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OPTICAL FIBER SENSORS: ACCELERATING APPLICATIONS IN NAVY SHIPS

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Contents

Appendices

Executive Summary

The Navy needs new sensors for shipboard machinery monitoring and control, condition-based maintenance, and damage assessment. Optical fiber sensors are strongly preferred because of their immunity to electrical disturbances, as well as potential size, weight, and performance advantages. But despite well over a decade of development and promise, relatively few optical fiber sensors available today can meet the Navy's needs with acceptable performance and cost. This report examines the reasons and recommends strategies to help the Navy achieve its goals. Some of the recommendations confirm approaches that the Navy is already implementing.

Optical fiber sensors have very valuable potential advantages, but those that the Navy can use may remain too expensive to be deployed if the Navy uses traditional methods of writing specifications and soliciting development and procurement bids. For this reason, the study focuses on cooperation with industry and promoting commercial off-the-shelf and dual-use technology.

Certain general technical issues that affect choices of fiber sensor technologies are addressed. Networking and multiplexing strategies are important for controlling costs of fiber sensor systems and interact with survivability. Electrical sensors, powered by light over fiber, may play a valuable near-term role in reaping the advantages of fiber before purely optical technology is competitive for some measurands.

Twelve general impediments and opportunities are identified. These exist regardless of what technologies the Navy may choose for its sensor systems. Cost can be reduced, and experience and reliability increased, by increasing the manufactured volume of sensors. To exploit this strategy, the Navy needs industrial partners that are proven manufacturers and marketers, and it needs to bear some of their risks and motivate them to enter markets substantially larger than shipboard sensors alone. Cultural and organizational differences have recently hurt the Navy's ability to attract the best industrial partners, but certain actions can improve both the image and the substance of Navy/industry cooperation. The Navy can also benefit from certain management tools for focusing both internal and industry development efforts on the right objectives.

Both packaging of optical components and optical switching (for multiplexing) can substantially affect fiber sensor system costs and can be improved in cooperation with other industry or government partners.

Opportunities and recommendations are discussed for six specific technologies with promise, in most cases for multiple measurands: optically powered electrical sensors; fiber-based spectroscopic components; blackbody temperature sensing; polarimetric components; Bragg-grating fiber sensors; and sensing by low-coherence reflectometry. Most of these are applicable to multiple measurands.

Simplified estimates place the combined cost of the recommendations in this report at approximately $7 million and suggest that they may yield, over time, a saving or value of approximately $45 million.

Key words: Navy ships; optical fiber sensors; optoelectronic manufacturing; technology commercialization

1. Objectives and Methodology

This project arose from concerns within the Naval Sea Systems Command that optical fiber sensor technology was not advancing rapidly enough to allow the introduction of that technology into the fleet, quickly and at an acceptable cost.

1.1 The Problem

Today's Navy ships use large numbers of sensors. Future ships will use considerably more to support new hull, mechanical, and electrical (HM&E) systems now under development. Optical fibers is the preferred sensor technology, for well-known reasons discussed elsewhere in this report.

The optical-fiber-sensor market and industry are far from mature. This is manifested in high cost, limited performance and scope of measurands, poor or unproven reliability, low market volume, and a general lack of confidence found in parts of industry and the Navy. This may seem surprising considering the effort and publicity that have been given to fiber sensors during the past decade. Navy programs (described in Appendix C) have played leading roles in developing fiber sensors, but the work is not nearly finished. Many private efforts have been made to develop fiber sensors for commercial and military markets, but to date most of the results are limited in scope, high in cost, and low in manufacturing volume. (Notable exceptions are discussed in Section 1.4 and Appendix B.) It is not clear how soon this situation will change or what forces will cause it to change.

Fiber optics has compelling advantages. The Navy cannot simply wait with the hope that industry will eventually create what it needs, but must play an active role in managing the process. Historically, the Navy has successfully deployed new technology by creating specifications and funding development specifically for its own needs, without regard to other applications. This is the old paradigm, which is rapidly becoming unacceptable to the Navy in many areas of technology. It results in very expensive custom products. Even if the Navy wanted to fund this approach, it would encounter difficulty in optical fiber sensors, because the limited Navy market size, decline and uncertainty in military funding, and unrewarding experience with recent military projects, are making the best companies wary of undertaking a development project for the Navy alone.

The new paradigm is embodied in the Navy's current emphasis on COTS (commercial off-the-shelf) and dual-use technology. The strategy is to use standard commercial products where possible, or moderate modifications of commercial designs that still benefit from the economy of high-volume production serving a larger market outside the Navy.

This report assumes that the new paradigm will apply to the majority of fiber sensors used by the Navy. The authors believe not only that custom development is becoming less attractive to industry, but also that the old approach would substantially decrease the likelihood of deployment. Although it might succeed technically, the resulting procurement costs will prevent the future Navy from deciding to use the technology.

Because of these considerations, the problem addressed by this study is not simply how to develop the technology, but how to stimulate industry to develop fiber sensors for commercial applications simultaneously with Navy applications. The resulting programs may benefit broad industries even more than they benefit the Navy, but this constitutes an attractive bonus, not an added expense to the Navy.

In order to design programs that stimulate the industry, it is necessary first to understand what is holding the industry back.

1.2 Project Objectives

The objectives of this study and report are:

a. Identify the critical impediments to the wide spread commercialization of optical fiber sensors, especially for Navy shipboard applications.

b. Develop strategies that the Navy can pursue to overcome these impediments.

Every impediment represents an opportunity if it can be overcome. But the authors have also identified some opportunities that are not clearly associated with impediments and have taken the liberty to include these in the report. The recommended strategies are not directed at the fiber sensor industry in general, but toward the Navy's specific goal of providing inexpensive shipboard sensors, sufficient to support the introduction of advanced system designs for hull, mechanical, and electrical equipment.

Manufacturability is a focal point of this study. In many cases, inventing and demonstrating the performance of a basic idea is minor compared to the less romantic effort of incorporating the principle into a design and a process that permit manufacturing in high volume at low cost. Reliability is an inseparable aspect of manufacturability. A design that can be assembled efficiently at low cost is not manufacturable unless it functions properly and endures. Because the authors believed at the outset of this study that monolithic and hybrid integrated optics hold promise for improving manufacturability of future fiber sensors, a separate report entitled "Integrated Optics for Fiber Sensors" was written in conjunction with this project. A summary of that report is presented in Appendix D.

Optical fiber sensors encompass a wide range of different technologies and approaches. To limit the scope of the project to encompass sensor technologies that are promising specifically for the Navy, it is necessary to study other goals and requirements of the Navy. These are discussed in the next Section.

1.3 The Navy Context

The objectives of this project must serve certain more general goals and strategies for Navy sensor systems. Systems currently under development will perform automatic damage assessment, automatic machinery control and monitoring, and condition-based maintenance. Performance goals, supporting the above developmental systems and other existing machinery systems, include immunity to EMI, survivability, capacity for new measurands, improved performance, reduced size and weight, and reduced true cost.

These goals and benefits are explained briefly below. They help to define and limit the scope of the technologies addressed in this study, as discussed in Section 2.

Automatic Machinery Control and Monitoring: Presently, most machinery control systems on a ship are hard-wired instead of being software controlled. While this is reliable, it is not possible to rapidly reconfigure systems in the event of damage. Electrical power often is interrupted for a long time after damage, leaving the ship vulnerable to additional attack. Computer controlled systems are being developed to reconfigure electrical systems quickly and automatically. These systems will take their input from networks of sensors.

Automatic Damage Assessment: Presently, when a ship is hit, a damage control officer sends runners to assess the damage. The process is slow, dangerous, subjective, and overly centralized compared to what can be accomplished with sensor networks communicating multiple measurands from each compartment to stations in different parts of a ship.

Condition-Based Maintenance: Presently, shipboard machinery is serviced according time-based programs, designed to replace parts before they fail by using estimates of lifetime. Such programs cause costly unnecessary service, while neglecting some problems that cause catastrophic failures at inopportune times. Sensor networks for machinery monitoring can alleviate both problems by detecting deterioration long before it is catastrophic.

EMI Immunity: Electromagnetic interference is abundant in the shipboard environment; it arises from machinery, power systems, communications systems, and radar. It can either temporarily or permanently disable sensors that have electrical lines for power or signals, because these lines act as antennas. The large numbers of sensors needed for the new strategies for damage control and machinery monitoring will make this a much more severe problem than it is today.

Survivability: To the greatest extent possible, shipboard systems must continue to function in the face of damage to the ship. This need places constraints on the sensors, on the data network that delivers their data, and on the subsystems that connect the sensors to the data network. The sensors and associated subsystems need to be designed with considerations for survival that are consistent and commensurate with the survivability of the data network.

Measurands, Ranges, and Performance: The parameters that the Navy wishes to measure, the ranges and accuracies for these parameters, and the environmental conditions over which the sensors must either perform or survive without damage, far exceed the scope of present sensors on naval vessels. These measurands and ranges have been discussed in detail in *Whitesel, Henry K., "Sensor Requirements and Availability for Shipboard Auxiliary Machinery, Phase I - Range and Accuracy," David W. Taylor Naval Ship Research and Development Center Technical Report DTNSRDC/PAS-79-14, Sept. 1979.* Some are not presently attainable by any developed technology; some can be accomplished with electrical sensors but not fiber; and for some there are promising optical or fiber approaches and no electrical means.

Size and Weight: Weight directly affects the quantity of ordnance and other material that a ship can deliver, and size affects the cost and the effectiveness of deployment for sensors. Reduced size and weight also facilitate backfitting.

Cost: Costs may be measured in absolute terms, in relation to available budgets, or in relation to function and performance. It may be argued that the third measure has generally dominated military procurements, but the importance of the first two is growing rapidly. The needs for added functionality and improved performance are driving the Navy toward a substantial increase in the number of sensors (and toward fiber), making the cost per sensor more important. It must be understood, however, that the true cost resides not only in hardware procurement costs, but also in other areas that are harder to measure, including installation, maintenance, calibration, spare parts inventories, training, and the cost of untimely failure.

Navy personnel have realized for some time that the range of sensors presently used or available for use in shipboard applications will not meet the above goals. Sensors must be improved, or new sensors must be developed. Possibly, improvements or new designs for electrical sensors will be superior to fiber by some of these measures. But the overriding importance of EMI immunity makes it compelling to attempt all measurands with fiber and justifies the focus of this study. The motivations for fiber optics are discussed in detail in Appendix A.2.

1.4 Optimism and Pessimism

In industry and the Navy, there are strong advocates of fiber sensors and there are skeptics. Much of the optimism is driven by belief that the advantages of fiber will create high-volume markets that will drive prices down. There are not yet many examples of this process actually happening. Skepticism is driven by a number of issues. Some people believe that components and assemblies in optical sensor systems may never become inexpensive enough even in volume; or that most of the sensor market does not need the advantages of fiber enough to increase production volumes and lower the cost soon. Others believe that the Navy may not make a firm enough commitment to optical fiber sensors; or that commercial off-the-shelf components (assumed necessary to make fiber sensors inexpensive enough) will never meet Navy specifications. By most criteria, the shipboard environment is one of the markets most in need of the advantages of fiber. But even within the Navy there are earnest believers that electrical sensors are adequate and will continue to dominate.

In this report, the authors assume that the Navy believes strongly enough in the potential of fiber sensors to make serious investments and to bear the risk that they may not pay off.

It is beyond the scope of this study to recommend the extent of the Navy's commitment, except that the consequences of an industry perception of lack of Navy commitment and continuity are discussed in Section 3. Efforts by the Navy in the late 1980's to develop and deploy fiber on an accelerated schedule have been interpreted by some as premature or overambitious. This history may have damaged the reputation of fiber within the Navy, and the reputation of the Navy's fiber programs in industry. The appropriate rate of investment in fiber sensors should be considered on the merits of the risk and reward as measured today, independently of this history.

The authors are personally optimistic about the potential for cost reduction and the development of markets for fiber sensors. This optimism is not based on scholarly market studies. Predictions of future markets are unreliable, no matter how sound the logic may seem. For example, in studying the market for cellular telephones a decade ago, it was predicted that nearly a million would be in use in the U.S. by the year 2000. But by 1993 there were already about 13 million. [*The Economist, 23 Oct. 1993, "A Survey of Telecommunications," p. 7.*] Both the demand and the cost reductions far exceeded expectations. The optimistic predictions in the early 1980's for early deployment of optical fiber communications to homes proved false. This led to considerable discouragement in the late 1980's. But then business accelerated and caught many companies off guard. The configuration of "local loop" fiber systems is different than expected (glass fiber to the curb and copper into the home), but business is booming.

A certain type of optical fiber pressure sensor is being sold to the medical market in volumes exceeding 50,000 per year. The customer pays $150 to $300 for the sensor, which is discarded after use. Several companies are making distributed optical fiber sensors for intrusion detection, using interferometric principles. Although the business is less than three years old, at least one of these companies is already profitable and has found that many customers buy because the system is cheaper than the electrical sensing alternatives, not because of performance advantages. In Japan, two major companies are selling optical fiber gyroscopes for use in automobile navigation systems. Recently, several companies that make automotive components have been investigating magneto-optical rotation sensors for use in anti-lock brake systems and transmissions. According to one of them, at today's small volume prices the parts for this sensor would cost about $100, making it out of the question for automobiles. But deeper work with several vendors revealed that, in the volume expected for the product, it could probably be *sold* for under $15.

Last year, one prominent U.S. fiber sensor company was downsized, sold at a loss, and moved, fueling the pessimistic view of fiber sensor technology. But it is arguable that this was brought about by the company's difficulties in making the transition from a research orientation to a marketing and manufacturing orientation, rather than a fundamental problem with the technology and the market for it. For example, the company has at least one sensor that can be used by the food-processing industry, costing less than half what the alternative non-fiber system costs.

Observations like these give the authors optimism that the Navy will benefit from careful investment in optical fiber sensors. The report is not intended to argue this point of view. Rather, it assumes that the Navy will make the investment and then explores some judicious ways to do it.

1.5 Methodology and Scope

The primary input for this study has been direct discussions with key personnel at various companies manufacturing optical fiber sensors, companies and other organizations using fiber sensors, and certain Navy facilities concerned with the introduction of optical fiber into the fleet. Generally, these discussions took place at the company or facility. Usually they included a brief presentation of the Navy's applications, followed by general discussion of technical and marketing issues. This was often followed by a laboratory tour and more specific discussions of the organization's primary interests. A total of 17 on-site visits were conducted (see Appendix F). Approximately 45 individuals at these various organizations were involved in the discussions. Several other organizations were contacted by telephone. Although there is fiber sensor work in other countries, only U.S. organizations were contacted.

Resources for the project did not allow visiting every important U.S. company or laboratory working in optical fiber sensors, investigating every pertinent technology, or studying sensors for every measurand of interest. For example, chemical sensing has been largely omitted from this study. That field will require considerably more research and development before the Navy's ultimate objectives can be met, and the authors did not expect investigations to lead further than a general recommendation to continue work of the type that the Navy is already doing in this area.

This report provides more of an industry perspective than a Navy perspective on impediments to the Navy's requirements for fiber sensors. It does not necessarily represent a position of the Navy or the office within the Navy that funded the work. Neither is it simply a survey, because it expresses many interpretations and opinions of the authors. This is particularly true in the recommendations of Section 4.

The authors have deep respect for work done by the Navy in fiber sensors, but they attempted to find different approaches that will improve the effectiveness of efforts to create sensors that serve the Navy simultaneously with commercial markets. This project was originally conceived as a study of impediments in industry, independent of the Navy. But to keep the project directed at the Navy's needs, and because the subject came up frequently in discussions with industry, the authors found it appropriate to include the subject of interactions between the Navy and industry. The quality of these interactions plays a crucial role in the development and deployment of optical fiber sensors for ships.

2. Technology Issues and Navy Requirements

The observations in this section concern general technical issues which affect choices of fiber sensor technologies and which underlie the observations and strategies presented later. They also summarize some key issues that require future decisions by the Navy.

2.1 Incremental Development of Technology

The Navy might simply specify today a complete fiber sensor system for all measurands of interest and solicit procurement bids. The authors believe that this one-step approach would be overly expensive and would fall short of both the Navy's needs and the technology's promise for performance and reliability.

The recommendations in this report are designed to move toward complete systems in areas where clear advantage can be seen today and to position the Navy to make later decisions in areas where the choices are not clear today. This incremental approach is generally consistent with present Navy sensor programs.

There are two main reasons for moving forward incrementally. One reason, noted in Section 1.1, is that the technology is not mature, so further development is needed before making certain decisions. The other reason is that the technology is widely diverse, with multiple options for each measurand, all having very different cost, reliability, and survivability implications. (These issues relate to network architectures and to the cost-reduction strategy of multiplexed signal conversion, discussed in Section 2.4.) The authors do not believe that there is sufficient experience, either in industry or the Navy, to make decisions today that will endure without high probability of costly changes in direction later.

One consequence of this approach is that the recommendations encompass investigations of several technologies for the same measurand.

2.2 Long Term versus Short Term Goals

The Navy has both immediate needs and long term goals for improved performance and functionality at low cost. This study was done with the intent of serving both, and in the belief that the two do not need to be contradictory. Getting incomplete fiber sensor systems on ships as soon as possible will provide experience that helps direct further development efforts and decisions towards the long term goals. It is expected that the Navy's systems (including communications network and control software) will be developed in a sufficiently modular way so that partial systems on early ships can evolve into complete systems on later ships without discarding earlier modules. It is also understood that the Navy can permit early ships to have partial functionality, for example, some damage-control measurands but not all, and a temporary mixture of condition-based and time-based maintenance.

2.3 Sensor Networks

It is not adequate to think of the large number of sensors on a future ship as a collection of individual sensors. They must be interfaced to data networks, and the data must be transmitted to computers and processed. Design of the data network falls outside the scope of this report, but it is important to note here that sensor technology decisions are closely entwined with network decisions. A particular area of concern is the influence that topology has on survivability.

It is common practice simply to connect the outputs of individual single-point sensors to nodes of an independently designed data network. But this approach fails to exploit important cost reductions that can be achieved with multiplexed signal conversion for a single measurand (see Section 2.4) or for multiple measurands that use a common technology (see Section 2.5). Optical fiber sensors offer a particularly rich variety of options for multiplexing. They also offer possibilities for distributed sensing, in which a measurand is continuously determined along the length of a fiber.

Because of these concerns and opportunities, it is appropriate to think of the sensing system as a network of subnetworks. And while it may be premature to specify a complete system (Section 2.1), it is not too early to address network issues and, perhaps, design or specify subnetworks.

