A Solar Energy System for Long-Term Deployment of AUVs

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History of the Solar AUV (SAUV) Program:

Autonomous Underwater Vehicle (AUV) development began in the early 1960's and has progressed slowly towards meeting the needs of the oceanographic community ever since. Much of the AUV development was funded by DOD to meet military requirements (Wernli 1999). The AUVs developed, therefore, were not as constrained to meet the low cost requirements necessary to be commercially successful. On the other hand, many of the technological issues that need to be resolved, were.

Today, over 12 countries have AUV development capabilities or, they are buying the capability from other countries. There are currently over sixty-six AUVs either under development or in operations (Wernli 1999). Commercially built AUVs are now available and being considered as solutions to meet unique requirements.

Probably the most important technological breakthrough has been the rapid growth of computers. Today's computers provide enormous computational capability, in very small packages, with very low power demands. This has allowed AUVs to be programmed with increasing levels of autonomy. An AUV can be programmed to go from here to there, know where it is going, know when it gets there, and know what to do when it gets there. It can acquire data from onboard mission sensors and transmit that data to remote users.

Key to an AUVs ability to perform missions of importance to a user is its onboard energy system. If a mission is only of a few hours in duration, energy and power are most likely not a big issue for most situations. Battery capacity can be incorporated into the vehicle to meet energy demands. Trade-offs will always be required relative to how much of the battery capacity is needed to move the vehicle and maintain required internal systems vs. energy available for mission specific subsystems. If mission endurance exceeds the energy capacity of the onboard batteries, alternative solutions are required.

Submerged recharging stations, such as used by Woods Hole Oceanographic Institution's "ABE" vehicle system could be the solution. But, if the vehicles are transiting long distances or the mission does not always allow coming back to a recharging node, this approach will not work. Other propulsion solutions have been considered, some actually have been, or are being, used. For example, nuclear power can be considered but, while technically feasible, is politically, an unsatisfactory solution. Both aluminum-air and zinc-air semi-fuel cells have been developed and prototypes deployed. These systems have demonstrated that one can at least triple the endurance capabilities of silver-zinc batteries and have 10 times the endurance of lead-acid. Probably the biggest limitation is the cost. While these systems may be acceptable to meet military requirements, they would be cost prohibitive to meet most scientific and oceanographic missions. So, there remains a need for a long endurance, low cost vehicle that can be put to sea, transit the world's oceans, and collect data for researchers, oceanographers, and others in need to understand the world's ocean dynamics.

The AUSI staff has been involved in the development of AUVs since 1976. During that time, a number of different platforms have been designed, fabricated and evaluated in open water demonstrations. For a number of years AUSI recognized the need to develop a low cost AUV that had the capability to stay at sea for extended periods. In July of 1997, a cooperative research program began between AUSI and the Institute of Marine Technology Problems, Russian Academy of Sciences, Far Eastern Branch (IMTP) in Vladivostok. In January of 1998, AUSI and IMTP were awarded an ONR Navy International Cooperation Program (NICOP) contract to evaluate the technologies required for a Solar powered Autonomous Underwater Vehicle (SAUV). This program was to investigate a number of issues that would impact a vehicle powered by using available environmental energy. One of the products of this program was the development, fabrication and testing of a solar AUV engineering prototype. (Figure 1)

Figure 1. Solar Powered AUV (SAUV)

Project efforts where divided between IMTP and AUSI. Working together, the vehicle requirements were developed. IMTP then set out to develop the vehicle and the vehicle operating systems. AUSI took the task of determining the effect of wave action and bio-fouling on the amount of solar energy collected by the vehicle during recharging. To do this, AUSI fabricated a second vehicle, closely duplicating the IMTP vehicle, but containing the solar energy system. This energy system testbed (EST) provided AUSI with the opportunity to conduct research into the various operational issues associated with SAUVs. The EST allowed energy acquisition and utilization strategies to be developed. Acquired energy was monitored and then communicated to a remote location. The initial focus was on developing the ability to provide two way communications between the EST, wherever it may be located, and researchers developing operational strategies appropriate for local energy availability.

Solutions to other operational issues, such as sensor integration and communications between the AUV and other underwater platforms and between the AUV and surface to surface and surface to satellite to surface end points, are also being developed.

