Development of a Multi-AUV SLAM Testbed at the University of Michigan

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Abstract—This paper reports the modifications involved in preparing two commercial Ocean-Server AUV systems for simultaneous localization and mapping (SLAM) research at the University of Michigan (UMich). The UMich Perceptual Robotics Laboratory (PeRL) upgraded the vehicles with additional navigation and perceptual sensors including 12-bit stereo down-looking Prosilica cameras, a Teledyne 600 kHz RDI Explorer DVL for 3-axis bottom-lock velocity measurements, a KVH single-axis fiber-optic gyroscope for yaw rate, and a WHOI Micromodem for communication, along with other sensor packages discussed forthwith. To accommodate the additional sensor payload, a new Delrin nose cone was designed and fabricated. Additional 32-bit embedded CPU hardware was added for data-logging, real-time control, and in-situ real-time SLAM algorithm testing and validation. Details of the design modification, and related research enabled by this integration effort, are discussed herein.

I. MOTIVATION

The Perceptual Robotics Laboratory (PeRL) at the University of Michigan is actively involved in three major research efforts: real-time vision-based simultaneous localization and mapping (SLAM), heterogeneous multi-vehicle cooperative navigation, and perception-driven control. The laboratory chose to purchase two commercial-off-the-shelf (COTS) Ocean-Server Technology AUVs to support these research goals, and upgraded the vehicles with additional perceptual and navigation sensors to enable this research.

The first of the three PeRL research domains, real-time vision-based SLAM algorithms [1], has direct application to ship-hull inspection and deep sea archaeological missions. Inefficiencies arise when using human divers to inspect the hulls of offshore vessels due to the slow speed of the diver through water and the navigation inaccuracies incurred in using "kick-counts" for navigation along the hull. PeRL's goal is to create a fully-automatic real-time Feature Based Navigation (FBN) framework based upon the synthesis of visual and acoustic perception for automated hull inspection with an autonomous underwater vehicle (AUV).

In addition to real-time SLAM, PeRL is working toward cooperative multi-vehicle missions for large-area survey. The navigation system uses Woods Hole Oceanographic Institution (WHOI) acoustic modems and highly accurate subsea stable clocks to enable one-way travel time (OWTT) inter-vehicle ranging and communication [2]. The goal here is to distribute state estimation between the vehicles in a coordinated fashion—allowing for navigation impoverished vehicles (e.g., no inertial measurement unit (IMU) or Doppler velocity log (DVL)) to share from positional accuracies of better equipped vehicles (e.g., DVL bottom-lock). A typical mission would consist of two or more vehicles surveying some area of interest. For example, a near-seafloor visually augmented navigation (VAN) [3] enabled vehicle could perform highly detailed inspection over small regions, while a mid-water column vehicle enabled with side-scan sonar could traverse larger regions to identify specific sites of interest. As the VAN vehicle's state estimation improves over time, distributing this knowledge to other vehicle could refine the non-VAN vehicles' state estimate. This coordinated effort would result in faster overall survey times and more attention to regions of interest, rather than using the full VAN capabilities over feature-barren tracts of seafloor.

Another research focus is in the domain of perception-driven control. Algorithms are under development to enable a vehicle to respond to the environment by autonomously selecting alternative search patterns based on perceived feature distributions in the observed data. This creates improvements in productivity by eliminating long surveys of feature-poor areas and instead allows more bottom-time spent over actual targets. A seafloor survey vehicle, for example, may drive into an area devoid of features during a mission. Instead of continuing to search the featureless space, where there is little return on investment from the expense of running a vision system, the vehicle would return to a previously known feature rich area and begin searching in another direction. The PeRL group is currently working on algorithms to assist in the decision making process of when to revisit known landmarks versus continuing new exploration.

