Long-Endurance Test Results of the Solar-Powered AUV System

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Abstract – **The solar-powered autonomous underwater vehicle (SAUV) was designed for long-endurance missions, such as monitoring, surveillance, or station-keeping, where real-time bi-directional communications to shore are critical. In April 2006, the Naval Undersea Warfare Center (NUWC) Division Newport, Falmouth Scientific Inc. (FSI), and Autonomous Undersea Systems Institute (AUSI) conducted a 30-day, long-endurance test using SAUV II primarily to demonstrate that the vehicle is capable of conducting long-term oceanographic data collection and to validate the vehicle's mechanical integrity. This test also served to evaluate possible anomalies and risk-reduction measures for future production-level vehicles.**

A key part of this long-endurance test was the logging of the SAUV II charge and discharge rates under different sky and weather conditions with the vehicle under varied energy load situations—data that can be used to assess vehicle endurance and help establish future mission capabilities of the SAUV II. This paper describes the SAUV II test vehicle, test methods, data collected, and the results of the long-endurance test.

I. INTRODUCTION

A. *SAUV II Test Vehicle*

Autonomous underwater vehicle (AUV) technology has evolved over the past 10 years to a point where the technology is relatively stable and has been accepted as a viable method for many underwater applications [1]. SAUV II, the test vehicle used in this study, is a solar-powered AUV designed for long-endurance monitoring, surveillance, and station-keeping missions where real-time bi-directional communications to shore are critical. The SAUV II—capable of around-the-clock operations—uses solar energy to recharge its lithium ion batteries during the daylight hours and conducts its assigned mission during the nighttime hours. This strategy manages energy consumption and allows the vehicle to remain on station for several months. This concept offers a paradigm shift for coastal surveillance by providing an ocean survey tool that is both autonomous and mobile with virtually unlimited endurance [2].

SAUV II is 2.3 m long, 1.1 m wide, and 0.5 m high; its topside solar panel is 1 m^2; and its overall weight in air is 200 kg. Because of it relatively small size, the SAUV II is easy to deploy and operate: it can be launched from a boat ramp on shore and can independently swim to a predetermined area of interest. SAUV II can be pre-programmed before the mission, or it can have the program changed during the mission via radio frequency (RF) communication or Iridium satellite phone. The mission planner is a Windows-based graphical-use-interface (GUI) that renders intuitive programming and mission viewing. The mission controller is based on a PC-104 embedded single-board processor that is capable of interpreting high-level commands to direct the vehicle's behavior during the mission.

The SAUV II is made of a fiberglass composite material capable of operating in depths up 500 meters. A vectored thruster provides directional control at 1 to 3 knots, depending on mission parameters. Vehicle status and performance data are relayed to the operator by an acoustic modem where they are logged and displayed on the mission planner laptop computer. The effective bandwidth used by the vehicle modem limits the amount of data that can be transferred via underwater acoustic communication while the vehicle is submerged; however, a restricted amount of mission data can be sent to shore as part of the vehicle's acoustic status packet. The mission data are transmitted to shore by RF communication when the vehicle surfaces. A characteristic mission scenario includes submerged nighttime operations of approximately 12 hours followed by approximately 12 hours of daytime recharging and communications to offload data. Mission duration could be adjusted to keep the vehicle on station for weeks to months with daily updates provided by the user via RF communication or Iridium satellite phone.

B. *SAUV History*

The SAUV II is a second-generation vehicle. The first generation was designed and developed under a cooperative research program between the Autonomous Undersea Systems Institute (AUSI) and the Institute for Marine Technology Problems, Russian Academy of Sciences. In January 1998, the Office of Naval Research (ONR) Naval International Cooperative Opportunities in Science and Technology Program funded a joint proposal to evaluate the technologies required for a solar-powered AUV. One of the products of this program was the development of the first-generation solar vehicle, SAUV I (see Fig. 1).

Successful testing of the prototype design led to the development of the second-generation SAUV II. In January 2003, with funding from ONR, AUSI partnered with Falmouth Scientific Inc. (FSI) and Technology Systems Inc. (TSI) to develop the new SAUV II (see Fig. 2).