In conjunction with this program, AUSI began the development of a distributed simulation tool that would enable testing of strategies for cooperation of multiple AUVs. This capability is called the Cooperative AUV Development Concept (CADCON). CADCON was developed to provide a testbed for development of high-level communication and control for multiple AUVs. CADCON, and its role in SAUV development and testing will be discussed in detail later in this paper.

The SAUV:

It is important to remember that the SAUV is an engineering prototype and was designed to validate various investigations undertaken during the program. It is a small platform with limited energy capacity.

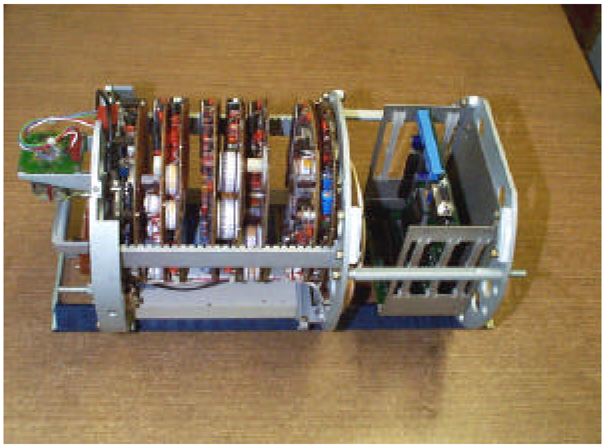

Figure 2. SAUV Electronics Card Cage

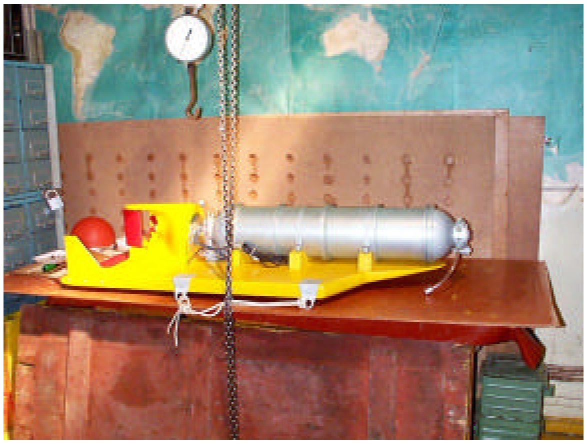

Figure 3. SAUV With Outer Cowling Removed

Figure 4. SAUV Vehicle Recovered From Sea Tests

The critical dimensions of the vehicle are:

length:	1.7 m
width:	.7 m
weight:	90 kg
pressure case diameter:	.24 m
pressure housing, inner diameter:	200 mm
cylinder length:	850 mm
electronics chassis length:	305 mm
solar panels:	2 Solarex (MSX30L) 30 watt
batteries:	32 NiCd cells
four battery (8 cells in a series) configuration.	
battery chassis length:	480 mm
has positive buoyancy of about	1 kg
depth capability: 101 MPa	1000 m

Battery issues: Battery storage capacity is determined by the amount of solar energy the solar panels can capture during daylight. In addition, an allowance must be made for cloud covered days. In this case, a factor of two was used. In other words, the battery capacity was sized to be able to store twice the amount of energy that could be captured during a single average day.

For example: The SAUV has two Solarex panels of 1/4 m2 area each with a 10% efficiency factor. This enables them to capture 200 Wh/day. The average daily solar energy m2 in the northeastern US is about 4 kWhr (Rein 1993). This will require the battery to have a 400 Wh energy capacity. To meet this need, Ni/Cad batteries (10V X 40 Ah = 400 Wh) were chosen.

Obviously, an important factor in choosing the solar panels is efficiency. Most industrially produced panels have efficiency of 10-12%, though experimental models show 20-25%.

The energy management system (EMS) will be a critical subsystem in any AUV. In this case, the EMS and the recharging system was designed and manufactured by IMTP. IMTP used two separate inverters of 90% efficiency feeding two battery modules. The EMS is then programmed to accommodate the mission scenario.