A. Other Subsea SLAM Testbeds

One of the major limitations in the field of underwater robotics is the lack of radio-frequency transmission modes. The opacity of water to electromagnetic waves precludes the use of GPS and high speed underwater radio communication. To overcome this obstacle, several approaches have been undertaken by researchers, such as employing SLAM algorithms in conjunction with sensor-fusion techniques [4], [5], [6], [7], or constructing acoustic time-of-flight navigation systems
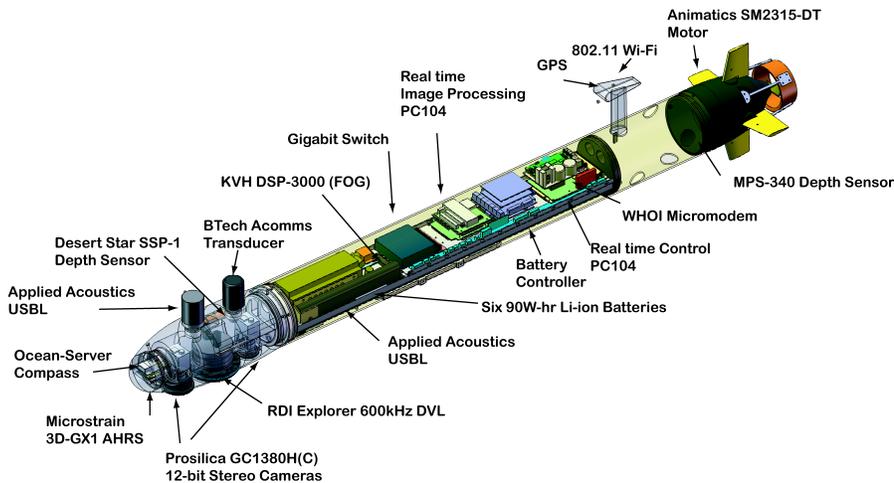
Fig. 1. Internal component layout.

[8], [9]. For an overview of current underwater navigation methodologies and technology see [10].

One popular approach to reducing navigation uncertainty is the use of multiple sensors, especially sonar and vision sensors. Stanford University is currently working on remotely operated vehicle (ROV) positioning systems that use DVL and ultra short baseline (USBL) sonar combined with a camera for vision-based localization and control. This work has been demonstrated in real-time vision-based tracking applications such as locating a jellyfish in an image and simultaneously tracking two jellyfish in an image sequence [4].

A similar sensor combination is used by the University of Sydney on their Sirius vehicle to build an multi-sensor data fusion (MSDF) system [11]. This vehicle, though, places more emphasis on sonar by the employment of dual scanning sonar, DVL, USBL, and stereo cameras. Their navigation algorithm is based on the two scanning sonars, and enhanced by the visual information in navigation and map building. This combination also appears on the Naval Postgraduate School (NPS)'s AUV, PHEONIX, which achieves position information through the use of an onboard scanning sonar, video cameras, an acoustic modem, and DVL [6].

Carnegie Mellon University (CMU), in collaboration with Stone-Aerospace, is applying three-dimensional (3D) SLAM techniques, with their vehicle, Deep Phreatic Thermal Explorer (DEPTHX), to the challenge of autonomous underwater cave exploration and survey. DEPTHX, an AUV capable of depths of 1000m, is an AUV that employs an inertial navigation system (INS), DVL, sonar array, and a camera [7]. This research focused on the control and navigation challenges associated with the vehicle, as well as the mapping of an underwater cave system. The team succeeded in using a particle filter based 3D SLAM algorithm to build a complete 3D map of the world's deepest cave, the Zacatón Cenote (at depths up to 270m).

Massachusetts Institute of Technology (MIT) and Bluefin Robotics are currently experimenting with SLAM algorithms on the Hovering Autonomous Underwater Vehicle (HAUV) [12], an open-frame AUV that uses a Dual-frequency IDentification SONar (DIDSON) in addition to a DVL for ship-hull inspection. MIT is also working on an autonomous surface vessel, the Surface Craft for Oceanographic and Undersea Testing (SCOUT), based on a kayak framework, that can relay global positioning system (GPS) position information from the surface to subsea vehicles for highly accurate localization information [13].

Seafloor mapping at 2600m of depth was successfully reported using WHOI's Autonomous Benthic Explorer (ABE), which is equipped with DVL, USBL, scanning sonar, and video camera [14]. Another vehicle from WHOI, SeaBED, conducts surveys on coral reef habitats with a high resolution CCD camera, DVL, and side scan sonar [15].

