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ADVANCEMENTS IN UNDERWATER INSPECTION

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16. Abstract

This report summarizes the advancement of underwater inspection and nondestructive evaluation capabilities being made in the Structural Integrity Monitoring Program, a joint industry program in the United Kingdom. Inspection techniques are discussed that will advance capabilities in the Marine Inspection program area of the U.S. Coast Guard. For example, the Underwater Survey in Lieu of Dry Dock program, mobile offshore drilling unit (MODU) underwater hull inspection, tension leg platform (TLP) inspection and inspection of floating facilities mooring system will benefit from this technology. Inspection systems discussed are eddy current, AC field measurement, and fiber optics. A manipulator is being developed that will perform inspection with these inspection techniques in deep water without human intervention. Participation in this technology building program keeps the Coast Guard at the forefront of underwater inspection technology. It provides an insight to the industry's viewpoint through contact with commercial sponsors of the joint industry program.

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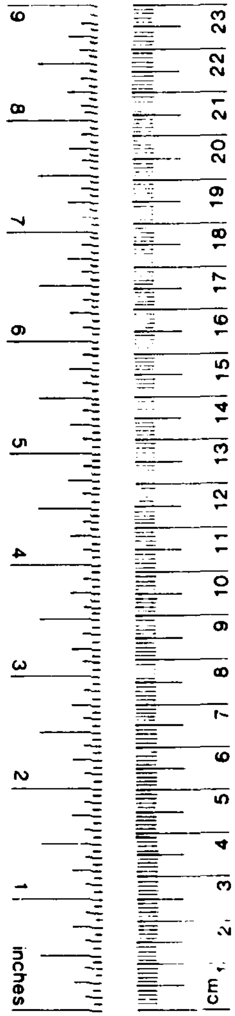
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	[illegible]	milliliters	ml
tbsp	tablespoons	[illegible]	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

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		LENGTH		
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cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
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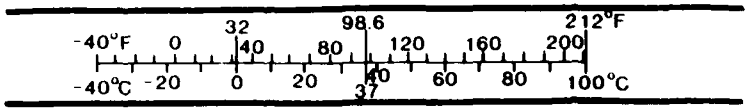
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 PURPOSE

The purpose of this report is to: describe the underwater inspection technology being developed in the Structural Integrity Monitoring (SIM) Joint Industry Program (JIP), and describe how it supports the Marine Inspection (MI) program area.

This report is generally organized in two parts. The first part discusses the original underwater inspection requirements that were to be addressed by joining SIM, and the eventual expansion of the scope of the Marine Safety project. The second part of the report discusses the technology being developed in SIM and how it will advance the state of the art in underwater inspection as related to MI. For simplicity, some of the details of the research resulting of the inspection systems are not included in this report. Rather, the SIM final reports are cited as references so that the reader can obtain complete information if desired.

2.0 BACKGROUND

2.1 Inspection Requirements

In 1983, the R&D Center began a study to survey the state of the art of underwater inspection systems that could be used to perform various types of underwater inspection on tension leg platform (TLP) tendons and templates. Understanding inspection capabilities is an important factor in evaluating the design, inspection and maintenance plans for a TLP. This work was begun in preparation of the first TLP in U.S. waters, the Conoco Jolliet TLWP located in Green Canyon, Block 184 in the Gulf of Mexico.

Inspection of tendons and templates could require a wide range of capabilities including the ability to locate and size nonsurface breaking cracks in threaded tendon connectors, measure corrosion potential on the template, locate and size cracks in welded joints on the template, and locate dented or missing members in the template caused by dropped objects. Inspection, in this context, refers not only to visual observation of the structure, but also nondestructive evaluation (NDE) as well. The problems of these inspection requirements are complicated by performing them in deep water where divers are expensive or not practical. The visual inspection aspect of TLP tendon and template inspection is well in hand. Many years of visual inspection with black and white television, color television, still photography and remotely operated vehicles (ROV) has developed visual inspection of offshore structures to a high degree.

The underwater NDE aspect of TLP inspection is less developed. Crack detection and sizing techniques, though used for many years, are primitive and produce dubious results. The implementation of underwater NDE techniques from ROVs, using manipulators, is also rudimentary. The ability to fix an ROV at a work site and move a manipulator with an NDE tool attached over a precise inspection path is not routine. The need to exercise that kind of precise dexterity with a manipulator is not common. Most tasks requiring dexterity have been performed by divers. In the waters depth of future inspections, NDE by divers may not be possible.

In 1986, the need for underwater inspection techniques expanded. The Collisions, Rammings and Groundings project (3305), Marine Structural Adequacy project (3306) and Flooding, Capsizing and Foundering Prevention project (3307) were combined into one project, Marine Safety, (3300). By virtue of the amalgamation of the three programs, the Marine Safety project has a broader scope than the individual programs. The TLP inspection project was pursued under the 3306 project.

