SOLAR-POWERED AUTONOMOUS UNDERWATER VEHICLE DEVELOPMENT

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Abstract

To meet the rapidly expanding requirements for Autonomous Underwater Vehicles (AUVs), Falmouth Scientific, Inc. (FSI) is working in cooperation with the Autonomous Undersea Systems Institute (AUSI) and Technology Systems Inc. (TSI) to develop a vehicle capable of long-term deployment and station-keeping duties. It has long been considered that AUV platforms, in-principle, could provide an effective solution for surveillance (security and anti-terrorist), environmental monitoring and data portal (to sub-sea instruments) requirements, but limitations in battery life have limited AUV usefulness in such applications. The concept of a vehicle that would allow on-station recharging of batteries, using solar cells, has been presented as a means to significantly enhance the effectiveness of AUV platforms where long-term or ongoing deployment is required.

The Solar Powered AUV (SAUV) is designed for continuous deployment (weeks to months) without requirement for recovery for service, maintenance or recharging. The SAUV under development is designed as a multi-mission platform to allow payload configuration by the end-user to optimize the SAUV for coastal/harbor monitoring, data portal (to moored sub-surface instruments) applications, or any other application where long-term deployment is required. The SAUV is designed to reside on the surface while recharging batteries and then to execute its programmed mission. While on the surface the SAUV is designed to communicate via Iridium® satellite or RF communications link to upload collected data and to allow reprogramming of mission profiles.

Development of the SAUV has generated numerous engineering challenges in design of the solar recharge system, design of a propulsion/direction control system capable of handling the unique shape requirement, design of the telemetry system, and development of mission control algorithms that include surfacing and battery recharge requirements.

This paper discusses the details of unique SAUV design requirements, specific engineering solutions for hull, panel, battery, communication, charge control, navigation, mission control, and propulsion systems.

SAUV II System Description

The SAUV II is a solar powered AUV designed for long endurance missions that require monitoring, surveillance, or station keeping, with real time bi-directional communications to shore. The vehicle can be pre-programmed to submerge to depths down to 500 meters, to transit to designated waypoints, or to operate on the surface during conditions suitable for battery charging via solar energy input.

The SAUV II system functional requirements include:

- Operate autonomously at sea for extended periods of time from weeks to months. Typical missions require operation at night and solar energy charging of batteries during daytime.
- Communicate with a remote operator on a daily basis via Satellite phone, RF radio, or acoustic telemetry.
- Recharge batteries daily using solar panels to convert solar energy to electrical energy.

- Operate at depths to 500 meters.
- Operate at speed up to about 3 knots when needed and cruise at speed of about 1 knot.
- Battery system is to provide a total capacity of about 1500 whrs.
- Acoustic altimeter capable of 100 meter altitude tracking and depth sensor to 500 meters.
- Capability to acquire GPS updates when on the ocean surface. Capability to compute SAUV position at all times using GPS when on surface and Dead Reckoning when submerged.
- Capability to maintain fixed depth and fixed altitude and to smoothly vary depth or altitude profile.
- Capability of navigating between waypoints (latitude and longitude).
- Capability to log and upload all sensor data correlated in time and SAUV geodetic position.
- Provide sufficient volume, power, interfaces, and software hooks for future payload sensors.
- Allow user to program missions easily using a Laptop PC. Allow user to checkout basic operation of SAUV system in the lab or aboard ship using the Laptop PC.
- Provide for graphical display of mission and payload sensor data on Laptop PC.

A block diagram of the system is shown in Figure 1. The vehicle sensors measure: pressure depth, acoustic altitude, speed, compass heading, pitch, roll, thruster current and various thruster actuator parameters. The main processor is a PC104 that communicates with and controls the various subsystems including the Energy Management Subsystem (EMS), the Navigation subsystem (NAV), the Propulsion and Motion Control Subsystems (PMC), and the Communication systems (COMMS) which include the FreeWave radio, the Iridium satellite phone and the acoustic modem. These will be discussed below.