Furthermore, researchers at Virginia Tech are developing low-cost miniature AUVs that act cooperatively to build a sensor network able to survey large tracts of seafloor simultaneously [16]. Researchers at Georgia Institute of Technology [17] are also working on cooperative underwater robots.

II. VEHICLE OVERVIEW

Although several vehicles currently include stereo-vision systems and DVL sensors, the Iver2 (Fig. 2) was selected as a technology development platform due to its ability to be transported in a personal vehicle and launched by a single user. Sensor upgrades were required to enable the original vehicle to perform SLAM and coordinated multi-AUV missions.

The vehicles, as shipped, are rated to a depth of 100m. A maximum survey speed of approximately 4 knots (2m/s) is possible, but missions typically require a speed over ground of 1 knot for imaging continuity. The standard vehicle weighs

29.48kg and can be transported by two people. [18]. To boost computational power, an additional PC104 board with an Intel Core 2 Duo CPU was added to the onboard electronics.
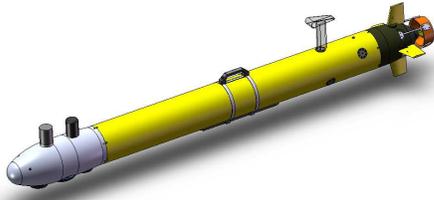

Fig. 2. Modified OceanServer Iver2.

Fig. 3. Mechanical layout.

A. Mechanical Design and Integration

The design goals during the integration phase of vehicle development consisted of minimizing hydrodynamic drag, maintaining neutral buoyancy, and maximizing sensor payload capacity within the pressure hull. These requirements were achieved through the use of lightweight materials such as ABS, Delrin, and aluminum, and careful center of buoyancy and center of mass computations. The entire vehicle was modeled using Solidworks solid modeling software and extensive use of these computer aided design (CAD) models provided optimal arrangements of internal components prior to actual installation (Fig. 3).

The addition of a redesigned SLAM nose cone and sensor payload shifted both the original center of buoyancy (CB) and center of gravity (CG). New positions were estimated using the CAD models and optimized during ballast tests were performed at the UMich Marine Hydrodynamics Laboratories (MHL). The vehicle is ballasted to achieve .45kg buoyancy for emergency situations when the vehicle must surface without power. Vehicle trim is set neutral to achieve passive stability and to optimize both diving and surfacing operations.

In determining the location and orientation of each component within the vehicle body, heat dissipation and interference in between sensors were considered as the critical constraints after spatial constraints were satisfied. Due to the high density of sensors and other devices in the pressure housing, the components with the highest heat radiation, such as computing units and dc-dc converters, are placed in direct contact with the aluminum chassis to allow better heat dissipation. Also, sensors that are prone to electrical noise from surrounding electronics are spatially separated in the layout (e.g. the MEMS Microstrain 3D-GX1 in the nose cone tip).

B. Electrical Systems Integration

The design constraints for electrical integration included both internal chassis mechanical footprint limitations and power consumption limitations. As previously stated, mechanical positioning was achieved through the use of CAD models.

Stereo Prosilica 1.3Megapixel 12-bit GigE GC1380H cameras each support up to 20fps sample rate, but missions will typically run with sample rates of 1-5fps. The current vehicle configuration (Fig. 1) includes a local network supported by a Parvus Gigabit ethernet switch that allows communication between the nose cone cameras and the PC stacks on the electronics carriage.
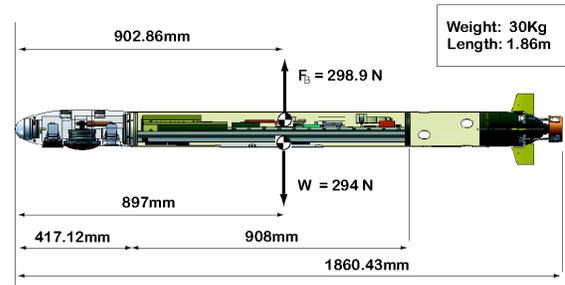
Overall, a 53 Watt load increase for sensors and computation, above the original load of 9W hotel and 110W propulsion, was realized with the additional sensors for a total maximum draw of 172W. This assumes the vessel is using all available components and the motor at full power. Future plans include integrating a seventh battery to achieve $665W \cdot hr$ for an estimated run time of 3.8 hours at maximum speed (5 hours or more at 75W (2 knots) propulsion speed).