As has been discussed, one of the critical factors in selecting subsystems for vehicle operations must be the power consumption. The following are approximate power demands on the SAUV:

Control system: sleep mode	0.1 W
Operation	1.1W
Navigation system:	
magn. compass	0.3W
Roll & Pitch sensors	0.3W
Depth Sensor	0.01W
GPS (episodic)	1.5W
RF modem	wait mode - 1.1W
receive mode	1.35 W
Transmit mode	3.15 W
Rudder & flap drives	approx. 3.5 W
Main thruster motor	

V, m/s	0.4	0.5	0.6	0.7	0.8
Power, W	5.0	7.9	11.4	16.5	23.7

Ocean Data Link (ODL) SatComs : about 30W

SAUV Control System and Hardware Structure: It was considered important in designing the mission program such that it be acceptable to multiple users not familiar with this particular vehicle structure. For this reason, a generic language based approach was used. The SAUV programming language is a set of functions based on C language that includes the SAUV motion subroutines and the on-board unit and device operation subroutines. The SAUV motion subroutines define the mission profile (trajectory or path). The on-board unit and device operation subroutines are for operations of the on-board equipment and sensors during the mission execution. The SAUV mission program is prepared and tested by a network between the SAUV and an operator computer on the support ship. The final version of the mission program is loaded on-board the SAUV just prior to launching.

The structure includes an on-board PC for mission execution. The computer was chosen for extremely low consumption (about 0.5 W, Epson SCE86406-03, 486, 16 MHz, 4 MB). There are two means of communicating between the SAUV and the operator computer. One is by RF modem when the SAUV is in the water, and the other is through a direct electrical link when the vehicle is on-board the support ship.

An RS-485 universal interface on-board the SAUV allows it to utilize standard software protocol for communications between the on-board PC and other on-board devices through the serial port. The other serial port on the on-board computer is used for communication with the operator computer. Using the RS-485 universal interface provides a simple for upgrading of the SAUV hardware structure.

Sea Trials: The first sea trials were conducted May of 1999 in Peter the Great Bay (near Vladivostok). Forty-eight runs were executed during 22 working days with the objective of defining performance of the vehicle and verifying it's ability to function as a moving platform for long endurance measurements in the ocean. Also, the properties of vehicle behavior in conditions unique to the SAUV such as sea-keeping during drifting or moving on the surface were considered. The full report of the sea trials are available through the AUSI web site. The conclusions are summarized as follows:

1. The sea-keeping properties of the prototype vehicle matched predicted values well and satisfy all the initial operational requirements.

2. The acquisition of solar energy under conditions of rolling and flooding is satisfactory. The reduction of efficiency caused by incidences of the vehicle hull and panel flooding is partially compensated at the cost of their cooling.

3. The GPS navigation system functions safely at sea states up to 2-3.

A Mission Equipped SAUV: AUSI will be conducting several operations with the SAUV during the next several years. The first will be in Penobscot Bay off the coast of Rockland, Maine in July, 2000. The second will be conducting missions in Hawaiian operating areas. The plan will be to equip the SAUV with mission sensors to full specific mission scenarios.

Next Generation Vehicle: As was stated earlier in this paper, the SAUV we are operating today is a proof-of-concept prototype vehicle. It is now important to start looking at what a vehicle would look like to meet the demands of longer duration and more mission sensors. During the next year, AUSI and its partners will be evaluating just what the next vehicle characteristics should be. The mission selection will be critical to the design of this vehicle.

Multiple Cooperating AUVs: SAUVs and AUVs in general will be operated in the future as teams. Technologies being developed by AUSI and others will allow AUVs to communicate with each other, share data and other information, make decisions based on this information, and carry out coordinated mission operations.

If AUVs can communicate with each other and with systems/people ashore, the number of missions are endless. Since it may be necessary for real-time information, and, range and data rate are always a limitation for underwater communications, SAUVs could be positioned near or even over other AUVs performing a submerged mission. This would provide a “gateway” to allow short range acoustic communications to be relayed via RF or satellite to surface ship(s) or shore stations.

A number of scenarios are being developed to meet a variety of requirements. The driver will still be costs.

AUSI is working closely with other researchers in developing a “common control language” that will allow both data and command information to be transmitted to and from vehicles and users. The AUV/SAUV fleet operations concept introduces both solutions and more technical challenges. Since the AUVs are to make decisions based on the information from on-board sensors and other AUVs, strategies must be developed whereby a remote user controls only higher level functions of the fleet operations. To accomplish this complicated task, AUSI has developed the CADCON tool.