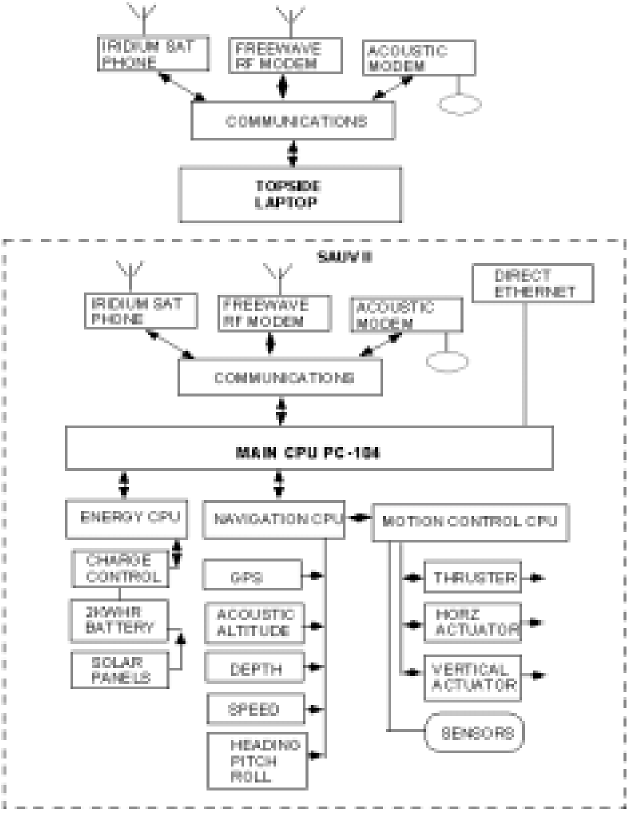

Figure 1. SAUV II Block Diagram

Solid models of the vehicle’s major mechanical structures are shown in Figure 2. The wing section is a fiberglass shell filled with syntactic foam capable of 500 meter depths. The pressure tube is 8 inch ID and 46 inches long and houses the batteries and all dry electronics. The vectored thruster section attaches to the wing and includes the thrusters motor as well as the vertical and horizontal actuators. The fuselage is a flooded fiberglass shell that covers the pressure tube and also provides space for wet components such as acoustic altimeter, speed sensor, and depth sensor and payload sections.

Figure 2. Solid Models of Major Structures

Two BP 585 solar panels are mounted atop the wing section. These are each 85 watt high-efficiency monocrystalline photovoltaic modules with the following specifications:

BP585 Solar Panel Specifications

Maximum power (Pmax): 85W
Voltage at Pmax (Vmp): 18.0V
Current at Pmax (lmp): 4.72A
Warranted minimum Pmax: 80.8
Short-circuit current (Isc): 5.0A
Open-circuit voltage (Voc): 22.1V
Panel weight: 13.4 pounds

The Current-voltage (I-V) curves for the solar panels is shown in Figure 3.

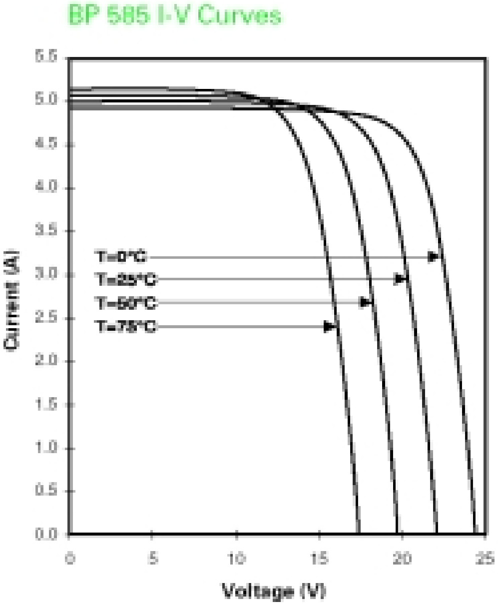

Figure 3. I - V Curve for BP 585 Solar Panels

The overall SAUV II System Specifications are :

Total Vehicle: Length = 78" Width = 47”
Pressure tube: Length = 46” ID = 8” OD = 9”
Weight in air: 370 lbs
Buoyancy (net) = 2 lbs
Max operating depth = 500 meters
Speed: 0.75 to 3 knots
Endurance: week to months
Energy source: Li-Ion battery (2kWh) with Solar Panel charging at sea and Gas Gauge monitoring of battery system.
Communications:
  Iridium Satellite phone
  FreeWave radio modem
  Acoustic modem
Navigation: GPS with Dead Reckoning
Thruster: Vectored thruster

AUV sensors:
- Pressure Depth
- Acoustic Altitude
- Speed sensor
- Compass
- Pitch
- Roll
- thruster parameters

Payloads: TBD

Figures 4, 5, and 6 are photographs of the SAUV II at Buzzards Bay, Massachusetts during initial in water testing of vehicle systems.

