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Underwater Gliders: Recent Developments and Future Applications

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(Invited Paper)

***Abstract*— Autonomous underwater vehicles, and in particular autonomous underwater gliders, represent a rapidly maturing technology with a large cost-saving potential over current ocean sampling technologies for sustained (month at a time) real-time measurements.**

In this paper we give an overview of the main building blocks of an underwater glider system for propulsion, control, communication and sensing. A typical glider operation, consisting of deployment, planning, monitoring and recovery will be described using the 2003 AOSN-II field experiment in Monterey Bay, California.

We briefly describe recent developments at NRC-IOT, in particular the development of a laboratory-scale glider for dynamics and control research and the concept of a regional ocean observation system using underwater gliders.

I. INTRODUCTION

Sampling the oceans has traditionally been conducted from ships, with the first global oceanographic research cruise by Sir Wyville Thomson on the *HMS Challenger* from 1872-1876, Figure 1, which led to numerous discoveries such as the mid-Atlantic ridge and the *Challenger Deep* in the Mariana Trench to name only a few. It took over 23 years to compile the results from this cruise.

Today with increasing use of remote sensing techniques from satellites and airplanes more and more data becomes available and needs to be processed. Current remote sensing technologies, airborne or from space, do not penetrate very far below the ocean's surface. In order to gain more insight into the temporal and spatial processes below the surface we were until recently still depending on ship based measurements and moorings. Over the last decades alternative technologies such as subsurface floats, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have emerged to complement the existing sensing techniques. Visions of autonomous platforms roaming the oceans as described in [9] and [1] have not come true yet, but technological advances pushed by these visions brought us a long way from the *Challenger* cruise.

In this paper we report on a special type of autonomous underwater vehicle, an underwater glider, and on the implementation of coupled ocean observation and modeling systems.

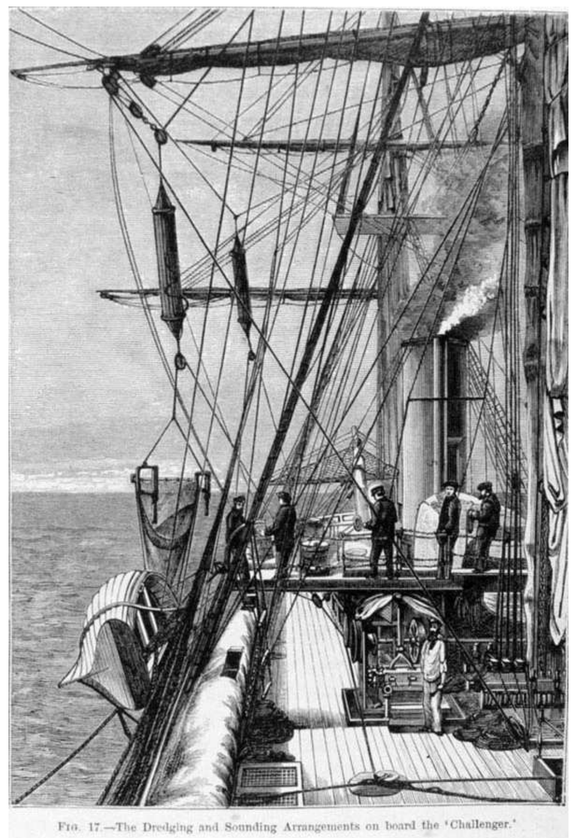

Fig. 1. Dredging and sounding arrangements on board the *Challenger*. Photo Credit: NOAA Photo library, source: http://oceanexplorer.noaa.gov/history/breakthru.html.

In Section II we describe the current glider technology and their mode of operation. Section III-A briefly describes the AOSN-II field experiment in Monterey Bay and Section III-B highlights the approach and implementation of multi-glider operations for the AOSN-II effort. In Section IV-A we describe NRC-IOT's role in developing an asset management tool for a regional ocean observation modeling and prediction facility in Newfoundland. Current efforts at NRC-IOT to develop a laboratory-scale glider to support the above described effort and to enhance in-house expertise in AUV development, control and operations, is described Section IV-B.