2.4 Multiplexed Signal Conversion

An optical fiber sensor generally consists of a sensing element coupled by one or two fibers to a separate subsystem that converts the sensing element's optical properties into some kind of electrical information. This function is called signal conversion.

For many fiber sensor types, the main expense is not in the sensing element, but in the signal conversion subsystem. This subsystem may contain a light source that injects light into a fiber and a means for analyzing what comes back through the same or another fiber. Or it may simply receive and analyze light originating in the sensing element. The optical components and assemblies contained in the signal conversion unit are often expensive, though they may become less expensive with time and in higher volumes. Nonetheless, for a number of years, it be difficult for this unit to compete in cost with the analogous signal conversion units used in many electrical sensors.

Because of the cost of signal conversion, it may be advantageous for a single unit to serve a number of sensing elements. With electrical sensors, this can be achieved by switching the input of the signal conversion unit from one sensor to another, as long as the time required for a single measurement is shorter than the required maximum time interval between measurements. Optical sensing techniques allow similar switching, but also offer several other strategies for multiplexing, in particular the possibility of separating signals from different sensing elements in time (time division multiplexing) or by wavelength of operation (wavelength division multiplexing). Similar schemes may be available in electrical sensor systems, but are much less practical.

The variety of multiplexing techniques (including distributed sensing, mentioned above) available with optical fiber sensors is one of their greatest attributes, and decisions on multiplexing design have critical implications for network topology and therefore cost, reliability, and survivability.

2.5 Common Technology versus Best Technology

Many fiber sensor technologies are available, and some can serve multiple measurands. For example, pressure and temperature can both be measured by a change in the spectral reflectance of a small interference cavity. The sensing elements are designed differently for the two measurands, but both temperature and pressure transducers can be probed by the same signal conversion subsystem, with multiplexing. The cost saving in such commonality goes beyond the saving from multiplexing. Fewer subsystem types will mean lower parts inventory and less training.

However, the cost savings of using a common technology may come at a price in performance and reliability. For example, suppose temperature is measured by the spectral reflectance of a cavity as described above. An optical connector in the line between the sensing element and signal conversion unit can also cause a reflection with a spectrum that depends on wavelength. This can cause calibration errors or drift, and necessitates cautious connection procedures and perhaps frequent calibration checks. In the future, it may be possible to reduce this sensitivity (Section 3.2.1, below). But, by contrast, consider measuring temperature by determining the fluorescent decay time of a material on the end of a fiber, after applying a short pulse of light to excite the material. The decay time is an intrinsic temperature-dependent property of the material, and is independent of the quality of the connections. Because of this robustness, fluorescence decay may be called one of the "best" technologies for measuring temperature. No recalibration is needed, and installation does not require particular skill. But the same principle does not appear to be easily adaptable to pressure or other measurands.

For some measurement problems these questions do not arise, because there is only one technology capable of making the measurement. It may be, for example, that blackbody sensors are the only optical fiber sensors able to measure temperatures at 900 °C, and that polarimetric sensors are the only ones adequate for measuring electric current.

These examples illustrate tradeoffs that may arise for a number of measurands. The Navy will need to confront these choices and make appropriate decisions or guide its contractors in doing so. There will likely be significant advantage to addressing these issues earlier rather than later.

2.6 Power-by-Light

It is possible to design a sensor system which appears much like a typical optical fiber sensor system and which has many of the same advantages, but in which the sensing element is an electrical sensor. In such a system, the electrical output of the sensing element is used to control an optical signal which is transmitted to the signal conversion unit. Light from a source in the signal conversion unit can be transmitted to the sensing element, converted to electrical power, and used by the sensing element. This approach to sensing is sometimes called hybrid sensing, and the transmission of power to the sensor through an optical fiber is called "power by light."

In many cases, hybrid, power-by-light sensors are not included within the scope of optical fiber sensors. Indeed, all-optical sensing may ultimately lead to simpler sensors with fewer parts. But in the present study, power by light clearly needs to be included, because it supports the principal goals of the Navy.

From an operational point of view, an optical fiber sensing element is simply a module that is connected to a remote location by fiber only, with no electrical connections. What is contained in the module and whether it is all-optical or hybrid are immaterial, so long as it reliably functions within its specifications. The chief advantage of fiber, electrical immunity, derives mostly from the fact that there are no electrical signal or power lines to act as antennae. Electrical devices inside the module can be shielded effectively without enormous cost, bulk or weight, so that a power-by-light sensing element approaches the immunity of an all-optical module.

The power-by-light approach is valuable for some measurands because it may help to create all-optical-fiber sensor systems sooner, and with better performance, than would be possible if every measurand were required to be addressed by purely optical elementary transducers. It may also offer some benefits in retrofitting existing sensors.

2.7 Discrete versus Continuous Sensing

While many sensors report continuous measurand values, others are discrete two-state devices that simply indicate whether the measurand is above or below a preset value. There are strong arguments in favor of this discrete type of sensing, because of the relative robustness of the sensors and the simplicity of the information that they produce. Two-state fiber sensors have been made and tested for the Navy, and it may well be right to use these in near-term systems. There is not complete agreement among different Navy groups on whether discrete or continuous sensors will be used on future ships, nor should there be at this stage of development.

This study serves mainly continuous devices. The authors believe that both reliability and simplicity of information can be kept well under control with future continuous devices, and that much value will be found in detailed continuous multi-sensor information as system designers use it and find ways to analyze and present it simply. Despite the belief that these trends will dominate Navy policy, the recommendations are designed in the knowledge that discrete sensing is still a viable option, and the outcome of some programs may reveal problems that favor it.

3. Impediments and Opportunities

Some of the impediments to the commercialization of optical fiber sensors identified in this study are general, in the sense that they relate to the entire fiber sensor industry or to the manner in which the Navy interacts with industry. The existence of these problems is largely independent of decisions the Navy will make about which technologies to adopt.

Other impediments are specific to particular technologies. Their importance to the Navy will depend on whether these technologies are ultimately used on ships. The issues discussed relate to technologies that the authors believe are good candidates for deployment.

Both types of impediment represent opportunities for advancement. In addition there are both general and technology-specific opportunities for progress that do not relate to clearly definable impediments.

3.1 General Impediments and Opportunities

3.1.1 Low investment incentives: Chicken and egg

Sensors in general constitute a very large market (Appendix B), although it is somewhat fragmented into many niches. It is also a competitive market, with many products available for each application, competing on cost and performance. Most fiber sensors today are too expensive to compete with dominant electrical sensors in mainstream applications. In many cases the performance (e.g., accuracy, resolution, and, especially, reliability of the measurand) is also not competitive. Fiber sensors mostly sell where these deficiencies are outweighed by the advantage of EMI immunity, or other benefits.

Fiber sensors could sell in much higher volumes than they do today if their performance and price could compete in broad markets where their benefits are attractive but not essential. In a number of cases this appears possible technically, but the enabling technology (e.g., better manufacturing techniques, improved design for manufacture, or new materials or designs that enable better performance) is expensive to develop.

Small companies, or small profit centers within large companies, experience the "chicken and egg" problem: fiber sensors are not selling in large volumes because they are expensive or have poor performance; fiber sensors are expensive or perform poorly because there is insufficient present sales volume to fund investment in improvements. This simple principle is not unique to fiber sensors, but exists in many industries. It is largely a cultural problem: companies or profit centers have quarterly or yearly financial horizons. This prevents substantial investment in areas that may ultimately be profitable, but will produce negative short-term results.

This financial impediment represents an opportunity for the Navy, because its financial horizons are longer than most industry. It should be possible for the Navy to bear or share the development risk so that a technology can be brought to the point where it can access a large market that will sustain low-cost production. Although it is not discussed in the recommendations of Section 4, innovative contracts may also make it possible for the Navy to recoup its investments by sharing in the profit if the commercialization is successful.

3.1.2 Lack of marketing and manufacturing focus

Much of the diverse fiber sensor technology that has been publicized in recent years has come from research environments that are disjointed from the kinds of people and organizational structures needed to create sellable, manufacturable products from technology. This is a part of a the same cultural problem in industry that was discussed in 3.1.1. The connections to manufacturing and to commercial markets are crucial for achieving volume and low cost.

As an example, NASA Lewis Research Center, through a number of contractors, has developed a fiber sensor system for use in aircraft control systems. This is a valuable program that has produced excellent technical results. But its end product comprises publications and reports describing the technical performance of certain types of fiber sensor systems in aerospace and avionics applications. Low-cost, volume manufacturability of sensors was not emphasized.

In development programs designed without significant attention to manufacturability, there is a good chance that decisions made early in the project will prevent the resulting designs from being inexpensively manufacturable. Furthermore, when development is done in a research organization without ties to marketing and manufacturing organizations, the human energy that went into designing a system will not usually be available to help drive it into a market and into manufacturing. This is a substantial but often ignored handicap.

Difficult technologies are often appropriately developed in an isolated research environment, so commercialization requires "technology transfer." (U.S. companies are reputed to practice this art with only limited success.) But much of fiber sensor technology is not sufficiently complex to warrant isolation from real-world marketing and manufacturing considerations. Development work can benefit if it is motivated by the promise of reward from selling products to a known market at reasonable cost and if the threat of loss from a design that costs too much or is not what the customer wants.

It is possible to link manufacturing and marketing to a funded technology development project. As an example, this is done routinely in the Small Business Innovation Research (SBIR) program. The same individuals who plan the research part of the project must be concerned about and demonstrate a path to producing manufacturable commercial products, or the project will not be funded. Because of the importance of volume production in bringing costs down, the Navy may benefit from making the commercialization requirements more stringent than the SBIR program normally does.

The Navy can and must seek more marketing and manufacturing focus in its procurement decisions, particularly at the research and development level.

3.1.3 Indirect costs discourage the use of fiber

In a complete cost analysis, it is not sufficient to include only the cost of procuring sensors. There are significant additional costs that may exceed the procurement costs. Personnel must be trained to install and maintain the sensors. An inventory of parts and supplies must be established, maintained and made available. Regular maintenance and calibration must be done.

Training and the establishment of inventory are especially expensive when a new technology is first introduced. This discourages the Navy from implementing new technologies.

This impediment can be managed by creating, for new ships, costing structures that encourage rather than discourage new technology, or by simply requiring that certain systems use fiber. These strategies do not eliminate the cost, but deal with the disincentive for designers to specify new fiber systems on ships. It may be valuable also to reduce the additional costs by using fiber and components for sensors that are specified for other shipboard systems, particularly the data network. But this strategy has a potent danger. The properties of the fiber and other components are crucial to many sensor types. For example, some sensors only work with multimode fiber, and some require single-mode fiber. Many require specific wavelengths of operation. Requiring that particular components be used for fiber sensors would seriously limit the technology options and would be likely to impede progress and increase costs, instead of facilitating deployment.

3.1.4 The Navy's volume requirements are low

If we assume that two ships per year are produced with 5,000 sensors per ship and that the average hardware procurement cost per sensor is $500, then the market for shipboard sensors is $5 million per year. An annual market this size is marginally attractive to some manufacturing companies but unattractive to most.

But assume further that the market encompasses a substantial number of different sensor types, each requiring different engineering and manufacturing. And assume either that there is serious competition or that it is uncertain whether the customer will stay with the technology that is initially chosen. Each of these assumptions increases the uncertainty in the sales volume that can be achieved. It then becomes clear that this market is simply too small, perhaps by a factor of 5 or

10, to entice many or most companies to develop custom products to be sold only to the Navy.

A market this small can be much more attractive if the vendor feels confident of dominating it without competition and if the research and development investment risk is shared by the customer. But these advantages are also needed to offset the common current expectation of low margins due to government pricing practices and the high manufacturing cost associated with military specifications.

This impediment is reduced to the degree that the Navy can use or adapt standard products targeted at other, larger markets. Commonality with other markets represents an opportunity that the Navy can exploit.

3.1.5 The Navy is not perceived as an attractive partner

It became apparent, in a number of interviews, that the Navy was not perceived as an attractive partner in technology development, at least in the area of optical fiber sensors.

Manufacturing companies are not attracted by contract research, unless they can see a clear potential to develop a product that is sold in volume. In the view of many companies, the likelihood that the Navy will place significant orders for a cooperatively developed product is low.

It is important to recognize that a manufacturing company is structured very differently from a contract engineering organization. In a manufacturing company, a project that generates only contractual development expenses with overhead but does not lead to a product sold in volume, actually loses money as well as opportunity. The company needs, instead, to create products that will generate sales of at least twenty times the development costs over their lifetime.

The financial loss is very real, even if the Navy funds the development project. A manufacturer is not set up to survive on margins from contracts to its engineering department. Only volume manufacturing can generate the quantity of revenue needed to support the sales, marketing, production, administration, R&D, and other parts of a manufacturing company, and provide some profit. If the company is not confident that a Navy project is very likely to lead to a volume product with good margins, the project should not be undertaken. This confidence is missing today, and the lack extends beyond manufacturers to the financial community. Holding a Navy contract used to make it easy to get a bank loan. That is no longer true.

Two other perceptions are raised here with caution, because the reasons behind the perceptions have not been thoroughly studied and the authors are not able to judge their validity. However, whether they are based in fact or incorrect information, the perceptions cited below are real, and they influence industry decisions about cooperation with the Navy.

It is perceived that, in the area of fiber sensors, the Navy has different internal groups with strongly differing views vying for power and funds. One result of this may be a lack of constancy or reliability in developing and maintaining a direction.

Some companies also perceive that the Navy lacks respect for intellectual property rights. Companies that invest heavily in the creation of intellectual property and seek to maintain that property are reluctant to submit research and development proposals to the Navy.

The Navy needs serious manufacturing partners to develop and produce reliable sensors at low cost. To attract them, it must address these perceptions.

3.1.6 Network design constraints are important but unclear

If shipboard sensor systems could be thought of as a collection of independent single-sensor modules, sensors might be selected independently of network design considerations. But that approach is probably uneconomical for many measurands, as explained in Sections 2.3 and 2.4. Some kind of multiplexing of signal conversion subsystems is necessary in order for fiber sensor technologies that are good technically also to have acceptable cost. Multiplexing creates architecture and topology problems that must be considered in the choice of systems. Besides cost, survivability and reliability are key concerns.

The Advanced Optical Sensing System (AOSS) project was executed with a star network topology. Independent of other merits of the system, some observers believe that the star topology has poor survivability, in that damage at a single point can disable a large number of sensors.

Network design criteria and constraints may be clear within certain areas of the Navy, but they are not clear to the engineering and manufacturing organizations that the Navy needs to motivate. This can diminish the convictions that potential partners need to participate in Navy programs and could contribute to the impediment described in Section 3.1.5.

Most of the focus of fiber sensor manufacturers is on individual sensors for specific measurands and not the network concerns that affect the Navy. This may or may not be an impediment to the widespread commercialization of fiber sensors, but it will be an important impediment to the needs of the Navy, unless the network aspects of the Navy's sensor needs are emphasized. This can be done by appropriate design of specifications and development projects.

3.1.7 Optical switching for multiplexing is expensive

As explained in Section 2.4, multiplexed signal conversion is a key strategy for reducing the costs of fiber sensors. But in order to implement multiplexing, many sensor types will require optical switching, which will add to the cost and cancel some of the advantage gained by multiplexing. The appropriate switch type is a "1 × N" switch, where N might range from 4 to 100. High-speed switching is not essential. Loss, repeatability, and reliability are important technical issues that interact with cost. A recent estimate by a manufacturer suggests that such switches can be sold commercially for a cost of around $250 per channel with present technology, depending on volume. This is a substantial part of the $500 per channel that the Navy would like to spend on sensors. The real cost will be significantly higher if the manufacturer of the final sensor system does not build the switch, but purchases it as a separate component from another vendor, and then adds margin before selling it to the Navy.

Much work is being done on switching for telecommunications, but the requirements are not always the same as for sensor multiplexing. For example, N × N operation is of interest, as are high speed (millisecond to sub-microsecond) and very high speed (nanosecond or sub-nanosecond, synchronous with data streams). A particular area that has synergy with 1 × N sensor multiplexing is switching designed for automated testing, in both manufacturing and field environments. To date, volume requirements have not been adequate to drive costs down, but this may change soon. Remote-controlled testing of installed fiber links is promising to use large numbers of 1 × N optical switches, and there is pressure for the cost per channel to come down toward $50 (which may be feasible) or even $10 (which may not).

3.1.8 Optical components and assemblies are expensive

Sensing elements for fiber sensors are not always expensive, but some of the optical components used in other parts of a fiber sensor system (e.g., the signal conversion subsystem) are usually costly. These components include light sources, light detectors, couplers, lenses, filters, polarizers, modulators, and connectors. Also, it is often expensive to manufacture assemblies of optical components. This is especially true when they are miniature or involve precise alignment.

In high-volume industries, manufacturing engineers have substantial experience in working with suppliers to take advantage of volume to reduce cost. There are a few examples where this has been effectively applied in the fiber sensor industry, but they are rare.

In cases where a specific sensor may never be made in such high volume, it may still be possible to benefit from high-volume components or assembly techniques directed at other markets. The telecommunications market is the most prominent example. Sources, detectors, couplers, connectors, and assembly methods are definitely less expensive because of the volume of telecommunications applications.

3.1.9 Packaging dominates cost

Packaging is a substantial part of the broader issue in Section 3.1.2 above. It is becoming increasingly apparent within the optical electronics community that a major issue in developing markets for components is the cost of packaging. There appears to be a consensus among those knowledgeable in the manufacture of laser diodes, detectors, and various types of active and passive devices that packaging costs average 75 to 80% of the manufacturing cost of the component. Research and development work in this area is accelerating rapidly; the number of conferences and the body of technical literature in this area are growing rapidly.

Much of the cost associated with packaging relates to the alignment of optical components to tight tolerances and maintenance of that alignment in demanding environments. Most alignments (a fiber pigtail coupled to a laser diode, for example) are now accomplished actively; that is, the transmitted light is monitored as the pigtail is attached. Most often this is performed manually, by a highly skilled technician. Automatic techniques have been developed for some operations, but have not been widely adopted. Many in the field believe that the costs associated with packaging cannot be reduced substantially until passive alignment techniques replace active techniques. Some progress in this area has occurred, particularly the use of micromachining technology to create accurately positioned grooves and other structures in device assemblies.

3.1.10 Many optical fiber sensors are not measurand-specific

The abundance of effects that make optical fiber sensors possible is also a problem. Optical and other properties of materials depend on temperature, stress, electric and magnetic fields, among other stimuli, and sensors respond to more than one of these at the same time. The unwanted effects may arise in the sensing element or in the fiber leads that connect the sensing element to the signal conversion unit.

