

A SOLAR-POWERED AUTONOMOUS UNDERWATER VEHICLE

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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. A bi-directional acoustic link provides for data acquisition from sub-sea instrumentation.

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 some of the more pertinent details unique to the solar AUV design requirements.

I. 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, and to underwater instrumentation. 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 speeds up to about 3 knots.
- Battery system provides 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 end user 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.

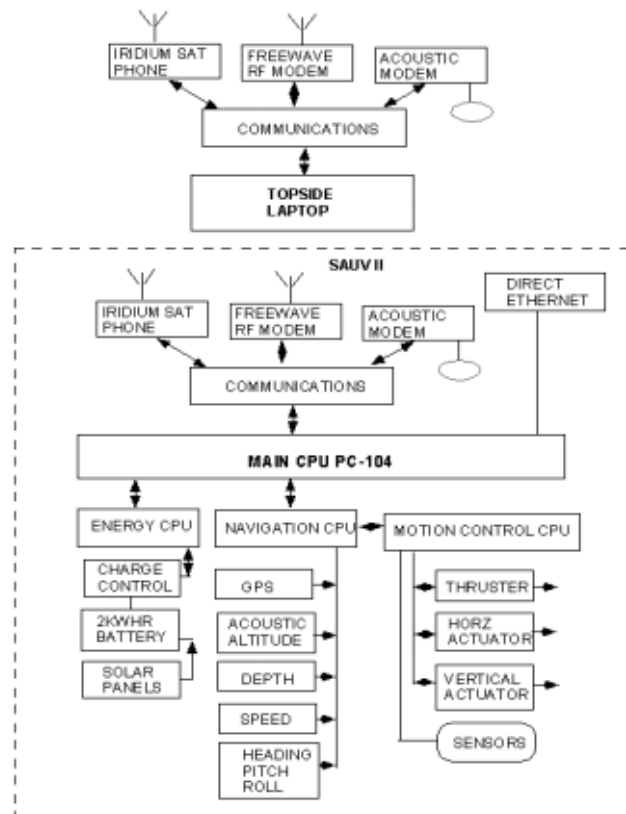


Fig 1 SAUV II Block Diagram

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 thruster 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, the depth sensor and payload sections.



Fig 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 (P_{max}): 85W
 Voltage at P_{max} (V_{mp}): 18.0V
 Current at P_{max} (I_{mp}): 4.72A
 Warranted minimum P_{max} : 80.8
 Short-circuit current (I_{sc}): 5.0A
 Open-circuit voltage (V_{oc}): 22.1V
 Panel weight: 13.4 pounds

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

BP 585 I-V Curves

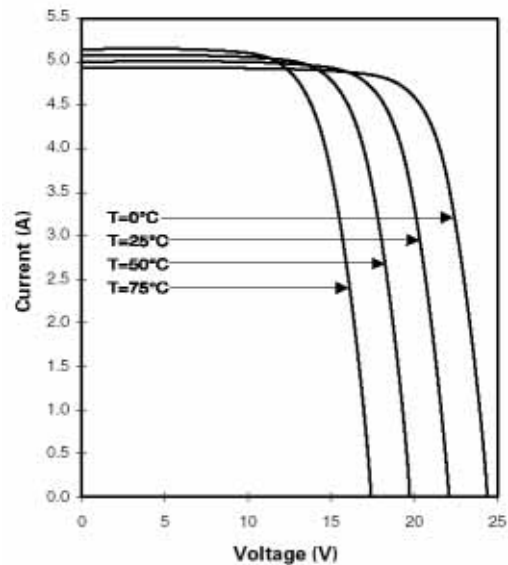


Fig 3 I - V Curve for BP 585 Solar Panels

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: up to 3 knots
 Endurance: weeks 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: User Specified

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



Fig 4 SAUV II on Trailer



Fig 5 SAUV II Initial Trim & Balance Check

II. 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) simplification of the system.

The technical features of the vectored thruster includes:

- 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
- $\pm 20^\circ$ degree 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. Peak propeller efficiency is estimated at 84% and peak motor/driver efficiency is estimated at 76% with a resulting peak system efficiency of 64%.



Fig 6. 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 6.). 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.

IV. Energy Management System Description

A diagram of the energy system is shown in Figure 7. 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 are 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.

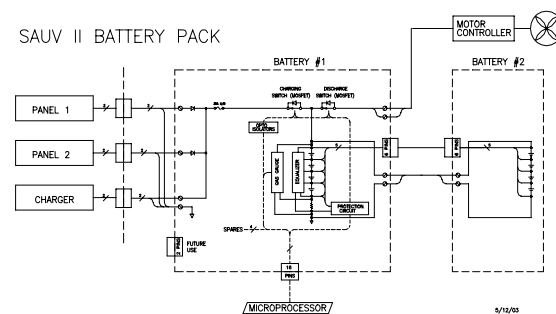


Figure 7 Li-Ion Battery Pack Diagram

Battery Physical Layout: The battery cell and PC Board configuration and location are shown in Figure 8. The component area is outboard of the battery cells and below the top plate of the battery chassis.

