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Sensor and Actuator Networks for Acoustic Signature Monitoring and Control

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ABSTRACT

An important consideration in the development of new submarines is reduced detectability. The design and operational condition of propulsion and auxiliary machinery largely determine the submarine acoustic signature. Recent advances in commercial high-speed network technologies such as ATM-SONET and Fibre Channel have been leveraged to develop high-speed sensor and actuator networks which provide monitoring of ship radiated noise and machinery condition, as well as providing active noise and vibration control. These new commercial network architectures are relatively simple and inexpensive as compared to previous ship monitoring systems, and provide improved performance. In this paper, we discuss the design of a 1024-channel sensor network for total ship monitoring which uses an ATM-SONET network backbone. We also discuss the design of a 256-channel sensor and actuator network for active noise and vibration control which uses a Fibre Channel network backbone.

INTRODUCTION

In the mid-1990s, the U.S. began trials of high speed commercial networks on Navy ships in applications such as combat systems, towed arrays, and C4I [References 1-7]. Success in these trials have prompted the U.S. Navy to formally adopt a "network-centric" doctrine, upgrading existing systems and developing new systems based on network technologies such as ATM, Ethernet, and Fibre Channel as shown in Table 1. For example, the Navy IT-21 program plans to deploy ATM backbone networks on more than 40 ships and submarines for local and wide area communications. [Reference 10].

Planning Systems Incorporated, a leading developer of high-speed sensor networks, is currently developing and building measurement systems and active noise and vibration control systems which leverage ATM and Fibre Channel networks. In this paper, we will discuss how these sensor networks can be applied to submarine noise monitoring and control.

SHIP MONITORING SYSTEMS

The modern classes of U.S. submarines, including the Trident, 688, and Seawolf-class, have various types of monitoring systems for the measurement of self-noise, transients, vibration, and machinery. These systems include the Noise and Vibration Monitoring System (NVMS), Transient Monitoring System (TMS), and Total Ship Monitoring System (TSMS).

These self-noise monitoring systems generally consist of a suite of analog sensors (e.g., hydrophones, accelerometers, towed arrays, etc.), a data acquisition subsystem (signal conditioning, A/D converters), and a processing subsystem (digital signal processing, noise monitoring algorithms).

The systems currently aboard the operational fleet were generally designed and built prior to the 'network-centric' and 'COTS' eras and have custom interfaces between the subsystems, custom transmission schemes, and closed 'stove-pipe' architectures. Although these legacy systems have been effective, next-generation systems will need to cost less and provide higher performance. To achieve this, new architectures for submarine monitoring are being developed based on the concept of 'sensor networks'. These new open architectures leverage high-speed commercial network standards such as ATM-SONET and Fibre Channel to provide standard interfaces between subsystems.

State-of-the-art submarine monitoring systems consist of a distributed network with data from many of the major ship systems such as platform noise monitoring, total ship monitoring, machinery condition monitoring, conformal arrays, bow sonar arrays, environmental sensors, and towed arrays [reference 11]. Data from these various sensors are 'fused' to provide a global estimate of the radiated acoustic signature. Processed data from the monitoring system is networked to the command and control (C2) system and to the active noise and vibration control system.

ACTIVE NOISE AND VIBRATION CONTROL SYSTEMS

An active noise and vibration control system consists of sensors, data acquisition units (A/Ds), processors, D/A converters, power amplifiers, and actuators in a control loop. The sensor signals, typically accelerometers on a frame, mount, or machine, are digitized and processed. The process measures the complex signal and creates a digital cancellation signal which is converted to analog and driven by power amplifiers to the actuators. The actuators are located at key locations on the structure frames and machinery mounts. The control loop, when stable and optimized, provides active cancellation of noise and vibration. State-of-the-art active control systems can provide as much as 20-30 dB of attenuation at low frequencies (<100 Hz).

