

## **YIP: Generic Environment Models (GEMs) for Agile Marine Autonomy**

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### **LONG-TERM GOALS**

This project develops a roadmap to achieve agile marine autonomy that endows unmanned marine systems with ability to take fast responses to environmental changes. Agile marine autonomy may help unmanned systems to out maneuver opponents in future naval battles.

### **OBJECTIVES**

The proposal will overcome the demand for significant amount of computing resources and complex software packages from existing ocean modeling methods. The technical objectives include the following:

1. Establish the methodology of constructing generic environment models (GEMs). A GEM does not rely on a specific region or a specific ocean process. It can have higher resolution in both space and time and can be computed much faster than classical ocean models. In combination with existing ocean models, GEMs enable navigation of mobile agents in the marine environment in real time.
2. Develop control and navigation algorithms that benefit from the GEMs. GEM provides fast information to unmanned systems whose motion also affects the quality of GEMs. Through a new theory called Controlled Lagrangian Particle Tracking (CLPT), we develop methods to refine control and navigation algorithms due to GEMs.
3. Provide multi-disciplinary training to graduate and undergraduate students who will be the future task-force in marine technology.

GEMs for agile marine autonomy reflect a tight integration of research in robotics/control with research in physical oceanography. On one hand, it may significantly extend the capabilities of existing ocean modeling theory to better serve operations of autonomous agents. On the other hand, it may results in novel map-making methods and navigation methods in four-dimensional marine processes that have not been achieved in the field of robotics. Therefore, the proposed research program may create new opportunities to advance both oceanography and robotics/control engineering research.

## **APPROACH**

The work is currently performed by PI Fumin Zhang and three graduate students in Georgia Tech: Chuanfeng Wang (started Fall 2010), Dongsik Chang (started Fall 2009), Klementyna Szwaykowska (started Fall 2007). The PI is leading the team, Chuanfeng Wang focuses on the environmental modeling and map-making algorithms with implementation on the YSI Ecomapper. Dongsik Chang focuses on the automation middleware systems and control of underwater gliders. Klementyna Szwaykowska focuses on the CLPT theory and path planning algorithms using the Generic Environment Models. The approach and methodologies employed, corresponding to the above objectives, are as follows:

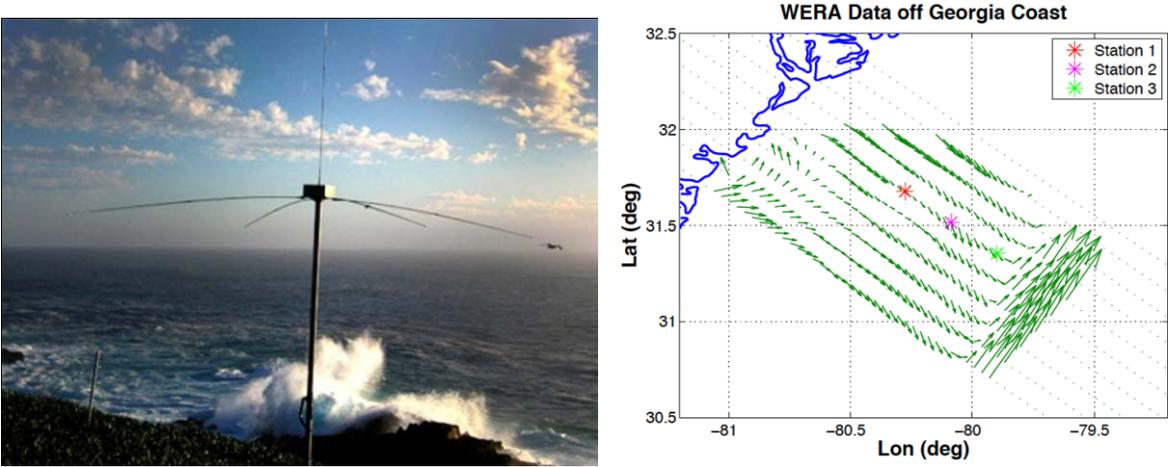
1. A novel methodology to construct the generic environment models (GEMs) is being developed. This method is based on the insight that ocean circulation models produces modes in certain time and spatial scales. These modes can be used as basis functions for the GEMs. The structure of the GEM is initialized through existing ocean models by parsing output data from the ocean models. A set of model updating algorithms are then developed to assimilate data collected by unmanned marine systems or from other sources. The time required to compute the GEMs are much lower than computing the ocean models since it is not necessary to solve the geophysical fluid equations. From this point of view, GEMs are tradeoff between computing time and accuracy.
2. The fundamental theoretical principles governing the interactions between the GEMs and unmanned systems are discovered. These principles are formulated as the theory of controlled Lagrangian particle tracking (CLPT). In-depth analysis are performed about the discrepancy between the trajectories of unmanned marine systems in the ocean and in predictions generated by using the GEMs.
3. Strategies to achieve agile marine autonomy with GEMs are being developed. PI's work in automation middleware provides systems support for GEM guided path planning. Autonomy algorithms generates biologically inspired behaviors can be used as path planning tools. CLPT will provide guidance on how frequent replanning based on GEMs needs to happen.
4. Cost effective and lab-scale experiments have been carried out to validate and inspire the theoretical work. Methods and algorithms are first tested on ground mobile robots in a lab. YSI Ecomapper and student developed marine robots are used to perform experiments in a small lake. PI's existing collaborations with the industry and Naval Research Labs are leveraged to transfer the research findings from academia to applications.
5. Education and outreach activities are performed at the graduate, undergraduate, and K-12 levels. A multidisciplinary training program is established at the graduate and undergraduate level. Agile marine autonomy have been taught in a robotics course, and a new book on mobile sensor networks is being prepared.

