Hexapod posture control for navigation across complex environments

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Abstract Hexapod locomotion in unstructured environments relies on an efficient posture adjustment with the terrain topology. This paper presents a strategy to adapt the hexapod torso orientation through ground plane estimation. With an Inertial Measurement Unit (IMU) and the robot kinematic model, the current supporting feet coordinates are calculated, and the relative inclination between the ground and the torso angular position can be obtained. This information is used to adjust the novel foothold positions, in order to ensure the hexapod posture remains stable. The torso height is also controlled to avoid collisions with the ground asperities and decrease its deviation during motion. The proposed method is evaluated in a complex terrain made of 0.1×0.1 m blocks with variable height, causing different slopes across the field. Through result analysis, a significant behavior improvement is observed, due to the reduction of the torso posture oscillation and the increase of its locomotion efficiency.

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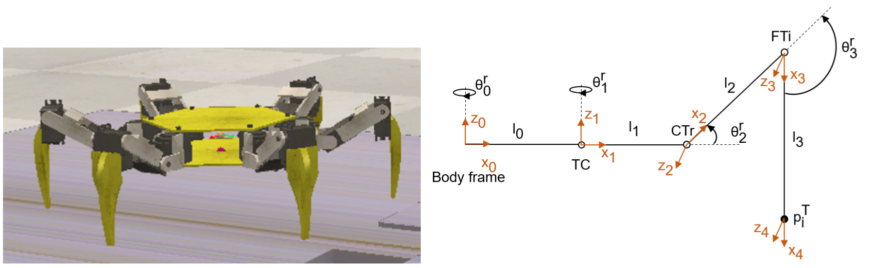
1 Introduction

The design of hexapods has an increasing interest for the execution of tasks in uncontrolled and dangerous environments (Rubio et al., 2019). Nonetheless, the generation of adaptive locomotion remains an important research question in the control of these robots (Coelho et al., 2021). In an unstructured ground, a hexapod deals with an oscillation of its posture, due to the variable feet forces distribution, which compromises the system stability (Irawan and Nonami, 2011). Furthermore, the field slopes cause the torso Center of Mass (CM) to translate to the robot rear side, having also a negative influence in the hexapod locomotion (Molnar et al., 2017). Thereby, the body orientation control is important for the adaptive locomotion efficiency. Amongst the existent solutions, Molnar et al. (2017) proposes a body levelling method for climbing ramps which translates the hexapod CM to ensure its quasi-static stability. Likewise, Faigl and Čížek (2019) also increased a hexapod stability in unstructured environments by centering the CM position with the legs support polygon. Besides that, the presented method also ensures that the body remains at a certain relative height through the ground plane estimation based on the feet coordinates. Nonetheless, the robot resorts to inverse dynamics calculations to detect the limbs interaction with the ground, which increases the system computational complexity. The main disadvantage of these researches is not assuming the torso pose adjustment with the slope variation. This is important not only when the hexapod must transport hardware or cargo in this type of environment but also to improve the system efficiency. In a different approach, Bjelonic et al. (2016) proposes a redundant limb kinematic design with five Degrees of Freedom (DOF) to adjust the body posture and feet orientation by forcing the legs tarsus to be aligned with the gravity vector for efficiency improvement. However, the increase of the hexapod DOF results in more complex kinematic calculations for the foot trajectory generation, requiring a higher computational efficiency.

This article aims at improving the hexapod pose for navigation across unstructured terrain. The proposed method avoids increasing the system kinematic design complexity by resorting to an optimal simplification of the insects appendages, i.e. three DOF per leg (Buschmann and Trimmer, 2017). The torso pose is adjusted through estimation of the plane formed by the footholds in the stance phase, using the robot kinematic model. Moreover, this method also introduces the usage of an infrared sensor to control the body height. In sum, the advantage of this strategy is to ensure a stable body pose despite the slope variation. To study the impact of this approach in the hexapod locomotion, the proposed method is added



(a) **(b)**

Figure 1. Model description: (a) hexapod design and (b) limb kinematic design with the relative references for the forward kinematics calculation.

to a control framework which applies a reactive behavior to the limbs, to improve the system adaptability. This architecture is tested through computational simulations in CoppeliaSim, which provides a diverse library of sensors and is commonly used for mobile robots to test navigation planning in real-time (Ivaldi et al., 2014; Collins et al., 2021). Besides that, a Robot Operating System (ROS) framework communicates with the remote control API, which facilitates the transition of the simulation to the real world once the algorithm is ready to be implemented. Since the goal of this paper is to study the proposed method efficiency, the controller is implemented in a hexapod model provided by CoppeliaSim. The results obtained confirm an improvement of the hexapod performance in a slope variable irregular ground.

