Reactive locomotion of a hexapod for navigation across irregular ground

Joana Coelho, Bruno Dias, Gil Lopes, Fernando Ribeiro and Paulo Flores

Abstract In controlled environments, the hexapod limbs actuation can be controlled as a closed system. However, the increase of the terrain complexity implies an adaptation of their trajectory based on the robot interactions with the environment. Thus, the implementation of terrain data to the legs actuation potentially improves the hexapod quasi-static stability in these scenarios. This paper presents an adaptive control system based on the limbs reactive behavior for navigation across complex environments. Through force sensors placed on the foot-tips, the model detects the foot-ground interactions and adjusts the limbs trajectory accordingly. Furthermore, to ensure that the robot posture remains stable throughout locomotion, an impedance control is implemented in each limb. The proposed control architecture was tested in an irregular ground through dynamic simulations with five different configurations. Through result analysis, an optimized model was achieved which reduces the oscillations of the torso and slippage of the feet when walking across obstacles.

Joana Coelho
CMEMS-UMinho, Department of Mechanical Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal e-mail: id8667@alunos.uminho.pt

Bruno Dias
Center Algoritmi, Department of Informatics, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal e-mail: bruno.dias@di.uminho.pt

Gil Lopes
University of Maia, Avenida Carlos de Oliveira Campos, 4475-690 Maia, Portugal e-mail: alopes@ismai.pt

Fernando Ribeiro
Center Algoritmi, Department of Industrial Electronics, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal e-mail: fernando@dei.uminho.pt

Paulo Flores
CMEMS-UMinho, Department of Mechanical Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal e-mail: pflores@dem.uminho.pt

1 Introduction

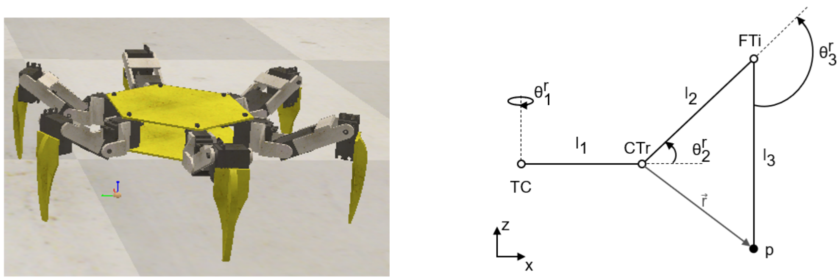
The six limbs of hexapods ensure them a higher static stability in comparison to other legged robots [4]. However, with the increase of the environment complexity, this ability is not sufficient to maintain an efficient locomotion and adequate torso posture. In fact, the system requires more information both about the environment and the robot internal state to adjust the limbs actuation accordingly. Based on the most recent publications about the control of hexapods, the majority still focuses on the generation of adaptive locomotion for indoor environments with uneven ground and proposes control strategies which resort to kinematic or dynamic models of the robot [2]. Thus, the generation of an adaptive control for unstructured environments remains an open question. In this case, the perception of the foot-ground interaction is important to plan the actuation of its legs according to the terrain topology. Thereby, Xia et al. [6] and Liu et al. [5] resorted to force sensors placed on the feet to evaluate the normal contact forces and adjust the limbs trajectory. Both studies aim at detecting a variation of the contact forces to switch the actuation of the legs. Along with this reactive behavior, it is important to ensure that the posture of the body remains unaltered with the irregularities of the ground. Thus, to avoid high attitude and height fluctuations of the torso, some research projects implemented virtual elastic elements to stabilize the feet positions with the normal contact forces [3, 1]. On the other hand, a ground topology identification method and a virtual suspension model to the hexapod and foot-force compensation model was presented by Liu et al. [5], which requires a more accurate model of the robot interactions.

This work deals with a new approach for a proprioceptive adaptive design. For this purpose, a set of force sensors is implemented to achieve a reactive control of the limbs, changing their trajectory when an early contact force is detected. The advantage of this model is not requiring previous knowledge of the ground irregularity, as well as not resorting to a large amount of data from exteroceptive sensors to adjust locomotion. Furthermore, the posture of the hexapod is controlled using impedance models on each foot. The proposed control strategy was built as a remote Python API, and was tested and verified in CoppeliaSim. The results of the computational simulations performed on an irregular ground were compared against the results when a non-adaptive control method was used and could confirm the applicability of the proposed solution.

The remaining of this article is organized as follows. Sect. 2 describes the kinematic design of the hexapod selected for this study and Sect. 3 presents the proposed control architecture. Sect. 4 discusses the computational simulations and the obtained results. Finally, Sect. 5 presents some concluding remarks and future developments.

