A Fluid-filled Deformable Robot That Exhibits Spontaneous Switching among Versatile Spatio-temporal Oscillatory Patterns Inspired by True Slime Mold

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Abstract: This paper presents a fluid-filled modular robot inspired by a living coupled oscillator system constructed by plasmodium of true slime mold. The robot consists of homogeneous modules which are physically coupled with fluid-filled tubes. Exploiting this physical long distant interaction, the robot is capable to induce versatile oscillatory patterns and transitions between the rich oscillatory patterns in a fully decentralized manner. The simulation results obtained are expected to shed new light on design scheme of life-like robots to reproduce astoundingly versatile and adaptive behaviors.

Keywords: Morphological computation, fluid-driven robot, modular robot, autonomous decentralized control

1. INTRODUCTION

Animals exhibit qualitatively-different versatile behaviors and switch these behaviors according to the situation encountered. This versatility of the behaviors enables animals to reproduce astoundingly adaptive motions in unexpected complex environments. In contrast to this, most robots fail to negotiate with unexpected complex environments as quickly and smoothly as their biological counterparts. One goals of the research described here is to understand how animals generate versatile behaviors and to use these findings to build life-like robots that reproduce truly versatile and adaptive behaviors.

To this end, we have employed a so-called "back-to-basics" approach. More specifically, we have focused on plasmodium of true slime mold. The plasmodium is of interest to biologists as well as roboticists for the following reasons. First, the plasmodium exhibits versatile spatio-temporal oscillatory patterns[1], which is driven by interacting homogeneous elements of the plasmodium in the absence of a central nervous system or specialized organs. Second, and more surprisingly, transitions between the versatile oscillatory patterns occur autonomously[1]. Exploiting this versatility, the plasmodium is thought to be capable to induce adaptive locomotions. Hence, the plasmodium is thought to have archetypal structure to induce the behavioral intelligence, and therefore it is one of the best-simple models to investigate essential for the behavioral intelligence of animals.

One factor that helps the plasmodium exhibit such oscillatory patterns is its reliance on physical communication (morphological computation) stemming from the protoplasmic streaming. The plasmodium employs purely decentralized control mechanisms based on coupled biochemical oscillators similar to CPG, which is physically coupled with tubes filled with the protoplasm. By producing protoplasmic streaming through the tubes, physical long-distance interaction is induced between the oscillators, which is akin to that observed in waterbeds. This physical interaction leads to phase modification on each oscillator based on its pressure from the protoplasm[2]. In light of these facts, the physical interaction stemming from the protoplasmic streaming plays an essential role in creating and switching the versatile oscillatory patterns. Therefore, the purpose of this study is to build such autonomous decentralized system that induce rich oscillatory patterns and to understand archetypal structure to induce such intelligence.

Based on the above considerations, we introduce a fluid-filled modular robot inspired by a living coupled oscillator system constructed by plasmodium of true slime mold. Each module of the robot has a deformable outer skin, stemming from Real-time Tunable Springs (RTSs), filled with fluid. The robot consists of these homogeneous modules which are physically coupled with fluid-filled tubes. Exploiting this physical long distant interaction, the robot is capable to induce surprisingly versatile oscillatory patterns and transitions between them in a fully decentralized manner.

2. THE MODEL

2.1 Mechanical system

The fluid-filled modular robot consists of several modules that are physically connected with tubes (Fig. 1). Each module of the robot is composed of its control system (*i.e.*, decoupled oscillators), a deformable outer skin, and fluid as protoplasm inside the outer skin. The outer skin consists of 4 mass particles and 2 pairs of RTSs that are able to actively alter their resting lengths (*i.e.*, unstretched length of the elastic element). By altering the resting length of each RTS, the protoplasm are pushed and pulled competitively. This physical interaction is simulated by potential constraint on area surrounded by the mass particles on each module. Here, module i contains two de-coupled phase oscillators. According to the

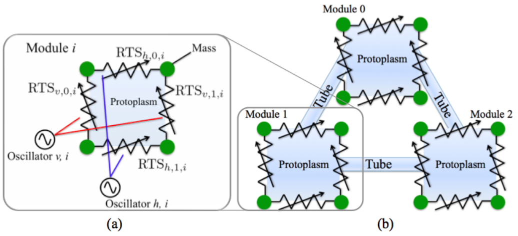

Fig. 1 A schematic of (a) the single module and (b) the robot composed of three modules.

phase, $\theta_{n,i}(n = v, h)$, resting lengths of one pair of $\mathrm{RTS}_{n,m,i}(m = 0, 1)$ are controlled (see Fig. 1 (a)).

2.1.1 RTS

The resting length of $\mathrm{RTS}_{n,m,i}$, $l^{RTS}_{n,i}(\theta_{n,i})$, alters according to $\theta_{n,i}$, and is given by

$$l^{RTS}_{n,i}(\theta_{n,i}) = \bar{l}_{n,i}(1 - a\cos\theta_{n,i}), \tag{1}$$

where a is a constant in space and time and $\bar{l}_{n,i}$ represents the mean length. Depending on its resting length, spring constant $k^{RTS}_{n,i}(\theta_{n,i})$ of $\mathrm{RTS}_{n,m,i}$ varies as follows:

$$k^{RTS}_{n,i}(\theta_{n,i}) = \frac{\alpha_i}{l^{RTS}_{n,i}(\theta_{n,i})}, \tag{2}$$

where α_i is a constant given by the material and geometric properties of the elastic material.

