MAS 04 A Benthic Robotic Sentinel

MAS 04.1 People

- Principal Investigator: Jnaneshwar Das, David Caron and Gaurav S. Sukhatme
- Faculty: Prof. Gaurav S. Sukhatme, Dept. of Computer Science, USC; Prof. David A. Caron, Dept. of Biological Sciences, USC
- Staff: Carl Oberg, Dept. of Computer Science, USC
- Graduate Students: Jnaneshwar Das, Dept. of Computer Science, USC; Beth Stauffer, Dept. of Biological Sciences, USC

MAS 04.2 Overview

Underwater observing systems are used for making physical, chemical and biological measurements of aquatic environments. Automating such systems can lead to significant savings in scientist time, while increasing the possibility of new discoveries in limnology and oceanography. This project is a novel benthic robotic observing system designed to periodically patrol a transect while capturing images of the water above it. Using a combination of inertial sensing, absolute position measurements at the transect endpoints, and a simple dynamic model, we are able to apply a Kalman smoother to obtain accurate position estimates for the robot. These estimates are used a posteriori to align sensor scans of the water made by the main observational instrument on the robot—an Acoustic Doppler Current Profiler (ADCP). The aligned scans produce a map of unprecedented accuracy and coverage (presently such measurements are typically made by manually lowering the ADCP or winching it down). Our design is energy-friendly since energy is needed only to move, not to hold station. It is also unobtrusive relative to the water surface. Importantly, the approach is potentially highly repeatable and precise. A pilot deployment done at commercial marina demonstrates accurate observation of water flow rate and water flow direction across a section of the marina inlet.

MAS 04.3 Approach and System Description

Our focus in this work is on the development of a system for long-term deployment. We envisage a robotic sentinel that is able to maintain a presence underwater for weeks or months at a time allowing seasonal-scale repeatable measurements. Mobility is energy expensive, and a long-term presence may naturally suggest a Lagrangian approach where the robot moves with the water mass (e.g., a set of drifters or a glider). For increased precision and repeatability we considered an alternative approach wherein a guide-rail is used to mechanically support the motion of the robot as it moves to and fro between the transect endpoints. The advantages of this approach are discussed below. Our design is energy-friendly since energy is needed only to move, not to hold station. It is also unobtrusive relative to the water surface. Importantly, the approach is potentially highly repeatable and precise. The main contributions of this paper are 1. the design of the prototype robot, and 2. the experimental evidence, including data from a field experiment, in support of its precise and repeatable positioning ability, leading directly to the mapping of water column properties with unprecedented accuracy and repeatability. Since this is our first
report on this novel robot, we make the following assumptions (we plan to relax some of these in future work). For the purposes of the work reported here the guide-rail is rigid and has negligible slack. The yaw of the robot is mechanically restricted. The robot is not equipped with sensors to directly sense its precise location on the guide-rail. Finally, we do not envisage real-time, fine-grained location estimates being necessary for robot operation.

A. Packaging and Support Infrastructure

The components of the robot are packaged into two separate levels, each being an off-the-shelf drybox for underwater use. The upper level is a small (19 cm x 3.6 cm x 3.3 cm), transparent unit which houses the computing hardware, inertial measurement unit, power converter, safety fuses, motor control board and an upward looking camera. The lower level is a larger drybox (30.4 cm x 22.8 cm x 15.2 cm) which holds the batteries, magnetic power switches, and hall-effect sensor for marker detection. A communication and power link between the upper and the lower units is established via cables running through a tygon hose, clamped to the dry-boxes using tapped hose fittings. The dryboxes are fixed to a custom-made aluminum frame, on which the thruster is mounted. At the very bottom of this frame is a roller assembly that links the robot to the guide rail. Stainless steel guide rods at each end restrict yaw. The robot is powered by two 7Ah, 12V sealed lead-acid batteries housed within the lower deck. One battery is dedicated for the computing and sensing hardware, whereas the other battery is used by the thruster. A DC-DC voltage converter supplies the required voltages to the computer, motor control board and the sensor suite.

Hermetically sealed reed switch assemblies were mounted within the robot housing to serve as power switches. They are triggered externally with small neodymium magnets, allowing easy power cycling and emergency shutdown. The guide-rail is a multi-segment PVC pipe, with embedded neodymium magnets at the endpoints to serve as markers. The pipe is mounted to supporting structures at either end using aluminum structural fitting s.

B. Computing

The robot uses a Gumstix 600MHz single board computer for all tasks. Additional expansion cards provide IO and storage functionalities (RS232, I2C, Ethernet, 802.11b and microSD). The software has been written using C and C++ to run on the Linux operating system.

