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

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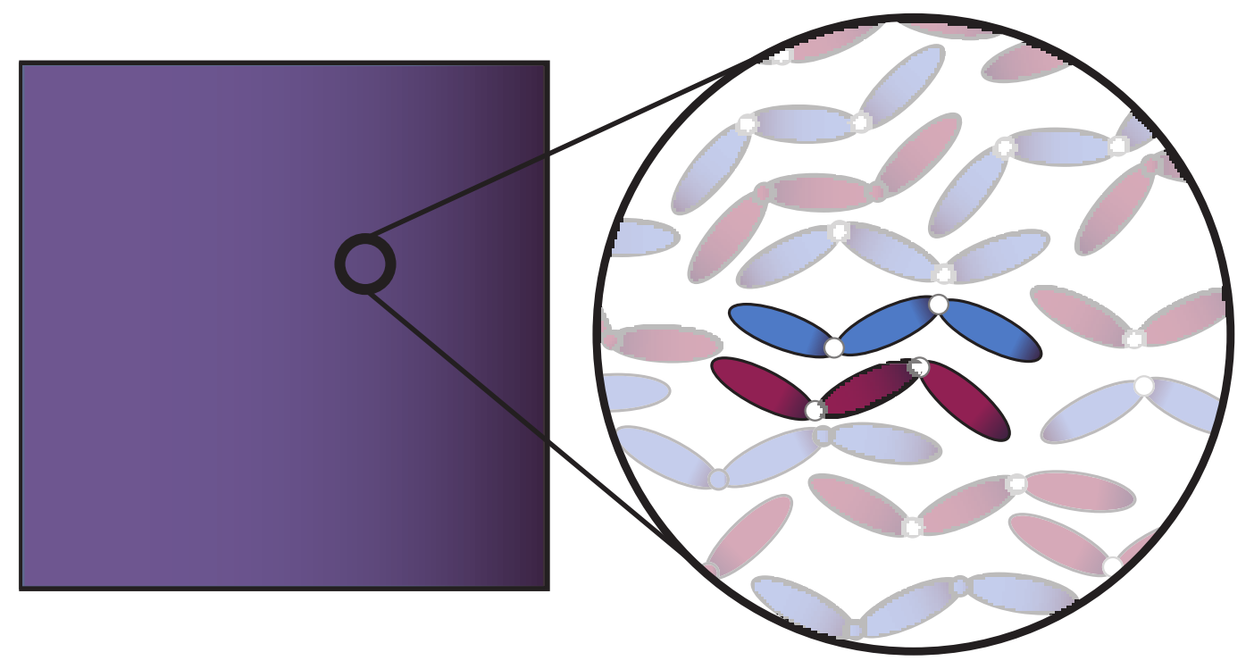
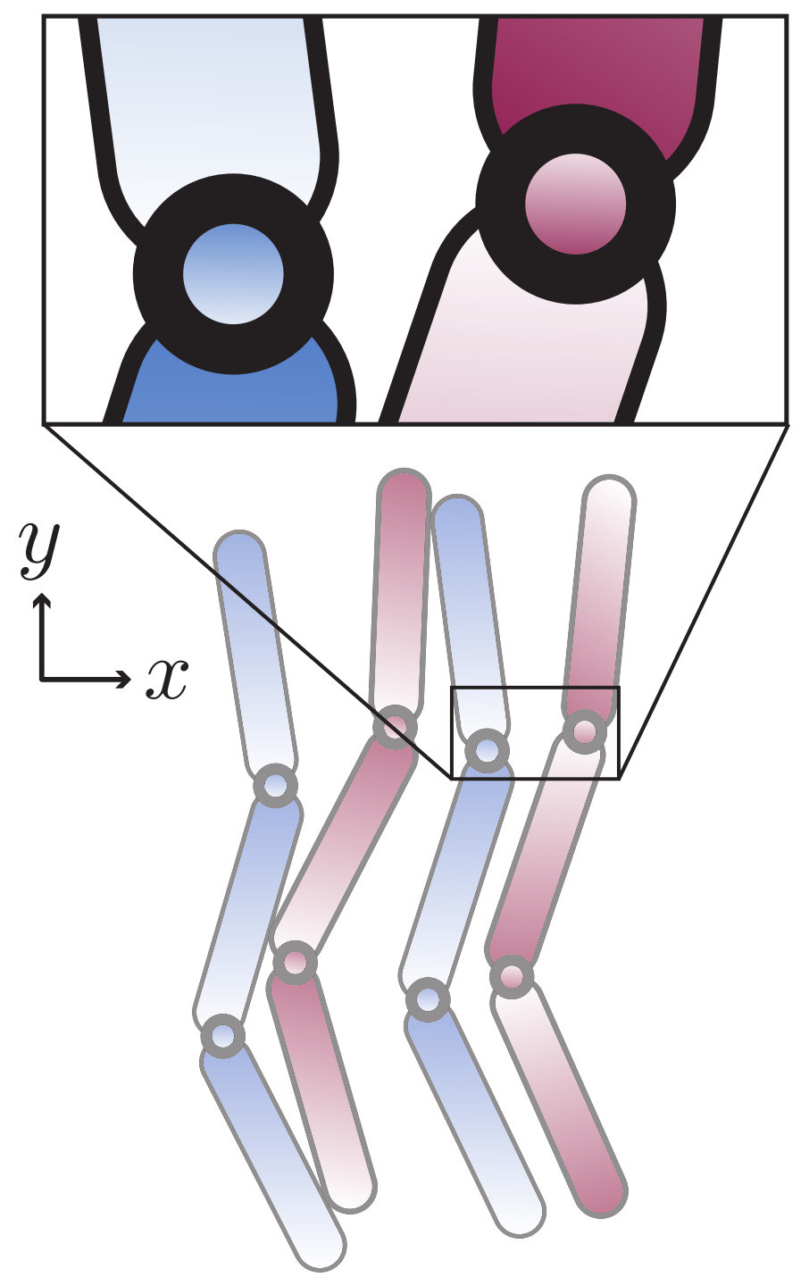
Introduction

