

Development of the REMUS 600 Autonomous Underwater Vehicle

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Abstract – The Oceanographic Systems Laboratory of the Woods Hole Oceanographic Institution has developed the REMUS 600, a new 12.75 inch (32.385 cm) diameter autonomous underwater vehicle that will be used to carry mine countermeasures sensors for the Office of Naval Research. Vehicle Control Technologies has been tasked by ONR to develop autopilot and simulation software for several REMUS 600 sensor configurations, with the objective of achieving enhanced platform steadiness to improve sensor performance in the shallow water and very shallow water environment.

The most stringent motion steadiness requirements for the REMUS 600 vehicle are derived from the image forming specifications of a new side-looking synthetic aperture sonar developed for ONR by the Penn State Applied Physics Laboratory and the Coastal Systems Station, Panama City, Florida. This payload necessitated the use of a forward fin section for enhanced control authority. This forward fin section gives the vehicle the ability to command vertical and horizontal sideslips, in addition to roll, pitch, and yaw control, using independently commanded fins. This is a unique capability for a vehicle of this class. In addition, the 12.75 inch diameter vehicle class offers new capabilities for endurance and payload capacity. The REMUS 600 software architecture has been designed with the flexibility to accommodate various payloads and both the VCT autopilot and the Woods Hole autopilot.

We present the VCT approach to autopilot design which makes use of a high-fidelity hydrodynamics model, software in the loop simulation test, vehicle motion steadiness performance predictions, and post-test validation. The REMUS 600 vehicle has collected extensive in-water data. We present performance results based on this data.

I. INTRODUCTION

The REMUS 100 Autonomous Underwater Vehicle (AUV) developed by the Oceanographic Systems Laboratory (OSL) of the Woods Hole Oceanographic Institution (WHOI) is a mature stable product that has been successfully transitioned to the Navy, and is now commercially available from Hydroid, Inc^[1]. It is a small (36 kg), affordable, and easily transported, with specifications that exceed those of larger vehicles. It has become a workhorse in a number of Navies throughout the world, as well as with academia and the commercial sector.

However there are some missions for which a small, lightweight vehicle is not appropriate. Sometimes a vehicle is required that has longer endurance than the nominal 8 hours/5 knots of the REMUS 100, larger payload capacity, or greater available energy for powering payloads. For this reason OSL has developed the REMUS 600 class of vehicles. This vehicle has the diameter of a standard half size torpedo (12.75", 32.385 cm) and thus is compatible with existing Navy handling equipment.

The initial application for this vehicle is as a platform for the Small Synthetic Aperture Minehunter (SSAM) being developed by Penn State University and the Coastal Systems Station (CSS). The principle of synthetic aperture sonar is that as the sonar moves along track it insonifies the same spot on the seafloor with multiple pings. This produces a synthetic

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array equal to the distance traveled. By coherently merging the data from all the pings, an image with improved along-track resolution is created. In order coherently merge the data, it is essential that the motion of the platform be accurately measured and that perturbances be minimized^[2,3]. In the turbulent near shore mine counter measure regime, this represents a rather extreme challenge. Thus one of the key goals in the design of this system was to make it a suitable platform for this work.

II. BACKGROUND

The Oceanographic Systems Lab has developed an extensive family of AUVs, from the small, 36kg REMUS 100, to the 700 kg REMUS 6000.

REMUS VARIANTS

Type	Weight	Depth Rating
REMUS 100	36 kg	100 Meters
REMUS 600	200kg	600 Meters
REMUS 6000	700 kg	6000 Meters
REMUS TIV	270 kg	450 Meters



The REMUS Family

The original REMUS 100 (shown in the foreground) weighs about 36 kg, and has been licensed commercially to Hydroid, Inc. Over 80 have been produced in a variety of configurations that include forward and side look sonars, video and electronic still cameras, modems, inertial navigation systems, GPS, and numerous environmental sensors. It has proven to be a reliable and adaptable workhorse.

