An Automated Naval Oceanographic Monitoring System

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Abstract **- An automated prototype oceanographic monitoring system has been developed for extended operational use aboard U.S. Navy submarines. The system, consisting of a mix of commercial off-the-shelf data processing electronics and tailored oceanographic sensors, augments previously time-consuming manual monitoring procedures. Results show that the system can automatically indicate incipient changes in water mass conditions associated with ocean fronts, improves the quality of environmental input to the ship's operational decisions, and offers new opportunities to collect oceanographic information in data-poor areas of the world.**

I. INTRODUCTION

Scientific vessels deploy various underway *in-situ* measurement devices to obtain data for rapid characterization of a local oceanographic area prior to detailed measurements. Such conventional, scientific-oriented measurement techniques are impractical for most naval vessels. Consequently, naval submarines and surface ships rely primarily on shore-based forecasts, coupled with historical data bases and local data (primarily obtained from expendable sensor probes) to determine the expected local environmental conditions. As the significance of mid-ocean and coastal water-mass variability has become more apparent [1,2,3], ship's personnel have augmented intermittent depth-profile measurements with manual monitoring of sea water injection temperatures or sound speed (if available from sound velocimeters). Unfortunately, manually generated plots are time-consuming to produce, difficult to interpret, and error-prone. To address these problems, the U.S. Oceanographer of the Navy, in consultation with the naval submarine community, initiated in 1989 the development of a prototype, automated *in situ* submarine tactical oceanographic monitoring system (TOMS). The key issues were:

- Could an automated oceanographic monitoring system be developed for routine use by naval submarines.
- Could oceanographic sensors be used in harsh operational environments for extended periods of time, with minimal upkeep, yet provide reliable data?
- How might a system be designed to accommodate easily a variety of prototype sensor configurations, without requiring repeated redesign of the system components?

A prototype TOMS was installed aboard a U.S. submarine for testing in March 1990 and remained on the test platform for four years where it was evaluated in various operational conditions. In this article, we examine the technical characteristics of this TOMS prototype and discuss the monitoring capabilities demonstrated in the initial system trials.

II. TOMS SYSTEM DESCRIPTION

The TOMS architecture has four principal subsystems as illustrated in Fig. 1: a suite of oceanographic sensors installed in an expandable, external sensor bus; a commercial computer for data processing and archiving; an interface manager that networks the processor to various existing ship auxiliary sensors and systems; and a graphics user interface that serves both for system observation and control.

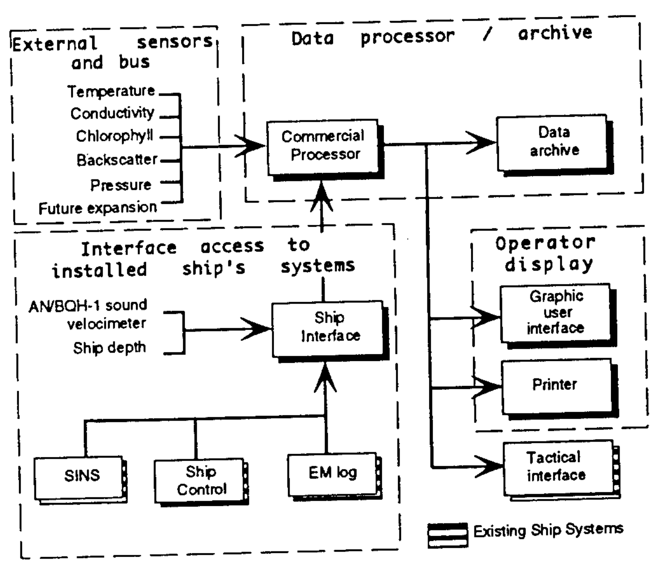

Fig. 1. TOMS system architecture.

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Components that might comprise a single point of failure are replicated. These replicated components also serve as repair parts should a failure occur at sea. Dual sensor sets also facilitate monitoring the calibration health of the sensors.