Several areas of the MI program will require advanced inspection technology in the coming years as drilling and oil production move into deeper water. At a March 1988 auction, 43% of the acreage leased in the Gulf of Mexico was in water over 1000 ft deep. The mooring chains of floating facilities to be used in those waters will be installed for 15 years and must be inspected periodically. It has been proposed that these chains be inspected with ROVs carrying an ultrasonic tool. The technology base developed in the SIM will provide the Coast Guard with information for a critical review of proposals such as that.

The underwater inspection of hulls will benefit from the technology in SIM. Ships and MODUs can be inspected in the water in the Underwater Survey in Lieu of Dry Dock Program. This avoids the cost of dry docking the vessel. TLPs will require the same type of hull inspection because they will remain on station through the life of the oil field. Techniques being developed in SIM will allow rapid scanning of hull plates and welds by divers. Some of the techniques do not require extensive cleaning to bare metal. This reduces the time and cost of inspection. Involvement in the SIM will indicate which techniques are best suited for those tasks, how much cleaning is required, and what the reliability and probability of detection are.

2.2 Contribution of JIPs to Inspection Capabilities

Two JIPs have been used to assess the current state of underwater inspection and to track the development of new techniques: a) the Underwater Engineering Group's (UEG) underwater inspection project assessed the current state of technology, and b) SIM is developing new underwater inspection techniques in an effort to overcome the inspection shortcomings identified in the UEG study.

UEG Inspection Project (Ref. 1) - Early in the TLP tendon and template inspection survey study, it became obvious tha· the bulk of underwater inspection knowledge and experience is in the countries around the North Sea where regulatory inspection requirements have driven the development of underwater inspection systems much faster than in the U.S. To gain access to the information in that area, the R&DC joined the UEG project "Underwater Inspection and Inspection Philosophy for Offshore Platforms." UEG is located in London and has extensive offshore experience around the North Sea.

This program, managed by UEG, addresses the relationship of design, maintenance and inspection in offshore platforms and is comprised of approximately eight individual studies. The reason for joining this program was primarily for the study on the state of the art of underwater inspection systems for conventional steel jacket platforms, concrete platforms and TLPs. Since this program was conducted in the United Kingdom (UK) and since the body of knowledge on underwater inspection systems is centered there, joining that program would contribute significantly to the TLP tendon inspection study.

The UEG underwater inspection study concluded that there is very little reliable performance data on underwater inspection systems. Manufacturers have been building systems, contractors have been using these systems and owners have been accepting results from systems when no one really knows how well these systems work. There have been almost no detailed probability of detection (POD) trials in which the performance of systems are estimated using scientific methods.

Structural Integrity Monitoring (SIM) program - Because there is so little performance information on underwater inspection equipment and because that industry lacks understanding of the capability and use of their equipment, the R&DC needed a means of tracking current developments of new inspection systems. To accomplish this, the R&D Center became a sponsor of SIM. Twelve underwater inspection techniques are being developed in this program for eventual use on offshore structures. Being involved with the development of these systems "from the ground up" will provide the Coast Guard with an understanding of the inherent capabilities and limitations of the systems as well as the types of evaluations that should be performed to demonstrate the effectiveness of them. The Coast Guard will, in effect, go up the learning curve with the manufacturers (also sponsors of this program) who will be marketing the technology to platform owners who will present these systems to the Coast Guard during plan review. Participating in SIM also provides an insight to the point of view of the commercial inspection industry because the Steering Committee of 16 members has 12 commercial sponsors.

The SIM program contains an intelligent manipulator project that is developing a manipulator and controls for use with NDE equipment in deep water without divers. The manipulator is driven by a computer that positions the inspection device at the inspection site and passes it along a predetermined inspection path such as a weld. This capability could be used to inspect TLP tendons and templates and floating facilities moorings where divers are expensive or not feasible because of other physical constraints such as water depth. Diverless inspection capabilities may also yield more accurate and repeatable inspection results by removing the human factor.

In summary, the UEG inspection program provided a state-of-the-art survey of underwater inspection systems' performance; determining that there really is essentially no reliable performance information, SIM was joined to be involved with the improvement or development of underwater inspection systems.

This section has been a brief discussion of the history of these JIPs and how they supported the specific requirements of the TLP inspection study and more recently the broader scope of the Marine Inspection Program. The remainder of this report will focus on the technology being developed in SIM. But first, programmatic aspects of SIM are discussed briefly to provide a complete view of that program, how it functions and the type of exposure it provides the Coast Guard.

3.0 STRUCTURAL INTEGRITY MONITORING PROGRAM

3.1 Objectives and Organization

The objective of SIM is to improve current underwater inspection practices and procedures in offshore engineering by developing new or improved NDE techniques for crack monitoring and remote continuous monitoring systems.