## **WORK COMPLETED**

### **1. Work performed on GEM.**

We have deployed two underwater gliders for ocean sampling in Long Bay, SC during winter 2011, spring 2012, winter 2012, and spring 2013, SC for a related NSF project: "Mechanisms of nutrient input at the shelf margin supporting persistent winter phytoplankton blooms downstream of the

Charleston Bump.” Our team have controlled the motion of the two gliders to navigate near the edge of the Gulfstream, where strong current exceeding glider horizontal speed is often observed. Through this process, our method for GEM has been verified. An example is shown in Figure 1, where an ADCIRC model is used to initialize the GEM. After initialization, the GEM is updated from observations of the gliders and from a long range Wave Radar (WERA) system, which measures sea surface currents.



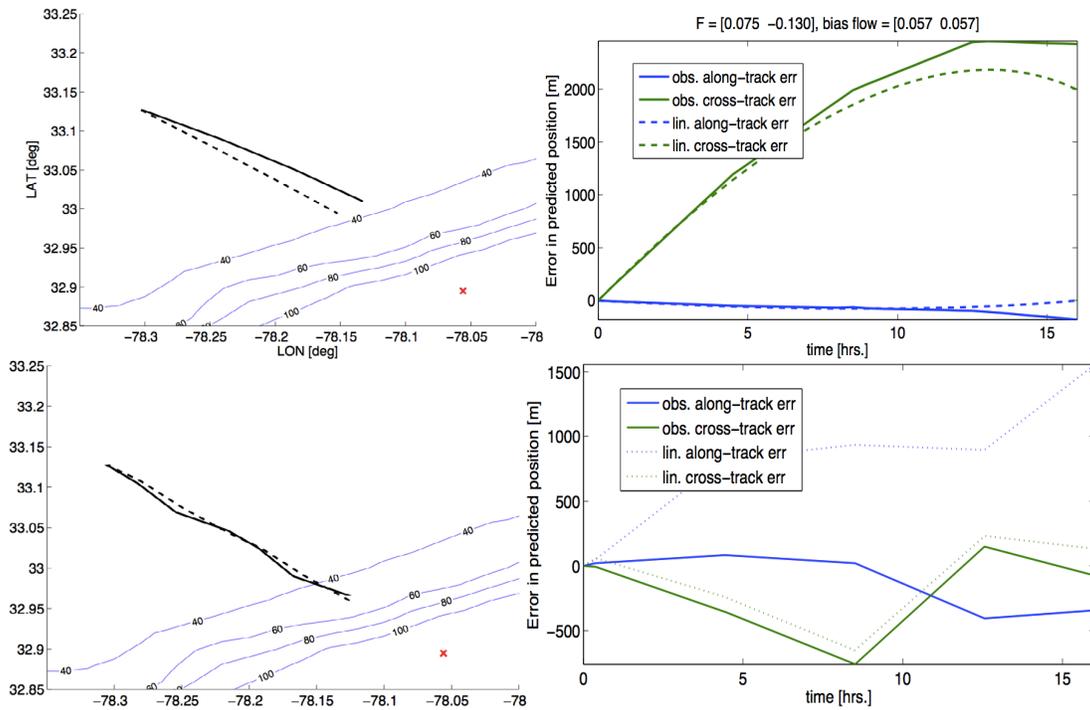
**Figure 1. A station-keeping algorithm produces paths of simulated gliders in Long Bay, SC. A GEM is developed to combine tides and the gulfstream.**

