploration and rescue missions. The mechanism design of the limbs consists of a simplification of the appendages of insects, considering only their largest segments, i.e., coxa, femur, and tibia, which [9] assumed as the optimal design for the robotic legs of a hexapod. This model has a total of 18 Degrees of Freedom (DOF), having 3 DOF per leg. Each joint is rotational and actuated by a servo motor with a stall torque of 1.89 Nm. Additionally, each foot contains a force sensor, to detect interaction with the ground. The body is hexagon-shaped to increase the robot's capability to generate turning gaits [10], and contains three sonars for the detection of obstacles. Table I presents the dimensions of the body and the segments of the limbs, as well as their respective mass. Fig. 2 portrays a simplified model of the leg, where the variables l_1, l_2 and l_3 correspond to the lengths of the coxa, femur, and tibia, respectively. Due to the simplification of the insect's leg, this mechanism only contains the Thorax-Coxa (TC), the Coxa-Trochanterofemur (CTr) and the Femur-Tibia (FTi) joints, where the angular motion of the TC joint is non-planar in comparison to the rest. The range of motion for the TC joint is between [-35; 35] º, while the CTr and FTi are between [-30; 70] and [-120; 0] º, respectively.

A. Forward kinematics

Denavit-Hartenberg parameters were used to describe the coordinates of the foot in relation to the hip (a fixed referential in Fig. 2, coincident with the TC joint). The transformation matrix between them is expressed as,

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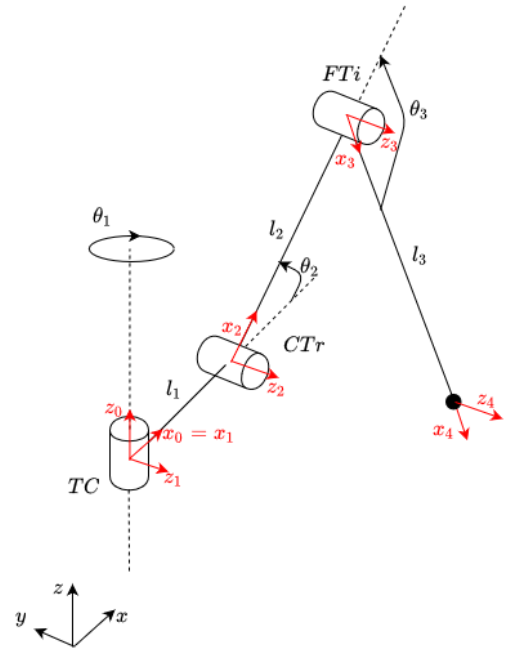


Fig. 3. Representation of the leg and the relative referential of each joint

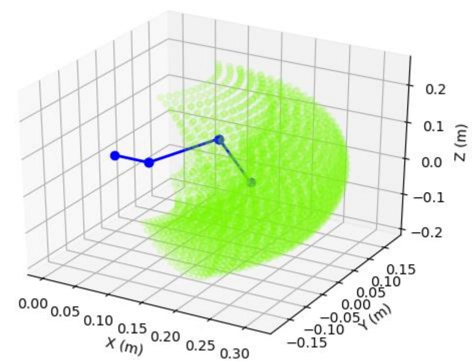


Fig. 2. Workspace of the leg

$$T_4^0=\begin{bmatrix} c\theta_1 c(\theta_2+\theta_3) & -c\theta_1 s(\theta_2+\theta_3) & s\theta_1 & p_x \\ s\theta_1 c(\theta_2+\theta_3) & -s\theta_1 s(\theta_2+\theta_3) & -c\theta_1 & p_y \\ s(\theta_2+\theta_3) & c(\theta_2+\theta_3) & 0 & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where $c\theta = \cos\theta$, $s\theta = \sin\theta$, and p is the vector with the relative coordinates of the foot,

$$p=\begin{bmatrix} c\theta_1(l_3 c(\theta_2+\theta_3)+l_2 c\theta_2+l_1) \\ s\theta_1(l_3 c(\theta_2+\theta_3)+l_2 c\theta_2+l_1) \\ l_3 s(\theta_2+\theta_3)+l_2 s\theta_2 \end{bmatrix} \quad (2)$$

Using this expression, and the ranges of motion of the joints, the resulting workspace of the leg can be represented as in Fig. 3.