A. The External Sensor Bus

The external sensor bus is an expandable sequence of full-duplex local sensor networks, each managed by a data acquisition node (DAN). The bus uses the RS-485 communications standard to support multi-nodal serial communications over greater distances than the 15 m RS-232C standard. Data rates are generally low enough to allow the serial bus to operate asynchronously at the bit communications level at 38.4K baud, simplifying both the hardware and software interfaces. The RS-485 standard accommodates up to 32 nodes on the network, each capable of hosting up to four sensors. This design facilitates the rapid prototyping of future sensors, and allows for future expansion of the system to support additional requirements with minimal re-engineering.

A data bus interface (DBI) acts as the "bus master" and is the only transmitter allowed on the command path. The DBI transmits synchronous commands in a broadcast fashion that direct each node to acquire and buffer data. Then, once a second, without interfering with the consistency of new sample commands, it sequentially requests each node to dump its 1 s buffer. The DAN nodes transmit responses to received commands onto the return data bus for reception internally at one or more data-processing stations. No unsolicited communications are allowed on the return data path. The result is a consistent concurrent sampling over all DAN node sensors and a high utilization communications bandwidth of the return data path with minimal transmission overhead. This scheme allows for a simpler network design with no need for complicated collision avoidance hardware or software algorithms.

The DBI supports other types of commands for general system operation, such as a request for calibration coefficients for converting raw binary data to the engineering units for each specific sensor suite of the DAN node. This flexible architecture greatly simplifies field maintenance procedures as various types of sensors are swapped out for maintenance or evaluation.

B. Sensors

The TOMS oceanographic sensors are located high in the submarine sail (also known as the submarine's fin) in a specially fabricated sea water access port, where they have access to water flow less contaminated by hull boundary layer turbulence. The standard sensor suite includes temperature, sea water conductivity, chlorophyll, optical backscatter, and precision pressure. Sensor analog-to-digital signals are processed external to the submarine's pressure hull. This minimizes electrical connections through the hull and significantly reduces external electrical noise sources that might contaminate the low-level analog sensor signals.

1) Temperature: Temperature is measured by two, commercially available thermistors: a fast-response glass bead thermistor with a 20 ms thermal time constant, and a metal-cased glass bead thermistor with a response time of 120 ms. The fast-response sensor resolves small-scale sea water temperature variations, while the slower one provides data for bulk property calculations, such as sea water density and sound speed. The thermistor outputs are pre-emphasized at high frequencies prior to digitization to improve signal-to-noise levels at high sampling frequencies [4]. After digitization and de-emphasizing, the sensitivity of the fast-response temperature sensor is 2.8×10^{-6} °C/Hz$^{1/2}$ in a 6-Hz bandwidth. The metal bead thermistor outputs data at 1 Hz.

2) Sea water Conductivity: Sea water conductivity is a direct measure of oceanographic water-mass properties that affect various submarine operations (e.g., ballasting and tactical sensor performance prediction). Since the system was expected to operate unattended for extended periods of time, we elected to use a non-fouling, four-electrode, planar contact cell design developed for oceanographic towed instrumentation chains [5]. The sensor design represents a trade-off between sensitivity and calibration stability. The long-term stability of the redesigned sensor is 0.005 siemens (S)/m and the sensitivity is 3×10^{-10} (S/m)/Hz$^{1/2}$ in a bandwidth of 6 Hz.

3) Chlorophyll: The chlorophyll sensor is a miniaturized fluorometer [6]. The fluorometer generates a bright, high-voltage halogen light beam at 430 nm (the absorption wavelength band of chlorophyll-a) which traverses a fixed-length water path. A red-extended gallium arsenide-phosphide photodetector captures light transmitted at 670 nm (the emission wavelength of chlorophyll molecules) and outputs a signal proportional to the level of chlorophyll in the water. The fluorometer incorporates a self-calibrating circuit that compensates for variations in the halogen light bulb output. The sensor light paths are shielded so that the transmitted light is not visible to an outside observer. The fluorometer signal-to-noise ratio levels (sensitivities) are comparable to laboratory chlorophyll fluorometer instruments.