II. Underwater Gliders

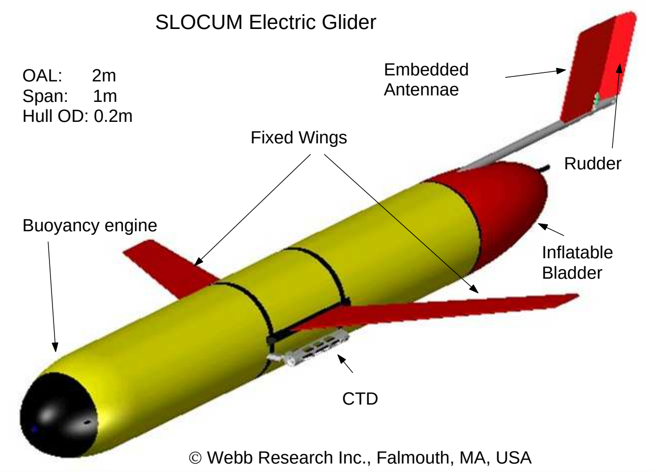

Fig. 2. Rendering of a *SLOCUM* electric glider. Built by Webb Research Inc., Falmouth, MA, USA; http://www.webbresearch.com.

Autonomous underwater gliders, represent a rapidly-maturing technology with a large cost-saving potential over currently-available ocean sampling techniques, especially for sustained, month at a time, real-time oceanographic measurements.

Underwater gliders move efficiently through the water-column by exploiting their ability to change their weight in water. As a result there is an upward/downward force acting on the glider. Successive weight changes combined with a change in attitude result in a concatenation of up/down glide cycles. The combination of upward/downward force with the change in attitude (i.e. pitch) allow the wings and body to generate the hydrodynamic lift and drag forces which propel the gliders horizontally and vertically through the water. The mechanism to achieve this change in weight is referred to as a buoyancy engine (see Figure 2). Currently operational gliders, such as *Seaglider* [3], *Spray* [8] and the electric *SLOCUM* glider use an electromechanical displacement actuator, pump or piston, to change their weight. A prototype glider using an alternative thermally driven buoyancy engine is currently under development [11]. The closed-loop control of attitude and depth is performed by an on-board computer that also executes a pre-programmed mission while submerged. At the surface the gliders acquire their location using a GPS receiver and compare that position to the desired position from the mission plan. The position error is used to compute an estimate of the average current flow encountered between two surfacings. The current estimate is then used to correct the dive parameters (i.e. heading) for the next dive cycle. At the surface the gliders are able to communicate globally using an IRIDIUM satellite connection (datarate$\approx$2400 baud) or, for local line-of-sight communication, some gliders (i.e. *SLOCUM*) are equipped with a high bandwidth RF-modem (datarate$\approx$115.2 kbaud). An ARGOS transmitter is implemented as a fall-back solution. The antennae are integrated into the gliders such that while the glider is at the surface, the antennae are at a maximum height above the water surface for reliable communications. In the case of the *SLOCUM* glider, the antennae for communication and GPS are embedded within the rudder assembly, Figure 2 and, by means of an inflatable bladder in the tail cone, can be brought out of the water. Once communication to a control center has been successfully established, the current glider mission can be updated and/or data recorded during previous missions can be downloaded from the vehicle.

Besides the vehicles' position, attitude and other internal states, the gliders collect data from their scientific sensors. Typically the gliders carry a conductivity, temperature and depth sensor (CTD), but more recently additional instrumentation such as Photosynthetically Active Radiation (PAR) sensors and fluorometers have successfully been operated. The drawback due to additional sensors as well as frequent communications and shallow dives, which imply frequent changes in buoyancy, is an increase in power consumption and therefore a reduction in mission length. Currently the operational endurance of the gliders varies from 3 to 4 weeks for the shallow *SLOCUM* glider (max. depth $\leq$ 200m) to several months for the deeper diving gliders *Seaglider* (max. depth $\leq$1000m) and *Spray* (max. depth $\leq$1500m). All three gliders are comparable in size and handling requirements. Their weight in air is approximately 50 kg and their total volume change capacity is between 0.5 and 1% of their total displacement. The horizontal speed relative to the surrounding water is typically around 35 cm/s. For more detailed information on the specific performance of the gliders the reader is referred to [3], [8], [11] and [4].

