

## Infrastructure for Mobile Sensor Network in the Singapore Coastal Zone

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### ABSTRACT

Singapore is an island nation located at southern tip of the Malaysian Peninsula. She is at a strategic location along major shipping routes and therefore has one of the busiest harbors in the world. Having a safe and secure harbor environment is vital to maintain trade and growth in the country and region. To help build and maintain a safe harbor environment, the Center of Environmental Sensing and Modelling (CENSAM) under the Singapore-MIT Alliance for Research and Technology (SMART) is developing a mobile sensor network in the Singapore coastal zone.

In this paper, we will describe the infrastructure for a mobile sensor network that has been developed and set up. It consists of a range of sensors and autonomous platforms, including underwater and surface vehicles. The algorithms developed, such as collision avoidance and path-planning, to make such a network feasible are also illustrated. Further descriptions on the applications of these sensors and platforms to carry out inspection of marine structures and data sampling of the water column that can be used for data assimilation to improve forecast accuracy for the coastal zone ocean environment are included. The results of two sea trials conducted in 2009 to test the viability of these systems and algorithms will be summarized. Further work to integrate the individual systems into a network to give a more effective and robust system will be outlined.

**KEY WORDS:** Marine robotics; harbor security; sensor networks; coastal zone.

### INTRODUCTION

Singapore is an island nation located at the southern tip of the Malaysian Peninsula. She has limited natural resources but has a Gross Domestic Product Per Capita (PPP) of US\$48,500, which makes Singapore the 8<sup>th</sup> highest PPP in the world (CIA, 2009). One of the contributing factors to her strong economy is her excellent location along the major shipping routes. She lies at the crossroads of trade between Europe and China and Japan, and has become an important trading hub for the South-East Asian region. Owing to this, Singapore is the busiest port in the world in terms of container traffic (AAPA, 2007). Figure 1 shows a picture of the shipping traffic globally.

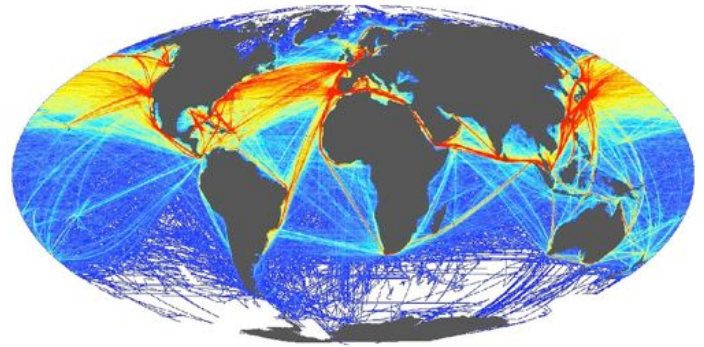


Fig. 1. The global shipping traffic. The blue represents low traffic while red represents high traffic. Photo is from <http://www.seaweb.org/>.

As the shipping industry is one of the major components of Singapore's economy, the security of the harbor and a safe harbor environment is crucial. Therefore, one of the goals of the Center for Environmental Sensing and Modeling (CENSAM) from the Singapore-MIT Alliance for Research and Technology (SMART) is to set up a mobile network of sensors such that a safer and more secure harbor environment can be achieved.

When sensors are mounted on various platforms that are inter-linked through communication, they become a sensor network. These platforms can be stationary or mobile and would be located both underwater and above the surface of the water itself. Stationary platforms would include buoys and sea-bed mounted equipment as shown in Figure 2. These platforms are placed to collect data with certainty in their positions. The mobile component of the network is made up of the Autonomous Surface Vehicles (ASVs), Autonomous Underwater Vehicles (AUVs), Airplanes and Satellites. The mobility of these platforms allows the network to be adaptive in the measurements required.

The mobile network of sensors not only allows the realization of a safer and more secure harbor environment, but its adaptive nature also enables data to be collected intelligently such that it can be assimilated into numerical models to improve the quality of the forecast for the region around Singapore.

The paper will first start with a literature review on network sensors and a brief description of the flow characteristics around Singapore.