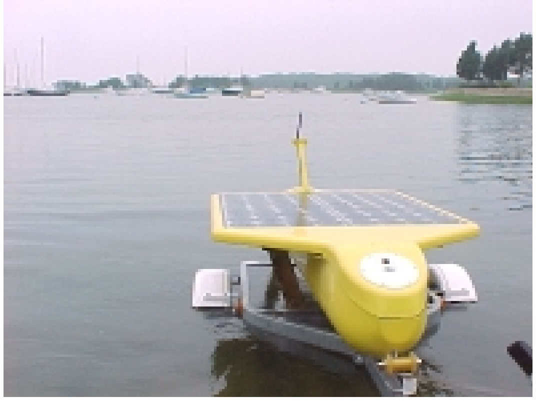

Figure 4. SAUV II on Trailer

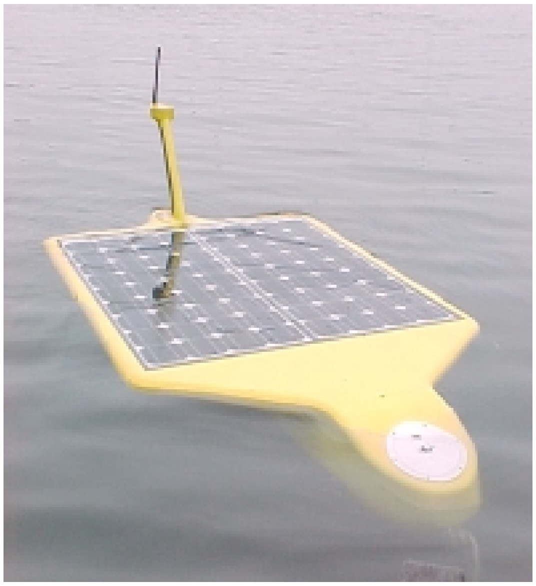

Figure 5. SAUV II Initial Trim & Balance Check

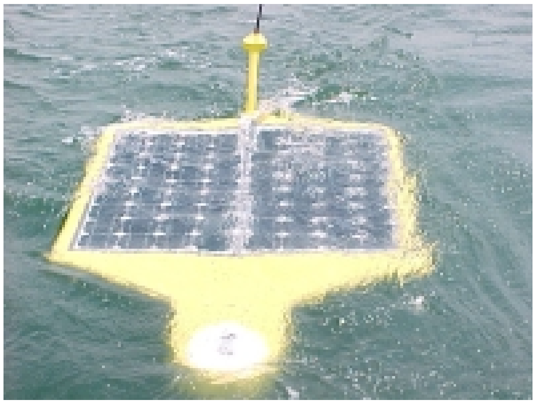

Figure 6. SAUV II Enroute to Test Area

Vectored Thruster Description

A vectored thruster design was selected over a fin and thruster design for (1) better motion control when the vehicle is on the surface, (2) smoother transition from surface to underwater operation and (3) simplify the system.

The technical features of the vectored thrusters include:
- 12 bit absolute position sensors for angle feedback
- High efficiency stainless steel ball screw actuators
- Propeller shroud for safety and to deflect debris from propeller
- High aspect ratio adjustable pitch propeller blades
- High efficiency brushless dc thruster motor
- +-20degree actuation capability
- Single underwater cable to thruster

The vectored thruster implemented on the SAUV II has the following components:
- Thruster motor
- Body with linkages
- Actuators
- Control electronics
- Control software

The thruster motor is a brushless frameless dc motor with high energy rare-earth magnets. The winding is pressed into an aluminum motor case. The motor case has the propeller shroud welded to it. Inside the aluminum motor case is a sensorless brushless motor driver circuit with the FETs for driving the three phases for the motor. The aluminum motor case is filled with a low viscosity dielectric oil and is pressure compensated. Several propellers were analyzed and tested. The selected propeller is a custom two bladed adjustable pitch propeller designed with using blade element methods. Peak propeller efficiency is estimated at 84% and peak motor/driver efficiency is estimated at 76% with a resulting peak system efficiency of 64%.

Figure 7. SAUV II Vectored Thruster w/3 Bladed Propeller

The thruster body holds the thruster motor and has three pivots for connecting to the two actuators and the vehicle structure (Figure 7.). The pivots for the actuators are custom and hold the stainless steel ball screw nuts. Though ball screws require additional maintenance, they offer about 50% higher efficiency over acme thread lead screws.

The ball screws are driven with custom actuators with DC gearhead servo motors and position feedback sensors. The actuator system efficiency can be estimated from the ball screw efficiency of 80%, the gear motor efficiency of 69% and the driver electronics of 95% resulting in a system efficiency of 52%.

The control electronics have circuits for monitoring the thruster current, driving the servo motors and providing the intelligence for the low level control. There is an RS232 communication port for passing control information to the navigator.

The control software is written in C and implements PID control loops. The pitch controller is cascaded with the depth controller. The control loop runs at approximately 20Hz. The controller operates in several modes. There are a series of modes that allow testing of the mechanical systems and the software controllers. There are also modes that allow the navigator to send/request controller information. At startup, the navigator sends a coefficients file for the controllers. The navigator then sends a series of commands including the desired heading, depth, pitch, altitude, speed and thrust along with the actual pitch, heading, altitude and depth of the vehicle. The low level controller then executes the commands by controlling the vectored thruster.

Drag analysis of the SAUV

The drag for the vehicle was calculated primarily using the 1965 classic *Fluid-Dynamic Drag* by Hoerner. The example chosen is a wing with a nacelle suspended below.

