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

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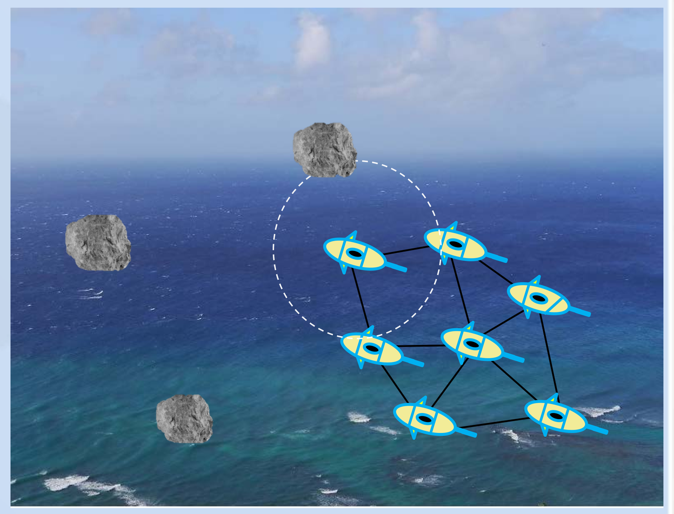
Motivations and Challenges

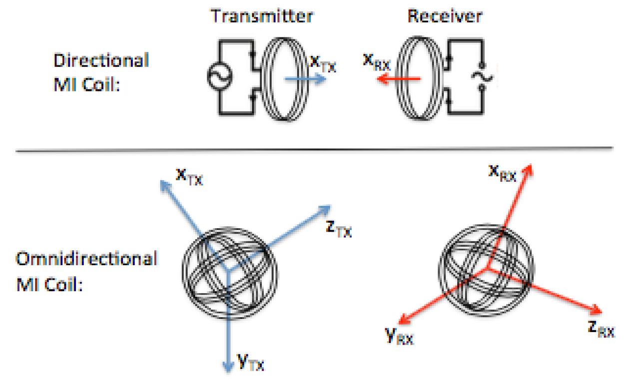
- Complex and strongly coupled sensing-motion dynamics of swarming CPS
- Inherent environmental uncertainties such as communication delay and package loss, unpredictable and/or confined spaces, and highly spatially and temporally varying environments
- Resource constraints of mobile computing entities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

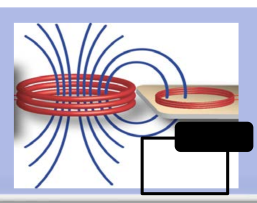


MI Underwater Communications & Localization

Channel Model for 3D Directional MI Coil

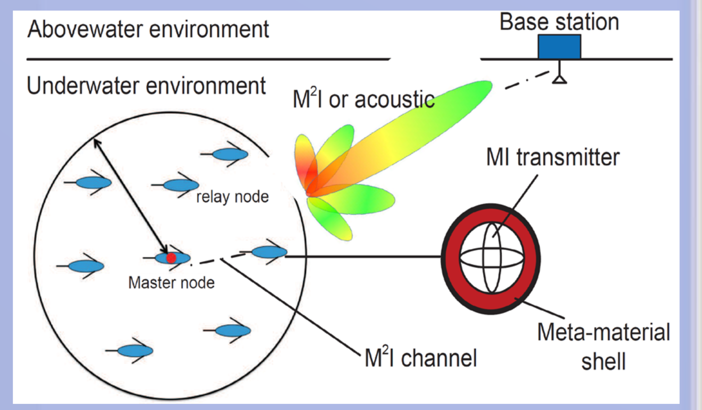
- Each robot in the swarm is equipped with an MI transceiver
  - To enable low-delay communication among robots for real time control
  - To provide accurate position information of each robot
  - To enable reliable long distance communication between robot swarm to surface
- The new contribution in this year
  - A new hybrid MI-Acoustic underwater communication architecture
  - Design and implementation of MI-assisted acoustic distributed beamforming technique





