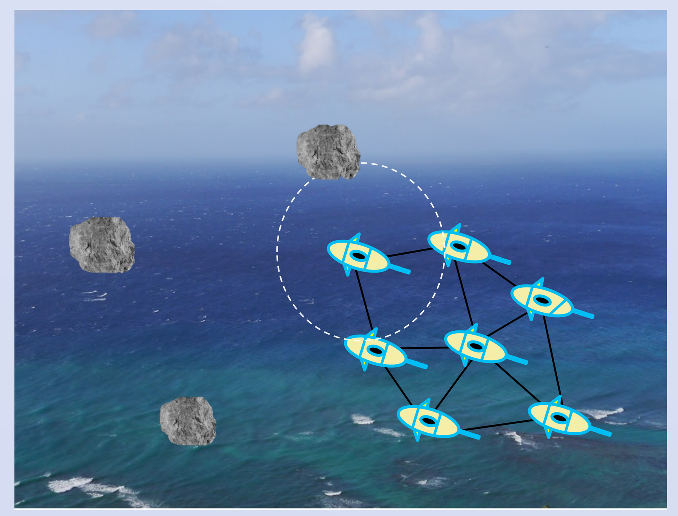
Towards Effective and Efficient Sensing-Motion Co-Design of Swarming Cyber Physical Systems

Wencen Wu* , Pu Wang**, Zheng Chen**, Animesh Chakravarthy**, Zhi Sun***
* Rensselaer Polytechnic Institute, ** Wichita State University, ***State University of New York at Buffalo

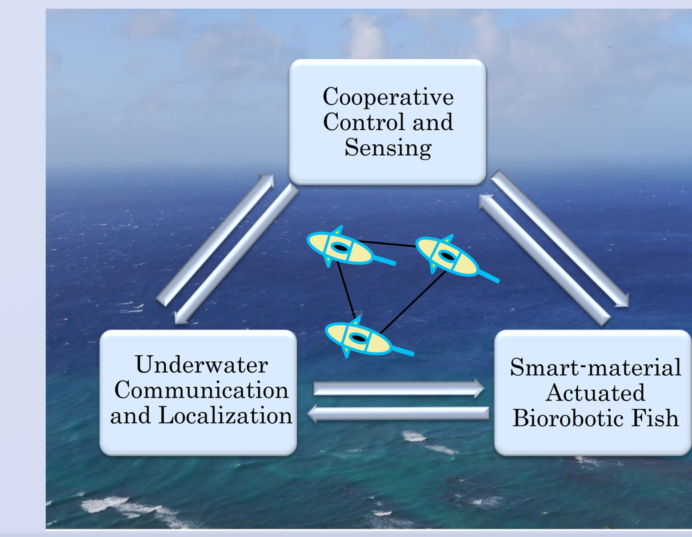
Motivations and Challenges

- 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

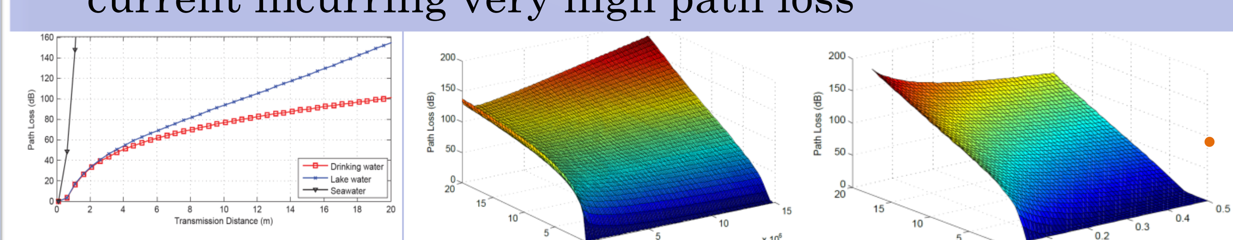
- The overall research objective is to establish and demonstrate a generic motion-sensing co-design procedure that
  - significantly reduces the complexity of mission design for swarming CPS
  - greatly facilitates the development of effective and efficient control and sensing strategies, which are computation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