III. Applications

A. *Autonomous Ocean Sampling Network II - Monterey Bay 2003 (AOSN-II)*

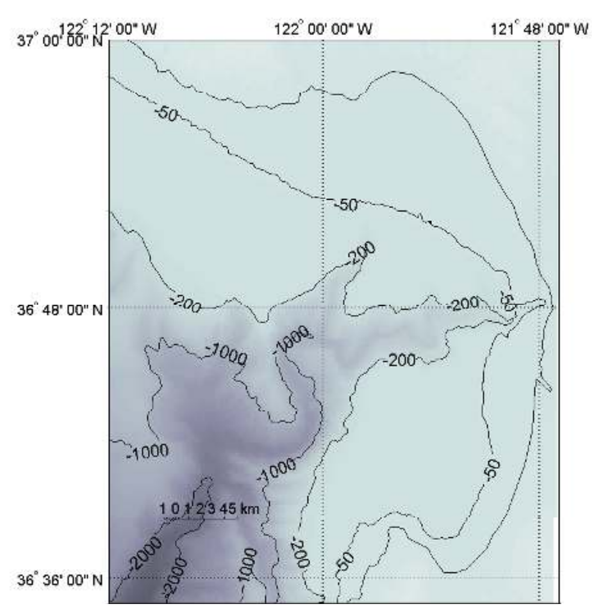

Fig. 3. Bathymetric map of Monterey Bay, California, USA (depth in meters).

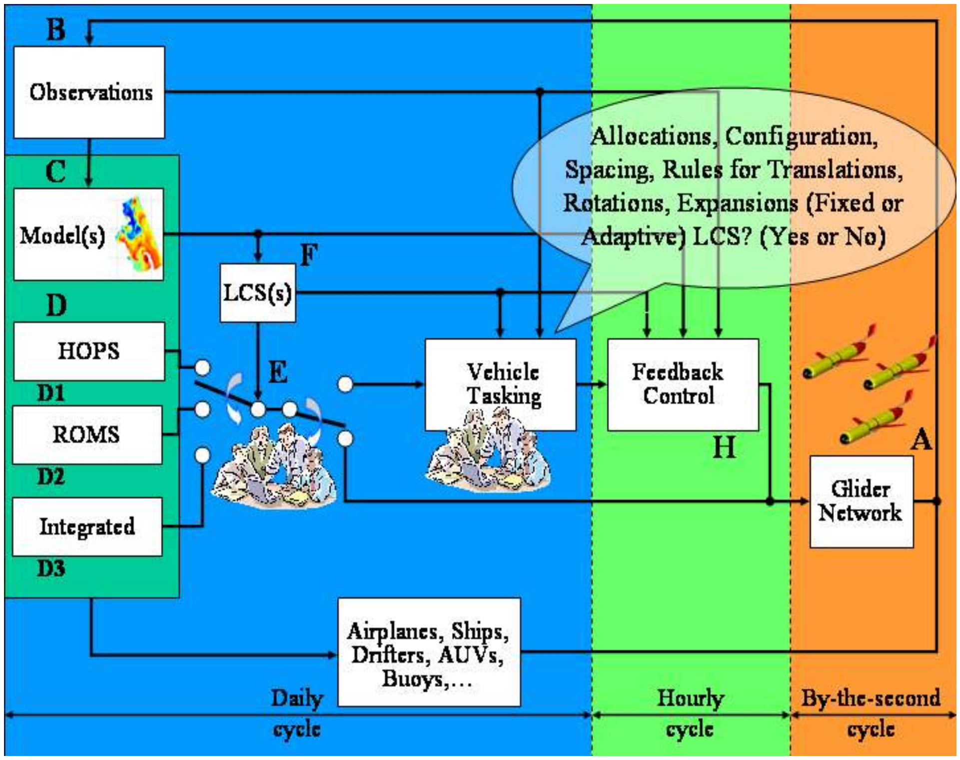

Fig. 4. Diagram of Real Time Operations Plan for AOSN-II. LCS stands for Lagrangian Coherent Structures, ROMS for Regional Ocean Model (JPL/UCLA) and HOPS for the Harvard Ocean Prediction System [7].

