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

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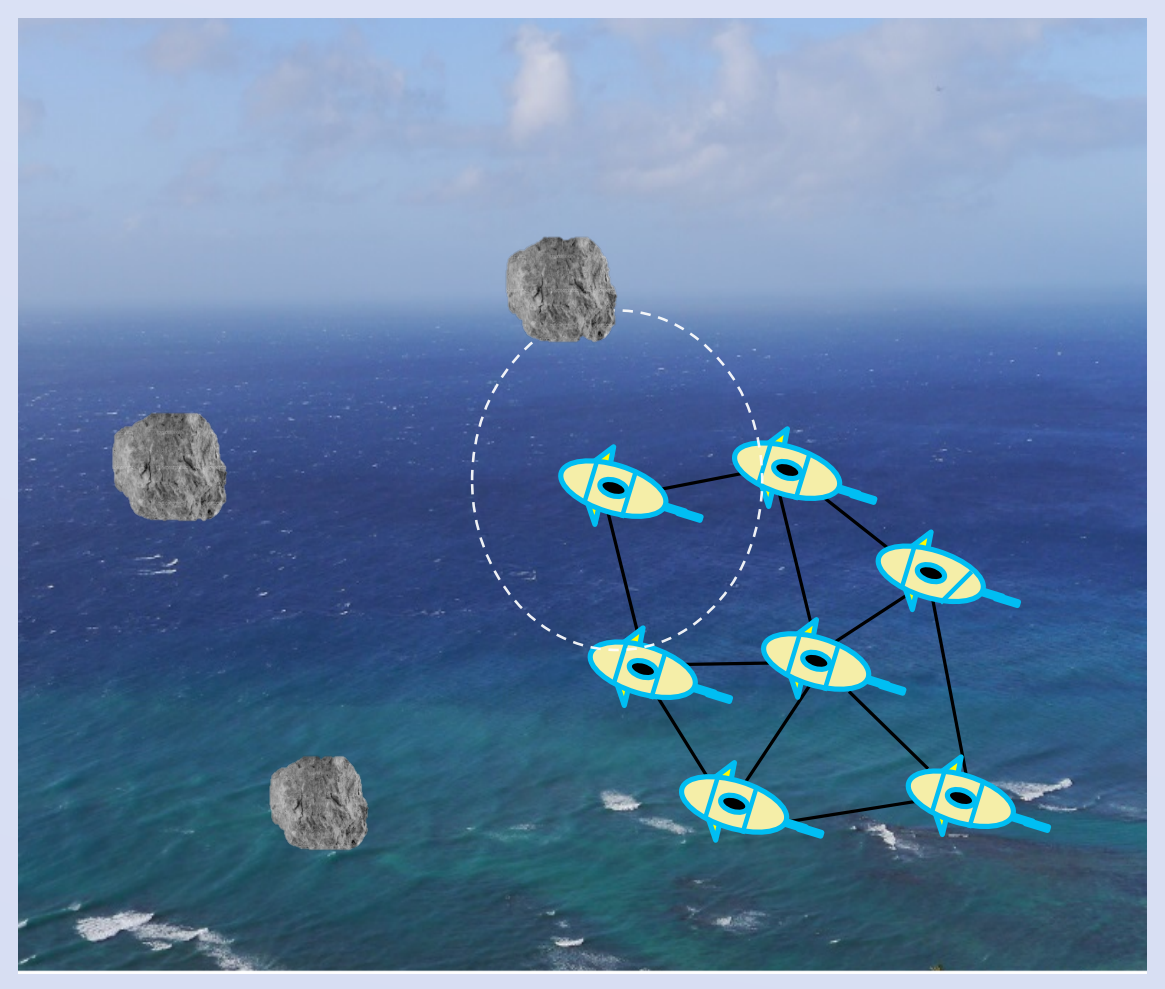
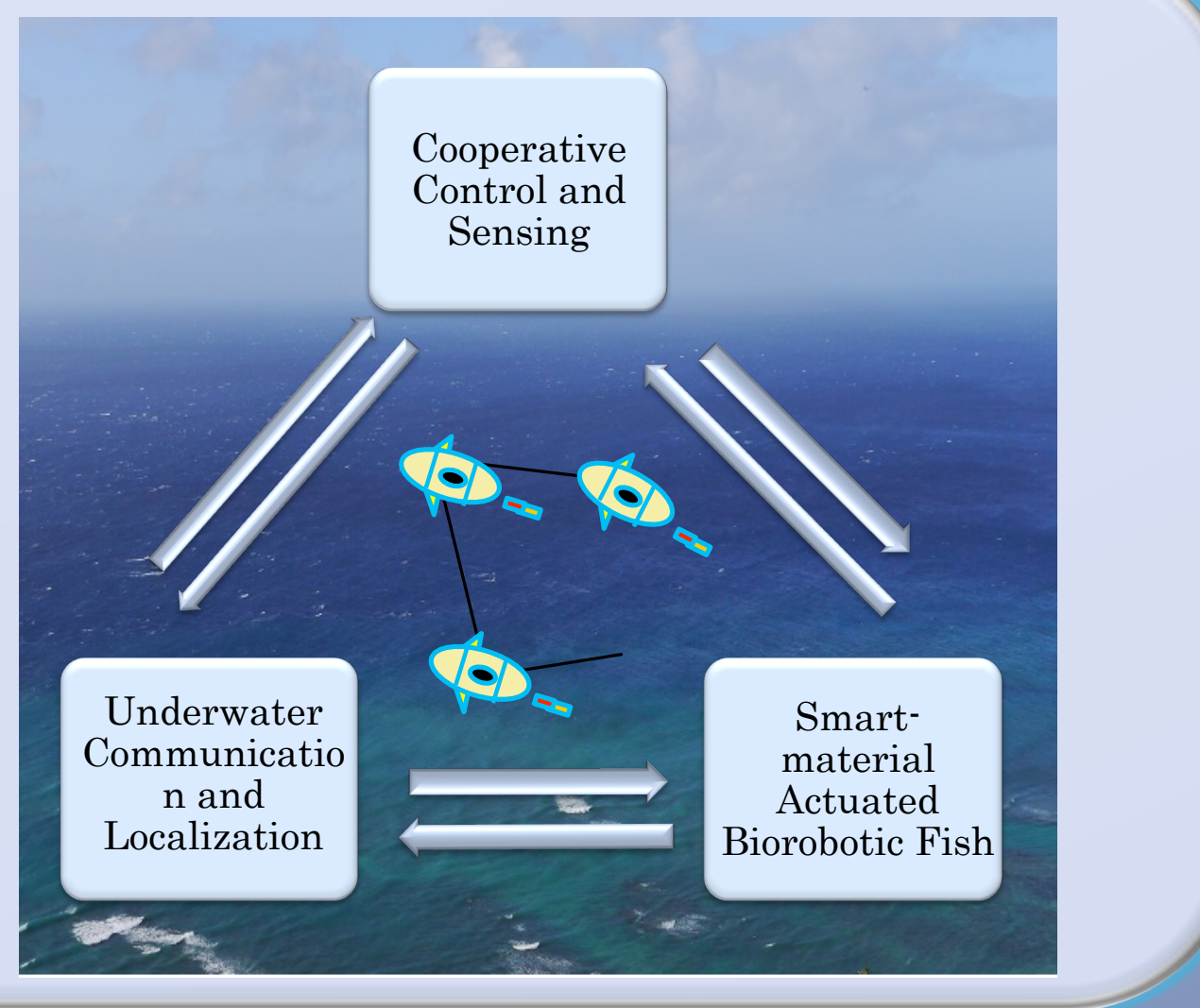
Motivations and Challenges