The structure of this article is as follows. Section 2 describes the hexapod kinematic design and Section 3 presents the proposed control framework. Section 4 discusses the obtained results from the computational simulation. Finally, Section 5 presents the concluding remarks and future developments.

2 Model description

The model description includes the following aspects: presentation of the hexapod kinematic design and discussion of the limbs forward kinematics. Figure 1(a) presents the hexapod used in this study, which is provided by the software CoppeliaSim and has three DOF per limb. Regarding the model dimensions, the torso radius (l_0) is 0.0799 m, and the the coxa (l_1), femur (l_2) and tibia (l_3) lengths are, respectively, 0.0502, 0.0723 and 0.1159 m. The revolute joints nomenclature is as follows: Thorax-Coxa (TC), Coxa-Trochanterofemur (CTr) and Femur-Tibia (FTi). For this work, the feet relative position in respect to the torso coordinates is important not only to plan the hexapod locomotion but also to adjust the foothold positions based on the field slope. Using the Denavit-Hartenberg convention, the foot relative position of the ith leg is expressed as,

$$p_i^T = \begin{bmatrix} \cos(\theta_0^r + \theta_1^r)\,(l_3\cos(\theta_2^r + \theta_3^r) + l_2\cos(\theta_2^r) + l_1) + l_0\cos(\theta_0^r) \\ \sin(\theta_0^r + \theta_1^r)\,(l_3\cos(\theta_2^r + \theta_3^r) + l_2\sin(\theta_2^r) + l_1) + l_0\sin(\theta_0^r) \\ l_3\sin(\theta_2^r + \theta_3^r) + l_2\sin\theta_2^r \end{bmatrix} \quad (1)$$

where θ_0^r is the relative angle between the references of the torso and the TC joint, and is expressed as $\theta_0^r = \frac{\pi}{3}i, i = 1, ..., 6$.

3 Control strategy

Figure 2 portrays the system control framework. The higher layer plans the robot motion and synchronizes the limbs actuation based on the desired footholds and the gait phase. For the swing phase, the leg executes a Bézier curve, while for the stance phase the motion is similar to the one proposed by Liu et al. (2020). Along with sending the joints desired angular positions to the actuators, the low level control also gathers the data from the hexapod sensors for the adaptive behavior. The force sensors placed on the feet measure the normal contact forces, and the legs change from the swing to the stance phase when these sensors detect an unexpected foot-ground interaction. Besides this reactive behavior, the impedance controller adapts the foot coordinates during contact detection, to adjust the leg stiffness and absorb some impact energy.

The posture controller is responsible for adjusting the torso angular position with the terrain topology. The goal is to ensure the minor fluctuation of the torso angular position when walking across complex environments. Thereby, the approach is as follows. The current hexapod orientation $[\alpha_T, \beta_T, \gamma_T]^T$ is obtained using an IMU placed on the hexapod CM. With this information, the foot coordinates are expressed as,

$$p_i^W = Rot_z(\gamma_T)Rot_y(\beta_T)Rot_x(\alpha_T)p_i^T, i = 1, ..., 6 \quad (2)$$

where Rot is the rotation matrix and p_i^T is obtained using the forward kinematics. From Figure 3, the supporting feet coordinates form a relative plane $a_p x + b_p y + c_p z = d$, and its respective roll (α_p) and pitch (β_p) are obtained through the norm vector. Thus, the angular position adjustment can be obtained through the following translation for each TC joint,

$$Trans_{TC} = Rot_y(\beta_p - \beta_T)Rot_x(\alpha_p - \alpha_T)TC_i^W - TC_i^W, i = 1, ..., 6 \quad (3)$$

