Towards Effective and Efficient Sensing-Motion Co-Design of Swarming Cyber Physical Systems

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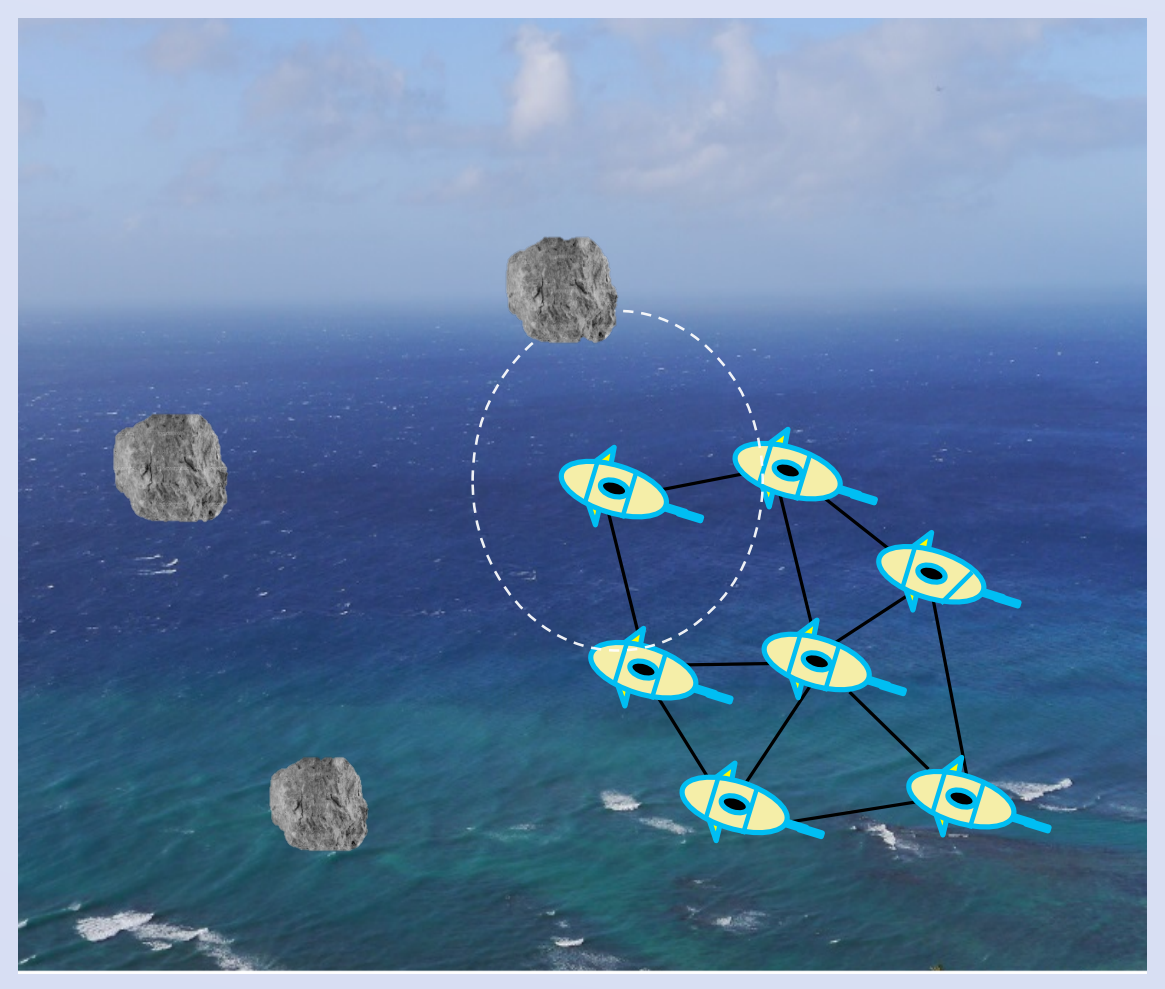
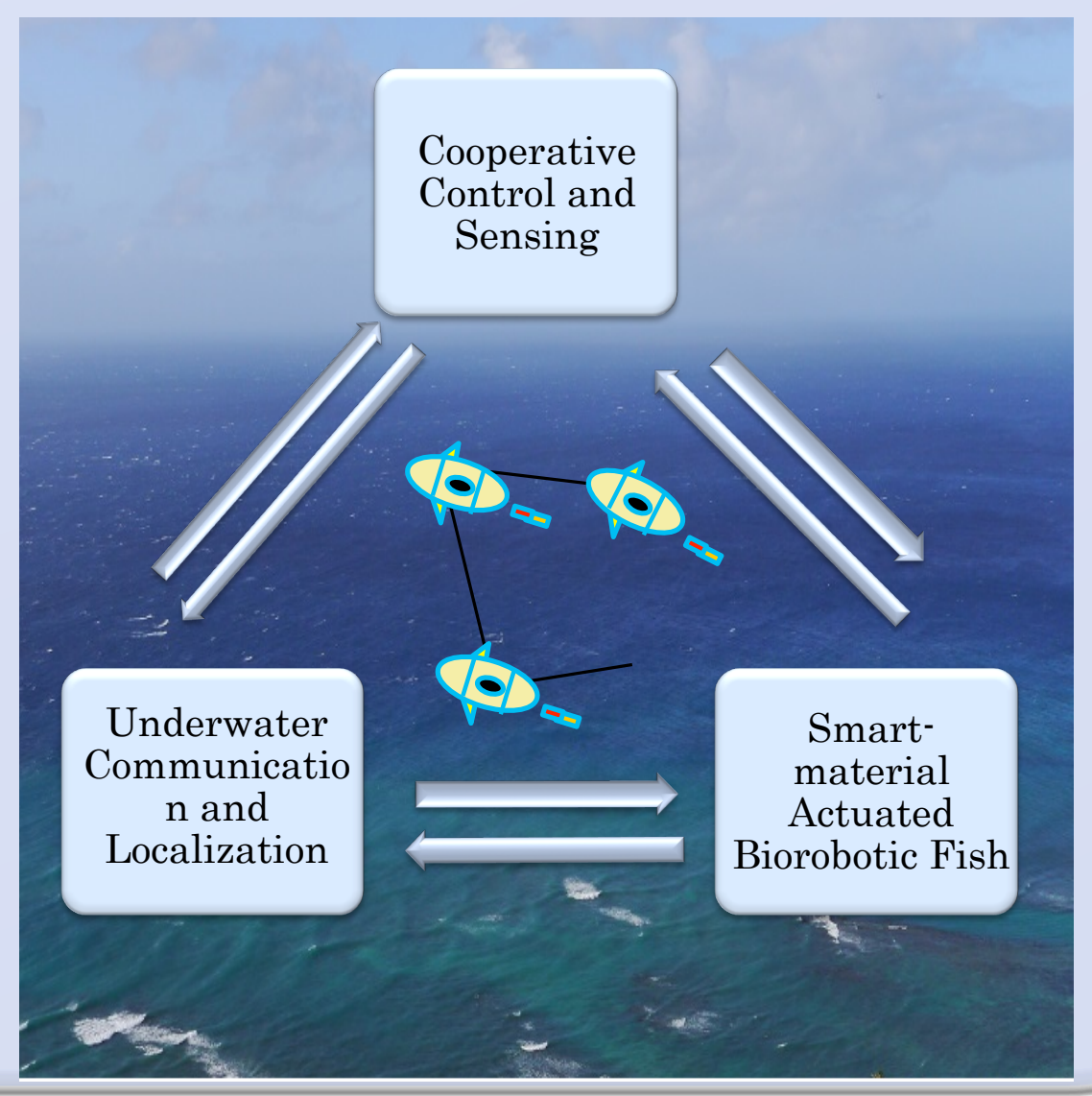
Motivations and Challenges

- Complex and strongly coupled sensing-motion dynamics of swarming CPS
- Inherent environmental uncertainties such as communication delay and package loss, unpredictable and/or confined spaces, and highly spatially and temporally varying environments
- Resource constraints of mobile computing entities such as limited computational power, communication capability, and sensing ability



Objectives

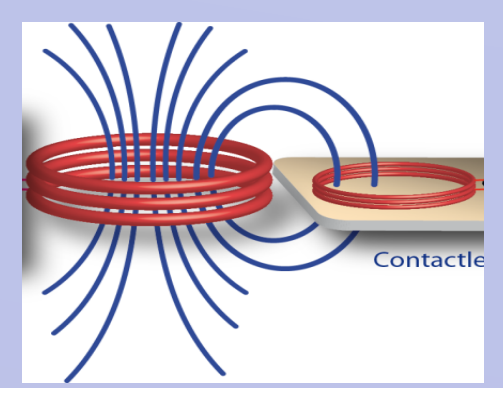
- The overall research objective is to establish and demonstrate a generic motion-sensing co-design procedure that
  - significantly reduces the complexity of mission design for swarming CPS
  - greatly facilitates the development of effective and efficient control and sensing strategies, which are computation efficient, communication light, and adaptive to various environment uncertainties