- 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



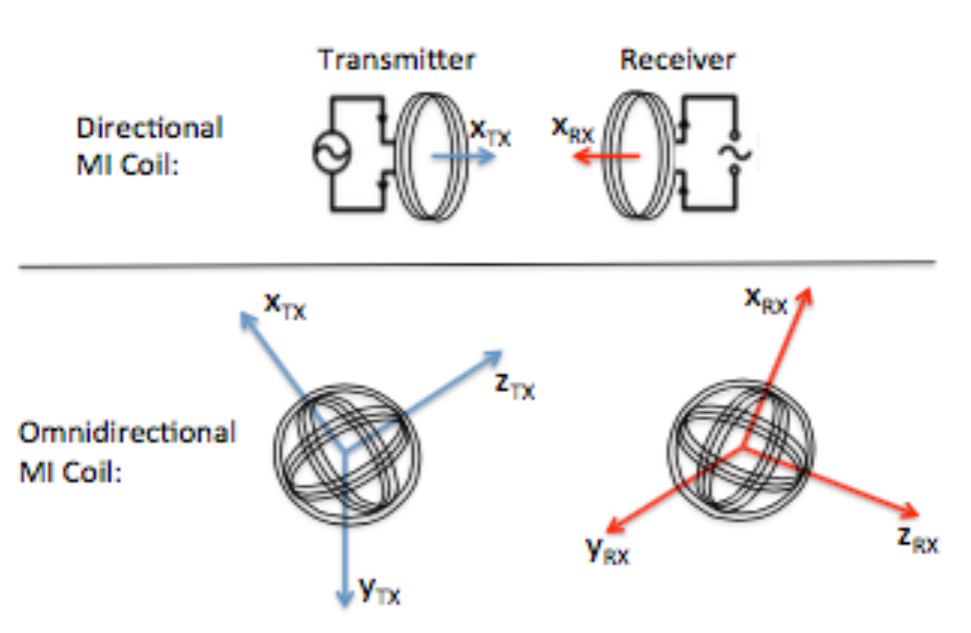
Objectives

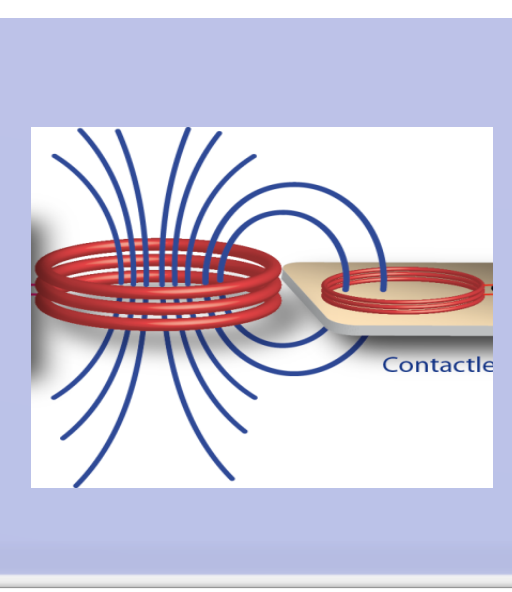
- The overall research objective is to establish and demonstrate a generic motion-sensing co-design procedure that
  - significantly reduces the complexity of mission design for swarming CPS
  - greatly facilitates the development of effective and efficient control and sensing strategies, which are computation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



MI Underwater Communications & Localization

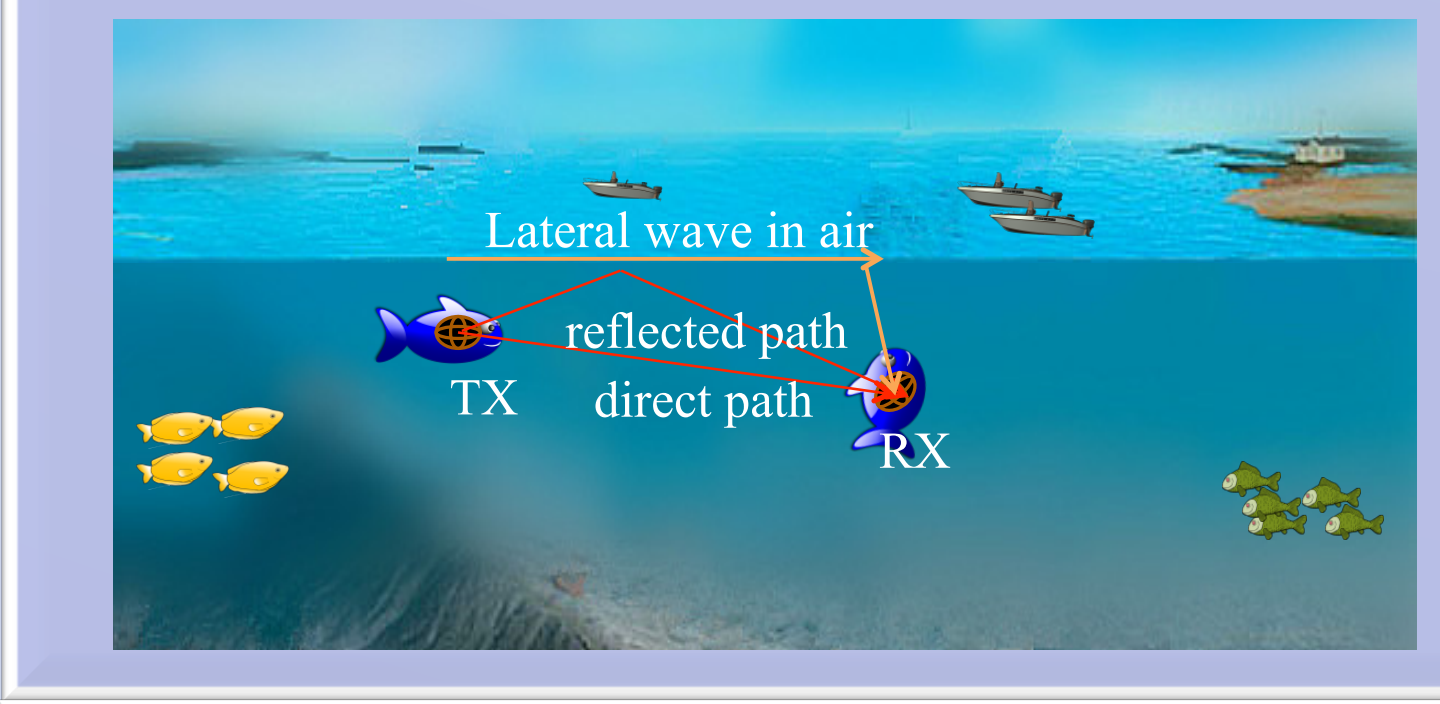
- Magnetic Induction (MI) communication is realized by a time varying magnetic field through 3D coil antenna.
- Each robot in the swarm is equipped with an MI transceiver:
  - To enable low-delay communication among robots for real time control
  - To provide accurate position information of each robot
- The new contribution of this project:
  - Comprehensive understanding of MI underwater channel characteristics
  - Design and implementation of MI underwater transceivers using 3D coil antennas
  - Design and implementation of MI underwater localization system

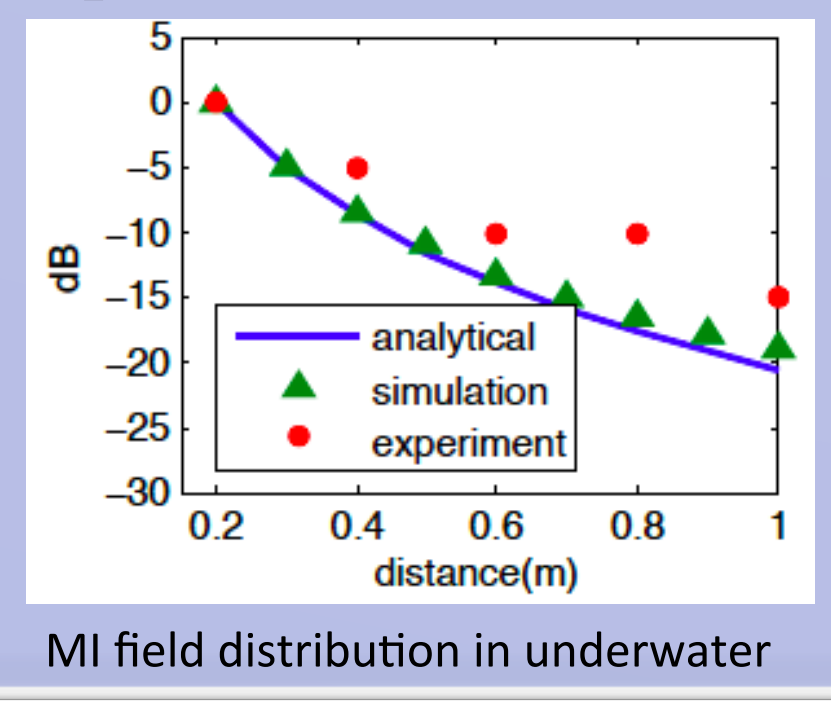




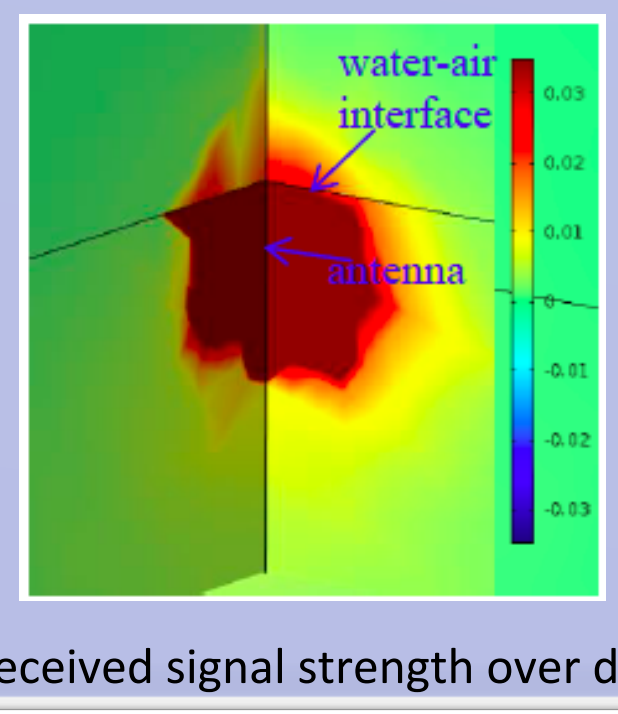
MI Transceiver with 3D Coil Antenna

- We can quantitatively and analytically characterize the underwater magnetic field propagation:
  - At any point in the 3D underwater space
  - Both the near and far fields of all feasible signal bands
  - The impacts of lossy underwater medium on not only the propagation path but also the MI antenna itself are captured