Total drag = pressure or form drag + skin friction drag + interference drag

The components of drag are shown in a bar graph below (Figure 8) for comparison at a normalized speed of 1m/s. It quickly becomes evident that the largest contribution of drag, the wing and specifically the trailing edge of the wing, may also be the easiest to reduce. By tapering the bottom surface of the wing at a ratio of about 8:1 up to the top surface, the drag can be substantially reduced. The second largest contribution in the calculation is the body drag. This has several interdependent components including the hull taper, the interference drag with the wing, the blunt end below the wing, the blunt lip around the thruster and the parallel midbody. Improvements can be made on the current design by fairing the trailing edge around and above the thruster.

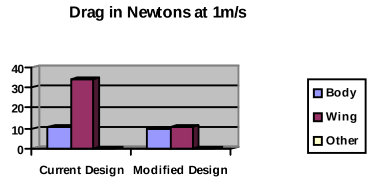

Figure 8. Components of Drag - SAUV II

An obvious way to reduce drag is by reducing the frontal area. The drag is proportional to frontal area so a reduction of the diameter of 10% yields a reduction of drag of 19%. For the best possible performance, a shape from the

Gertler series can be used for the main body with a well-faired strut holding the body at ½ the body diameter away from the wing. This will result in a drag coefficient of less than 0.13 for the entire vehicle.

A comparison of these results with the field tests described in the report *Results of sea tests of the prototype of solar powered vehicle (SAUV) conducted in 1998* by M.D. Ageev shows good agreement. Though Ageev expected an overall Cd of about 0.05, he measured an actual coefficient of 0.15 to 0.17. With the recommended modifications, the SAUV at FSI will approach this value with this analysis predicting a Cd of 0.17.

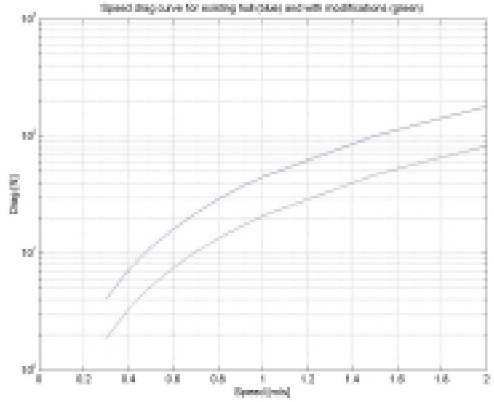

Figure 9. Drag vs Speed Calculations

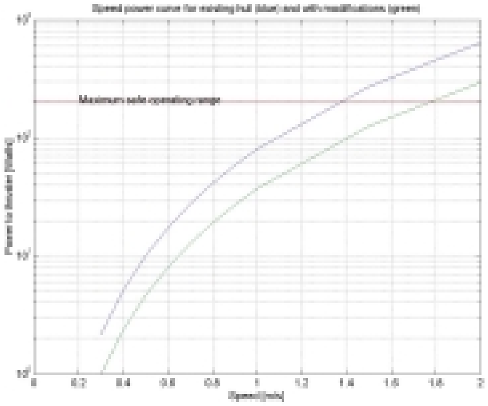

Figure 10. Thruster Power vs Speed Calculations

Propeller Design: The thruster/propeller combination was designed for a vehicle with a speed/drag curve close to that experienced by Ageev and with a goal of a top speed around 3 knots (Refer to Figure 9.). The motor system is actually capable of much greater torque with a correspondingly greater current draw only limited by the current carrying capacity of the wires and connectors. Using the existing propeller and existing hull form, the required thrust to maintain 2.5 knots is achievable (See Figure 10). With the proposed modifications to the wing and body, 3 knots is easily attained using the existing thruster/propeller combination A propeller analysis using the blade element method was used to investigate a variety of propeller types. The propellers supplied can achieve an efficiency of over 81%. A propeller design that achieved an efficiency of over 93% was also investigated. This design has the same blade length but uses only 2 blades with a width of 0.4" and a twist of 10 degrees. One of the existing propellers has 3 blades with a width of 0.9" and 0.7" and a twist of 15 and 20 degrees. Though higher efficiencies can be obtained with a two bladed hub, propeller/eddy interaction will increase vibrations. Alternatively, a three blade configuration with 0.3" wide blades will also achieve about 93% efficiency but the blades will be so narrow as to be difficult to machine. The model airplane blades used currently are simply not available in this width and if they were would be too weak. The optimized blades shown in the table below with a tip angle of 20degrees will be operating near stall and will be sensitive to any changes in the operating conditions such as an added sensor increasing drag marginally… etc.