The program includes projects on techniques currently used in industry such as AC field measurement (ACFM), eddy current (EC) and acoustic emission. Phased array ultrasonics, optical fibers and hydrogen sensors are being developed but have not yet been used offshore. SIM includes the development of a variety of inspection techniques because the industrial sponsors feel that they will be using a mix of inspection techniques in the next decade just as they have in the past decade.

The SIM is a consortium of 5 UK universities. The total funding for the program is approximately $850K, 60% of which is provided by the Science and Engineering Research Council (SERC) in the UK. The SERC commits its share of the funds if the managing institution can interest commercial sponsors in joining the program and providing the remaining 40% of the funds. This ensures that the R&D conducted by the universities is relevant to offshore needs because many of the sponsors are involved because they want to commercially exploit the new technology. This connection to reality is also evident when the sponsors decide at the end of each two-year program which project will be continued in the next phase and which will be dropped. The current program is sponsored by 16 different companies from five countries. The SIM is a continuing program that operates in two-year phases. The Coast Guard sponsored Phase II (1985-1987) and sponsors Phase III (1987-1989). The cost to the Coast Guard is approximately $11K per year.

3.2 Program Overview

The emphasis in the following overview of the projects is on those that were continued from Phase II to Phase III because of technical merit (i.e., high probability of success). The projects of both Phases are shown in Table I. Some of the inspection techniques in these projects are more advanced than others and some may never reach commercial development. The objective of all the Phase III projects is to work increasingly toward satisfying the long term NDE requirements of industry. These are techniques that can be:

a. deployed from a ROV
b. operated in a rapid scanning mode
c. operated with increased stand-off from the structure thereby reducing the need for extensive cleaning

The SIM projects discussed below are those that will have the broadest application to the MI mission and offer an advanced capability not currently available. While the technical development of these systems are advancing, none has developed to the level where commercialization is appropriate.

4.0 AC FIELD MEASUREMENT (ACFM)

4.1 Uses

ACFM is a surface crack depth measurement technique. It has been developed in England and systems have been introduced for underwater use by OSEL and Det Norske Veritas. They are extensions of a system developed for manufacturing plant inspection purposes. ACFM is conventionally used to measure the depth of a surface crack that has been located by another underwater NDE technique. Through the work in this program, ACFM is also being developed to scan over metal surfaces to locate as well as measure the depth of surface cracks in metal plates and welded joints.

ACFM systems could be used by a diver to locate and size cracks in the hull plates and welds of ships (as in the Underwater Survey in Lieu of Dry Dock program) and MODUs. In the near future, ACFM systems will be deployed by ROV with a manipulator for inspection in water depths beyond diver capabilities. This may include the inspection for surface cracks in the mooring chains of floating offshore facilities. These moorings will be deployed for 15 years and will be inspected in place in several thousand feet of water.

TABLE I

STRUCTURAL INTEGRITY MONITORING PROGRAM
LIST OF PROJECTS

Project Title	Phase II	Phase III
Development of AC Field Measurement Techniques	X	X
An Eddy Current Instrument for Offshore Applications	X	X
Integrated Eddy Current - ACFM Probe System for Rapid Detection of Surface Cracks	X	X
Three Dimensional Radiological Imaging of Thick Underwater Structural Sections	X	X
Robotic Underwater Inspection	X	X
Use of Hall Effect Probes for Detecting Magnetic Flux Leakage in Magnetized Cracked Weldments		X
Further Development and Application of the Hydrogen Sensor NDT program	X	X
Subsea Crack Detection and Monitoring Using Optical Fiber Devices	X	X
Plate, Leaky, Rayleigh and Creeping Wave NDT for Offshore Structures		X
Ultrasonic Phased Arrays for Flaw Sizing in Offshore NDT	X	
SQUID magnetometer for NDE	X	
Fatigue Crack Face separation and Opening	X	
CAD based Ultrasonic Inspection Strategies For Complex Node Geometries	X	

4.2 Theory of Operation

ACFM measures surface crack depths by measuring the resistance of an electrical path across a metal surface containing a crack. An AC electrical current is applied to the surface and the electrical resistance of the steel surface gives a potential drop between two point contacts on the surface (Figure 1, Δ). When the points are set across a surface crack, the electrical path is longer and the resistance reading is greater. If the contact point separation is held constant, the crack depth is a function of the change in voltage caused by the crack.

The field can be developed in the metal surface with two techniques: (a) field injection - placing contacts on the surface and allowing current to flow through the surface and (b) field induction - placing an electrical conductor near the metal surface and inducing the field in the surface with the magnetic field around the conductor. The penetration of the current path under the metal surface (Figure 1, δ) is a function of the field excitation frequency. Because the current path travels in a straight line between the two contact points, tight or bridged cracks may be transparent to this technique because the induced current may "jump" these cracks and not produce the potential drop required for crack indication. Crack depth measurement accuracy of +/- .04 inches has been reported (Ref. 2). It should be noted that the performance evaluation (i.e., crack sizing capability) of ACFM and all other underwater inspection technique are not performed to any standard and are generally considered to be suspect. This was discussed in Section 2.2.