Cooperative AUV Development Concept: As an aid to investigations in the area of multiple cooperating vehicles, AUSI has developed the Cooperative AUV Development Concept (CADCON) facility. This facility employs multiple distributed vehicle simulation, a visualization system, and control harness designed to simulate a fairly accurate underwater environment, which can be shared by simulated or real vehicles connected via the Internet. The facility is available via the Internet for others to use and has been utilized by independent workers in industry and academia to support their own research. To enable broad use, CADCON has been implemented the on Pentium class computers. The software on these computers embody the client/server model and communicate via a low bandwidth application protocol over TCP/IP.

2. AUV Simulator Client: This is the Simulator component that allows users distributed around the Internet to participate in joint mission scenarios. Using this client, a user can configure a local simulation of a particular kind of submersible vehicle on his/her own workstations, login to the remote Environment Server, start at any desired position, and move a simulated vehicle through the simulated underwater environment.

3. Visualizer Client: This Simulator component was implemented in order to provide users with a real time, three dimensional, animated image of the ongoing simulation scenario. The Visualizer presents a global, multiple AUV view of the simulated environment. Thus, it is an observation tool, used only as an aid in understanding the scenario ground truth. As such, it has no means for controlling scenario participants. The Visualizer is the principal tool used by observers who wish to monitor the status of a VIP in the field.

CADCON at Work: As part of the development of the SAUV system, in November 1999, AUSI participated in the ONR AUV Demo 99 in Gulfport, Miss. For this event, AUSI used the Solar Energy Test Bed to connect the vehicle's energy system into the Internet and make the information available to users located in remote locations. We were joined in this effort by ViaSat, who provided the expertise and hardware that allowed us to connect via satellite links. In addition, to

As currently implemented, there are three major components in the CADCON facility:

1. Environment Server: This is the heart of the CADCON Simulator. Its purpose is to generate the cyberspace in which CADCON participants can operate and interact. Cyberspace in this case is usually a body of water containing a number of features that the user can program. It is the data distribution server for real data collected by field platforms.

the direct communications using RF and Satellite telemetry links, the demonstration was to establish two-way command communications between the EST and personnel in remote shore locations. Due to a number of difficulties, some of the link demonstrations occurred following the actual demonstration in Miss. None-the-less, the EST did send energy data to people ashore via the Internet and the CADCON Visualizer Client.

The EST was successfully linked via modem to a surface ship and in turn connected the EST energy management system with the Internet through a satellite. Two way communication was thus established between both the AUSI headquarters in Lee, NH and the ViaSat headquarters in Acton, Mass. More information on CADCON is available at www.ausi.org.

There are two additional CADCON Clients under development:

1. External Model Interface Client. This Client is to provide interface to external environment models.

2. Autonomous Systems Monitoring & Control Client. This Client will enable multiple vehicle control and allow users to evaluate multi-AUV behaviors and organizational protocols.

