Physical Modeling and Software Synthesis for Self-Reconfigurable Sensors in River Environments

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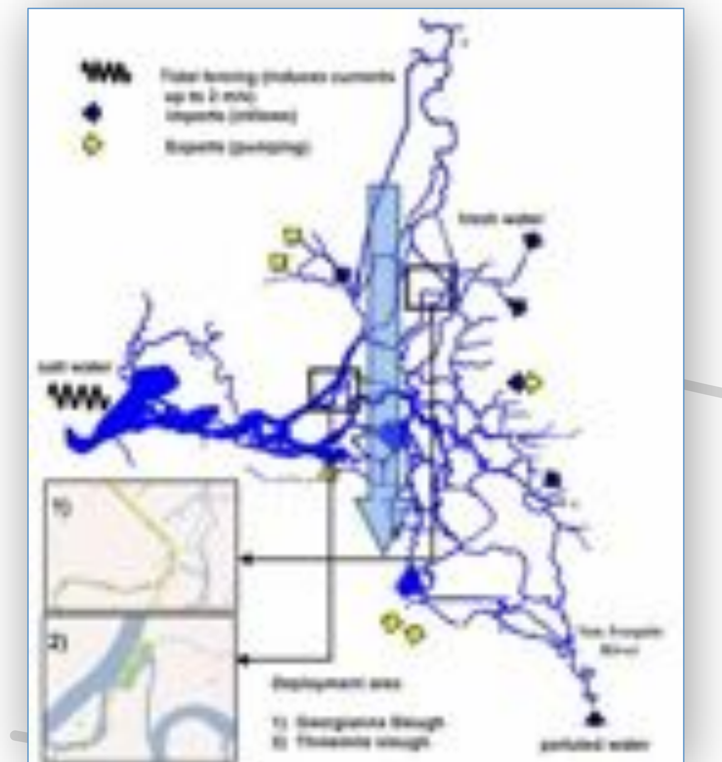
Abstract

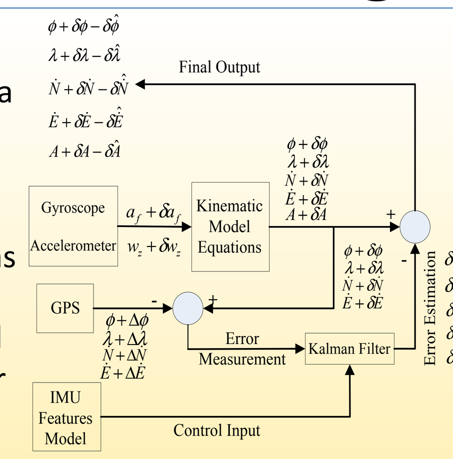
Our work in this collaborative research project examines the role of software synthesis for monitoring and planning of autonomous sensors evolving on tidally forced rivers. The goal of the sensors is the coordinated sampling of currents and salinity to reconstruct the distributed state of the river. This project integrates the development of theory for the coordination of autonomous agents in motion-constrained environments, and of algorithms to perform motion planning tasks, with software tools for design, analysis, and code synthesis for implementation.

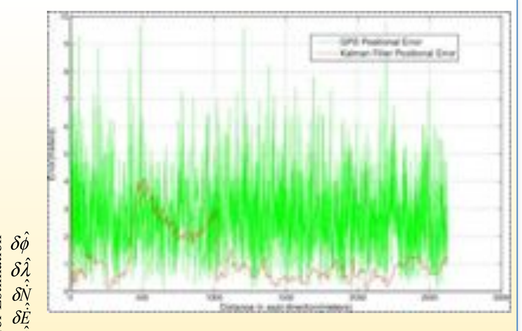
San Joaquin River Delta



Kalman Filter for Localizing Mobile Agents

We designed a Kalman filter based algorithm to localize mobile agents in a horizontal flow field based on measurements from a mobile-phone with a GPS receiver, gyroscope and two accelerometers. This algorithm has been demonstrated on an iPhone 4, and provides more accurate positional information than only a GPS or cellular network.





$\lambda(\varphi)$ is longitude (latitude), A is azimuth
N (E) are linear velocity in north (east) direction
Prefixes δ and Δ refer to the measurement error

Closing the loop

Solutions to problems such as this require an approach that considers reliable sensing, fast computation and safety verification. Our approach utilizes Kalman filter based localization algorithms to facilitate calculating Voronoi partitions and autonomously deploying drifters (to detect salinity intrusion). Safety verification blocks can be inserted to controller models to ensure parameters for the controller are within the safety range. In addition, low-level event based control has been studied to ensure the safety of drifters.