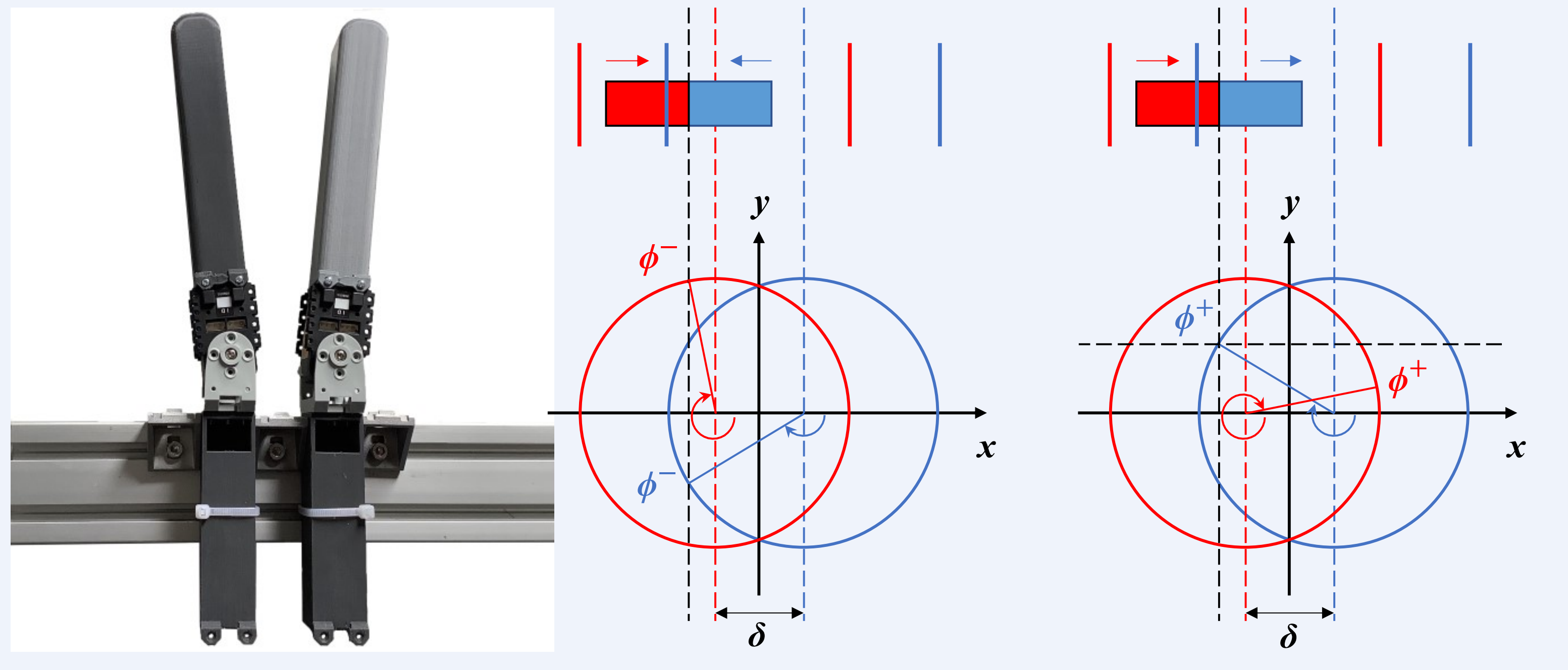


Many microorganisms are capable of synchronizing their body or appendage motion for locomotion or for driving fluid flows [1-2].
Recent studies have determined that intermittent mechanical contact among organisms is responsible for synchronization in larger organisms [3-4].



We present a neuromechanical hypothesis for emergent synchronization through contact and demonstrate the robot-robot interaction by means of limit cycle in a simplified system as below. Further, the control law is executed on multi-link robot system for experimental purpose.