The following section details the various platforms, sensors and algorithms developed for the mobile network of sensors. The application of both hardware and software, together with results from experimental trials, will be described subsequently. The work required for improvements in the future will conclude this paper.

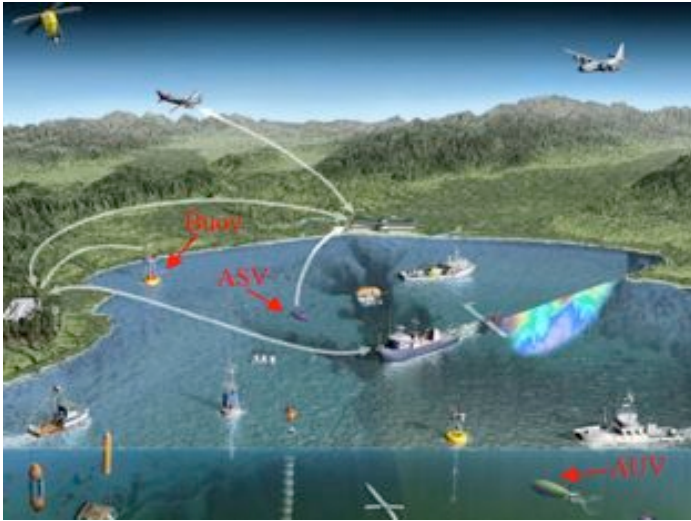


Fig. 2. A cartoon of a sensor network. Buoys and sea-bed mounted equipment (bottom left) form part of the static component of the network. Autonomous Surface Vehicles (ASVs) (center) and Autonomous Underwater Vehicles (AUVs) (bottom right) make up part of the mobile component of the network. There is communication between the various nodes in the network. Cartoon is from <http://www.mbari.org/aosn/>.

## LITERATURE REVIEW

The idea of a mobile sensor network is similar to that of the Autonomous Oceanographic Sampling Network (AOSN) (Curtin et al, 1993) project at the Monterey Bay Aquarium Research Institute (MBARI). The project merges sophisticated new robotic vehicles and advanced ocean models to improve the ability to observe and forecast the state of the ocean at Monterey Bay, California, USA (MBARI, 2009). In that system, the data are collected on smart and adaptive platforms and sensors that can relay information to the shore (hours). The data can then be assimilated into the numerical models to correct and improve forecast.

The current work aims to emulate the AOSN project but modify it accordingly to suit the local conditions and interest of Singapore. The understanding of the hydrodynamic conditions around Singapore is then important.

The bathymetry of the Singapore and Johor Straits and the proximity of the coastal boundaries are the main factors affecting the currents and circulations in the seas around Singapore. Between Malaysia and Singapore lies a body of water known as the Johor Strait. The strait itself is divided into an eastern and western side by a causeway linking Singapore and Malaysia. Water depths in the Johor Strait range from a few meters along the boundaries to about 10-20 *m* along the center of the Strait. The width of the Johor Strait varies from about 0.5 to 2 *km* including the tidal flats on both sides of the strait (Chan, 2006). There are two major rivers flowing into the Johor Straits - Sungai Johor on the east and Sungai Pulai on the west. Both these rivers are located in Malaysian territory.

The other body of water that lies south of Singapore is the Singapore Strait. It is bounded by the southern coasts of Singapore and Malaysia on one side and the northern coasts of the Riau Islands of Indonesia and Singapore southern coasts on the other end. The Malacca Strait and the South China Sea are connected by the Singapore Strait. The Malacca and Singapore Straits are connected to the Java Sea through Selat Durian, Selat Combol, Selat Riau and several other minor straits between islands. The narrowest part of the Singapore Straits is about 5 *km* and between Singapore and Pulau Batam, the range is about 5 *km* to 15 *km*. From the southern end of the Malacca Strait to the South China Sea, the water depths are generally less than 50 *m* (Chan, 2006). A map of the region around Singapore can be found in Figure 3.



Fig. 3. A geographical map of the region around Singapore. Map is obtained from Google Maps.

The Singapore Strait is influenced by the exchange of waters between the Indian Ocean, the Malacca Strait and the South China Sea. Tides in both the Malacca and Singapore Straits are semi-diurnal (Chan, 2006).