2 Model description

This section presents the hexapod kinematic model, in order to describe its inverse kinematics. This analysis is important for the legs trajectory generation, in order to



(a) (b)

Fig. 1: Hexapod design: (a) portrays the model adopted for this study, and (b) presents the limbs kinematic design, with the relative angular position of each joint.

obtain the joints relative angular positions based on the imposed trajectory of the feet. The robot adopted is presented in Fig. 1(a). It contains three revolute joints per limb and an overall of 18 degrees of freedom. The radius of its hexagonal-shaped body is 0.0799 m. Each limb has three segments which in this work are denominated as coxa (l_1), femur (l_2) and tibia (l_3), and their dimensions are respectively, 0.050, 0.072, and 0.116 m. Its overall mass has a value of 1.347 kg.

Fig. 1(b) portrays the legs kinematic design of the hexapod. The adopted nomenclature for the joints is as follows: Thorax-Coxa (TC), Coxa-Trochanterofemur (CTr) and Femur-Tibia (FTi). Based on this representation, the value of θ_1^r is obtained through the following expression,

$$\theta_1^r = \arctan_2\left(p_y^{TC}, p_x^{TC}\right) \tag{1}$$

where p^{TC} is the relative position of the foot using the TC joint as reference. Since the controller uses the torso as reference to generate the feet coordinates, this variable is expressed as,

$$p^{TC} = (T_{TC}^{Torso})^{-1} p^{Torso} \tag{2}$$

where T_{TC}^{Torso} is the transformation matrix between the torso and the TC joint, and p^{Torso} is the foot coordinate with respect to the torso reference. With this transformation, the following relative angular positions can be obtained with respect to the first quadrant. Considering r, which is the norm vector between the foot and the CTr joint, the values for θ_2^r and θ_3^r can be obtained by,

$$\theta_2^r = \arccos\left(\frac{-l_3^2 + l_2^2 + r^2}{2l_2 r}\right) - \arcsin\left(\frac{CTr_z^{Torso} - p_z^{Torso}}{r}\right) \tag{3}$$

$$\theta_3^r = -\pi + \arccos\left(\frac{-r^2 + l_2^2 + l_3^2}{2l_2 l_3}\right). \tag{4}$$

3 Control strategy

The hexapod locomotion control has the two hierarchical control layers presented in Fig. 2. The high-level control is responsible for the trajectory planning, while the low-level adjusts the motor commands according to the ground topology. Based on the gait planner, which provides data about the torso desired motion, the forward kinematics obtains the desired foot positions. Consequently, the footpath planner generates the adequate foothold trajectories according to the gait phase. During the swing phase, the limb searches for a new foothold position by executing a Bézier curve. Its intermediate coordinates are calculated using the desired leg stroke and step height. As for the stance phase, since the foot remains in contact with the ground, its actuation is as follows [4],

$$p(t) = \begin{bmatrix} p_x^0 \\ p_y^0 + \frac{S_y}{T} t \\ p_z^0 \end{bmatrix} \tag{5}$$

where p^0 is the initial foot position, S_y is the leg stroke along the Y-axis and T is the gait phase period. Using the desired foot position, the joints angular positions are obtained using the inverse kinematics. The reactive behavior comes with the contact detection module. Similarly, to the model presented by Xia et al. [6], the robot locomotion in an irregular ground is adjusted according to the early detection

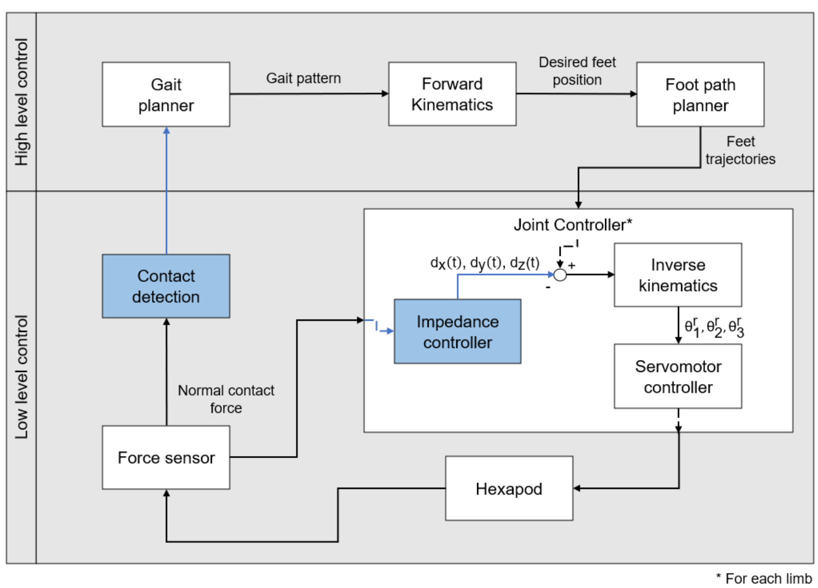


Fig. 2: Hierarchical control architecture.

