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Integrated Neural Adaptive Control for In-pipe Robot Locomotion

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1 Introduction

In the modern industrial era, pipelines are widely utilized to transport oil, gas, and other fluids. Traditionally, the inspection of pipelines has been carried out by inspectors checking the pipelines. This can be erroneous, time-consuming, and labor-intensive. To overcome the problem, different types of mobile robotic systems for pipeline inspection have been developed [1, 2]. In [1], electromagnetic actuators were utilized to create a worm-like robot for in-pipe inspection. Due to its morphology, the worm-like robot cannot be used for different pipe sizes and must be customized specifically to match the diameter of each pipe. Additionally, it is only applicable to pipes made of magnetizable materials. In [2], four-bar linkages were used to attach tracked wheels to the main robot body to deal with different pipe diameters. During in-pipe navigation, the four-bar linkage mechanism allows the wheels to be adjusted to make contact with the surface of different pipe diameters. However, due to the size and structure of the wheels, the robot can only work in a limited range of pipe diameters, and if the pipe is made up of several sections with different diameters and distinct transitions between them, the robot may struggle to ascend the transition step, for example, when moving from large to small sections.

To address the aforementioned limitations and accomplish in-pipe locomotion with varying pipe sizes and distinct transitions, we introduce here a multi-segmented, legged robot with integrated neural adaptive control (Fig. 1). The neural adaptive control, proposed here for the first time, is created by integrating the different neural mechanisms developed in our previous work [3,4].

2 Materials and Methods

2.1 Bio-inspired Multi-segmented Robot

We developed a multi-segmented robot with a modular structure [4]. Each segment has two body joints and two legs. Inspired by a millipede/centipede, one body joint provides upward and downward movements around a horizontal axis (BBH), while the other enables left and right bending movements around a vertical axis (BBV). Each leg has three active joints (three DOFs): the body-coxa joint (BC-joint) for forward and backward movements, coxa-femur joint (CF-joint) for elevation and depression of the leg, and femur-tibia joint (FT-joint) for the extension and flexion of the tibia. Each leg is also equipped with a foot contact sensor. All joints are driven by Dynamixel XH540-W270-R motors for providing the all-important proprioceptive feedback (such as position, velocity, and current/torque). The inertial measurement unit (IMU) is also implemented on each body segment for body orientation detection. The robot can be setup with different configurations (e.g., two-legged robot (one segment), four-legged robot (two segments), six-legged robot (three segments), or eight-legged robot (four segments)). According to our empirical tests, a three-segmented robot with six legs (Fig. 1(a)) is the best and most stable configuration for in-pipe navigation. Thus, this setup is used for the study.

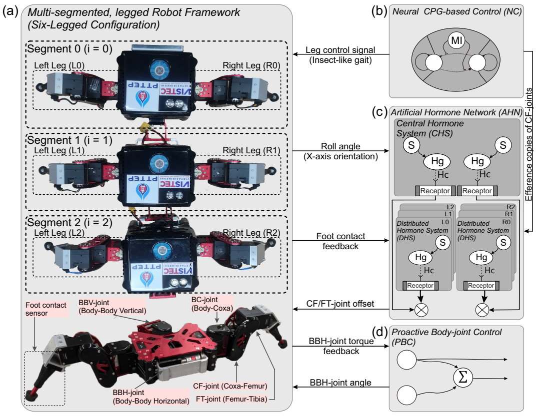

Figure 1: (a) Bio-inspired multi-segmented robot. (b), (c), and (d) Bio-inspired neural adaptive control architecture for in-pipe locomotion of the robot.

2.2 Integrated Neural Adaptive Control

The control consists of three main modules: 1) a neural central pattern generator (CPG)-based control module (NC, Fig. 1(b)) for basic locomotion generation, 2) an artificial hormone network module (AHN, Fig. 1(c)) for leg adaptation, and 3) a proactive body-joint control module (PBC, Fig. 1(d)) for body adaptation. All neurons of the control are non-spiking neurons (see [3,4] for details).