**2. Work performed on CLPT**

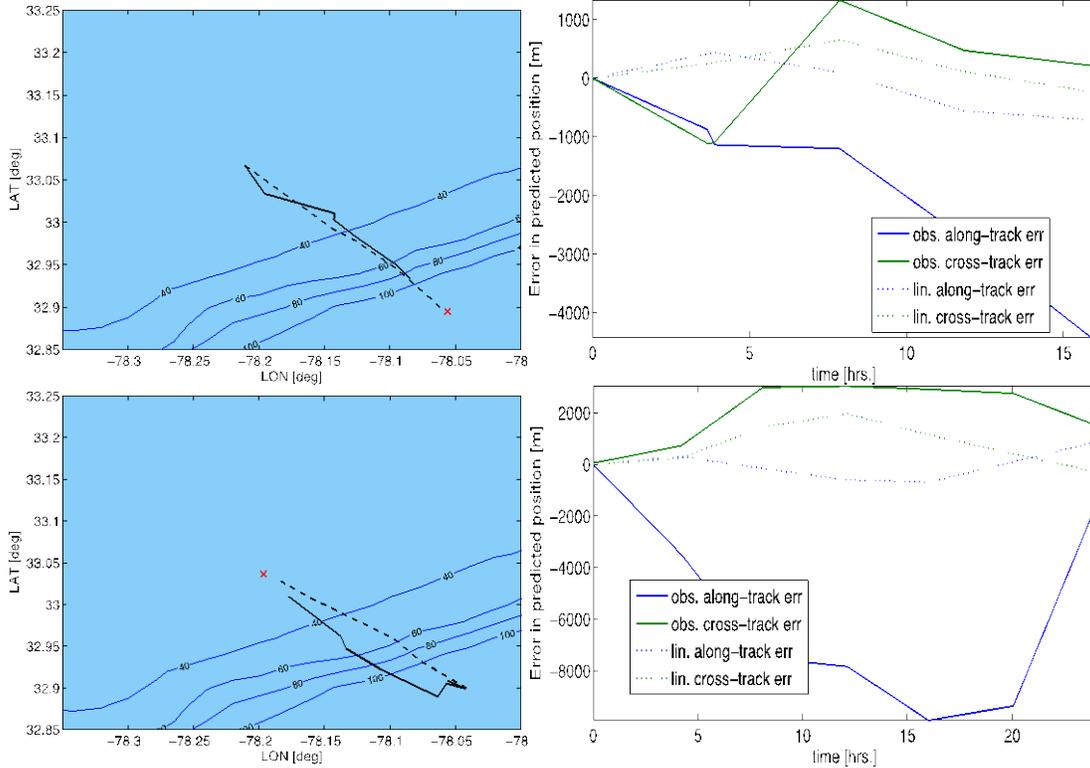
The CLPT theory has been validated and greatly advanced based on new observations from the experiments. Using the Glider Environment Networked InfOrMation System (GENIOS) developed by PI’s team, we designed and tested the CLPT for three typical control laws to achieve the following behaviors for a glider: (1) to maintain a glider’s position near the edge of Gulfstream; (2) to follow a predefined track; (3) to reach a desired waypoint from a location a distance away.

We derived a first-order model for growth of error about the modeled vehicle trajectory. We found the form of error growth for the specific case of a flow-canceling station-keeping controller, which is used to steer a constant-speed vehicle toward a fixed station-keeping position using heading control. We tested the accuracy of the error growth model under different flow conditions, including constant flow and tidal flow, using simulations run in GENIOS.