B. Inverse kinematics

The angular position of the joints can be calculated using the relative coordinates of the foot. Since the angular motion of the TC joint occurs in the XY plane, θ_1 is expressed as

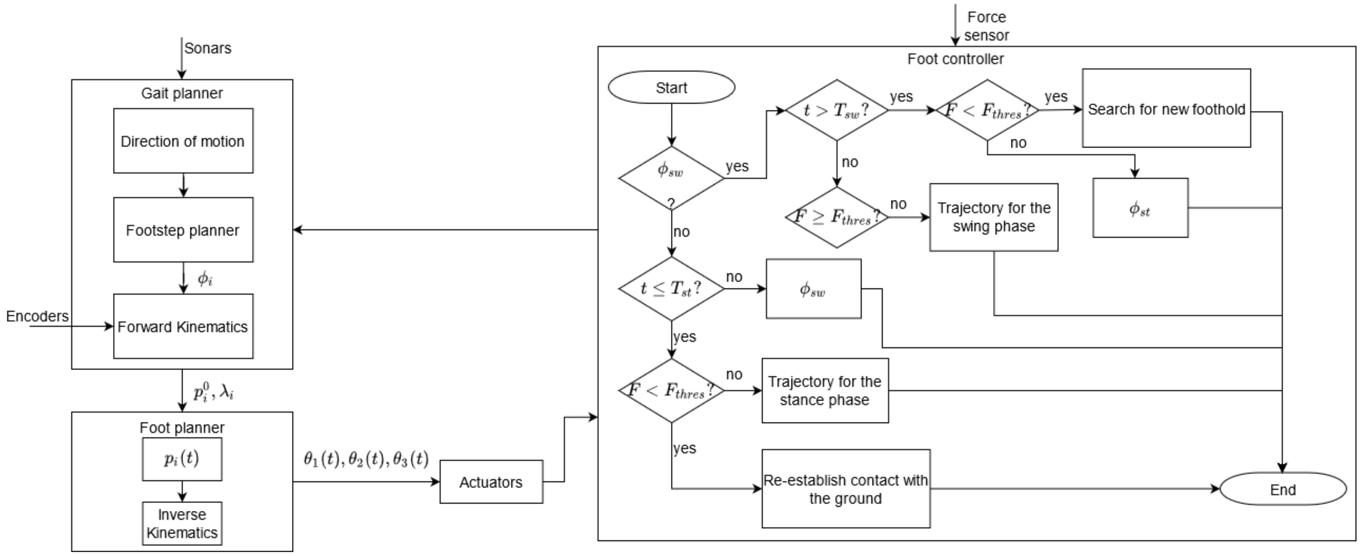


Fig. 4. Control architecture of ATHENA

$$\theta_1=\begin{cases}\arctan\left(\frac{p_y}{p_x}\right), \text{ if } p_y\neq 0\\ 0, \text{ if } p_y=0\end{cases} \quad (3)$$

Assuming that the relative position of the CTr joint is $p_{CTr}=[l_1c\theta_1;l_1s\theta_1;0]$, θ_3 is expressed as

$$\theta_3=\pi\text{-}\arccos\left(\frac{\left(p_x\text{-}l_1c\theta_1\right)^2+\left(p_y\text{-}l_1s\theta_1\right)^2+p_z^2\text{-}l_2^2\text{-}l_3^2}{2l_2l_3}\right) \quad (4)$$

Through (2), θ_1 and θ_3, the value of θ_2 is obtained,

$$\theta_2=\frac{p_x^{'}\text{-}l_1\frac{p_zl_3s\theta_3}{l_2+l_3c\theta_3}}{l_2+l_3c\theta_3+\frac{l_3^2s^2\theta_3}{l_2+l_3c\theta_3}} \quad (5)$$

Where $p'=\frac{p_x}{\cos\theta_1}$.