4) Optical Backscatter: The optical backscatter of sea water (which is related to water turbidity and transparency), is difficult to measure *in-situ* . The optical geometry of the sensor and the heterogeneity of the scattering components (which also vary temporally and spatially) force trade-offs among sensor size, measurement sensitivity, and volume sample size. We designed a compact underwater instrument to measure blue backscatter at a sampling rate of 1 Hz [7]. The sensor assembly houses an incandescent lamp whose output is filtered to produce blue light (~480 nm). That light is projected out in a beam 8 degrees wide by 12 degrees high. A photodetector (located above the projected lamp beam) is oriented such that its imaging beam (having the same angle dimensions as the transmitted beam) intersects the transmitted beam at a 9 degree angle. This crossed-beam geometry is a compromise between competing goals: ensuring measurements close to the 180° backscatter angle, but as narrow as possible. The transmitted beam is modulated at 16 Hz which allows the returned scatterance signal to be bandpassed filtered to minimize noise from external light sources (e.g., sunlight). The sensor has a broad sensing range of 0.0 to 0.01 per steradian per meter, permitting the sensor to operate over the range in backscatterance values in both open, clear ocean (typically near 4×10^{-4} per steradian per meter) to coastal (above 2×10^{-3} per steradian per meter).

5) Precision Pressure: A commercially-available precision pressure sensor provides independent depth (sea water pressure) data. This data is recorded and used to reconcile the depth data obtained from the ship's sensors with that directly measured by the TOMS sensors. This reconciliation is necessary as a result of calibration ambiguities noted early in the test period concerning the operation of the submarine's existing twin pressure transducers. This ensures a consistency between the data derived from existing ship's sources and those added by the TOMS system.

C. Data Recording and Archiving

Three separate types of time- and position-tagged data record structures are managed by TOMS. Data used in supporting real-time monitoring/display applications are recorded in display data records at 5 s intervals (0.2 Hz). Platform parameters recorded at 1 s intervals (1 Hz) are stored in ship's data records. The high resolution TOMS sensor data (temperature, conductivity, and chlorophyll) are recorded in fixed length sensor data records at 1 and 16 Hz. An optical disk drive is located in the submarine's Control Room for use as the master data archive supporting real-time data acquisition and recall. Approximately one week of data can be placed on each side of the optical disk (~ 1 Mbyte of data per day). A second optical disk drive is available to the Sonar Supervisor to allow a review of previously recorded data without interrupting data acquisition and display management in the Control Room.

D. Internal System Description

The TOMS prototype uses a commercially available Apple MacIntosh IIci® computer as the system's central processing unit (Fig. 1). This unit was selected as a result of its data and high speed graphics processing capability, as well as its small footprint (which provides considerable flexibility in installation aboard submarines). A high-resolution color graphics printer is provided for hard copy output, and is accessible from either the Control Room or Sonar.

The principal TOMS display is located in the submarine's control room for use by the ship's operators. A second display is located in the sonar room for use by the sonar supervisor. The two displays operate independently, allowing each to be set to a format best suited for the specific watch-standing support requirements at the different stations.

System functional control is provided through a graphical user interface employing an industrial-quality trackball that allows the operator to "point-and-select" the system control functions without having a need for a keyboard. A black-and-white example of the TOMS operator display is shown in Fig. 2. Frequently-used system commands are represented as macro command "soft key buttons" along the bottom of the screen. These macro functions, activated by a simple "point-and-click" of the cursor, include commands such as: capture a depth profile, switch between real-time and archived (both strip chart and depth profile) data, and color screen capture .

