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Synchronized swimming: adaptive gait synchronization through mechanical interactions instead of communication

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1 Introduction

Many microorganisms are capable of synchronizing their body or appendage motion for locomotion or for driving fluid flows. For small organisms such as bacteria the synchronized motion of cilia [1] and flagella [2] are driven by fluid-mechanical interactions. However, in larger organisms such as the worm *C. elegans* fluid interactions are less important and recent studies have determined that intermittent mechanical contact among organisms is responsible for synchronization [3]. Even for smaller systems contact interactions may be important in high population swarms [4]. In this abstract we present a neuromechanical hypothesis for emergent synchronization through contact and we demonstrate this in experiments with undulatory robot swarms.

The worm *C. elegans* moves by generating a traveling wave of body bending along its body, traveling from head to tail. Recent studies have determined that intermittent mechanical contact is responsible for synchronization of the undulatory gaits of groups [3]. Biomechanical and neural experiments have demonstrated that the generation of this wave is largely through local proprioceptive reflex responses along the body that sense the local body bending and generate a bending actuation in response [5]. Thus, the propagation of the body bending wave occurs as a “reflex chain” in which the wave propagation doesn’t involve communication between oscillators and instead responds only to the bending state of the local body region. Experiments have demonstrated this local oscillator principle by isolating regions of the body and showing that a propagating wave is halted at a body region where bending is inhibited.

We hypothesize that local reflex responses from body bending can enable synchronization of bending movement between neighboring swimmers that make contact with each other. When two undulatory swimmers make contact they will inhibit the bending motion and thus will cause a phase disruption to the swimming gait. The ability for these systems to adjust each other’s phase through contact may give rise to synchronization phenomena. Critically this process would not require communication between the systems and thus could greatly simplify coordination of robot groups. In the following we will demonstrate theoretically and experimentally that bending joints with only self position and velocity (proprioceptive) feedback can synchronize. We further demonstrate how an inhibitory versus excitatory proprioceptive gain controls whether robots synchronize to in-phase versus anti-phase motion. We lastly demonstrate how this is useful for emergent coordination of snake-like robots to traverse narrow gaps.

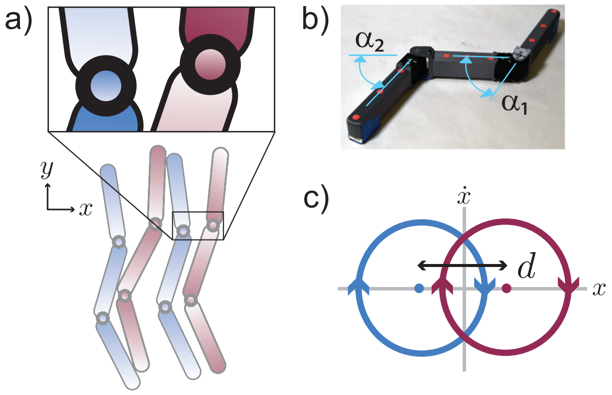

Figure 1: a) A collective of three-link robots that coordinate the motion of their joints (expanded view) through emergent synchronization. b) A picture of the robot used in experiment. c) The oscillatory motion of the gaits can be considered as constant radius limit cycles with a robot separation distance of d.

2 Body oscillation control

We study and perform experiments with a simplified system capable of undulatory motion, a three-link swimmer. Each robot has two joints which have angles α_1 and α_2. The generation of body oscillations are controlled through a local phase oscillator

$$\dot{\phi}_i = \omega \pm \lambda f(\phi_i, \phi_j) + \gamma g(\phi_i, \tilde{\phi}_i) \tag{1}$$

which has two regulation terms: 1) an inter-joint regulation that controls the phase offset between the joints 1 and 2, $f(\phi_1, \phi_2)$, and 2) proprioceptive feedback which compares the commanded phase of the joint ϕ_i to the measured phase $\tilde{\phi}_i$, $g(\phi_i, \tilde{\phi}_i)$

$$f(\phi_i, \phi_j) = \sin(\phi_j - \phi_i - \Delta\phi) \tag{2}$$
$$g(\phi_i, \tilde{\phi}_i) = \sin(\phi_i - \tilde{\phi}_i) \tag{3}$$

Lastly, the joint motions are generated by PID controlled servos that take position trajectories and can report back in-

