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Leg Morphologies Essential for Environmental Adaptive Hexapod Walking Driven by Reflex-based Intra-limb Coordination

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1 Introduction

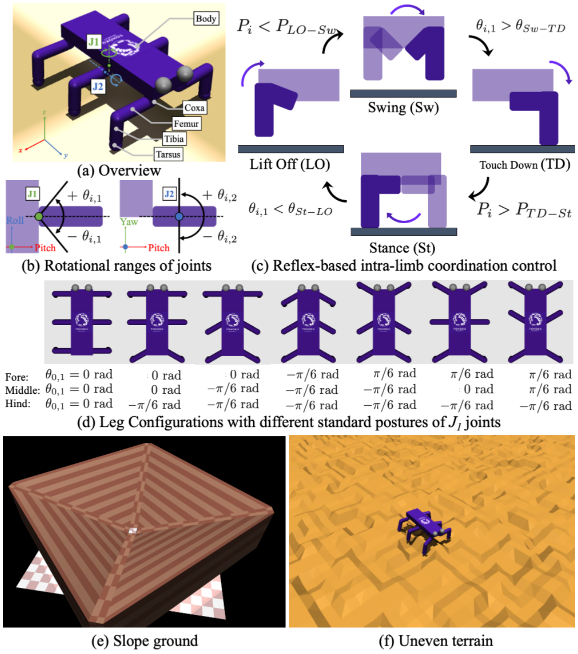
Insects exhibit adaptive walking behavior in an unstructured environment, despite having only an extremely small number of neurons (10^5 to 10^6). This suggests that not only the brain nervous system but also physical body properties, such as the leg morphology, play an essential role in generating such adaptive behavior. Although previous studies [1,2] have primarily focused on neural control mechanisms for gait generation, the functional role of leg morphology is a crucial aspect associated with the ability of insects to adapt their simple and limited neural architecture to diverse environments, representing *embodiment* concept [3].

In this abstract, we investigate the environmental adaptability of a hexapod walking model driven by reflex-based intra-limb coordination [4,5]. Inspired by the leg morphology of insects, we focus on the standard position of the legs relative to the body. Especially, we investigate the effect of leg structure on walking performance under (1) slope ground and (2) uneven terrain.

2 Hexapod Walking Robot

The hexapod robot (Figure 1 (a)) used in the walking simulation was constructed based on the parameters of the cockroach (*Blaberus discoidalis*). The body of insects consists of a head, thorax, and abdomen, and each leg consists of five segments: coxa, trochanter, femur, tibia, and tarsus [6]. The hexapod robot consists of a body with six legs ($i = 1, \dots, 6$), each of which has four segments excluding the trochanter, as shown in Figure 1 (a). Each leg has two joints ($j = 1, 2$): a yaw-axis joint between the body and coxa (J_1) and a roll-axis joint between the coxa and femur (J_2).

The walking control of the hexapod robot is based on the reflex-based intra-limb coordination control [4,5] inspired by Ekeberg's model [7]. The hexapod robot model walks by actuating two joints of each leg, with the J_1 joint moving the leg forward and backward and the J_2 joint moving the leg up and down to lift it off the ground or ground it. The reflex-based intra-limb coordination (Figure 1 (c)) performs walking motion by transitioning between the following four states: (i) Swing (Sw) to move the leg forward; (ii) Touch Down (TD) to ground the leg; (iii) Stance (St) to support the body; and (iv) Lift Off (LO) to lift the leg off the ground. To simplify the control law, in each state, the torque $\tau_{i,1}$ and $\tau_{i,2}$ are kept constant input.

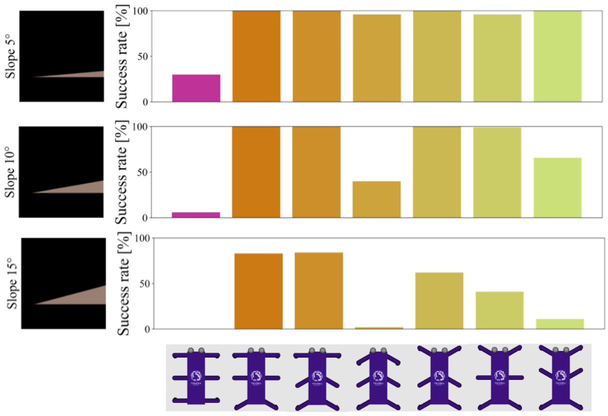


(a) Overview
(b) Rotational ranges of joints
(c) Reflex-based intra-limb coordination control
(d) Leg Configurations with different standard postures of J_i joints
(e) Slope ground
(f) Uneven terrain