Behind that is shown the “Tunnel Inspection Vehicle” (TIV) which was built to survey the 4 meter diameter Delaware-West Rondout Aqueduct for the New York City Department of Environmental Protection. This vehicle surveyed the entire 72 kilometer aqueduct, which provides over 60% of the water for the city of New York, in a single 15 hour mission, and took over 200 thousand high resolution images, providing 100% coverage of the system.

The largest of the four vehicles shown is the full ocean depth (6000 meter) rated REMUS 6000. Two of these vehicles have already been delivered to the U.S. Naval Oceanographic Office, with a third under construction. These reliable vehicles



REMUS 6000 Launch and Recovery System

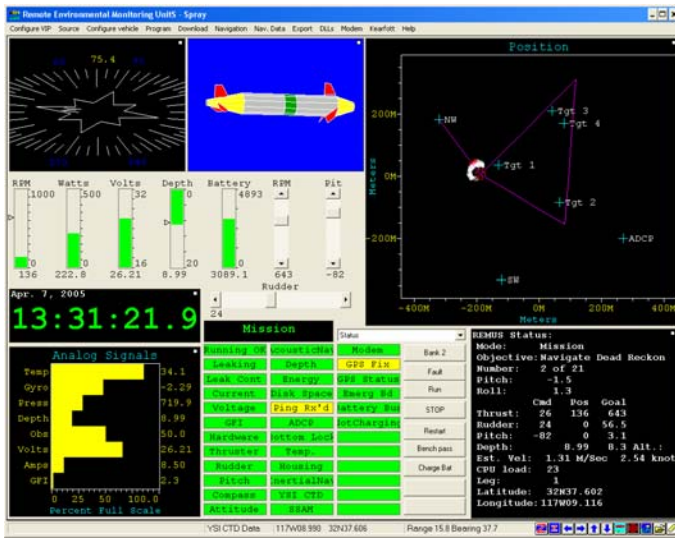
have already performed over 160 missions in very deep water, and have dramatically cut the survey time and costs with respect to towed systems. The associated launch and recovery system, also designed and built by WHOI has allowed operations in conditions as rough as sea state 5 (3 meter waves).

The REMUS 600 (shown in the back), provides a more moderate depth capability, but allows very large payloads and/or endurance. The SSAM payload for example, weighs 87 kilograms, and requires about 150 watts power when transmitting. A single battery module

provides over 5400 watt-hours of energy. By using the available payload space (i.e. by removing the SSAM), two additional battery modules can be added. This vehicle configuration would have sufficient endurance for several days operation. This would allow operations in excess of 280 nautical miles; enough to transit to the edge of the continental shelf and back. A demonstration of that capability is planned for later this year. Also under development for the Naval Oceanographic Office is a titanium version rated for 3000 meters with a launch and recovery system similar to the one shown for the REMUS 6000.

III. FEATURES

The new REMUS 600 vehicle is equipped with a Kearfott KN-4902 Inertial Navigation System (INS). This ring laser gyro based system is fully integrated with the long baseline (LBL) acoustic navigation system available on all REMUS variants. The vehicle is also capable of operating using a standard “REMUS” navigation system. An up-down looking 1200 KHz RDI ADCP provides altitude and bottom velocity information. A tail mounted antenna provides GPS input, WIFI connectivity at ranges up to 1 kilometer, and an Iridium satellite link. The Iridium link is ideally suited for long range operations, since it enables the vehicle to periodically “phone home” from any location on the planet. In addition, the vehicle is equipped with a WHOI micro modem supporting the latest version of the Compact Control Language^[5]. This allows real-time acoustic transmission of status and data to either the REMUS ranger (a small hand held tracking device) or to a modem equipped laptop. This not only facilitates tracking, it also allows confirmation that systems and the mission as a whole are proceeding as planned.



REMUS Vehicle Interface Program (VIP)

One of the vehicle's most important features is its compatibility with the existing REMUS fleet. This vehicle is based on the same mature software system used in its larger and smaller brethren. As a result, it leverages the developments and lessons from earlier systems, and thus the time in the water so essential to achieve a robust and reliable system is minimized. From a training perspective, individuals that operate one find they can operate any of the REMUS vehicles.