This problem is not unique to optical sensors; other sensor technologies must be concerned with measurand selectivity. Optical sensors may or may not be more prone to this problem. Nevertheless, optical fiber sensor technology is certainly not sufficiently mature to have resolved these problems.

Some sensor technologies, such as the fluorescence-based temperature sensor described in Section 2.5, provide excellent selectivity. Unfortunately, sensors with intrinsically good selectivity are less likely also to offer the advantages of a common technology for several measurands.

The Navy's long term goals would be well served by searching for and supporting technologies that can potentially minimize these problems.

3.1.11 Prior Navy work can be exploited

The Navy has been a leader in developing optical fiber sensor technology since the early 1980's. A brief listing of some key Navy projects is included below in this report, because these past programs and the experiences of the personnel who executed them constitute assets that the Navy and its industry partners can exploit to help introduce optical fiber sensors into the fleet. While it is not true in all cases, the authors have found evidence of a tendency for some Navy work to be commissioned, executed, and then forgotten, even though some of the results may be quite pertinent to newer programs. The Navy's optical fiber efforts have recently endured shifting organizational structures and centers of influence. A highly centralized approach to managing optical fiber work in the late 1980's had mixed results. In the aftermath, as noted in Section 3.1.5, there are different groups executing different projects with what appears to some people to be competition rather than communication and cooperation. The authors believe that certain actions discussed in Section 4, not involving organizational changes, can enable the Navy and the fiber sensor industry to glean considerably more value from past and present programs.

In 1986, NAVSEA began a program to develop specifications and standards for components required in shipboard optical fiber systems including both communications and sensor applications. The goal was to standardize on a few components that are qualified to operate in the shipboard environment. About 15 specifications have been approved to date, all pertaining to fiber, fiber cables, transmitters, optical receivers, etc.

In FY92, NAVSEA started the Fiber Optic Sensor Specifications and Standards Program. The goal is to specify and demonstrate optical fiber sensors for direct replacement of electrical sensors. Draft specifications are being developed for six sensors — pressure, temperature, voltage, current, position, and shaft RPM — with specifications for liquid level, salinity, chemical gases, and multiplexing to follow.

In 1987, 31 optical fiber sensors were installed on the USS MOBILE BAY (CG53) in a trial damage control system. The program, called AOSS (Advanced Optical Sensing System), was intended to provide three years of experience in operation and evaluation. The sensors were threshold sensors for temperature, rate of rise of temperature, smoke, and flooding. The system performed well and remained on the ship for several years.

The Fiber Optic Control Systems Integration Program (FOCSI) is an eight year joint program of NASA and the Navy Air Systems Command to develop and test a fiber sensor network for use in aircraft control systems. The network will involve 19 sensors, produced by 9 companies, in propulsion system and flight control monitoring. The program will culminate in a flight test during 1993. If the flight test is successful, the FOCSI program will have demonstrated that optical fiber sensors can be operated in the combat aircraft environment (one that is very similar to the shipboard environment), providing improved sensing capability with added advantages of reduced EMI, reduced weight, and reduced electrical shock and fire hazard.

Over the last decade, the Naval Research Laboratory developed the All Optical Towed Array (AOTA) and tested it. The program demonstrated that optical fiber sensors can be designed for, and operated in, the shipboard environment. Indeed, performance exceeded that of conventional technology arrays. The authors understand that the Navy has chosen not to deploy AOTA's on operating submarines at the present time. The authors are not familiar with all of the reasons for this decision, but some Navy personnel believe that costs, including especially the indirect costs discussed in Section 3.1.3, were among the considerations.

3.1.12 Opportunities for synergy: Aerospace, power, automotive

Regarding the potential benefits of using technology that has other applications, at least three industries seem to have common interests with the Navy.

Applications in the aerospace industry have similar requirements in measurands and in reliability, though they will probably not involve networks on the same scale. Most of the major aerospace companies already have substantial programs in fiber sensor technology, and there is a substantial history of collaborations through contract/subcontract structures.

The electric power industry also has similar requirements in measurands and may well benefit from work on sensor networks. Perhaps most importantly the power industry has an independent organization, the Electric Power Research Institute, through which research and development programs could be planned and managed.

Finally, the automotive industry shares requirements in sensor reliability and provides market sizes that could lead to substantially lower costs.

These industries are large, but are only examples. Synergy may also be found in other markets which, even if smaller overall, require substantial volumes of particular sensor types. The obvious opportunity is in cooperative development with organizations in these industries. Another valuable opportunity lies in the potential for motivating a manufacturer in a cooperative development program. Although funding might be provided for a sensor specifically for the Navy, the greatest attraction might lie in the volume that could be sold to some other market. This is no disadvantage to the Navy, because the volumes would help to lower the cost.

3.2 Technology-Specific Impediments and Opportunities

The authors believe that there are a number of technological barriers which, if overcome soon, could have a substantial impact on the near term commercial availability of specific types or categories of fiber sensors. These barriers can be appropriately viewed as impediments or opportunities; most often they are both.

Six such examples are discussed below. They were selected because they address one or more of the following issues: sensor performance; sensor cost; the use of common technology for several measurands; and robustness, including especially reliability and selectivity. This should not be regarded as a complete list. The Navy is strongly encouraged to refine the criteria and to adjust and extend the list. Because technology can move rapidly, some of the information in this section of the report may be out of date shortly after publication.

3.2.1 Spectral modules

Widely varying types of measurands and of sensor design types can be served by broad spectral illumination combined with spectral analysis of reflected or transmitted light. Several examples follow below.

Interference cavity sensors, discussed in Section 2.5, can be used to measure both temperature and pressure. They are presently monitored by measuring the intensity of reflected light in just two wavelength regions. A modified sensor design (a different cavity size) combined with detailed measurement of the reflectance spectrum (e.g., at 10 wavelengths or more) could improve the accuracy and repeatability, and make the device less sensitive to reflections in connectors.

Encoder plates for position measurement can be read by determining the presence or absence of reflectance from different channels. (Transmission may be used also.) There may be typically 6 to 14 channels. To multiplex all of the channels onto a single fiber, it is convenient and potentially inexpensive to assign a different wavelength to each channel. Broadband light travels down the fiber, the wavelengths are separated at the primary transducer and recombined after reflection onto the same fiber (or combined after transmission onto a different fiber), and the returning spectrum is analyzed at the secondary transducer. Encoders can be used for a number of measurands because elementary transducers can convert various phenomena into position changes.

Chemical sensing often relies on spectral information. Spectral modification by the chemical or by molecules that interact with the agent to be detected can be accomplished by a number of means, including direct transmission via bulk optics, evanescent wave absorption in a planar waveguide device, and transmission through a porous optical fiber permeated with the medium to be analyzed. Any of these techniques can use reflection (the light will then make two passes through the active medium) to bring the spectrum back on the same fiber that caries the incident light. The optimum wavelength region may vary significantly for different reagents.

All of these techniques, and others, could benefit from technology that makes broad spectral excitation and detailed spectral measurement less expensive, more manufacturable, and more compact. This is recognized in the industry, but there has evidently not been clear enough incentive for the investment.

Incentives do exist in telecommunications for creating detector arrays with means to direct different wavelengths to different devices. This is largely driven by the advent of doped-fiber amplifiers, which enable massive wavelength-division multiplexing at low cost. (The amplifiers boost a moderate spread of wavelengths, so that wavelength-division multiplexing must be done only at the transmitter and receiver, and not at each booster station.) Although the wavelength range of telecommunications devices is specialized, the designs may be adaptable to other regions. Compact spectrometers have been developed for chemical process control also.

3.2.2 Power-by-light systems

In a power-by-light sensor system, the sensing element generally includes a power receiver that efficiently converts optical power to electrical, an electrical sensor subsystem, and an optical transmitter for the sensory information. The signal conversion will generally include an optical power source, plus a receiver for the sensor information. A key challenge is how to deliver enough power for the sensor subsystem and the transmitter.

One approach to the problem is to use a very powerful light source. This is being done commercially by at least one company that the authors have investigated. The product does not include sensors, but is limited to the optical source and the receiver that converts optical power to electrical. These commercial units may be used as building blocks for adapting existing electrical sensors.

Another approach to the problem is to keep the power of the optical power source low (e.g., use a light-emitting diode) and devise a special sensor and transmitter that have very low power requirements. At least one laboratory has done this for position sensing with pulsed reactive dividers, which require extremely low energy per measurement and offer good immunity to temperature and other environmental parameters.

Navy applications could be served by either approach or a combination. The work needed to realize this opportunity for some measurands appears to be of a predictable developmental nature rather than research.

3.2.3 High temperature sensor technologies

The Navy needs high temperature measurement capability for both damage control monitoring systems and condition-based maintenance systems.

For its damage control monitoring systems, the Navy's highest priority is for sensors capable of measuring temperatures from room temperature to the highest temperatures (1100 °C) encountered in fires. These sensors are required for fire detection and for monitoring cool-down temperatures to avoid flash-over accidents. Optical fiber sensors were tested over two temperature ranges of 0 °C to 400 °C and 400 °C to 1100 °C in a program sponsored by the Office of Naval Research in 1992. The tests successfully demonstrated the operability of optical fiber temperature sensors in the shipboard environment; however a major impediment to broad scale application in damage control systems is the lack of a single sensor to measure the range of 0 °C to 1100 °C.

For its condition-based maintenance systems, the Navy requires measurements of the temperature in the hot sections of internal combustion engines. This will provide essential information for detecting and predicting the health of machinery to change the maintenance approach form time based to need or condition based, resulting in large savings and increased fleet readiness.

Several optical fiber technologies potentially provide the possibility measuring temperatures over the range of 0 °C to 1100 °C in a single instrument. They include blackbody sensors, combined fluorescent and blackbody sensors, rare-earth optical absorption sensors, Raman backscatter sensors, and Fabry-Perot cavities. Each technique requires additional development and engineering to overcome operating impediments.

The optical fiber blackbody temperature sensor, made commercially by several companies, is a particularly attractive technology for measurement of the highest temperatures. It analyzes emissions from the tip of a sapphire rod that acts as a waveguide.

The sapphire "fiber" that guides radiation from the emissive tip to the signal conversion unit is actually a short rigid rod. In damage control applications, attaching the signal converter directly to this rod and locating it on the adjoining wall of an adjacent compartment is not acceptable to the Navy. It might not endure the heat transmitted by the wall during some fires; it probably has inadequate deployment flexibility to meet survivability requirements; and it would severely limit multiplexing of the signal converter. One solution is to use flexible fiber cable between the sapphire rod and the signal converter. Another solution is to use a complicated network architecture that employs redundancy of cable and processing systems.

Today, flexible sapphire fibers are not available, so silica fibers must be used. Unfortunately however, using silica fiber in this way limits the low temperature performance of the blackbody sensor because silica does not transmit the longer wavelength infrared radiation. Thus, even though it has the intrinsic capability of measuring temperatures over a wide range, perhaps nearly down to room temperature, in Navy applications the blackbody sensor would be restricted to only high temperature applications.

There are two direct solutions to this problem. One is to develop thin, flexible sapphire fiber that can transmit the longer wavelengths and can be fabricated in lengths of at least several meters. Cost and scattering loss are key issues. The other is to find ways to measure lower temperatures using the shorter wavelengths of light that common silica fiber can transmit. Measurement at 100 °C has been achieved recently, and there is hope of going lower.

Another method of extending the operation of a blackbody temperature sensor down to room temperatures is to employ a second measurement technique for a lower temperature range. Fluorescent decay time temperature sensors do not function at temperatures above about 400 °C but survive hotter temperatures. In this way two temperature sensors could be designed in one package that covers the full range. The fact that there are two temperature sensors resident in one package can be transparent to the operators. The major impediment with this technique is probably cost.

Rare-earth elements can be used as dopants in designing optical fibers that selectively absorb optical power as a function of wavelength. This kind of spectral absorption technology is particularly attractive as a potential sensor design because of its simplicity, implying very low cost. It would operate from room temperature to 1100 °C, if the silica fiber can be made to survive. Several university and private laboratories are getting outstanding results with coating fibers with metal, allowing operation to above 1000 °C for short periods of time.

Raman backscatter temperature sensors have been implemented with optical fibers for many years. They offer the prime advantage of time division multiplexing temperature measurements along the length of a fiber that might be 10 km long with measurement resolution along the fiber of a few meters. One system might instrument an entire ship. Measurement at high temperatures has been impeded by the formation of microcracks in the fiber causing high noise signals that overcome the Raman signal. The use of metal coated fiber technology offers a probable solution to this problem that might allow operation to above 1000 °C for short periods of time.

Fabry-Perot cavities have been used to measure temperatures for several years and are available commercially in packages suitable for the shipboard and industrial environment. The present maximum temperature measurement capability is 400 °C; it might be extended to 1100 °C through the use of different fabrication techniques for the sensor element. These might involve use of mechanical packaging as a substitute for low temperature glues or high temperature ceramic epoxies. The development and use of metal-coated fibers or flexible sapphire fibers would also be required.

The Navy also needs sensors for other measurands, for example pressure and liquid level, that will perform well at high temperatures. Many of the issues associated with developing sensors for measuring high temperatures apply to these other measurands, as well.

3.2.4 Polarimetric sensing

It is nearly certain that polarimetric sensors will be included in the network of sensors in future ships, principally because polarimetry is the primary method of measuring electric current and voltage. Polarimetric techniques could be applied to other measurands as well, but these other uses are much less certain.

Polarimetric sensors are those in which the measurand acts to change the polarization of light propagating in a fiber or other optical component, such as certain crystals. The change in polarization is usually converted to a change in optical transmittance, which is measured with a laser source and an optical detector.

The Navy is already developing specifications for optical fiber current sensors, and specifications for voltage sensors are anticipated. While these specifications do not dictate specific technology, polarimetric techniques are presently the leading approach to the design of such sensors.

In polarimetric sensors, one large portion of the cost is associated with the optical components that provide a controlled state of polarization to the sensing element and that analyze the polarization state of light returning from the sensing element, and with their assembly into rugged and reliable systems. The components include polarizers, waveplates, couplers, and lenses.

Another large cost is associated with providing a laser source with high spectral stability. The stability of polarimetric sensors usually varies inversely with the source wavelength or its square. Most diode laser sources shift wavelength with temperature. Usually the required stability is achieved by mounting thermoelectric coolers on the sources, but this represents a substantial cost in components and assembly, and results in a larger, heavier signal conversion unit than would otherwise be necessary.

These problems are ripe for attack using advances in integrated, hybrid, and micro-optic technology.

3.2.5 Bragg-grating sensors

On ships of recent vintage, as many as 75% of the sensors measure temperature or pressure. These quantities are the obvious first target for the development of suitable sensors. And if a common technology can be used for just these two parameters, the attendant benefits would have been achieved in a large fraction of the sensor network. Fiber Bragg-grating sensors seem to be a candidate for achieving these goals.

Sensors that monitor the spectral reflectance of an interference cavity can also measure both temperature and pressure using a common technology. The Navy has studied this technology and should continue to do so. Bragg technology is discussed here because the authors believe it deserves the Navy's attention.

Fiber Bragg gratings are refractive index gratings (periodic variations in the refractive index) permanently induced in optical fiber. These gratings reflect light only at very specific wavelengths determined by the periodicity of the refractive index variations. This periodicity is affected by temperature and pressure, so that, if they are illuminated with spectrally rich light, the wavelength of the light reflected from the grating is related to the measurand. Spectral sensors such as these have the advantages of being relatively immune to variations in the amplitude of the light.

They should also be easy to multiplex, using components and techniques used for wavelength division multiplexing in communications systems. One concern about such multiplexing schemes is that each sensing element in the system would be unique, leading to increased inventory.

Fiber Bragg gratings offer the potential of being very inexpensive to produce. Research aimed at very rapid manufacturing, on line with fiber production, is showing considerable promise.

It is challenging to make a fiber Bragg-grating sensor that responds to just one measurand (temperature *or* pressure) and not the other. Techniques to overcome this limitation have been proposed, and seem promising, but have not been thoroughly evaluated.

3.2.6 Low-coherence technology

Low-coherence technology involves the use of spectrally broad (low-coherence) sources in interferometric configurations. If light from a spectrally broad source passes through an interferometer with a path difference greater than the coherence length of the source, no interference is observed. But if the light exiting that interferometer passes through a second interferometer identical to the first, so that the total path difference through the two interferometers is less than the source coherence length, interference effects can be observed. If the second interferometer can be tuned to maximize the interference signal, by keeping its path length difference equal to the first, a means of measuring a variable path difference in the first interferometer is obtained.

Because the path difference in an interferometer can be contrived to depend on many different parameters, this technique provides a means of measuring those parameters with nearly identical technology. Furthermore, in principle, such measurements are independent of effects that occur between the two interferometers, a problem noted in Section 3.1.10.

Because of the high spatial resolution it provides, low-coherence technology has begun to be exploited commercially in instruments designed to characterize optical components and assemblies. Research into suitable sensor configurations and their properties is underway, but commercialization of sensors does not seem imminent.

4. Recommendations

The authors believe that the impediments and opportunities described in Section 3 can be addressed, and many of them must be addressed successfully in order to make cost-effective optical fiber sensors available to the Navy soon. The authors also believe that the recommendations described below will be both effective and efficient. A number of different approaches may be possible, however. Whatever methods are used, the most important thing is to address the challenges of Section 3 successfully.

The Navy has recognized some of the problems described in Section 3 and is already taking actions similar to some of the recommendations below. This document makes no comprehensive analysis of the Navy's present strategies and programs, and does not attempt to avoid recommendations redundant with present Navy programs. Instead, the authors have tried simply to present a fairly complete set of strategies.

Where there is overlap, the recommendations below may be taken as confirmation of present Navy strategies. But this conclusion should not be drawn too readily. Seemingly small differences in the design of a strategy can make profound differences in its success. Consider, for example, recommendation 4.1.3 about managing information and communication. The Navy certainly does this. But the recommended openness, blunt questions, and legitimacy given to opposing views are less common in the Navy than in industry. These features could make a substantial difference in industry cooperation, because they are more closely aligned with successful modern corporate cultures. To date, the total progress of joint efforts by the Navy and industry towards viable, inexpensive fiber sensors has been disappointing. To improve the record, the Navy should look not only for major new approaches, but also for small but significant adjustments or changes in emphasis of some of the fundamentally sound strategies in effect today.