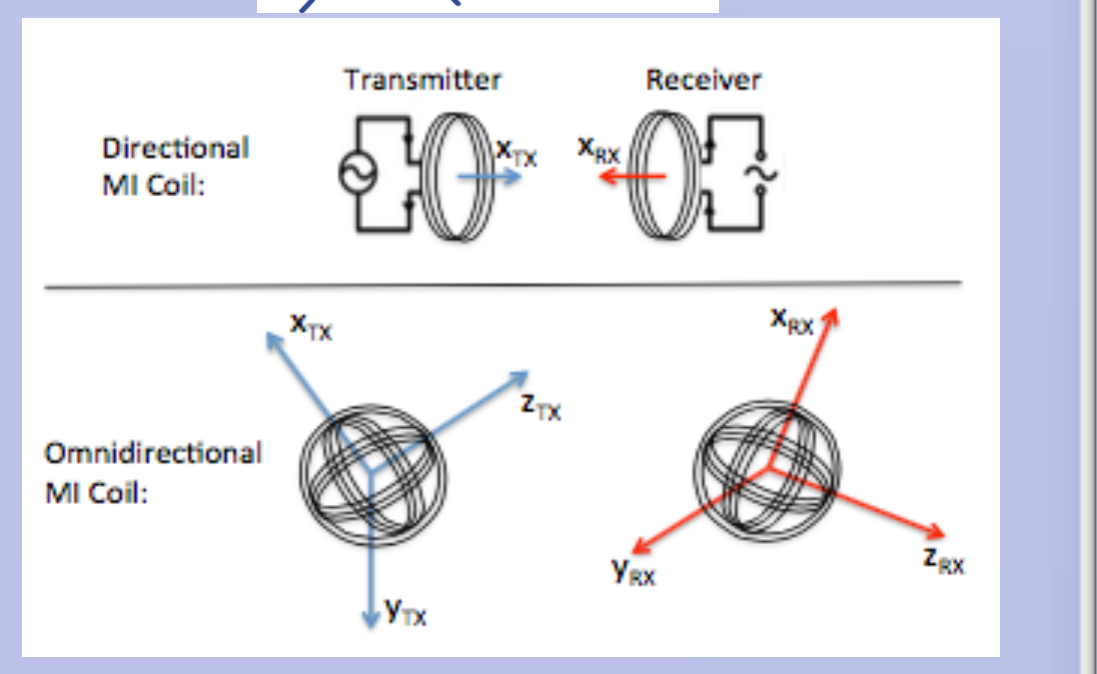


MI Underwater Communications & Localization

Overview

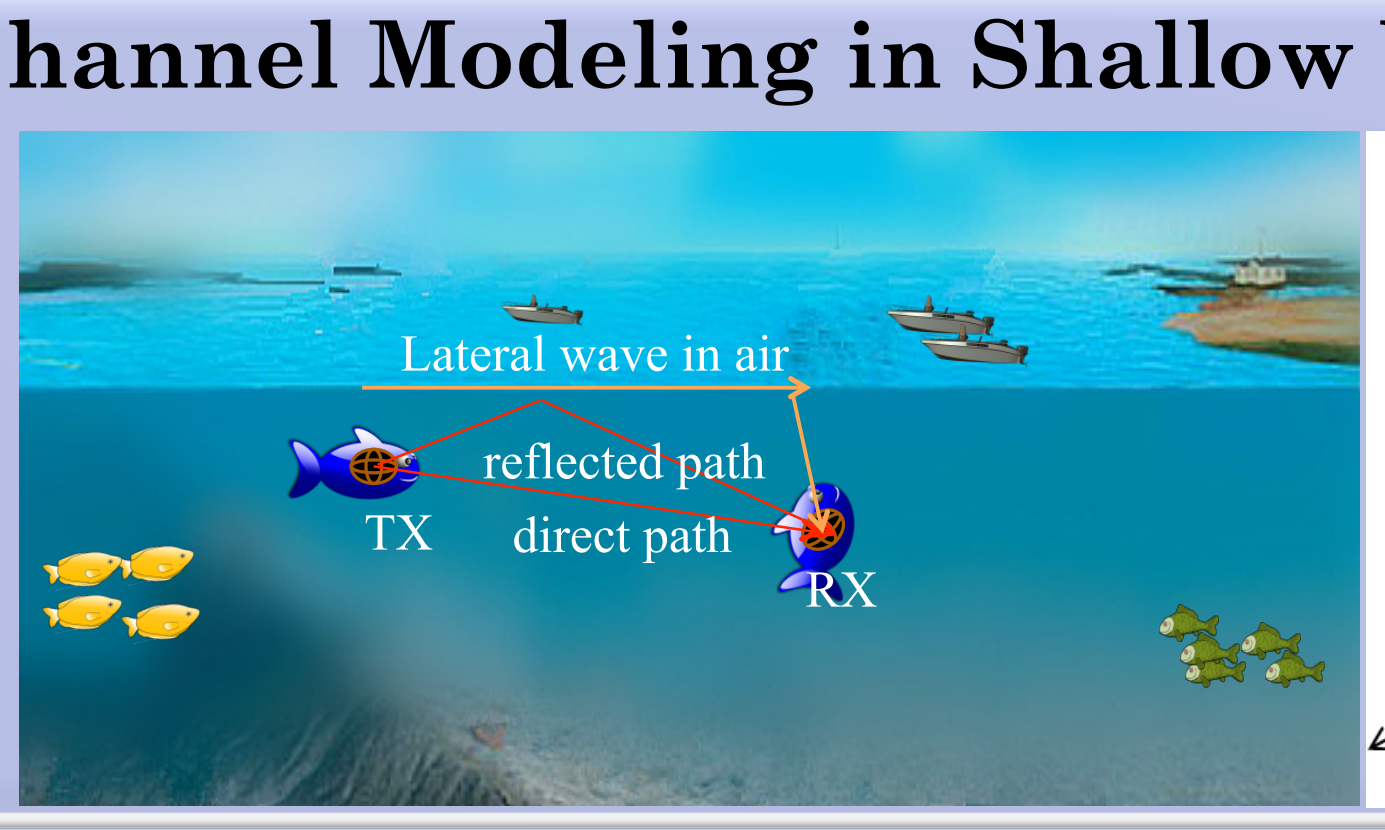
- Magnetic Induction (MI) communication is realized by a time varying magnetic field through 3D coil antenna.
- Key advantages
  - Negligible signal propagation delay
  - Good bandwidth (~ MHz)
  - Sufficiently long transmission range (~ tens of meters)
  - Very small (~ centimeters) & low cost coil antenna (~ 1 dollar per unit)
  - Highly constant & predicable channel response in harsh underwater environment
  - shallow water
  - confined & cluttered UW structures
- The contribution of this project in the past year focus on:
  - Developing an analytical channel model for MI underwater communication to characterize the complex underwater MI channels, especially in the shallow water with omnidirectional antennas.
  - Developing and implementing the environment-aware and MI-based localization technique