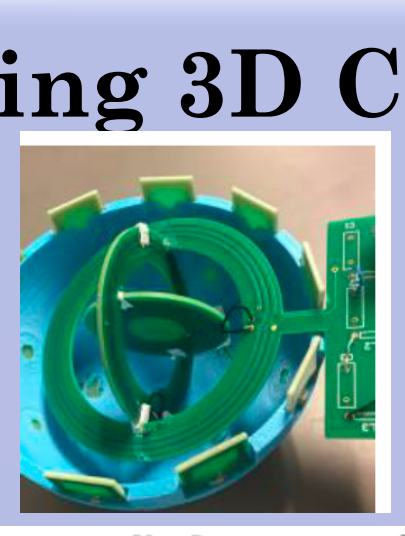
MI field distribution in underwater

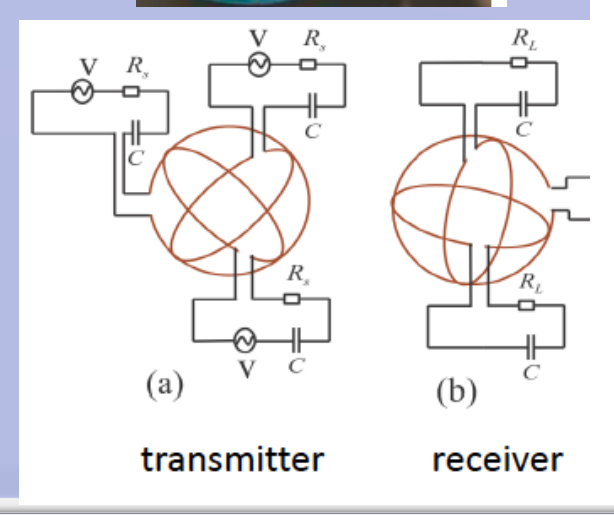


Received signal strength over distance

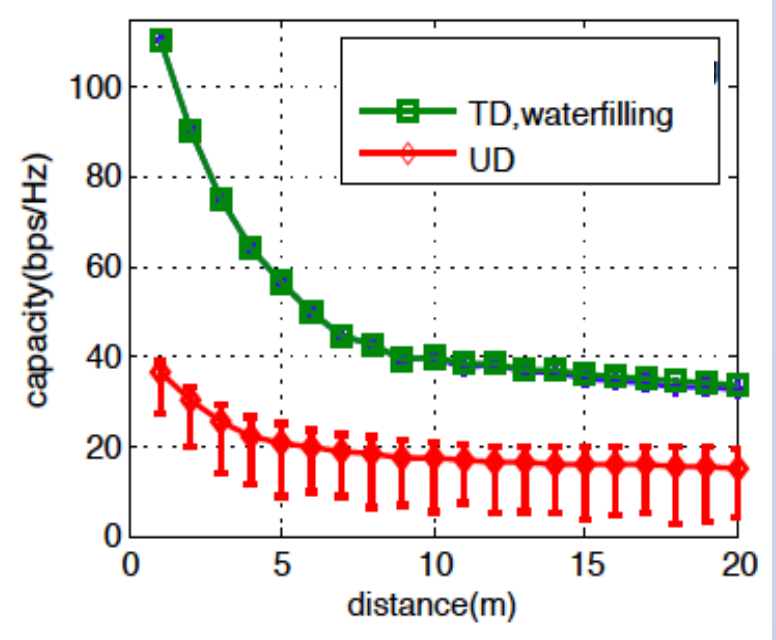
MI Underwater Transceivers using 3D Coil Antennas

- The arbitrarily orientated Tri-directional (TD) coil antenna that can eliminate the MI antenna's susceptibility to orientation changes
  - The three orthogonal coils at both transmitter & receiver form a 3 by 3 MIMO system
  - By using waterfilling algorithm, the 3D coil antenna can achieve much higher channel capacity and much reliable performance





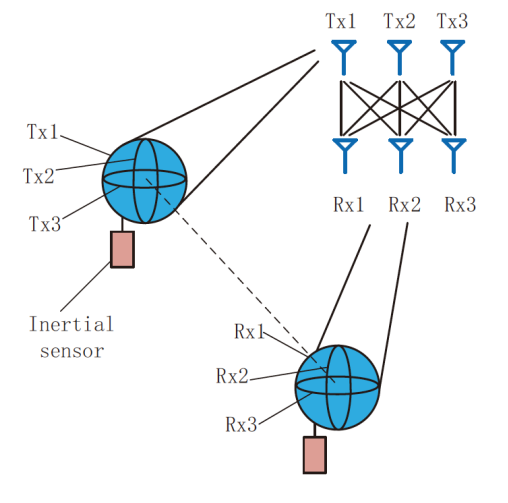
transmitter (a) receiver (b)



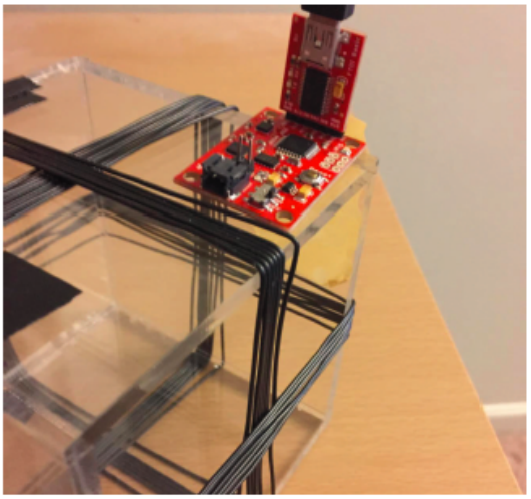
Channel capacity with/without 3D coil antennas

MI Underwater Localization

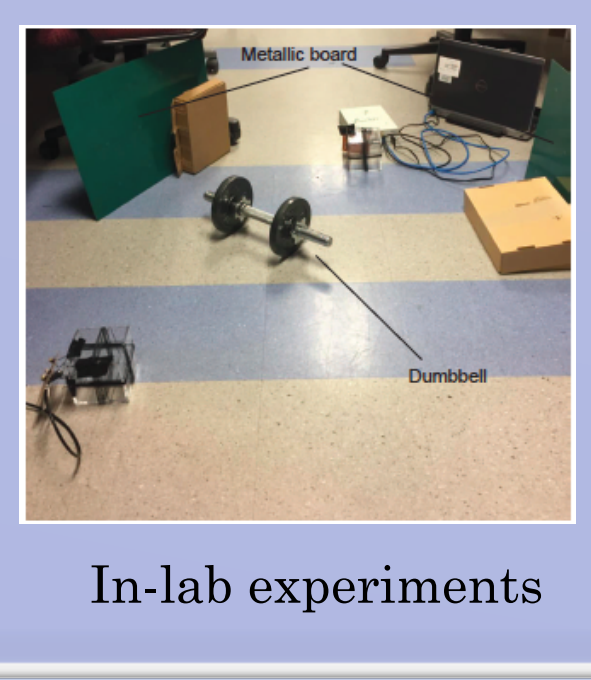
- We developed a joint device localization and environment sensing algorithm
  - To estimate the position of each robot in the swarm
  - Also estimate the distribution of the high-conductive objects in underwater
  - Additional inertial sensor to further improve the accuracy
- Experimental validation based on in-lab testbed