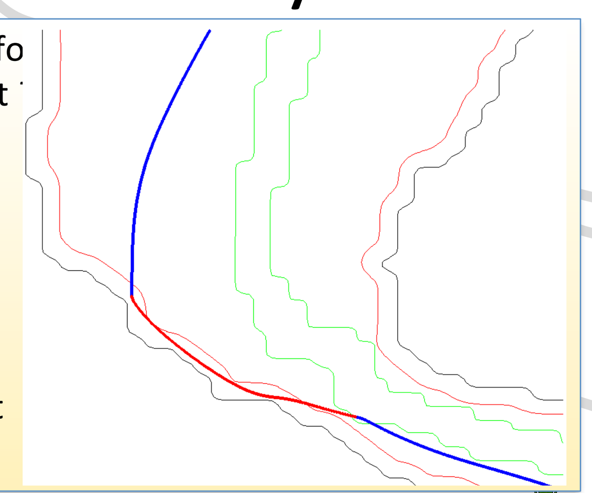
Low-level Event Based Safety Control

The minimum time-to-reach (MTTR) function fo a vehicle moving in a field to reach a target set can be found with the static HJB PDE:

$$-1 = \nabla V(x)\cdot g(x) - U\|\nabla V(x)\|$$

$$\text{BC: } V(x) = 0 \text{ where } x \in T$$

- MTTR functions are computed with shoreline and centerline targets
- Gradient of MTTR gives optimal control
- Hysteresis control determines when to drift passively and when to seek centerline



Region Assignment Based on Voronoi Partitions

HJB Voronoi Paritiitions

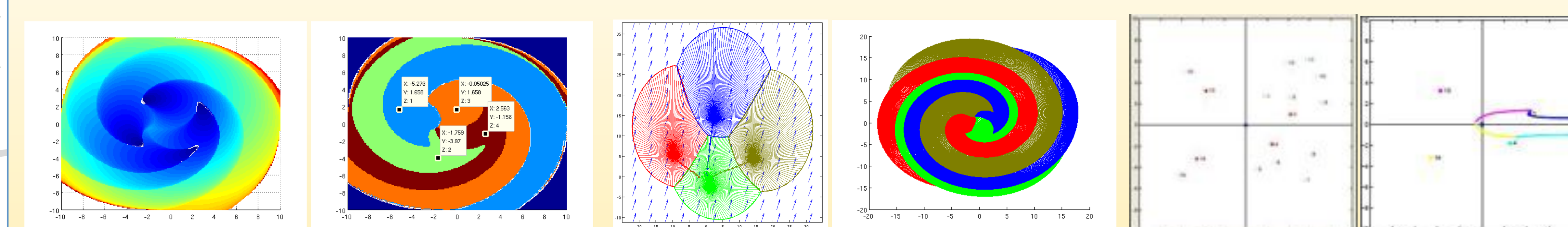
- Points in a Voronoi Regions are given by the agent whose MTTR at that point is the smallest
- Method works in arbitrary flow fields and obstacle environments

Zermelo Voronoi Parititions

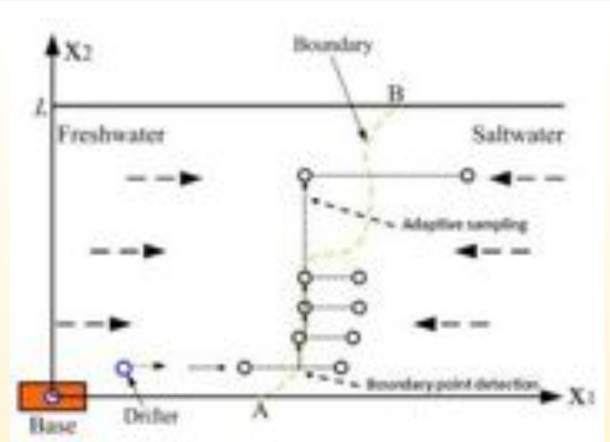
- Forward simulation of multiple optimal trajectories in a linear flow field
- Intersections of growing regions define Voronoi boundaries

Energy-based Partitions

- Mobile vehicles are commonly powered by batteries of limited capacity
- Energy-based Voronoi partitions are useful in task assignments and distributed coverage controls