In the simulation shown in Figure 2, a vehicle was initialized at a starting position 17.7 km from the goal. The “virtual“ vehicle traveled along a straight line toward the goal position. We decompose the error in predicted vehicle position into an along-track component (parallel to the simulated vehicle straight-line trajectory) and a cross-track component (normal to the trajectory). The “real” and “virtual” vehicles were both simulated in GENIOS, and the flow field for the real vehicle included a constant or tidal perturbation. We found that, under constant flow, the first-order error model performs quite well; under tidal flow, the along-track error diverges from its first-order estimate, while the cross-track first-order error approximation closely matched the error observed in simulation.

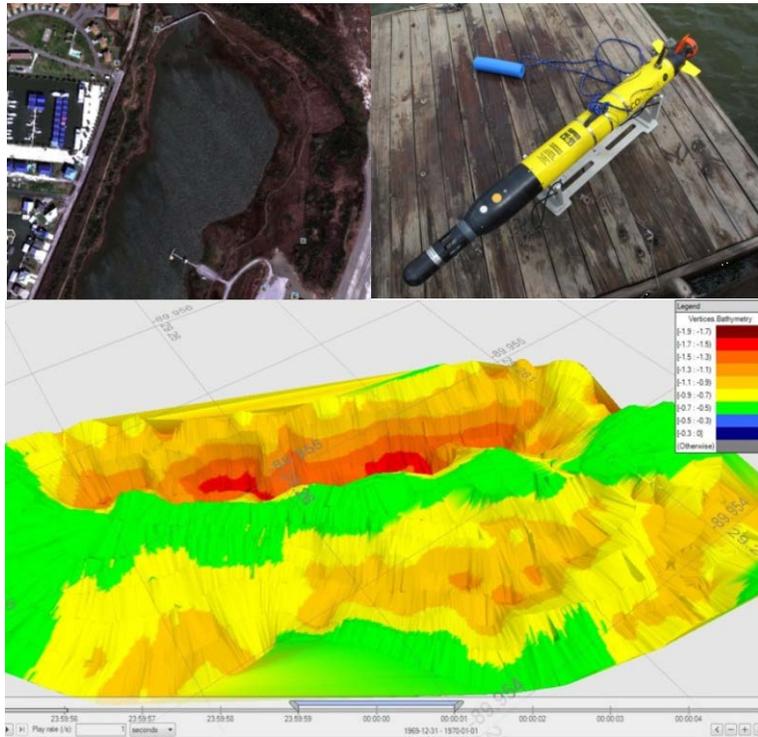


**Figure 2. (Left) Trajectories of “real” (solid line) and “virtual” (dashed line) station-keeping gliders in simulation, in constant flow field (top) and tidal flow field (bottom). The red cross shows the location of the desired station-keeping position. (Right) Along-track and cross-track error in predicted glider position over time, observed in simulation (solid line) and predicted based on linearization of error growth equation (dashed line). The constant flow has speed 0.15 m/s; the corresponding perturbation is constant, with speed 0.08 m/s. The tidal flow has amplitude 0.20 m/s; the corresponding perturbation has a tidal component with speed 0.07 m/s and a constant bias of 0.02 m/s. The vehicle through-water velocity is 0.30 m/s.**



**Figure 3. (Left) Trajectories of real (solid line) and virtual (dashed line) station-keeping gliders from a field experiment in Long Bay, SC, in February 2013. The red cross shows the location of the desired station-keeping position. (Right) Along-track and cross-track error in predicted position over time, observed (solid line) and predicted based on linearization of the error growth equation (dashed line).**

We further tested the error growth model in a ten-day field deployment in Long Bay, SC, in February 2013. A single Slocum glider was used to collect measurements of ocean conditions along a 20.5-km cross-shore transect. The glider used a flow-canceling station-keeping controller for transect following; the goal position switched between transect endpoints, with switching occurring each time the glider reached one of the transect endpoints. The results for testing of the linearized error model are shown in Figure 2. We note that the first-order estimate of error in the cross-track direction matches error observed during the experiment, while the along-track component diverges from the observed values. This may be caused by strong tidal flows over the study domain.