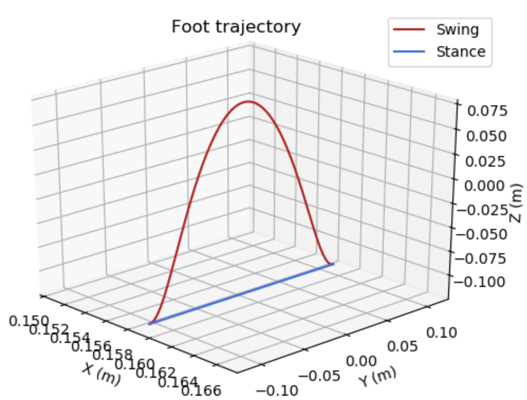


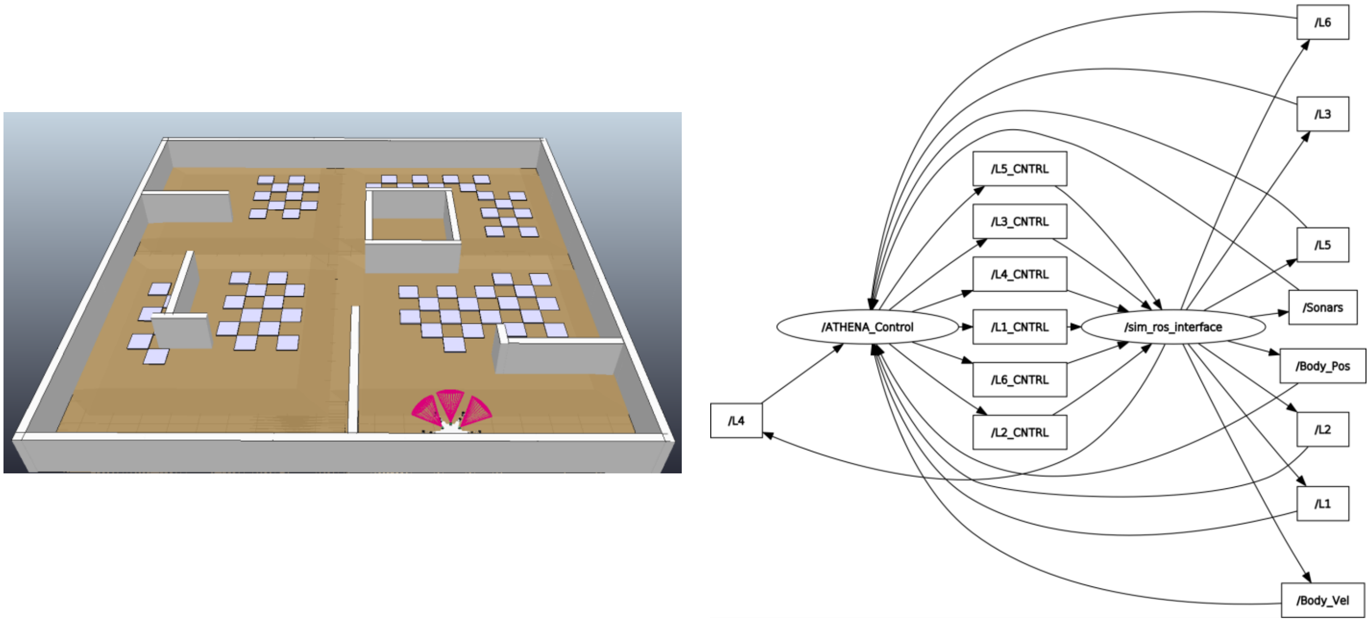
Fig. 5. Trajectory of the foot

III. Adaptive Control System

The control system of ATHENA is portrayed in Fig. 4. The gait planner processes the information provided by the sonars and selects the adequate motion for the hexapod. Despite walking forward by default, it can adopt a crab-inspired gait to move right or left, overcoming the encountered obstacles. Furthermore, if two or more sensors detect an obstacle, the robot rotates around its torso until it finds a safe path. A similar motion occurs when the front sonar detects an object, but, in this case, the direction of rotation is chosen arbitrarily. Knowing the desired motion of ATHENA, the coordination of the limbs is established, by selecting the adequate gait phase ϕ_i for each cycle. Besides that, to ensure their correct actuation, the planning of footsteps requires obtaining the desired positions of the feet through (2). Considering the current position of the feet p^0, which is also determined using (2) in conjunction with the data provided by the encoders of the joints, the stroke λ of the phase is determined. Both variables are then processed by the foot planner.

A. Foot planner and foot controller

At this stage, each leg is studied individually, without considering the others. Given the information about the λ of each phase and p^0, all the intermediate positions of the foot must be calculated. The foot trajectory assumed for the swing and the stance phases is similar to the one proposed in [11], which is presented in Fig. 5. In an unstructured terrain, the footholds may not always occur in a constant time step. Consequently, three different events may take place, namely the foot landing on the ground before the end of the swing phase, the non-establishment of contact with the terrain after the swing motion, and the slippage and contact loss during the stance phase. To avoid these occurrences, the foot controller processes the data provided by the force sensor (considering a force threshold F_{thres}, due to possible false positives) and adapts the motion,



a) b)

Fig. 6. Setup of the simulations. In a) the environment designed in CoppeliaSim, and in b) the ROS framework

- If the force sensor detects an early contact during the swing phase, the controller stops the execution of its trajectory until the time t reaches the period of the phase T_{sw}.
