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Self-organized Locomotion Control with an Adaptive Compensator for Adaptation to Robot Leg Amputations

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1 Introduction

A hexapod robot is one of the most versatile and flexible robots for performing adaptive locomotion behavior. While on a mission, partial damage might occur, resulting in leg loss. A typical control system based on machine learning or trial and error has been developed to deal with the scenario by selecting a suitable walking pattern [1]. However, the method requires learning/training periods to optimize parameters in simulation first before deploying to the robot. Another method based on decentralized control with active load sensing can effectively and quickly adapt robot locomotion [2]. While the control method can deal with robot leg amputations, it failed when both front legs were amputated. This is because the robot can easily become unstable (tipping over) since its center of mass (COM) can move outside the support polygon during the stance phase of the middle legs.

From this point of view, to deal with extreme amputations (missing both front legs, both hind legs, or other combinations), we propose an adaptive compensator for adapting to various robot leg amputations (ACAL, the main contribution of this study), which functions in conjunction with self-organized locomotion control [3]. We investigate the performance of the control method on a stick insect-like robot with heterogeneous leg lengths in a CoppeliaSim simulation. Our adaptive control method allows the robot to automatically and quickly form its gait as well as adapt to extreme leg amputations. In other words, even if its legs are amputated, the robot can continue to move forward.

2 Materials and Methods

This section describes the control system for self-organized locomotion [3] and ACAL. In this setup, each leg is driven by one self-organized locomotion control (Fig. 1A, clear area), where the middle legs additionally utilize ACAL (Fig. 1A, shaded area).

2.1 Self-organized Locomotion Control for Gait Generation

The locomotion control was based on a neural central pattern generator (CPG)-based control circuit [3],

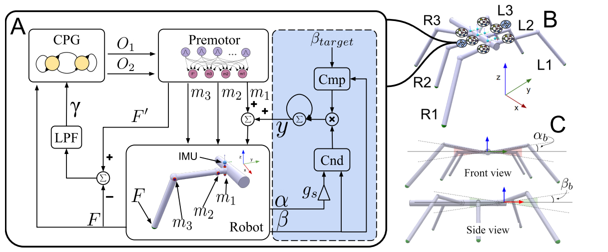

Figure 1: The control diagram showing a simulated stick insect robot. (A) The control diagram consists of self-organized locomotion control (clear area) and ACAL (shaded area). (B) The stick insect robot with heterogeneous leg lengths (the front legs are the longest, the middle legs are the shortest, and the hind legs have the intermediate length). (C) The allowed magnitude angles of the robot body orientations at roll α_b and pitch β_b angles.

with one circuit controlling each leg. Each circuit consists of three main modules. The first module is a CPG with foot contact feedback for generating and adapting periodic signals (O_1, O_2). The second module is a premotor network for i) shaping the periodic CPG signals to obtain proper motor commands (m_1, m_2, m_3) to control leg joints and ii) translating the CPG signals into expected foot contact feedback (F') to compare with actual foot contact feedback (F). Finally, a low pass filter (LPF) is used for smoothing an error signal (γ, a mismatch between the expected and actual foot contact feedback). The error signal with error-based online learning is used to adapt foot contact feedback strength projecting to the CPG. This setup results in fast and stable self-organized interlimb coordination (see [3] for more details). Note that for the intralimb coordination, a predefined semicircular foot trajectory is used to define the swing and stance periods.

2.2 Adaptive Compensator for Leg Amptation Adaptation

We developed ACAL to change the motor command m_1 of the middle legs by using roll and pitch orientation signals from IMU (inertia moment unit) sensors.