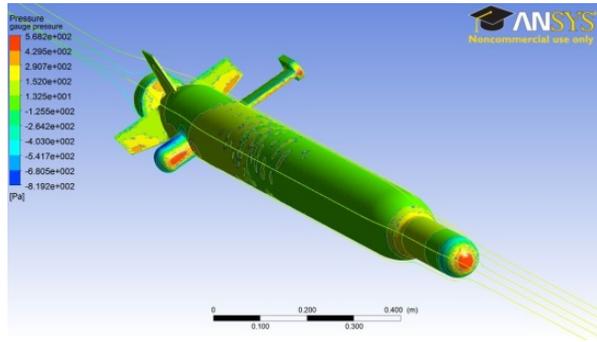


**Figure 4. Bathymetry survey using an YSI Ecomapper for a retention pond in Grand Isle State Park, LA**

### 3. Other related work

The strength of GEM goes beyond ocean flow modeling. We have deployed a YSI Ecomapper for bathymetry survey at a location near the Gulf of Mexico, where the GEM is built to represent the bathymetry data. The EcoMapper (Figure 4, upper right) is an autonomous underwater vehicle purchased from YSI Inc. If operating in the autonomous mode, the EcoMapper follows a predefined course, either on surface or below surface and records all sensor measurements into log files. As part of an NSF funded project “Autonomous Control and Sensing Algorithms for Surveying the Impacts of Oil Spills on Coastal Environments” led by the PI, the EcoMapper was deployed to survey the tidal lagoon located at the Grand Isle State Park (Figure 4, upper left) in Louisiana where oil pollutions have been spotted in 2010. Five autonomous missions between surface and 0.5 meters below surface were executed. By interpolating the DVL data, we obtained a bathymetry map for this pond (Figure 4, bottom). The salinity of the lagoon varies between 13ppt and 17ppt under different weather condition.

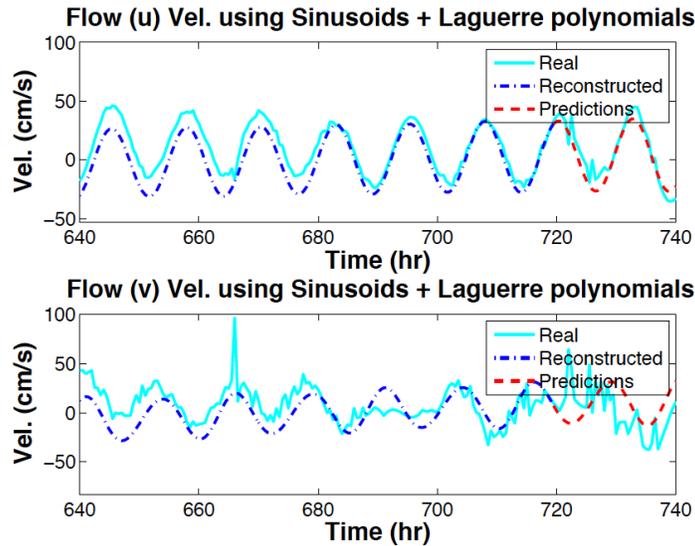
A sister version of the Ecomapper, the IVER, has been adopted by the Navy. To enable further developments of the autonomy capability of this device, we have developed a detailed hydrodynamic model for the YSI Ecomapper using computational fluid software as illustrated by Figure 5. The model has been verified in field tests.



