Optimal Actuation in a Peristaltic Crawler

Presenter: Andrew Gusty
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(1) Kernbaum, Alexander & Shaw, Kendrick & Chiel, Hillel & Quinn, Roger. (2012). Continuous wave peristaltic motion in a robot. International Journal of Robotic Research - IJRR. 31. 302-318. 10.1177/0278364911432486.

Purpose

- Our lab is interested in the efficient control of systems with wave-like dynamics
- An example of such a system is a *peristaltic crawler*
- My objective is to uncover the optimal actuation of such crawlers

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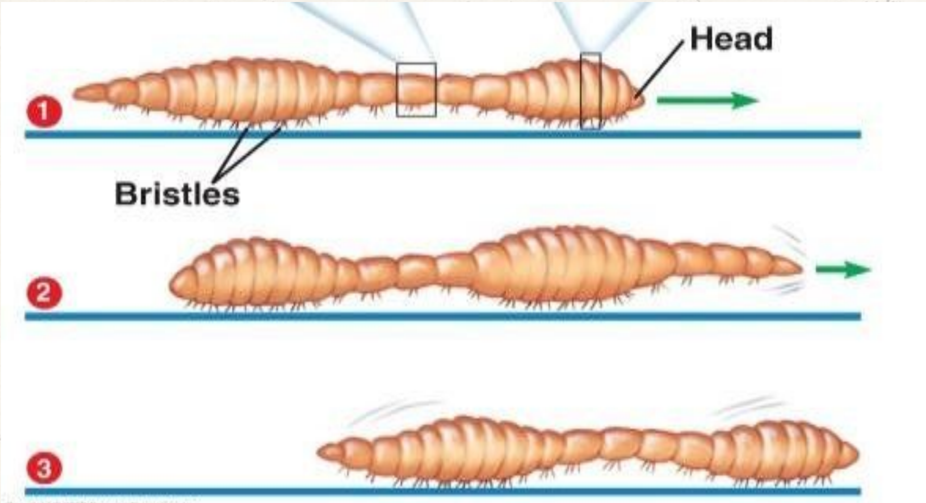
Peristaltic Motion



Longitudinal Waves + Friction Control = Movement

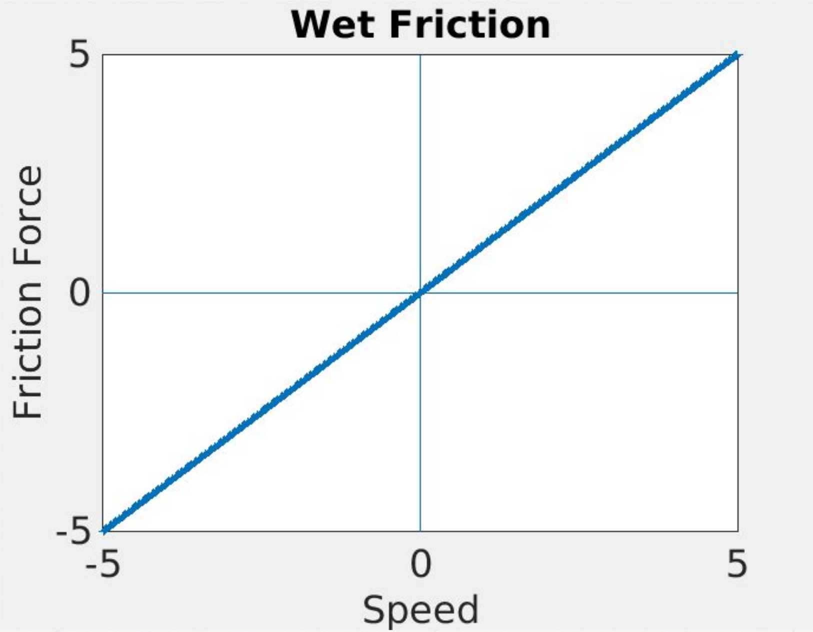
(2) Niu el al. (2015). Enabling earthworm-like soft robot development using bioinspired IPMC-scissor lift actuation structures: Design, locomotion simulation and experimental validation.