4.1 General Recommendations

The recommended strategies in this section are expected to benefit the Navy independently of what specific sensor technology is chosen for each measurand. A number of them attempt to reduce costs and increase experience by increasing the manufactured volume of a particular type of sensor, either by spanning other markets besides the Navy or by decreasing the likely number of sensor types to be used by the Navy. Some recommendations are suggested management tools for creating awareness and attitudes that will steer sensor work more efficiently towards the right objectives. Others target general technical problems that affect costs for a variety of fiber sensor technologies.

4.1.1 Exploit large markets.

The Navy should:

a. Understand the sensor needs of aerospace, electric power, automotive, and other industries. Find those requirements that have enough synergy with the Navy to show promise of commonality between a product that the Navy needs and a product that another industry can use.

b. Identify technologies likely to meet these common needs. Verify these perceptions with the market.

c. Provide funding, either alone or in cooperation with other industries, for development of the needed sensors. Help the contractor by bearing some of the investment risk, but use the attractions of the larger market, outside the Navy, as a primary tool for motivating the contractor. Require that the contractor be a proven manufacturer, with intentions and a credible path towards manufacturing for and marketing to the larger market. Manage the development in cooperation with representatives from the larger market, to ensure applicability.

The goal of this recommendation is to make fiber sensors much less expensive than they would be if the Navy paid for custom development and manufacture of sensors just for its own specific needs. It is a cornerstone of the recommendations in this report. Low-cost, high-volume manufacturing will not be achieved in a custom sensor, simply because the Navy's volume requirements are not high.

4.1.2 Establish joint service development programs for optical fiber sensors.

The Navy should take the initiative in searching for similar sensor needs within the other services and NASA. Where such needs are identified, the Navy should promote the establishment of joint development programs. A long-term objective should be the establishment of common DoD sensor specifications.

One precedent, which might serve as a model of a suitable management structure, is the Joint Services Automatic Testing Program, which coordinates efforts among the three services to develop testing techniques. Another possible model is the Calibration Coordination Group, which serves to provide for the calibration and metrology needs of DoD.

The goals of this recommendation are the same as for recommendation 4.1.1: cost reduction through the use of technology that has other applications and therefore the possibility of greater volume manufacturing. As in recommendation 4.1.1, the development programs should be closely tied to manufacturing capability, in order to avoid the problems of Section 3.1.2.

4.1.3 Manage information and stimulate communication.

The recommendations below should be read as examples of methods for stimulating a better access to information and better communications regarding technology development within the DoD. Different or better methods might be devised to achieve the same goals.

For managing information, the Navy should compile and constantly maintain an inventory that catalogs the status of fiber sensor technologies and designs and the programs associated with them. The inventory should be visible to all personnel close to the work, including outside contractors. As an important operating principle, when there are substantial conflicting views about the value or conclusions of particular work, different views should be included in the inventory, instead of just a single doctrine.

The proposed inventory has the form of a document that would be revised and circulated at regular intervals, probably yearly and with supplementary updates at other times when appropriate. Brevity and clarity are crucial to its usefulness. It should provide the reader with a fresh summary of the Navy's technological assets and key unanswered questions, in a relatively short time. For each technology or system, the inventory should contain direct answers to the following questions:

a. Is the technology ready for deployment? Are there specifications and successful operational test results? Is there a vendor that is known to be able to manufacture the technology in volume at acceptable cost?

b. If it is ostensibly ready but is not being used, why not? Are there substantial reservations about its suitability? If so, what are they, and who holds them?

c. If it is not ready, what are the key problems? Does anyone believe they are surmountable? Are efforts being made to surmount them? Why and by whom; or why not?

Periodic answering and reviewing of direct and pertinent questions like these is an effective management tool that can help ensure that valuable work is not lost or abandoned for weak reasons. By sharing this inventory with industry, the Navy will clarify its needs and help to generate the conviction that is needed for industry to invest resources. By including the questions above, the Navy will underline, both internally and externally, that the final goal of any project is deployment.

Promoting communications both within the Navy and with industry should be a continuous priority for those charged with the introduction any new technology into the fleet. Much can be achieved simply by emphasizing the need for good communications at all levels of management.

The Navy has legitimate concerns about close communications with industry, both for security and because of concerns about neutrality in procurements. Within these boundaries, the Navy should actively promote communications with industry as a means to identify potential partnerships and as a response to the impediments noted in Section 3.1.5.

The Navy has experimented in the past with topical conferences on fiber sensors. These seem to have been discontinued. A regular topical conference involving both Navy personnel and industry representatives would seem to be a highly effective means of stimulating communications. Perhaps, rather than initiating a new meeting, a session or sessions attached to another conference would be more efficient. The biennial DoD Fiber Optics Conference seems to be a logical choice.

The authors believe that a disciplined approach to managing information and communications can make a significant difference in the value that the Navy and industry derive from past and current Navy programs, and can substantially facilitate internal and external cooperation and more consistent directions in the Navy's fiber sensor programs.

4.1.4 Coordinate fiber sensor work with network design programs in the Navy.

The Navy practices this recommendation in many of its programs. It is important because many decisions need to be made about which technologies to fund, develop, and use. Input from designers of network systems will be crucial in making these decisions correctly. As discussed in Section 3.1.6, an early decision that saves cost through multiplexing, but is later found to conflict with network considerations (particularly survivability), may result in wasted effort.

Attention must be given to including this coordination in new programs, particularly because the manufacturers the Navy needs to work with are not knowledgeable about the Navy's network requirements, as discussed in Section 3.1.6. Coordination does not need to be expensive, and can be as simple as including data network experts in key sensor planning and review meetings, with the task of identifying possible conflicts with current network strategies. Efforts to keep industrial partners aware of network issues can be incorporated into the activities of recommendation 4.1.3.

4.1.5 Develop specifications for a sensor network of limited scale for hull, mechanical, and electrical systems. Execute an advanced technical demonstration project. Deploy the system.

It is premature to create specifications for a complete sensor and communications system. But, as explained in Section 3.1.6, the authors believe that it is dangerous to think of sensors only as independent components, isolated from network concepts. One cannot know what unexpected problems will be discovered when a sensor network is actually built and evaluated not only on its sensing capability, but also with respect to broader network criteria, including survivability, and the total cost of integrating it with a network.

The objectives of the specifications and demonstration project should be to create real, high-performance systems at reasonable cost that the Navy will be expected to use in ships. The only differences are that the set of measurands will be limited, and the communications network will not be expected to be in final form. But another important goal of the whole exercise, which is harder to control or measure, is to *position* the Navy early to discern issues relating to sensor networks. There are many sensor technologies to choose from, and this project will reduce the danger of devoting considerable resources to a technology that later proves to have a fatal flaw.

The sensor specifications should be sufficiently general to give the contractor the latitude to study several technologies before selection. The communications interfaces for the sensor subsystems, and the general topology of the data communications network, should be specified consistently with the present state of optical fiber communications network design in the Navy. (It may be impractical, and not as important, to make higher levels of the communications network also consistent.)

The demonstration project includes both the hardware creation and testing. The deliverables (including results of Navy testing) should include the following elements:

a. Manufacturing cost analysis.
b. Installation cost analysis.
c. Complete cost analysis for a large-scale system.
d. Sensor performance evaluation.
e. Survivability assessment.
f. Analysis of limitations imposed by multiplexing.

In defining and executing the overall specification and demonstration program, the Navy should focus on at least four internal objectives:

a. Create fiber sensor subsystems as a step toward complete systems.
b. Discern network issues, and begin to address them.
c. Seek, test and demonstrate more effective ways to work with contractors.
d. Bolster the Navy's reputation in the sensor industry.

Objectives a and b are part of the philosophy discussed in Section 2.1 of a multistep approach to the introduction of shipboard sensors, with an emphasis on positioning the Navy to introduce large-scale sensor systems.

Objectives c and d are closely related; essentially objective c serves d. Certainly, the Navy already knows many effective ways to work with contractors. But the perceptions discussed in Section 3.1.5 remain. Furthermore, effective relationships between vendor and user are a particularly effective means of acquiring low-cost products. Because the economic incentives to work with the Navy are relatively small, as explained in Section 3.1.4, a special effort should be made to find creative ways to make cooperation profitable to industry.

To obtain the full benefit of this recommendation, the system developed should be deployed on an active ship for a significant period of time. Only then can the performance of the system be fully evaluated and the costs and benefits demonstrated.

4.1.6 Systematically monitor sensor costs. Balance development investments with expected reductions in sensor costs.

As a tool for managing the costs of sensor systems, the Navy should assemble estimates of costs associated with each type of sensor that is under consideration for future ships. These should be revised and reviewed periodically, and circulated widely as a means of keeping cost issues prominent.

The information that is compiled should include the following:

a. Estimated unit costs for procurement.
b. Assumptions about manufacturing volume.
c. Assumptions about schemes for multiplexed signal conversion.
d. Assumptions about the stage of development, including the investment necessary to reach the state for which the estimate applies.
e. Estimated installation costs.
f. Estimates or discussion of cost reduction that could be attained with additional development.

Where appropriate, different estimates should be compiled with different assumptions. In particular, it will be valuable to compare unit costs for volumes based on the Navy's needs to volumes that include some other larger market that has a realistic chance of being served by the same sensor.

This regular exercise can be integrated with recommendation 4.1.3. The inclusion of industry partners or potential partners in the circulation will confront them with the Navy's challenges, establish dialogue, and motivate them to help find solutions. It is expected that this may help the Navy to find other markets that can, by means described in recommendation 4.1.1, substantially reduce costs. It is also expected that this will lead to revision of some of the Navy's cost targets. For example, a target of $500 per sensor (as indicated in H. K. Whitesel, William F. Zeller, and Catherine A. Miller, *Sensor Requirements and Technology for Damage Control*, Report DTRC-PAS-90/7, June 1990) may require too expensive a development program to achieve for some measurands. The Navy may decide that it is cheaper, and motivates industry better, to be willing to pay six times that cost per unit, especially when the Navy dos not need many of that type of sensor.

4.1.7 Study multiplexing and switching. Define and execute programs, coordinated with other sensor work, to exploit the potential cost savings.

The Navy should select some number of promising sensor technologies, and, in cooperation with representative manufacturers for these technologies, do a study of the likely costs in relation to multiplexing and switching. For each sensor, assumptions should be made about manufacturing volume, and the following questions should be studied:

a. What cost can be achieved without multiplexing?
b. What multiplexing schemes are viable for the technology? Are they consistent with network design and survivability strategies?
c. What changes in costs can be expected for the most promising multiplexing schemes?
d. If the favored multiplexing schemes use switching, what part of the cost per channel is in the switch mechanism?
e. If the switching cost is significant, what avenues can be pursued to reduce it?

This exercise should create background and expertise within the Navy to allow multiplexing strategies to be wielded effectively as tools for cost reduction. If recommendation 4.1.7 is implemented, this work should probably be integrated with it; but the conclusions about multiplexing should not be simply buried in the broader cost analysis.

If multiplexing is deemed a valuable strategy, it is important to have at least one engineer/scientist and one manager become expert on the subject in a general way. But the Navy's ability to glean value from this expertise will depend on internal communication and cooperation of the kind that other recommendations in this report are designed to create, including Sections 4.1.2, 4.1.3, and 4.1.4.

If, as the authors suggest in Section 3.1.7, multiplexing proves to offer significant cost reduction that is nevertheless limited by switching costs, then the study described above should provide the conviction needed to define a program for reducing the cost of switching (or any other impairment to multiplexing that is discovered). Such a program may involve cooperation with other sensor users (see Sections 4.1.1 and 4.1.2) or with switch users in other industries (see Section 3.1.7).

4.1.8 Reduce costs of optoelectronic packaging.

The Navy should seek an effective and efficient means by which it can help to speed the reduction of costs in optoelectronic packaging.

Progress in this area is probably the single most important development that could lead to the reduction of manufacturing costs for fiber sensors, as discussed in Section 3.1.9. But it is a broad and difficult problem that exists well beyond the sensor industry and the Navy.

The authors are unable to make a more specific recommendation at this time, other than that the Navy may be able to encourage a DoD-wide response to the problem. It is perhaps obvious to say that ARPA would be a logical focal point for an effort to address optoelectronic packaging. The authors further believe that addressing broad problems such as this may be appropriately supported by recently available "defense conversion" funding.

4.2 Technology-Specific Recommendations

The following recommendations are aimed directly at the technological barriers cited in Section 3.2. The authors believe that these are appropriate responses with a reasonable probability of success and that they will, in any case, provide valuable steps forward. But just as with the identification of the barriers themselves, this is not a completed process. The Navy is encouraged to assess these recommendations individually and collectively and to adjust them and extend them.

4.2.1 Investigate power-by-light sensors thoroughly. Develop and test a small family of these sensors for selected measurands.

The investigation phase of this project should address the following questions:

a. What measurands can be addressed? Of these, which appear harder to address today by other optical fiber methods, and which appear easier to do quickly by this technique?

b. What are the likely manufacturing costs of power-by-light systems using technology that has been developed to date? Where are cost reductions likely to be attained?

The development phase should involve contracts to one or several companies with known ability to engineer products to be manufactured. The deliverable should include not only prototype quantities for testing, but also a detailed analysis of the expected manufacturing costs. Targets specifications for EMI immunity should be included in the project objectives, and some EMI testing should be done during development.

4.2.2 Develop an integrated spectrometer and broadband light source.

This task should be undertaken in two phases. An investigation phase should answer the following questions, among others:

a. What measurands and sensor techniques will benefit from this technology? What wavelengths and resolutions are required? Which sensors address the largest potential markets (especially commercial markets). Can a single source and spectrometer serve a significant part of the market and meet significant needs of the Navy?

b. What technologies are available for the spectrometer? What wavelengths and resolutions can they serve? How amenable are they to multiplexing? What are their potential manufacturing costs? Can an inherently high-resolution device still be cost effective in an application that does not require high resolution? Are other markets (e.g., chemical processing or telecommunications) likely to lower cost through high-volume production of similar devices? (Similar questions should be asked about light sources.)

As Section 3.2.1 explains, the hope is either that one wavelength range and resolution will suffice for a variety of measurands, or that a single technology will enable devices for different wavelength ranges to be manufactured without loosing much of the economy resulting from volume production.

This investigation should be followed by a program in which the most promising technologies identified can be developed and tested. In this phase, analysis and consideration of manufacturing costs should be central considerations.

4.2.3 Conduct a critical examination of several high temperature sensor technologies. Choose the most promising and fund development.

It is not yet known which of several technologies will yield the most robust and least expensive high temperature sensors for the range of 0 °C to 1100 °C. It is therefore recommended that the Navy initially undertake a critical examination of several technologies, including those cited in Section 3.2.3, with the goal of determining the most likely to succeed and the principal technical and cost considerations limiting their development. The investigation phase should answer the following questions:

a. How far can the cost be reduced on high temperature optical fiber sensors, with volume production and multiplexing of the signal converters? Can good room temperature measurements be made with blackbody sensors using silica fiber? If not, is flexible sapphire fiber viable, or can it be developed? What length can be used without excessive loss, and what is it likely to add to the cost of a system? Can metal-coated fibers be developed to meet the Navy requirements within acceptable cost limits?

b. Can adequate performance be achieved at lower cost by using a sapphire blackbody sensor with silica fiber leads limited to high temperatures, and then adding a second temperature sensor for low to moderate temperatures?

(The low temperature sensor must survive high temperatures up to 1100 °C, and resume operation when the temperature is lowered again.)

c. What temperature must be endured by a connecting assembly on the wall of the adjacent compartment, and what conditions must be endured by the leads to the signal conversion unit? Does the preferred approach satisfy these requirements? Can alternate network architectures employing redundancy meet Navy cost limits?

Similar appropriate questions should be answered for rare-earth sensors, Raman backscatter sensors, and Fabry-Perot cavities.

With the identification of one or two promising temperature measurement technologies, the Navy should proceed to invest in the development of these technologies. The development project and testing program should be defined after the study. Manufacturability should be a key emphasis in the development phase. Because the need for high temperature sensors is common in industrial environments, especially in the power industry, the Navy is strongly advised to pursue this recommendation in collaboration with an industrial partner.

Problems of importance to several technologies, for example high temperature fiber coatings and flexible sapphire fibers, may be isolated and become the targets of separate projects. Since the payoff will significantly improve optical fiber sensor technology in general, the Navy is also advised to seek industrial partnerships for these projects.

4.2.4 Develop an inexpensive polarimetric receiver using integrated optics or micro-optics.

A reasonable goal for this program would be a unit the size of a small dual-inline package, with input through a high-birefringence (polarization maintaining) fiber, and output from two optical detectors. Cross talk between the two outputs should be less than -20 dB and preferably -30 dB. The unit should be designed to operate over broad temperature ranges. The development of manufacturing technology to insure reliability and reduce costs to the range of $100/unit in modest volume, should be essential parts of the program.

The program should begin with a determination of the wavelength, sensitivity, and other performance requirements for different measurands (particularly including electric current and voltage), in order to ensure broad applicability.

4.2.5 Develop Bragg-grating sensors for temperature and pressure.

A program to further develop fiber Bragg-grating temperature and pressure sensors should be undertaken. This work should be aimed primarily at applications in machinery monitoring where temperature and pressure measurements are frequently made close to one another.

The Navy should vigorously explore the possibility of a joint program with the power industry. In generating stations as in a ship, a majority of sensors are for measuring either temperature or pressure.

The program should have three main thrusts: (1) the development of sensors that respond only to temperature and only to pressure; (2) the development of sensor multiplexing techniques, in which the sensors are identical; and (3) the development of efficient manufacturing techniques.

4.2.6 Investigate low-coherence sensing technology.

The Navy should investigate low-coherence sensing technology as a means to address two issues: (1) there are substantial potential benefits of using common technology wherever possible; and (2) sensitivity of fiber leads to various effects (see 3.1.10) is a problem in many types of sensors.

The initial goals of this program should be to determine the feasibility of using this technique for the measurands most often required by the Navy, and to establish the practicality and potential benefits of using such technology. Should low-coherence technology be judged applicable and beneficial for many of the Navy's requirements, the initial program should be followed with experimental development work.

As in the case of recommendation 4.2.5, the Navy should explore the possibility of carrying out this recommendation with an industrial partner.

5. Cost and Benefit Scenarios

The recommendations in this report will cost money to implement, but will yield benefits that the authors believe substantially exceed the costs. It is difficult to evaluate these benefits with certainty, because the recommendations are either investigative, with no guaranteed outcome, or they are designed for positioning the Navy to increase the likelihood of success, again with no guaranteed outcome.