The harbor area where some of the work was carried out has quite strong currents of up to 2 *m/s* in certain places. This makes it both an interesting place to study water properties and a challenging environment to operate autonomous systems.

## PLATFORMS, SENSORS AND ALGORITHMS

### Platforms

The platforms that form the basis of the mobile network of sensors are the ASVs and AUVs. A large variety of sensors can be mounted on these vehicles in different configurations depending on the intended purposes.

**Autonomous Surface Vehicle.** The hull of an ASV is a 3 *m* long hull kayak that is manufactured by Pungo (model Pungo100). The main compartment has a low-density polyethylene lid cover that has a rubber seal to prevent most of the water from entering the kayak hull. A 245 *N* thruster produced by Minn Kota is used for the propulsion while a steering servo, manufactured by Vantec, is used for steering of the ASV.

The Main Vehicle Computer (MVC) is a Dual Pico-ITX computer stack (core and payload) with 1 GB RAM each. The core and payload MVC has a 4 GB FLASH drive and 250 GB 2.5" Hard Drive respectively. An internal thermostat controlled fan is included for passive cooling.

Communication and control is possible with a remote controlled radio and receiver pair, Maxstream 1 *W* RF modem and 802.11 WiFi modem



with hyperlink 1 *W* amplifier. The GPS, compass and Inertial Measuring Unit (IMU) are integrated in a sensor box that is mounted onto each kayak. The entire unit is powered by one (or two, depending on configuration) 105 *AH* sealed absorbent glass mat battery. A spare is carried and can be used in parallel if required.



Fig. 4. A photograph of the Autonomous Surface Vehicle (ASV).

The ASV is a versatile platform that can be configured to house a wide range of sensors, such as a Doppler Velocity Log (DVL), Paddlewheel, SICK Range Laser, Velodyne LiDAR, Microbathymetry, etc. Its small size makes it highly maneuverable and it is built to be robust to function in harsh conditions.

**Autonomous Underwater Vehicle.** The AUV, manufactured by the OceanServer Technology, has a diameter of 0.15 *m* and a length of 1.5 *m*. The weight of the AUV varies between 18 – 22 *kg* depending on the weights added for buoyancy and sensors carried. It can travel up to a maximum speed of 2 *m/s*. At a speed of 1.25 *m/s*, it can function up to 10 hours. A digital three-axis compass and depth sounder are built into the AUV to measure its orientation and depth from the seabed.



Fig. 5. A photograph of an AUV manufactured by OceanServer.

Various waypoints can be programmed for the AUV to transverse between. The AUV communicates with the Control Ship via WiFi but since electro-magnetic waves attenuate rapidly through water, for the period that it is submerged, the AUV is under dead reckoning. When the AUV surfaces, it can communicate with the Control Ship again and the position of the AUV can be corrected using the GPS built in the antenna.

As communication is lost between the AUV and the Control Ship when the AUV dives, modifications were done to the AUV to include a pinger on the vehicle. The pinger will send out an acoustic ping every second and it will be picked up by an acoustic receiver that is connected to the Control Ship. The placement of a pinger on the AUV

allows the position of the AUV to be tracked by the operators on the ship accurately.

## Sensors

**Water Quality Probes.** The nose section of the AUV holds a variety of probes that can assess the water quality. With these sensors, the following parameters can be measured: temperature, conductivity, salinity, dissolved oxygen, turbidity, chlorophyll and pH. These probes are manufactured by YSI (YSI, 2010) and are commonly used on water quality assessment Sondes. Due to the mobility of the AUV, the suite of sensors mounted on the AUV allows these water quality parameters to be measured over space in a relatively short time interval.