4.3 Limitations of Current Systems

The ACFM technique has several characteristics that make it attractive for use for underwater offshore inspection applications. However, several limitations, which are present in current systems, must be overcome in order for this technique to reach full potential. The understanding and resolution of these limitations are the focus of the research conducted in SIM. These limitations are a prime example of the need for scientific research in this technique. The application of ACFM to underwater inspection has been an extension of land-based inspection techniques that were "marinized" and sent underwater. This was only partially successful because the physics of the technique were not fully understood and several phenomenon occurred that could not be explained previously using limited knowledge.

Previous ACFM systems have used the field injection technique. This required having two probes that the diver must attach to the structure. The injection probes are open circuits and there is a potential electrical hazard to the diver. To increase diver safety, induction technique have been used. Previous attempts at field induction technique have produced strong

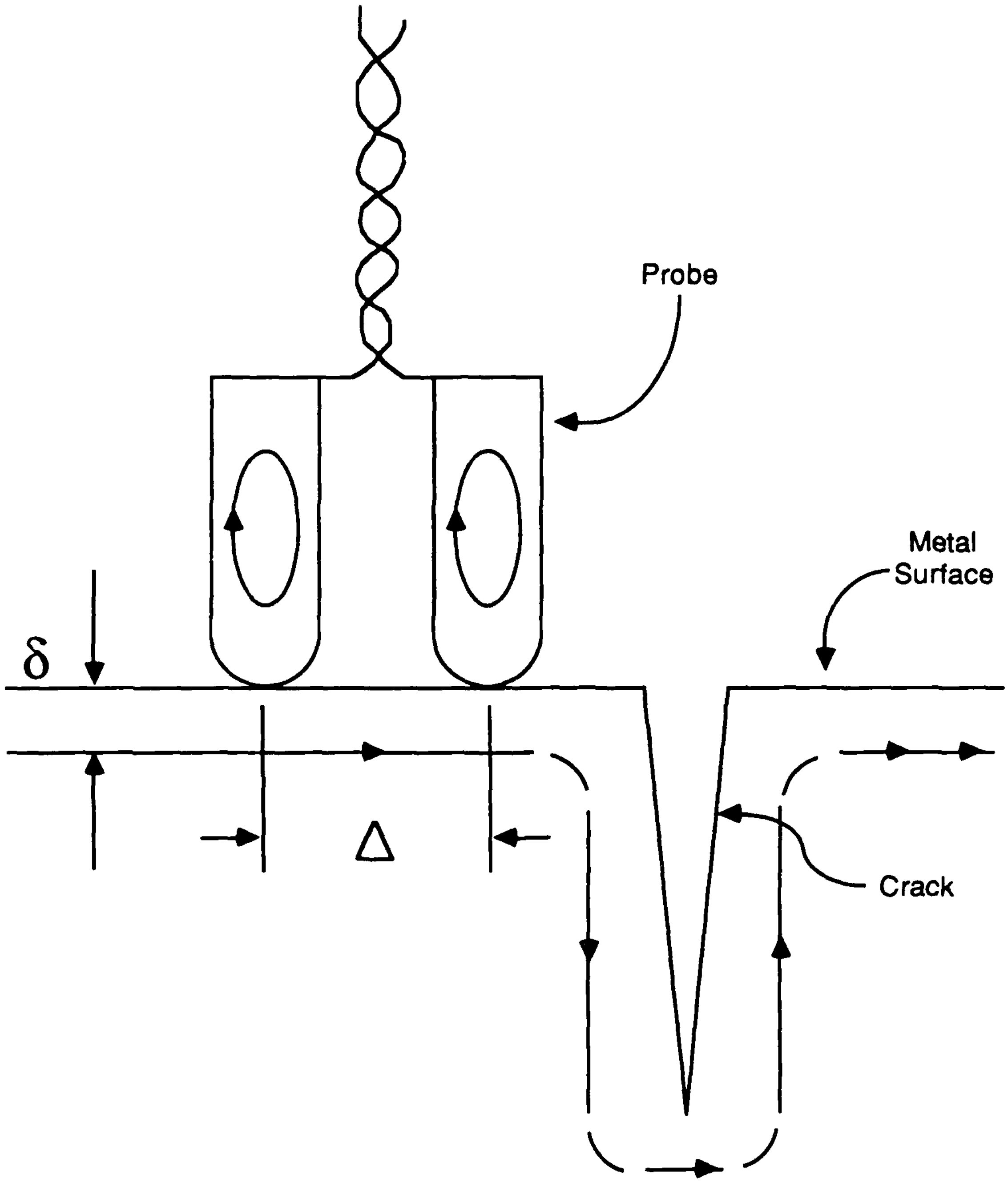


Figure 1
ACFM Principle

spurious signals that are believed to enter the system through the contact probes, and signal and power cables from sources elsewhere on the structure.