Figure 1. SAUV I

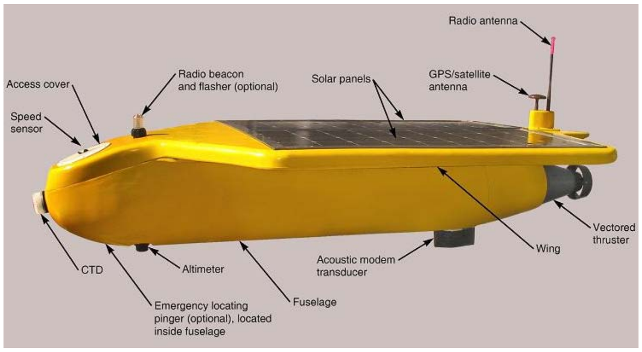

Figure 2. SAUV II

This development process continues as a team-based program in which FSI focuses on the platform and lower level subsystem software, TSI focuses on the user interface that gives the user the tools necessary to create mission plans and monitor the system progress, and AUSI focuses on program management and the development of the high-level mission/system software. The SAUV II system is commercially available from FSI in Cataumet, MA.

The Naval Undersea Warfare Center (NUWC) Division Newport purchased a SAUV II to serve as an affordable and flexible test bed for research and development efforts related to multiple cooperating AUVs, distributed control, and autonomy. The NUWC SAUV II operates in conjunction with four other SAUV vehicles owned by AUSI to promote multiple vehicle technology and group behavior. In addition to autonomous research, the NUWC SAUV II supports applied research demonstrations in environmental monitoring and coastal security.

II. SAUV II ENDURANCE STUDY

Although five vehicles are available to the research team, none of these systems had been endurance-tested for an extended period of time. The team believed that in order to develop the autonomous methods needed for a long-endurance mission, the SAUV II must undergo a long-endurance experiment—the primary focus of which would be the team's ability to quantify the energy system characteristics and to create a database on which to confirm the vehicles mechanical integrity and plan for future vehicle development.

III. METHODS

The testing was conducted at the NUWC Stillwater Basin Shallow-Water Test Facility because of its secure location and convenient access to support services and test infrastructure. Test personnel closely monitored the vehicle with visual, radio, and acoustic communications to the command center located at the pier (see Fig. 3).

Figure 3. NUWC Stillwater Basin test site command center

The vehicle was placed in Stillwater Basin on the first day of the mission, and the team ran a series of box missions to confirm that the vehicle was functioning correctly and to establish a baseline of observations, taking into consideration vehicle performance while monitoring actual power consumption during the missions. The SAUV II uses dead reckoning while it is submerged and uses global positioning system (GPS) coordinates while it is on the surface. During the preliminary series of trials, the team observed how well the vehicle maintained its station while factors such as the wind and tidal conditions varied. The purpose of beginning the experiment with box missions was to allow the vehicle to drain as much battery power as possible so the team could monitor how long it took for the solar panels to recharge the batteries to the pre-test value.

SAUV II is equipped with a 32-V, 2-kWh energy system. This system is composed of 288 commercially available lithium ion cells, which are arranged into two trays that reside under the electronics chassis within the pressure hull. Each tray is broken into six packs of 24 cells (see Fig. 4).

During the majority of the test period, the vehicle was tethered to a slip where it was protected from extreme sea conditions. While tethered, the vehicle was exercised under a variety of mission scenarios (see Fig. 5).

Although it was realized that, by having the vehicle operating under load, some anomalies in power dissipation would occur, restricting the vehicle in this controlled situation would allow for the maximum amount of data to be collected without endangering the vehicle.