Toy model with limit cycle demonstration



Collision position

$$x < -\frac{\delta}{2}$$

Contact condition

$$r\cos(\pi - \phi_2^-) - r\cos(\phi_1^- - \pi) = \delta$$

$$\Leftrightarrow r\cos\phi_1^- - r\cos\phi_2^- = \delta$$

Separation condition

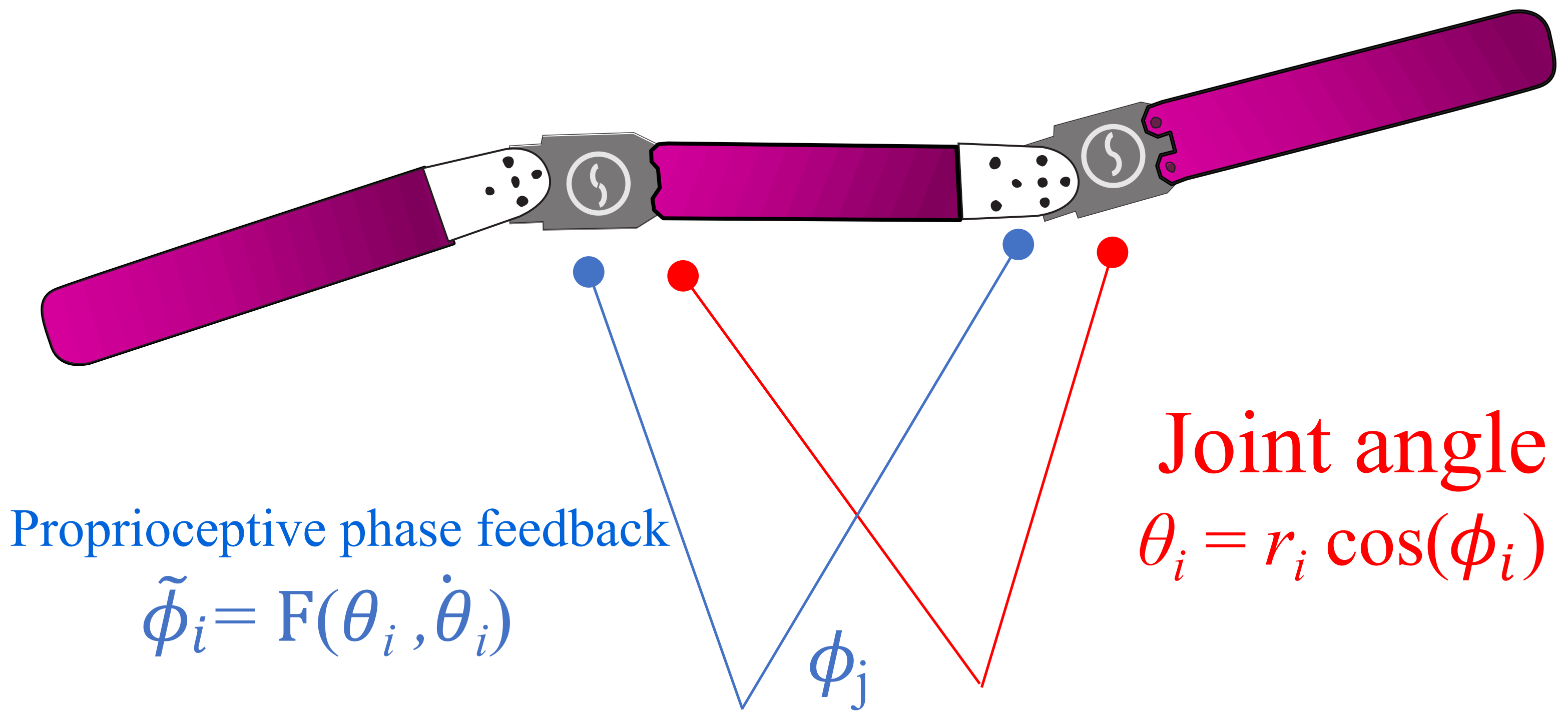
$$\text{(a) } \phi_2^+ = 2\pi - \phi_2^-$$

$$\text{(b) } \sin\phi_1^+ < \sin\phi_2^+$$

Joint oscillations are controlled by a phase oscillator or limit cycle, when joints collide their position (x-axis) is equal and they will be in contact until the oscillator phases reach the separation condition.

Body oscillation control

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:



$$\boxed{\begin{aligned} \dot{\phi}_i &= \omega \pm \lambda f(\phi_i, \phi_j) + \gamma g(\phi_i, \tilde{\phi}_i) \\ \dot{r}_i &= r_i(\mu - r_i^2) \end{aligned}}$$