- In case there is no contact established with the ground when $t > T_{sw}$, the limb continues searching for a new foothold, according to the limits of the joints, for a period of $\frac{T_{sw}}{2}$, until the force sensor detects any magnitude.
- During the stance phase, if the force sensor stops detecting contact with the ground, the controller changes the trajectory of p_z by determining a novel λ_z, which considers the limits of the joints, until the contact is re-established.

TABLE II. COMPONENTS ADDED TO THE MODEL FOR THE SIMULATION

Component	**Number**	**Objective**
Sonar	3	Detect the distance towards obstacles
Encoders	18	Measure the angular position of the joints
Force sensor	6	Detect the contact forces of each foot
Dummy	1	Get the position and velocity of the torso
Torque sensor	18	Measure the torque generated for each joint

TABLE III. ROS TOPICS

Topic	**Message type**	**Data**
L#_CNTRL	*Vector3*	Desired angular position for the actuators
L#	*ArrayofSensors*	1) Contact force measured; 2) Current angular position of the joints; 3) Torque of the joints.
Sonars	*Point*	Distance measured by the sensors
Body_Pos	*Accel*	Linear and angular positions of the body
Body_Vel	*Accel*	Linear and angular velocities of the body

These adjustments increase the adaptability of the generated locomotion. Despite that, to ensure that the hexapod is stable at the end of each gait cycle, the transition between phases only occurs when all legs are in contact with the terrain.

IV. SIMULATIONS

The 3D model of ATHENA was imported to CoppeliaSim, and the simulation of its locomotion was carried out using the Bullet physics engine, version 2.78, a timestep of 50 ms, and a PC with an Intel CORE i7 9th Gen (3.6 GHz), NVIDIA GeForce GTX 1650, 16 GB RAM and Ubuntu LTS 20.04. The environment of the simulation is presented in Fig. 6a). It contains a heightfield with slopes of 5.71 º, and walls with a height of 0.8 m. Moreover, it also has several 0.4 per 0.4 m steps displaced throughout the ground, which have a height of either 1×10^{-2}, 2.5×10^{-2} or 3×10^{-2} m. All these obstacles were set as collidable, measurable and detectable. Despite the graphic visualization shown, the software required a simplification of complex parts into pure shapes, to increase the performance and accuracy of the dynamic simulation. All masses, whose values are presented in Table I, were assumed centred. All joints of the hexapod were defined as revolute, and their motor properties were enabled in the torque/force mode for the position control. Besides that, the components described in Table II were implemented in the model, for both control and data analysis.