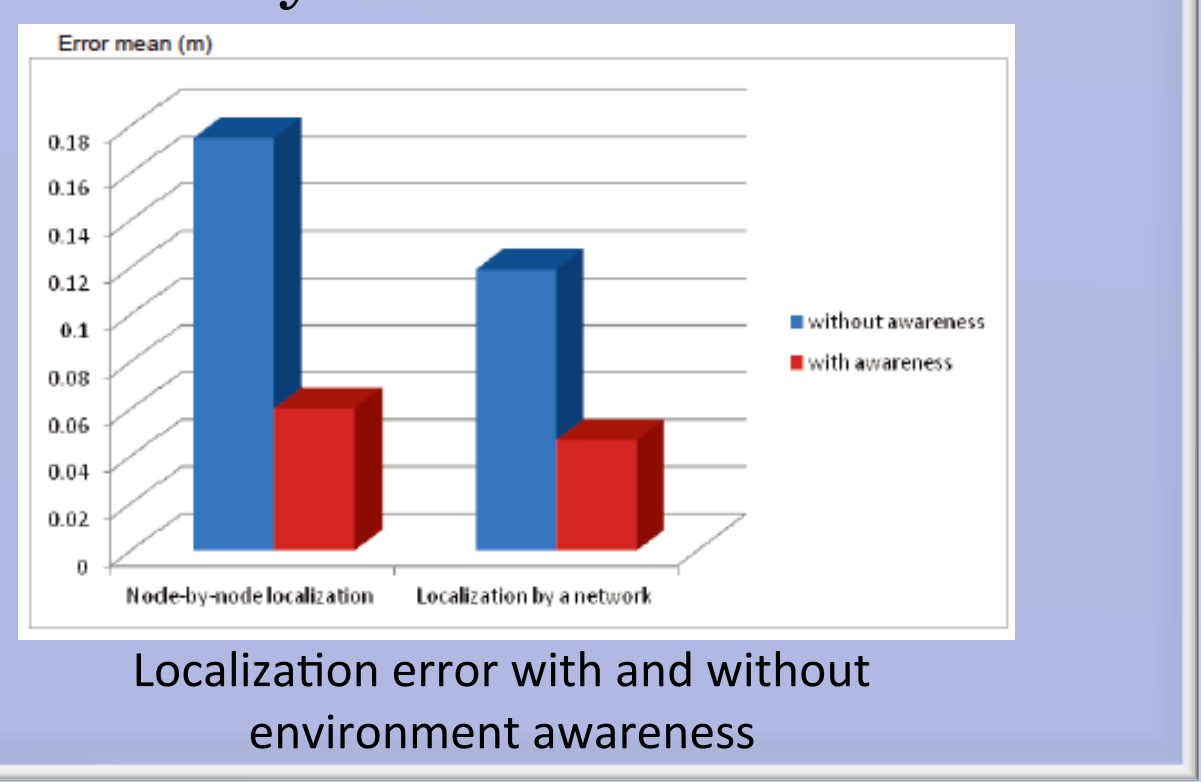
Localization based on 3D coil antenna



3D MI coil with inertial sensor



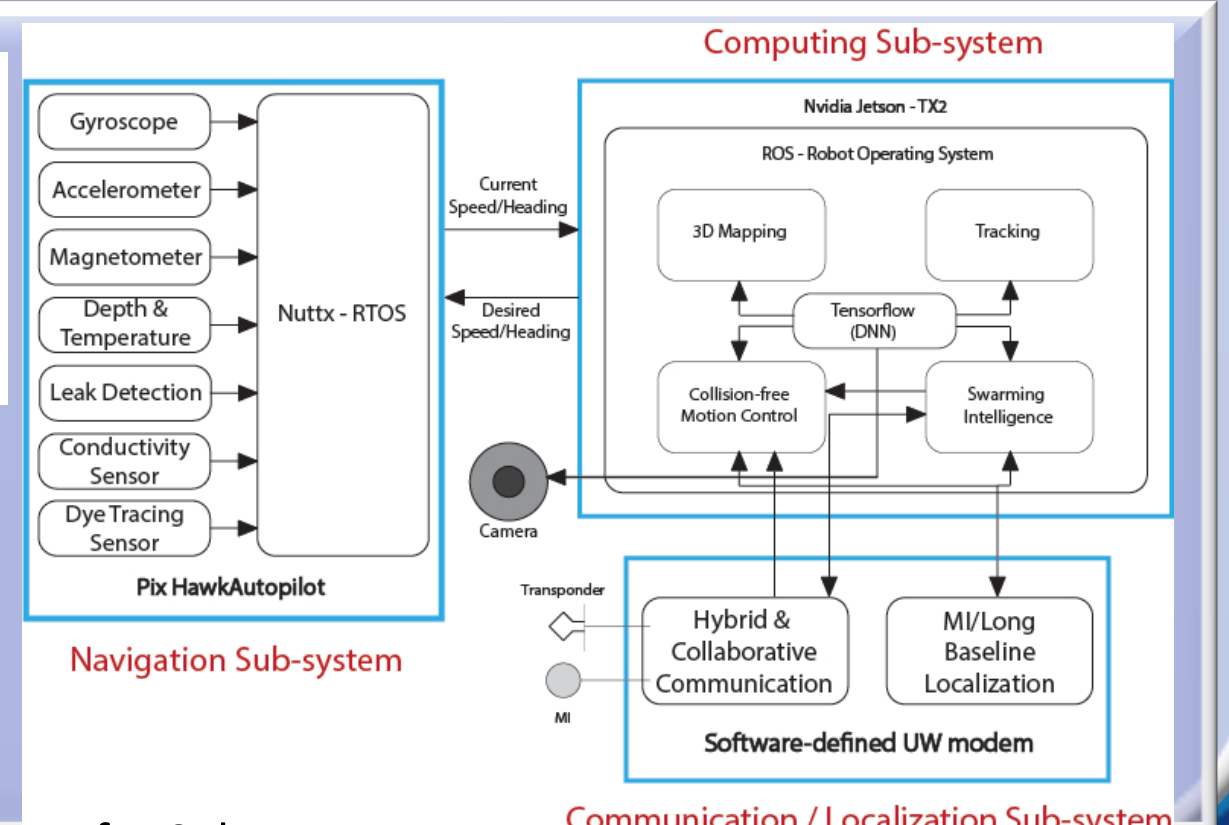
In-lab experiments



Localization error with and without environment awareness

DeepBlue

- Underwater wireless Communication
- AI-powered Navigation with swarm collision avoidance and 3D-localization
- High-performance Computing using Nvidia mobile micro-datacenter
- Power Management through underwater wireless charging

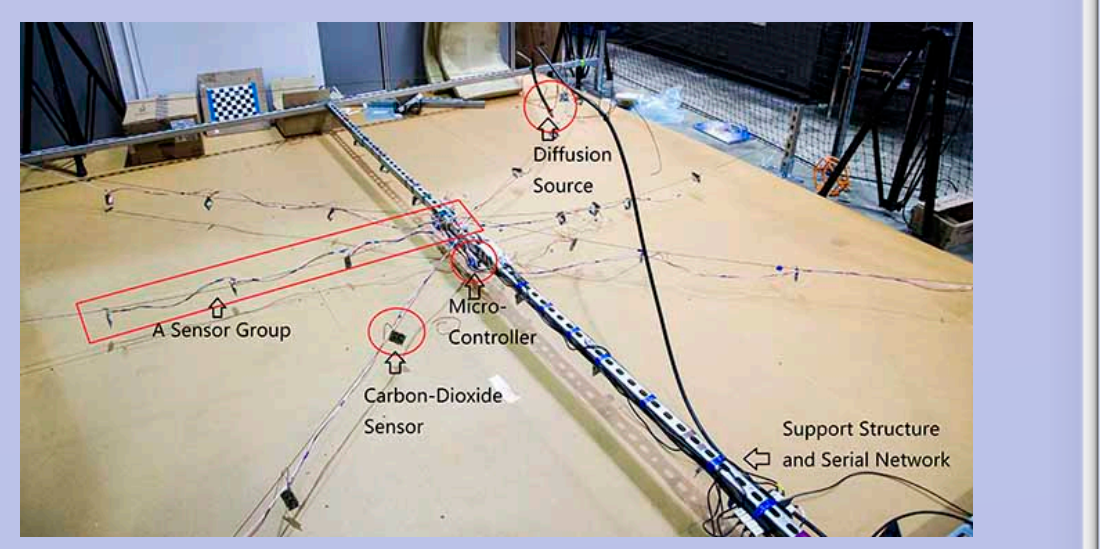


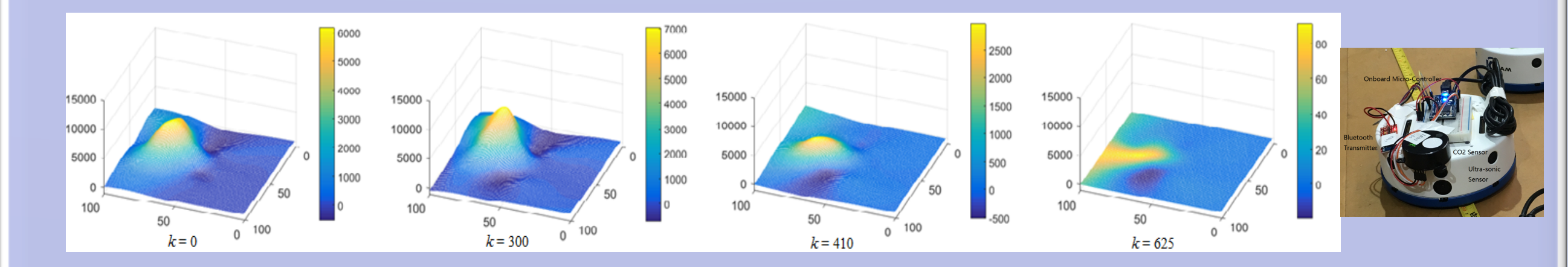
Water-tight Chambers for Sub-systems

Cooperative Motion and Sensing Co-design

Cooperative Parameter Identification and Source Seeking in Spatially Distributed Fields