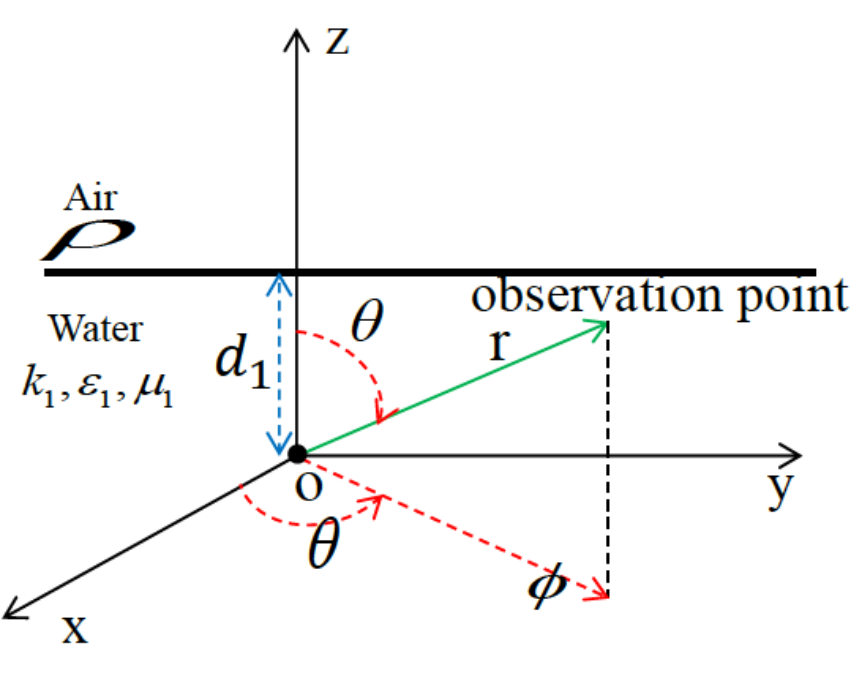




MI Channel Modeling in Shallow Water

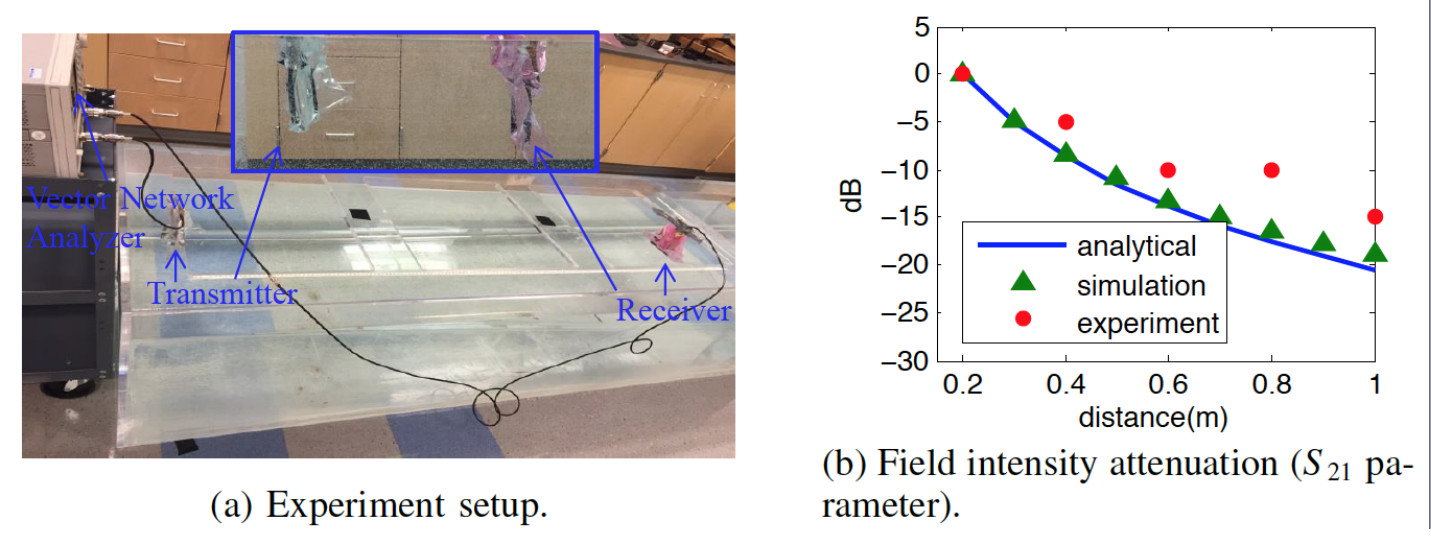
- Three propagation paths are theoretically modeled
  - Direct path
  - Reflected path
  - Lateral wave





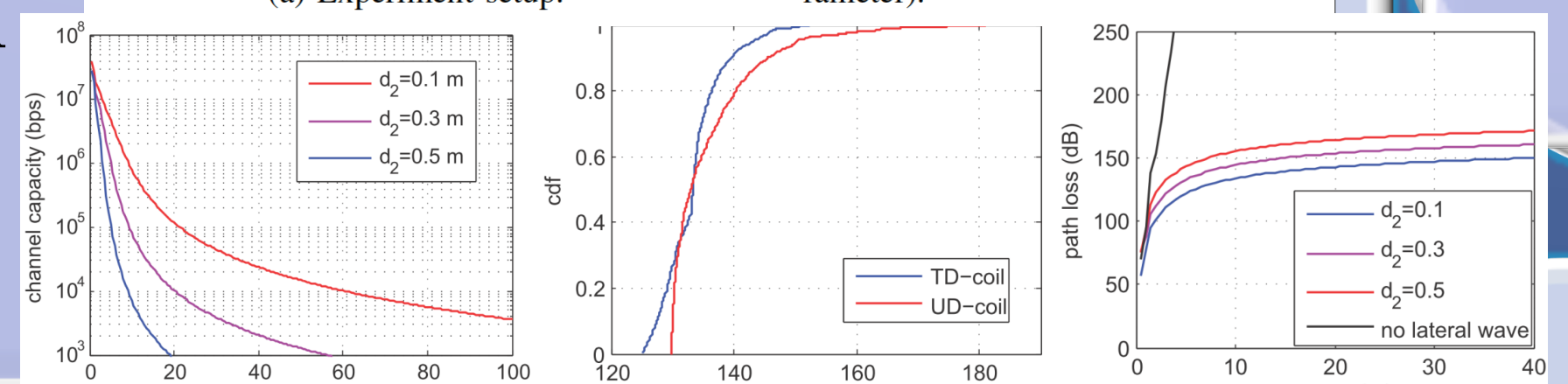
Underwater MI Channel Characteristics

- In-lab experiments and COMSOL simulations are conducted to validate the theoretical model
- Tri-directional coil antenna can reduce the orientation effect
- Lateral waves take strong effect in shallow water, especially when distance is larger than the depth of transmitter and receiver
- Mbps data rate in near region (less than 5m); kbps data rate in several tens meters



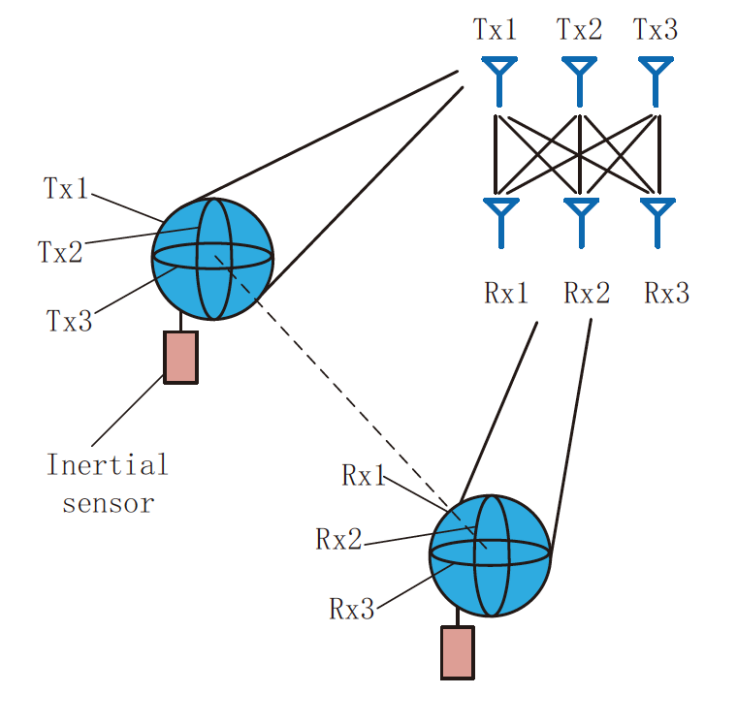
(a) Experiment setup.

(b) Field intensity attenuation (S_{21} parameter).