of foot-forces. For this purpose, the system reads the values from the force sensors placed on each foot-tip to detect irregularities in the normal contact forces. Thus, in the swing phase, if the normal force is higher than a threshold value then the trajectory of the limb stops and switches to the stance phase. Moreover, in an unstructured environment, the variable foot-force distribution and the different characteristics of the ground can cause deviations in the legs actuation [3]. Consequently, this implies an adjustment of the legs stiffness to respond to the changes of the system. Similarly, to the models presented by Irawan and Nonami [3] and Bjelonic et al. [1], this strategy adds a virtual mass-spring-damper system to each foot-tip, which can be expressed as,

$$-F_z(t) = M_{virt}\ddot{z}(t) + D_{virt}\dot{z}(t) + K_{virt}z(t) \tag{6}$$

where F_z is the normal contact force, M_{virt} is the virtual mass, D_{virt} is the virtual damping coefficient and K_{virt} is the virtual stiffness coefficient. The characteristic frequency and the damping ratio of the system [5] are, respectively,

$$\omega_n = \sqrt{\frac{K_{virt}}{M_{virt}}} \tag{7}$$

$$\xi = \frac{D_{virt}}{2\omega_n M_{virt}}. \tag{8}$$

4 Results and discussion

The designed control strategy was implemented using the dynamic simulator CoppeliaSim. For the computational simulation setup, the Bullet physics library version 2.78, was selected, with a time-step of 50 ms. Since the control system is designed as a remote Python API, a Robot Operating System (ROS) framework establishes the communication between the software and the controller. To ensure real-time data acquisition, its rate is set to 20 Hz.

Fig. 3 presents the tested scenario. It includes six 0.1×0.1 m blocks with 0.02 m of height. The goal is to walk across the ground and adjust the legs trajectories, ensuring the body posture remains quasi-statically stable. To study the hexapod behavior, five different configurations for the control system, presented in Table 1 were selected. The first one consists of a non-adaptive model, without impedance controllers on the limbs and the next following cases considered values of ξ which could increase the system response, as suggested by Liu et al. [5]. In all simulations, the hexapod adopted a tripod gait, with swing and stance period of 1 s, a step height of 0.06 m and a stroke of 0.015 m. During the transition between gait phases, all six limbs remain in contact with the ground for a short time instant. Consequently, this event is not taken into consideration in this study. Thus, it is assumed that only three legs remain in contact with the ground, and the value of M_{virt} was set to one third of the system total mass, i.e., 0.4491 kg. The force threshold for the contact detection was set to 1.0 N.

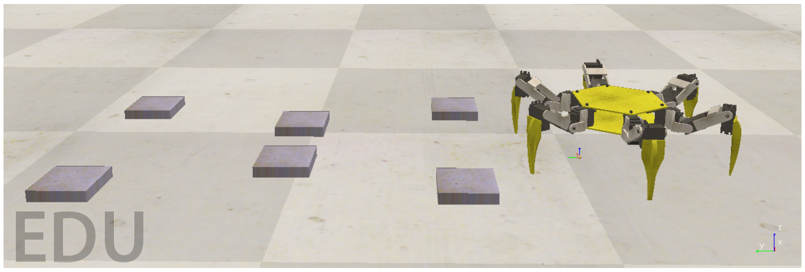


Fig. 3: Simulation scenario where the potential obstacles are visible.

Table 1: Parameters of the five control configurations.

Case	Adaptive control	ω_n (s^{-1})	ξ
1	No	-	-
2	Yes	300	0.85
3	Yes	240	0.85
4	Yes	300	0.7
5	Yes	240	0.7

The analysis of the roll and pitch angles variation of the body, which are portrayed in Fig. 4(a) and 4(b), leads to the conclusion that the first configuration has a higher perturbation of the hexapod posture, due to the lack of reflexive and impedance control. Additionally, the parameters selected for case 5 increased fluctuation of the posture parameters. This could be influenced by the value of ω_n, which may not be high enough to reduce resonance according to the implemented ξ. Thereby, this configuration is not considered an adequate solution to the tested scenario. Along with the body posture, the variation of the foothold height, and the consequent transition between the gait phases, also influences the torso oscillation in the Z-axis, which can decrease the system stability. From Fig. 4(c), when the hexapod has no control adaptation, its height has a higher variation, which is caused by the lack of response to the ground disturbances. Similarly, to the previous analysis, the fourth case presents the lowest variation in the Z-axis, which emphasizes the stability provided by this configuration.