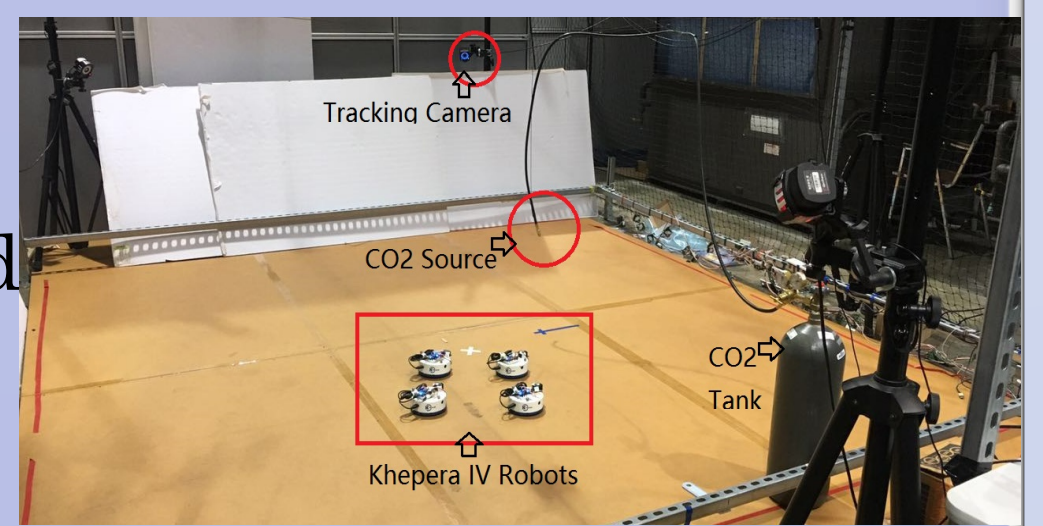
- Many environmental processes are spatial-temporal varying that can be described by partial differential equations (PDEs)
- Source seeking is one of the fundamental and representative missions for swarming CPS with a wide range of practical applications
- A cooperative filtering scheme is developed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

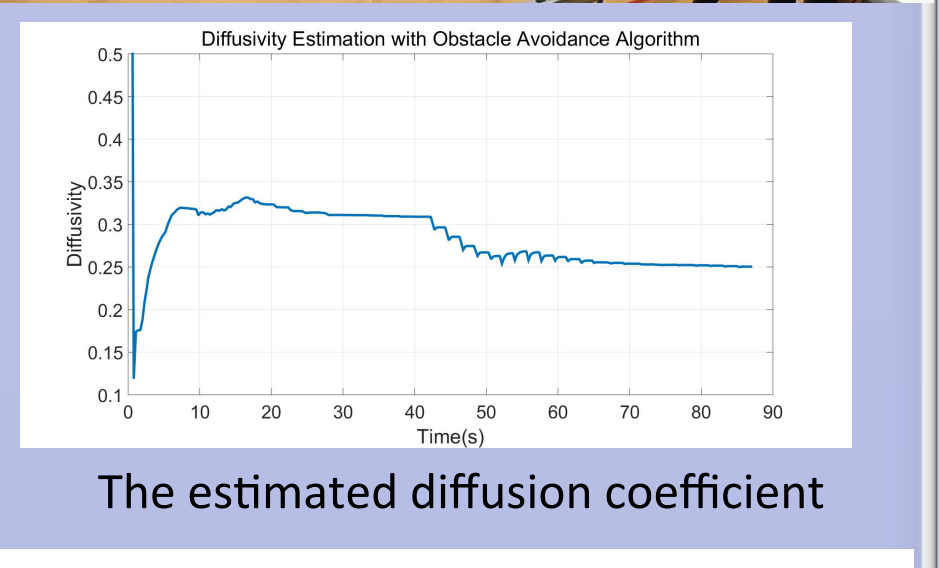




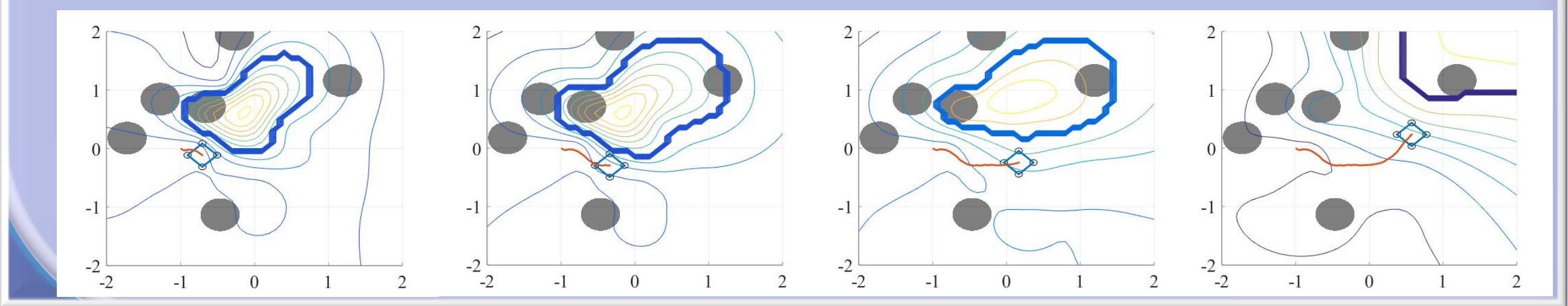
The diffusion field collected by the static sensor network and visualized in Matlab

- Experiments are conducted using four Khepera IV mobile robots with CO_2 sensors in the controllable diffusion field
- The four robots successfully locate the source of the diffusion field while providing the online estimate of the diffusion coefficient
- Simulations are conducted in the realistic diffusion field collected by the sensor network with obstacles and hazard zones