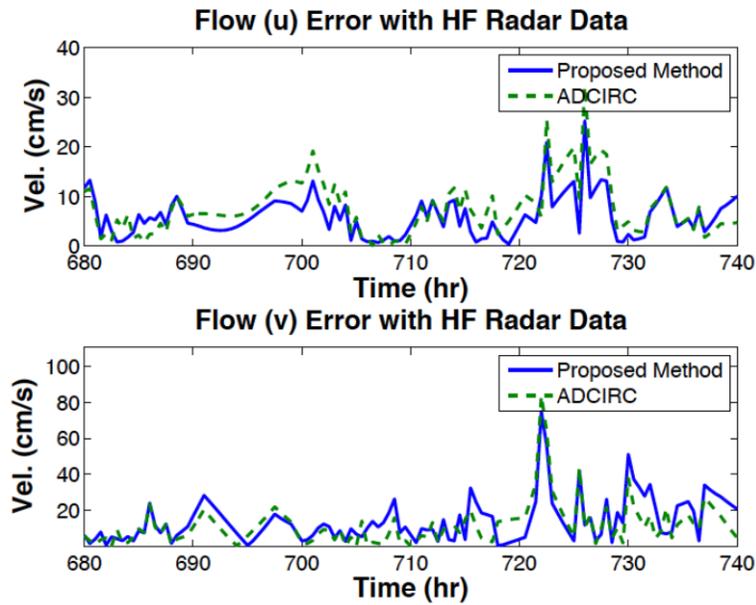
**Figure 5. Hydrodynamic modeling of the YSI Ecomapper.**

## RESULTS

The performances of GEM in the Long Bay experiment are illustrated by Figures 6 and 7. After the GEM is initialized based on the ADCIRC model and historical WERA data, we use it to make predictions for flow at a known mooring location, and then compare the prediction with the observed flow from the mooring. The learned (or reconstructed) flow is illustrated as the blue dashed lines, the predicted flow is illustrated as the red dashed lines. The real flow is illustrated by the light blue solid lines. We see more errors in the along-shore component ( $v$ ) than in the cross-shore component ( $u$ ) since the along shore component is more influenced by the Gulfstream, which is a nonlinear phenomena that is very challenging to predict for any ocean model. Figure 7 compares the prediction error between GEM and ADCIRC. We see that the errors are on the same scale. But GEMs take much less time to compute and offers higher spatial resolutions. We may tentatively conclude that GEMs may be as accurate or slightly less accurate than computational ocean models. But offers higher spatial and temporal resolutions in a smaller region in the proximity of the vehicles.

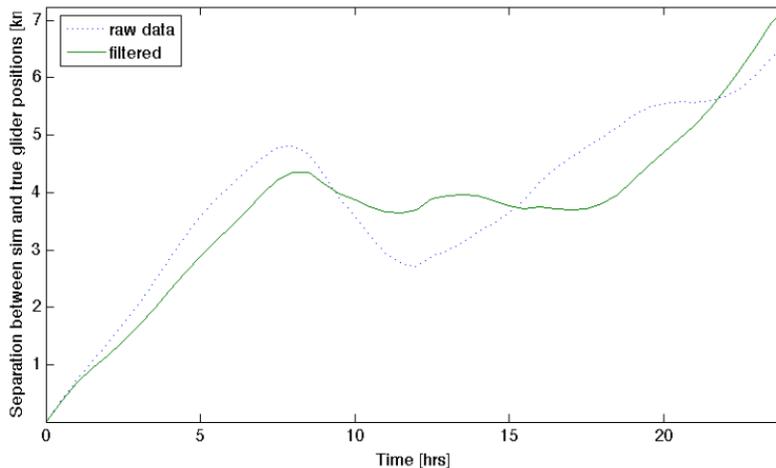


**Figure 6. Ocean currents at coordinate  $(-79.8984, 31.3531)$  modeled by a GEM: Real flow (light blue line), reconstructed flow (blue dash-dotted line), and predicted flow (red dashed line). The model is trained using 30-day historical WERA data from January 1, 2011 to reconstruct the flow and predictions are produced for the next 20 hours without updating model parameters.**



**Figure 7. Comparison between modeling errors made by GEM and ADCIRC. Solid blue line represents the prediction error made by GEM. Green dashed line represents the prediction error made by ADCIRC. We see most of time the two errors are comparable to each other.**

The controlled Lagrangian prediction error obtained for one of the gliders in the Long Bay experiment is shown in Figure 8. The error grows fast until the averaged grid size of the ADCIRC model (5km). Afterwards, the error growth significantly slows down. The error sees a fast growth again after 20 hours. Similar error growth behaviors have also been observed in glider deployment previously during the 2006 ASAP experiment in Monterey Bay. Based on these evidences, we are able to conclude that the theory of CLPT may be a trustworthy tool to predict navigation performance for underwater gliders under the guidance of ocean circulation models. Therefore, a higher resolution modeling approach, such as a GEM, may be crucial to improve the navigation performance of long endurance marine robots.



