Emergent Locomotion Patterns from A Quadruped Pneumatic Musculoskeletal Robot with Spinobulbar Model

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I. MOTIVATION, PROBLEM STATEMENT, RELATED WORK

Evolutionary processes shape the animal’s morphology and nervous system to adapt themselves mutually from each others and to achieve one efficient sensorimotor integration within the environment. As a result, various complex behaviors marked by energy consumption efficiency as well as self-organization can emerge from the dynamical interaction between the body, the neural system and the environment. Those skills are possible because the neural system exploits the physics of the body on the one hand, while on the other hand the body dynamics structure the neural dynamics via sensory stimuli. This constitutes a fundamental property of embodied intelligence [1][2][3].

In recent years, many researches have been developed to understand better the mechanisms underlying the animal’s locomotor skills and how to apply them in robots [4][5]. Moreover, particular attention has been focused on central pattern generator (CPG) to replicate animal locomotion in biologically-inspired robots [6]. For instance, the dog-like Tekken series [7] can realize stable locomotion using sensory feedback whereas the insect-like AMOS-WD06 [8] can generate various complex behaviors by exploiting the chaotic properties of CPG models. However, these robots achieve locomotion without exploiting readily the physics of the body because the body is either too rigid or controlled linearly by electromagnetic motors. In contrast, animal’s musculoskeletal system is constituted of a complex and redundant structural morphology with nonlinear materials for the visco-elastic muscle-tendon tissues [9]. Few studies have focused on the study on both the nervous system and their body [10][11][12]. For this reason, we propose to investigate this issue in a quadruped robot and how the neural system along the body dynamics interact each others in order to generate various and adaptive behavioral motions.

II. TECHNICAL APPROACH

We designed a simplistic quadruped robot sufficiently realistic to capture the important features of animals’ musculoskeletal system in order to realize the embodiment of the neural system. Classical actuators have been replaced by McKibben type pneumatic artificial muscles that reproduce some of the non-linear properties of biological muscles in terms of damping and elasticity [12][13][14] (Fig. 1). In real muscle, the sensory feedback is done by the muscle spindles that sense the muscle length and by the Golgi tendon organs that sense the muscle tension. We replicated this feature by computing the length and the tension of the artificial muscles using pressure sensors and potentiometers.

We designed the nervous system with the model of the spinobulbar system developed by Kuniyoshi and colleagues [15][16] based on biological considerations (Fig. 2). One unitary element of the spinobulbar model consists of a muscle, one α and γ motor neuron, one afferent sensory interneuron, and one neural oscillator models. Though each element is not directly connected to the ensemble, we expected that the nonlinear properties of the oscillators embodied into the robot would create the conditions for mutual entrainment and dynamical coupling to generate various whole-body movements (Fig. 3).
III. RESULTS

In our experiments, the sensorimotor interactions between the body dynamics with the spinobulbar system modified dynamically the legs coordinations to various behavioral patterns sequentially during the same experiment in a self-organized fashion.

For example, the robot generated dynamically forward movements for several steps (Fig. 4 : left). Then, the robot switched to another pattern by performing backward movements for several steps (Fig. 4 : middle). After a period, it returned back to its previous dynamics and re-generated forward movements (Fig. 4 : right). In terms of each joint angle in the experiment, we observed some phase synchronization and alternance patterns (Fig. 5).

We note that this type of locomotion did not occur always throughout the experiments, which shows the dynamical nature of the system. For instance, in one experiment, we observed that the locomotion was only backward. However, the behavioral movements presented various patterns such as phase synchronization between the left and the right legs or alternance.

IV. EXPERIMENTS

We conducted several experiments to generate a locomotion behavior in a quadruped musculoskeletal robot with a spinobulbar model (Fig. 6 and Fig. 7). In the spinobulbar model, each leg muscle is isolated from each other and has no direct connections. However, we predicted that embodiment would create the conditions for mutual entrainment during interaction with environment in order to generate various and adaptive behavioral patterns.

The artificial muscles were supplied with air from an external air compressor and we used proportional pressure control valves to control the inner pressure of the muscles. The robot was mounted with a CPU board running a real-time OS that sent the pressure commands to the valves and received the sensor values from the pressure sensors and potentiometers. One external PC communicated with the CPU board and computed the neural dynamics.
V. MAIN EXPERIMENTAL INSIGHTS

During the experiments, we observed various and complex locomotion patterns although we used the same parameters for the nervous model. These locomotion patterns were the result of the dynamical coupling of the individual muscles—i.e., which have no direct connections from each others—through the dynamical interaction of body physics and nervous system with the environment. This mechanism of dynamical synchronization explores the natural locomotor patterns of the body which are complex and adaptive to the situation.

In future experiments, we will investigate further the mechanisms underlying the self-organization of behavioral patterns and the required properties of the body and the neural system contributing to them.

REFERENCES