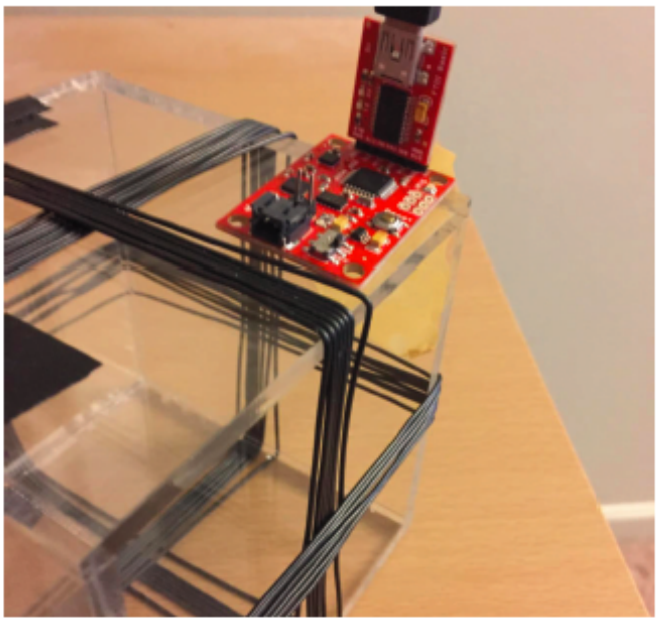


Environmental-aware and MI-based Localization

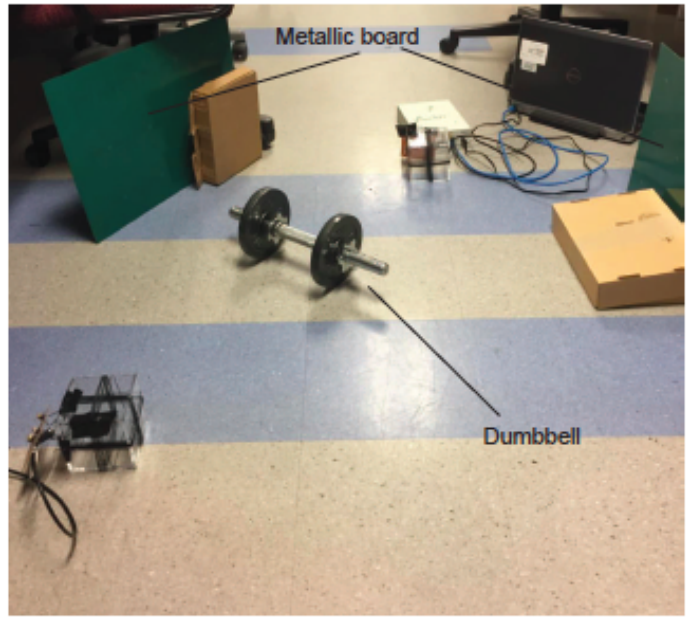
- Multi-path fading-free MI channel & orthogonality of tri-coi MI antennas → accurate, simple, and convenient localization strategy
- By using 3 coils in orthogonal planes, we can determine the positions of sensors in 3D space while only one anchor node is needed
- However, the existence of the highly-conductive objects may influence the received MI signal strength
- Hence, we developed the environment-aware MI localization technique