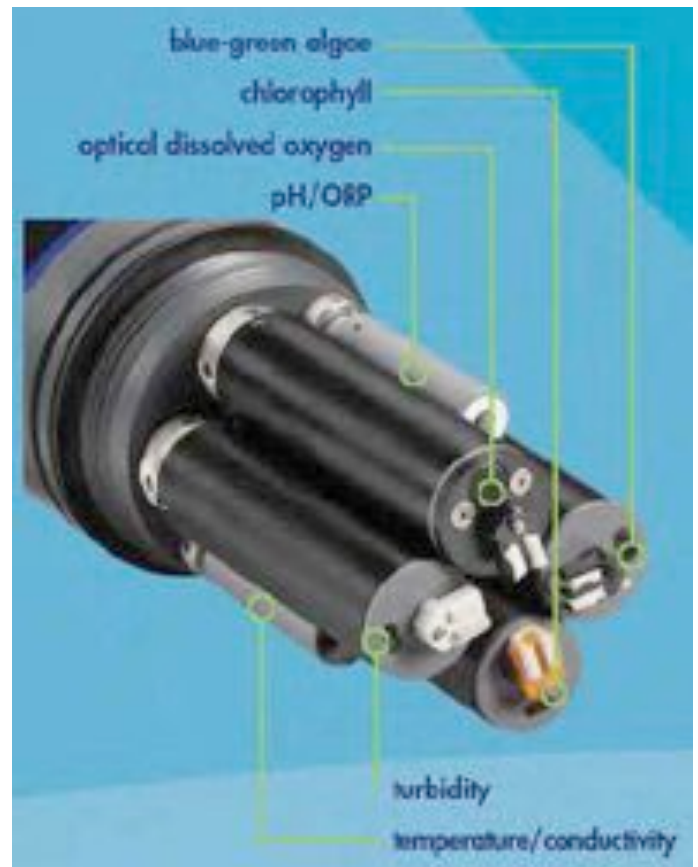


Fig. 6. The water quality assessment probes which are located on the nose of the AUV.

## LiDAR.

To scan environment above the water surface, a 3-D LiDAR (Light Detection and Ranging) is used. It has 360° horizontal field of view, with 0.09° angular resolution, -2° to 24.8° vertical field of view with around 0.4° resolution, and around 50 *m* to 100 *m* range. The LiDAR spins at 5 to 15 *Hz*, which can be adjusted as needed.

## LD-LRS

Apart from having a 3-D LiDAR, a 2-D laser scanner, SICK LD-LRS-1000, is used for navigational purposes on the ASVs. The LD-LRS has an effective scan angle of 360°, with an angular resolution of 0.125°. The maximum range of the scanner is 250 *m* and the scanning frequency varies from 5 to 10 *Hz*. However in the choppy sea surface

conditions, the effective detection range can drop significantly.

### Sonar.

To scan environment below the water surface, a high frequency sonar is used. It uses 2.25 MHz sound wave. It has  $45^\circ \times 1^\circ$  field of view and its range is 9 m. The sonar can be set to update its data to a maximum of 40 Hz. It is light and small, with a weight in air of approximately 3.7 kg. The dimensions are 22.6 cm x 11.9 cm x 10.9 cm.

### Algorithms

**Path-planning.** Forecasts of the state of the ocean in a certain region are carried out by solving the Navier-Stokes equations but initial and boundary conditions have to be assumed and imposed on the simulations to make the computations viable. These assumptions will lead to inaccuracies in the simulation results but the inaccuracies are not constant throughout the entire computational domain. Within the computational domain, depending on the flow conditions, there are some areas which the accuracies of the simulation results are more uncertain and others less.

For certain mathematical models, the uncertainty of the simulation result can be quantified and a map of the uncertainty can be produced. Given this map of uncertainty, the simulation results can be best improved by using vehicles to sampling data from these high uncertainty areas and assimilating the measured data into the simulations.

However, due to limited time and resources, all these areas cannot be sampled and the points that the vehicles can visit need to be optimized to improve the accuracy of the forecast as much as possible. The problem of trying to solve what points the vehicles should visit is known as a path-planning problem. By using a formulation that involves Mixed Integer Linear Programming, Yilmaz *et al* has developed a program that can plan the path of multiple numbers of a homogenous type of vehicle (Yilmaz, 2008). The program has been modified to not only be able to plan the path for multiple numbers of one type of vehicle, but to be able to plan the path for multiple numbers of different types of vehicles as demonstrated on Figure 7 (Ooi, 2008).