Inter-joint regulation

$$f(\phi_i, \phi_j) = \sin(\phi_j - \phi_i - \Delta\phi)$$

Proprioceptive feedback

$$g(\phi_i, \tilde{\phi}_i) = \sin(\phi_i - \tilde{\phi}_i)$$

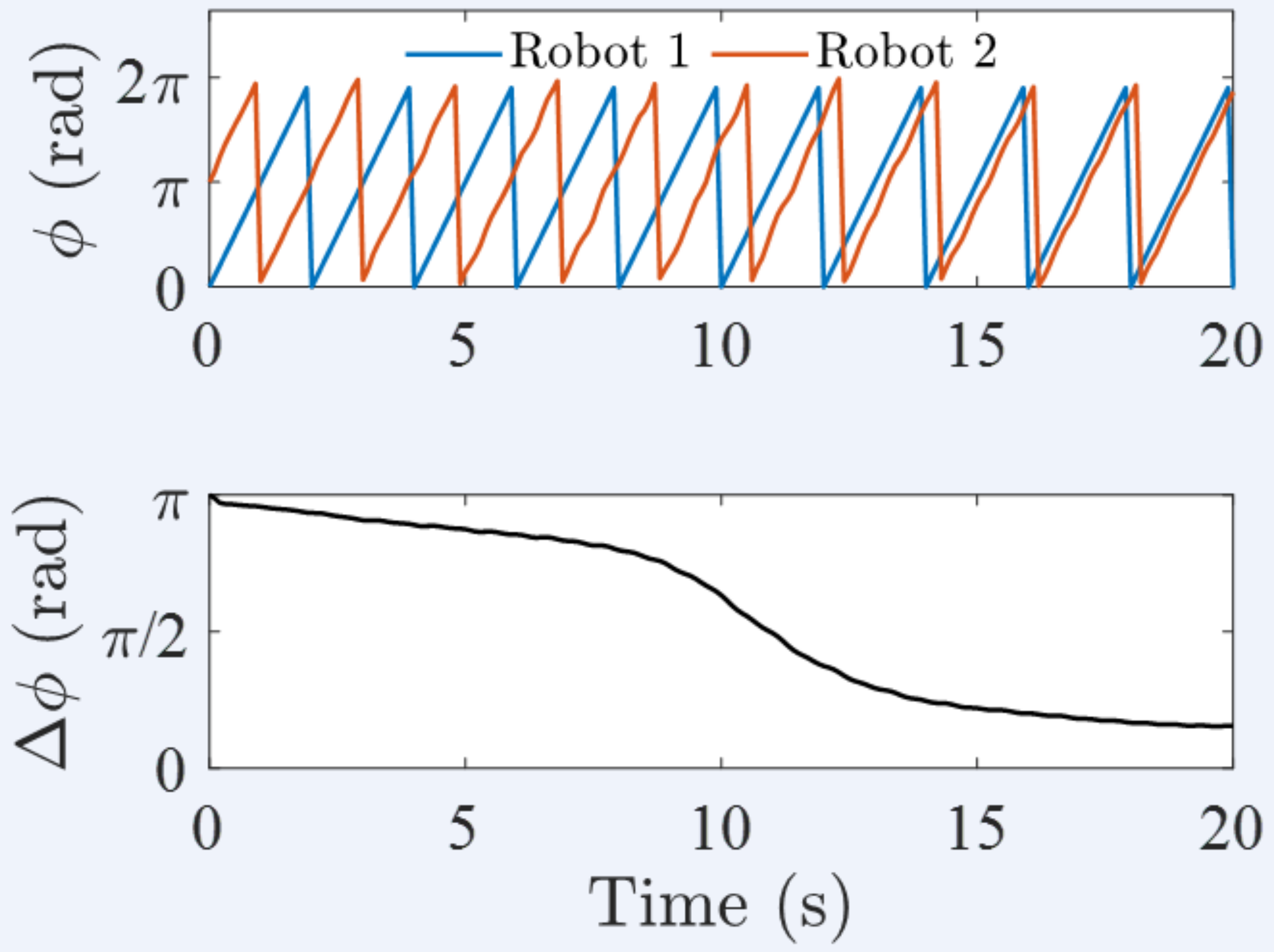
Measured phase

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

The difference between measured phase and internal phase is used to sense contact interactions among robots. Critically, in the regulation equations there is no robot-robot communication and the feedback only takes into account the phases of the individual robot kinematics.