C. SLAM Nose cone

In order to support the real-time VAN objectives of PeRL, a stereo-vision based system was added to the Iver2 vehicles. Stereo vision allows scale information to be extracted from images thus improving state estimation by observing velocity scale error in DVL measurements. A new nose cone was designed and fabricated to house both the two-camera vision system and the DVL transducer.

The UMich custom-design nose cone (Fig. 5) was fabricated from Acetron GP (Delrin) due to the material's high tensile strength, scratch resistance, fatigue endurance, low friction, and low water absorption. Threaded inserts are installed in the nose cone to prevent stripped threads and stainless fasteners with a polytetrafluoroethene (PTFE) paste (to prevent corrosion issues) are used in all locations.

The designed working depth of the nose cone is 100m (to match the full rating of the Iver2). Calculations were performed according to ASME Section VIII Boiler and Pressure Vessel Code to verify wall thickness in each of the nose cone sections. A minimum factor of safety of at least 2.64 was attained for all sections of the nose cone. Pressure tests, conducted at Woods Hole Oceanographic Institution, demonstrated the structural integrity of the nose cone to 240m water depth. Three short duration dives of 12 minutes each were made to 360psi and one long duration dive of five hours was made to 360psi.

The Teledyne-RDI 600 kHz Explorer DVL (Fig. 4) is integrated into the nose cone using fasteners to attach the DVL head to threaded inserts in the nose cone material. The internal cavity space precludes the use of the recommended

TABLE I
INTEGRATED SENSORS ON THE PeRL VEHICLES.

IVER2 STOCK INSTRUMENTS	VARIABLE	UPDATE RATE	PRECISION	RANGE	DRIFT
OceanServer OS5000 Compass	attitude	0.01-20 Hz	$1-3°$ (Heading), $2°$ (Roll, Pitch)	$360°$	—
Measurement Specialties Pressure Sensor MSP-340	depth	—	$< 1\%$ of FS	0-15000 psi	—
Imagenex Sidescan Sonar (Dual Freq.)	—	330 or 800 kHz	—	15-120m	—
USGlobalSat EM-406a GPS	XYZ position	10 Hz	5-10 m	—	—
NEW INSTRUMENTS	VARIABLE	UPDATE RATE	PRECISION	RANGE	DRIFT
Prosilica GC1380H(C) Camera (down-looking stereo-pair)	color image	1-5 fps	1360x1024	—	—
Teledyne RDI 600kHz Explorer DVL	body velocity	7Hz	1.2-6 cm/s (@1m/s)	0.7-65m	—
KVH DSP-3000 (FOG)	yaw rate	100 Hz	$1-6°/hr$	$±375°/sec$	—
Desert Star SSP-1 300PSIG Digital Pressure Transducer	depth	.0625-4 Hz	0.2 % of FS	15-300 PSIA	—
Applied Acoustics USBL	XYZ position	1.0-10.0 Hz	+/-0.1 m Slant Range	100 m	—
OWTT* Nav (Modem+PPS)	slant range	—	18.75 cm (@1500m/s)	—	< 1.5m in 14hr
–WHOI Micromodem	communication	Varies	—	Varies	—
–Seascan SISMTB v.4 PPS Clock	time	1Hz	$1\ \mu$s	—	1ms/14hr
Microstrain 3D-GX1 AHRS	attitude, body rates	1.0-100 Hz	$±0.5°$	$±180,180,90$	—