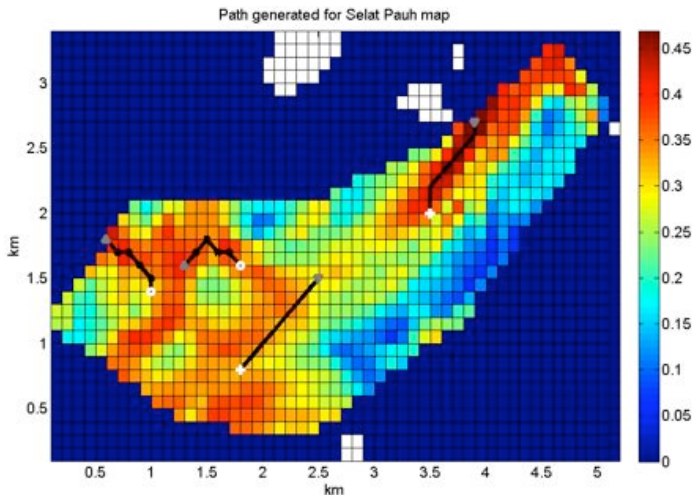


Fig. 7. A map of the uncertainty of the forecast of the currents in Selat Pauh, Singapore. An algorithm was developed to plan the paths of multiple types of vehicles such that they will sample from the regions that have the highest uncertainty. The white markers are the starting positions and the gray markers are the ending positions. The circle

markers represent one type of vehicle and the plus markers represent another type of vehicle.

For simulation models that do not generate uncertainty maps, work has been done to create an objective map to identify dynamic hotspots. Using the result of the simulation, an objective map, which is similar to the uncertainty map, can be created using the current speed and its gradient, and the vorticity of the flow (Zheng 2009a). The value of these three parameters can be computed for each point on the computational domain and the corresponding maps can be obtained accordingly. A weighted sum of these three maps can be calculated to obtain an objective map, which can then be put into the path-planning program.

**Collision avoidance.** A vital requirement for running autonomous vehicles is collision avoidance. This is especially true for cluttered and busy environments such as harbors where vessels of many sizes travel in and out. The objective of the collision avoidance algorithm is to devise a motion strategy such that it enables safe navigation of the autonomous vehicle along a desired direction, in the presence of unknown ocean currents and surface waves from nearby boats.

Currently, this algorithm has been implemented on the ASV. In this collision avoidance program, the ASV estimates the relative position and motion of the obstacle and subsequently chooses a direction that avoids collision (Bandyopadhyay, 2009). Its approach is a 'sense-plan-act' paradigm that is carried out at high frequency. The major difference between this algorithm and that used by terrestrial robots is that the current algorithm is designed to function even when uncertain environmental factors, such as wind and currents, move the ASV in any arbitrary direction.

The surrounding of the ASV is scanned using the LD-LRS described in the previous section. The world is represented in terms of clusters, which are determined from the scan data by using a simple thresholding based range segmentation. Using the laser data range and angle data, a single obstacle is considered to be a single cluster of points. A starting and ending point could then be picked out of this cluster. Each such terminal point can either be an *occlusion point* that occludes the sensor's line of sight visibility, or a *range point* which is the limit of the cluster visible due to the sensor's range limit (see Figure 8(a)). The range points are an artifact of the sensors limitations and do not reflect information about the obstacle.