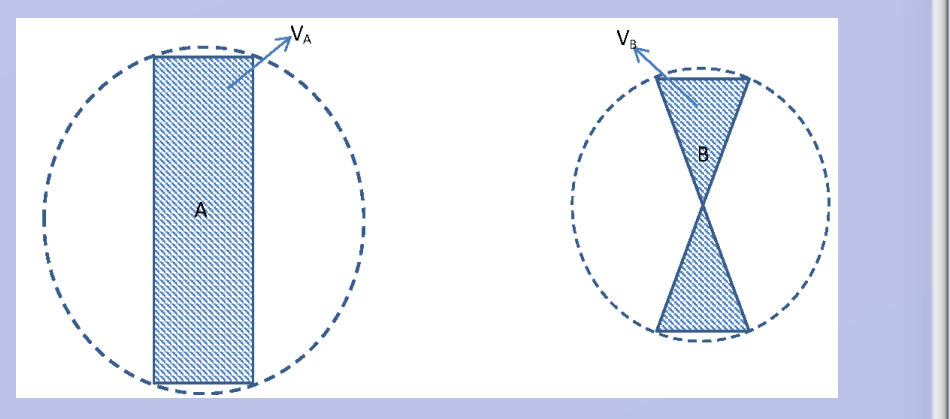


The estimated diffusion coefficient

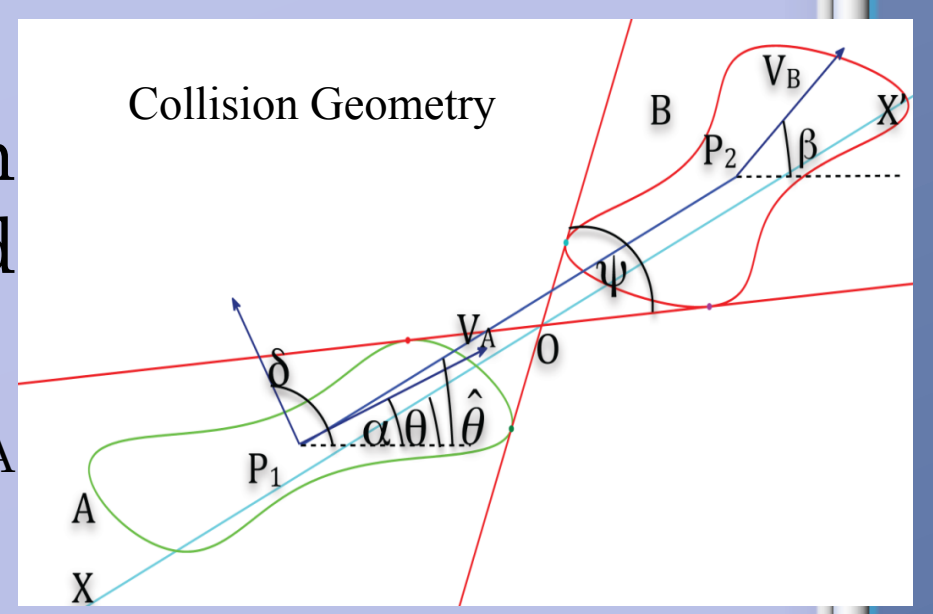


Collision Avoidance

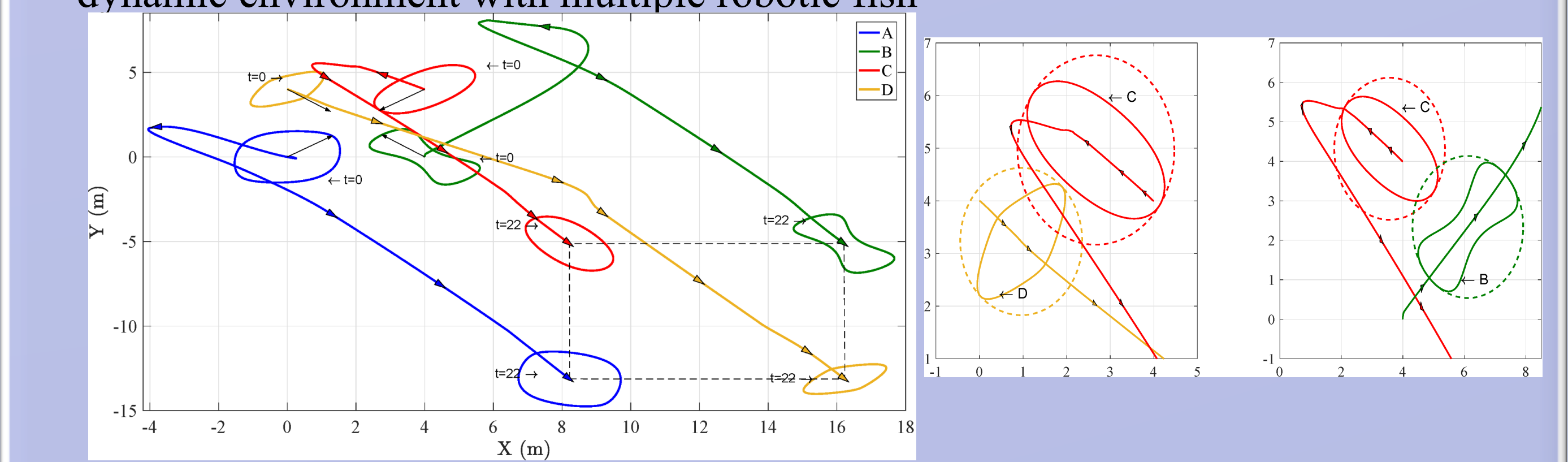
- Collision avoidance is an important requirement in vehicle swarms.
- We employ the collision cone approach to determine analytical guidance laws for collision avoidance
- These analytical guidance laws lead to computational savings on resource-constrained robotic platforms
- These guidance laws are 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.

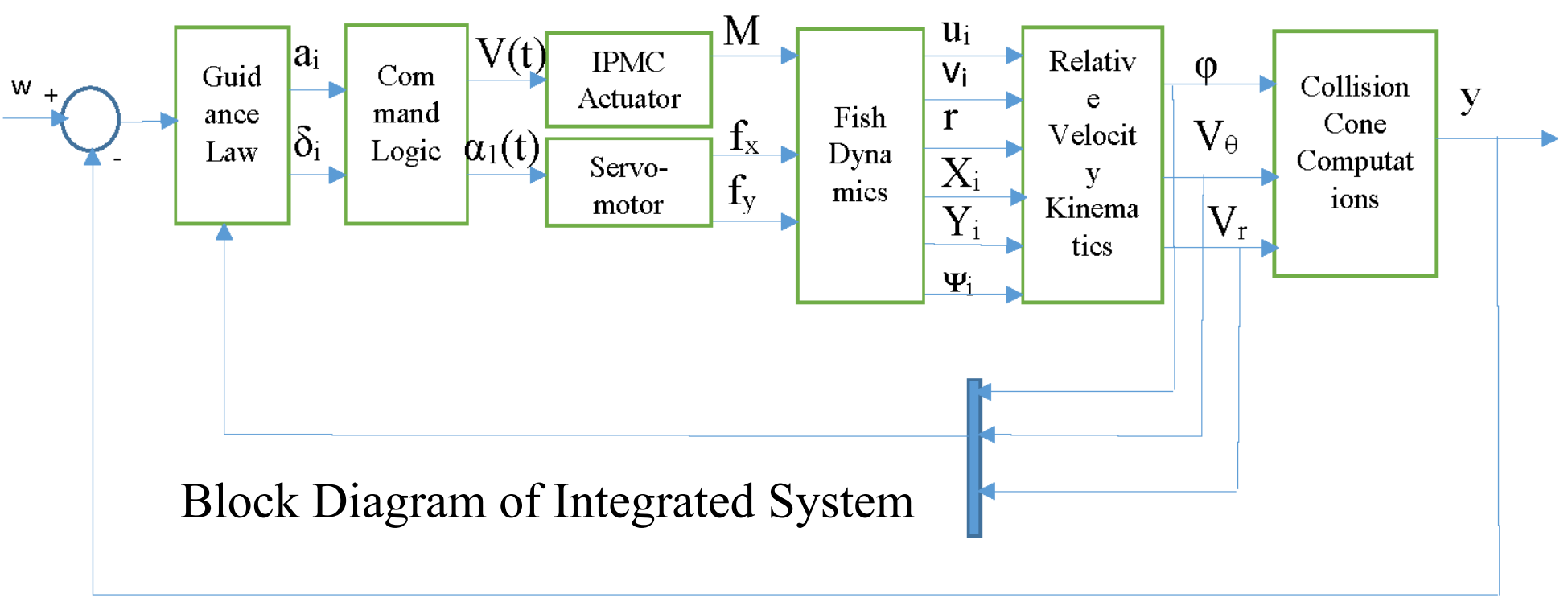


Circular approximations for A and B lead to over-conservative solutions



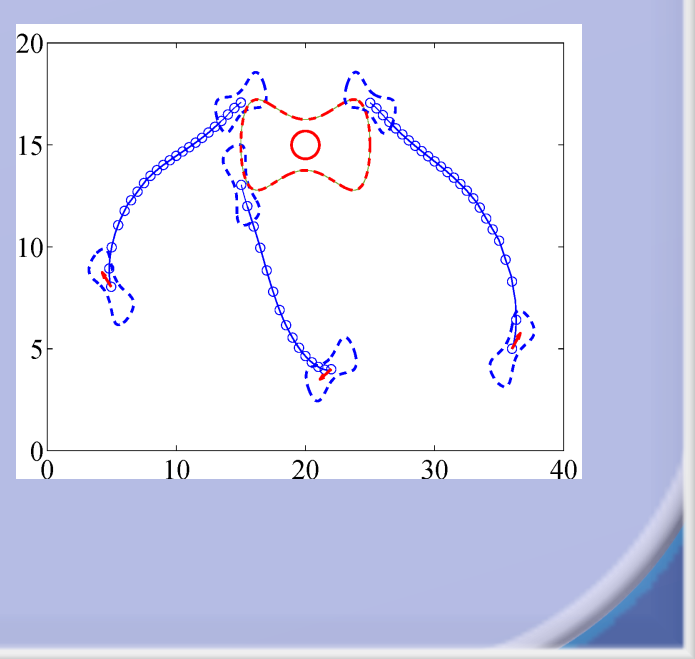
- Demonstration of cooperative collision avoidance laws with formation control in a dynamic environment with multiple robotic fish