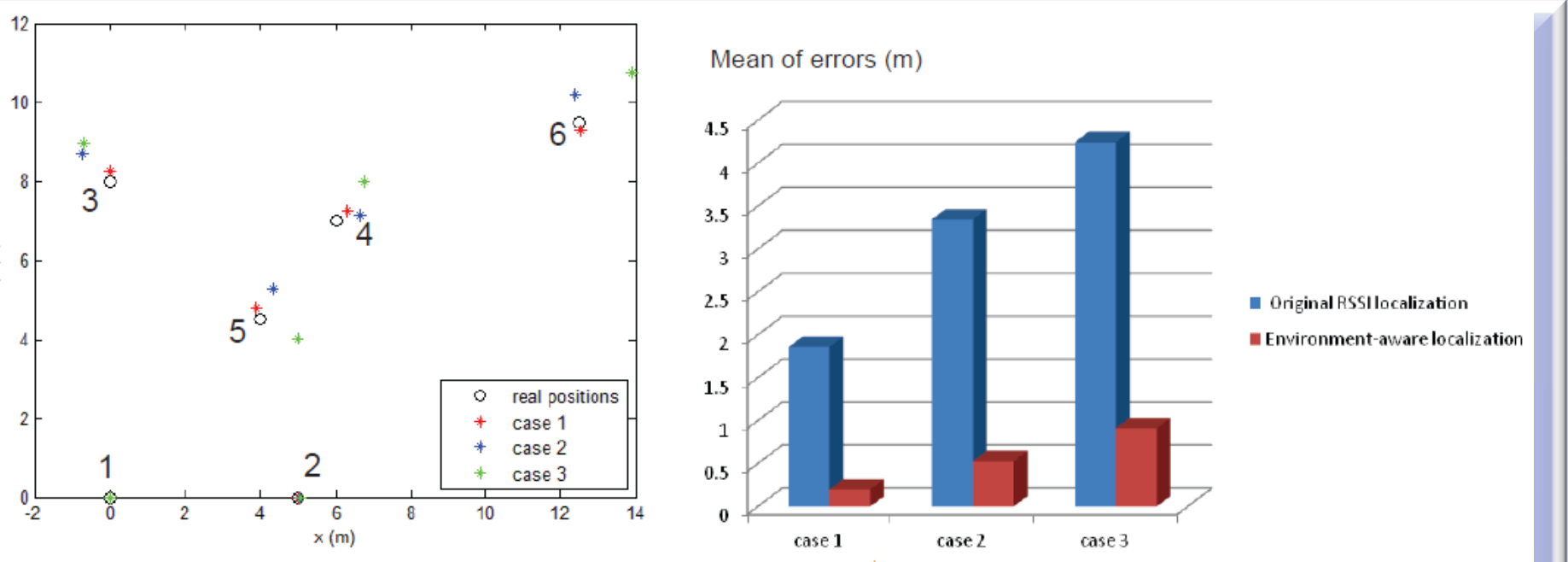
System Implementation & Experiments



3D MI coil with inertial sensor

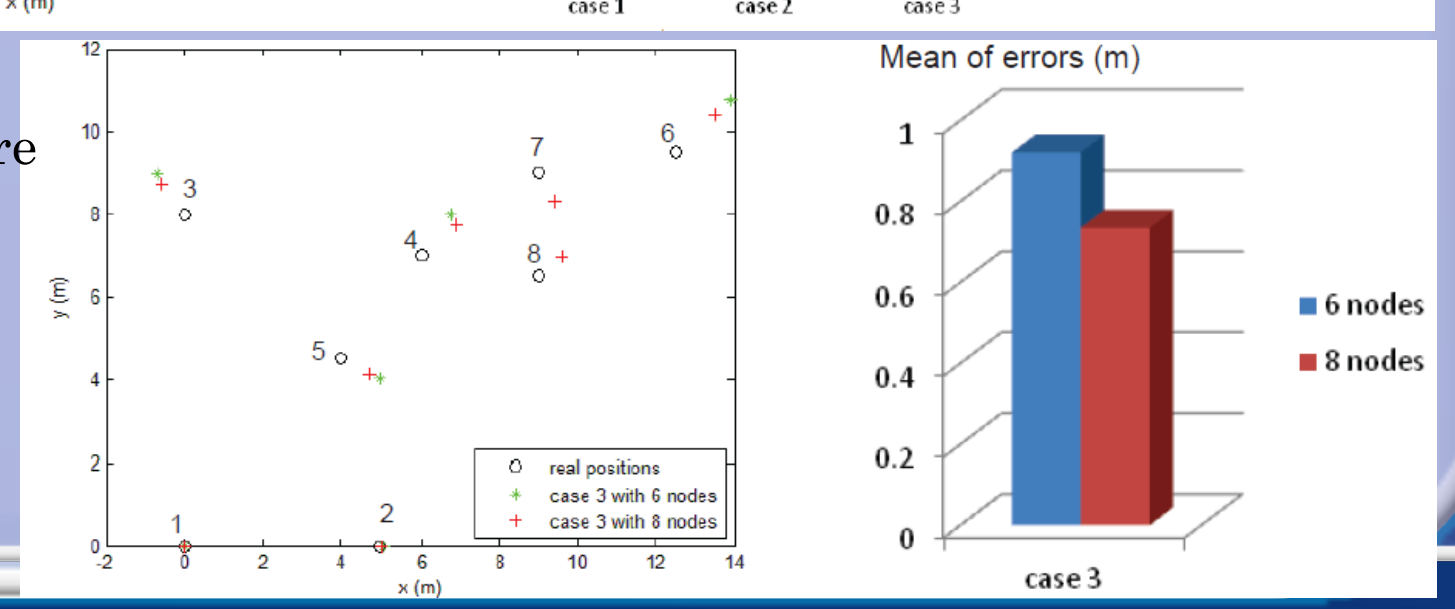


Experiment setup



Environment-aware localization vs Original RSSI localization

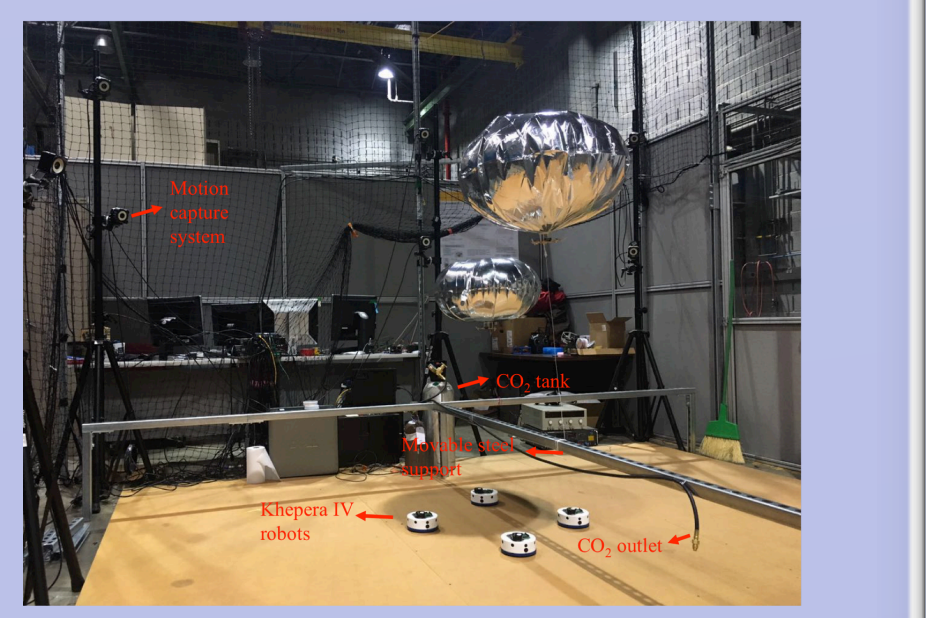
6 nodes vs 8 nodes

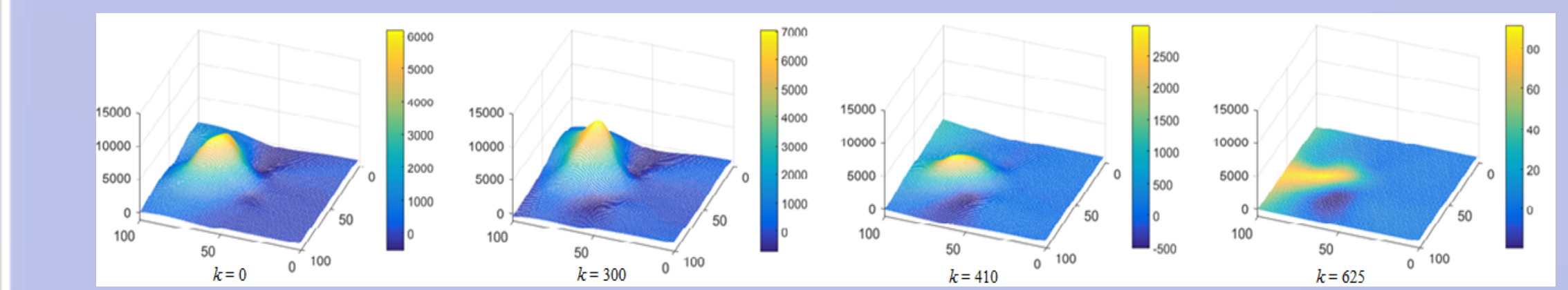


Cooperative Motion and Sensing Co-design

Cooperative Parameter Identification and Source Seeking in Spatially Distributed Fields

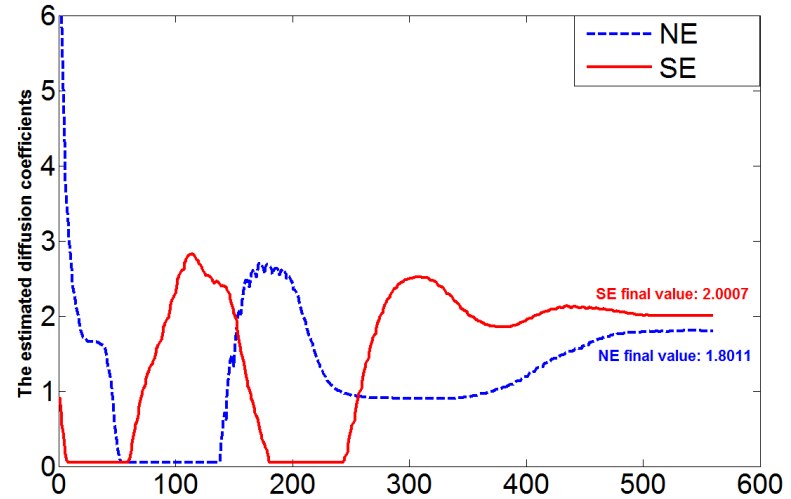
- Many environmental processes are spatial-temporal varying that can be described by partial differential equations (PDEs)
- Source seeking is one of the fundamental and representative missions for swarming CPS with a wide range of practical applications
- A cooperative filtering scheme is developed to achieve online parameter identification of the field using a swarming CPS
- Source seeking algorithms are extended to accommodate the spatial-temporal feature of the field
- We build a controllable CO_2 diffusion field to allow the validation of the proposed algorithms under realistic uncertainties and disturbances
- A CO_2 sensor grid is constructed to calibrate the field



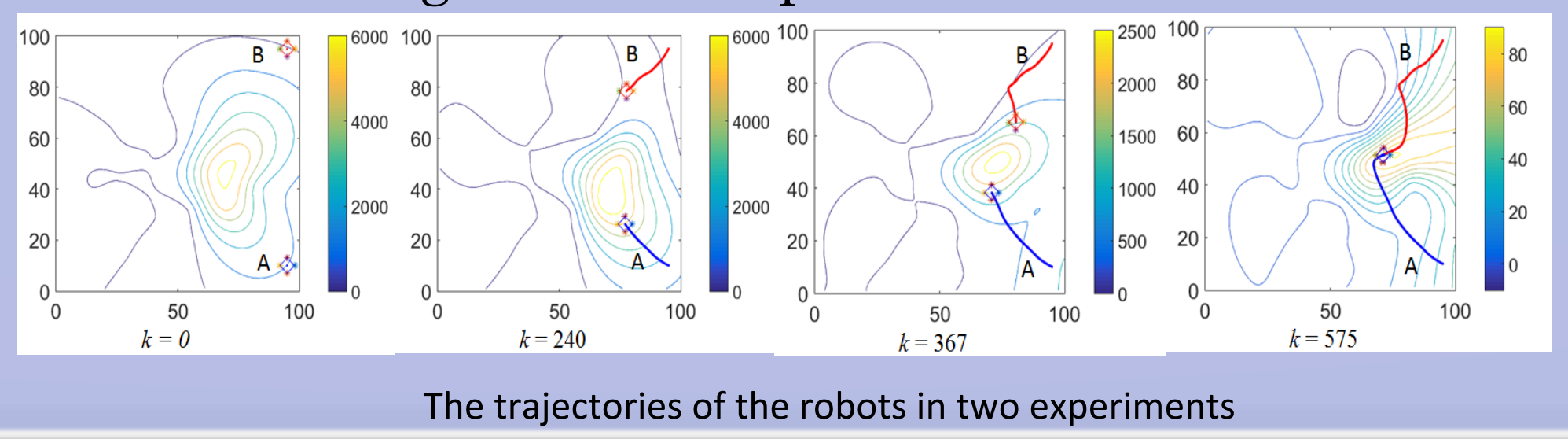


The diffusion field collected by the sensor grid and visualized by Matlab

- Experiments are conducted using four mobile robots with CO_2 sensors in the controllable diffusion field
- The four robots successfully locate the source of the diffusion field while maintaining a desired formation
- The online estimates of the diffusion coefficient converge in both experiments



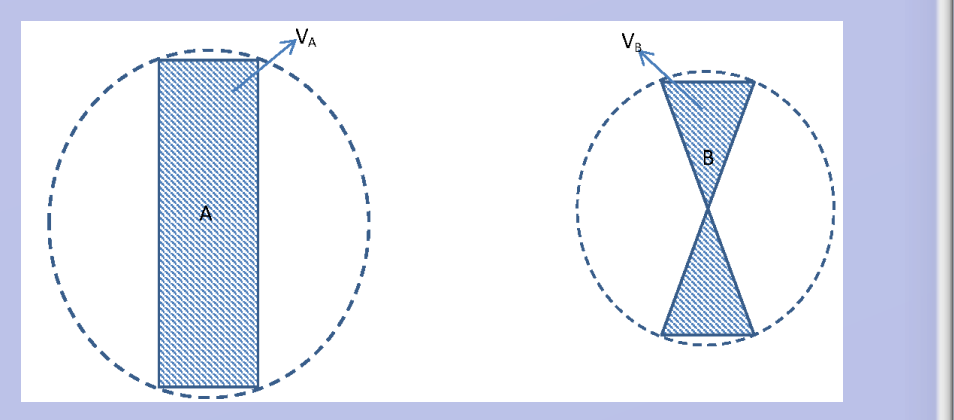
The estimated diffusion coefficient



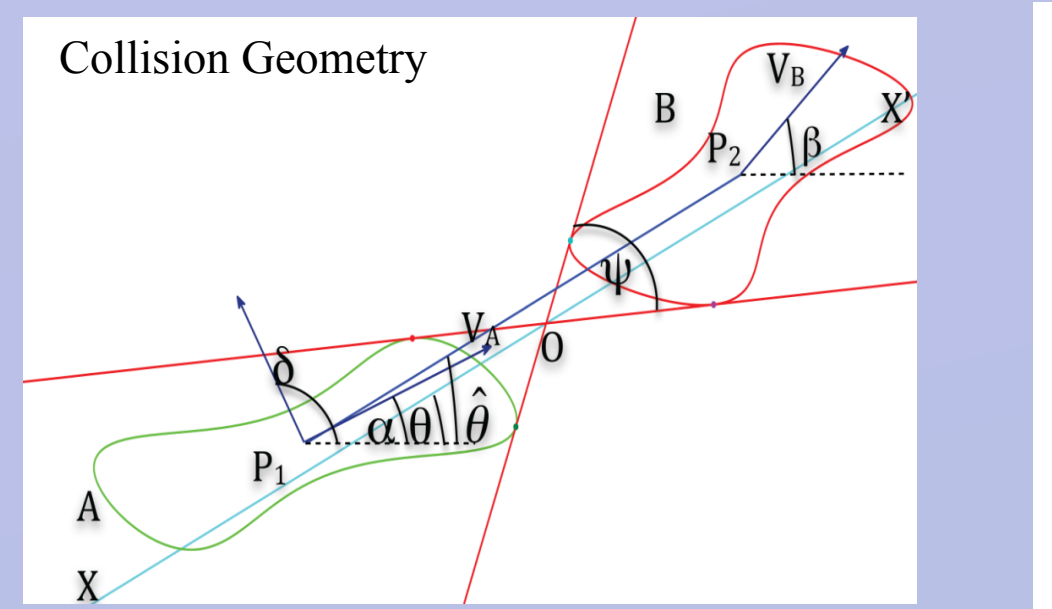
The trajectories of the robots in two experiments