In conclusion, the existing 3-blade configuration will have good efficiency at 81% to 84% while keeping propeller loading acceptable and vibrations minimal. Actual achieved efficiency will always be a little lower due to irregularities in the flow into the propeller and losses due to the propeller/shroud interaction not taken into account in blade element analysis. Sea trials will help to verify these results. The propellers constructed are adjustable in pitch. This allows tuning to accommodate changes in the vehicle configuration. Each blade is adjusted individually and so care must be taken to keep the angles the same. The blades are fixed with a setscrew. The angle is set at the tip. Reference angles are given in the table below.

Results are summarized for the modified hull form with a speed of 1.5 m/s and a motor rpm of 1000.

TABLE 1. Propeller Design Summary

Blade width	Number blades	Tip angle	Efficiency
0.9	3	5	81%
0.9	2	8	83%
0.7	3	5	84%
0.7	2	8	88%
0.3	3	20	93%
0.4	**2**	**20**	**93%**

Energy Management System Description

A diagram of the energy system is shown in Figure 11. There are two Li-Ion battery packs, connected in parallel as a single battery, each having 1056 Whr capacity resulting in a total capacity of 2.1 kWhrs. Included in the battery system is battery management, safety circuitry, charge equalization, charger and solar panel interface, and provision for gas gauge monitoring of battery capacity. The Open Circuit Voltage is 16.8 volts when fully charged. The Nominal Operating Voltage is 14.7 volts. Note that the available energy (Whr) is calculated using this nominal voltage. The Battery Cut-off voltage is 10 volts.

The estimated weight (total battery system, including charging circuitry) is 31 pounds. The estimated self discharge rate is -6% for the first month, -4% for the second month and approximately -2% per month thereafter.

Two solar panels (BP585) are connected in parallel with each rated at 85 watts. The direct battery output is routed to the thruster controller, and other system voltages (5, 12, & 24) are provided by DC/DC converters that are not shown in the figure.

The energy management microprocessor interfaces with the battery system. The input labelled as Charger is essentially the external battery charger to be used for charging batteries in the lab or when charging is required on deck.

The interface signals are for switching battery charge and discharge control, gas gauge communications and fault monitoring.

The battery has a gas gauge (BQ2050SN) connected to it that essentially provides many battery state variables including battery charge state. Communication with the gas gauge is via a single wire (with ground) from the DQ pin. Timing of this communication interface and register explanations are shown in the BQ2050SN data sheets.

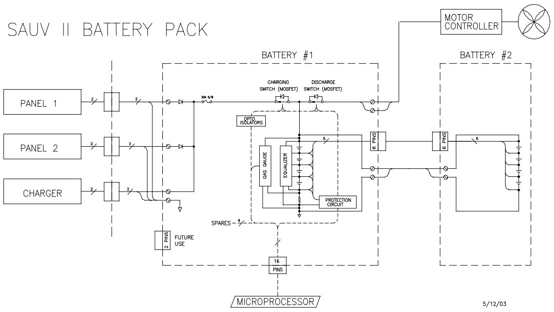

Figure 11. Li-Ion Battery Pack Diagram

Battery Physical Layout: The battery cell and PC Board configuration and location are shown in Figure 12. The component area is outboard of the battery cells and below the top plate of the battery chassis.

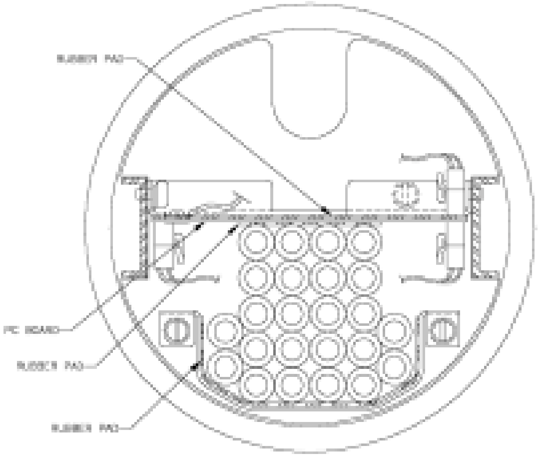

Figure 12. Li-Ion Battery Physical Layout

The first battery (Battery #1) was tested on May 29th starting about 9:21 AM. A plot of the energy acquired in mWh is plotted versus time in Figure 13. The battery was connected to 2 BP585 Solar Panels manufactured by BP Solar Inc. The weather was bright and sunny with no clouds. Temperature was about 85 degrees. Battery #1 had been completely discharged the night before.

The figure shows continuous charging during the period of test time. The vertical jumps in the data are due to the software program occasionally hanging up while the batteries continued to charge though the data was not logged during these periods. (This problem was subsequently corrected). The data shows that the battery acquired about 134 wHrs of energy during a 1.5 hour period starting about 9:20 AM to about 10:50 AM. The constant slope of the data indicates that there were essentially no clouds in the vicinity during the tests.