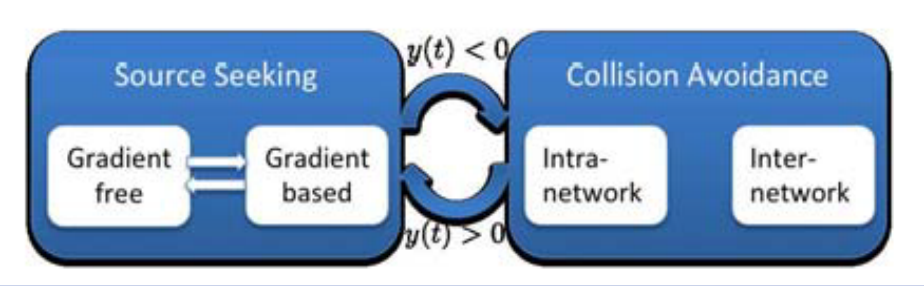




Block Diagram of Integrated System

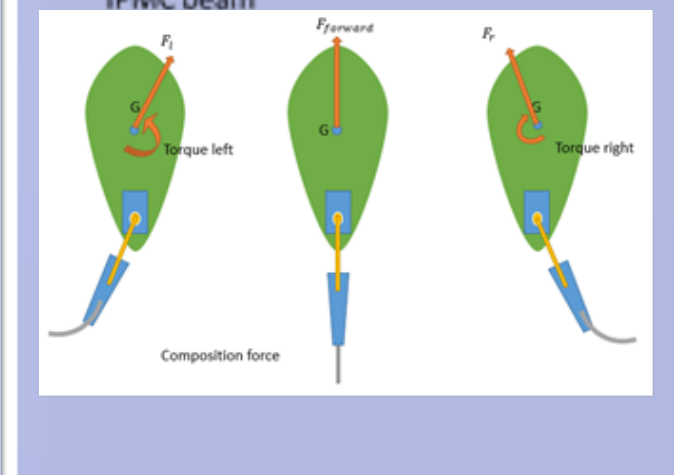
- Achieving Overlap of Sensing Footprints of Mobile Agents using Rendezvous Cones

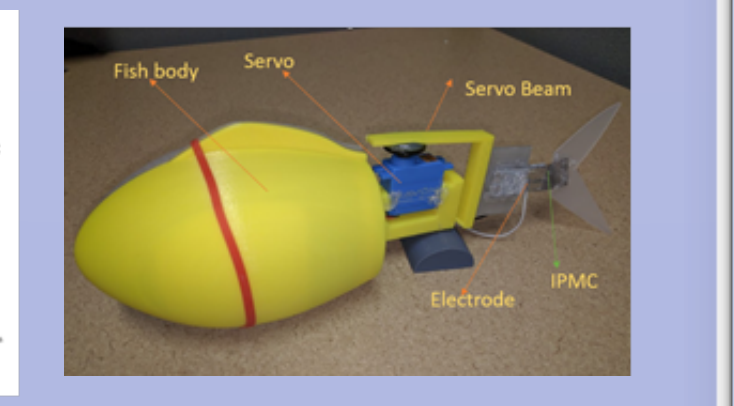




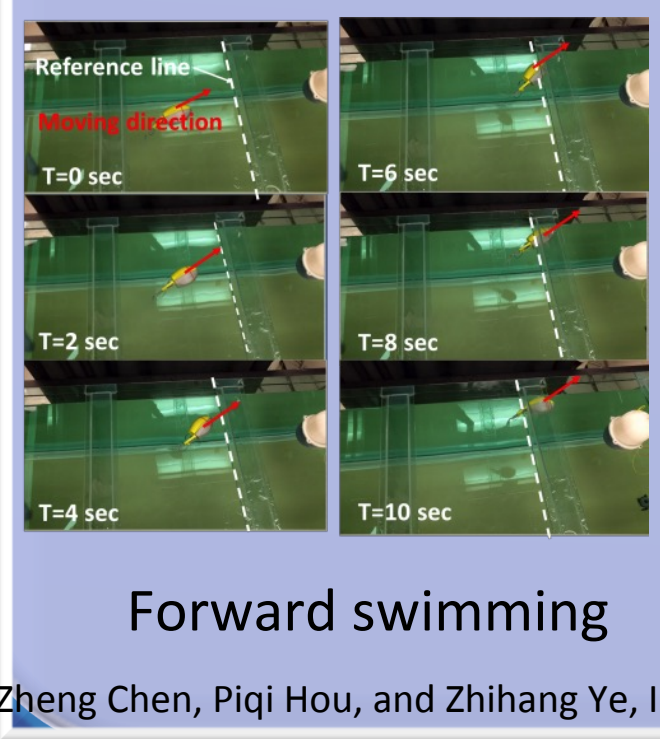
Smart-material Actuated Biorobotic Fish

2D Maneuverable Robotic Fish Propelled by Servo/ IPMC Hybrid Tail

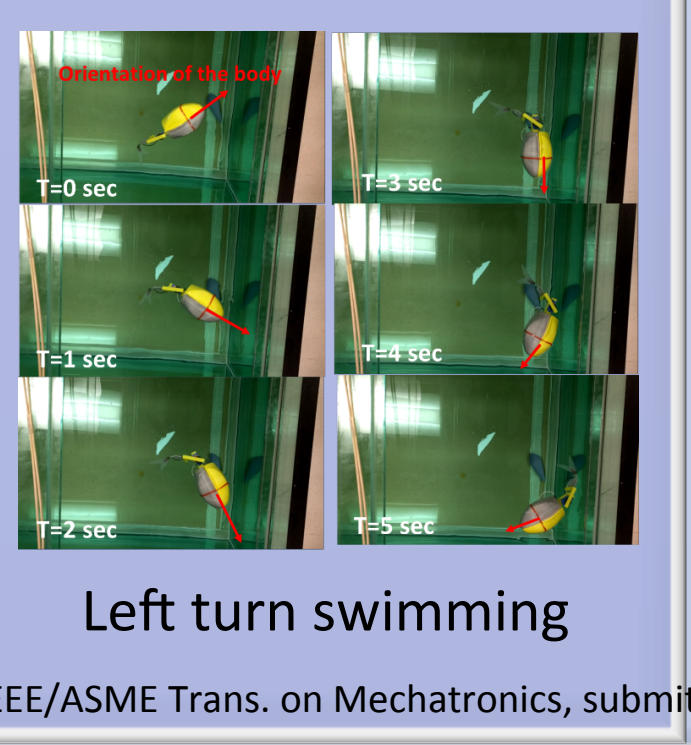




Prototype



Forward swimming



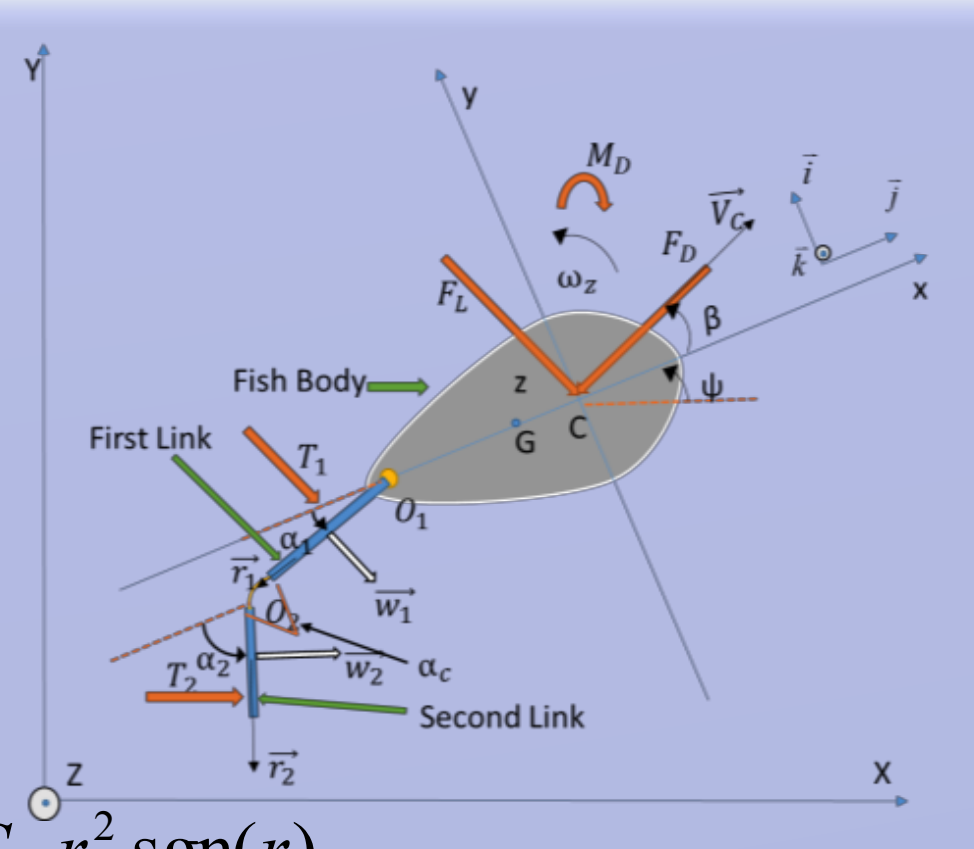
Left turn swimming

Zheng Chen, Piqi Hou, and Zhihang Ye, IEEE/ASME Trans. on Mechatronics, submitted

Dynamic Modeling

- Body dynamics $\beta = \operatorname{atan}\left(\frac{v}{u}\right)$ $|V_c| = \sqrt{u^2+v^2}$

$$(m_b - X_{\dot u})\dot u(t) = (m_b - Y_{\dot v})v(t)r(t) + F_x(t)$$
$$(m_b - Y_{\dot v})\dot v(t) = -(m_b - X_{\dot u})u(t)r(t) + F_y(t)$$
$$(J_{bz} - N_{\dot r})\dot r(t) = (Y_{\dot v} - X_{\dot u})u(t)v(t) + M_z(t)$$