**Figure 8. CLPT Error analysis for glider navigation performance during the 2012 Long Bay Experiments.**

## IMPACT/APPLICATIONS

The Navy and other branches of the armed forces are now in transition to a new era of unmanned systems. The next Naval battle may prove that an agile marine autonomy is key to victory. The GEMs proposed in this proposal are stepping stones for unmanned marine systems to react promptly to a changing operational environment so that they can gain an upper hand by out-maneuvering their opponents. The generic nature of the methods makes GEMs scalable and portable. Furthermore, as the intelligence of unmanned systems grows, GEMs may be shifted from the network level to the platform level to achieve a new level of agile autonomy.

## RELATED PROJECTS

Generic environment modeling and agile autonomy are closed connected with other ONR and NSF projects the PI is participating.

1. ONR: Bio-Inspired Autonomous Control for Optimal Exploration and Exploitation in Marine Environments (BioEx). PI participated in this project. The project goal is to institute an innovative multidisciplinary investigation of autonomous collective foraging in a complex environment that explicitly integrates models and insights from biology with models and provable strategies from control theory. The work on Agile autonomy is complementary to the bio-inspired engineering solutions on autonomy.
2. NSF: Mechanisms of Nutrient Input at the Shelf Margin Supporting Persistent Winter Phytoplankton Blooms Downstream of the Charleston Bump. We will deploy underwater gliders in Long Bay, SC to study mechanisms of nutrient input at the shelf margin supporting persistent winter phytoplankton blooms downstream of the Charleston Bump. GEM and GCCS has been applied to this project.

## PUBLICATIONS

### Journal articles:

- W. Wu and F. Zhang, "Cooperative Exploration of Level Surfaces of Three Dimensional Scalar Fields," *Automatica, the IFAC Journal* 47(9): 2044-2051, 2011. [published, refereed]
- M. Malisoff, F. Mazenc, and F. Zhang, "Stability and Robustness Analysis for Curve Tracking Control using Input-to-State Stability," *IEEE Transactions on Automatic Control*, 57(5):1320-1326, 2012. [published, refereed]
- H. Yang and F. Zhang, "Robust Control of Formation Dynamics for Autonomous Underwater Vehicles in Horizontal Plane," *ASME Journal of Dynamic Systems, Measurement and Control*, 134(3): 031009 (7 pages), 2012. [published, refereed]
- W. Wu and F. Zhang, "Robust Cooperative Exploration with a Switching Strategy," *IEEE Transactions on Robotics*, 28(4):828-839, 2012. [published, refereed]
- W. Wu and F. Zhang, "A Switching Strategy for Target Tracking by Mobile Sensing Agents," *Journal of Communications*, 8(1):47-54, 2013. [published, refereed]

- F. Zhang, Z. Shi, and S. Mukhopadhyay, "Robustness Analysis of Battery Supported Cyber-Physical Systems," *ACM Transactions on Embedded Computing Systems*, 12(3):69.1-27, 2013. [published, refereed]
- M. Malisoff and Fumin Zhang, "Adaptive Control for Planar Curve Tracking under Controller Uncertainty," *Automatica, the IFAC Journal*, 49(5):1411-1418, 2013. [published, refereed]
- K. Szwaykowska and F. Zhang, "Trend and Bounds for Error Growth in Controlled Lagrangian Particle Tracking," *IEEE Journal of Oceanic Engineering*, (online preview), 2013. [published, refereed]
- H. Yang, C. Wang and F. Zhang, "Robust Formation Control of Autonomous Underwater Vehicles with Time Delays," *IET Control Theory & Applications*, 2013. (online preview) [published, refereed]