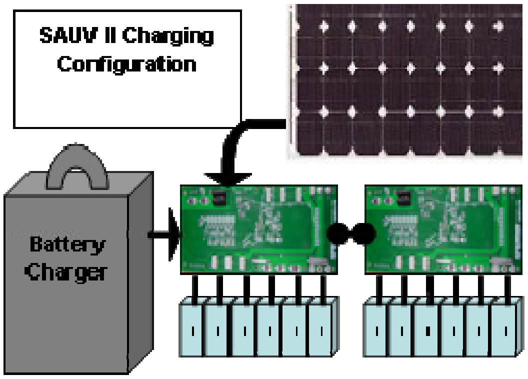

Figure 4. SAUV II lithium-ion solar panel, energy manager, and battery system

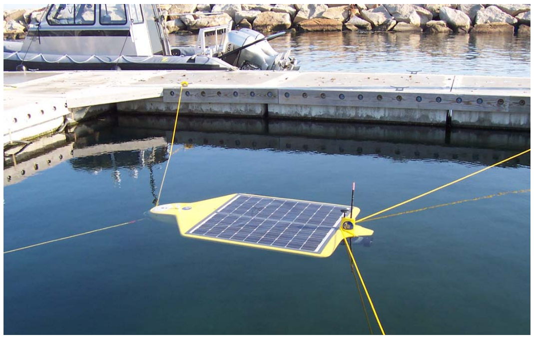

Figure 5. SAUV II stationary test setup

IV. DATA COLLECTED

The vehicle was left in a "powered up" state for the duration of the 30-day experiment. In this state, three modes of operation were employed: open-water dive maneuvers, watch circle position, and stand by. In these operational modes, the vehicle logs all system and sensory data to an onboard PC-104 192-MB disk-on-chip. Seventy-seven individual system parameters were recorded at a rate of once per second continuously for the duration of the experiment. The log files were copied to the mission planner laptop and analyzed using Matlab.

Two specific parameters, both of which pertain to energy consumption, were closely monitored during the experiment: nominal available capacity (NAC) and direct current voltage (VDC). NAC is calculated by a chip located on the battery management board, which measures the current in and out of the batteries. The device acts as a Coulomb counter or gas gauge to measure current as it flows in and out of the batteries; this value can be represented as a percentage of total remaining capacity or as remaining ampere-hours (amp-hour), providing the state of the battery capacity and charge/discharge values. The VDC represents the battery DC voltage. Early in the test cycle, it was discovered that the NAC readings were inaccurate, so VDC became of particular interest to reconcile the true energy consumed.

In addition to the internally recorded data, the team maintained daily mission log sheets documenting weather conditions, visual inspections, anomalies, actions, and general observations. Because one objective of this test was to understand how the system logged data over a long period of time and to determine the point at which the internal drive reached full capacity, disk usage was monitored on a daily basis. The PC-104 was queried, and the free space was recorded at intermittent intervals during the test.

V. RESULTS

After the first day's operational mission, the vehicle did not appear to be recovering its lost energy. Although an obvious charge/discharge cycle occurred each day, the vehicle did not gain considerable net increases in energy as reported by the NAC.

As can be seen in the right side of the graph in Fig. 6, the voltage dropped in response to thruster activity on the first day, but the voltage was then later recovered and showed a net increase from the first day. The voltage is directly correlated to the battery capacity. The NAC, on the other hand, as seen on the left side of the graph, never recovered capacity—suggesting that the NAC, which is a calculated entity, is reporting an incorrect state of the SAUV II energy system.

On day 16, the vehicle entered a passive state as a result of the NAC reaching 12.8 amp-hours—a value below the system safety threshold. The actual battery voltage, however, was much higher than what this value indicated. The system voltage was 30.5 VDC, which corresponds to a NAC of over 30 amp-hours (see Fig. 7).

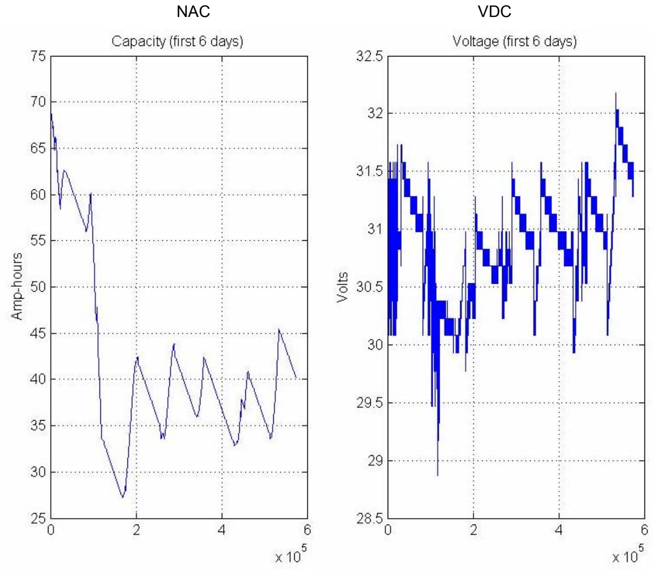

Figure 6. Plots showing the first six days of the 30-day test and the NAC and the VDC recorded for those days