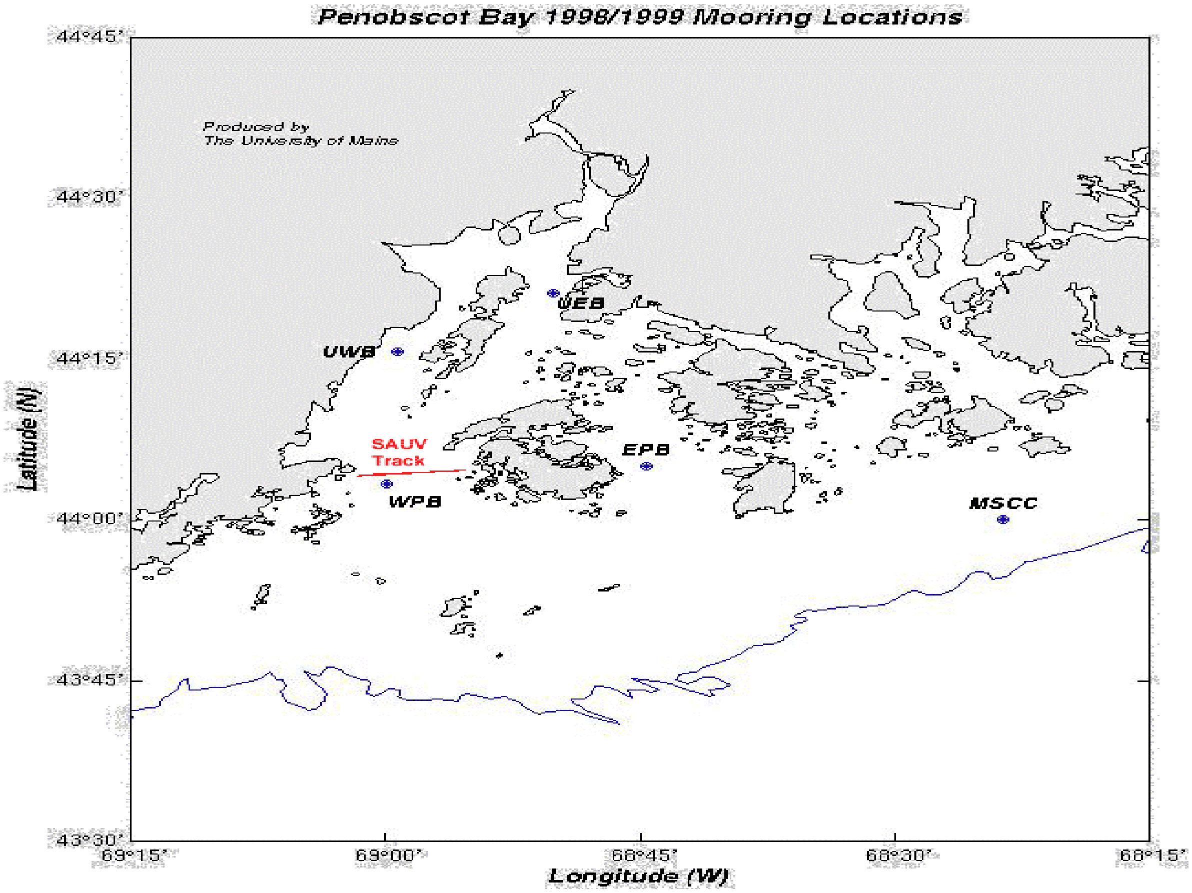

Figure 5. SAUV testing – Penobscot Bay, July 2000

AUV in Penobscot Bay: In the summer of 2000, AUSI will be working with Dr. Neal Pettigrew, an ocean researcher at the University of Maine, to collect data in an area off of Rockland, Maine using the SAUV. Figure 5 shows the area of this testing

The objectives of this effort will be:

1. To integrate the SAUV into an ongoing ocean science programs.
2. Test critical vehicle elements prior to the Hawaii operation (energy, navigation, communications).
3. Test critical CADCON elements prior to Hawaii (mission planning/control, vehicle comms, data distribution).

4. Demonstrate a one week endurance.

Summary

The SAUV program is investigating the feasibility of utilizing solar energy and proven AUV technology to provide long endurance, autonomous sampling systems. The SAUV, with its small size and simple energy system is inherently low. The SAUV equipped with the mission equipment to meet the researchers needs, is affordable and opens new dimensions in the oceanographic community's ability to understand the global ocean processes. The SAUV also provides other users the ability to "stay on station" for extended periods, to perform a variety of missions.

The technical issue that now needs to be addressed is the sensor suite. The aerospace community have been actively developing and using highly capable, small sensors that use a minimum of energy and power. They are, however, very expensive. It is critical that an effort be made to capitalize on the efforts of the aerospace industry and make these capabilities available to the underwater community at affordable prices.

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Dave Patch is the Assistant Director for Program Development at AUSI. He received his BS in Naval Science from the United States Naval Academy in 966. Before retiring from the Navy in 1986, he was the program coordinator for Advanced Navy Vehicles on the staff of the Chief of Naval Operations. In addition, he was the Chairperson for NATO's Special Working Group 6 on Advanced Naval Vehicles. After leaving the Navy, he led a number of business development efforts in industry, state government, and non-profit organizations. During the past 14 years, David has worked in the fields of advanced electronics for antisubmarine warfare and advanced propulsion systems for electric vehicles (land and undersea). David was part of the State of Maine's leadership team in developing Maine's composite materials and marine industries. In addition, he developed and led the State of Maine's National Award winning Small Business Innovation Research (SBIR) Assistance program. Working with eligible small business in Maine to capture grants and contracts in the $1 B Federal program to assist small business develop new technologies, the Maine SBIR Assistance program achieved over a 60% win rate. David joined AUSI in 1993 as a member of the founding Board of Directors. His current focus is to expand the applied research efforts at AUSI.