The Autonomous Ocean Sampling Network-II [1] field experiment was conducted during the summer of 2003 in Monterey Bay, California. This bay was chosen for its accessibility, resident research institutions with on-site hardware (i.e. ships, airplanes, AUVs) and its interesting bathymetry, Figure 3. Since the region is well studied there is a large amount of historic data available for intercomparisons. The objective of the experiment was to demonstrate the feasibility of an integrated ocean observation, modeling and prediction system. This experiment differs from previous efforts because of its high degree of system integration, allowing for real-time adaptation based on ocean model predictions. The sampling patterns of mobile observational assets, such as ships, airplanes, underwater gliders (i.e. Spray, *SLOCUM*) and propeller driven AUVs (i.e. *REMUS*, *DORADO*) were planned and, in some cases, adapted using the numerical modeling and prediction capabilities of two independently-running numerical modeling codes developed by two groups from Harvard University (HOPS [7]) and the Jet Propulsion Laboratory (ROMS). Those models in turn were supplied with data coming from the mobile assets, as well as other sources such as CODAR data (COntinental raDAR), satellites, fixed moorings and surface drifters. Figure 4 gives an overview of the interactions between the different parts of the system as well as an idea of the different time-scales involved in the experiment.

B. Glider Operations

The core observational assets of AOSN-II were autonomous underwater vehicles and in particular a fleet of underwater gliders. Two types of gliders were available, five *Spray* gliders [8] operated by Jeff Sherman and Russ E. Davis of the Scripps Institution of Oceanography and 10 *SLOCUM* gliders [11] operated by David Fratantoni from Woods Hole Oceanographic Institution. Prior to the experiment all gliders were shipped to the Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California. On site the gliders were assembled, ballasted and tested in MBARI's test-tank. Since the gliders were deployed for long periods of time, special attention was given to sensor calibration; the sensor data were closely monitored during the course of the experiment. After initial shakedown dives close to shore, the gliders were directed towards their operational area. To take full advantage of the different depth capabilities of the gliders, (see Section II), the five *Spray* gliders were deployed in the deep water further outside the bay while the *SLOCUM* gliders were flown closer to the bay.

Figure 5 shows a snapshot of the glider tracking display from 25 August 2003, with a three day position history plotted behind each glider. The two large dots represent fixed moorings in the Bay (M1, M2). The Spray gliders were flying on straight lines almost perpendicular to the shoreline, while the *SLOCUM* gliders were either flown on a fixed "racetrack" (a,b,c,d) or operated in an adaptive sampling mode where the trajectories of several gliders were coordinated and adjusted in a real-time experiment [2]. Communication to and from the gliders during regular operations used the IRIDIUM satellite system. Due to their more frequent inflections and higher sensor load, the *SLOCUM* gliders had to be recovered during the course of the experiment. The gliders were either directed