Synchronization is controlled by proprioceptive gain

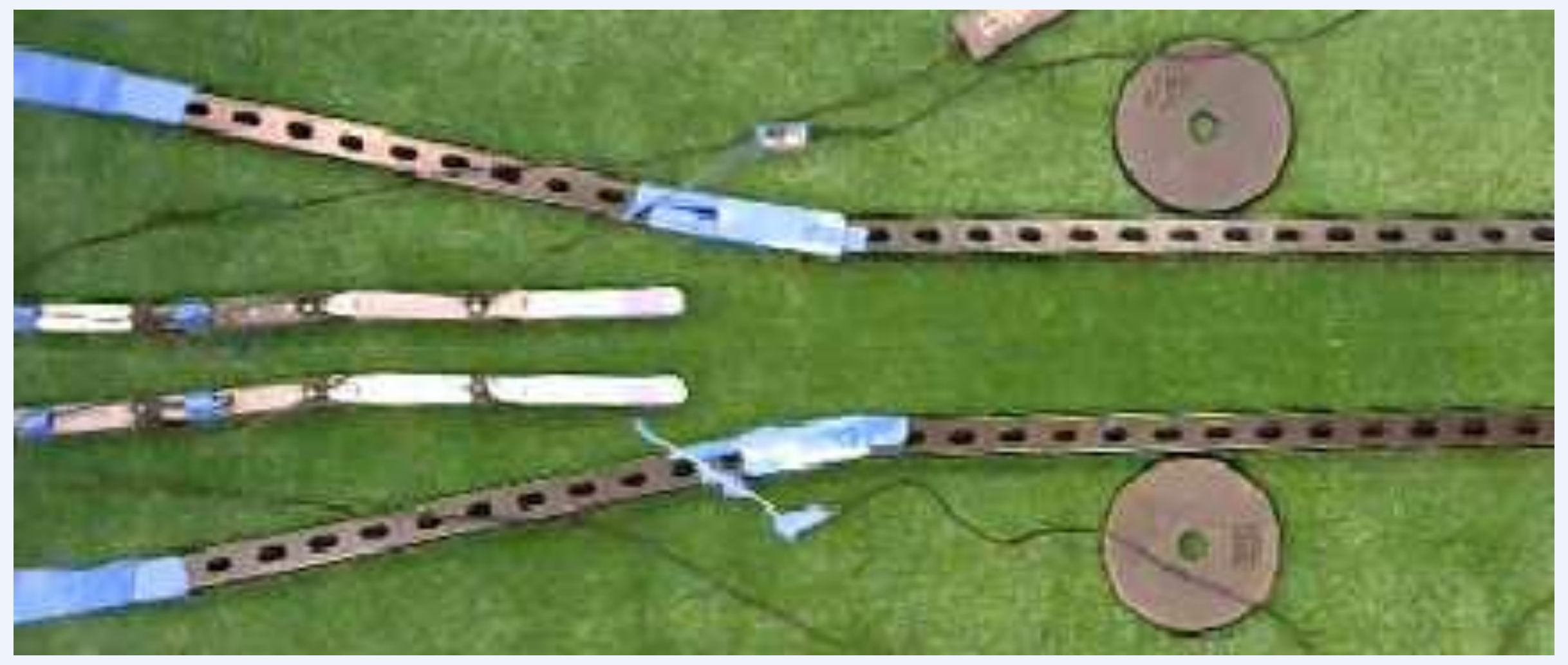
Robot joints synchronize through contact when proprioceptive gain is $0 < \gamma < \omega$