MI Underwater Communications & Localization

Channel Model for 3D Directional MI Coil

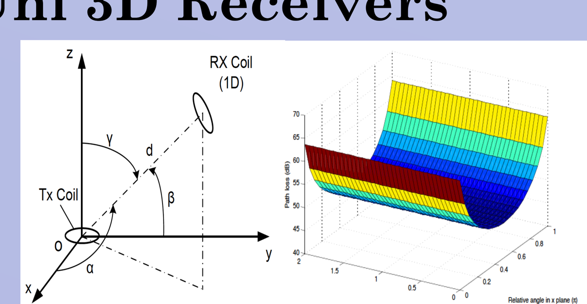
- Data information is carried by a time varying magnetic field generated by the modulated sinusoid current along an MI coil antenna at the Tx
- Rx retrieves the information by demodulating the induced current along the receiving coil antenna
- Small sensor can achieve 20m & 10m range in Case 2 and 2 but less than 1m range in Case 1
- High conductive seawater induces significant Eddy current incurring very high path loss

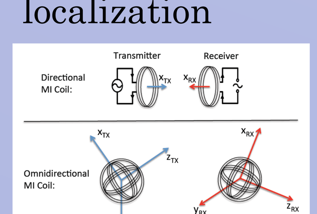

(a) Path loss of MI underwater communications

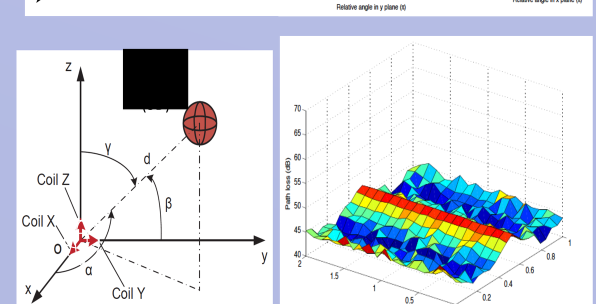
- Transmission range can be increased by using optimal operating frequency and the larger size coil antennas
- Influence of the operating frequency and coil antenna size on the MI channel path loss in the lake water
- As the operating frequency increases from 100 KHz to 15 MHz, the MI path loss decreases at the first and keeps increasing after a point.
- Path loss can be further reduced by increasing the wire turns of the coil antenna.

Path Loss of Uni 3D Receivers

- MI antenna with 3 orthogonal coils
  - Omni-directional communications
  - Enhanced received signal strength
  - Can be used for 3D localization

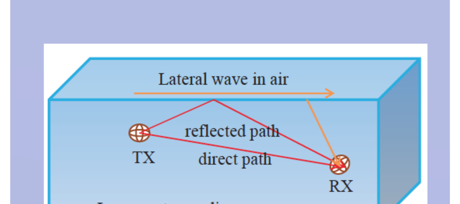


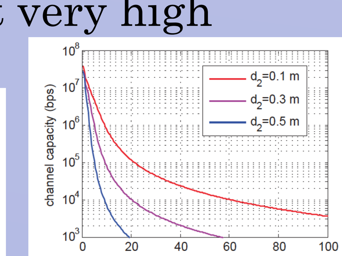




Effects of Surface Wave

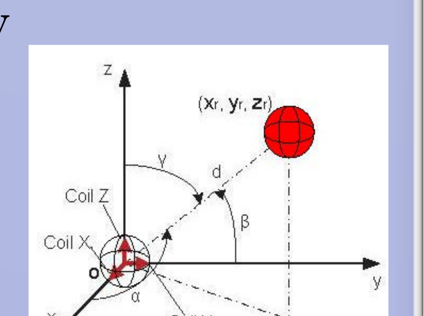
- The reflection and surface wave can significantly increase the communication range of underwater MI.
- If the depth of the underwater transceiver is not very high





MI-based Relative Localization

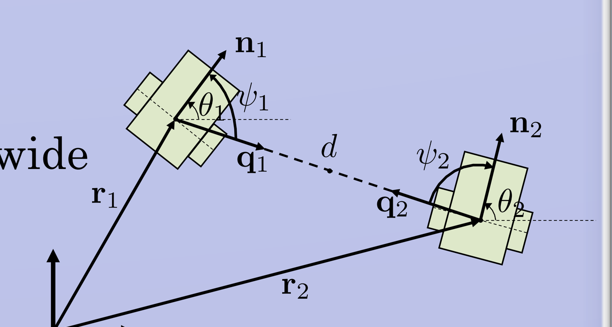
- Multi-path fading-free MI channel & orthogonality of tri-coil MI antennas → accurate, simple, and convenient localization strategy
- By using 3 coils in orthogonal planes, we can
  - Estimate distance in each of three directions separately
  - Calculate angular coordinates of the sensor node to a reference node, e.g., the MI anchor node
- Only one anchor node is needed, e.g., MI data sink, to determine the positions of sensors in 3D space