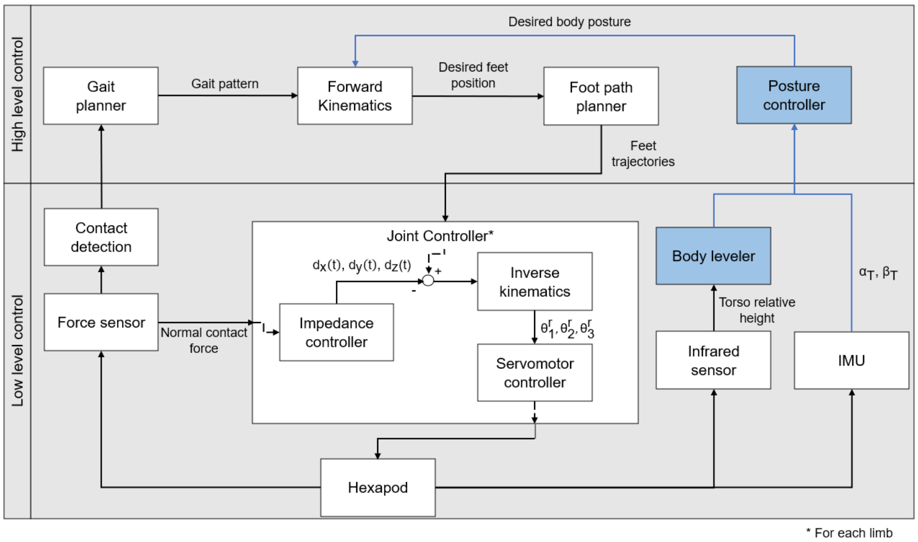


Figure 2. Hierarchical control architecture.

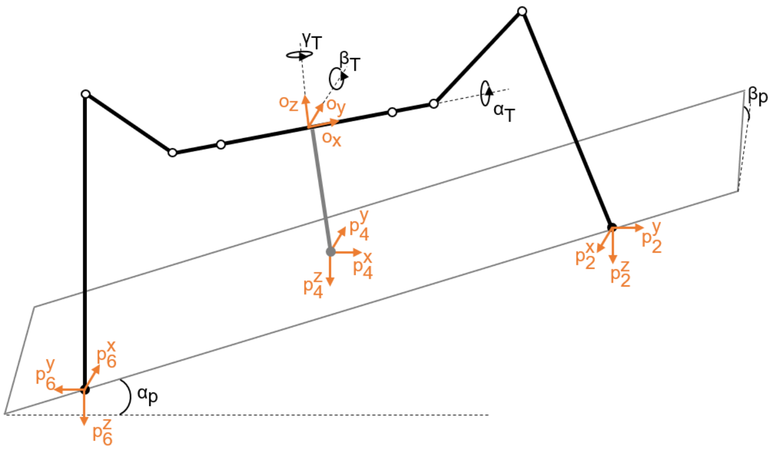


Figure 3. Representation of the relative ground plane formed by the limbs 2, 4 and 6.

The obtained translation matrix is applied to the foot desired coordinates, and the limb trajectory is re-adjusted. Besides the posture control, since the hexapod relies only on proprioceptive information, it is important to maintain a body height high enough to avoid obstacle collisions. Thus, this framework controls the torso relative height through an infrared sensor placed on the body CM, which measures its distance to the floor, despite the slope and terrain topology. By setting up a threshold value, the foot final Z-coordinate of each gait phase is adjusted to ensure the hexapod height remains equal or higher than the pre-defined goal.

4 Results and discussion

This section describes the implementation of the proposed method through computational simulations. The proposed framework was implemented using the simulator CoppeliaSim, with the Bullet physic engine version 2.78 and a 50 ms simulation time-step. A ROS framework with a rate of 20 Hz establishes the communication between the simulator and the designed control, which is a remote Python API. It is important to mention that during the transition between the simulation and the real word, the framework rate needs to be re-adjusted to synchronize with the real-time sensors frequency. Figure 4 presents the tested scenario. It consists of a 0.1 $\times$ 0.1 m blocks test bed with a height value within 0.01 and the 0.09 meters (Figure 6b). The hexapod adopts a tripod gait, with a phase period of 1 s, step height of 0.2 m and a stroke of 0.015 m. The proposed control strategy has a force threshold of 1 N for the contact detection, and the impedance controller damping ratio, characteristic frequency and virtual mass are, respectively, 0.8, 280 s^{-1} and 0.4491 kg. For the body leveler, the height threshold is 0.1241 m. For result analysis, the designed approach behavior is compared to the one of a non-adaptive controller. Besides the posture evaluation, the Cost of Transport (CoT) is also analysed, which is expressed as (Bjelonic et al., 2016),

$$CoT = \frac{P}{mgv} \tag{4}$$

where P is the overall power consumption, m is the system mass and v is its velocity. This parameter gives an insight into the locomotion efficiency, based on the energy required to actuate the limbs. The value of P was calculated using the torque and angular velocity of each joint.