A key design parameter in control loop stability is the feedback delay or latency from the sensor signal measurement to the actuator drive. Feedback latency must be minimized in order to maximize system frequency response. Primary components of latency include the A/D conversion delay, the signal processing delay, the D/A conversion delay, and the communication delays between these primary subsystems.

HIGH BANDWIDTH

Self-noise monitoring systems require a large number of sensors to accurately measure the acoustic signature of a submarine. For example, the noise and vibration monitoring system (AN/WSQ-7) on the Seawolf-class submarine may accommodate inputs from up to 496 accelerometers, 24 hydrophones, and 384 machinery contact closures [Reference 12]. Even with relatively limited frequency coverage (< 1 kHz) and medium resolution (16 bit A/D samples), such a system can generate on the order of 20 Mbit/sec of sensor data.

An accurate, directional 3-D, wideband (>20 kHz), high-resolution (24-bit A/D samples) self-noise submarine measurement requires thousands of sensors. Such a system generates sensor data bandwidths on the order of 1 to 10 Gbit/sec.

The advent of high-speed speed commercial networks now offers the opportunity to build affordable, very large sensor networks. A typical off-the-shelf ATM network switch can network 10 Gbit/sec of data, with up to 64 connections, and connection speeds ranging from 25 Mbits/sec to 2.5 Gbit/s. A typical off-the-shelf Fibre Channel network switch can network up to 16 Gbit/sec of data, with up to 16 connections, and connection speeds of 1 Gbit/sec. A single network switch, for a cost of approximately $50K, can provide an entire network backbone for a very large, wideband, high-resolution signature monitoring and control sensor network.

LOW LATENCY

Active vibration and noise control systems require low latency data communications between the sensor data acquisition, processing, and actuator subsystems. As a rule of thumb, the total latency across these subsystems must be much less than the period of the highest signal frequency of interest. For example, active noise cancellation at relatively low frequencies (<100 Hz) requires latencies of less than a millisecond between subsystems.

An accurate wideband (>100 Hz) active noise and vibration control systems require extremely fast A/Ds, D/As, processors, and data links. Such a system requires data link latencies between the subsystems on the order of microseconds.

Latency in an active vibration and noise control data network has two delay components. One delay is the amount of bytes in a packet which must be transmitted at the data link throughput rate (bytes per packet/throughput rate). The second delay is the latency of the network backbone which consists of the delays through the network switch and the network interfaces.

Fibre Channel and ATM networks, when configured in star network topologies, provide excellent low latency data links. For example, a typical ATM-SONET OC-3c star network can move a 256-byte data packet from point A to B via a 16-port ATM switch in less than 10 microseconds. A Fibre Channel star network can move a 256-byte data packet via a 16-port Fibre Channel switch in less than 2 microseconds.

ATM-SONET NETWORK

Exhibit 1 shows an example ATM-SONET sensor network for wideband self-noise monitoring. A single network switch provides the backbone for 1024 sensors. Data acquisition nodes with ATM network interfaces are distributed throughout the ship, located near the sensors to minimize cabling and improve data acquisition accuracy. Processors, recorders, and adjunct systems are also connected via the network.

Each OC-3c ATM-SONET fiber optic link operates at 155 Mbit/s with approximately 130 Mbit/sec payload throughput. A data acquisition node operating at 50 Ksamples/sec per sensor with 24-bits A/D resolution can transmit up to 108 sensors per OC-3c link. Importantly, the sensor network can support a variety of sensor types, A/D resolutions, and sample rates. Equally important, particularly for submarine applications, the network requires very little hardware (a couple of VME cards at each data acquisition node and a rack-mount ATM switch).

FIBRE CHANNEL NETWORK

Exhibit 2 shows an example Fibre Channel sensor/actuator network for active noise and vibration control. A single network switch provides the backbone for 128 sensors and 128 actuators. Nodes which contain integral A/D, processing, and D/A functions are distributed throughout the ship on the network. The actuators contain integral power amplifiers for optimum power distribution efficiency.