IV. FIN CONTROL SYSTEM

The most unusual aspect of the system design is its fins. The vehicle is equipped with three aft fins in an inverted 'Y' configuration. A forward fin section, also with 3 fins in an inverted 'Y' configuration, can also be installed. The six highly responsive fins allow the vehicle to control not merely heading and depth, but additionally allow control of pitch and roll, as well as yaw, i.e. the vehicle can maintain a straight heading in a cross current, as opposed to crabbing down a track line. This alignment and stability is essential for optimizing the performance of a synthetic aperture sonar.



Inverted 'Y' Configured Tail Assembly



Forward fin assembly

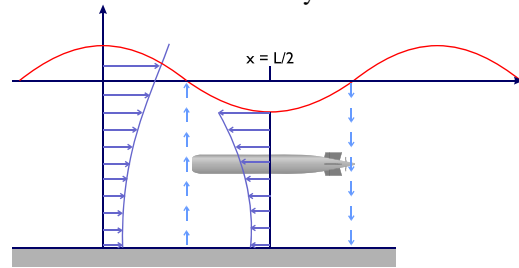
The vehicle has two autopilot systems for operating the fins, each with an identical interface to the rest of the vehicle. The first is the "standard" REMUS control, extensively modified to take advantage of the enhanced capabilities of this vehicle. The second is an autopilot developed by Vehicle Control

Technologies (VCT), of Reston, Virginia, a company that specializes in providing engineering and analytical expertise in the allied fields of control, simulation and guidance of hydrodynamic and aerodynamic vehicles. The use of two different controllers allowed WHOI to verify operation of the vehicle, the fin and thruster system, and the interface, independent of any scheduling conflicts with VCT's personnel. The vehicle can easily be switched between the two versions at a moments notice.

V. VCT AUTOPILOT DEVELOPMENT

VCT uses a combination of hydrodynamic modeling, software in the loop simulation, performance predictions, as well as actual hardware tests to develop and validate their systems.

The vehicle characteristics used in the VCT developed simulations were modeled with hydrodynamic forces and moments computed for individual contributions from the body, the various fins, and the thruster. More than 240 vehicles have been designed or analyzed using this method of flow decomposition into component features which allows accuracy rivaling that of experimentally based approaches, but at much lower cost. The hydrodynamic model was used for non-linear time domain simulation, using actual autopilot code and accurate models of the vehicle sensor and actuator systems. In addition, a complex environmental model that took into account water depth, sea state, and water current was used to input disturbances. The fact that instantaneous effect of these disturbances varied at different points on the vehicle at each time step is included in the VCT developed model that was used. This exacting capability was critical to modeling the response of the vehicle in a seaway.



Fluid motion as a vehicle disturbance

The low level guidance and control software that was run in simulation was the same code that is run on the vehicle. The higher level supervisor functions were emulated as much as is practical, however the REMUS autopilot interface was sufficiently complex that the most expedient approach to software integration was debugging on the vehicle itself. However software in the loop simulation was invaluable in testing the dynamic control algorithms internal to the vehicle.

The standard REMUS vehicle uses a 9 Hz autopilot control loop. For this application the control loop speed was doubled to 18 Hz. Because other system latencies are low and the actuators have high bandwidth this reduced seaway disturbances by 50% in some cases.

The autopilot generates logical commands, which act on the five orthogonal axes easily controllable by the fins. These are: aileron (x rotation), elevator (y rotation), rudder (z rotation), y-

force (y translation), and z-force (z translation). To produce angle commands for each of the six individual fins (actuals), these logical commands must be passed through a logical-to-actual fin transformation. The resulting actual commands have to be limited so that the resulting commands do not exceed the limits of an individual fin. Prioritization is a vehicle safety oriented algorithm in which logical fin commands are reduced in a coordinated way. In addition, integrator windup and rebalancing has to be performed to preserve performance in the non-linear domain.