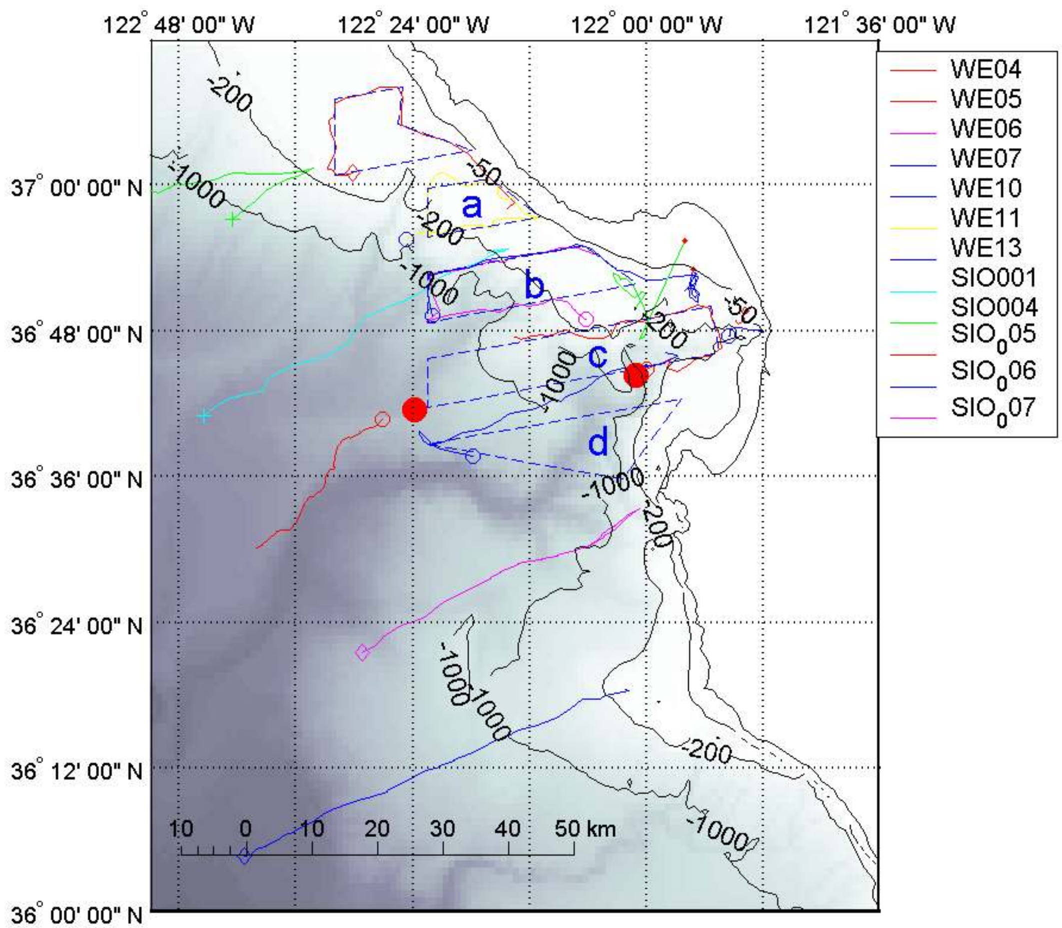

Fig. 5. Snapshot of real-time display for asset location. The length of the tail behind each asset corresponds to the positions during the last three days. Large dots represent moorings M1 (right) and M2 (left). In the figure legend, WExx stands for Woods Hole Oceanographic Institution Electric Glider (*SLOCUM* gliders), SIOxx for Scripps Institution of Oceanography (*Spray* gliders).

to a designated recovery area close to Moss Landing or were directed to an area to rendezvous with a surface vessel for recovery. When in range of the surface vessel, the gliders were able to directly communicate with the vessel and were controlled using the high bandwidth RF-link. After recovery the gliders' battery packs were replaced, the systems re-ballasted, checked out and readied for redeployment.

In order to manage the number of different assets in the water, as well as to provide a quick overview of the last available positions, a realtime operational display was designed and made available in the control center at MBARI, Figure 5. The display was developed in the beginning of the experiment and was continuously improved during the course of it. The display was automated and ran continuously during the experiment, which enabled the control room staff to closely monitor progress of the gliders and if necessary intervene. On several occasions the operators noted that the gliders were advancing only marginally over the course of several hours. This behavior was associated with strong head currents close to the southern end of the bay (i.e. Monterey); those currents were on the order of the gliders' horizontal velocity. On other occasions the gliders' progress was far above its theoretical limits and continued slightly on shore. This behavior was observed three or four times and was attributed to fisherman "recovering" the equipment. The vehicles were retrieved from the recovery teams, checked out and re-deployed if necessary.