2.2.1 Neural CPG-based Control (NC)

The NC is developed based on a CPG to generate insect-like gaits (e.g., tripod and wave gaits). The CPG, realized by a recurrent two-neuron oscillator network, processes intralimb and interlimb coordination of the legs. In this study, the CPG was set to generate a wave gait for in-pipe inspection

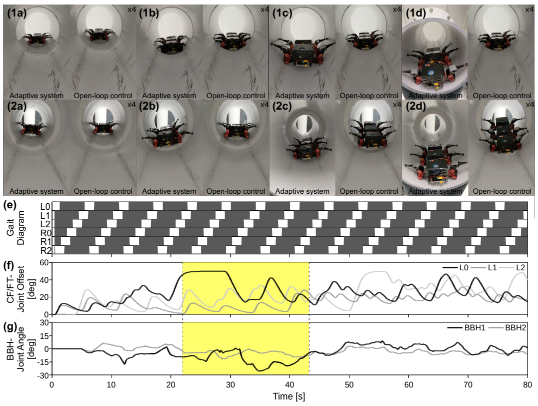

Figure 2: Snapshots of robot locomotion in a pipe driven by our adaptive control system (NC, AHN, and PBC) and open-loop control (only NC). (1a)–(1d) In-pipe locomotion from large to small pipe sections. (2a)–(2d) In-pipe locomotion from small to large pipe sections. (e)–(g) Example of control signals generated from our adaptive control system during in-pipe navigation, where (e) shows a wave gait, (f) CF- and FT- joint offset values of the left legs (L0, L1, and L2), and (g) shows the BBH-joint angle signals. The yellow-highlighted areas indicate the climbing period over the transition step. Supplementary videos of the experiments can be viewed at https://youtu.be/QlCxuYoAO1E and https://youtu.be/hphDXPKYnW4.

(see [3] for more details of the NC).

2.2.2 Artificial Hormone Network (AHN)

The AHN is a bio-inspired mechanism derived from the endocrine system of the living creature. It is designed to allow the robot to adapt its legs to maintain ground contact with the terrain (pipe) surface. The AHN consists of two artificial hormone systems: central hormone system (CHS) and distributed hormone system (DHS). The DHS adjusts each leg's offset individually based on force feedback from the foot contact sensor, whereas the CHS adapts the legs to stabilize the robot body posture based on the IMU feedback (see [3] for more details of the AHN).

2.2.3 Proactive Body-joint Control (PBC)

The PBC is applied with online unsupervised learning for robot body adaptation [4] to overcome distinct transitions in a pipe. The online learning, based on the cross-correlation between a predictive signal (an early input or here the joint torque signal of an anterior body segment) and a reflex signal (a later input or the joint torque signal of a to-be-controlled body segment), allows the robot to automatically learn and proactively bend its body segments propagating from anterior to posterior when negotiating a step. The PBC relies only on torque feedback from the BBH-joints and temporal data storage (short-term memory) for generating and propagating the body bending control signal. As a result of this control mechanism, the robot can adaptively ascend and descend the step at the transition point between pipe sections of different diameters.

3 Results

We evaluated the performance of our robot and adaptive control system using two different pipe diameters. Our adaptive control was also compared with nonadaptive CPG-based control (only NC acting as open-loop control). The leg movement of the open-loop control system was tuned to its initial pipe diameter. The robot was set to walk in two directions (i.e., from small (20-inch diameter) to large (24-inch diameter) pipe sections and vice versa) to examine the robot locomotion performance while ascending and descending the steps/transitions in the pipe.

The results are shown in Fig. 2. The robot driven by our adaptive control system can successfully traverse through the pipe in both directions, whereas the robot driven by the open-loop control system can only move within the initial size of the pipe since without leg and body adaptation, its body and legs became stuck at the transition or step between the pipe sections. In addition to in-pipe locomotion, our adaptive control can automatically adapt the leg and body movements for locomotion on uneven terrains (see https://youtu.be/dLNPBSZ1Xhs).

4 Conclusion

This study presents bio-inspired neural adaptive locomotion control derived from an integration of the NC, AHN, and PBC modules. The control approach relies on proprioceptive feedback (joint torque, foot contact, and body orientation) and short-term memory for adaptation rather than robot kinematics or environmental models. Although the robot can navigate in different-sized pipes, it still cannot navigate through a non-straight pipe which requires lateral body bending to follow the pipe curve. Thus, in the future, we will introduce neural lateral body bending control [5] into the control architecture to enhance the robot's mobility.

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