Previous ACFM systems were not developed to the level that achieved accurate interpretation of crack size from field measurements.

To overcome these limitations, two different ACFM systems have been developed in SIM, each with a somewhat different objective. Both systems have advanced the capability of this inspection technique. The two systems are discussed below in the context of the shortcomings in the previous section.

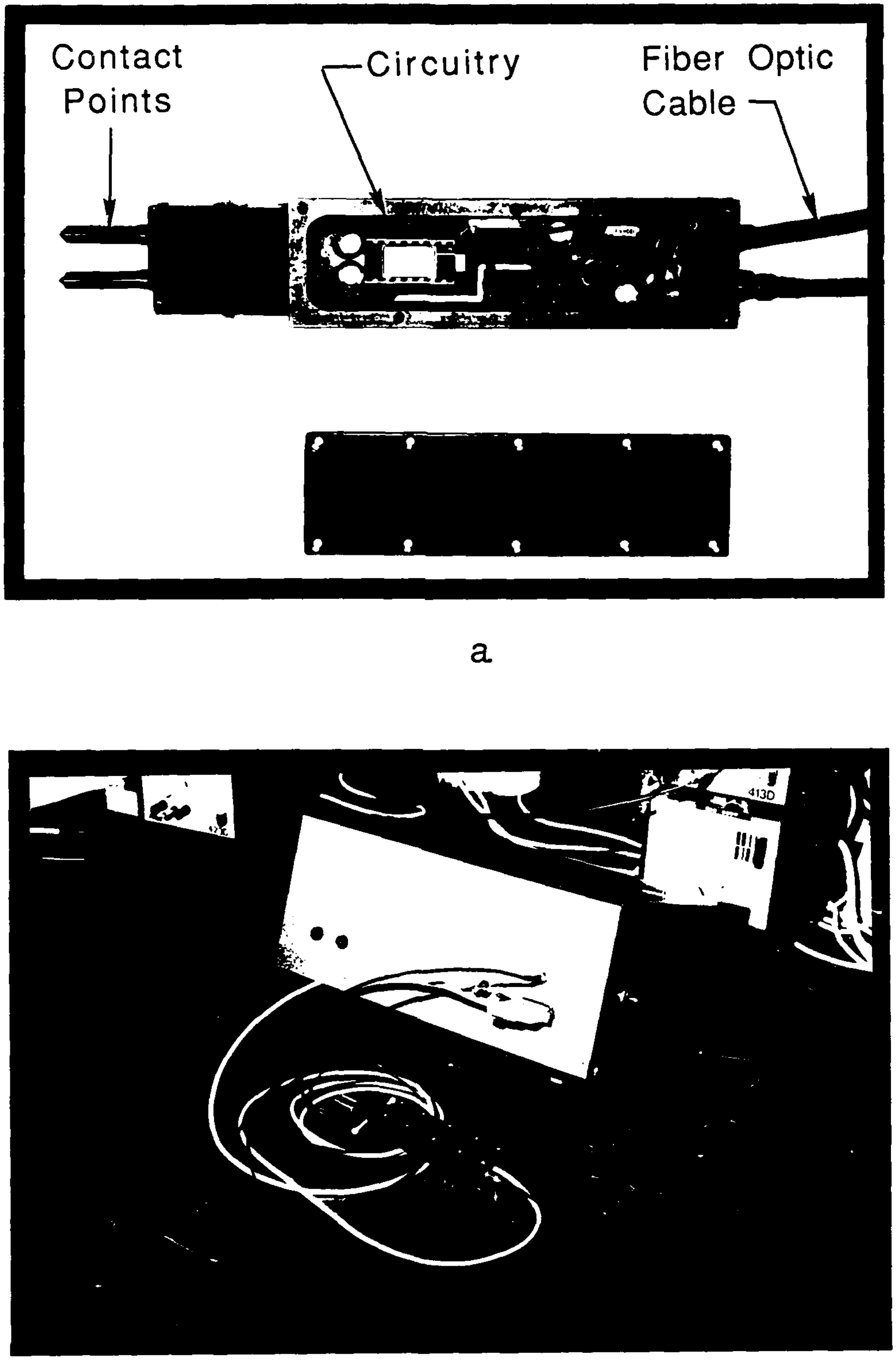
4.4 Integrated System

The so-called "integrated system" (Ref. 3) is referred to as such because the contact probes and signal conditioning and amplifying circuits are combined in one unit that fit the diver's hand (Figure 2, (a)); the instrumentation is located in a box away from the diver (Figure 2, (b)). This configuration overcomes the problem of noise introduction into instrumentation through the signal cables. This configuration has the following features:

- The Integrated Probe contains a fiber optic cable between the probe and the primary instrumentation box. The probe amplifies and conditions the crack measurement signal and transmits it up the fiber optic cable to the instrumentation box on the surface. Since the fiber optic cable is unaffected by stray electrical noise from the structure or from the power cable for the field induction system, the crack measurement signal reaches the surface with no interference or distortion. This allows the power cable to be combined with the signal fiber optic cable so that the diver (or ROV) only has to handle one cable.