The system provides up to three simultaneous real-time graphical displays or "strip charts" to monitor real-time data, or review previously recorded data off the data archive. Real-time data is animated, scrolling from right (most recent time) to left. Pull-down menus along the top are used to configure the display, and allows the independent display of any of the available data on any strip chart. The system provides dynamic scaling of the charts on both the horizontal and vertical axes. Time frames from 15 min to 24h are available, depending on the operator's monitoring requirements. The ship's present position and time are provided in text boxes on the right. A depth profile display format (not shown here) is also available that sorts and presents the measured data into depth bins.

Fig. 2. shows an example of the sea water temperature (top strip chart), conductivity (middle) and sound speed (bottom) time history plots while the test submarine was conducting coastal training operations near the Aleutian Islands in March 1991. The most recent sound speed measurement (taken off the submarine's existing AN/BQH-1 sound velocimeter) is given in the data box to the right of the temperature strip chart, and in time-series format the lower strip chart. A coastal front is observed in this example associated with the sharp changes in measured sea water properties (changes of 2.5°F in temperature, 0.13 S/m in conductivity, and 18 f/s in sound speed) at approximately 00:45 a.m. as the submarine entered the Gulf of Alaska during the coastal island transit.

E. Correcting for Depth Motion-Induced Biases

TOMS implements a simple, but effective, procedure to compensate for submarine depth-change related ambiguities in the displayed time series data. This is needed since submarine depth excursions can produce changes in the time history plots of temperature and other parameters that appear similar to spatially-measured frontal changes. TOMS can automatically capture and archive a reference depth profile of temperature (or any of the depth-dependent measured parameters). A synthetic depth-ordered profile is constructed that is used as a reference. Differences between subsequent measurements and the reference profile at the same depth represent a measure of the horizontal variation in water mass conditions - a direct indication of the ocean water mass variations. The results of this process are defined as "compensated values", allowing the operator to examine the estimated horizontal changes in value rather than the actual measure parameters.

III. AUTOMATED FRONTAL DETECTION OPPORTUNITIES

Small-scale horizontal temperature fluctuation spectra exhibit significantly higher spectral energy levels within and near ocean fronts than in the surrounding, more quiescent water mass [8]. Consequently, increases in temperature fluctuation variance may be an indicator of the horizontal mixing between the water types across the front, and may offer an opportunity for early alertment of an ocean front as a ship approaches the front.

We have investigated whether increases in small-scale temperature and conductivity turbulence can be detected automatically using an operationally-oriented (vice scientific) sensor system in an unconstrained operational environment such as that experienced by TOMS. The concept is as follows. The time series data (e.g., temperature) are subjected to a moving, ship's speed normalized FFT window (resulting in an equivalent transform in physical space) designed to capture, for example, the 1 m to 10 m horizontal wave band. The window is constructed to provide independent spectral estimates. The variance in the waveband of interest is summed, and the sequence of variance estimates is compared with the contemporaneously measured temperature and sound speed measurements across the front. We have observed that the small-scale scalar turbulence in many cases does exhibit higher mean variances by up to two orders of magnitude than that of the background, and often can be identified on the platform as the front is approached. Investigations are continuing concerning the reliability of the proposed methods.