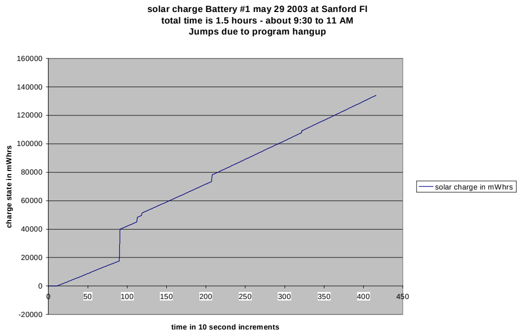

Figure 13. Charge Accumulation - Battery #1

The second battery was tested under similar conditions as the first battery on the following day (May 30). The principle difference is that the tests started about an hour earlier (8:20 TO 10:00) in the morning hence the solar angle of incidence was lower than during the first battery test, and there were clouds in and out of the sun during this period. This battery was about 40% full when charging began.

Referring to Figure 14, the initial slope of the charge curve (time is 0 to ~275) is increasing indicating an increasing charge rate as the sun gets higher in the sky. This is more noticeable when looking at the data itself. Another interesting point is that cloud effects are noticeable and detectable during the time period from about 390 to 480 (x axis). During this period clouds are detected by watching the charge slope decrease then subsequently increase as the clouds move away. The data shows this battery acquired about 95wHrs during the 1.5 hour period. Again the jumps in the data are due to program hang-ups.

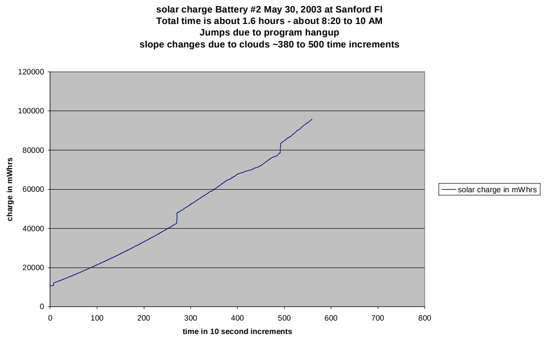

Figure 14. Charge Accumulation - Battery #2

BQ 2050SN Li-Ion Gas Gauge

The gas gauge used in this system is a BQ2050SN from Texas Instruments, Inc (TI). It is permanently attached to the battery and continuously measures the amount of charge (coulombs in and out) in a battery. The microprocessor only has to periodically determine the state of the battery by accessing registers in the BQ2050SN through a communication port. Once the microprocessor acquires the information from the registers, it can make intelligent decisions about how it should conduct missions and manage the energy budget. There are a dozen or so registers in the BQ2050 that provide both data and flags related to the battery state. Most are read by the microprocessor presently at a rate of once every 10 seconds.

The total amount of energy available at any given point can be determined by reading the battery's maximum capacity (maximum current that can be stored in mAhrs) which is acquired by accessing the Last Measured Discharge (LMD) register. The battery's current capacity (amount of energy currently available) is found by accessing the Nominal Available Charge (NAC) Register. Using these two variables, the battery's "true capacity" can be found.

The Scaled Available Energy Registers (SAEH/SAEL) are used to compute energy in mWhrs. There are 2 equations used to compute this value depending on whether the system is charging or discharging. Another means of estimating energy availability is to use the Compensated Available Capacity (CAC) and the battery total capacity (LMD) to simply compute battery capacity as a percentage of full capacity. This is very useful in the EMS algorithm. The

LMD register also will automatically decrement over time as battery degrades.

SAUV II Navigation System

The purpose of the SAUV Navigation System is to navigate the vehicle from one location to another without the assistance of the mission manager. The Navigation System is a self-contained navigator that drives the vehicle from one mission segment to the next. To drive the vehicle, the Navigation System provides real-time data to the propulsion system to control the dynamics of the vehicle.

The main processor on the Navigation System is the Persistor CF2. The CF2 uses a Motorola 32 bit processor, 1M byte of program space, 512K RAM and Compact Flash for data storage. The Persistor provides an operating system known as PicoDOS. This provides the Navigation System with file IO and other standard features offered by the operating system. The Compact Flash cards can record up to 1 Giga Byte of data.

A daughter card supports the CF2 and provides the interface to the RS-232 ports and other sensor inputs. The Navigation System acquires data from several sensors. Most sensors use RS-232 to transfer data to the CF2. Position data from Thales A12 GPS Receiver; heading, pitch and roll from a TCM2 compass; Altitude from the Benthos PSA916; Depth from the FSI Excell OPM and speed from the RH Manufacturing. The speed sensor provides a frequency output that is measured by the CF2.

The Navigation System supports several waypoints or legs. There are three ways to set the waypoint heading: GPS coordinates, North & East meters or commanded heading. These waypoints are commanded in one of four ways: commanded heading, pitch, altitude, speed and depth. The Mission Manager interprets mission plans and the Navigation System executes each segment until the mission is complete.