The AOSN-II experiment successfully integrated all the above mentioned components and collected a valuable data-set for evaluation of various sampling strategies and modeling efforts. The performance of several multi-vehicle experiments during the course of AOSN-II show the potential for added value by using coordinated control strategies [2]. New tools are under development that allow for improved planning and monitoring of the observational assets which will provide a higher degree of autonomy during future deployments.

IV. Future Developments and Applications at the Institute for Ocean Technology

A. Newfoundland Ocean Observation, Modeling and Prediction Facility (NOOMPF)

A team of researchers from NRC-IOT, Memorial University of Newfoundland and Labrador (MUN) and the Department of Fisheries and Oceans (DFO) (R. Bachmayer and C. Williams from NRC-IOT, B. de Young, L. Zedel, N. Bose and S.

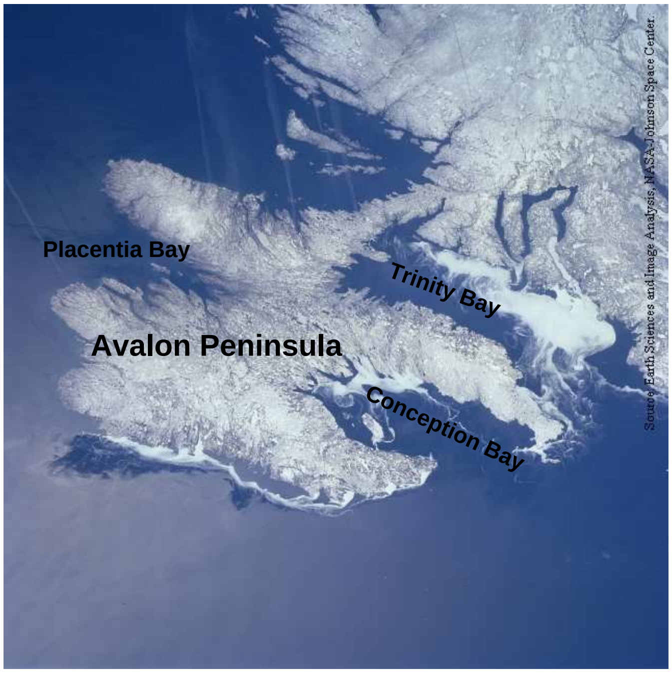

Fig. 6. Photo Credit: Earth Sciences and Image Analysis, NASA-Johnson Space Center. Candidate areas for implementation of an ocean observation, modeling and prediction system in Newfoundland. Note: North is to the right. Trinity Bay is approximately 140 km by 40km in size.

O'Young from MUN and F. Davidson from DFO) is currently developing a plan to implement a regional coupled ocean observation and modeling system in Newfoundland (NOOMPF). Possible sites for implementation are Conception Bay, Trinity Bay and Placentia Bay as shown in Figure 6. The goal is to develop a capability for automated coupled ocean observations and model predictions on a regional scale. NOOMPF will integrate novel approaches to ocean sampling, modeling and prediction. The potential improvements in the modeling and prediction capabilities of the ocean will significantly enhance our ability to predict and manage the ocean as a resource for food production, transportation (e.g. ice-drift predictions), and exploration. This facility will also provide a unique testing ground for future developments in sampling strategies and technologies as well as a possibility to benchmark future improvements in the modeling and prediction of the ocean environment.

Observations will be based on a suite of different sampling platforms. We will perform conventional observations based on time series from moorings, weather stations and ships. In addition to those measurements we will utilize available data-products from satellites including AVHRR and Radarsat. Besides these assets several autonomous mobile platforms, such as autonomous underwater gliders and propeller driven AUVs will be deployed for extended periods of time. NRC-IOT's role in the development of such a system is to develop the control and communication infrastructure necessary to direct and monitor the observational assets. We are going to develop an asset management tool (ASMT), Figure 7, that will serve as the main control and monitoring interface. The modular design of the tool will allow us to sequentially develop and improve individual components of the system. In the baseline version the ASMT will provide a basic display of asset locations in an area of interest. Together with the first display module (Asset Location) a data interface will be developed that will allow us to access position information and collected data from a selection of platforms (i.e. gliders, AUVs, buoys, ships, etc.) as soon as they become available. Other parts to be developed include a planning module, a vehicle health monitor and a general asset status module. Some of these components, such as the planning module, require access to meteorologic and oceanographic databases and models. The vehicle health monitor will analyze data coming from the vehicles to provide an automated early fault detection mechanism to warn the operators of possible failures. The ASMT can also be used as a simulation and practice environment using real-time, recorded or generated data as inputs into the system.