To observe the influence of the reactive behavior, Fig. 5 compares the trajectory of one of the mid limbs throughout the simulation for the case 4 and the non-adaptive system. As it can be observed in the Y-axis, the limb walks across one of the steps between the position 0.15 and 0.30 m. Since the first method cannot absorb any impact caused by the normal contact forces, it continues to send the desired angular positions for the swing trajectory. As a consequence, the feet slippage and their position has a higher oscillation when surmounting this obstacle. On the contrary, the foot motion in the fourth experiment remains the same in this condition.

5 Conclusions

This paper focuses on the navigation of a hexapod in unstructured ground and discusses the proposed control architecture that relies on proprioceptive information and is inspired by the reactive behavior of insects to detect terrain obstacles and adjusted their gait. Moreover, to avoid the body posture oscillations caused by the foot-force distribution variation, each foot-tip has an impedance controller to decrease the contact force impact. The designed architecture was tested in five different configurations. In comparison to the non-adaptive controller, the configuration with a ω_n of 300 s^{-1} and ξ of 0.7 provided the optimal response to the system disturbances, having the smaller fluctuations in terms of the roll, pitch and height of the torso. By analysis of the trajectories, it was also concluded that, without the reactive behavior, the feet are forced to try to reach a position which is not achievable. This increases foot slippage when walking across the step and, consequently, also increases the deviations of the feet positions. On the contrary, the trajectory of the limbs for the fourth model remains unchanged throughout the simulation, being clear that there is a transition of the limb trajectory when traversing the block. Considering the obtained results, the future stage of this work must test the proposed control strategy in more unstructured ground, to evaluate the torso posture control when the hexapod navigates across different slopes. Besides that, it is important to study the locomotion efficiency, by efficiently tuning the impedance control parameters to avoid body oscillation and feet slippage in different types of terrain.

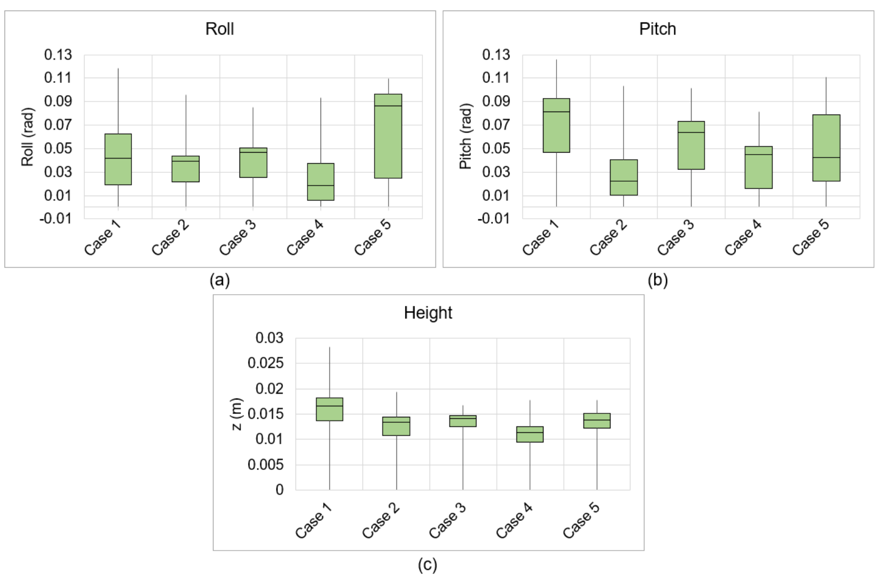


Fig. 4: Results obtained from the computational simulations: (a) roll angle, (b) pitch angle, and (c) torso height.

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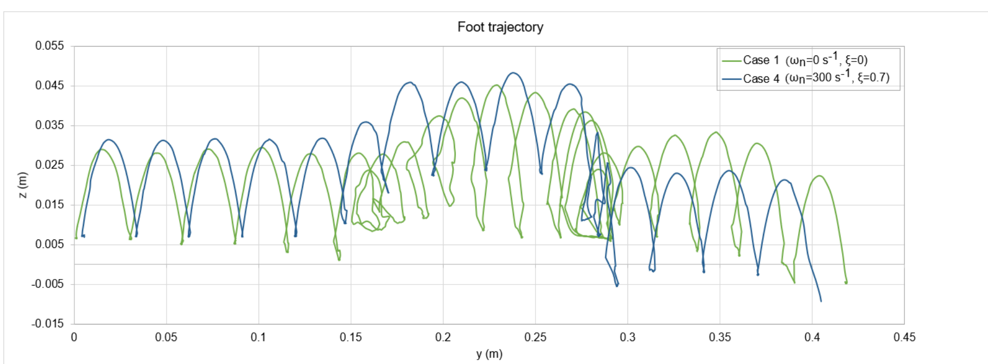

Fig. 5: Influence of the control on the limbs trajectory.