It is, of course, a grave mistake to fund only programs that have predictable outcomes, and to avoid those that do not lend themselves easily to numerical evaluation of the benefit. Programs of the second kind often produce the greatest advances and benefits, and they should be executed on the basis of judgment, rather than because of easily computed predictions. Despite this observation, however, it is still valuable to do the exercise of making imperfect estimates of financial benefits. The estimates will be no more certain than the uncertain assumptions on which they are based, but the exercise can play a valuable role in establishing the convictions needed, either to define and carry out a program, or to drop it.

Each of the recommendations of Section 4 is discussed below in terms of expenditure and the cost savings or value that it may create. Net present value computations are also done for the projected cash flows. These computations are explained in Appendix E. The assumptions and calculations are greatly simplified and are presented only as examples, for it is expected that any recommendation that is followed will be modified, budgeted, and scheduled in a different way by the Navy. For the scenarios presented here, the cost of implementing all of the recommended strategies and programs is $6.9M; the combined savings or value is $44.6M; and the combined net present value of making the investments (assuming 5% interest) is $24.5M.

In most of the computations, it is assumed that one person-year costs the Navy $140k, and that fiber sensors will be used at a rate of 10,000 per year with a target price of $500 each (for hardware procurement only) starting after five years. As the authors are not convinced that the target $500 average sensor price is practical, many of the estimated cost savings result from getting the price down toward that goal rather than reducing it lower. (Hypothetical cost reductions are sometimes presented as percentages of the target $500 cost rather than the uncertain actual cost.) Most of the programs described are modest in size, and might be increased to yield greater benefit. Some of the estimated benefits result from savings in successful sensor subsystems that will eventually be deployed on ships. Other benefits are expected from early elimination of flawed approaches, saving misdirected development funds. (An eliminated development project may, of course, be replaced by another. Money is saved by making this decision early rather than after spending a lot on the doomed technology.) Benefits in performance and accelerated introduction of superior technology and new functionality may significantly outweigh such financial benefits in some cases, but these are not evaluated below.

In writing these scenarios, some thought has been given to avoiding the problem of counting the same benefits in two different sections. (That would make it wrong to compute the total cost savings from the combined programs by adding the results of individual recommendations.) However, this potential problem is not accounted for in any rigorous way. The different structures used for the estimates in different scenarios would make such accounting difficult. It is possible for two different recommendations to benefit the cost of a single sensor additively. Considerable cost savings are "available," because fiber sensors that are close to meeting Navy requirements today are mostly quite expensive. (Some of the low costs from market studies in Appendix B are dominated by devices not suited to the Navy.) Assume that the average procurement cost of noncommercial (custom) sensors would be $2,000 per sensor, and that commercial mass-production and other measures can reduce this to $500. Then the cost of 10,000 sensors per year for five years will decline from $100M to $25M, saving $75M. The procurement part of the total savings in the scenarios below depends on some unspecified assumptions, but adds to roughly half of this crude estimate of the "available" procurement savings. Some of the procurement savings does not represent actual cash, because if the price were not brought down, procurement would never be done.

It would be easy to criticize the assumptions and figures below for being simplistic or wildly speculative, but this would miss the point. These are examples, and the authors make no claim that the assumptions are deeply founded. The real value of these exercises only accrues when they are re-done more deeply with the Navy's own assumptions. In order to make them easy to comprehend, the models below are unrealistically simple, mostly spending money on the recommended programs in years 1 through 5 and procuring systems at a steady rate in years 6 through 10, with no assumed benefit after year 10. Some scenarios are written optimistically and some with pessimism, as examples rather than as statements about likelihood of success.

Section numbers correspond to the numbers of the recommendations in Section 4.

5.1 Cost and Benefit Analysis for General Recommendations

Some of the general recommendations in Section 4.1 overlap in the impediments they address; and they are complementary, in that they may be done beneficially in concert with each other. The simple scenarios below treat each recommendation independently. (Note also the question of attributing the same benefits twice, discussed in Section 5.)

5.1.1 Benefit of exploiting large markets

Assume that the Navy allocates $100k in year 1 to study a number of markets briefly, to identify at least three applications with good potential and study them thoroughly, and to find and cultivate contacts within these markets. This work could be done by outside consultants or Navy personnel. (Using Navy personnel rather than a trained marketing expert might require a longer learning curve, but would cost less for the time and would leave the Navy with a valuable internal asset.) Assume that, for years 2 through 5, the Navy spends an extra $300k per year on development programs that it would not otherwise have spent, because the Navy is now supporting efforts to make products for broader markets.

Year	Cash	Item
1	−100k	Market study
2	−300k	Development
3	−300k	Development
4	−300k	Development
5	−300k	Development
6	+1500k	Savings
7	+1500k	Savings
8	+1500k	Savings
9	+1500k	Savings
10	+1500k	Savings

Assume that some of the identified applications result in partnerships with manufacturing companies, and development of sensors that simultaneously serve the Navy's highest volume applications and other larger markets; and that, as a result, 30% of the Navy's sensor procurements are reduced in cost by $500 per sensor during years 6 through 10.

The five-year expenditure is $1.3M, and the savings is $7.5M. The net present value of this cash flow is $3.98M. These figures ignore the main development costs for the sensors, and the early savings that may result if they are partly borne by another industry.

5.1.2 Benefit of joint services development

Assume that the Navy allocates one person-year of resources to studying commonality with other armed services and NASA. Assume that two separate development projects would normally be funded by the Navy for $400k each over two years, but that, as a result of this effort, each project is modified to be funded by two organizations simultaneously. Assume the scope of each project is expanded some to accommodate both organizations, so that the total cost of each project is now $500k, but the Navy's share is $250k.

Assume that just one of the two projects results in sensors that are deployed by both organizations (but not by another broader market); that the increased volume reduces the hardware cost by $300 per sensor; and that the Navy buys 500 of these sensors per year during years 6 through 10, thus saving $150k per year in procurement costs.

These assumptions are more modest than in Section 5.1.1, because the authors believe that the Navy will be more successful in finding synergy with broader industry (where there are more applications to choose from) than with other armed services and NASA (where the requirements are more specialized); and that commonality with broader industry will create higher volumes and cost reductions than with other armed services and NASA.

This costs $140k and returns $1.05M, with a net present value of $641k.

Year	Cash	Item
1	−140k	Study commonality
2	150k	Development savings
3	150k	Development savings
4		
5		
6	150k	Procurement savings
7	150k	Procurement savings
9	150k	Procurement savings
9	150k	Procurement savings
10	150k	Procurement savings

5.1.3 Benefit of information and communication management

Recommendation 4.1.3 is important but difficult to quantify for both cost and benefit. Because the Navy already has systems for managing information, implementation of this recommendation might amount to re-examining those systems and modifying them, but not spending substantial new money. The authors believe that a very fundamental and beneficial aspect of the recommendation is the open inclusion of conflicting views in the information that is gathered and disseminated. This may be at odds with present Navy practices or culture. Modern corporate management practices give legitimacy to differing views, and exploit them as a technique for extracting the most from people and making the best ultimate decisions. This has widely-proven benefit in industry, but it may be difficult to practice in an organization like the Navy, which requires a structure and culture optimized for waging war rather than for technology development. Still, it is an aspect of the recommendation that could create substantial value.

Assume that one full-time person is assigned to gather, maintain, and disseminate information of fiber sensor technologies in the Navy, including answers to the pointed questions listed in recommendation 4.1.3. Assume (as recommended) that the information is disseminated to potential industry partners as well as within the Navy, with classified information stripped as necessary. Assume that distribution costs $20k per year.

Assume that, as a result, one laboratory uses expertise found in another laboratory to save six months of study by two people valued at $140k. Assume that an intelligent but politically weak proponent of a particular technology is heard, enabling that technology to be modified and used for a development cost of $200k instead of mounting another program for $500k, saving $300k spread over years 3 and 4; and enabling a cost savings of $300 per sensor for 20% of the sensors to be acquired in years 6 through 10.

Year	Cash	Item
1	−160k	Program expense
2	−160k	Program expense
	140k	Redundant work savings
3	−160k	Program expense
	150k	Development savings
4	−160k	Program expense
	150k	Development savings
5	−160k	Program expense
	200k	Development overrun savings
6	600k	Procurement savings from first technology
	200k	Procurement savings from second technology
	500k	Procurement savings from third technology
7	1300k	Procurement savings
8	1300k	Procurement savings
9	1300k	Procurement savings
10	1300k	Procurement savings

Assume that improved openness and visibility of the Navy's technology leads one high-quality commercial manufacturing company to work with the Navy, that this saves $200k that a less-competent developer would have incurred in development overruns to make a design manufacturable, and that it saves $400 per sensor for 5% of the Navy's sensors because the design and manufacture are handled more competently, and because the commercial product is marketed better, increasing the volume. Assume that increased awareness of manufacturing issues, stimulated by the pointed questions in the inventory of sensor technology, leads to the discrediting of a technology that would have added $500 per sensor to 10% of the sensors to be acquired.

This scenario costs $800k over five years, saves $7.14M, and has a net present value of $4.25M.

5.1.4 Benefit of coordination with network design

Assume that the Navy enlists the participation of one additional person, with expertise and responsibility in network design, at each of 50 sensor-related meetings per year. Assume that the average time for each meeting and related discussions is one half day. This costs the Navy approximately one tenth of one person-year or $14k per year.

Year	Cash	Item
1	−14k	Program expense
2	−14k	Program expense
3	−14k	Program expense
	250k	Savings from canceled program
4	−14k	Program expense
	250k	Savings from canceled program
5	−14k	Program expense

Assume that, in the second year, as a result of increased awareness of network issues, a development program for just one promising fiber sensor technology is scrapped in favor of another technology, because it is identified early that its topology is not compatible with network survivability requirements. Assume that without this realization, the original program would have continued another two years, at a cost of $250k per year, but the flawed results would never have been used.

In this scenario the total expenditure is $70k and the savings is $500k, with a net present value of $361k. This ignores the harder-to-evaluate benefits of avoiding delay in the deployment of fiber sensors, and possible system performance advantages.

5.1.5 Benefit of limited sensor network program

Trials of systems must be done in any case before they can be deployed. Therefore, in evaluating the cost and benefits of this program, it is appropriate to compare it to some other approach, and look at the difference. This section is intricate because the program integrates a number of aspects that have potential benefits. Integration into a single program is important in order to reap the benefits. For example, it does no good to save 30% of the manufacturing cost of a sensor if that sensor is later found to be incompatible with network design principles.

Assume that this program costs $2M over 4 years, and it replaces three fewer development and testing programs costing $500k each, so that the tangible net cost is $500k. (By including other aspects here we might make the tangible net costs compute to zero, but other aspects can as well be accounted for in the benefits.)

Year	Cash	Item
1	−125k	Incremental program expense
2	−125k	Incremental program expense
4	−125k	Incremental program expense
	+250k	Program dropped because of network principles
4	−125k	Incremental program expense
	+250k	Program dropped because of network principles
5	+250k	Program dropped because of failure
6	+700k	Savings: selection of good manufacturer
	+150k	Savings from improved network principles
	+350k	Installation cost savings
	+400k	Other savings from improved vendor relations
7	+1600k	Combined savings
8	+1600k	Combined savings
9	+1600k	Combined savings
10	+1600k	Combined savings

Assume that the project includes approximately four sensors, including temperature and pressure, and encompasses candidate technologies for 40% of the Navy's potential dollar volume. Assume that the program has only mixed success, with negative results for one or two of the sensors, and that the other sensors are ultimately approved for shipboard use, so that the final results lead (among other benefits) to approved sensors for 20% of the Navy's sensor needs in dollars, and 35% in the number of devices.

Assume that the seriousness of the program attracts several high-powered companies that would not have bid on single-sensor projects, and that the inclusion of requirements for analysis of manufacturing costs and marketability enables the Navy to select a company that can not only do a good technical job, but can also generate devices that will be sold to another market and manufactured in higher volume, with designs that are more amenable to low-cost manufacturing. Assume that this saves half of the cost that the Navy would otherwise have to pay, cutting the hardware procurement budget from 40% over target to 30% under. For a $5M per year target for all the sensors, this is a saving of $0.2 \times \$5M \times (1.4 - 0.7)$ or $700k per year in procurement costs, by comparison to having a different company develop these same sensor technologies.

Assume that the network emphasis, including survivability and multiplexing, leads to dropping from the Navy's agenda a technology that looks cheap but cannot be deployed in a cost-effective way that is consistent with network criteria, and that this eliminates a doomed development effort that otherwise would have cost $500k spread over years 3 and 4. Assume that the program develops and tests another technology that initially appears to meet network criteria, but that flaws are found in final testing. Because a less integrated approach would have found these flaws at a later stage, assume that this saves $200k of development effort that would otherwise have been spent in year 5. Assume that the interaction between sensor and network design principles leads to the realization of some simple topological or architectural principles that can reduce the entire system cost (sensor subsystems plus data network) by an amount equal to 3% of the target hardware procurement cost for the sensor subsystems, or $150k per year.

Assume that inclusion of analysis of installation costs, and disciplined attention to that issue during early phases of the project, leads to technology and design choices that save $100 per sensor for those in this program that are eventually deployed, saving $\$100 \times 10{,}000 \times 0.35 = \$350{,}000$ per year.

Assume that the disciplined exercise of examining how the Navy works with its contractors, including regular review of that specific issue with the contractor all through this program, leads to the discovery of some useful principles; establishes a precedent; creates awareness of these issues; and bolsters the Navy's reputation somewhat in the sensor industry. Assume that this benefits other sensor projects, making them more effective and bringing some superior companies to participate that would not otherwise have bid, and that this improves sensor efforts enough to save 10% of the target procurement costs for the remaining 80% of the sensor dollar volume, or $400k per year.

This scenario has a $500k incremental cost and yields a saving of $8.7M, with a net present value of $5.56M. If we use the $2M program cost rather than the incremental cost, ignoring other programs that this integrated approach replaces (keeping the savings figure at $8.7M), then the net present value computes to be $4.23M.

5.1.6 Benefits of monitoring sensor costs

Costs will be studied and monitored in some way in any case. But recommendation 4.1.6 proposes a formalized process for continually summarizing cost information and creating an increased awareness of it throughout Navy sensor groups and among current and potential partners in industry. As has often been demonstrated in industry, increasing the awareness of an issue can create significant improvements without overtly commanding specific changes. (Improvement of plant safety records is an example.)

Year	Cash	Item
1	−140k	Personnel expense
	−15k	Dissemination
2	−70k	Personnel expense
	−15k	Dissemination
3	−85k	Program expense
4	−85k	Program expense
5	−85k	Program expense
6	+500k	Savings from Navy effort on one sensor
	+500k	Savings from industry effort on one sensor
	+425k	Modest savings on remainder of sensors
7	+1425k	Combined savings
8	+1425k	Combined savings
9	+1425k	Combined savings
10	+1425k	Combined savings

Assume that one person devotes a full year to creating a methodology and an initial set of cost estimates for the key sensing technologies under consideration by the Navy. The information is widely disseminated, both in detailed form and in a summary format that includes bottom-line cost estimates for different aspects (development, procurement, installation, etc.) but excludes assumptions and detailed discussion. The summary information will clearly favor some technologies over others, and is therefore expected to generate study and debate over the detailed assumptions. These will be revised and redistributed, perhaps with frequent updates of the summary and just those assumptions that have been revised, and a complete update of all the information annually. Assume that in subsequent years the same individual can continue gathering and disseminating information by working half time on this project, and that dissemination and related overhead cost $15k per year.

Assume that the initial cost summary casts into disfavor one of two competing technologies for a particular measurand, and that proponents of this technology, fearing cuts of their program, devote extra effort to finding ways to reduce the cost. Assume that these efforts are successful and result in reducing the combined cost of procuring and installing 10% of the sensors on a ship by $500 per sensor, or $500k per year.

Assume that a sensor manufacturer, marginally interested in Navy applications, sees the high expected cost of competing technologies for a less-common and somewhat expensive measurand and realizes that its own technology can significantly undercut these costs. Assume that this knowledge also clarifies the nature and size of the Navy market, and gives the manufacturer the conviction to pursue a Navy contract that it would not otherwise have sought. Assume that this leads to a successful development resulting in a saving of $1000 per sensor for procuring and installing 5% of the sensors on a ship, or $500k per year.

Assume that increased concern about both installation and procurement cost, in the Navy and in industry, bring about a modest procurement saving of 5% of the target $500 cost on the remaining 85% of the Navy's sensors, and an equal dollar amount per sensor in installation, for a total of $50 per sensor multiplied by 0.85 × 10,000 per year, or $425k per year.

This scenario has a cost of $495k and generates a saving of $7.125M, with a net present value of $4.4M.

There are many instances of product costs being cut more radically than assumed above when renewed awareness and motivation are created. The authors believe that a disciplined implementation of recommendation 4.1.6 could easily generate substantially more savings than indicated.

5.1.7 Benefit of studying and exploiting multiplexing and switching

Multiplexing and switching will be studied to some degree in any case, because individual fiber sensor technologies will focus attention on them. But Section 4.1.7 recommends that these topics be studied in a general and concerted way, so that the Navy acquires an internal source of expertise that can be applied to a number of different sensing technologies.

Assume that one person spends half time during the first year studying the cost and network design implications of multiplexing and switching in relation to five particular fiber-sensing technologies. Assume that the results of this work are publicized within the Navy and among active and potential industry partners. Assume that for the subsequent four years, this individual spends one-half time assisting groups inside and outside the Navy in applying multiplexing strategies to reducing cost for different sensor technologies, so the direct program cost is $70k per year for 5 years.

Year	Cash	Item
8	−70k	Direct program expense
2	−70k	Direct program expense
4	−70k	Direct program expense
	−150k	Switching program expense
4	−70k	Direct program expense
	−150k	Switching program expense
5	−70k	Direct program expense
6	+400k	Savings from switching technology
	+300k	Savings from multiplexing one sensor class
	+425k	Broad savings from multiplexing
7	+1125k	Combined savings
8	+1125k	Combined savings
9	+1125k	Combined savings
10	+1125k	Combined savings

Assume that the initial study clarifies the requirements for a general switching technology and leads to the definition and execution of a program in which a switching technology needed by another larger market is adapted or developed cooperatively, at a Navy cost of $300k spread over the third and fourth years.

Assume that a broadly applicable switching technology is developed that saves an average of $100 per sensor for 40% of the sensors used, in procurement, training and inventory management costs. This is 0.4 × 10,000 × $100 or $400k per year.

Assume that a good multiplexing strategy, resulting from the internal expertise that this program creates, helps just one class of sensor become cheaper, by 40% of the target cost, than the type that otherwise would have been used. Assume that this sensor accounts for 15% of the shipboard sensors, and therefore saves 0.4 × $500 × 0.15 × 10,000 = $300k per year.