Each Node digitizes the sensor data, processes the data, and drives out the actuator signals. Both processed and raw data from each node is shared among all nodes via the network. Neural network adaptive algorithms at each node provide the capability for the system to learn and to adapt to changes in signal as well as to failures of sensors, actuators, and/or nodes for optimum signature control.

Each Fibre Channel fiber optic link operates at 1 Gbit/sec with approximately 800 Mbit/sec payload throughput. In the example network each Node supports up to 8 sensors and 8 actuators. Sample rate and frequency coverage is a function of the algorithm size and processor type. A system with 1 GFLOP processors at each node, running a fully adaptive disturbance cancellation algorithm with 16-bit inputs and outputs, and 100% data sharing with all other nodes in the system, could theoretically provide sample and reconstruction rates of approximately 3-4 kSamples/sec per sensor or actuator, adequate for precision control of systems up to approximately 400 Hz.

Similar to the previous ATM network example, the Fibre Channel active control network requires very little hardware to implement, with only a couple of VME cards at each Node and a rack-mount Fibre Channel switch.

SUMMARY

The advent of commercial ATM and Fibre Channel network technologies provide the capability to build high bandwidth, low latency, high channel count networks for demanding applications such monitoring and adaptive control of submarine acoustic signatures. Importantly, these systems can be built with relatively little hardware and at relatively low costs as compared to legacy systems.

REFERENCES

1. John Walrod, “ATM Telemetry Systems for Sensor Arrays”, U.S.N. Next Generation Computer Resources Conference, Sept. 21, 1995, Washington, D.C.

2. Wesley Kaplow, "The Role of ATM in Unifying C4I Networks", U.S.N. Next Generation Computer Resources Conference, Sept. 21, 1995, Washington, D.C.

3. John Walrod, “Advanced Data Networks for Navy Ranges and Arrays”, Undersea Defense Technology ‘96, July 2-4, 1996, London, U.K. pp.502-506.

4. John Walrod, “Using the Asynchronous Transfer Mode in Navy Communications”, Sea Technology, May 1997, pp.19-28.

5. John Walrod, “ATM Telemetry in Towed Arrays”, Undersea Defense Technology ‘97, Hamburg, Germany, June 24-26, 1997.

6. John Walrod, “Inboard Sonar Data Acquisition with Standard ATM Networks”, Undersea Defense Technology ‘97, Hamburg, Germany, June 24-26, 1997.

7. Alan Rees, "The Application of ATM within Surface Ship Towed Array Systems", Undersea Defense Technology ‘97, Hamburg, Germany, June 24-26, 1997.

8. John Monroe, "Navy's 'Smart Ship' passes tests", Federal Computer Week, October 6, 1997, p. 21-22.

9. Edward Walsh, "Fleet wrestles with interoperability in the move to network fighting ships", Military & Aerospace Electronics, p. 15-19, March 1999.

10. Capt. Mark Lenci, C4I Day Brief, November 3, 1998.

11. William Hamblen, "Next Generation Stealth Submarines", Sea Technology, November 1998, p.59-62.

12. "AN//WSQ-7 Noise and Vibration Monitoring System", Smiths Industries, www.smithsind-sps.com/sub.htm, April 1999.