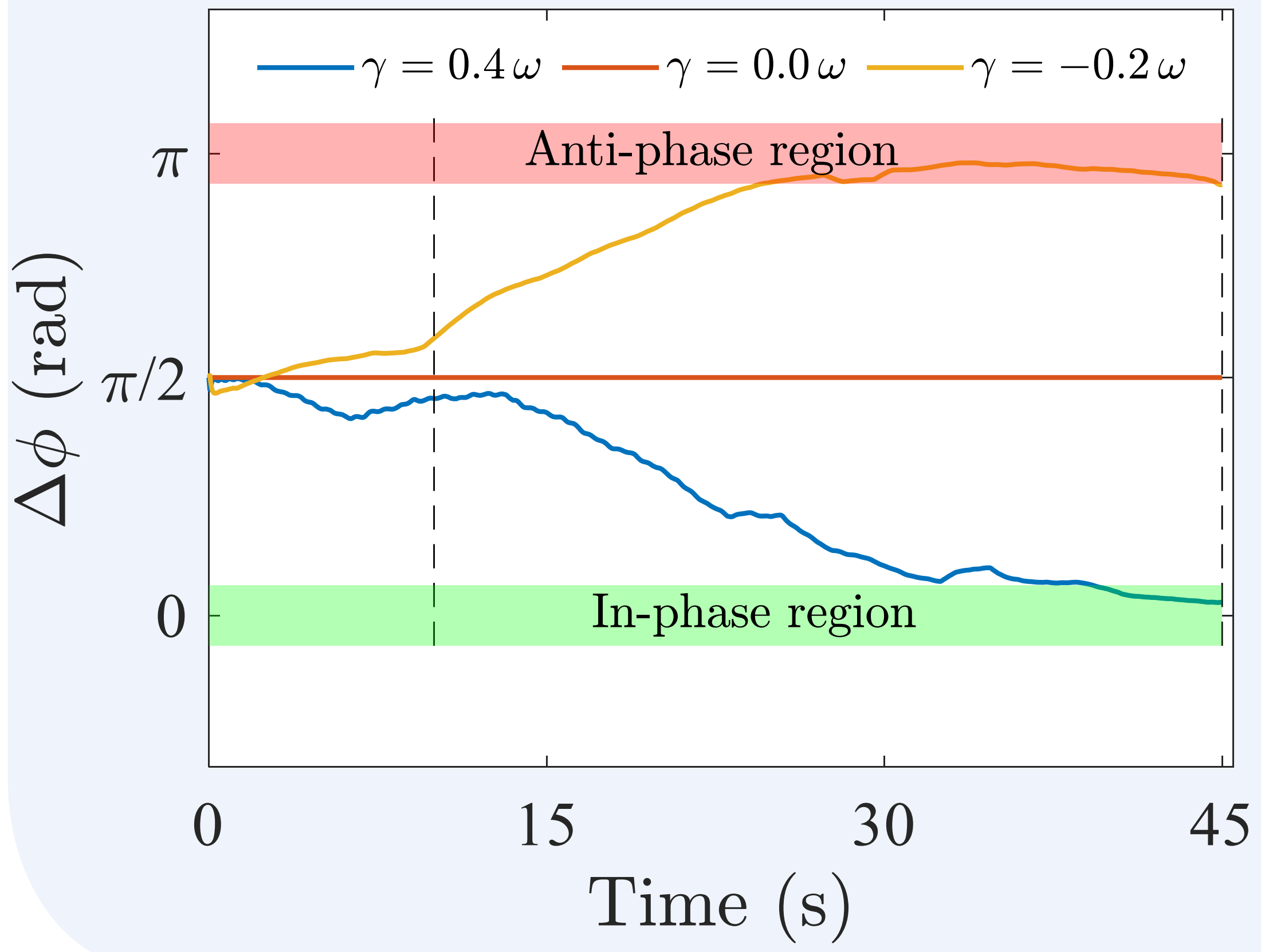


Phase difference of two joints decreases as they synchronize.

Synchronization enhances channel traversal

Channel traversal





Two robots challenged to move through a narrow channel. Relative phase change between the two robots showing:

- in-phase sync at 0 < γ < ω
- anti-phase sync at γ < 0
- non-feedback at γ = 0

[1] Jens Elgeti and Gerhard Gompper. Emergence of metachronalwaves in cilia arrays. Proc. Natl. Acad. Sci. U. S. A., 110(12):4470–4475, March 2013.
[2] Gwynn J Elfring and Eric Lauga. Hydrodynamic phase locking of swimming microorganisms. Phys. Rev. Lett., 103(8):088101, August 2009.
[3] Jinzhou Yuan, David M Raizen, and Haim H Bau. Gait synchronization in caenorhabditis elegans. Proc. Natl. Acad. Sci. U. S. A.,111(19):6865–6870, May 2014.
[4] Raghunath Chelakkot, Michael F Hagan, and Arvind Gopinath. Synchronized oscillations, traveling waves, and jammed clusters inducedby steric interactions in active filament arrays. Soft Matter, December 2020.