Since the control system was designed as a remote Python API, its interface with the simulation software was established through a ROS framework. This architecture contains two nodes, the *sim_ros_interface* which corresponds to the simulation running in CoppeliaSim, and the *ATHENA_Control*, which is the control system. The communication between them results in a large number of topics containing data from the

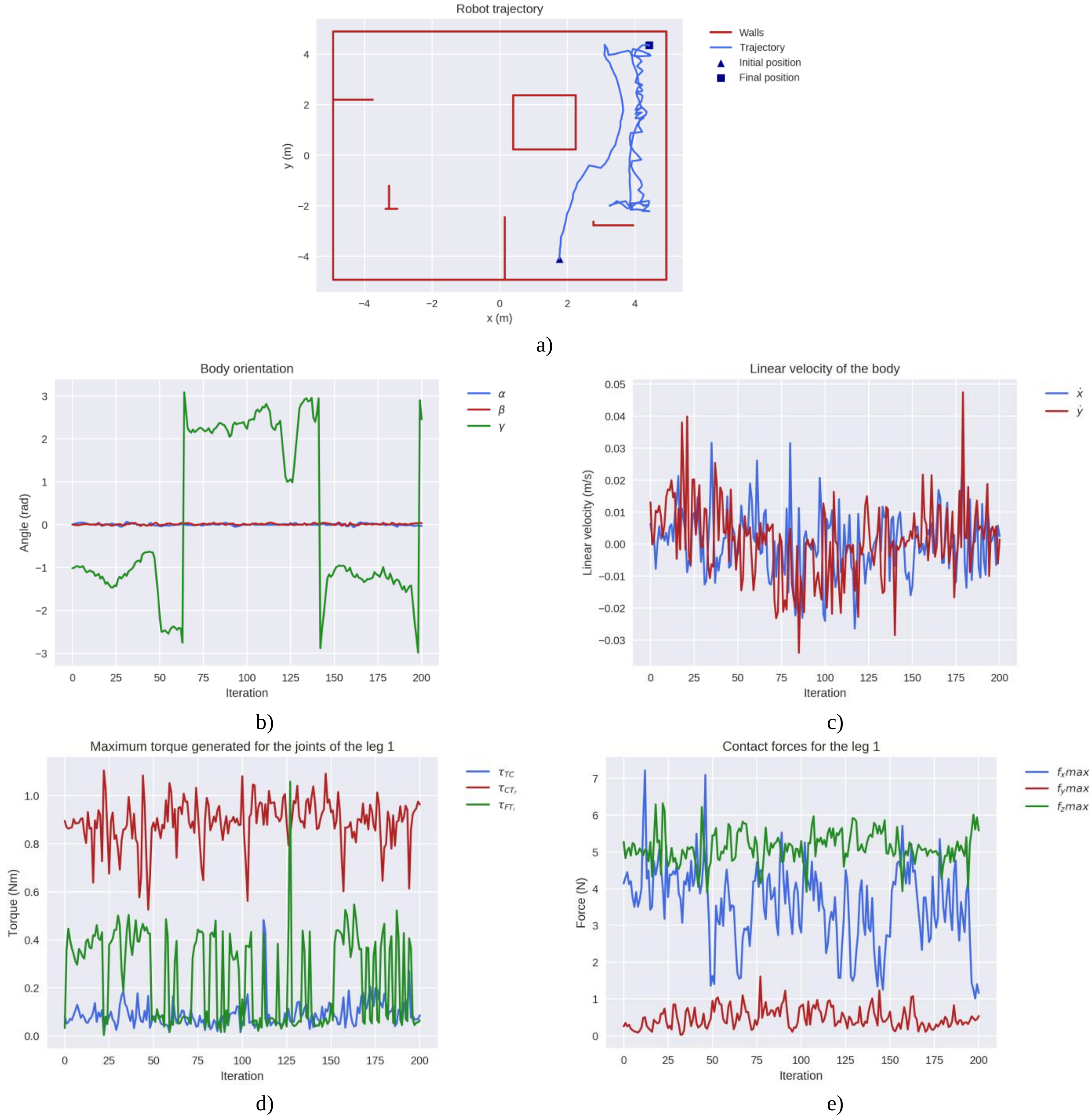


Fig. 7. Results for the first simulation of the tripod gait: a) represents the trajectory of the robot, b) and c) portray respectively the body orientation and linear velocity, and d) and e) represent the maximum torque generated and the maximum contact forces, respectively.

sensors and actuators. For simplification, a custom message *ArrayofSensors* was defined, which gathered all the data provided by the sensors of the limbs into one topic. The advantage of this methodology is the fact that during the transition between simulations and real world, the control can be implemented in the prototype by using a ROS node with the same topics defined for this structure. As a result, the framework has 15 topics which are presented in Fig. 6b) and described in Table III.

A. Results discussion

The simulations conducted for studying the locomotion of ATHENA, considered a tripod gait with T_{sw}=T_{st}=3 s. The difference between both experiments is the trajectory adopted through a total of 200 iterations. The displacement of the hexapod for both cases is presented in Fig. 7a) and Fig.8a), and the maximum and average values of the analyzed variables are presented in Table IV. Despite starting in the same position, the randomness associated with the rotation around the torso causes the generation of different trajectories. For both movements, the