- The contact points in the Integrated Probe are pointed and can be used through light scale, rust or marine fouling. This would reduce the need for cleaning to bare metal. Experiments have shown that crack depth measurements are possible through scale and rust if satisfactory contact with metal is obtained.

Pointed contacts cannot be used to scan a surface for cracks. Considerable research was required to arrive at the optimum probe point separation and field excitation frequency. Previous systems have selected the point configuration almost arbitrarily. This is the source of parasitic signals that could not be eliminated in previous systems. A frequency of 1500 Hz is used in this system. A change to another probe configuration would require some tuning to obtain the optimum frequency.



a.

b.

Figure 2
Integrated Probe

4.5 Scanning Probe

As discussed in Section 3.2, recent SIM program interest has emphasized the ability to (a) scan surfaces to locate as well as size cracks, (b) deploy these inspection systems from ROVs (with the Intelligent Manipulator, Section 6.0) for deep water applications, and (c) locate cracks in welds. To accommodate these expanded requirements, a new probe configuration was developed. A schematic of the Scanning Probe is shown in Figure 3 and a breadboard model is shown in Figure 4. This configuration has the following features:

- The probe contact points are round so that they will slide over the inspection surface. This does require that the surface be clean so that contact is maintained.

- The contacts are spring loaded so that each contact maintains contact as the probe slides over an irregularity such as a weld bead.

- Scanning over irregular surfaces can cause variations in the signal that could confuse the interpretation of crack sizes. To effectively filter out this effect, an averaging circuit has been included that calculates a running average of a fixed number of signal observations. When a crack is encountered, a significant change in the average signal occurs.

4.6 Hand-Held Crack Gage

A breadboard hand-held crack micro-gage has been developed (Ref. 4) that incorporates the electronics, probe, induction coil and a direct readout display of crack depth for diver use. A breadboard model appears in Figure 5. It is battery powered and requires only 50 milliamps of power instead of 2 amps as in other systems. The device was tested underwater on a large diameter tubular section with actual fatigue cracks at the Underwater NDE Center at University College London. Results indicate (Ref. 4, Figure 37) a very close correlation with the actual crack depths in depths up to 10mm. Beyond that, the estimates are conservative because of the non-uniformity on the induced field. Cleaning to bare metal is required for this device. Work is progressing on a system that will not require surface contact.

5.0 EDDY CURRENT (EC)

5.1 Uses

Eddy Current is a surface crack location technique that can locate cracks in welds and plates. Removal of light marine fouling or non-conductive surface coatings (such as paint) is not required for EC. It is not suitable for use on surfaces with metallic coatings such as flame spray aluminum because the