Collision Avoidance

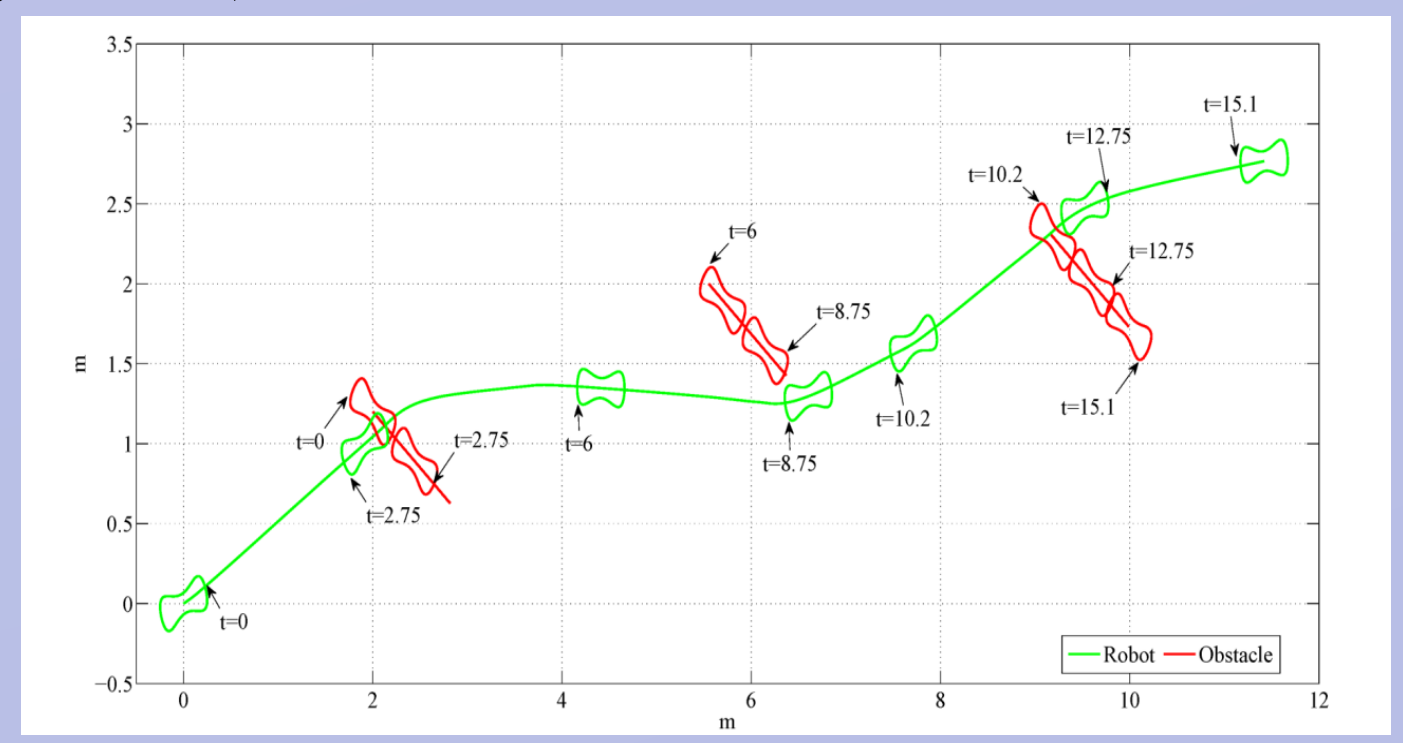
- Collision avoidance is an important requirement in vehicle swarms.
- We employ the collision cone approach to determine analytical guidance laws for collision avoidance
- These analytical guidance laws lead to computational savings on resource-constrained robotic platforms
- These guidance laws are determined for objects of arbitrary shapes, and do not require the objects to be approximated by circles/polygons as is commonly done in the literature
- Two cases are considered for the collision avoidance acceleration magnitude (a_A) and direction (δ):
  - ✧ a_A is of variable magnitude, and δ is such that a_A acts orthogonal to the velocity vector of the robot.
  - ✧ a_A is of constant magnitude, and δ is variable.



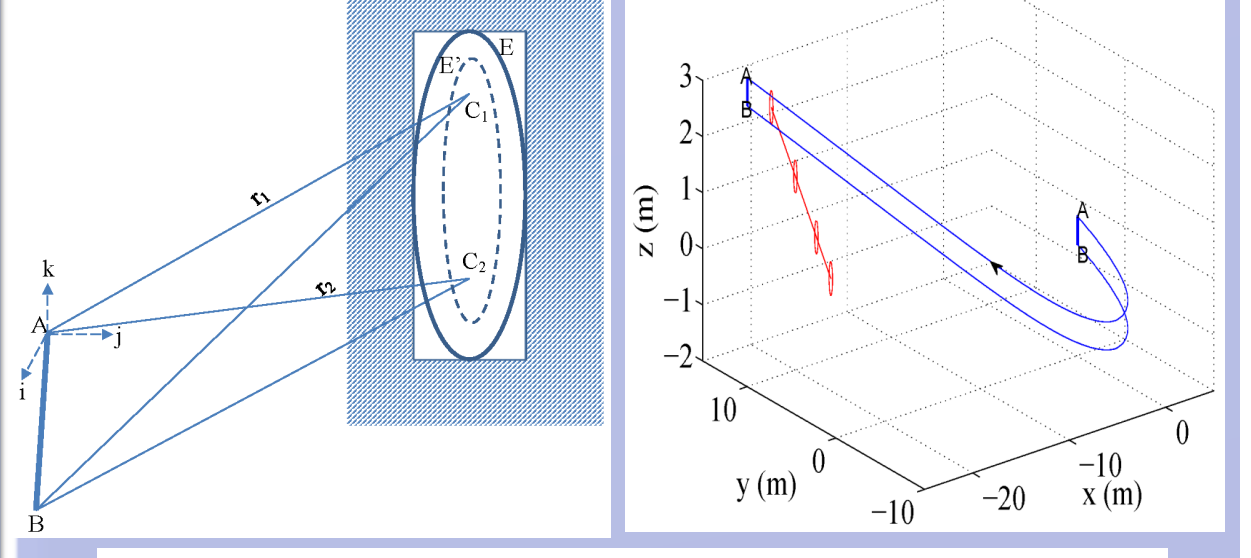
Circular approximations for A and B lead to over-conservative solutions