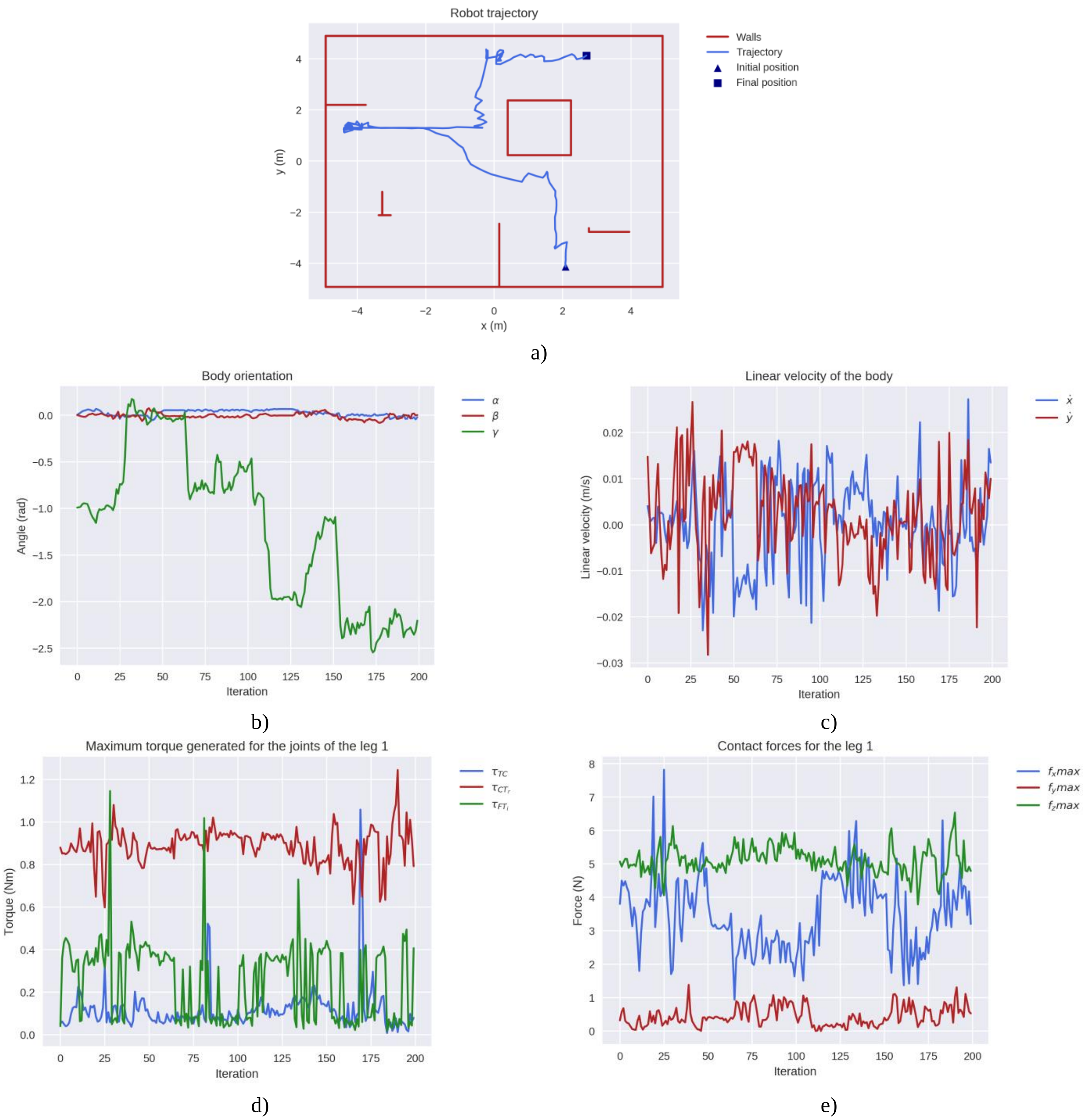


Fig. 8. Results for the second simulation of the tripod gait: a) represents the trajectory of the robot, b) and c) portray respectively the body orientation and linear velocity, and d) and e) represent the maximum torque generated and the maximum contact forces, respectively.

highest fluctuation of the body orientation occurred in the roll rotation, which is presented in Fig. 7b) and Fig. 8b) as the γ angle. This is the result of changing the direction of motion to contour the walls. In terms of α and β, which are the yaw and pitch rotations, their maximum magnitude in the first experiment was $\alpha_{max} = 0.0671$ and $\beta_{max} = 0.0479$ rad. For the second simulation, since the hexapod walked across an area with positive and negative slopes, resulting in higher rotations $\alpha_{max} = 0.0682$ and $\beta_{max} = 0.0753$ rad. For the linear velocities of the torso, which are presented in Fig. 7c) and Fig. 8c), the existent of peaks in their magnitude corresponds to the variation of the terrain topology. Hence, when the robot walked across ramps or steps there was a higher fluctuation of the velocity, which can be caused by the slippage of the feet during the transition between gait phases.

To analyze the influence of the adaptation of the gait, and the variation of the terrain topology, the contact forces and torques of the joints for Leg 1, which is one of the front limbs of ATHENA, were studied. This paper only studies this leg because the data from all legs provided similar results,