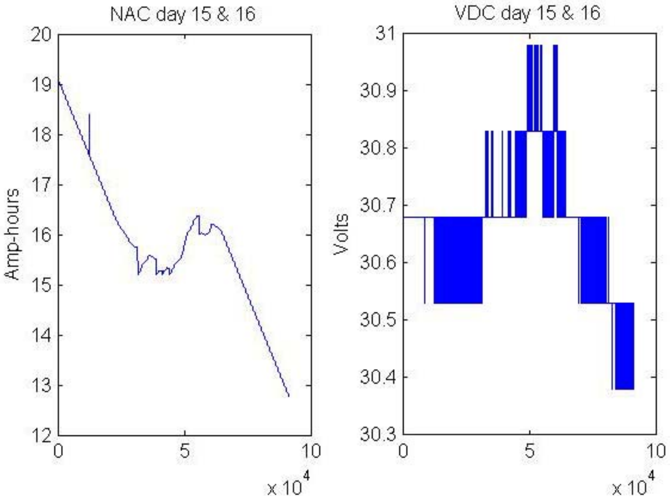

Figure 7. Plots showing days 15 and 16 of the 30-day test and the NAC and the VDC recorded for those days

On day 19, the vehicle's NAC value was reset via a software command so that the vehicle believed it had a full charge. Once again a cyclic pattern of charge and discharge characteristics was evident, corresponding to energy load, weather, and time of day (see Fig. 8).

Fig. 9 and Fig. 10 represent the vehicle during a normal charge and discharge cycle where both the NAC value and the VDC value coincide as expected for a typical sunny day (Fig. 9) and a typical cloudy day (Fig. 10). Each graph provides a glimpse into how the vehicle charge reacts with respect to external factors, such as weather conditions.

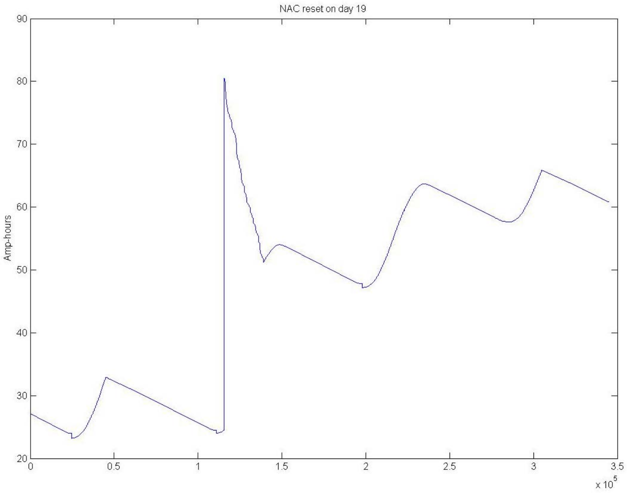

Figure 8. Plot showing the NAC reset on day 19 followed by a cyclic pattern of charge and discharge characteristics