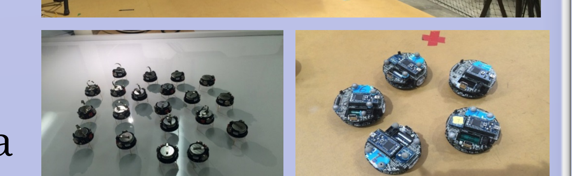


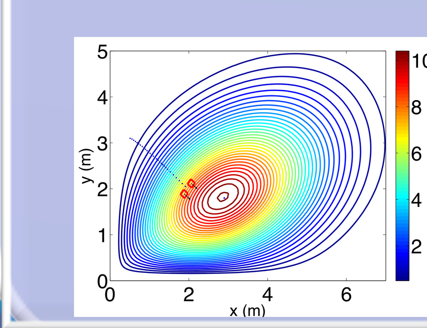
Cooperative Motion and Sensing Co-design

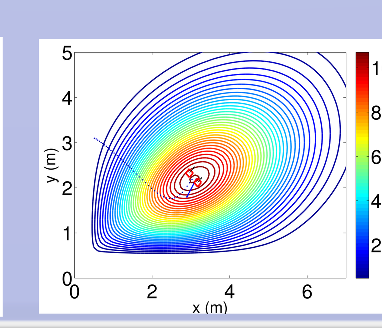
Distributed Source Seeking

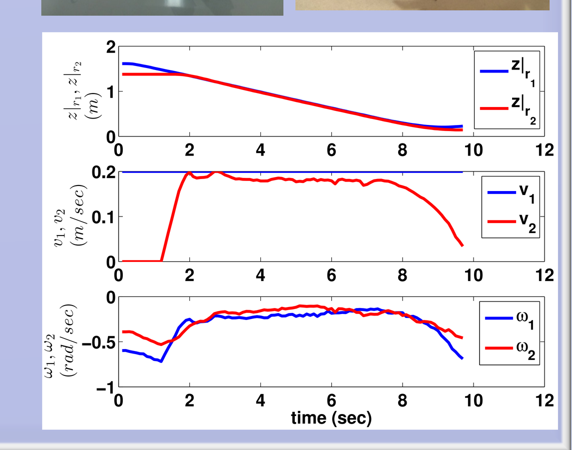
- Source seeking is one of the fundamental and representative missions for swarming CPS with a wide range of practical applications
- We propose a dual-module control approach that achieves fast source seeking in time-varying fields
- Key idea: velocity decomposition
  - Linear velocity: motion control
  - Angular velocity: formation control
- Only two nonholonomic mobile robots are needed in 2D
- No gradient is estimated → reduced computational cost
- The algorithm has been validated in a multi-robot testbed using both M3pi robots and Kilobots







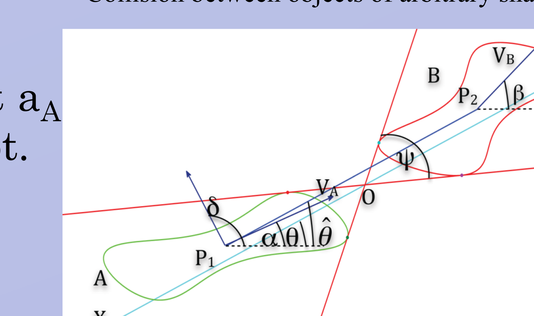




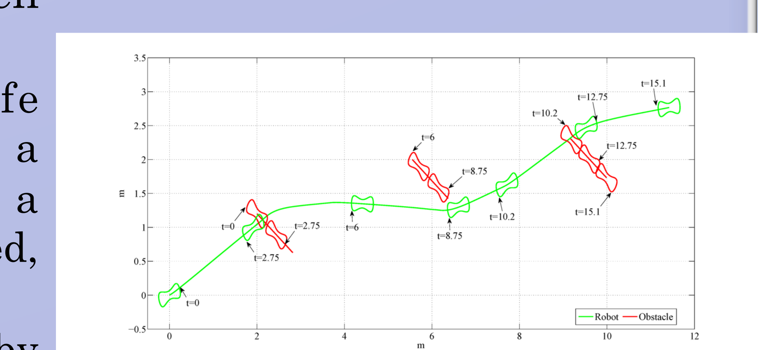
Collision Avoidance

- 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.