The tension on $\mathrm{RTS}_{n,m,i}$, $T_{n,m,i}$, can be measured by a force sensor, and then the actual length, $l_{n,m,i}$, can be calculated from the following equation:

$$T_{n,m,i} = k^{RTS}_{n,i}(\theta_{n,i})(l_{n,m,i} - l^{RTS}_{n,i}(\theta_{n,i})). \tag{3}$$

RTS is indispensable for this system in terms of the active-passive mechanical feature: by sensing the tension, force from the other RTSs through the protoplasm can be detected as “discrepancy” between the controlled value, $l^{RTS}_{n,i}$, and the actual value, $l_{n,m,i}$.

2.1.2 Protoplasmic streaming

In order to simulate protoplasmic streaming between the modules, area S_i on module i is expressed as

$$\frac{dS_i}{dt} = \sum_j D_{i,j}\{p_j(t) - p_i(t)\}, \tag{4}$$

$$p_i(t) = \lambda \sum_{m=0}^{1} \left(\frac{T_{v,m,i}}{l_{h,m,i}} + \frac{T_{h,m,i}}{l_{v,m,i}}\right), \tag{5}$$

where p_i, p_j are pressure on module i, j respectively, which are connected with the tube, and $D_{i,j}$ is constant that defines fluid conductance of the tube. p_i is calculated based on tension on RTSs. Eqs. (4), (5) express protoplasmic streaming between module i and module j via the tube based on the pressure difference and fluid conductance.

2.2 Control system

Here, we introduce the dynamics of the oscillator model to be implemented in each pair of RTSs. The equation of the oscillator is expressed as

$$\frac{d\theta_{n,i}}{dt} = \omega - \frac{\partial}{\partial\theta_{n,i}}\left(\frac{\sigma}{2}\sum_{m=0}^{1} T^2_{n,m,i}\right) + \xi_{n,i}(t), \tag{6}$$

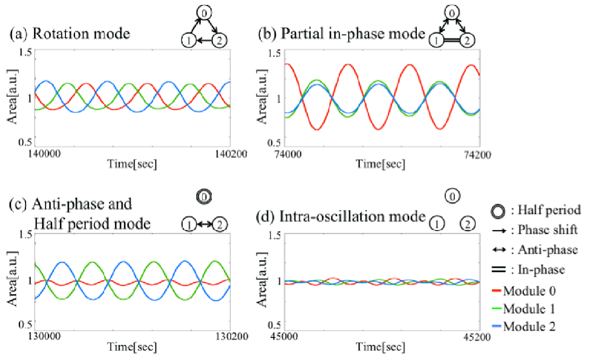

Fig. 2 Oscillatory patterns in three modules. Schematic diagrams of phase relations among three oscillators are indicated at upper right of the plots. A double circle shows that the corresponding module has double frequency. Relationships between two modules are indicated by $=$: in phase; $\rightarrow$: $\frac{2\pi}{3}$ phase shift; $\leftrightarrow$: anti phase.

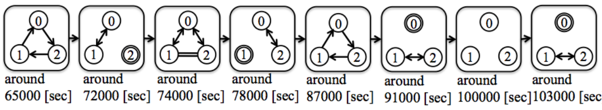

Fig. 3 Transitions between the several oscillation modes.

where ω is the intrinsic frequency of the oscillators, the second term is local sensory feedback so as to reduce the discrepancy (*i.e.*, tension on RTS) [2], and the third term is faint noise.

3. SIMULATION RESULTS

In order to confirm the validity of the model, we conducted simulation experiment on 3 modules[1] (see Fig. 2 and Fig. 3). As can be seen in Fig. 2, we confirmed 4 oscillatory patterns: (a) Rotation mode, (b) Partial in-phase mode, (c) Anti-phase and Half period mode, (d) Intra-oscillation mode[2]. More surprisingly, we confirmed transition between them as shown in Fig. 3.

4. CONCLUSION

A fluid-filled modular robot which exhibits versatile oscillatory patterns and transition between them without the need of any hierarchical structure were presented.

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[1] The parameters of the robot are as follows: $\alpha_0 = 10.0$ [a.u.]; $\alpha_1 = 10.0$ [a.u.]; $\alpha_2 = 11.0$ [a.u.]; $\sigma = 0.003$ [a.u.]; $\theta_{n,0}(t = 0) = \pi/4$ [rad]; $\theta_{n,1}(t = 0) = 0.0$ [rad]; $\theta_{n,2}(t = 0) = \pi/4$ [rad]; $D_{i,j} = 0.01$ [a.u.].

[2] The names of the oscillatory patterns (a), (b), and (c) were determined by reference to Takamatsu’s work [1].