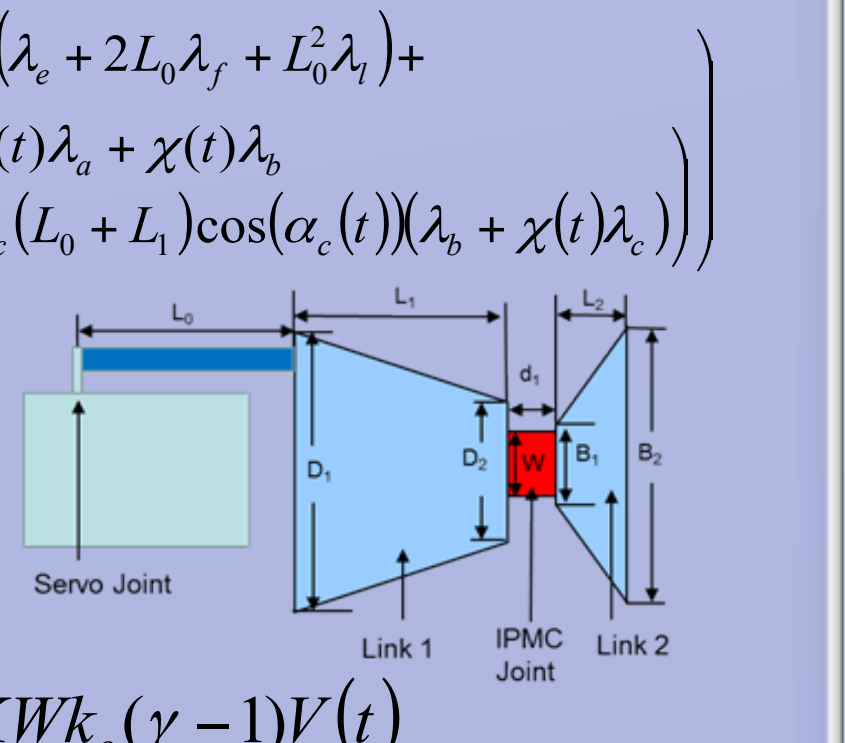


- Thrust and drag forces

$$F_D = \frac{1}{2}\rho_w|V_c|^2 SC_D \quad F_L = \frac{1}{2}\rho_w|V_c|^2 SC_L\beta \quad M_D = -C_M r^2 \operatorname{sgn}(r)$$
$$F_x = T_1\sin\alpha_1 + T_2\sin\alpha_2 - F_D\cos\beta + F_L\sin\beta$$
$$F_y = T_1\cos\alpha_1 + T_2\cos\alpha_2 - F_D\sin\beta - F_L\cos\beta$$
$$M_z = M_D + T_1 a_1\cos\alpha_1 + T_2 a_1\cos\alpha_2 + M_1$$
$$M_1(t) = -\rho_w\frac{\pi}{4}\left(\begin{array}{l}\Gamma_1(\omega)\ddot\alpha_1(t)\left(\lambda_e + 2L_0\lambda_f + L_0^2\lambda_l\right) + \\ \Gamma_2(\omega)\left(\begin{array}{l}(\ddot\alpha_c(t)\lambda_a + \chi(t)\lambda_b \\ + \ddot\alpha_c(L_0+L_1)\cos(\alpha_c(t))(\lambda_b + \chi(t)\lambda_c)\end{array}\right)\end{array}\right)$$

- Hybrid tail model

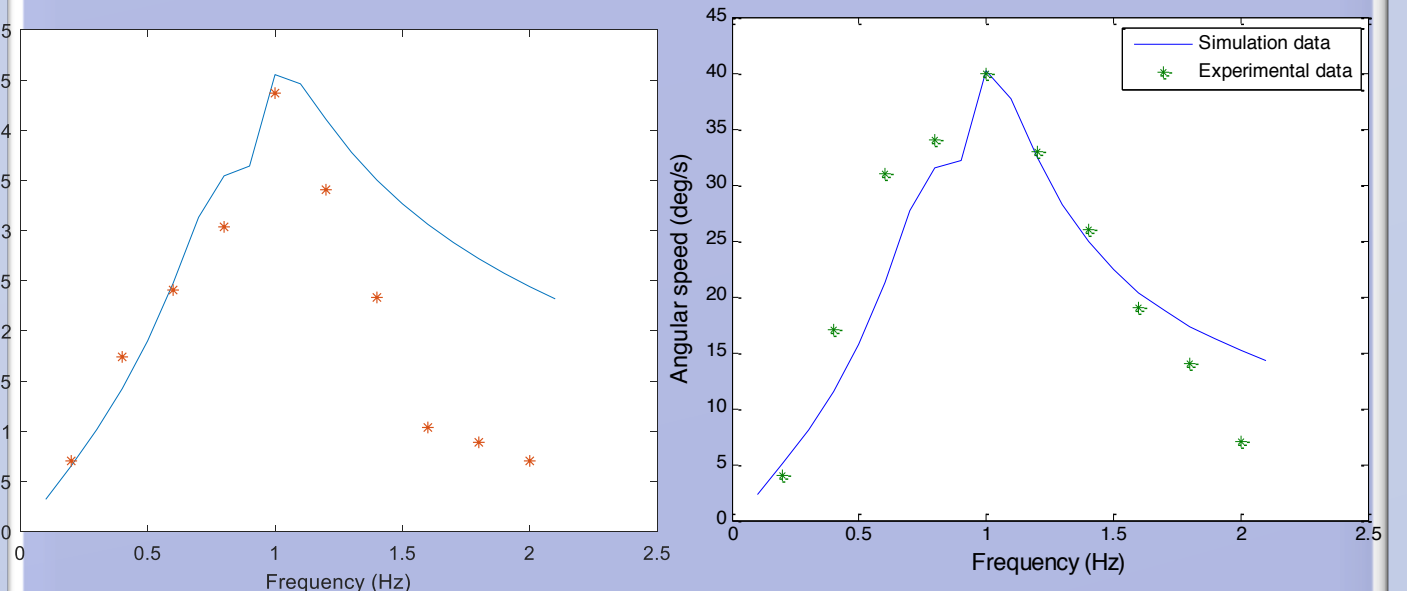
$$M_2(t) = \int_0^{L_2}\vec r_2\tau_2\times F_{h2}(\tau_2,t)\tau_2 d\tau_2 = -\rho_w\frac{\pi}{4}\Gamma_2(\omega)(\ddot\alpha_c(t)\lambda_a + \chi(t)\lambda_b)$$
$$\vec T_1(t) = \int_{L_0}^{L_0+L_1}\vec F_{h1}(\tau_1,t)d\tau_1 = -\rho_w\frac{\pi}{4}\Gamma_1(\omega)\ddot a_1(t)\left(\lambda_f + L_0\lambda_l\right)\vec w_1$$
$$\vec T_2(t) = \int_0^{L_2}\vec F_{h2}(\tau_2,t)d\tau_2 = -\rho_w\frac{\pi}{4}\Gamma_2(\omega)(\ddot\alpha_c(t)\lambda_b + \lambda_c\chi(t))\vec w_2$$



- IPMC fin dynamics:

$$K \overset{\Delta}{=} \frac{F^2 dC^-}{k_e RT}\left(1 - C^-\Delta V\right) \quad \gamma = h\sqrt{\frac{K}{d}}$$
$$\gamma\dot M_a(t) + KM_a(t) = 2\alpha_0 KWk_e(\gamma - 1)V(t)$$
$$I_2\ddot\alpha_c(t) + \xi\dot\alpha_c(t) + K_I\alpha_c(t) = M_a(t) + M_2(t)$$

Model Validation



Forward speed vs frequency Turning speed vs frequency

W	L_1	L_2	D_1	D_2
0.01 m	0.03 m	0.04 m	0.045 m	0.045 m
B_1	B_2	d_1	L_2	ρ_w
0.026 m	0.04 m	0.01 m	0.04 m	1000 kg/m^3

ξ	h	C^-	Y
0.001	280 um	1091	2.91×10^8 Pa
Γ_2	Γ_1	F	T
1.2	1.2	96487 C/mol	300 K
R	k_e	d	α_0
8.3143 J/mol.K	2.48×10^{-5} F/m	5.39×10^{-9} m/s	0.08 J/C

S	L	m_b	D_R
0.02 m^2	0.14 m	0.18 kg	0.08 m
c	C_D	C_L	C_M
0.03 m	0.6	4.7	4.5×10^{-5}
k_{11}	k_{22}	k_{66}	a_1
0.24	0.67	0.155	0.04 m

Zheng Chen, Piqi Hou, and Zhihang Ye, IEEE/ASME Trans. on Mechatronics, submitted