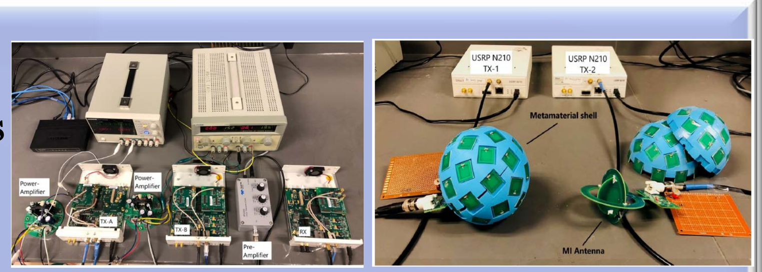
Hybrid MI-Acoustic Underwater Communication Architecture

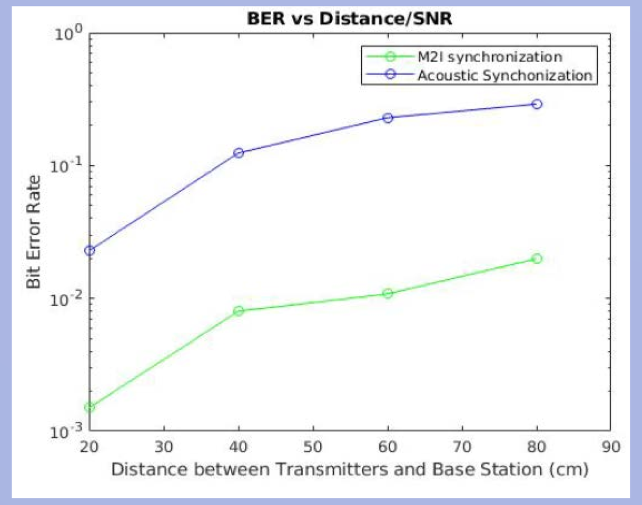
- While MI-based communication system established low-delay communication among robots
- It is still challenging to communicate between the robot swarm and the surface station
- We design the new hybrid MI-Acoustic underwater communication architecture
  - Robots in one swarm use MI to form virtual MIMO system
  - Each robot swarm use the distributed acoustic transducer or MI transceiver at each robot to form reliable directional beam
  - Long distance and reliable underwater communication link can be established



Underwater MI MIMO Technologies

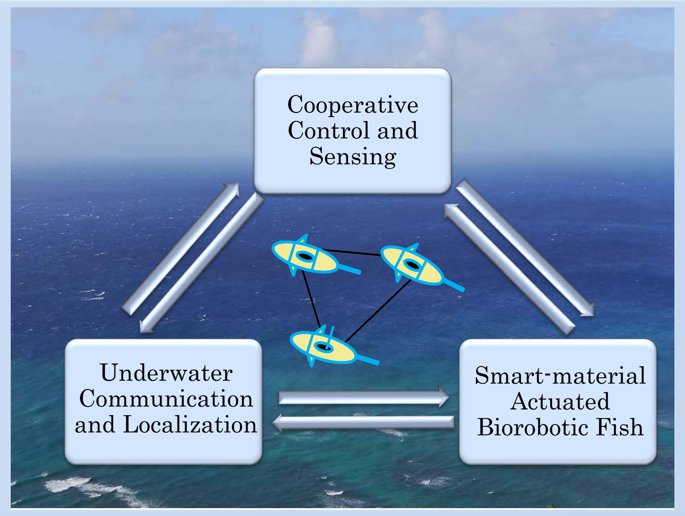
- **Tri-Coil Coil Magnetic MIMO: three-coils antenna array forms a 33 MIMO channel**
  - Orderly (2x- 5x) improved comm. capacity
  - spatial multiplexing for current multi-robot communications
  - simultaneous wireless charging and communications via smart antenna selection
- **MI-assisted Cooperative Acoustic MIMO**
  - combat the challenging internode synchronization issues faced by conventional cooperative acoustic beamforming
  - greatly decrease bit error rate or equivalently increase effective capacity of acoustic channel'
  - achieve long-range communication over several kilometers