Assume that the improved general understanding of multiplexing and switching leads to a modest average saving of 5% of the target procurement cost for the remaining 85% of the shipboard sensors, and an equal dollar savings for installation, resulting in $50 per sensor for 8,500 sensors per year, or $425k per year.

This scenario spends $650k and yields a saving of $5.625M, for a net present value of $3.26M.

5.1.8 Benefit of reducing optoelectronic packaging costs

Recommendation 4.1.8 is not very specific, and the objective is probably too big for the Navy to undertake by itself. The benefit of reducing packaging costs, especially in telecommunications, might be broad enough to justify a $10 to $50 million program. But Navy participation in large programs with other agencies and industry can help the programs, keep the Navy informed, and allow the Navy to influence directions so that it reaps some of the benefit. It may be that shipboard data network costs give the Navy greater incentive for such participation than sensors.

Year	Cash	Item
1	−140k	Initial study
2	−250k	Cooperative program support
3	−250k	Cooperative program support
4	−250k	Cooperative program support
5	−250k	Cooperative program support
6	+300k	Savings from first sensor
	+350k	Savings from second sensor
7	+650k	Combined savings
8	+300k	Savings from first sensor
	+750k	Savings from second sensor
9	+1050k	Combined savings
10	+1050k	Combined savings

Assume that the Navy applies one person for a year to a study of the effect of packaging on cost for a number of leading fiber sensor technologies, and identifies several specific problems or aspects that affect future fiber sensor systems. Assume this knowledge helps the Navy decide to participate in one substantial government and/or industry program, and that the Navy's contribution is $1M spread over years 2 through 5.

Assume that the Navy's contribution and influence in the program lead to a 60% cost reduction in components accounting for 25% of the cost of the signal conversion unit with multiplexing for a widely used sensor technology; that this signal-conversion unit is initially 80% of a current $1000-per-channel cost with multiplexing, causing a $120-per-sensor saving. Assume this signal-conversion unit serves several measurands accounting for 25% of the sensors on a ship, so the annual saving is 0.25 × 10,000 × \$120 = \$300k per year.

Assume there is another technology, accounting for only 5% of the number of sensors on a ship, that is quite expensive and does not lend itself well to multiplexing, so that individual electro-optic components are needed for each channel. Assume that today's cost is \$2500 per channel, and that reduced packaging costs cuts the commercial price initially to \$1800 for two years. Assume lower prices enable both the sensor system and the electro-optic components in it to address much wider markets, so that two years later revisions in the design and manufacturing process, coupled with higher volumes, allow the cost to be reduced to \$1000 per channel. Thus for 0.05 × 10,000 = 500 sensors per year, the cost is reduced by 500 × \$700 = \$350k per year for two years, and by 500 × \$1500 = \$750k per year in subsequent years.

This scenario spends \$1.14M and saves \$4.45M, for a net present value of \$2.0M.

5.2 Cost and Benefits for Technology-Specific Recommendations

The technology-specific recommendations can be discussed as a group rather than individually. Unlike Section 5.1, where a modest degree of success is assumed for each recommendation, a technology-specific recommendation is assumed to succeed or fail completely, depending on whether it results in sensors that are deployed. As in 5.1, the assumptions are extremely simple.

Six recommendations are made. Each deserves a study period before a decision is made to define and execute a complete project. Assume that each has an average budget of \$50k to investigate during the first year, then \$500k to carry out a project over the next two years. Assume that three investigations are negative; three lead to \$500k programs; and two of these result in technologies that are deployed, while the third fails.

Year	Cash	Item
1	−300k	Initial studies
2	−750k	Three programs
3	−750k	Cooperative program support
3		
5		
6	+500k	Value created
7	+500k	Value created
8	+500k	Value created
8	+500k	Value created
10	+500k	Value created

Assume that a successful program has a

value to the Navy equal to 40% of the target procurement costs of \$500 per sensor, either because it saves \$200 per sensor over the technology that would otherwise have been used, or because it brings functionality or performance that would still be worth buying at \$200 more per sensor. Assume that the successful technologies encompass at least one that serves multiple measurands, so that the programs result in providing 25% of the needed sensors. This amounts to a value of $\$200 \times 0.25 \times 10{,}000 = \$500k$ per year.

This scenario costs \$1.8M and creates a value of \$2.5M, with a net present value of \$82k.

A. Shipboard Sensor Requirements

A.1 Shipboard Sensor Populations

To provide a basis for estimating the potential Navy shipboard market for optical fiber sensors, investigations of the number of conventional sensors used on two ships of fairly recent construction were undertaken. One of these was the FFG-7, a light cruiser. The other was the DDG-51, a somewhat newer ship.

For the FFG-7, ship's manuals for each of the major hull, mechanical, and electrical systems — Propulsion Plant, Electrical Plant, Damage Control System, Air Conditioning Plant, Compressed Air System, Seawater Systems — were studied to determine the numbers of sensors installed by measurand and whether the sensor was a continuous reading or threshold type. Because these data were taken directly for the manuals describing each system they are thought to be accurate summaries of shipboard sensor populations.

Table A1 shows the continuously indicating shipboard sensor populations for the FFG-7. For present purposes, continuously indicating sensors are those that have an output that is a continuous function (analog or digital) of the parameter being measured. Alarm sensors transmit only a trigger signal when the measurand crosses a threshold.) There is a total of 1323 continuously indicating sensors on an FFG-7. They include the following measurands, in descending order by number of sensors: pressure, temperature, liquid level, electrical current, voltage, position, speed, liquid flow, moisture, salinity, vibration, air flow, flame, and torque. Pressure and temperature sensors alone comprise 78% of the total sensor population.

Table A2 shows the alarm type shipboard sensor populations for the FFG-7. It was not possible in some cases to divide the population by type. There seems to be a high population of position alarm sensors, relative to the continuously indicating sensors as indicated by the data for the damage control system; these sensors monitor fan and duct closures, and fire main limits.

There is a grand total of 2212 sensors on each of the FFG-7 class ships.

For the DDG-51, some versions of which continue in production, complete sensor population data was not available to the authors at the time of this writing. This is unfortunate because the DDG-51 is a newer ship than the FFG-7 and thus is more indicative of the sensor populations used in modern ship design.

It was possible, however, to determine the number of sensor signals transmitted on the data multiplexing system of the DDG-51. This data is presented below in Table A3. The data multiplexing system transmits only that data which must be displayed remote from the sensing site, and that is used for determining ship control and status.

Many sensors are resident on machines that are used for local control and monitoring and are not transmitted on the network. Thus, sensor population estimates obtained from transmitted signal counts are expected to be substantially low, but it is not known by what factor.

There is a total of 2311 sensor signals transmitted on the data multiplexing system on the DDG-51 class ships.

Table A1. Shipboard populations of continuously indicating sensors for HM&E systems on FFG-7 ships (Part 1 of 2).

Parameter	Propulsion Plant	Electrical Plant	Air Condition	Compressed Air	Seawater	Damage Control
Temperature	60	36	27	60	80	-
Pressure	41	40	18	206	114	-
Position	14	-	-	2	3	-
Speed	8	8	-	-	-	-
Vibration	8	-	-	-	-	-
Liquid Level	7	4	6	-	34	-
Torque	3	-	-	-	-	-
Air Flow	2	-	3	-	-	-
Liquid Flow	-	4	-	-	4	-
Flame	-	4	-	-	-	-
Current	-	35	9	12	-	-
Voltage	-	34	9	12	-	-
Moisture	-	-	-	6	9	-
Salinity	-	-	-	-	-	-
Totals	143	165	72	298	244	-

Table A2. Shipboard populations of continuously indicating sensors for HM&E systems on FFG-7 ships (Part 2 of 2).

Parameter	Fuel Transfer	Fresh Water	Refrigeration	Ventilation	Waste Heat	Totals
Temperature	6	89	15	87	36	496
Pressure	16	80	10	-	9	534
Position	-	-	-	-	-	19
Speed	-	-	-	-	-	16
Vibration	-	-	-	-	-	8
Liquid Level	24	9	2	-	-	86
Torque	-	-	-	-	-	3
Air Flow	-	-	-	-	-	5
Liquid Flow	-	7	-	-	-	15
Flame	-	-	-	-	-	4
Current	-	-	-	-	-	56
Voltage	-	-	-	-	-	55
Moisture	-	-	-	-	-	15
Salinity	-	11	-	-	-	11
Totals	46	196	27	87	45	1323

Table A2. Shipboard populations of alarm sensors for HM&E systems on FFG-7 ships (Part 1 of 2).

Parameter	Propulsion Plant	Electrical Plant*	Air Condition*	Compressed Air*	Seawater*	Damage Control
Temperature	56					81**
Pressure	29					42
Position	8					196
Speed	18					-
Vibration	8					-
Liquid Level	9					12
Torque	-					-
Air Flow	-					-
Liquid Flow	-					5
Flame	4					-
Current	-					-
Voltage	-					-
Moisture	-					-
Salinity	-					-
Misc.	5					-
Totals	137	127	48	53	76	336

* Type breakdown not available. ** Includes both temperature and smoke sensors.

Table A2. Shipboard populations of alarm sensors for HM&E systems on FFG-7 ships (Part 2 of 2).

Parameter	Fuel Transfer	Fresh Water	Refrigeration	Ventilation	Waste Heat	Totals
Temperature	-	24	3	-	6	
Pressure	2	23	4	-	-	
Position	-	-	-	-	-	
Speed	-	-	-	-	-	
Vibration	2	-	-	-	-	
Liquid Level	23	10	2	-	1	
Torque	-	-	-	-	-	
Air Flow	-	-	-	-	-	
Liquid Flow	-	10	2	-	-	
Flame	-	-	-	-	-	
Current	-	-	-	-	-	
Voltage	-	-	-	-	-	
Moisture	-	-	-	-	-	
Salinity	-	-	-	-	-	
Miscellaneous	-	-	-	-	-	
Totals	27	67	11	0	7	**889**

Table A3. Sensor Signals Transmitted on the Data Multiplexing System on the DDG-51.

Parameter	Continuously Indicating	Alarm
Temperature	142	51
Pressure	105	116
Air & Liquid Flow	38	21
Position	42	-
Speed	13	16
Liquid Level	12	120
Moisture	10	16
Electrical Current	10	-
Voltage	27	4
Vibration	11	4
Torque	6	-
Flame	-	232
Limit	-	106
Leak	-	2
Miscellaneous	-	1206
Totals	419	1892

A.2 Motivation for Optics

New technology is introduced and becomes successful generally for one of two reasons. It may be in response to a clearly understood problem with present technology. Present technology may not work well or it may be too expensive. Or there may be a clear need for a product that doesn't exist. This is a market-driven product introduction. Alternatively, it may be that new technology offers a new capability that is not widely understood to be needed, but when available becomes recognized as highly beneficial and desirable. This is a technology-driven product introduction. Both market-driven and technology-driven product introductions can be highly successful.

The potential for success of new market-driven technologies is far the easier to assess: the capability of the new technology can be judged against real, understood needs and established costs. With technology-driven technologies, the assessment is more difficult. Are the anticipated benefits real? Are the costs low enough to encourage the consideration of the new technology?

The introduction of optical fiber sensors into many application areas is widely seen as technology-driven. The electric power industry is a frequently cited example. The potential advantages of using optical sensors for electric current and voltage have been recognized for at least 20 years. But conventional electrical sensors are well understood, reliable, and affordable, and provide most of the needs of the industry. Developers of optical alternatives must provide these same attributes plus enough new capability or improved characteristics to entice customers to switch.

There are a few notable exceptions where optical fiber sensors have been developed specifically to meet a recognized problem. One of the best examples is catheterized sensors for use in intracranial and cardiovascular pressure monitoring. These sensors were developed to meet specific medical needs for sensors that could be directly inserted into the body, rather than require fluid coupling to an external sensor. The medical electronics specialists who addressed the problem concluded that optics was, technically and economically, the most attractive approach. Relatively low cost ($150-$300), disposable sensors were developed; these are now being produced in volumes of more than 50,000/year and have reached an estimated market share of more than 60% (Brett Trimble, *Fifty thousand pressure sensors per year: A successful fiber sensor for medical applications*, Proc. 9th Optical Fiber Sensors Conference, Florence, Italy, 1993; *World Fiber Optic Sensor Markets*, Report 912-40, Frost and Sullivan Market Intelligence (formerly Market Intelligence Research Corp.), Mountain View, CA, 1993).

Most technology that is introduced into ships is market-driven, and optical fiber sensors are probably not an exception. The need for new sensor functions will be the dominant driver. That is not to say that there are no advantages to be obtained by replacement of some of the many conventional sensors aboard present ships with optical sensors. But to compete with well established conventional sensors, optical sensors must provide substantial benefits. On the other hand, for new systems proposed for future ships, the performance requirements and the sheer numbers of sensors involved may make conventional technologies impractical.

Three new categories of sensor-intensive systems are expected to be introduced into future ships: Automatic damage assessment, automatic machinery monitoring and control, and condition-based maintenance.

Automatic damage assessment is essential to the Navy's goals of "fighting hurt." On all ships in the US Navy, a runner is sent to investigate damage immediately after notification of the casualty to the officer in charge. This process, though reliable, is too slow for fighting hurt with reduced staff levels. (In today's warfare a ship must defend against a second incoming attack, seconds after the first casualty, while launching offensive strikes at enemy targets.) Sensor networks communicating multiple measurands from each compartment to stations in different parts of the ship can provide the necessary information to automatically assess the damage situation in real time and develop the optimum damage control strategy, required to minimize secondary damage, while maintaining battle readiness. The most recent destroyer design in the Navy employs several hundred sensors connected through the resident "Data Multiplexing System" to report status of damage, but a runner is still sent to investigate to insure reliability of information. It is expected that future ships will need a family of about five sensors in each compartment to monitor for temperature, smoke, flame, flooding, and poisonous or combustible gasses. On a typical destroyer, this requires as many as 2500 sensors per ship, when just one gas is detected. In the more distant future, if all the expected toxic combustion gases are monitored, the total rises to 50,000 sensors per ship.

Conventionally, shipboard machinery control is hardwired rather than software implemented. This assures immunity from software bugs in critical ship maneuvers. While this procedure is reliable, it does not permit rapid reconfiguration of the systems in the event of damage. Electrical power often is interrupted for a long time after damage, leaving the ship vulnerable to additional attack. Computer controlled systems are being developed to reconfigure electrical systems quickly and automatically. These systems will take their input from networks of sensors. Best present estimates for the number of sensors used in machinery monitoring and control range between 1000 and 3000, most of which are likely to be electrical sensors. Optical fiber sensing offers several advantages for machinery control and monitoring systems. Fiber sensor networks are easy to implement. Optical fiber sensors provide a broader envelope of performance not available in electrical sensors; examples are long term monitoring of the hot section of internal combustion engines for temperature and pressure, and very low frequency measurement for motor current signature analysis systems (which are now being implemented for submarine machinery monitoring).

Presently, shipboard machinery is serviced at regular intervals, chosen to replace parts before they fail. Such programs cause costly unnecessary service, while neglecting some problems that cause catastrophic failures at inopportune times. Sensor networks for machinery monitoring can alleviate both problems by detecting deterioration long before it is catastrophic. It is expected that in the future, each major machine will be monitored with a group of sensors designed to provide early indications of impending failures. This implies the purchase and application of a large network of sensors that may only be achievable with optical fiber or microelectronic sensor technology.

One cannot appropriately think of these sensors as a collection of individual sensors. They must be interfaced to data networks, and the data must be transmitted to computers and processed. Concerns over survivability may lead to required redundancy and or highly complex network architectures. It is this projection of extensive and complex shipboard sensor networks that strongly encourages, if not dictates, the use of optical technology.

One of the prime considerations in the design of such a network is the avoidance of electromagnetic interference. [See, for example, N. Baron and D. Cebulski, *EMI-The enemy within*, 28th Annual Technical Symposium, Achieving Technical and Manage Excellence, Arlington, VA, 1991; J. F. Garret, et al. *Let's design out EMI*, Naval Engineers Journal, Feb. 1982.] Though largely unconfirmed in unclassified documents, horror stories are widely circulated about the inoperability and incompatibility of some of today's electrical shipboard systems.

Interference arises from many sources, from rotating machinery to radar, and may enter electrical systems in different ways. Long and complex electrical cable networks are particularly vulnerable; they function as antennas and provide numerous opportunities for ground loops. Properly designed and carefully constructed electronic systems minimize the problem of interference, but the quality of shielding must be maintained over the life of the system, through normal wear and tear, repairs, and routine maintenance.

Minimizing electromagnetic interference is undoubtedly the strongest motivation for introducing optical sensor systems into the fleet. Interference can be reduced substantially by replacing both electrical sensors and, especially, their associated cables with optical elements, though careful shielding of the signal conversion unit remains a necessity.

Size and weight are not commonly thought of as major concerns on ships, but in fact, every kilogram of extra instrumentation represents an equivalent reduction in payload capacity. Extensive networks of electrical cables, especially well shielded cables, are heavy and large; fiber cables are substantially lighter and smaller. A direct replacement of copper signal cables with fiber signal cables has been shown to result in a weight saving of 90% *(Military Fiber Optic News, "Creating Foundation for Navy in Fiber Optics," Phillips Publishing, Inc., Vol. 4,* *No. 16, 11 Aug. 1989).* A similar adoption of optical fiber in sensors should result in a similar saving of weight. In fact, implementing the kinds of massive populations of sensors and data transmission networks required to support the new control and monitoring systems currently planned for new surface combatants may demand the use of small sensors that are now only available in optical fiber or microelectronic form.

Finally, an often overlooked advantage of optical fiber sensors is the wide variety of opportunities they offer for multiplexing and innovative network design. Multiplexing can be achieved with switching, as with electrical sensors. Time division multiplexing is much easer to implement than in electrical sensor systems. Other forms of multiplexing — wavelength division multiplexing and coherence multiplexing — are unique to optical technology. Distributed sensing, while in principle conceivable in an electrical system, has only been commercially demonstrated in optical fiber form, where there are a variety of approaches.

Parts of the Navy have already concluded that if new systems requiring substantially increased numbers of sensors are to be introduced into ships, they almost certainly must use optical fiber sensors. The authors of this study agree with this conclusion, for the reasons cited above.

B. Markets for Optical Fiber Sensors

Much of the discussion in this report concerns the reduction of sensor costs. Since these costs are closely related to sales volume, it is appropriate to examine the best available estimates of present and future market sizes. The reader is cautioned, however, that market surveys are always subject to great uncertainty, especially in emerging technologies. In the optical fiber sensor industry, particularly, there have been many overly optimistic estimates of future markets.