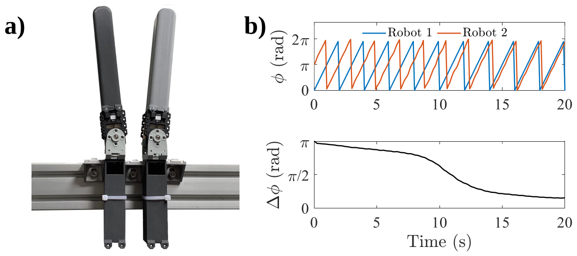

Figure 2: a) An overhead picture of two fixed robot joints synchronizing through contact. b) Kinematic phases of two joints (Top). Phase difference of two joints decreases as they synchronize through contact (Bottom).

stantaneous joint angle. The control and measurement variables are as follows

$$\theta_i = A\cos(\phi_i) \tag{4}$$

$$\tilde{\phi}_i = \arctan\left(-\frac{\dot{\theta}_i/\omega}{\theta_i}\right) \tag{5}$$

where A is the desired amplitude of joint oscillation. The difference between measured phase $\tilde{\phi}_i$ and internal phase ϕ_i is used to sense contact interactions among robots. Critically, in the phase regulation equations there is no robot-robot communication and the feedback only takes into account the phases of the individual robot kinematics.

3 Synchronization is controlled by proprioceptive gain

The feedback regulation function, $g(\phi_i, \tilde{\phi}_i)$, is multiplied by a single proprioceptive gain term γ. Here we demonstrate that two robot joints that make contact will synchronize to in-phase or anti-phase synchronization dependent on the sign and magnitude of γ. While a formal proof of robot-robot synchronization cannot fit within this manuscript one can demonstrate that for $0 < \gamma < \omega$ joints will asymptotically synchronize to the same phase through contact.

In figure 2 we show results from experiments of single joints actuated using equation 1. When $0 < \gamma < \omega$ we observe that joints always achieve in-phase synchronization of movement. The magnitude of γ controls speed of the synchronization process. However, if γ exceeds ω the synchronization dynamics break down because the oscillatory motion of the robot is no longer smooth. When $\gamma < 0$ the robot joints are driven to anti-phase synchronization and a $\gamma = 0$ puts the control into a purely feedforward form with no feedback and the dynamics equations can be trivially integrated to resolve the time-dependent actuation.

4 Synchronization enhances channel traversal

In a final demonstration we show how synchronization can enable robots to form close-proximity undulatory gaits and squeeze through a narrow channel (Fig. 3). The robots we use for locomotion studies have four links and the joint-control equations are the same as with three links, namely the proprioceptive phase regulation function is identical and the joint-joint phase regulation function is modified to just account for adjacent joints.

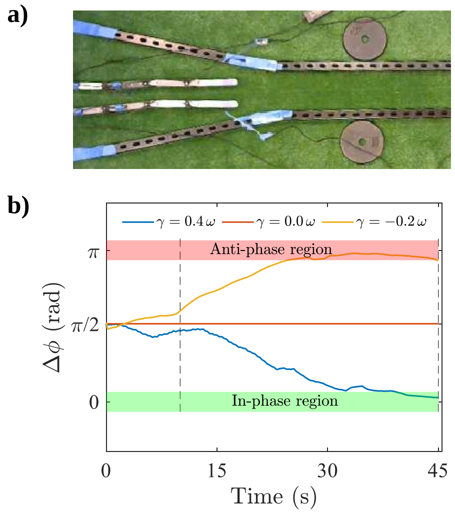

Figure 3: a) An overhead picture of two robots challenged to move through a narrow channel. b) Relative phases between the two robot showing: in-phase synchronization at $0 < \gamma < \omega$, anti-phase synchronization at $\gamma < 0$, and non-feedback at $\gamma = 0$.

The robots have snake-skin inspired structures placed on the bottom of their bodies which are angled plastic fins that generate anisotropic friction in the fore-aft direction. The lateral friction force is relatively low. These structures enable the robots to move forward through body undulation. We perform experiments on an artificial grass substrate which also helps in generating forward locomotion.

We observe in experiments that two robots are capable of synchronization through intermittent contact as our simple model predicts. Experiments with $0 < \gamma < \omega$ allowed robots to synchronize their motions to traverse the narrow channel. In experiments with $\gamma < 0$ the robots were not able to generate a synchronized behavior which is likely because anti-phase motion causes the robots to push each other away.

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