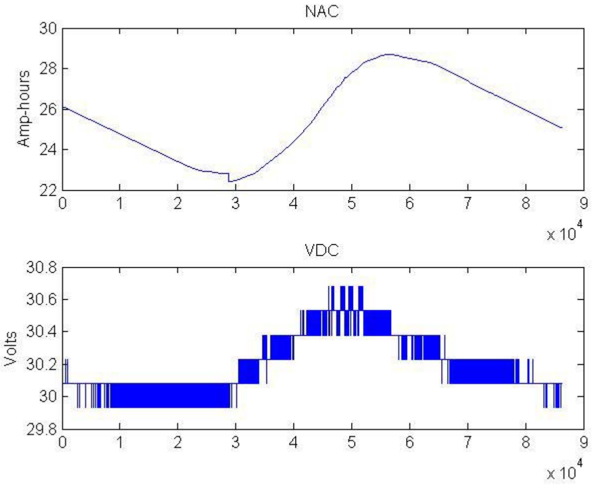

Figure 9. Plot for sunny day cycle (NAC and VDC

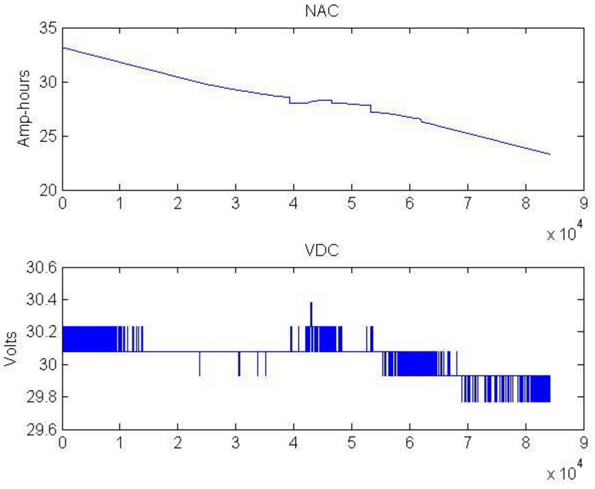

Figure 10. Plot for cloudy day cycle (NAC and VDC)

VI. DISCUSSION

A. Battery Management Board

It was learned early on in the test that the NAC value was not accurately representing the available energy in the system. As of the writing of this paper, it is still unclear as to why this is the case. Since the NAC acts as a fuel gauge for the system, if the value drops below a threshold, the vehicle is commanded into a passive state for safety reasons—which is what happened on day 16 of the experiment.

The battery manager board, which reports critical battery information directly to the energy management board, is a proprietary product developed by Matthews Battery Assemblers in Sanford, FL. The details of the battery board circuity are not available to the public nor were they made available to the authors of this paper. Several of the anomolies encountered during this experiment must be reviewed by Matthews Battery before a clear understanding of system performance may be realized [3] [4].

B. Disk Usage

The disk-on-chip reached full capacity on day 26 of the experiment. The SAUV II system did not lock up or become unresponsive; the SAUV II simply stopped logging to the disk-on-chip. Once the logfiles were deleted from the vehicle, normal logging operation resumed.

Disk usage was consumed at a rate of 2.9 MB/day, which does not appear to be problem for the SAUV II vehicle. The system offers great flexability in that the logging rate may be adjusted to suit specific sensor polling requirements.

C. Bio-Fouling

Although not formally investigated during this study, bio-fouling was evident on the vehicle shell and solar panels as early as day 11, as shown in Fig. 11. By the end of the experiment, the vehicle showed a significant amount of bio-fouling, as pictured in Fig. 12. The team plans to further investigate the effects of bio-fouling in future experiments.

Figure 11. Bio-fouling on vehicle shell: day 11

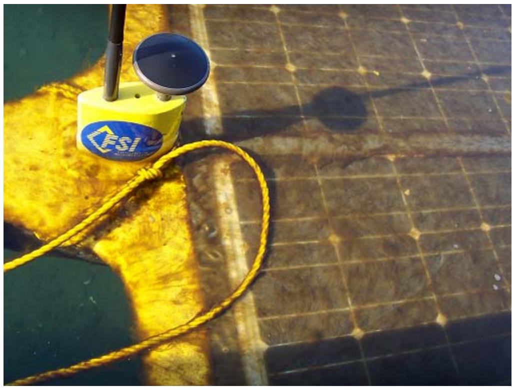

Figure 12. Bio-fouling on vehicle shell: day 25

VII. CONCLUSIONS

This endurance study proved invaluable in helping the team understand the system and subsystem energy characteristics, learn specific details about the energy management circuitry and software, and gain insight on possible system improvements.

The results reported here are preliminary, but they help define the unique characteristics of the SAUV II as it is built today. The results of this and other investigations [5] [6] [7] have allowed the establishment of an engineering database focused on the technologies to implement refinements in the SAUV II system. Work is currently underway to continue to evaluate performance through in-water experimentation and collaborative development efforts. The data collected during this experiment will continue to prove useful in evaluating the vehicle's ability to undertake long endurance operations.

ACKNOWLEDGMENT

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