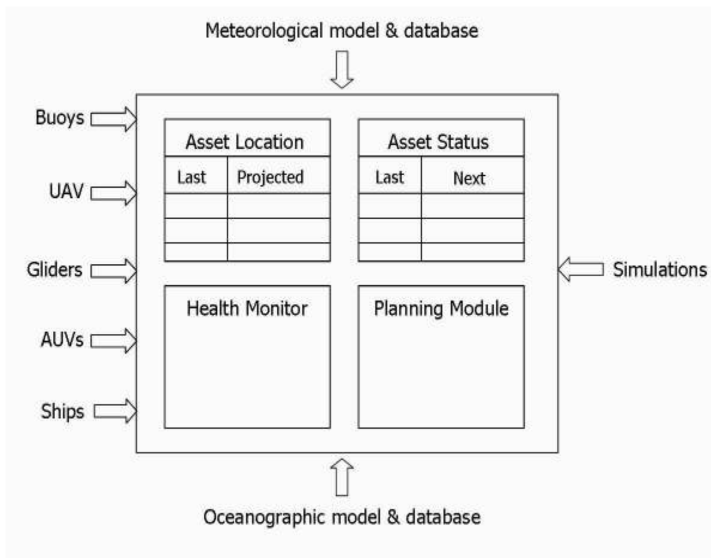

Fig. 7. Schematic of Asset Management Tool for NOOMPF.

B. *Laboratory Scale Glider*

In order to complement the efforts described in Section IV-A, NRC-IOT is considering developing a laboratory-scale glider, Figure 8. The purpose of the laboratory glider is to conduct experiments for hydrodynamic testing and control and to provide a test-bed for new actuation and flow sensing technologies. We are planning to perform a complete system identification using recently developed mathematical models [6], [10], [5] and [4] and experiments. The glider's mathematical model will be used to develop various parts of the ASMT, such as a health monitor and a planning module. The performance of those modules can then be evaluated using the data coming from the glider operating in our test facilities.

As a first step towards the design of a laboratory scale glider, we are currently investigating the design alternatives and constraints of a buoyancy engine. We decided to design the buoyancy engine for operations in up to 20 m of water-depth and a size such that it fits into a cylindrical housing of 10 cm in diameter. The particular characteristics of the engine,

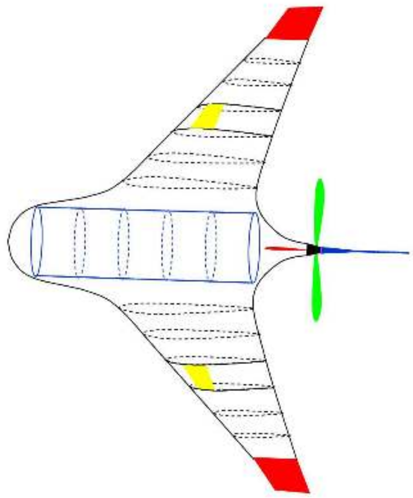

Fig. 8. Conceptual drawing for a laboratory-scale glider.

such as volumetric rate and absolute displaced volume are to be designed such that the glider reaches a steady state glide within 2/3 of the depth of IOT's towing tank (tank depth: 7m). In a next step we are going to perform vertical motion tests in order to evaluate the performance the buoyancy engine.

After the completion of the design of the buoyancy engine we are moving towards the hydrodynamic design of the glider. The design philosophy is to be able to build several glider hulls with significantly different hydrodynamic characteristics and reuse the electromechanical "internals" of the glider. This approach allows for experiments with uncommon designs such as flying wings or hybrid gliders (added propeller propulsion, see Figure 8) at a reasonable cost.

V. ACKNOWLEDGEMENTS

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