Equation of Motion

$$\underbrace{A_c E \frac{\partial^2 u}{\partial x^2}}_{\text{Elastic}} + \underbrace{A_m \frac{\partial f}{\partial x}}_{\text{Muscular}} - \underbrace{F\left(\frac{\partial u}{\partial t}\right)}_{\text{Friction}} - \underbrace{\rho \frac{\partial^2 u}{\partial t^2}}_{\text{Inertial}} = 0$$

Notation	**Definition**	**Units**
u	Displacement	m
x	Space	m
t	Time	seconds
f	Muscle Stress	$\frac{N}{m^2}$
E	Young's modulus	Pa
A_c	Body's cross-sectional area	m^2
A_m	Muscle's cross-sectional area	m^2
ρ	Density	kg/m

Modeling Friction



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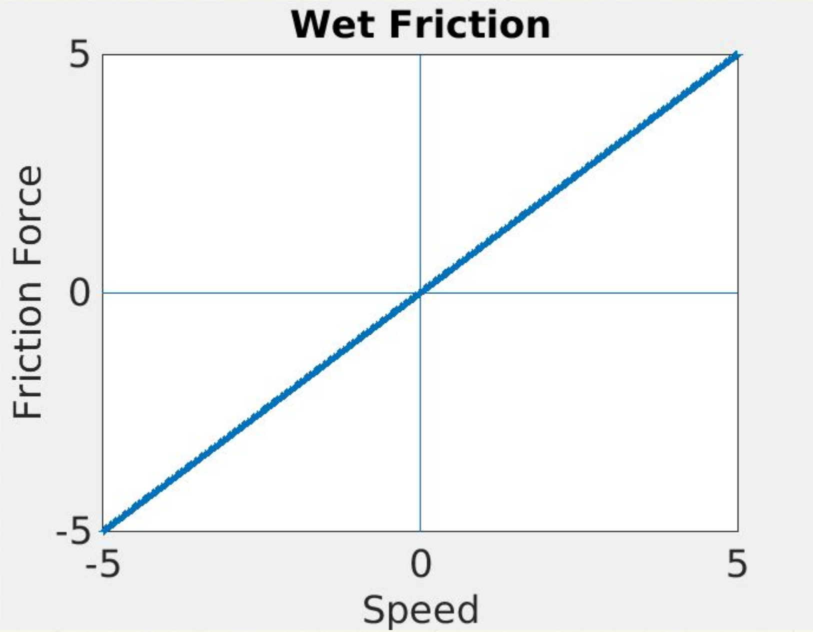
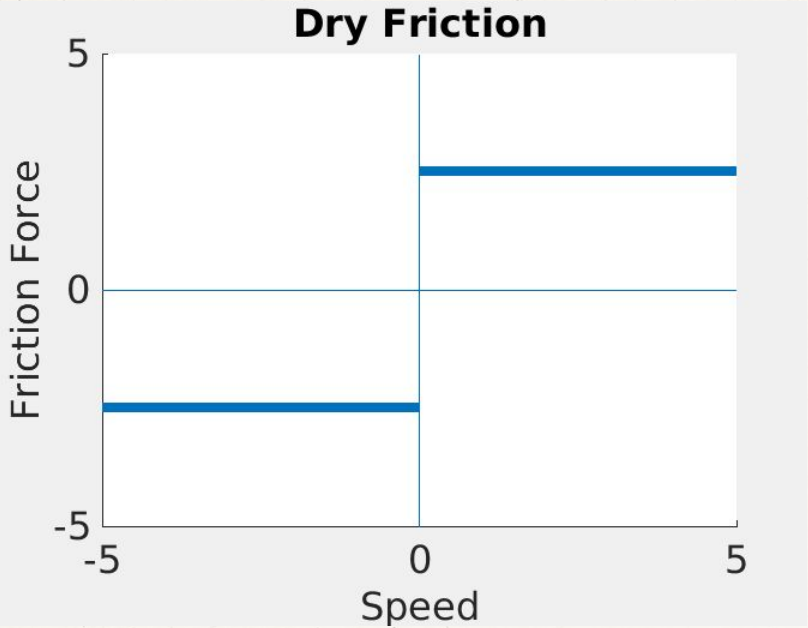
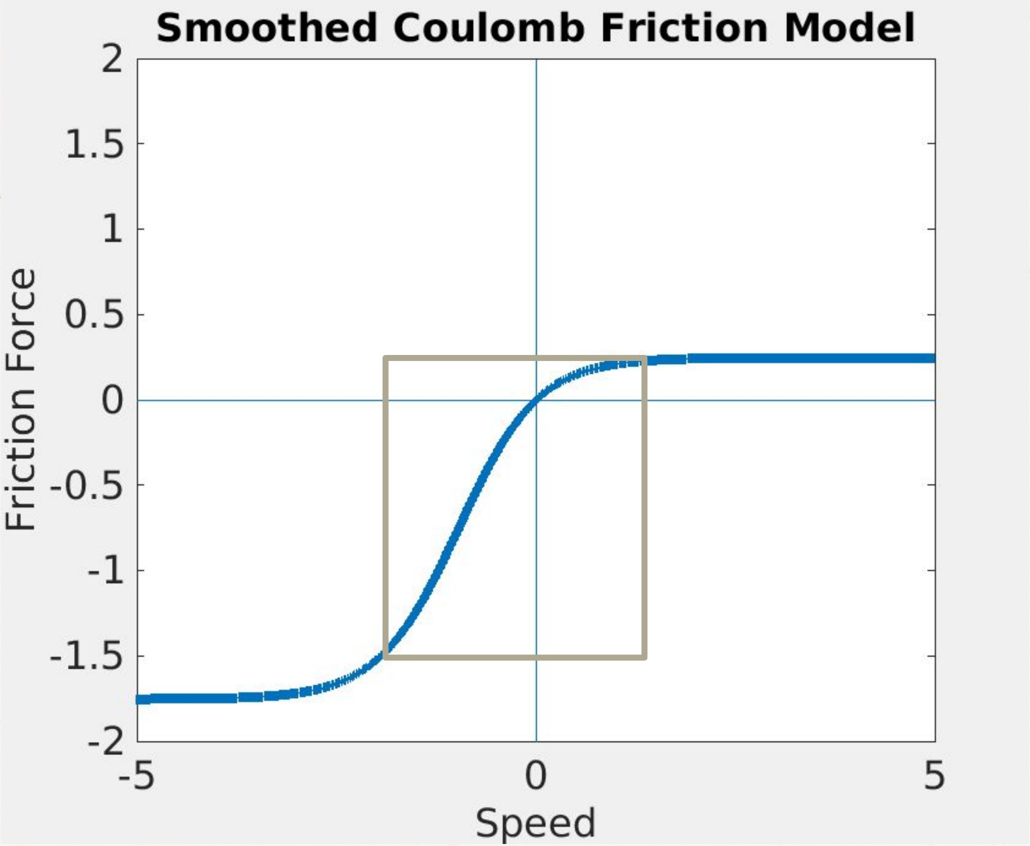