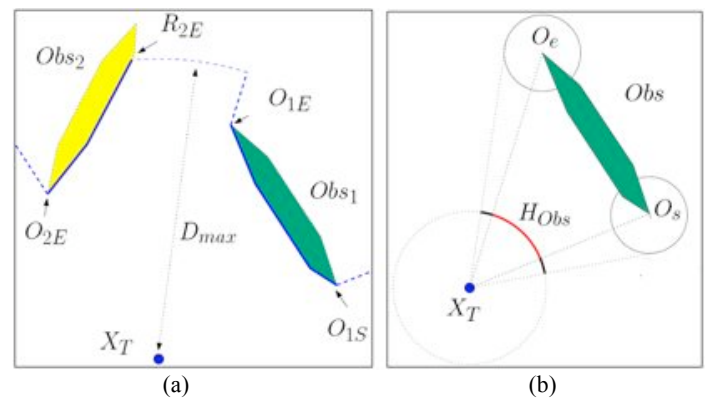


Fig. 8(a). A simulation of the collision avoidance algorithm.  $X_T$  marks the location of the ASV.  $Obs_1$  and  $Obs_2$  are obstacles respectively.  $O_{1S}$  and  $O_{1E}$  are the starting and ending occlusion points for obstacle 1.  $O_{2E}$  is the ending occlusion point for obstacle 2 while  $R_{2E}$  is a range point that is caused by obstacle 2.  $D_{max}$  is the maximum range of the laser scanner. (b) Due to the presence of an obstacle,  $H_{Obs}$  is the range of angles that ASV is forbidden to take.

Generally, the ASV has an underlying objective such as waypoint navigation which generates a desired heading. The collision avoidance algorithm modifies the heading command, based on the detection of nearby moving obstacles to avoid colliding into them. Planning is done in position space rather than velocity space due to the unreliability in velocity measurements of the ASV as well as the obstacles. By extrapolating the current velocity of the ASV in a simple linear model for a short duration  $\Delta T$ , the position space in the planning horizon  $\Delta T$  becomes the reachable set  $R_{AT}$ , which is the set of all positions that the ASC can reach in time  $\Delta T$ . Based on this simple model, the directions that will cause collision with nearby obstacles can be determined as shown in Figure 8(b).

## APPLICATIONS

### Improve Forecast Capabilities

As mentioned in the previous section, uncertainties in simulation results are introduced when assumptions regarding the initial and boundary conditions are made. The uncertainties can be reduced if the state variables in the regions of higher uncertainty are sampled and assimilated into the simulations.

In June 2009, experiments were conducted in Serangoon Harbor, Singapore to collect water quality data. The locations where the experiments could be carried out were allocated by the Maritime Port Authorities of Singapore. A variety of equipment was used to carry out the water quality measurements. These include a Conductivity-Temperature-Depth (CTD) probe, an AUV and Acoustic Doppler Current Profilers (AD-CP).

The CTD probe and AD-CP were used to create the profile of water quality parameters and current profile in a water column respectively. Assimilation of the measured profiles from the CTD probe was carried out to produce a hindcast. Comparison of the results from the hindcast and the forecast with no data assimilation showed that the results from the hindcast were closer to the true current profile measured by the AD-CP (Wei 2010).

Using the AUV, similar water quality parameters were measured. The mobility of the AUV allowed for data to be measured along the depth and over space in a short duration. Figure 9 shows the measured values of salinity at various longitudes and latitudes over different depths. A fleet of vehicles, using the path-planning algorithm, could be used to sample the ocean at crucial areas and the obtained data can be assimilated into simulation models to improve the accuracy of the forecast.

An accurate forecast of the ocean currents will be vital when accidents such as oil spills occur. The accurate prediction of the dispersion of the chemicals can lead to a much more efficient and effective containment plan.

### Safe and Secure Harbor Environment

Using the LiDAR, the cluster of points returned from the laser data can be used to reconstruct a surface in a virtual environment. This capability, used in a mobile network of sensors, can carry out inspections and identification of a ship or static structure that requires repair more efficiently. Structures, such as piers or moored ships, in a shipyard can be inspected using the network of sensors as well. Work is currently being carried out to reconstruct a pier located in an enclosed body of water called Pandan Reservoir. Photograph of the pier and the image of the reconstructed pier are shown in Figure 10.

This network of sensors could be also used to survey ships incoming to a port for explosives or illegal items that might have been attached to the exterior of the ship.