Objectives

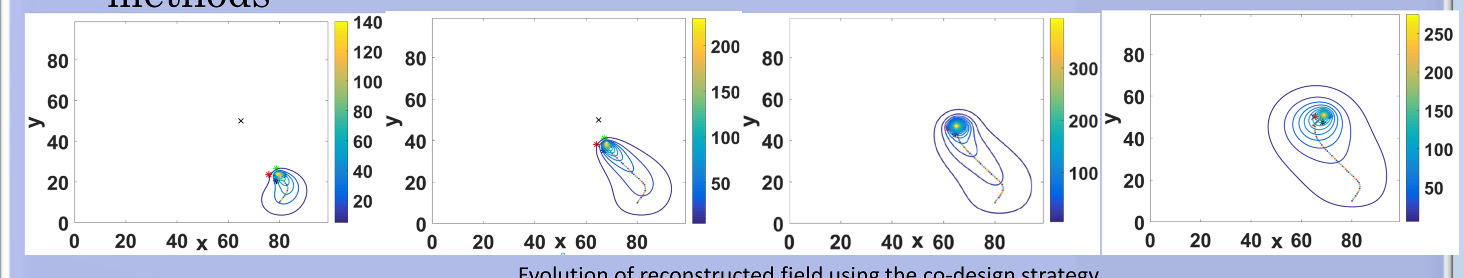
- The overall research objective is to establish and demonstrate a generic motion-sensing co-design procedure that
  - significantly reduces the complexity of mission design for swarming CPS
  - greatly facilitates the development of effective and efficient control and sensing strategies, which are computation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



Cooperative Motion and Sensing Co-design

Sensing-Motion Co-Planning For Reconstructing a Spatially Distributed Field

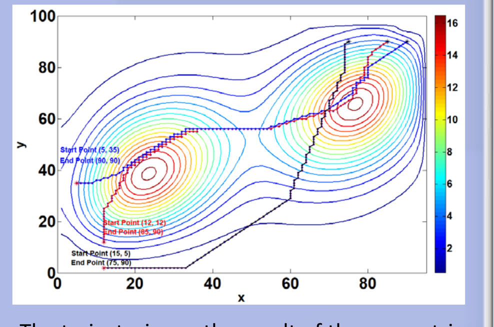
- We investigate the problem of simultaneous parameter identification and mapping of a spatially distributed field represented by a general nonlinear PDE model
- We develop a parametrized model to represent the nonlinear PDE, which enables the use of the modified version of the previous designed online parameter identification and state estimation methods



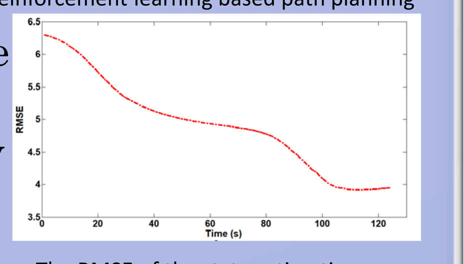
Evolution of reconstructed field using the co-design strategy

Geometric Reinforcement Learning Based Path Planning

- We develop a geometric reinforcement learning (GRL) algorithm for real-time path planning for mobile sensor networks for reconstructing a spatially distributed field
- The proposed GRL can balance the performance of the field reconstruction and the efficiency of the path
- The problem can be solved using DP efficiently
- The algorithm is verified in simulation in a realistic diffusion field collected in lab



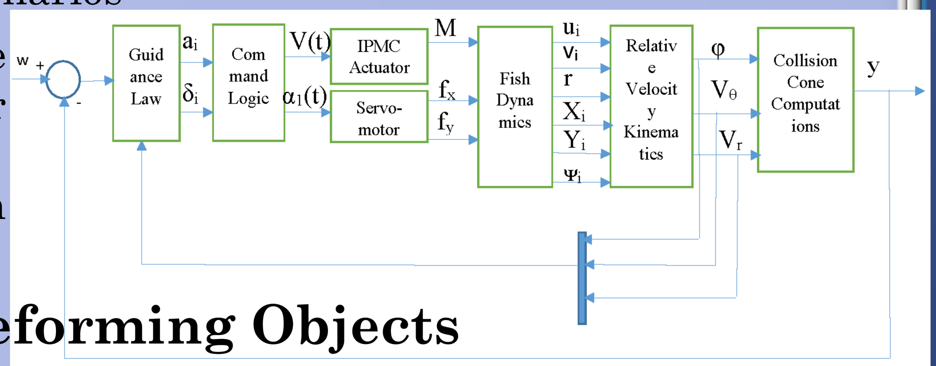
The trajectories as the result of the geometric reinforcement learning based path planning