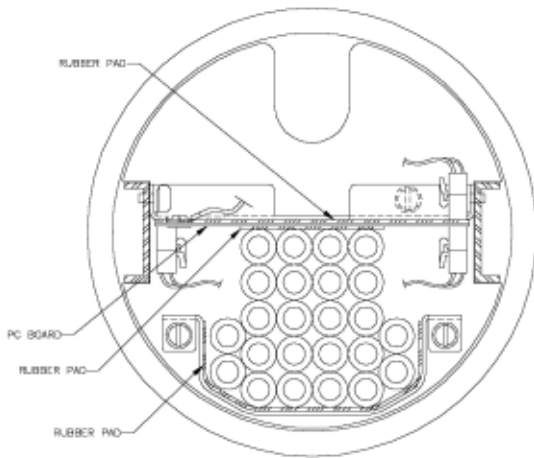


Fig 8. Li-Ion Battery Physical Layout

V. 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 mAh_{rs}) 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) is used to compute energy in mWh_{rs}. 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.

VI. 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 an RH Manufacturing sensor. 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.

VII. 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 ZF86 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 9) is comprised of the following processes:

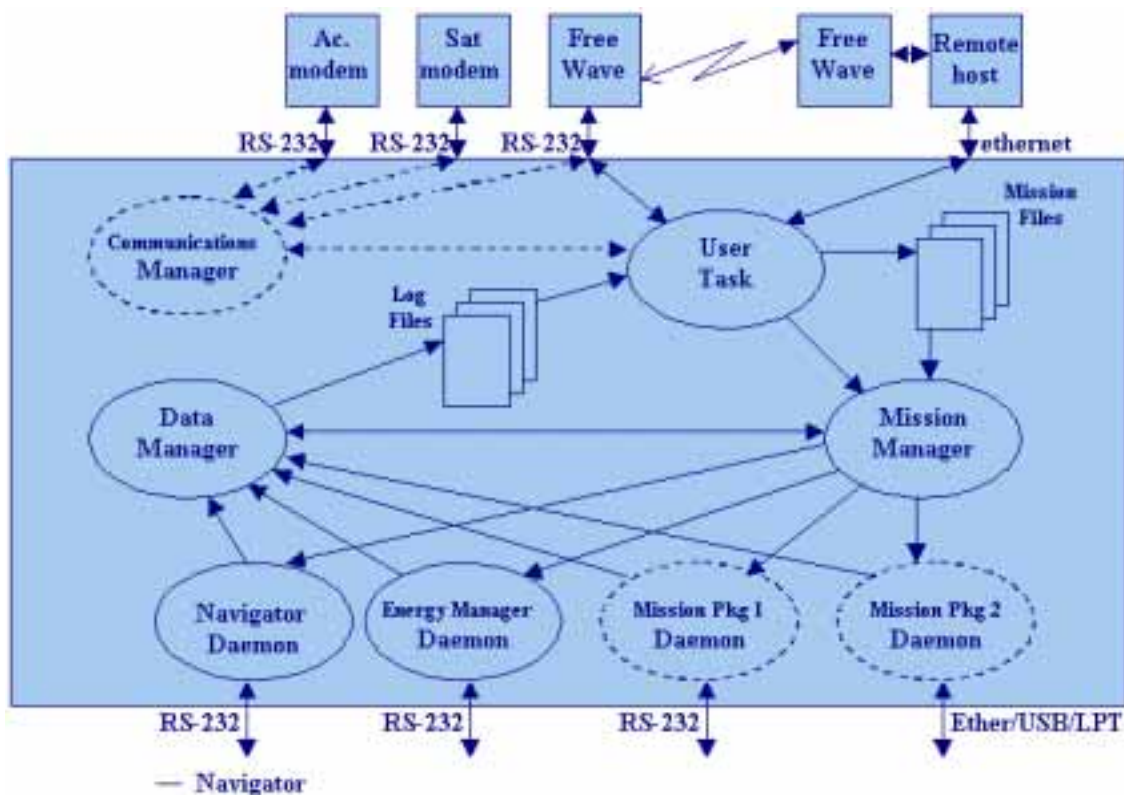
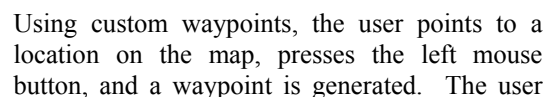


Fig 9. SAUV II High Level Software Architecture

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

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.

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



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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