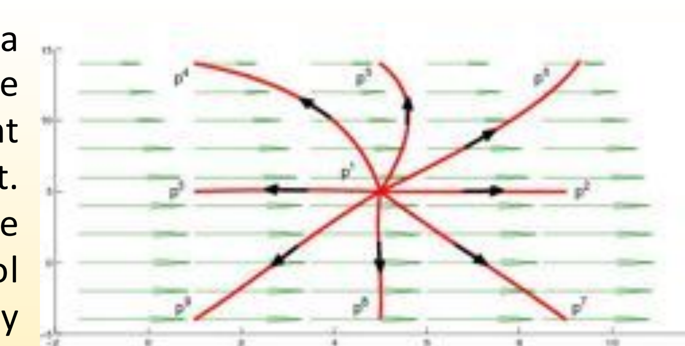
Salinity Intrusion Detection



Due to a reduction in the supply of freshwater in estuaries (e.g., due to a drought or the diversion of freshwater for agricultural and/or municipal uses), saltwater can intrude deeply into river channels. We study the salinity intrusion problem and identify a point on the freshwater-saltwater boundary that reflects the degree of salinity intrusion via autonomous drifter deployments.

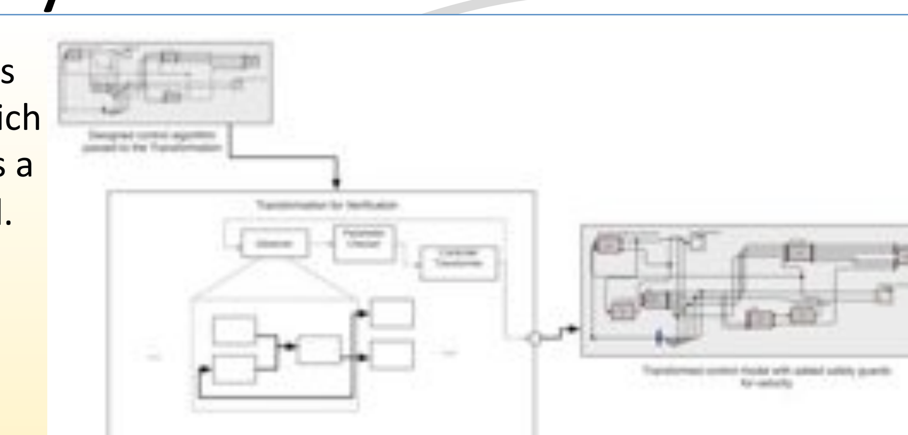
High-level Minimum Energy Control

We approximate the river flow using a quadratic function and study the minimum energy path from one point to another in the flow environment. Naturally river boundaries act as state constraints in the optimal control problem which can be solved by adjoining additional multiplier functions.



Controller Model Safety Verification

A controller model safety verification process is performed through model transformation, which takes in a proposed control model and outputs a transformed model with safety blocks inserted. Within the transformation a search is done for specific parameters (e.g. velocity and turning radius) and checks are made to ensure those values are within a safety range. If checks fail, safety blocks are added to adjust the controller, and can achieve similar results with safer execution. This cycle repeats until all of the model is searched, and the output is a control model with added blocks, or the original model if the safety check passed.



Experimental Hardware

We have developed a fleet of self-contained floating sensors. They carry a GPS receiver, GSM and Zigbee modules, and an embedded computer running Linux. Different water quality sensors can be mounted in the lower plate: examples include depth sensors, salinity sensors, or pH sensors.

Project Outreach

- Sponsored two capstone engineering projects at Univ. of Arizona, which supported 12 undergraduate students for a school year. The projects were related to CPS applications such as smart energy solutions for a home, and energy-efficient transportation.
- To raise interests in Science, Engineering and Mathematics, Ph.D. student Maribel Hudson visited Gridley Middle School and Sturgeon Cromer Elementary School at Arizona to give presentations and short lectures on electrical and computer engineering. She also participated in one demonstration at a weekend K-12 event called Laser Fun Day supported by Univ. of Arizona.

More Reading

1. Yu Ru and Sonia Martinez. "Freshwater-Saltwater Boundary Detection Using Mobile Sensors Part I: Drifter Deployment", to appear in Proc. of IEEE Conf. on Decision and Control, 2011
2. Yu Ru and Sonia Martinez. "Freshwater-Saltwater Boundary Detection Using Mobile Sensors Part II: Drifter Movement", to appear in Proc. of IEEE Conf. on Decision and Control, 2011
3. Kevin Weekly, Leah Anderson, Andrew Tinka, and Alexandre M. Bayen. "Autonomous River Navigations using the Hamilton-Jacobi Framework for Underactuated Vehicles", in Proc. of IEEE Conf. on Robotics and Automation, pp. 828-833, May 2011
4. Maribel Hudson and Jonathan Sprinkle. "Simplification of Semantically-Rich Model Transformations Through Generated Transformation Blocks", in Proc. of 8th IEEE Workshop on Model-Based Development for Computer-Based Systems, pp. 260-268, April 2011

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