Collision between objects of arbitrary shapes

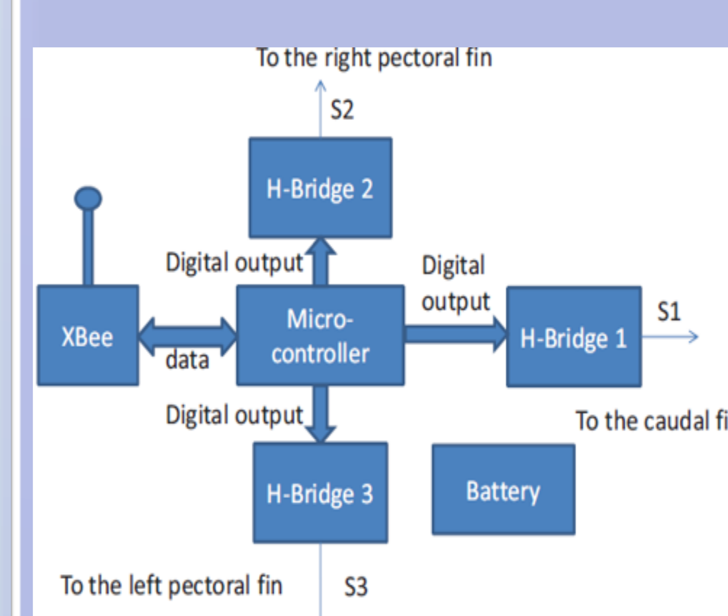


- Besides collision avoidance, the collision cone approach has also been used for:
  - Analytical laws governing safe trajectories for a robot to make a precision 3-D maneuver through a small orifice. The orifice may be fixed, moving and/or closing in size
  - Analytical laws for area coverage by mobile robot sensor networks.

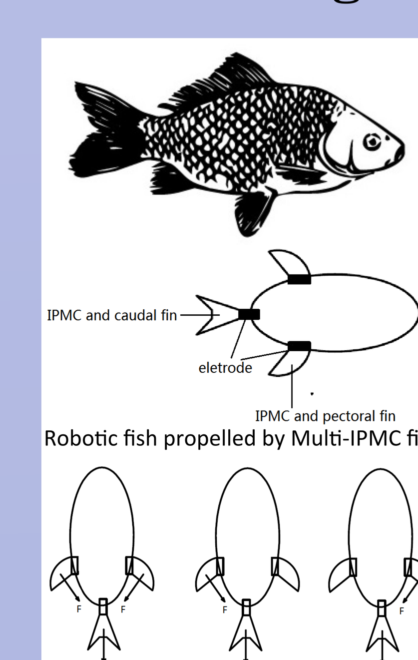

Demonstration of collision avoidance laws in a dynamic environment with multiple obstacles

Smart-material Actuated Biorobotic Fish

2D Maneuverable Robotic Fish Design



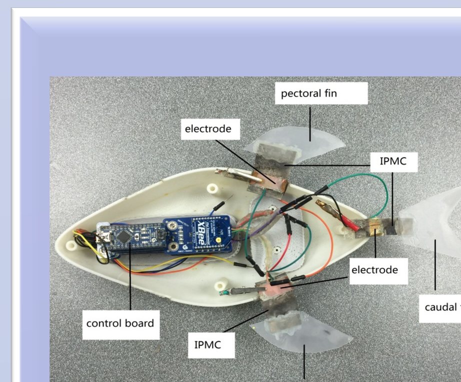
Wireless control system design



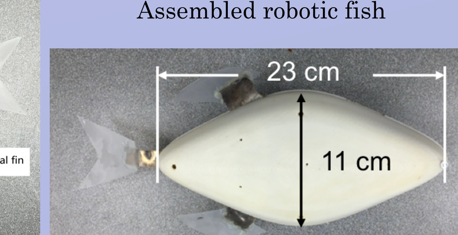
Forward swimming Left-turning Right-turning

Fabrication Result

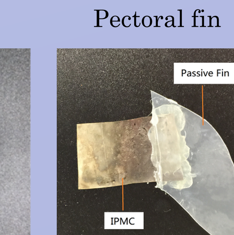
- The total weight of the robot: 290 grams



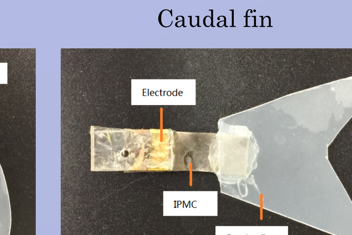
Assembled robotic fish



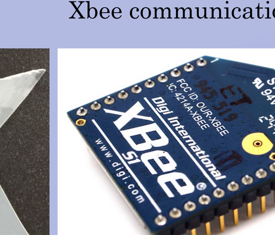
Pectoral fin



Caudal fin



Xbee communication



- The forward-swimming speed reached 0.5 cm/sec, and both the left-turning and right-turning speeds reached to 1.5 rad/sec.