The signals roll α and pitch β are sent to ACAL which consists of two modules: condition (Cnd) and compensation (Cmp) (see Fig. 1A, shaded area). Cnd acts as a joint adjustment permission, defined as:

$$c_\alpha = \begin{cases} 1, & g_s\alpha \geq \alpha_b \\ 0, & g_s\alpha < \alpha_b \end{cases}, \tag{1}$$

$$c_\beta = \begin{cases} 1, & |\beta| \geq \beta_b \\ 0, & |\beta| > \beta_b \end{cases}, \tag{2}$$

where g_s is the initial robot's side parameter ($g_s = -1$ for the left side and, $g_s = 1$ for the right side) and α_b and β_b the allowed magnitude angles ($\alpha_b = 4$ and $\beta_b = 8$). Cnd output y_{cnd} is defined as $y_{cnd} = c_\alpha c_\beta$, where c_α and c_β are condition outputs of roll and pitch angles. Cmp is used to calculate the proper offset angle, defined as:

$$\beta_{error}(t) = \beta_{target} - \beta(t), \tag{3}$$

$$E(t) = E(t-1) + \mu\beta_{error}(t)^2, \tag{4}$$

$$y_{cmp}(t) = E(t)\beta_{error}(t), \tag{5}$$

where β_{error} is the pitch error. We define $\beta_{target} = 0$, which means the robot should maintain its body parallel to the ground. E is the cumulative error for correcting the magnitude of β_{error} and μ is set to 0.02. The Cmp output y_{cmp} relies on E and β_{error}, which are the error magnitude and direction for adapting the motor command m_1. The correlation signal y between y_{cnd} and y_{cmp} is transmitted to finally adapt the motor command m_1 through a postprocessed single recurrent neuron. The recurrent neuron acts as a simple memory for stable adaptation.

3 Experiments and Results

We investigated the robot's locomotion under two control schemes: self-organized control with and without ACAL. We focused our investigation on amputating the front or hind legs (see Fig. 2E) since these extreme conditions cause the COM to become close to or beyond the edge of the support polygon, resulting in unstable locomotion or tipping over. We tested each control in the scenarios, running each for one minute and ten times per scenario.

The self-organized locomotion control with ACAL can travel longer distances in various amputations (amputating the front left and hind right legs (FL-HR), both front legs (BF), and both hind legs (BH)), ACAL improved stability by adapting the m_1 joint command of the middle legs. Without ACAL, the robot tipped over where its head and abdomen touched the ground. This results in the robot getting stuck and failing to travel a significant distance. However, in the case of the intact robot (ND), using ACAL results in a slightly shorter travel distance compared to not using ACAL. This is because ACAL tries to maintain balance, which results in a decrease in the robot's forward stride length.

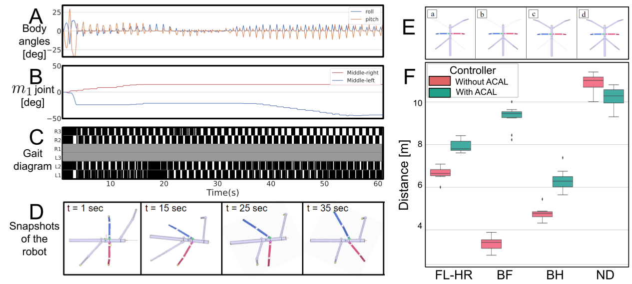

Figure 2: Changes in an FL-HR situation and the average distance traveled by the robot in simulation. (A) The robot's body orientation angles. (B) The m_1 joint angles compensation y. (C) Each leg's swing (black) and stance (clear) phases are defined by the height of the robot's feet. (D) Snapshots of the robot. (E) The leg amputation scenarios: a) front left and hind right legs (FL-HR), b) both front legs (BF), c) both hind legs (BH), and d) intact robot (ND). (F) The robot's travel distance in each scenario. The red boxes represent self-organized locomotion control, and the green boxes represent the control with ACAL. An example of leg amputation adaptation can be seen at https://youtu.be/m9zsRcMHysc.

4 Conclusions

We proposed the adaptive compensator for amputation adaptation in a hexapod robot. By adapting the upper joints m_1 (moving forward/backward) of the middle legs, the toe of the middle leg position shifts, maintaining the robot's stability. As a result, the robot still achieves walking motion and travels a greater distance in a leg loss situation. However, ACAL only adapts the upper joint causing the length of the robot's forward strides to reduce while also decreasing the travel distance. We plan to improve our approach by also adapting other joints, maintaining the robot's forward stride length, and increasing its travel distance to enhance the resilience of legged robots.

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