### Refereed Conference Proceedings:

- K. Szwaykowska and F. Zhang, "A Lower Bound for Controlled Lagrangian Particle Tracking Error," in *Proc. 49th IEEE Conference on Decision and Control (CDC 2010)*, 4353-4358, 2010. [published, refereed]
- K. Szwaykowska and F. Zhang, "A Lower Bound on Navigation Error for Marine Robots Guided by Ocean Circulation Models," in *Proc. 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011)*, 3583-3588, 2011. [published, refereed]
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- M. Malisoff and F. Zhang, "Adaptive Controllers and Robustness Analysis for Curve Tracking with Unknown Control Gains," in *Proc. 2012 American Control Conference (ACC 2012)*, 344-349, 2012. [published, refereed]
- W. Wu, I. D. Couzin, and F. Zhang, "Bio-inspired Source Seeking with no Explicit Gradient Estimation" in *Proc. 3rd IFAC Workshop on Distributed Estimation and Control in Networked Systems (NecSys'12)*, 240-245, 2012. [published, refereed]
- X. Liang, W. Wu, D. Chang, F. Zhang, "Real-time Modelling of Tidal Current for Navigating Underwater Glider Sensing Networks," *Procedia Computer Science*, 10:1121-1126, 2012. [published, refereed]
- F. Zhang, F. Zhang, and X-B. Tan, "Steady Spiraling Motion of Gliding Robotic Fish," in *Proc. 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012)*, 1754-1759, 2012. [published, refereed]
- S. Mukhopadhyay, C. Wang, S. Bradshaw, S. Maxon, M. Patterson, and F. Zhang, "Controller Performance of Marine Robots in Reminiscent Oil Surveys," in *Proc. 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012)*, 1766-1771, 2012. [published, refereed]
- W. Wu and F. Zhang, "Coherent Steps of Mobile Sensing Agents in Gaussian Scalar Fields," in *Proc. 51st IEEE International Conference on Decision and Control (CDC 2012)*, 2814-2819, 2012. [published, refereed]

- D. Chang, W. Wu, D. Webster, M. Weissburg, and F. Zhang, "A Bio-inspired Plume Tracking Algorithm for Mobile Sensing Swarms in Turbulent Flow," in *Proc. 2103 IEEE International Conference on Robotics and Automation (ICRA 2013)*, 2013. [published, refereed]
- K. Szwaykowska and F. Zhang, "Controlled Lagrangian Particle Tracking Error Under Biased Flow Prediction," in *Proc. 2013 American Control Conference (ACC 2013)*, 2581-2586, 2013. [published, refereed]
- H. Yang, C. Wang, and F. Zhang, "Robust Geometric Formation Control of Multiple Autonomous Underwater Vehicles with Time Delays," in *Proc. 2013 American Control Conference (ACC 2013)*, 1382-1387, 2013. [published, refereed]
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- W. Wu, F. Zhang, and Y. Wardi, "Energy-Information Tradeoffs in Motion and Sensing for Target Localization," *Proc. of 2013 European Control Conference (ECC 2013)*, 1250-1255, 2013. [published, refereed]

## HONORS/AWARDS/PRIZES

Recipient: Fumin Zhang  
 Institution: Georgia Institute of Technology  
 Award: 2010 ONR YIP Award  
 Sponsor: Office of Naval Research

Recipient: Fumin Zhang  
 Institution: Georgia Institute of Technology  
 Award: 2010 Lockheed Inspirational Young Faculty Award  
 Sponsor: Lockheed Martin Co.

Recipient: Fumin Zhang  
 Institution: Georgia Institute of Technology  
 Award: 2011 Roger P. Webb Outstanding Junior Faculty Award  
 Sponsor: School of Electrical and Computer Engineering, Georgia Tech

Recipient: Fumin Zhang  
 Institution: Georgia Institute of Technology  
 Award: 2011 Distinguished Lecturer on Cyber-Systems and Control  
 Sponsor: Zhejiang University, China

Recipient: Georgia Tech Savannah Robotics (Supervised by Fumin Zhang)  
 Institution: Georgia Institute of Technology  
 Award: 2011 Martin Klein MATE Mariner Award  
 Sponsor: Marine Advanced Technology Education (MATE) Center

Recipient: Fumin Zhang  
 Institution: Georgia Institute of Technology

Award: The 2012 SOE Industry Excellence Award  
Sponsor: Savannah Ocean Exchange

Recipient: Fumin Zhang  
Institution: Georgia Institute of Technology  
Award: GT Class 1969 Teaching Scholar Award, 2012.  
Sponsor: Georgia Institute of Technology