* One-Way-Travel-Time (OWTT)
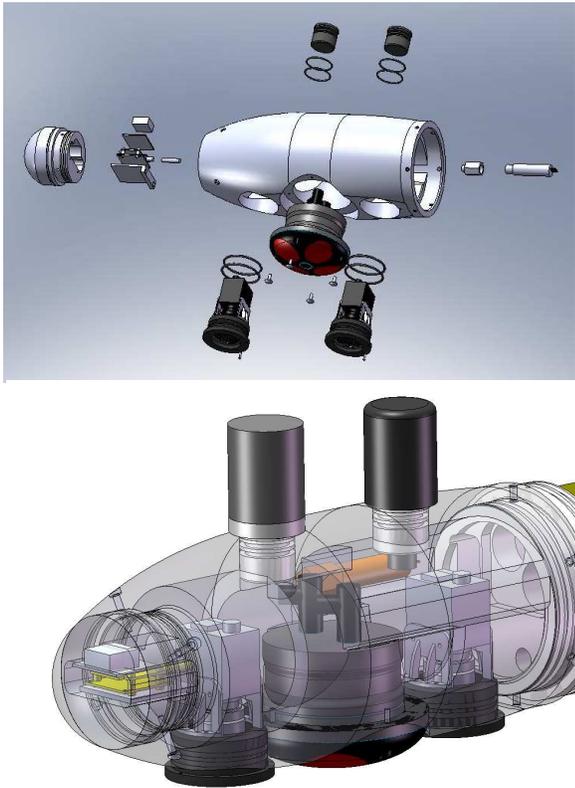
Fig. 4. Exploded and translucent view of PeRL's redesigned nose cone.

each. The synthetic sapphire window was chosen due to the high scratch resistance and superior tensile strength of sapphire versus plastic or glass materials. The mounting brackets were designed in CAD and printed in acrylonitrile butadiene styrene (ABS) plastic using a Dimension FDM Elite rapid prototype machine. Static face and edge o-ring seals prevent water ingress through the plug around the sapphire window.

Fig. 5. Fabricated SLAM nose cone with DVL and camera plugs.

clamp attachment scheme. Self-sealing fasteners are used to eliminate a fluid path through the mounting holes of the DVL to the interior of the nose cone.

Two nose cone plugs were designed for camera integration that include a sapphire window and two mounting brackets

A Desert Star SSP-1 pressure transducer is mounted to an internal face of the nose cone and is exposed to the ambient environment through a 1/8" shaft drilled perpendicular to the nose cone wall to reduce flow noise influence on the sensor. The Microstrain 3D-GX1 is integrated into the nose cone tip by mounting the Ocean-Server OS5000 Compass on top of the 3D-GX1 and milling a cavity in the tip to allow for the additional vertical clearance.

All o-rings installed in the nose cone are of material Buna-N (acrylonitrile-butadiene) and are lightly lubricated with Dow Corning #4 prior to installation.

III. MISSIONS AND TESTING

Initial in-water testing of the vehicle was held at the University of Michigan physical model basin (a 109.7m x 6.7m x 3.0m tank) (Fig. 6). Vehicle trim, propulsion, dive planes, and vertical stabilizers were tested to determine full range of motion. The maximum propulsion speed with the Animatics SM2315DT motor is approximately 4kts, and the control fins traverse through $\pm 30°$. Using the physical model basin and motorized towing carriage, engineers were able to tow the vehicle to isolate and troubleshoot individual sensors.

Fig. 6.   Vehicle testing at the Marine Hydrodynamics Lab.

Further test missions were run at the Huron River in Ann Arbor, Michigan (Fig. 9). GPS, side-scan sonar, and the onboard compass functionality were demonstrated through short surface missions using Ocean-Server's VectorMap GIS mission planning software. To increase the effective range of ship to vehicle 802.11g communications, a RadioLabs 2.4GHz wireless range extender amplifier was mounted to the standard Buffalo wireless switch in-line with a RadioLabs omni-directional 15dB antenna.

Current missions conducted by PeRL include automated visual ship hull analysis (conducted at Naval Undersea Warfare Center (NUWC), field demonstrations and engineering education at the University of Michigan Biological Station (UMBS), archaeological surveys of shipwrecks and ground imaging in Thunder Bay National Marine Sanctuary (TBNMS).