Major studies of optical fiber sensor markets conducted over the last five years include the following:

"New Markets in Fiber Optic Sensors," Report #Z2G-116, Business Communications Company, Norwalk, CT, 1989 (BCC89)

"Survey on Fiber Optic Sensors," Future Technology Surveys, Inc., 1989 (FTS89)

"Developments in the Fiber Optic Sensor Market," Corporate Strategic Intelligence, Middlebush, NJ, 1989 (CSI89)

"The Outlook for Fiber Optic Sensors," Arthur D. Little/Decision Resources, Burlington, MA, 1990 (ADL90)

"World Markets for Fiber Optic Sensors," Report #477-40, Market Intelligence Research Corp., 1991 (MIRC91)

"World Fiber Optic Sensor Markets," Report 912-40, Frost and Sullivan Market Intelligence (formerly Market Intelligence Research Corp.), Mountain View, CA, 1993 (FSMI93)

Estimates of the total world market for optical fiber sensors from these studies are compared in Table B-1. These data illustrate the wide variation and uncertainties in estimates of the industry size. The two rightmost columns are from the most recent and detailed studies, identified as MIRC91 and FSMI93 in the list above. These studies were done by the same organization, presumably using similar methodologies. Monetary values listed for these two studies are in current dollars for the year of the study.

From 1991 to 1993 estimates from MIRC91 and FSMI93 of both actual (prior to study year) and projected total market sizes were reduced by 40 to 50%. This is consistent with a general impression in the optical fiber sensor industry that markets have not developed as quickly as has frequently been predicted or as many in the industry had hoped. This should not be read, however, to suggest that all segments of the industry are expanding slowly, as will be shown below.

Price per unit is the key parameter of interest. MIRC91 and FSMI93 also provide some assessment of trends in unit costs (Table B-2), though they must be read with caution. Contrary to what seems to be indicated by the estimates, it is not possible, today, to buy a complete sensing instrument for any of primary measurands of interest to the Navy for a few hundred dollars. One reason for this apparent discrepancy is that simple position sensors, which are normally low cost, make up a large part of the market. Another is that in certain applications, including especially medicine, many sensors are disposable. One signal conversion unit is thus amortized over many low cost sensors.

Trends in unit costs have also required reassessment. MIRC91 suggests upward tending unit costs, presuming an increase in the market for sophisticated sensors such as high performance gyroscopes. FSMI suggests a steadily decreasing price, more dominated by disposable sensors, particularly in the chemical and medical areas.

As pointed out in Appendix A.1, the Navy has a particular interest in sensors for temperature and pressure. Market projections for these measurands are shown in Tables B-3 and B-4.

Estimates of unit sales of temperature sensors are fairly consistent in the 1991 and 1993 studies. 1993 estimates of unit costs are roughly 25% lower, leading to similar decreases in revenues. The costs of temperatures sensors are not foreseen to decrease to the level needed by the Navy within this decade.

Estimates of unit sales of pressure sensors show dramatic increases between the 1991 and 1993 studies. In 1989, the earliest year for which both studies provide data, the 1993 studies suggests that unit sales were nearly an order of magnitude greater than previously realized. Unit costs are now thought to be a factor of five lower than previously thought and are clearly tending downwards. These changes result especially from growth in disposable pressure sensors sales. The costs of individual pressure sensors, which are probably closer to the 1991 estimates, are low enough to allow optimism that they can be reduced to levels acceptable to the Navy.

MIRC91 and FSMI93 also reflect new assessments of the relative sizes of market segments (represented by revenues). In 1991 it was thought that the displacement/position/proximity sector of the market represented over 90% of the market and would continue to be over 80% of the market through the 1990s. It is now thought that this segment was never more than 42% of the market and its importance is rapidly decreasing. Temperature, pressure, and chemical sensors are thought to be the next largest segments at present, but the importance of temperature and pressure sensors is decreasing while sales of chemical sensors is growing much more rapidly than previously anticipated.

Table B.1 Total world market for optical fiber sensors from six market studies ($ Millions).

Year	BCC89	FTS89	CSI89	ADL90	MIRC91	FSM93
1986					91	
1987					105	
1988	122		80		128	
1989				30	139	80
1990		135			164	93
1991		222			208	106
1992		365	270		299	126
1993	313	600			409	151
1994					548	210
1995					723	392
1996					935	569
1997						751
1998	814					938
1999				560		1120

Table B.2 Estimated world market for optical fiber sensors from MIRC91 and FSMI93, unit volume prices.

Year	Units MIRC91 Estimates (000)	Estimated Revenues MIRC91 $M	Estimated Price/Unit MIRC91 $	Estimated Units FSMI93 (000)	Estimated Revenues FSMI93 $M	Estimated Price/Unit FSMI93 $
1986	170	91	535			
1987	196	105	535			
1988	226	120	531			
1989	262	139	530	265	80	302
1990	305	164	537	311	93	299
1991	357	208	582	363	106	292
1992	424	299	705	419	126	300
1993	506	409	808	506	151	298
1994	610	548	898	728	210	288
1995	744	723	972	1480	392	264
1996	915	935	1022	2247	569	253
1997				3291	751	228
1998				4840	938	194
1999				6997	1120	160

Table B.3 Estimated world market for fiber temperature sensors from MIRC91 and FSMI93 unit volume and prices.

Year	Units MIRC91 (000)	Revenues MIRC91 $M	Price/ Unit $k	Units FSMI93 (000)	Revenues FSMI93 $M	Price/ Unit $k
1986	3.0	11.2	3.7			
1987	3.3	12.9	3.9			
1988	3.7	14.7	4.9			
1989	4.2	17.4	4.1	5.0	16.5	3.3
1990	4.8	20.8	4.3	5.6	18.9	3.4
1991	5.5	25.4	4.9	6.2	21.4	3.4
1992	6.5	31.1	4.9	6.6	23.9	3.6
1993	7.8	38.2	4.9	7.2	26.7	3.4
1994	9.6	46.7	4.9	8.2	30.0	3.7
1995	11.7	56.9	4.9	9.6	33.8	3.5
1996	14.6	69.1	4.7	11.6	38.7	3.3
1997				14.3	45.0	3.4
1998				17.8	53.0	3.0
1999				22.8	62.9	2.8

Table B.4 Total world market for fiber pressure sensors from MIRC91 and FSMI93.

Year	Units MIRC91 (000)	Revenues MIRC91 $M	Price/ Unit $	Units FSMI93 (000)	Revenues FSMI93 $M	Price/ Unit $
1986	5.5	8.6	1600			
1987	6.6	10.0	1500			
1988	7.9	11.7	1500			
1989	9.5	13.8	1500	88.4	25.8	240
1990	11.5	16.3	1400	99.6	29.7	300
1991	14.0	19.4	1400	109.9	33.6	310
1992	17.1	23.2	1400	117.1	37.3	320
1993	21.0	28.0	1300	125.6	41.3	330
1994	25.9	34.0	1300	142.7	46.4	330
1995	32.2	41.6	1300	167.9	52.1	310
1996	40.2	51.3	1300	200.7	59.2	240
1997				243.5	68.0	280
1998				300.6	79.0	260
1999				380.3	92.7	240

C. Relevant Navy Programs

The authors believe that, among the many Navy programs involving optical fiber technology, the following programs have contributed particularly to the advancement of optical fiber sensor technology toward its introduction into the fleet.

C.1 Advanced Optical Sensing System (AOSS)

The Advanced Optical Sensing System was designed to put threshold fiber optic sensors for damage control monitoring in a standardized package for new ship construction. It began in the mid 1980s, sponsored by the Naval Sea Systems Command (NAVSEA). The initial program was carried out by the Naval Surface Warfare Center, Dahlgren, VA, with sensors designed by a contractor. Thirty-one sensors were installed on the USS MOBILE BAY (CG-53) in 1987, just prior to the ship's undergoing shock trials. The sensors successfully passed the ship's shock trials.

The sensors consisted of threshold measurements of temperature, rate of rise of temperature, smoke, and liquid level. All were based on measurements of optical amplitude. The measurement of temperature consisted of a bimetallic snap switch that interrupted the path of a light beam at specific set temperatures of 96, 125, and 150 °F. The measurement of rate of rise consisted of optical fiber wrapped around a metallic cylinder; when the cylinder expanded due to increasing temperature, microbending caused an optical signal drop proportional to the rate of rise of the temperature. Smoke was detected by measuring optical attenuation across a 9 inch path of light with fiber leading to and from the sensing area; the electronics were set to trigger at a specific, adjustable density of smoke in the range of 2% to 7% obscuration. Liquid level was detected at a specific point in each compartment by terminating two fibers with a lens; one fiber served as the transmitter and the other fiber the receiver. When the lens was covered with liquid, more light was transferred out of the optical system, lowering the optical power detected, and indicating the presence of a liquid. An optical fiber pull switch was also designed to transmit a manually activated fire alarm condition. All sensors used 100/140 µm diameter fiber and an 830 nm source wavelength. The sensors were installed in parallel with other conventional, electrical sensors.

Detector Type	Population
Temperature	12
Smoke	6
Liquid Level	6
Rate of Rise of Temperature	3
Alarm Pull Switch	1

The 31 sensors installed on the CG-53, were distributed by measurand as shown above.

After three years on the CG-53, five sensors were removed by the contractor and evaluated for performance. Test results showed some calibration shift, attributable to dirt and paint coatings. After cleaning, the sensors returned to their initial performance.

Since 1991 the AOSS program has had the new objective of providing a complete damage control monitoring system for new ships. The target ship was the DDG-51, Flight 2A. AOSS was planned to provide sensor input to a larger program called the Integrated Survivability Management System (ISMS). The objective of the ISMS is to automate the communication of damage control parameters to inform the Damage Control Officer of damage control status in near real time. ISMS is configured to provide damage control information to the Standard Monitoring and Control System (SMCS). This was planned for installation on the DDG-51, Flight 2A, but recent information suggests that an alternative system may be used, instead.

Additional sensors were purchased by CD, NSWC, Philadelphia, in 1991 and tested in the laboratory. Results showed that each threshold sensor passed the simulated shipboard environmental tests except for the smoke detector which exhibited false alarms when the sensing threshold was set near the minimum obscuration threshold.

The initial system configuration had 16 electronic cards connecting to a VME back plane, each card containing the electro-optics components for 16 sensors. The signal conversion units for sensors of temperature, rate of rise of temperature, smoke, and liquid level, are all of the same type. A flame sensor was added to the original list of sensors and requires a separate card for each sensor.

Experimental models of the AOSS sensors were installed on the ex-USS SHADWELL in April 1993 and were evaluated during several fire tests on that ship. Performance has not yet been documented. The results indicate that the sensors generally performed successfully, but need some improvements in design.

Standardization and operating in the shipboard environment have been a major focus of the AOSS program. The major advantage is in the standardization area where several sensors are operated from one common type of electro-optics card. This is a sound concept that must be practiced in future shipboard systems design to minimize cost and provide an open architecture that will provide the ability to incorporate new technical developments. There are concerns about the survivability of the AOSS system in its present form, since with the star configuration a failure at a single point can disable many sensors.

Standardization can be practiced on several levels. Building several ships of the same design, a ship class, is one form of standardization. Designing several kinds of fiber sensors to plug into the same backplane, as was done in AOSS, is another. Using the same optical fiber components for every fiber application onboard ship is another.

In the AOSS, the use of 100/140 μm diameter fiber and an 830 nm optical source are exceptions to the optical fiber components specifications already released by NAVSEA. The larger fiber was advantageous for its light gathering properties. Using the smaller, but Navy standard, 62.5/125 fiber would probably reduce the performance of the AOSS sensors. The difference in optical fiber components needed for sensor design compared with communications system design seems to be an impediment to the low cost manufacture of optical fiber sensors.

The AOSS program has demonstrated that optical fiber sensors can be operated successfully in the shipboard environment. The AOSS program also illustrates the difficulty of taking an optical fiber sensor development program all the way through the Navy developmental process to installation on a class of operating ships.

At the date of this writing, funding for the AOSS program has been withdrawn and there are no plans to develop the system further. The decision to stop the funding rests on perceived need versus funding other programs with different priorities. Navy sponsors are presently debating the need for any new sensor development for damage control monitoring.

C.2 Fiber Optics Control Systems Integration (FOCSI)

FOCSI is an eight-year NASA/Navy program designed to develop the technology necessary to incorporate optical fiber based control systems into advanced aerospace vehicles. The program has been led by the NASA Lewis Research Center, Cleveland. It includes the development and testing of passive optical sensors and optoelectronic components, and the design, development, and flight demonstration of an optical fiber based control system. The program began in 1985 and ground based testing of the sensors is in progress. Additionally, several of the propulsion system, optical fiber sensors have been flown successfully on an F15. The program will culminate with a flight demonstration on an F18 in the fall of 1993, in which the sensors will operate redundantly with equivalent conventional sensors. A followup program called the Systems Research Aircraft (SRA) Program has been planned and should result in flight demonstrations by 1996.

The program is being carried out by two prime contractors, one of whom is responsible for the sensors associated with the propulsion system and the other for the flight system. Each prime contractor is incorporating a group of sensors, as follows:

Propulsion system
3 Displacement
2 Rotation speed
2 Low Temperature
1 High Temperature
1 Flame

Flight System
5 Linear position
3 Rotary position
1 Pressure
1 Temperature

Nine subcontractors have provided the sensors, with typical procurements of three sensors for each function.

The general approach has been of strong, top-down design. A major investment was made in network architecture development and optimization. Specific subprograms were undertaken by each of the prime contractors to identify optimum technology, based both on sensor performance and compatibility with the system.

Ruggedness of the sensors has been a major emphasis. Each of the sensors to be used will have been extensively tested prior to installation on the aircraft. Furthermore, it was a specific goal to involve multiple sensor suppliers so as to expand the manufacturing base for rugged fiber sensors.

Reducing costs of the sensors or sensor network has not been a major emphasis. By the time of the full flight demonstration, the total program costs of FOCSI will have reached an estimated $17M; the average cost of sensors for this program is of the order of $100k.

C.3 Optical Fiber Sensor Research at NRL (Hydrophones and Magnetometers)

The Naval Research Laboratory (NRL) has developed and demonstrated numerous optical fiber sensors. Primary focus areas have been ocean surveillance sensor technology in the areas of hydrophones, magnetometers, and optical fiber sensor multiplexing; field models have been demonstrated at sea. Results of this research have been published in numerous international technical journals and symposia, documenting the leadership of NRL in the international community involved with optical fiber sensor technology. For reviews of these developments, see for example, the following: Davis, P. B., *All Optical Towed Array (AOTA) Sea Test Results*, DoD Fiber Optics '92, McLean, VA, 24-27 March 1992, pp 256; Bucholtz, Frank, and Anthony Dandridge, Naval Research Laboratory, *Magnetic Sensors*, DoD Fiber Optics '92, McLean, VA, 24-27 March 1992, pp 255; Dandridge, Anthony, and Alan D. Kersey, Naval Research Laboratory, *Multiplexing* *of Fiber Optic Sensors*, DoD Fiber Optics '92, McLean, VA, 24-27 March 1992, pp 257-259.

Hydrophone research and development at NRL has taken two forms, the All Optical Towed Array (AOTA), and more recently the planar array.

The AOTA was an array of hydrophones towed behind a search vessel in a cable like configuration. There was an Advanced Technology Demonstration of the towed array resulting in two sea trials in 1989 and 1990; the demonstration was supported with 6.3A funding from Naval Operations. Performance was superior to conventional hydrophones in all respects. AOTA will not be ready for deployment on operational ships until it is developed through advanced models and engineering prototypes with 6.3B and 6.4 funding. Data was gathered showing a payoff after a certain number of arrays were built. However, the Navy decided not to pursue further development of AOTA; the exact reason for not further developing AOTA is unknown to the authors at this time. But, there is always a strong competition for funds within the Navy development community and obviously a higher priority was assigned to other programs. Considering the shift in threat from deep water to shallow water, it is unlikely that AOTA will be further funded for several years. Optical hydrophone development at NRL has thus shifted to planar arrays aimed at countering a diesel threat near the ocean shore.

The demonstration of the AOTA was a major accomplishment in fielding an optical fiber sensor model on an operational ship. The number of channels was comparable to existing operational systems. [Davis, op. cit.] The in-water components consisted of an optical tow cable, vibration isolation module, and acoustic module, consisting of optical fiber interferometric sensors and two pressure insensitive interferometers. The optical fiber acoustic sensors were frequency multiplexed from optoelectronics mounted onboard ship.

Fiber magnetometer research and development at NRL has resulted in interferometric sensors that compete favorably with many of the conventional electrical types. These sensors have also been demonstrated at sea.

Most of the research and development in optical fiber sensor multiplexing at NRL has supported interferometric sensors used as hydrophones and magnetometers, as summarized as follows [Dandridge and Kersey, op. cit.]: In 1990, a 48-channel towed array hydrophone system was tested at sea. This and other tests have demonstrated both frequency division multiplexing, time division multiplexing, and combinations thereof in the sea environment. NRL has also demonstrated a code division multiplexing configuration for an array of eight optical fiber sensors. Optical fiber sensor developments have concerned both ac and dc measurands. Additional demonstrations involved the use of multiplexing techniques to measure pressure, displacement, and magnetic field on a single interferometer. A heading sensor was also demonstrated using a triaxial magnetometer and a triaxial accelerometer multiplexed in a single interferometer.

C.4 Fiber Optic Sensor Specifications and Standards (FOSSAS) Program

The Naval Sea Systems Command initiated development of optical fiber technology specifications and standards in 1986 under a program funded directly from Naval Operations. The goal was to develop specifications and standards to enable the introduction of optical fiber technology into the Navy fleet in the areas of shipboard data networks, sensors, and any other optical fiber systems that might be applied to the business of operating a war ship. At that time there were no governing standards for optical fiber components or systems; that is, the use of optical fiber components on board ship would have been outside the Navy logistics and training systems.