C. Sensing

The robot’s sensor suite consists of accelerometers, inclinometers, a proximity sensor, a camera, and an Acoustic Doppler Current Profiler (ADCP). A MicroStrain 3DM-G Inertial Measurement Unit (IMU) with a tri-axial accelerometer, inclinometer and rate-gyro provides acceleration, angular velocity, and attitude information respectively. We use the Philips KMZ51 hall-effect sensor to detect magnetic markers embedded at the endpoints of the guide-rail. The sensor was mounted inside the lower dry-box and calibrated such that the robot reliably detected magnetic markers at a distance of 20 cm with a field of view of 6 cm. The robot also has an upward looking USB digital camera to take pictures of the water surface.

Fig. 2: Schematic of the robot

Fig. 3: A cross-sectional view of the deployment at Redondo Beach Marina, the ADCP sampling locations, and the corresponding flow data axes used for the visualizations in Figure 9
We plan to stitch these images together using position estimates from the robot’s offline state estimator to produce a visual-panorama of the water surface. The primary payload on the robot is an advanced doppler sonar, Argonaut-XR, manufactured by Sontek. It is used for precise measurement of water velocity along three axes. The ADCP was mounted on the robot pointing up to measure the water velocity at various depths.

D. Actuation

The robot is actuated using a single Seabotix BTD150 bidirectional underwater thruster. The thruster is controlled using a Roboteq AX500 motor control board which receives commands from the Gumstix stack over the RS232 interface.

E. Workflow and Control

Traversal in each direction is implemented as a series of 'hops', with a specified time interval between each hop. Open-loop control was chosen over other techniques to keep the system simple (recall that the focus here is to test the accuracy at which we can reconstruct location estimates for the robot post-traverse). A triangular thruster actuation pattern was experimentally identified to be an ideal control primitive, since it allowed smooth traversal between locations.

MAS 04. 4 Results and Accomplishments

The system was tested at three locations, an indoor experimental tank with dimensions 2 m x 1.2 m x 2.3 m, a swimming pool (Figure 4), and a section of Redondo Beach Marina on the Southern California coastline (Figure 10). We performed the tank experiments in three phases. The first phase involved the developmental iterations to test the robot structure, actuation, workflow and control. The second phase was to determine the process model, and the third phase was to implement and evaluate the location estimator. The robot was mounted on a graduated guide-rail supported by appropriate structural fittings. A directional wireless antenna outside the tank in close proximity to the tank wall made it possible to maintain a continuous communication link between the robot and a laptop external to the tank. All experiments were video recorded so that ground truth position information could be obtained by manually processing the imagery. The forward Kalman filter, the backward Kalman filter, and the smoother were run on the data sets obtained from the tank experiments. The pool served as a larger testbed with a traversable span of 3.45 m. On an average, the robot needed thirteen thrusts to traverse the length. Images of the water surface was captured by the robot after every hop. A measuring tape with periodic markers was suspended on the surface as a source of images for the camera on the robot, and also provide the true position of the robot after each hop.

Fig. 5: Forward-backward filter estimates for a trial in the tank

Fig. 6: Smoother estimates for the trial in the tank

Fig. 7: Forward filter, backward filter and smoother estimates for the pool trial
Deployment at Redondo Beach Marina Inlet

A pilot deployment was performed at Redondo Beach Marina to observe water flow at a section of the marina inlet (Figure 5). The system had a traversable span of 6.4 m and was deployed at a depth of 3.4 m (Figure 10 shows a schematic in profile). The ADCP was programmed to record water flow at five depths. On average, the robot sampled seven points along the transect during each traversal. The ADCP data and the location estimates were then used to generate a snapshot of the flow during each traversal. Data logged over a period of an hour were used to generate registered flow plots for six traversals approximately 8 minutes apart. The following plots show water flow for six traversals on the marina transect. The traversals were spaced by 8 minutes, with a dwell time of 25 seconds at each location. The robot sampled 7 points on the transect in each traversal. The ADCP sampled flow data for 5 vertical points for each dwell point on the transect. The offline estimator was run to find the position of the robot for each flow datapoint and the data was then interpolated to generate the flow visualization.

Plots showing water flow for six traversals on the marina transect. The traversals were spaced by 8 minutes, with a dwell time of 25 seconds at each location. The robot sampled 7 points on the transect in each traversal. The ADCP sampled flow data for 5 vertical points for each dwell point on the transect. The offline estimator was run to find the position of the robot for each flow data-point and the data was then interpolated to generate the flow visualization.

MAS 04.5 Future Directions

In preliminary field trials at a commercial marina we show unprecedented, accurate, water flow measurements using the system. Our future plan is to work on long-term deployments in the field on larger transects. This will entail modifications in the prototype to withstand the rigors of a larger deployment, specifically the design of a new hull and fabrication of a longer transect assembly. We also plan to develop the ability to change the mission in realtime based on measured data.