TABLE IV. SIMULATION RESULTS

Variables	1st simulation (º)	2nd simulation (º)
α_{max} (rad)	0.0671	0.0682
β_{max} (rad)	0.0478	0.0753
γ_{max} (rad)	3.0873	0.1745
$\dot{x}_{max}$, $\bar{\dot{x}}$ (m/s)	0.0317, 0.0006	0.0272, 3.8834×10^{-5}
$\dot{y}_{max}$, $\bar{\dot{y}}$ (m/s)	0.0475, 0.0010	0.02661, 0.0020
τ_{TC}max, $\overline{\tau_{TC}}$ (Nm)	0.4819, 0.0899	1.0583, 0.1154
τ_{CTr}max, $\overline{\tau_{CTr}}$ (Nm)	1.1044, 0.8928	1.2446, 0.8890
τ_{FTi}max, $\overline{\tau_{FTi}}$ (Nm)	1.0584, 0.2473	1.1456, 0.2534
$f_x$max, $\overline{f_x}$ (N)	7.2169, 3.6059	7.8193, 3.4746
$f_y$max, $\overline{f_y}$ (N)	1.6115, 0.4801	1.3842, 0.4450
$f_z$max, $\overline{f_z}$ (N)	6.3245, 5.1491	6.5382, 5.1088

regardless of the irregularities of the terrain. Despite the changes in the trajectory, none of the generated torques, which are presented in Fig. 7d) and Fig. 8d), overcame the stall torque of the servo motors of ATHENA. Since the joint CTr actuates not only the femur but also the tibia, the average torque $\overline{\tau_{CTr}}$ is higher in comparison to the other joints, having a value of 0.8928 Nm and 0.8890 Nm for the first and second experiments, respectively. Furthermore, due to the trajectory of the first case, the footholds of Leg 1 occurred on ramps or in the steps placed across the environment, which implied a higher negotiation with the terrain, justifying the existence of peaks in the magnitude of τ_{CTr}. As for τ_{FTi}, the peaks in its magnitude correspond to instances when the foot is stuck in a depression while walking across the steps, increasing the moment required to actuate the tibia.

As portrayed in Fig. 7e) and Fig. 8e), the force sensors of CoppeliaSim provided information about the contact forces in the three Cartesian axes. The normal contact force f_z does not present any significant difference between simulations, with the average values of 3.6059 and 3.4746 N for the first and second simulations. However, the variation of f_x gives an insight into the interaction with the ground since it only has magnitude during the stance phase. When the hexapod walked across steps, the value of this variable increased, with some fluctuations related to the slippage of the foot. In a further study, the controller must have an accurate estimation of the friction forces, and their impact on the support of the robot, to adjust the trajectory of the stance phase.

V. CONCLUSIONS

The dynamic simulation of a robot provides a real-time estimation of its behavior under specific circumstances, which is important for the verification of the feasibility of the mechanisms and the controller. This paper implemented ATHENA in CoppeliaSim to simulate the designed control system in an irregular terrain. The usage of ROS simplified the setup of these experiments since it avoided the programming of the controller in an embedded script of the simulation software. Additionally, the definition of customized messages simplified the processing of information that was sent from the program to the controller and did not cause any delay in the real-time processing, despite the amount of data contained in each topic.

In terms of the performance of the hexapod, the difference between the two tested trajectories is not significant. The posture of the body remained the same throughout the simulations, which could cause the collision of the torso with the ground while climbing higher slopes. Consequently, it is necessary to estimate the angular position of the body and adjust it with the topology of the terrain. Despite this observation, the control system efficiently detected early contacts with the ground and changed the phase of the limb from swing to stance. Furthermore, it also generated a motion with a higher range to search for a new foothold in case none was detected. This caused an alteration of the period of each gait cycle, resulting in the tripod gait becoming asymmetrical in some instances. Through the analysis of the information gathered from the software, it was concluded that the robot generated higher dynamic efforts when it had to overcome the steps placed along the scenario. Nonetheless, the moment generated in the joints did not overcome the stall torque of the actuators. Despite that, it was observed that during the stance phase some slippage of the feet occurred, which may hinder the navigation of ATHENA in more complex situations. Therefore, it is necessary to estimate the friction forces during the stance phase and control the actuation of the joints to avoid a loss of stability of the torso, and the efficiency of the robot with different types of soil, i.e., different coefficients of friction, should be studied. Nonetheless, the values observed from this analysis can be used in further stages of the research for comparing the efficiency between different generated gaits and control strategies.

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