The RMSE of the state estimation error

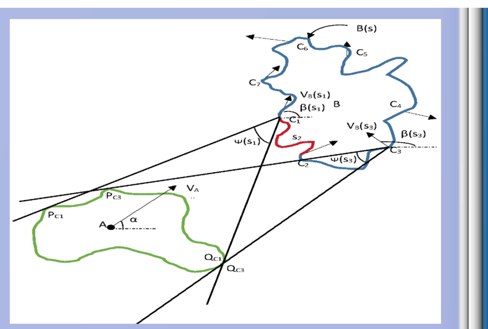
Collision Avoidance for a Hybrid-Tailed Robotic Fish

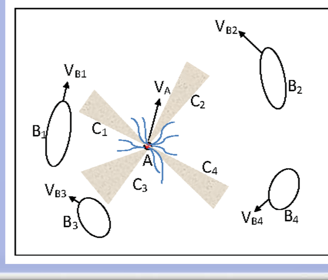
- We develop analytical laws that enable a hybrid tailed robotic fish to achieve energy-optimal collision avoidance
- The laws are in terms of the IPMC voltage and the servomotor flapping amplitude of the fish, and are developed for both cooperative and non-cooperative collision avoidance scenarios
- A theoretical quantification of the robustness of these laws to sensor measurement errors is performed.
- An experimental validation on an actual robotic fish is performed

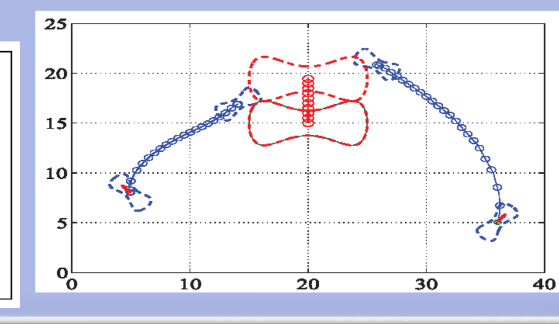


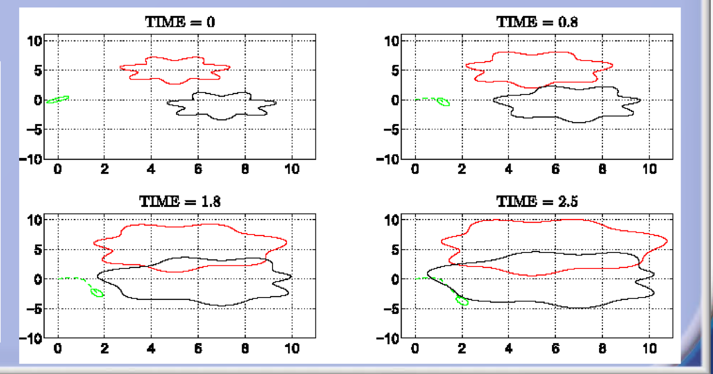
Collision Avoidance of Deforming Objects

- We consider the collision avoidance of moving objectives whose shape can change with time
- We obtain analytical expressions for collision cones and then integrate with a Lyapunov framework to determine analytical guidance laws
- Collision Cones associated with quadric surfaces moving in a n-d configuration space are developed, which can used for path planning in n-d