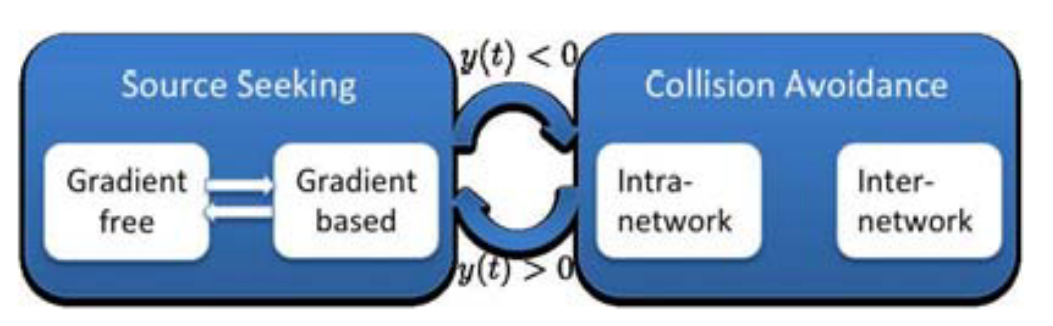


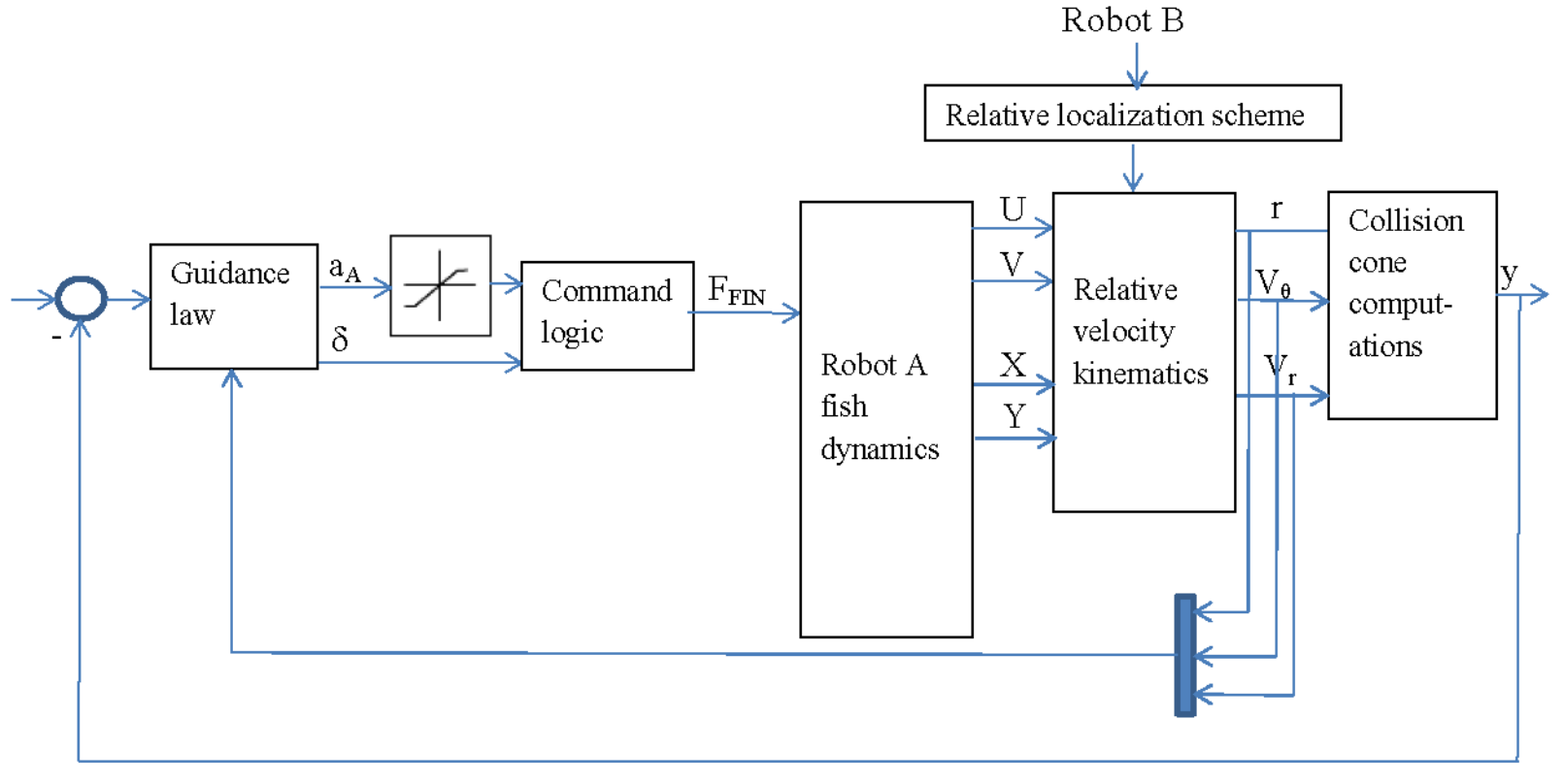
Demonstration of collision avoidance laws in a dynamic environment with multiple obstacles



- The collision cone approach has also been used to develop analytical laws governing safe trajectories for a robot to make a precision 3-D maneuver through a small orifice. The orifice may be fixed, moving and/or closing in size.



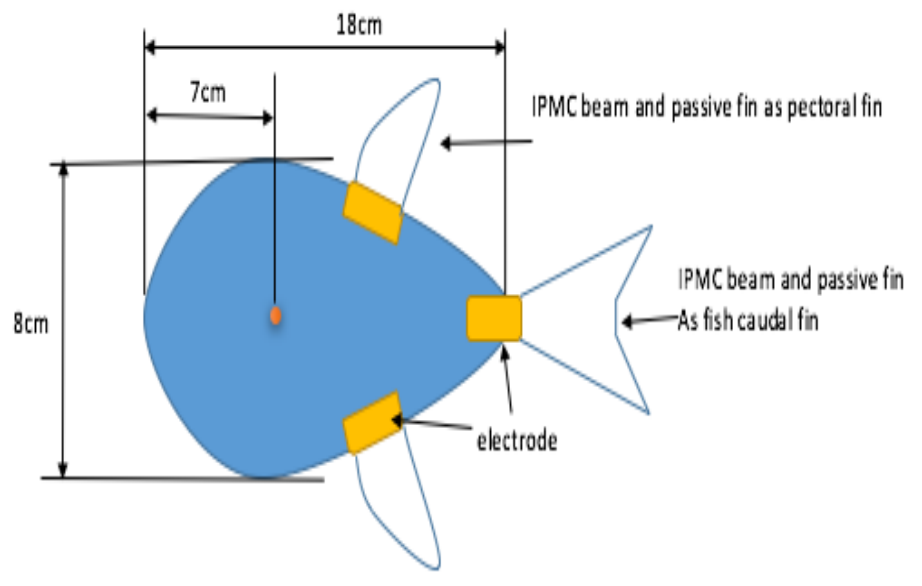


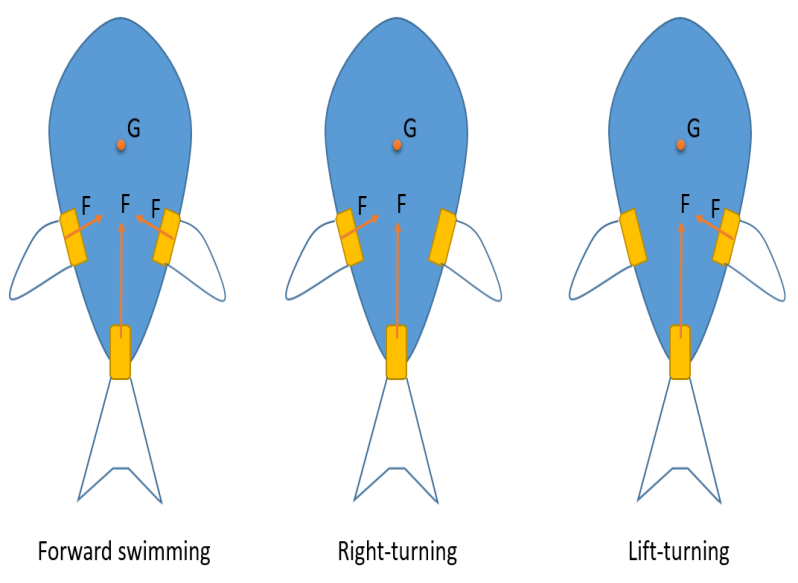


Block Diagram of Integrated System

Smart-material Actuated Biorobotic Fish

2D Maneuverable Robotic Fish Propelled by Multiple IPMC Fins





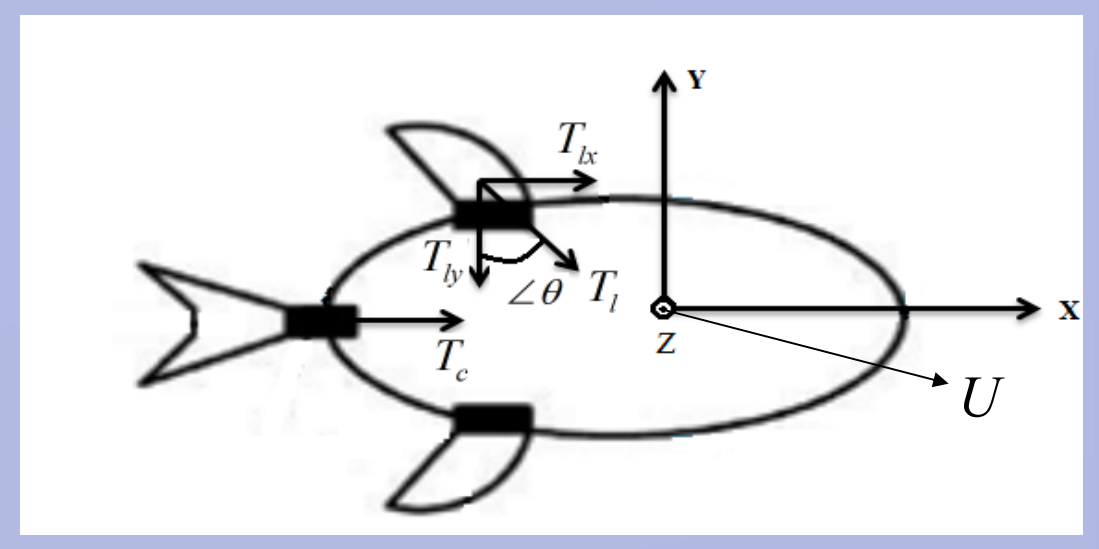
Piqi Hou, Zhihang Ye, and Zheng Chen, ASME Dynamic System and Control Conference, DSCC2016-9915, 2016