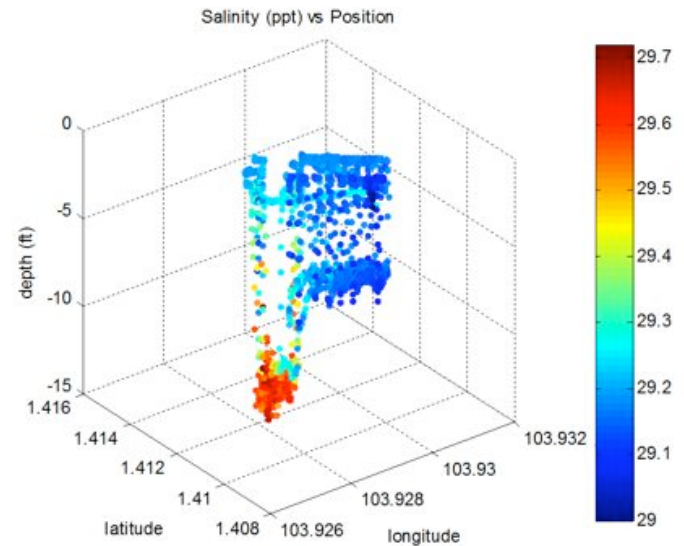


Fig. 9. Measured data of the salinity at Serangoon Harbor using an AUV in June 2009.

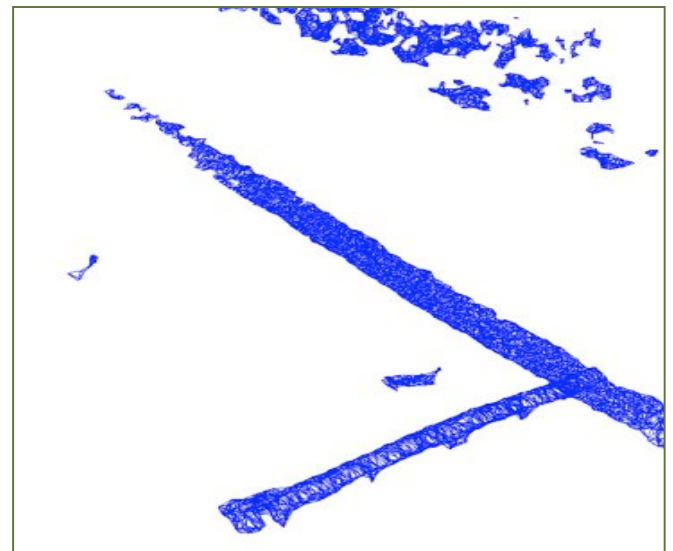


Fig. 10. (above) A photograph of an ASV with the pier in the background. (below) The reconstructed image of the pier.



## CONCLUSIONS AND FUTURE WORK

To summarize, we have presented the development of a mobile sensor network in the Singapore coastal zone. The mobile platforms consist of ASVs and AUVs, while the sensors range from various water quality probes to visibility sensors that operate above the water surface, such as, LiDAR and LD-LRS, to range sensors that operate under the water surface, such as, sonar. We presented some algorithms that we have developed to enable the mobile platforms to move effectively in the coastal area. Furthermore, we presented some of our work utilizing the sensor network developed.

The mobile sensor network we develop is still at its early stage. A number of improvements to the sensor network are being made and planned. One major aspect of the future work is to improve the communications capabilities between the platforms. On-going work includes improving communications and data transfer between ASVs and the servers located onshore and communications between the multiple AUVs, surface ships, and ASVs. The positioning and localization of the vehicles is also an important aspect of a mobile sensor network. Accurate evaluation of the mobile platforms' position and the position of objects around them is crucial to avoid collision, move effectively in the coastal zone, and to acquire physical data at positions that are known accurately. Work is currently being carried out to improve the accuracy of the position measurements via an Automatic Identification System (AIS). Papers included in the list of references from our group (Bandyopadhyay 2009, Chalfant 2009, Hover 2009, Jose 2009, Kalyan 2009, Kalyan 2010, Lee 2010, Ooi 2008, Ooi 2009, Ooi 2010, Tan 2009, Tkalich, Wei 2009, Wei 2010, Yilmaz 2008, Zheng 2009a, Zheng 2009b) provide further information on our past and current activities

## ACKNOWLEDGEMENTS

The research described in this project was funded by the Singapore National Research Foundation (NRF) through the Singapore-MIT Alliance for Research and Technology (SMART) Center for Environmental Sensing and Modeling (CENSAM).

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