Friction Model

- Asymmetry creates preferential direction of motion
- Incorporates features of dry and wet friction
- Fairly realistic at small velocities
- Model permits Taylor Series approximation



(3) Review and Comparison of Dry Friction Force Models *E. Penestri et al. (2016)*

Adding Friction to the Model

$$F(u_t) = \frac{1}{\epsilon} F_{max} \left(\tanh\left(\epsilon u_t - u_0 \right) - n_F \right)$$

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$$\underbrace{A_c E \frac{\partial^2 u}{\partial x^2}}_{\text{Elastic}} + \underbrace{A_m \frac{\partial f}{\partial x}}_{\text{Muscular}} - \underbrace{c_F u_t}_{\text{Wet Friction}} + \underbrace{\epsilon (c_F n_F) u_t^2}_{\text{Dry Friction}} - \underbrace{\rho \frac{\partial^2 u}{\partial t^2}}_{\text{Inertial}} = 0$$

Perturbation Theory

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$$\left(A_c E \partial_x^2 - c_F \partial_t - \rho \partial_t^2\right) u^{(0)} = \frac{\partial f(x,t)}{\partial x}$$

$$\left(A_c E \partial_x^2 - c_F \partial_t - \rho \partial_t^2\right) u^{(1)} = c_F n_F (u_t^{(0)})^2$$

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Muscular Force

Periodic function that drives the motion of the crawler

$$f(x,t) = f_0 \sin(\omega t - kx)$$

Three Parameters:

- f_0: strength of contractions
- ω: frequency of contractions
- k: wave number

Crawler Efficiency

$$\text{Velocity} = \frac{1}{\lambda}\int_0^{\lambda} u_t^{(1)}\, dx$$

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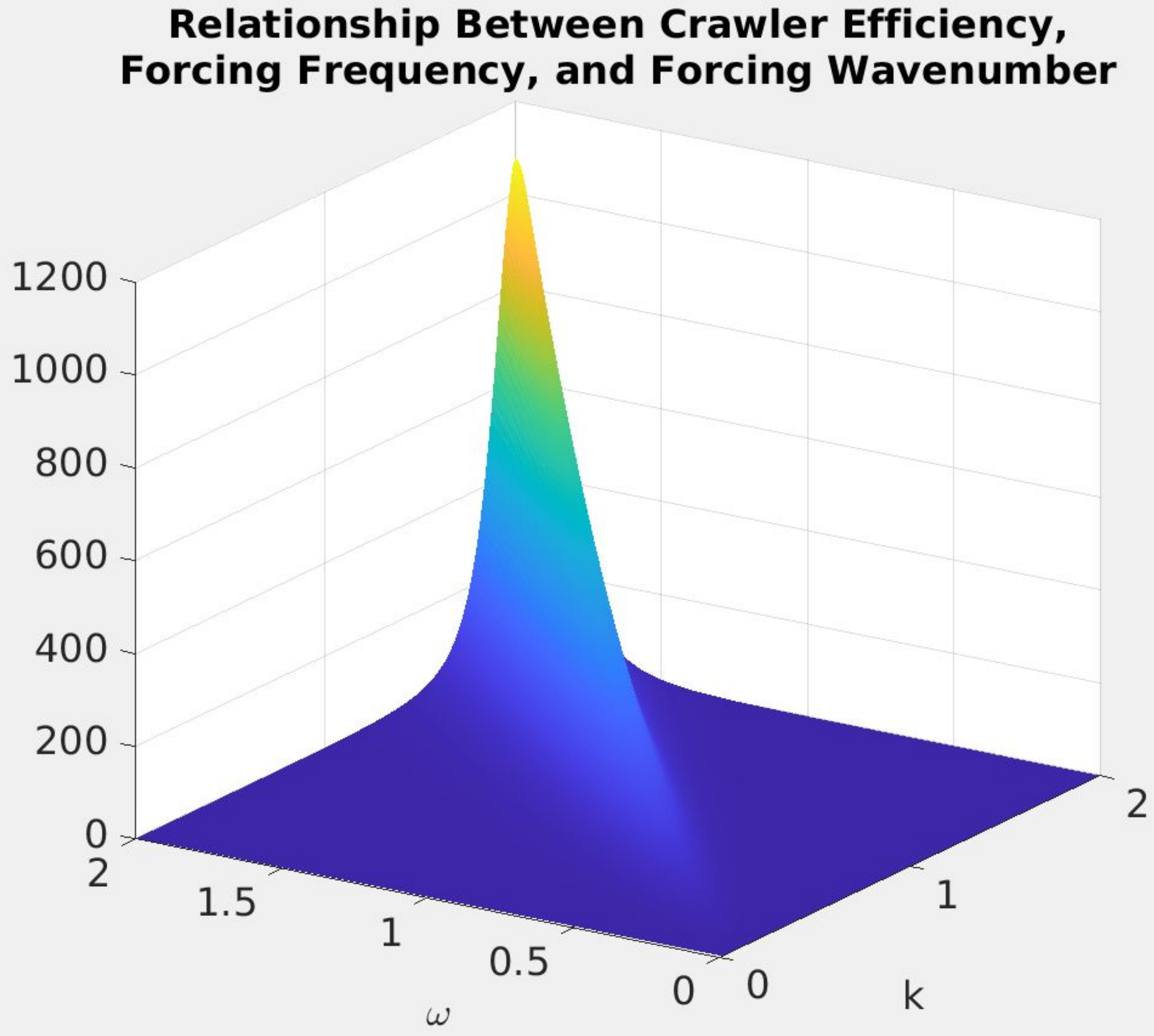
$$\text{Velocity} = \frac{1}{\lambda} \int_0^\lambda u_t^{(1)} \, dx$$

$$||\text{Force Input}||^2 = \int_0^\lambda (f(x,t))^2 \; dx$$

Crawler Efficiency

$$\text{Efficiency} = \frac{||\text{Velocity}||^2}{||\text{Force Input}||^2}$$



Main Result

- Optimal relationship between ω and k is linear
- Efficiency does not depend on f_0
- Slope of optimal line depends on other parameters (which are set to unity in this graph)

Conclusions and Future Work

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- Uncovered relationship between forcing frequency and wavelength

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Future Work

- Numerical methods for better approximation of dry friction
- Dimensional analysis of parameters
- Use these results for distributed control of peristaltic crawlers

Acknowledgements

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Questions