Dynamic Modeling

- Body dynamics

$$\dot{u} = \frac{(m_b - m_y)}{m_x} vr + \frac{f_x}{m_x} \qquad \dot{\beta} = r$$

$$\dot{v} = \frac{(m_b - m_x)}{m_y} ur + \frac{f_y}{m_y} \qquad \dot{r} = \frac{\tau_z}{I_z}$$



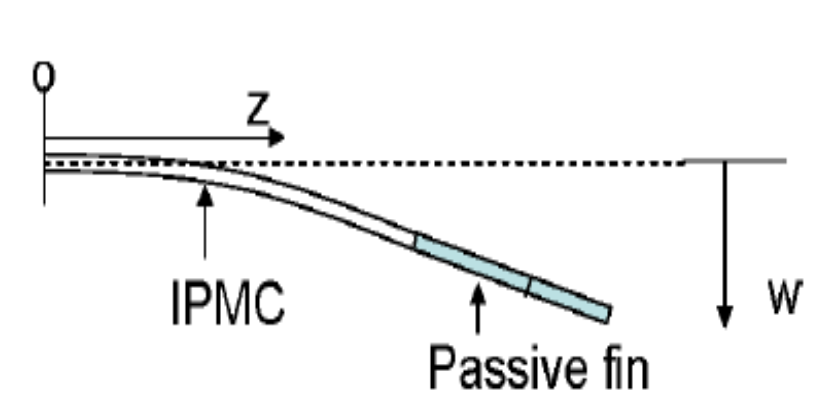
- Thrust and drag forces

$$f_x = T_c + T_r \cos(\theta) + T_l \cos(-\theta) - F_D \cos(\beta)$$

$$f_y = T_r \sin(\theta) + T_l \sin(-\theta) - F_D \sin(\beta)$$

$$F_D = \frac{1}{2} \rho |U|^2 S_A C_D \qquad \tau_z = M_h + M_D \qquad M_h = M_{hl} + M_{hr}$$

$$M_D = -C_M r^2 \operatorname{sgn}(r) \qquad M_{hr} = \vec{r}_{Cr} \times \vec{T}_r \qquad M_{hl} = \vec{r}_{Cl} \times \vec{T}_l$$



- Based on Lighthill theory, the thrust generated by each fin

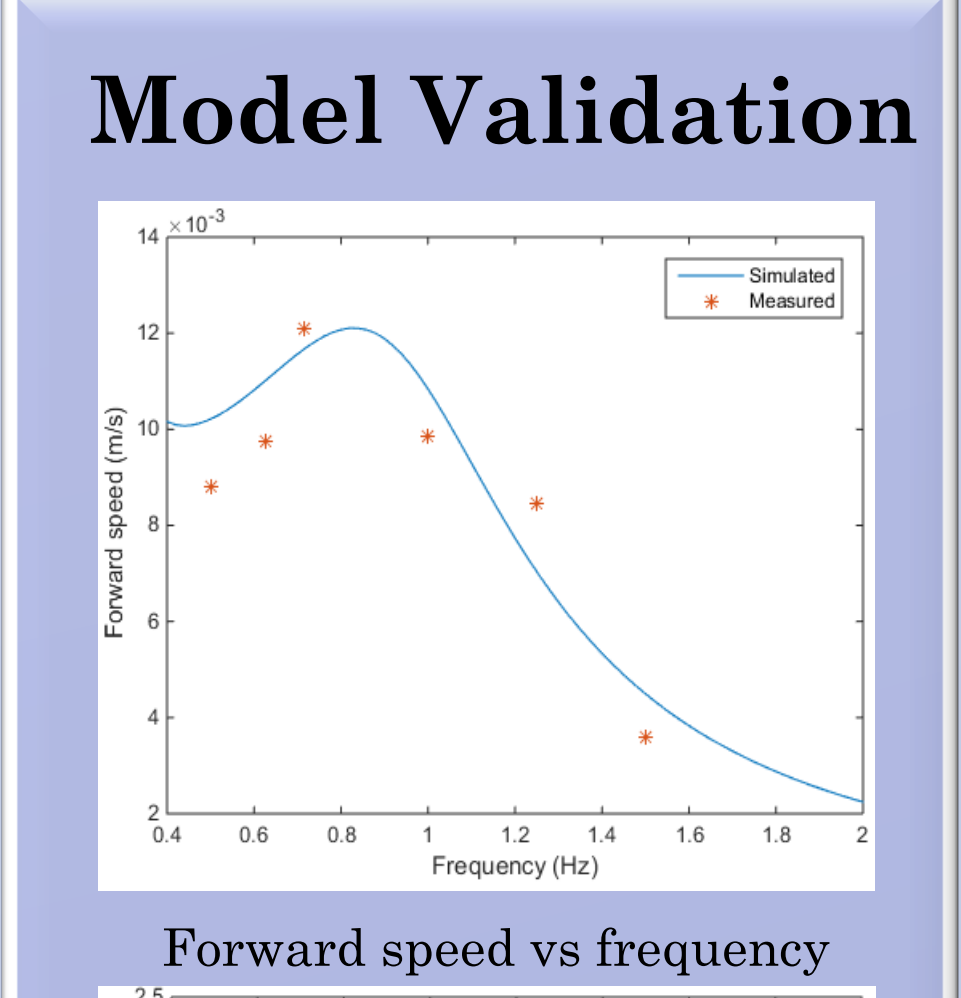
$$\bar{T} = \left[\frac{m}{2} \left(\overline{\left(\frac{\partial w(z,t)}{\partial t} \right)^2} - U^2 \overline{\left(\frac{\partial w(z,t)}{\partial z} \right)^2} \right) \right]_{z=L_1} \qquad \left. \frac{\partial w(z,t)}{\partial z} \right|_{z=L_1} = A_m |H_d(j\omega)| \sin(\omega t + \angle H_d(j\omega))$$

$$m = \frac{1}{4} S_c \rho_w B$$

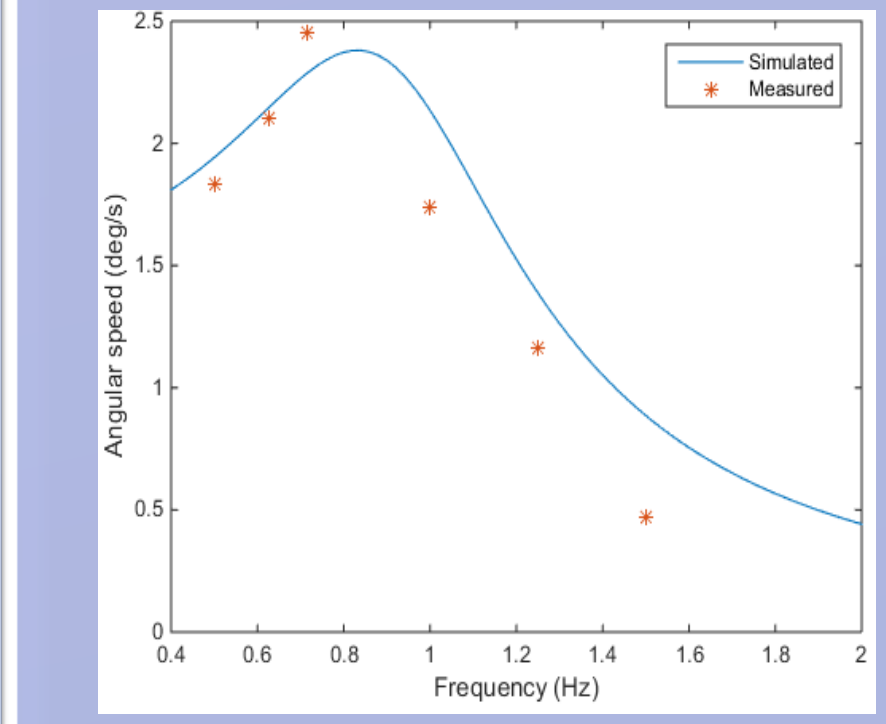
$$w(L_1,t) = A_m |H(j\omega)| \sin(\omega t + \angle H(j\omega))$$

- IPMC fin dynamics: $H(s) = \frac{w(L,s)}{V(s)} \qquad H_d(s) = \frac{w_d(L,s)}{V(s)}$

Model Validation



Forward speed vs frequency



Turning speed vs frequency

Zhihang Ye, Piqi Hou, and Zheng Chen, submitted to IEEE/ASME Transactions on Mechatronics, 2016