Table 1. U.S. Navy Deployment of High-Speed Shipboard Networks

Ship	Systems	Network
USS Yorktown (Smart Ship) Guided Missile Cruiser	All workstations and critical systems including Standard Machinery Control System, Damage Control System, Combat Information Center, Voyage Management System, Integrated Condition Assessment System, and Integrated Bridge System. [Reference 8]	ATM Network backbone with Ethernet drops
USS Oscar Austin (DDG-79) Arleigh Burke Class Aegis Destroyer	Navigation, GPS, wind sensor, digital indicators, Cooperative Engagement Capability. [Reference 9]	Boeing Proprietary Dual-Ring FDDI backbone with Ethernet drops. Eventual replacement of proprietary backbone with ATM is planned.
Baseline 7 Phase 1 (Future) Aegis Destroyers	SQQ-89 version 15 ASW combat system suite including the SQS-53 hull sonar, SQR-19 towed array, and SQQ-28 sonobuoy system. [Reference 9]	ATM-SONET
NSSN Virginia Class Attack Submarine (Future)	C3I systems including Combat Control, Exterior Communications, Navigation, Imaging, Sonar, Total Ship Monitoring Subsystem, and Ship Control [Reference 4]	ATM-SONET backbone with Ethernet drops, custom TAXI fiber optic links, and Fibre Channel links.
Kitty Hawk, Stennis, and Eisenhower Carriers	IT-21 local area and wide area network communications [Reference 10]	ATM-SONET backbone with Switched Ethernet segments
Mobile Bay, Port Royal, and Lake C'Plain Cruisers		
John McCain, McFaul, and Mahan Destroyers		
Belleau Wood LHA, Ft McHenry LSD, Germantown LSD, Juneau LPD, Wasp LHD, and BH Richard LHD		