The autopilot continuously records 203 separate fields of data each at each execution time step. This allowed validation of the proper operation of the system under real world conditions.

VI. TESTING AND OPERATIONS

Initial trials were done near the dock at Woods Hole, with later tests in the nearby waters of Buzzards Bay. Both areas are notorious for their complex currents which allowed adequate stress testing of the control system. In early April of 2005, the vehicle was shipped to San Diego for testing using a ship of opportunity, the RV Acoustic Explorer. These tests gave the Navy an initial exposure to handling a larger vehicle and provided valuable feedback to the developers. The system then came back to Woods Hole for further refinements, and was shipped to Keyport, Washington, where it participated in the 2005 AUV fest. The vehicle was operated both in the Hood Canal, in water currents exceeding one knot as well as in the Keyport range area #4, and in both cases produced outstanding synthetic aperture sonar data.

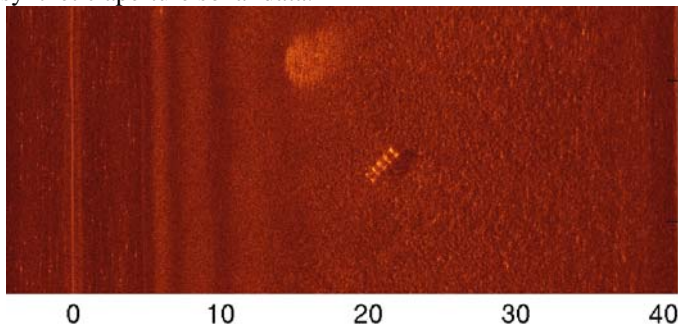
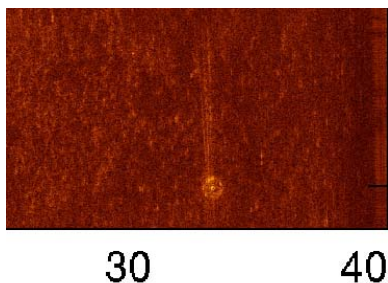


Image of frame, June 8th mission in Hood Canal at AUV-Fest



June 10th, Bucket on a rope at 34 meters (rope is moving)

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VII. PERFORMANCE

Testing with the VCT G&C software was conducted in range area #4 at the 2005 AUV-FEST. This range was set up with targets for the SSAM to detect and classify. Four check-out runs were performed with the VCT autopilot engaged. The results from the fourth run are shown in the table and figures below. The table shows comparison to the requirements originally set for SAS processing. All requirements were met.

Variable	Requirement	Achieved
Speed, V	0.5 to 3 ±0.2 m/s 1σ	0.04 m/s 1σ
Height above bottom, h	5 ±0.3m 1σ	0.025 m 1σ
Roll angle, φ	2° ± 1° 1σ	-0.001 ±0.14° 1σ
Pitch angle, θ	5° ± 1° 1σ	-1.28 ±0.44° 1σ
Drift angle, β	6° (steady state limit)	0.67°
Roll rate, p	1°/SEC 1σ	0.50°/SEC 1σ
Pitch rate, q	1°/SEC 1σ	0.20 °/SEC 1σ
Yaw rate, r	0.1 °/SEC 1σ	0.065 °/SEC 1σ
Surge vel., u	0.2 m/s 1σ	0.04 m/s 1σ
Sway velocity, v	0.2 m/s 1σ	0.005 m/s 1σ
Heave vel., w	0.2 m/s 1σ	0.012 m/s 1σ

The performance of the inertial navigation system has been outstanding. We have found it difficult to measure the actual error, because typically we have allowed the vehicle to run only about 20 minutes between fixes, and errors have been on the order of 3 or 4 meters. Since the WAAS GPS error is of the same order of magnitude, the actual error due to the INS cannot be measured reliably. This level of performance is important because frequent GPS fixes not only increase survey time; they also put the vehicle at risk with respect to surface craft, and may impose a liability issue^[7]. For these reasons, the standard LBL system used on all REMUS vehicles is preferable for survey work in the near shore region.

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