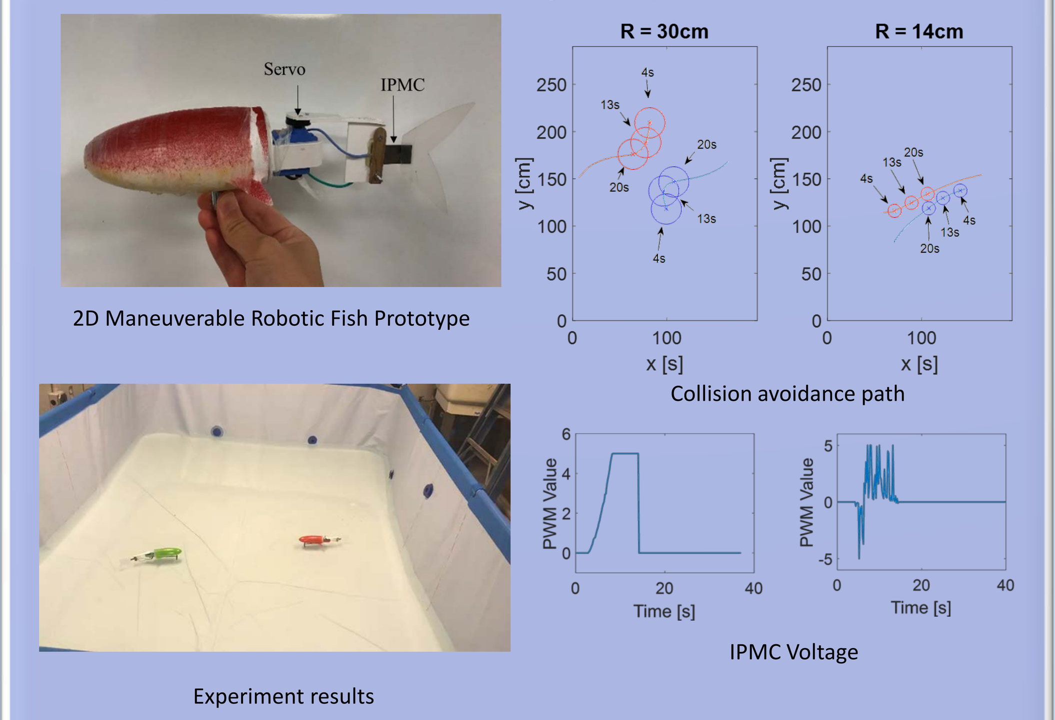




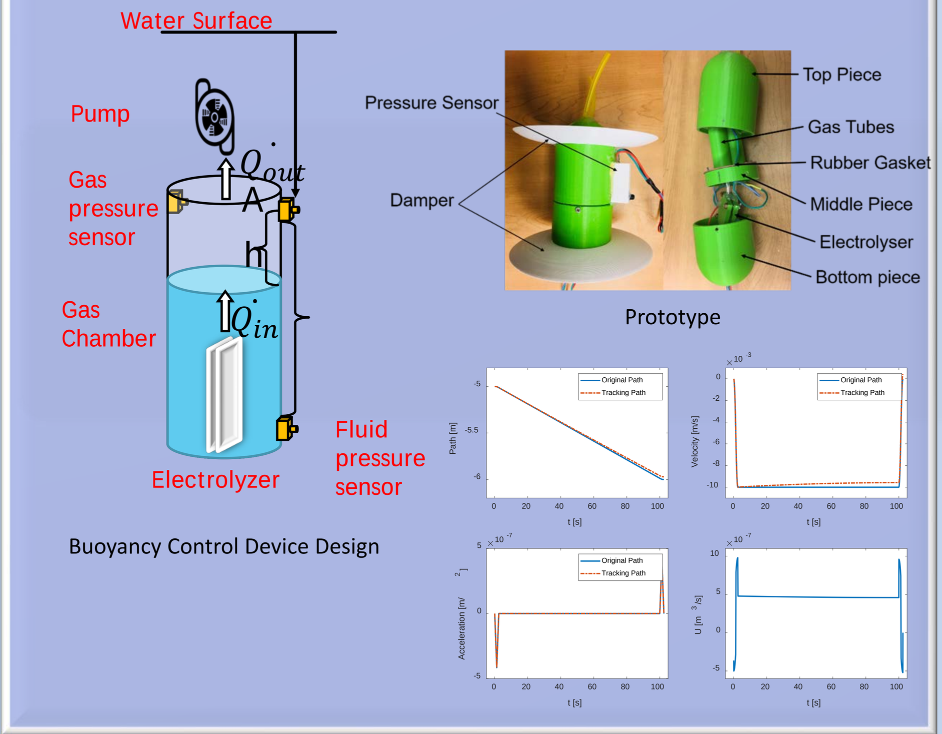


Smart-material Actuated Bio-robotic Fish

Cooperative Collision Avoidance Control of Robotic Fish



Feedback Control of Buoyancy Control Device



3D Maneuverable Robotic Fish

Control Requirements

$Z(0) = -5 \rightarrow Z(T) = -6$

$|Q| \leq Q_{max}; |\dot{Z}| \leq \dot{Z}_{max}$

Control Strategy