Solar AUV High Level Software System

The SAUV high level system is a three board PC-104 stack. The CPU board is a Tri-M Systems MZ104+, which provides a 100MHz ZFx86 CPU, 32Mbyte RAM, a 48 Mbyte Disk on Chip (DoC), two ethernet ports, plus the standard interfaces (keyboard, mouse, 2 serial ports, 2 USB ports, etc). Through Tri-M, we have added a Connect Tech Xtreme/104 8 port RS-232 board for communication with the various SAUV subsystems. At the top of the stack is a Tri-M Utility board which provides for standard interface connectors, as well as the battery for the real time clock.

The operating system for our MZ104+ is a Slackware 8.1 derived image called LinuxMZ and supplied by Tri-M. Most of the changes made by Tri-M for this derivation are in the realm of stripping out unneeded items from the standard Slackware distribution. We requested that our image contain Samba, Apache, Secure shell, networking, and FTP. This has resulted in a Linux footprint to about 27 Mbytes, which lives comfortably on the 48 Mbyte DoC.

In laboratory bound development mode, the MZ104+ platform is connected via Cat5 cable to the laboratory LAN. The Samba package allows the platform’s working directory to be mounted by Linux and Windows development systems. The SAUV software is built and initially tested on a Linux development system. Once ready, a “tarball” of the components is made and then copied over the network to the MZ104+ via the Samba mount. On the SAUV, the package is unbundled and the components exercised via a number of remote login windows. In the field, with no hard Ethernet link, the same procedure is accomplished over a PPP link through the Free Wave modems, although at a reduced bandwidth.

The SAUV high level software (diagrammed in Figure 15) is comprised of the following processes:

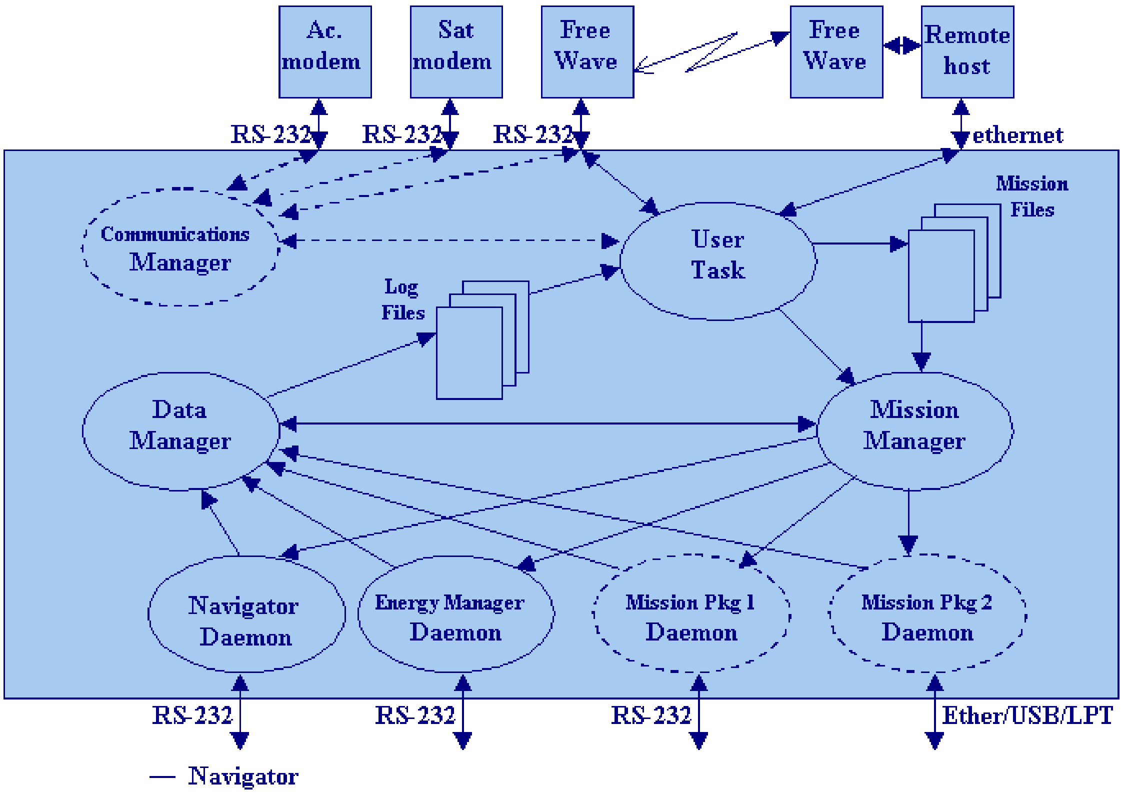

Figure 15. SAUV II High Level Software Architecture

Navigator Daemon: This process collects serial frames coming from the Navigator subsystem, tests for errors, packages them up into internal Navigator data packets and sends them on to the Data Manager.