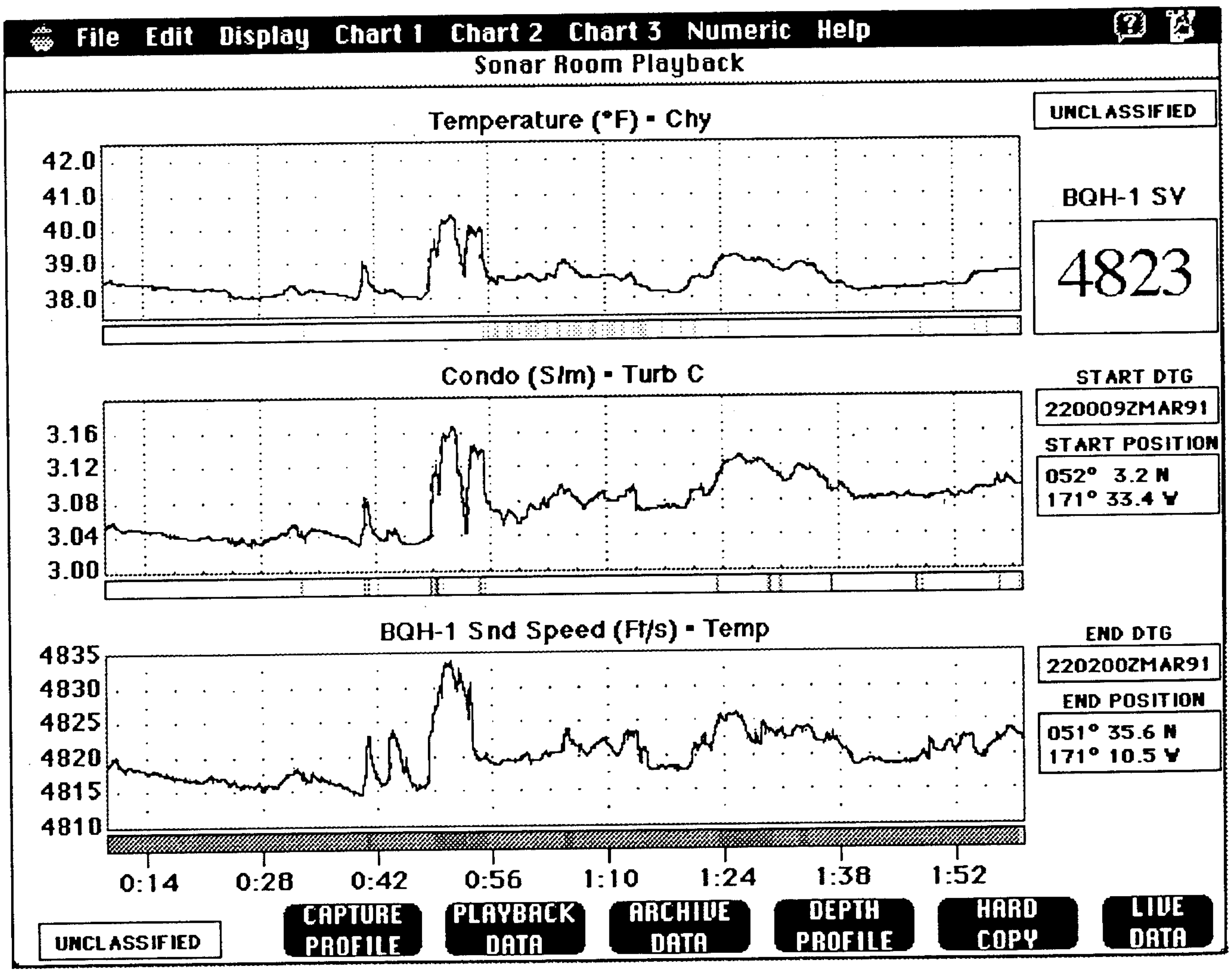

Fig. 2. Example of actual TOMS display obtained during submarine transit of Aleutian Islands in March 1991. The coastal front mentioned in the text is shown by the increase in observed temperature, conductivity and sound speed at approximate time 00:45. The units of measure are English, as is the custom on U.S. submarines.

IV. SUMMARY

The initial prototype system test period is drawing to a close. The data reveal the open and coastal ocean to be a complex environment, with significant variations occurring on scales not previously measurable by U.S. Navy ships, but which are of such a magnitude to potentially affect the performance of the ship's tactical sensing systems. Even though the initial TOMS installation was a prototype experiment, operational experience with the system has demonstrated the utility of real-time environmental data in a wide range to tactical operations. Based on the operational experience gained during the test period, plans are now proceeding with the U.S. Navy in establishing a permanent test-bed system. This permanent installation will support the continuing assessment of new sensor technologies and the development of accompanying tactical doctrine for future system use.

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