NUWC. Underwater imaging trials were conducted, in collaboration with MIT and Bluefin Robotics at the annual AUVFest held at NUWC in Newport, RI in May, 2008. PeRL field tested a calibrated Prosilica GC1380HC (Fig. 7) camera system, which is also used in the Iver SLAM nose cone, by photographing the USS Saratoga aircraft carrier hull in both artificial and ambient light conditions for post-processing off-line. Feature-based image processing tools provide vehicle relative position to the hull and feature-to-feature distance information. Vision algorithms implemented on the Iver vehicles will be tested on the data gathered during these missions.
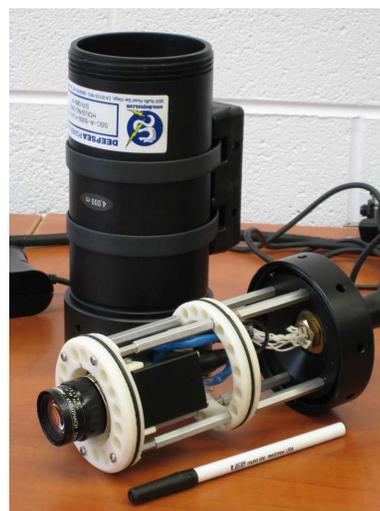
Fig. 7.   Prosilica GC1380C 12-bit camera and DSPL housing.

UMBS. Further sea trials were held on Douglas Lake at the University of Michigan Biological Station (UMBS) in Pellston, Michigan during July, 2008. Four days of on-water testing demonstrated maneuverability, vehicle speed, dead-reckon navigation, wireless ethernet communication, side-scan sonar functionality (Fig. 8), digital compass, and manual surface joystick operation modes. In addition to vehicle trials, PeRL staff presented guest lectures on AUVs and hosted hands-on training in conducting actual AUV missions. Launch and recovery conditions were conducted from shore, dock, and from a pontoon boat. A full side-scan survey of the south-eastern bay at Douglas Lake was run from the UMBS docks. After the completion of the mission, the vehicle was manually motored, from a portable wireless station on the dock, back for recovery.
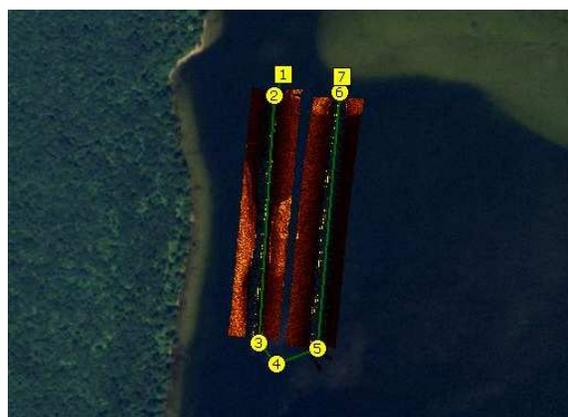

Fig. 8.   Side-scan sonar data from UMBS.

TBNMS. In August, 2008, PeRL staff will run multi-vehicle missions in collaboration with the National Oceanic and Atmospheric Administration (NOAA) Thunder Bay National Marine Sanctuary (TBNMS) off of Alpena, MI. Missions will include shipwreck surveys of known wrecks and wide-scale

search missions of suspected wreck sites. The vision-enabled vehicle will be used to conduct site-specific surveys and record photographic data. The vehicle equipped with side-scan sonar will be used to perform large-scale search swaths to locate potential sites of interest for closer inspection.

IV. CONCLUSION

This paper described the modifications performed by PeRL to off-the-shelf AUV platforms from OceanServer Technologies, Inc. The research goal of this integration effort is to provide a multi-vehicle research platform for the development of cooperative real-time SLAM algorithms. To this end, we have reported the design and integration phases of sensor integration. In addition, we have briefly described the field testing involved to-date for this project.
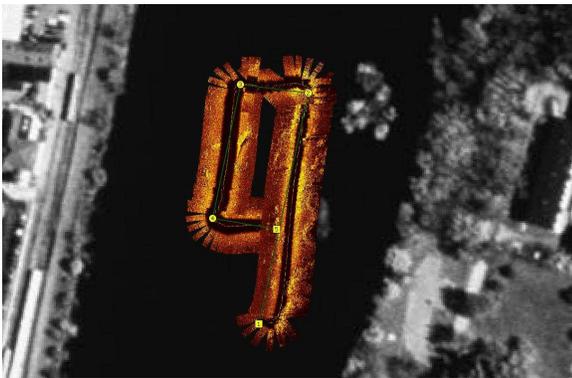

Fig. 9. Side-scan sonar data from Argo Pond in the Huron river.

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