To overcome this impediment to the application of optical fiber technology to the fleet, the following military specifications were developed and approved for use in ship design and procurement:

Specification	Title
MIL-A-24726	Attenuator
MIL-C-24621A	Coupler (only spec sheet 5)
MIL-C-85045D	Cable (only spec sheets 13 & 14)
MIL-C-24733	Controller interface unit
MIL-C-28876	Connectors, environment resisting
MIL-C-83522	Connectors, single terminus
MIL-F-49291A	Fiber (only spec sheets 6 & 7)
MIL-F-24734	Fiberscope
MIL-I-24728	Interconnection box
MIL-L-24732	Light source, fiberscope
MIL-M-24731	Multiplexer, frequency division
MIL-M-24736	Multiplexer, time division
MIL-P-24627	Penetrators, bulkhead, connectorized
MIL-P-24628	Penetrators, hull, connectorized, pressure-proof, submarine
MIL-R-24720	Receiver, digital
MIL-R-24727	Rotary joint

Specification	Title
MIL-R-24737	Receiver, analog
MIL-S-24623a	Splice (only spec sheets 4 & 5)
MIL-S-24725	Switch
MIL-T-29504	Termini, fiber optic connector, removable (used in MIL-C-28876 connector)
MIL-T-24721	Transmitter, digital
MIL-T-24735	Transmitter, analog
MIL-STD-2196	Fiber optic glossary

Creation of the optical fiber specifications and standards was a major step in the development of shipboard optical fiber systems, providing the ability of communication system and sensor designers to select optical fiber components with some confidence that they would operate in and survive the shipboard environment. The next step was to develop some of the systems that might be used on board ship.

In FY92, the NAVSEA Integrated Combat Systems and Fiber Optics Branch, began the Fiber Optic Sensor Specifications and Standards Program [Jacobson, Carl P., *NAVSEA Fiber Optic Sensor Program,* DoD Fiber Optics '92, McLean, Virginia, 24-27 March 1992, pp 261-262.]. The objective was to develop sensors that would be qualified for shipboard application with specifications to enable the procurement of the sensors for both new ship construction and back fitting onto existing ships where the advantages warrant. This a five-year program.

Specifications are being written for those optical fiber sensors that are commercially available. These specifications are supported by shipboard demonstrations of commercially available technology for optical fiber pressure sensors and position switches. Evaluation results have been excellent thus far and demonstrate that optical fiber sensors can be operated successfully in the shipboard environment [Whitesel, Henry, Carl Jacobson, and Frank Leland, *Fiber Optic Sensors for Shipboard Applications*, Tenth Ship Control Systems Symposium, Vol. 4, Oct. 1993, pp 4-157 to 4-170.] The status of the specification development is given in Table C-1.

Table C-I. Fiber Optic Sensor Specifications

Title	Status
Sensor, Absolute Pressure, Fiber Optic (Naval Shipboard Use)	In review
Sensor, Temperature, Fiber Optic (Naval Shipboard Use)	In review
Fiber Optic Transducer, Electromagnetic Sensing, General Specification For	In review
Tachometer, Fiber Optic, (Naval Shipboard Use), (Metric) General Specification For	In review
Switch, Position, Proximity (Non-Contact) or Limit (Mechanical Contact), Fiber Optic, (Metric), General Specification For (Naval Shipboard Use)	In review
Salinity	In draft
Accelerometer	In draft
Pressure Switch	In draft
Flowmeter	In draft

Those sensors that are not commercially available are being developed by the Annapolis Detachment of the Naval Surface Warfare Center; primary focus areas of development are sensors for liquid level, voltage, electrical current, chemicals, and optical fiber multiplexers. Plans are to carry this part of the development through shipboard demonstrations and specifications.[a]

The Fiber Optic Sensor Specifications and Standards Program also involves the development of cost reduction design efforts and increased reliability. (This study is part of the program.)

The preliminary results of the Fiber Optic Sensor Specifications and Standards Program already demonstrate the availability of optical fiber sensors that can function satisfactorily in the shipboard environment. Unlike many other developments, this program also attacks the high cost issues and manufacturability issues of optical fiber sensors. This unique foresight might provide a major stimulant in the future application of optical fiber sensors because it addresses issues that often inhibit the selection of new technology for new ship construction.

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a. In a related program, an optical fiber temperature sensor and smoke detector have been successfully demonstrated on the USS SHADWELL, the Navy's fire research test ship.

D. Integrated Optics (R. K. Hickernell)

Integrated optical technology demonstrates the capability for reducing size and cost and increasing reliability in the manufacture of optical fiber sensors. The purpose of this Appendix is to highlight the potential impact of integrated optics on the implementation of fiber sensors in Navy shipboard applications. We present an overview of the current state of the art and give specific examples of components and modules that may be a part of a sensor system. Further details are presented in a companion report.

Integrated optics offers several advantages over bulk and optical fiber components. Light is confined in two dimensions to a few micrometers, resulting in large reductions in device size. Size reduction leads to a reduction in power requirements in devices such as electro-optic modulators and switches. Many devices can be integrated on a single chip, which produces optical alignment stability. Active devices are combined with passive components without fiber pigtailing joints. The planar geometry allows the application of techniques well developed for integrated circuit fabrication, including material growth, photolithographic patterning, and wire bonding. Planarity is also an advantage in some intrinsic waveguide sensors. The integration of components decreases packaging complexity and increases robustness.

Most of the optical components used in fiber sensors have been fabricated in planar waveguide form. These include sources, detectors, optical amplifiers, lenses, mirrors, gratings, filters, beamsplitters, couplers, polarizers, modulators, and interferometers. Examples of the integration of optical and electronic components on a single substrate are rapidly increasing in complexity and performance. In the last few years, several planar waveguide devices have entered the commercial market.

Historically, the driving force behind the progress of integrated optics has been the telecommunications industry. The emphasis on higher bandwidth transmission, coherent detection, wavelength multiplexing and demultiplexing, optical switching, and network interconnection have increased the demand for multi-function optoelectronic circuits. Optical sensor technology is an indirect beneficiary of development in this field, since many of the research results can be implemented with few modifications. The aerospace industry has carried on long-term research on integrated optical chips for the optical fiber gyroscope. Other examples of integrated optics applied to sensors include electric field sensors and position sensors.

There are several specific areas mentioned in this report where integrated optical devices can contribute significantly to meeting sensor requirements for Navy shipboard use. Optical sensor networks (see Section 4.1.5) require passive branching, combining and coupling components which, in some cases, may be supplied more economically in planar waveguide format than by all-fiber devices.

The size and weight of sensors powered by light (see Section 3.2.2, 4.2.1) would be greatly decreased by the integration of optical and electronic components on a single chip. Various embodiments of integrated optical spectrometers and wavelength-division couplers have been demonstrated in the laboratory. Further development may produce modules suitable for the wide variety of wavelength-dependent sensors (see Section 3.2.1, 4.2.2). Polarimetric fiber sensors, such as those monitoring electric current or voltage, would benefit from a compact receiver module (see Section 3.2.4, 4.2.4).

Host materials which show the most promise for the manufacture of integrated optical sensor modules are the ferroelectric crystals lithium niobate and lithium tantalate; ion-exchanged glass; deposited silica on silicon; and the III-V semiconductors. Lithium niobate ($LiNbO_3$) is the most mature of the technologies. It bridges the gap between glass, which offers passive functions, and the semiconductors, which offer light generation and detection but are significantly more costly and complex in terms of device fabrication. Several companies offer $LiNbO_3$ intensity modulators commercially, and at least two manufacturers utilize a $LiNbO_3$ switch or modulator in optical fiber test equipment. Most of the devices are fabricated with titanium-indiffused waveguides. Proton-exchanged waveguides, which transmit only linearly polarized light, have a reduced sensitivity to photorefractive instabilities. This is critical to applications involving high optical power and/or visible wavelengths. Annealed proton-exchange is employed in an integrated optical chip manufactured for use in the optical fiber gyroscope; the chip consists of a beamsplitter and phase modulators. The pigtailed fiber-to-fiber insertion loss of simple $LiNbO_3$ devices is typically 4 dB or less. Although lithium tantalate ($LiTaO_3$) waveguide devices have a lower photorefractive sensitivity than $LiNbO_3$ devices, the quality of $LiTaO_3$ substrates is currently not consistent enough for large volume production.

Ion-exchanged glass waveguides are the simplest types of waveguides to fabricate. Packaged, fiber-pigtailed $1 \times N$ splitters are commercially available; 1×2 splitters have an excess insertion loss of 0.6 dB at 1.3 μm (McCourt and Cucalon, 1990). A wide range of host glasses and dopant ions allows flexibility in the tailoring of device parameters. Although the present commercial emphasis is on passive devices, recent research has demonstrated glass waveguide lasers and amplifiers.

An intensive development effort focussed on silica waveguides on silicon substrates has produced numerous functional devices applicable to telecommunications and sensors. The outstanding merits of the technology are its excellent compatibility with optical fibers and the use of fabrication techniques developed by the integrated circuit industry. The low propagation loss of silica waveguides (as low as 0.03 dB/cm) permits the production of complex optical circuits covering large substrate areas. Hybrid integration of passive waveguide components with fibers, lasers and detectors on a silicon "optical bench" is greatly facilitated by preferentially etched alignment features. The flexibility offered by the hybrid approach has certain advantages over monolithic integration in III-V semiconductors, including device yield, relaxed design tradeoffs and, in some cases, cost. $1 \times N$ splitters, up to $N = 32$, and wavelength demultiplexing splitters using silica-on-silicon technology are offered as commercial products. Also available commercially is a linear displacement sensor featuring an integrated optical interferometer composed of waveguide lenses, mirrors, a beamsplitter, and a passive phase shifter.

Most researchers agree that the III-V semiconductors offer the greatest potential for the realization of integrated optoelectronics. In principle, all of the components included in an optical sensor can be monolithically integrated on a single chip: passive waveguide devices, sources, modulators, detectors, and electronics. The main disadvantages for choosing semiconductors are the high cost of materials and fabrication, and the large optical insertion losses of waveguide devices. Loss can be compensated by optical amplification, with added device complexity. Device design involves tradeoffs between the various performance specifications. Waveguide lasers and modulators are most efficient with a small modal size, but small modes couple poorly to standard optical fibers. The doped region of an active waveguide contributes to absorption loss. Waveguides with a higher index difference between cladding and core enable tighter bends, but scattering loss is increased. Generally the disparate requirements for passive and active elements dictate the greatest compromises in performance and the higher cost of multiple processing steps.

Although several multi-function, prototype devices in III-V semiconductors have been developed, most are used for in-house research and systems demonstrations; few, if any, are available commercially. Since the capital equipment costs are larger for semiconductor device fabrication than for the other waveguide materials, the volume of production needed to drive product costs down and create commercial viability are proportionally larger. However, the history of semiconductor lasers suggests that, given sufficient consumer demand, III-V semiconductor technology will make significant inroads in the market.

For use in a wide variety of fiber sensor systems, the basic integrated optical module would include a laser source, detectors, and passive optics such as splitters or directional couplers. Both monolithic and hybrid techniques for fabricating such a module have been demonstrated. A monolithically integrated device which illustrates the versatility and maturity of current technology is the balanced heterodyne receiver, which combines five different types of waveguides on a single InP chip: two tunable Bragg reflection filters and an optical gain section (which make up the distributed feedback laser); an electrically adjustable phase shifter; a directional coupler switch; and two waveguide photodetectors (Koch et al., 1989). The core of the waveguide is continuous throughout the entire structure, which automatically aligns the various sections. After the first growth sequence, a longitudinal processing sequence removes the layers in the sections where they are not needed, and a lateral processing sequence defines the waveguiding regions. Only two regrowth sequences are needed to complete the photonic circuit. The length of the finished chip is 3 mm.

Coupling from a semiconductor waveguide to an optical fiber is typically accomplished with ball lenses or lensed-tip fibers in the same manner as in pigtailed laser packages. Tapering the mode profile by stepping the thickness of the waveguide core region allows coupling to cleaved fibers with reduced alignment tolerances.

Several research groups have demonstrated the benefits of monolithically integrating amplifier electronics. A receiver chip fabricated on InP for operation at 1.55 μm included a passive waveguide, MSM detector, and HEMT amplifier (Hong et al., 1991). A wavelength demultiplexing coupler, photodiode, resistor, and JFET amplifier were integrated on another chip, which was mounted in a dual in-line package for testing (Bornholdt et al., 1992). The integration of a MESFET drive amplifier with a interferometric intensity modulator in AlGaAs reduced the required input voltage swing from 6 V to 0.26 V (Ade et al., 1992).

Hybrid integration techniques that combine sources and detectors with dielectric waveguides include solder bonding and the grafting of epitaxial layers lifted off a substrate surface. Attaching a laser to a silicon substrate so that it efficiently couples light into a silica waveguide requires a precisely etched alignment basin. The thermal stability of hybrid bonds remains an issue. Amorphous silicon or germanium detectors are deposited directly on dielectric substrates for use at visible and near infrared wavelengths.

Optical power splitters are fundamental components in a number of important fiber sensor functions: power monitoring; driving many sensors with a single source; acting as beamsplitters and combiners in interferometers; wavelength demultiplexing; and signal routing in sensor networks. Channel waveguide splitters in glass are reported to have cost and performance advantages over optical fiber splitters in applications requiring four or more output branches, particularly where polarization control is critical. Splitters using multiple Y-branching elements have been fabricated in silica on silicon with up to 128 branches. Directional coupler splitters have a second input port and allow greater control over the coupling ratio. The splitters can be designed for strong or weak wavelength dependence.

The techniques of wavelength division demultiplexing are useful for common-mode rejection in intensity-based sensors, bit discrimination in code plates, spectroscopy in chemical or temperature sensors, and multiple sensor networking. Four basic techniques — directional couplers, Mach-Zehnder interferometers, optical phased arrays, and gratings — have been implemented effectively in planar waveguide format. Directional couplers are most useful for intensity noise rejection. Mach-Zehnder filters with channel spacings ranging from 0.008 nm to 250 nm have been fabricated in deposited silica (Takato et al., 1990). The acousto-optic effect in $LiNbO_3$ enables operation of a tunable filter with 145 nm tuning range (Smith et al., 1990). Optical phased array and grating devices provide a large number of output channels. The highest degree of integration in a waveguide spectrometer was demonstrated on an InP substrate. The monolithic device includes planar and channel waveguides, a curved reflective grating, and a 92 element, p-i-n detector array. Channel spacing is 1 nm in the 1.48 to 1.56 μm band (Soole et al., 1992). The total chip size is about 12 mm by 2 mm. Researchers claim that the technology is generic, so it can be applied to other semiconductors for shorter wavelength operation.

Depending on the design, the polarization-sensitive components needed for a polarimetric receiver module include polarizers, polarization splitters, and/or polarization-sensitive detectors. Channel waveguide polarizers on virtually any substrate material are constructed with metal or semiconductor cladding layers; they exhibit extinction ratios as large as 45 dB. Proton-exchanged waveguide polarizers in $LiNbO_3$ or $LiTaO_3$ have shown extinction ratios of greater than 50 dB and are relatively insensitive to wavelength. Material and waveguide birefringence induces polarization-dependent coupling. Extinction ratios of 20 to 35 dB have been measured in single-stage polarization splitters using this effect in glass or $LiNbO_3$. A pair of polarization-sensitive waveguide detectors is the simplest design for a monolithic polarimetric receiver module; detectors fabricated on InP substrates have thus far achieved extinction ratios of 11 to 16 dB.

Although most of the initial applications of integrated optics in sensor systems will be in the area of signal routing and receiving, the planar geometry and mechanical stability present unique advantages for the sensor head itself. Compact waveguide interferometers have detected electric fields with high sensitivity and dynamic range. They are envisioned for chemical sensing. Chemically active, waveguide claddings enhance measurand selectivity. For absorptive or fluorescent sensor heads, long interaction lengths are obtained on small substrates using serpentine patterns of low-loss waveguides. Multiple sensing heads can be combined on the same chip.

Solid-state waveguide sources provide access to wavelength regions unobtainable by semiconductor sources. Second-harmonic generation using domain-reversed gratings and upconversion luminescence in rare-earth-doped substrates are methods of achieving visible light emission from $LiNbO_3$ waveguides. The research area has particular relevance to fluorescence-based chemical sensors. Compact broadband sources could be constructed with multiple waveguide dopants and integrated beam combiners.

The fiber pigtailing and packaging of a simple integrated optical device can account for about two-thirds of its total cost. To achieve low insertion loss, single-mode fibers and channel waveguides must be aligned to tolerances which are an order of magnitude stricter than those for integrated circuits. Passive techniques using fibers bonded in silicon V-grooves will cut costs in the alignment of fiber arrays. The testing of packaged devices is similar to that for microcircuits. Further research is needed to fully understand the degradation mechanisms involved in accelerated aging tests.

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E. Net-Present-Value Computations

Net-present-value computations are done in Section 5 because, from an economic viewpoint, it is appropriate to consider not only how much money is spent and gained, but also when it is spent or gained. This appendix defines the computation, and provides a brief tutorial for unfamiliar readers.

Spending $1,000 today on something that will be worth $1,200 next year is a good investment. But if its value will not reach $1,200 until five years from now, one might do better to put the $1,000 in a 4% bond or savings account, where it will reach $1,216 in five years. This example illustrates that, to evaluate an investment, it is necessary to know both the dates of expenditure and revenue, and the prevailing interest rate.

A net-present-value determination applies to a cash-flow scenario or schedule (expenditures and receipts, with dates) and an assumed interest rate. The cash schedule and the interest rates are the inputs, and the net present value (in cash) is the output. It is a measure of how beneficial the scenario is in comparison to simply borrowing and lending (or investing) at the assumed interest rates. The comparison assumes that the scenario is funded by money borrowed at the assumed interest rate, and that revenues from the scenario are invested at the same rate. Its validity depends, of course, on how close the assumed interest rate is to actual bank rates.

If the net present value of a scenario is a positive $100, executing the scenario is equivalent to being given a gift of $100 today and investing it with compound growth at the assumed interest rate, until the date when the program ends. If the net present value is minus $100, scenario is equivalent to throwing away $100 today, whereas the money could otherwise be invested at the assumed interest rate. If the net present value is computed to be zero, the cash-flow scenario can be duplicated by borrowing and lending at the assumed interest rate with no net loss or gain. A scenario with a positive net present value is worth executing, provided there are no deficits excluded from the cash analysis that outweigh the net present value. A scenario with a negative net present value is not worth executing, unless there are benefits excluded from the analysis that are worth that price.

Most common "spreadsheet" programs for personal computers have a net-present-value function that can be applied to an interest rate and a range of negative and/or positive values representing expenditures and/or revenues at the ends of equal calendar periods for which the interest rate applies. Because it assumes that cash flow occurs at the end of a period rather than the start, this function will compute a first-year profit of $110 to have a net present value of $100 at 10% annual interest, rather than a value of $110. While this assumption is not correct for many scenarios, it makes little difference if the interest rate is low.

In Section 5, net present values for all the scenarios were computed using a standard spreadsheet function, assuming simplistically that expenditures and revenues occur at the ends of the indicated years. An interest rate of 5% is assumed.

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