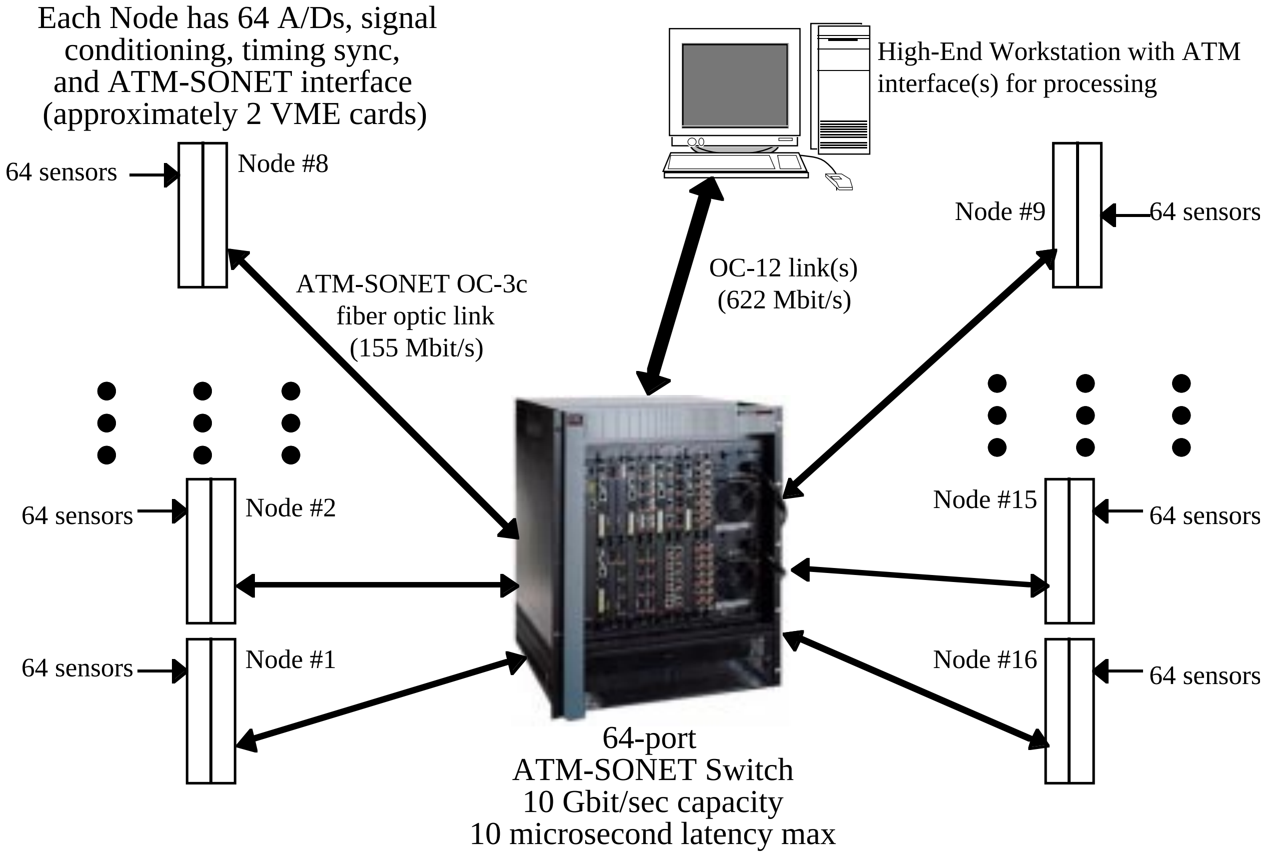

Exhibit 1. Example 1024-channel Sensor Network for Acoustic Monitoring

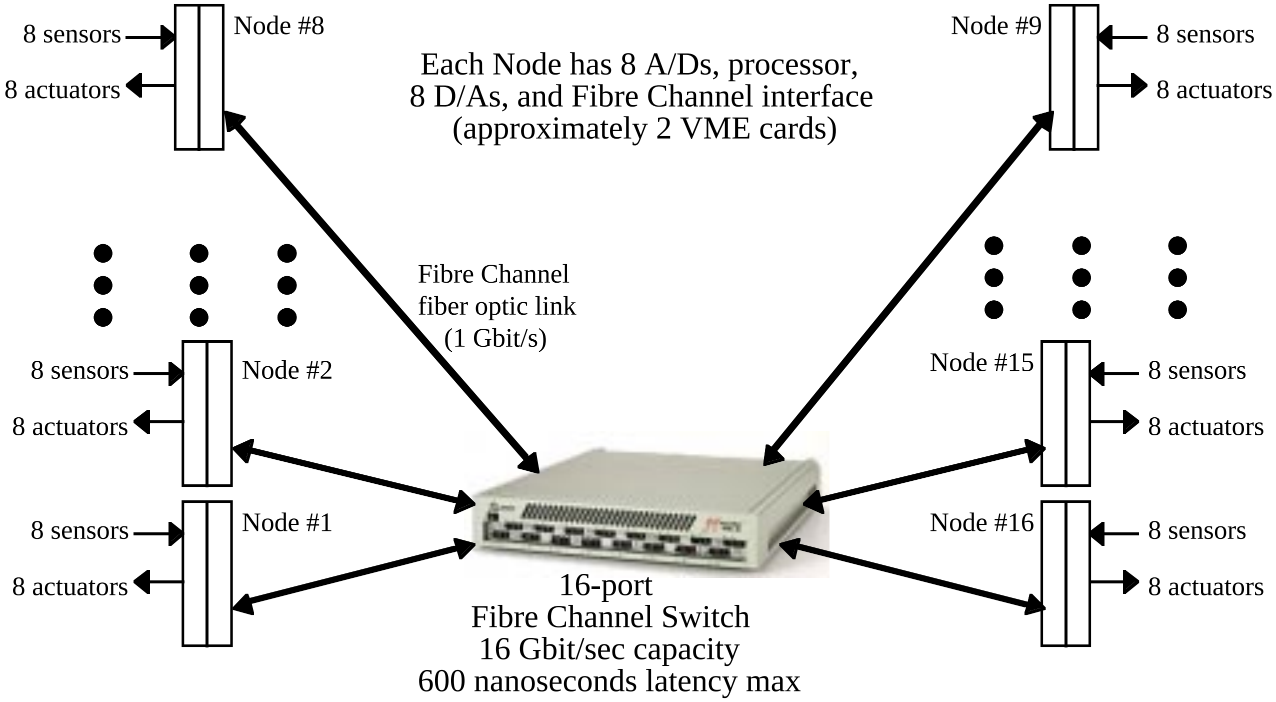

Exhibit 2. Example 256-channel Sensor/Actuator Network for Active Noise and Vibration Control