Energy Manager Daemon: This process collects serial frames coming from the Energy Manager subsystem, tests for errors, packages them up into internal Energy Manager data packets and sends them on to the Data Manager.

Data Manager: This process collects data packets from the various data collection daemons in the system. Copies of that data are logged to the Linux file system as well as sent on to the Mission Manager. The log files are FTP'ed back for post mission analysis.

Mission Manager: This process is the vehicle commander. While underway, its primary job is to receive data packets from the Data Manager process and react to them. Those reactions are to issue appropriate commands to the various subsystems. Missions are expressed as sequences of Common Control Language (CCL) [Komerska et. al. 1999] statements in mission files, which are generated by the Mission Planning Software resident on the Topside Laptop PC. Once such a file is generated, it is FTP'ed to the SAUV. In order to run a mission, the Mission Manager must first compile those CCL statements into a set of lower level commands (LLCs) specific to the SAUV's various subsystems. With that completed, it then runs an interpreter to step through the LLC set issuing them to the Navigator and Energy Manager subsystems in order to execute the mission.

User Task: This process provides the user with a presence onboard the vehicle. It is accessed by remotely logging into the SAUV via secure shell. That access is currently done via the Ethernet connection, or with a PPP link running over the FreeWave modems. Once User is running, it presents a suite of commands to the user for running and stopping missions, as well as testing various SAUV subsystems.

Communications Manager: This process is not fully developed as yet. This state is indicated with the dashed lines. When in place, it will take over some of the work now being done by the User task and it will make decisions as to which of the communications links should be used in any particular situation. In anticipation of that, we have been working with numerous heuristics concerning the various links such as:

- Link on which an originating communication arrived
- Presumed distance to intended receiver
- Amount of data to be sent
- Sender and receiver submerged or not

Mission Pkg 1 and 2 Daemons: As with the Communications Manager, these processes are not fully developed. They will, however, be modeled on the Navigator/Energy Manager Daemons, which currently share skeletal code. The diagram indicates the addition of another RS-232 daemon (Mission Pkg 1) and a USB based daemon (Mission Pkg 2). This demonstrates how mission packages will be added to the system. This scheme should work for low to medium bandwidth packages. Those that generate enormous amounts of data may require special treatment when interfacing.

SAUV Topside PC Description

The topside pc portion of the SAUV project, provides the end user Graphical User Interface (GUI) that is used to Plan Missions, Modify Missions, Upload Missions to the SAUV, and Monitor SAUV activity during SAUV operations.

During the Mission planning phase, a user has the ability to generate custom waypoints, or choose from a list of pre-defined missions.

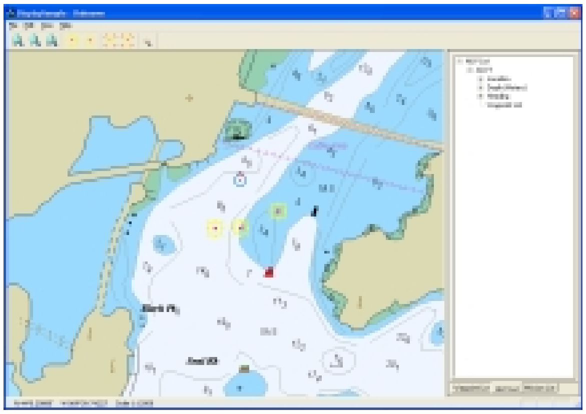

Figure 16. Example GUI in Mission Planner

Using custom waypoints, the user points to a location on the map, presses the left mouse button, and a waypoint is generated. The user continues “plotting” waypoints until they are confident that enough waypoints have been defined to “build” a mission.

The user then generates a mission by selecting mission wizard, selecting custom mission, and then choosing the waypoints they want within that mission, making sure to order the waypoints in the desired path.

There are 6 mission types defined at this time. They are:

Custom – Allows user to generate mission based on waypoints entered by user.

Spoke - A basic 4 leg routes that radiate from a central point leg lengths defined by user

Rectangle – A 4 sided rectangle with leg lengths defined by user.

Watch Area – Generates a mission where the SAUV would sit at a location for some amount of time. User specifies location, and area around to stay within.

Point and Go – A mission where the user defines a direction and a distance for the AUV to maneuver.

Once the mission has been generated, the user can then export the mission to an AUV Mission File, which can be downloaded to the SAUV. Once the file has been downloaded to the SAUV, at this time, the user runs a utility which logs him into the SAUV. The user can then command the

SAUV to run a mission, or check out the SAUV subsystems.

Once the SAUV is running a mission, or active in the water, the software receives updated information through the serial ports. Either by Iridium Satellite phone, Freewave radio, or Acoustic Modem. These updates are shown on the map in real-time and show AUV position, orientation, and status information.

Acknowledgement

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References

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