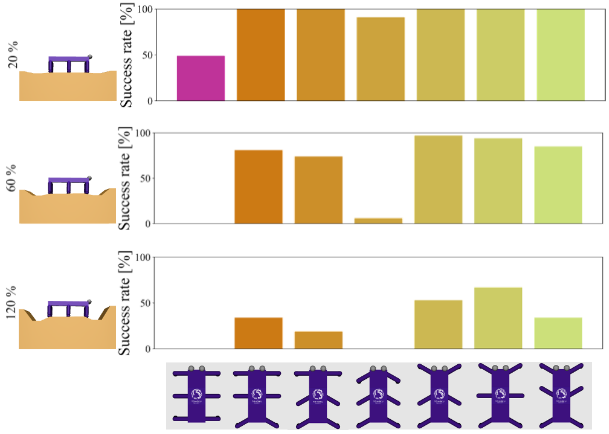
Figure 1: Hexapod robot modeled in simulation.

The transition between each state is reflexively achieved when the sensory input satisfies the following conditions (Figure 1 (c)): (i) Transition from Sw to TD is achieved when the J_1 joint angle $\theta_{i,1}$ increases beyond a threshold value θ_{Sw-TD}; (ii) From TD to St is achieved when the load (foot pressure) on the leg P_i increases beyond a threshold value P_{TD-St}; (iii) From St to LO is achieved when the J_1 joint angle $\theta_{i,1}$ becomes less than a threshold value θ_{St-LO}; and (iv) From LO to Sw is achieved when the foot pressure P_i becomes less than a threshold value P_{LO-Sw}.

For the simulation, we used the physics simulator MuJoCo. The parameters for a model with highly symmetrical leg structures (Figure (d) left: all $\theta_{0,1} = 0$) were optimized using Optuna (Preferred Networks), a python library capable of performing Bayesian optimization. For the evaluation function, we used the product of a normal distribution around the target velocity (0.4 m/s) and CoT (Cost of Transport) as an index of energy efficiency [5].



(a) Slope ground.



(b) Uneven terrain.

Figure 2: Robustness against environmental changes.

3 Simulation Results

We used the optimized parameters to test the robustness against environmental changes in the seven leg configurations as shown in Figure 1 (d). We performed walking simulations on 100 initial conditions, combining random initial joint angles and initial states for the reflex-based control conditions. After 300 seconds of walking on the slope (Figure 1 (e)) and 60 seconds of walking on the uneven terrain (Figure 1 (f)), we calculated the success rate as the ratio of the following success conditions achieved: no fall for 300 seconds or reaching a height of 5.0 m on the slope; in the uneven terrain, the robot did not fall for 60 seconds.

Figure 2 (a) shows the success rate of walking when the slope angle is set to 5, 10, and 15°. Each graph shows the success rate of walking for the corresponding leg configuration as shown in Figure 1 (d). The results indicate that the walking success rate was maintained when the J_1 standard posture angle of the hind leg was set backward even at a 15° slope, while it tended to decrease when the J_1 standard posture angles of the front and middle legs were set forward.

In the uneven terrain, we varied the ratio of the obstacle height difference (difference between highest and lowest points) to the center of gravity of the hexapod robot. Figure 2 (b) shows the walking success rates when obstacle height difference was set to 20, 60, and 120%. The results indicate that even at a 120% height difference, the walking success rate tended to be maintained by setting the J_1 standard posture angle of the front leg forward.

4 Discussion

On the slope ground, when the J_1 standard angle of the middle leg is set forward/middle, the anterior extreme position (AEP) of the middle leg is in front of the torso center of gravity, which generates a force that rotates the body backward, making the walking unstable. The J_1 standard angle of the front leg is forward, which makes it easier for a front leg to leave the ground even if the body tilts slightly, and the walking states in reflex-based control of the left and right front legs synchronize in the TD state, making support by the front legs unstable. On uneven terrain, the J_1 standard posture angles of the front legs are set forward, which serves as a brake to suppress collisions with the ground on a downhill, and the hexapod is less likely to fall over, which may have improved the success rate of walking. Further investigations into the role of leg morphology on uphill and downhill slopes may further clarify the contribution of leg morphologies to environmental changes.

In conclusion, we confirmed that setting the middle and hind legs of the hexapod robot to the backward position improves the robot's robustness against environmental changes. Furthermore, the robot was more robust when the front legs were set in the middle position in the slope ground, while the front legs were set in the front position in the uneven terrain, suggesting that adjusting the trajectory range of the front legs in a situation-dependent manner is the key to adapting to various environments.

Acknowledgements

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