Figures 5(a) and 5(b) portray the torso angular position throughout the computational simulations respectively for the non-adaptive control and the designed architecture. As it can be observed, the difference between the ob-

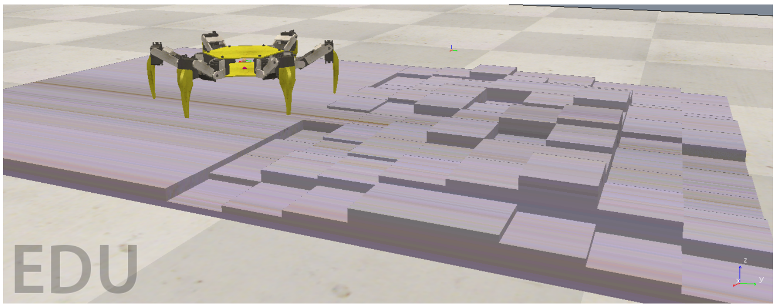


Figure 4. Scenario where the blocks with variable height are visible.

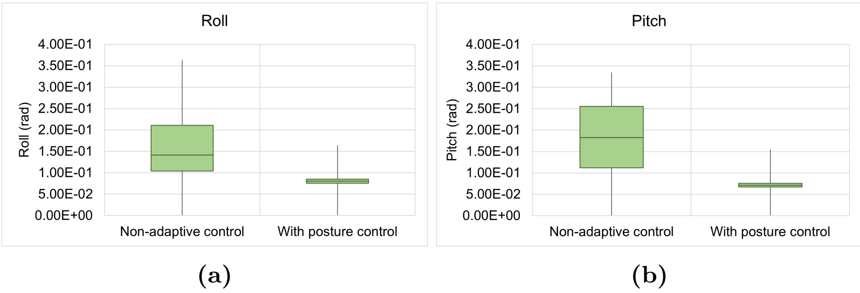


Figure 5. Results obtained for the torso orientation: (a) roll angle and (b) pitch angle.

tained results is significant. Due to the field height variation, the feet height is not constant, which has a strong influence on the torso posture. Since the proposed method estimates the ground relative plane at each time-step, the hexapod footholds are constantly adjusted to the terrain slope, leading to a lower posture variance. The hexapod reactive behavior and the feet impedance controllers also provide a better response to the field irregularities, which aids with the robot stability during its locomotion. The behavior difference is also observed in Figure 6. In opposition to Figure 6(a), the adaptive control forces the torso to remain horizontal while traversing the test bed (Figure 6(b)). This adjustment also influences the locomotion performance. The results presented in Table 1 highlight the higher performance of the designed method when walking across this environment. The average value of CoT is smaller for the posture control, thus, the hexapod joints require less power to actuate its limbs in the same conditions. The smaller CoT standard deviation observed in the adaptive controller also shows evidences of a higher locomotion stability.

(a) **(b)**

Figure 6. Hexapod posture during the simulation: (a) non-adaptive control and (b) with posture control.

Table 1. CoT results.

Test	Average CoT
Non-adaptive control	7.9873 ± 36.6401
With posture control	6.7998 ± 12.8485

5 Conclusions and future work

This article proposes a posture controller based on the estimation of the plane formed by the supporting feet. The designed system also levels the torso height to increase the locomotion stability and avoid its collision with the ground. This module is implemented in a proprioceptive adaptive control with reactive behavior, to detect unexpected foot-ground interactions, and feet impedance controllers, to adapt both the limbs trajectory and stiffness to the terrain topology. By comparing the results with the ones obtained through simulation of a non-adaptive control system, it is concluded that the proposed model reduces significantly the torso posture fluctuation, ensuring that it remains horizontal during most of the study. Since the purpose of this research is to verify the proposed controller behavior, the computational simulations were conducted in CoppeliaSim, which allows to use ROS for the communication establishment between the software and the remote control API. The advantage of this methodology is simplifying the implementation of the controller in the real world prototype. The values obtained for the CoT corroborate the system improvements, since the hexapod requires less actuator power to walk across the same scenario.

Since this paper is inserted in an ongoing research, the further stage of this work aims at studying the control architecture in different terrain topologies to evaluate both the consistency of the posture adapter and the gait efficiency. Furthermore, the controller will be implemented in a real world prototype and the obtained results will be compared with the ones obtained through computational simulations.

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