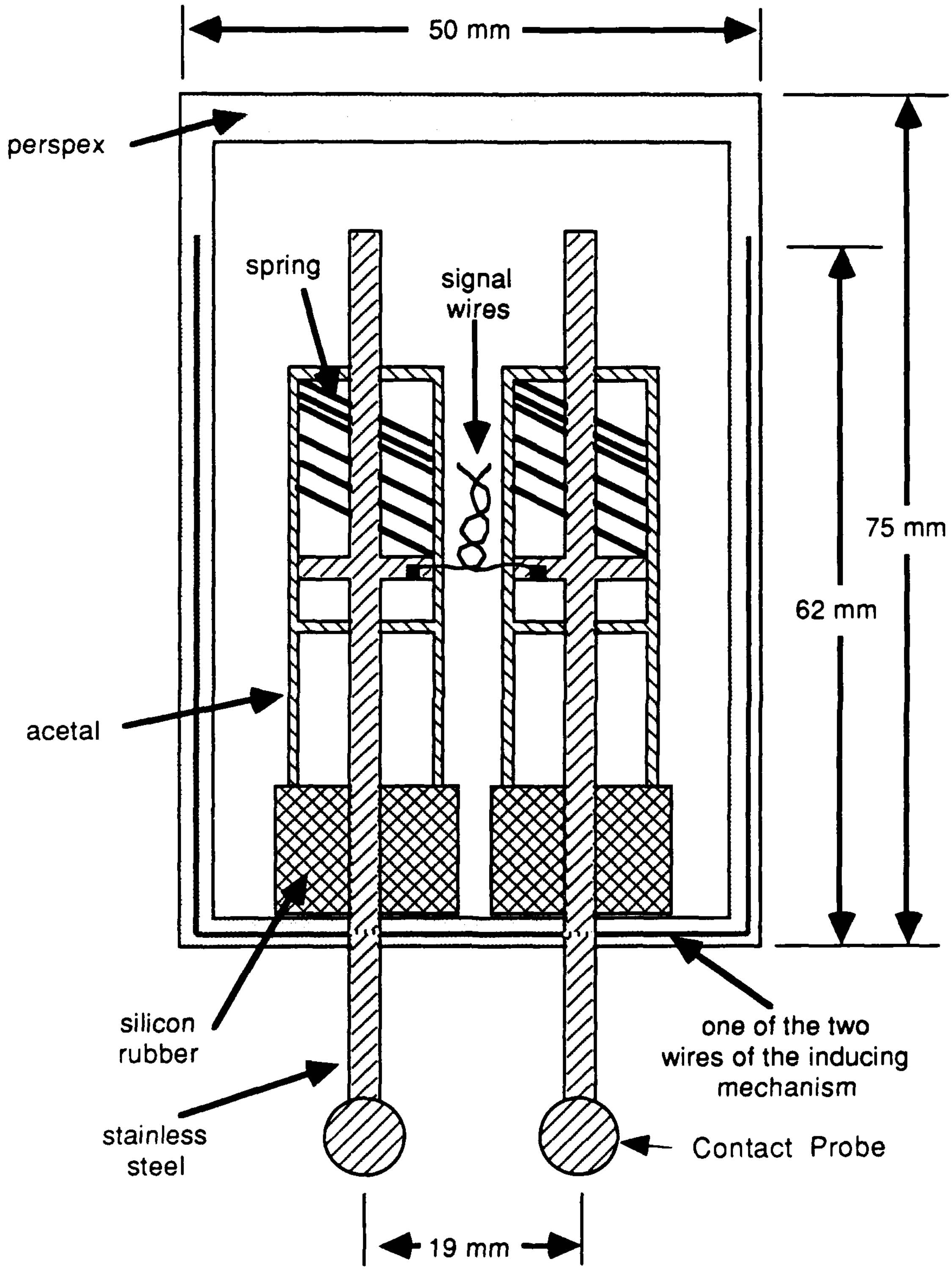


Figure 3
ACFM Scanning Probe
Sectional View

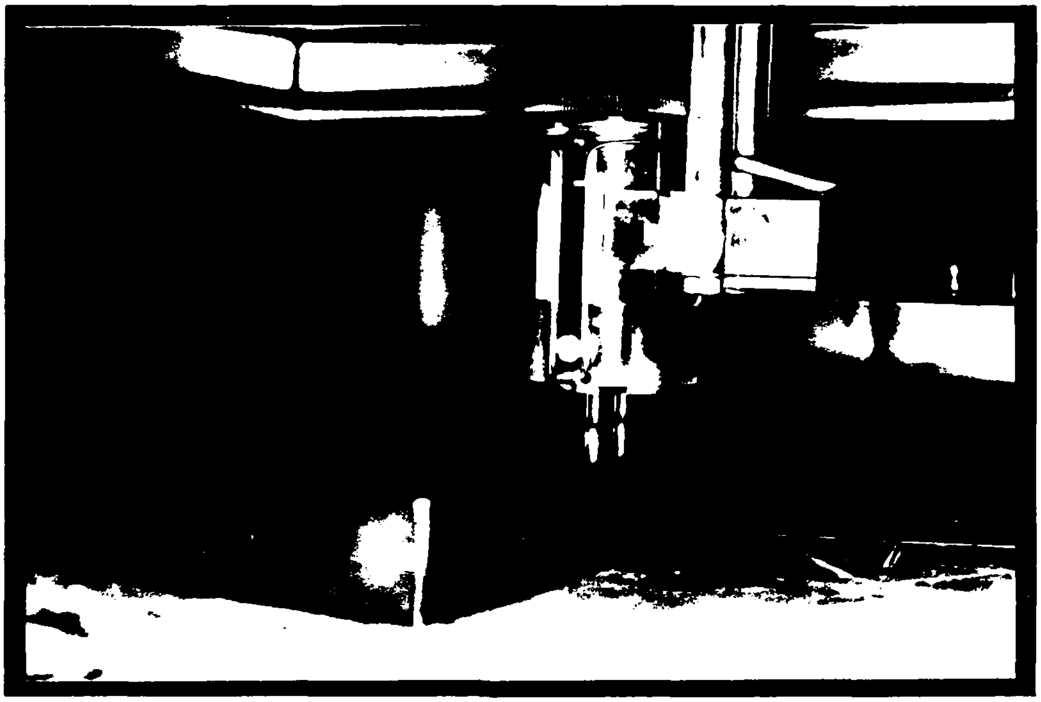


Figure 4
ACFM Scanning Probe
Breadboard Model

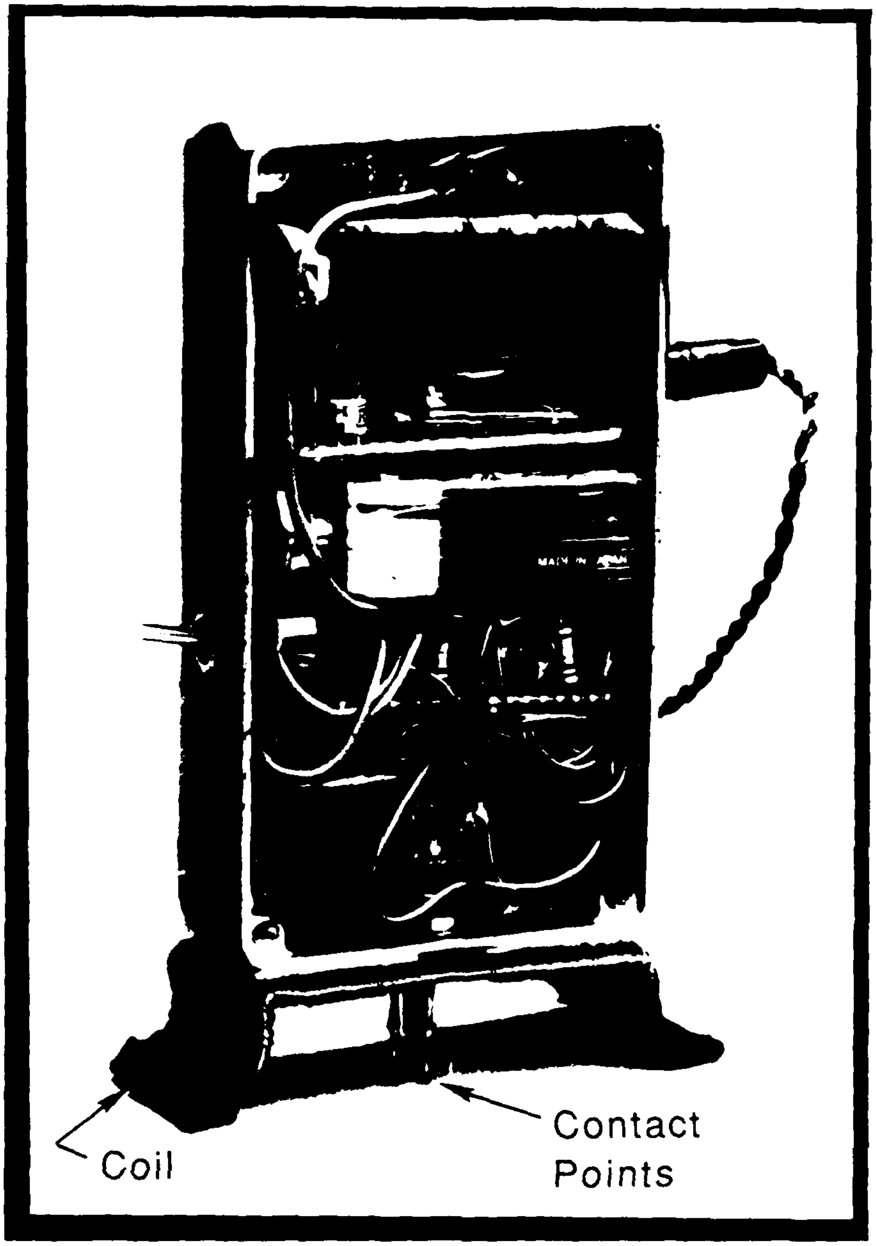


Figure 5
Hand-Held Crack Micro-gage
Breadboard Model

magnetic field is displaced through the coating instead of around the crack resulting in no crack indication.

EC can be used to locate surface cracks above or below the water line in ship hulls, TLPs, MODU's and deep water floating facilities.

5.2 Theory of Operation

EC inspection detects surface or near-surface defects by establishing an oscillating magnetic field on the metal surface and detecting the perturbation of the magnetic field caused by the defect. The magnetic field is induced in the surface by placing a coil next to the surface; perturbations in the magnetic field are sensed by another coil which is passed over the inspection area. The magnetic field is perturbed by cracks, voids, inclusions, and changes in permeability of the parent metal and weld material in the heat affected zone (HAZ). One of the primary shortcomings of conventional EC systems is the difficulty in separating valid defect indications from changes in metal properties (i.e., permeability).

EC is somewhat different from the ACFM technique discussed in Section 4.0 in that the probe does not necessarily have to make contact with the surface.

5.3 Limitation of Current Systems

The change in permeability across the HAZ and the sensitivity to lift-off (i.e., the spacing between the probe and the metal surface) are the root of the limitation of current EC systems.

Conventional systems developed for underwater inspection use one probe to scan across the inspection area. The change in the permeability of the ferritic steel (often found in offshore structures) requires constant tuning by the operator (who is topside) and communication between the operator and the diver. The very large change in permeability between the weld and HAZ may mask a defect. For this reason, EC is considered less reliable than other conventional techniques like magnetic particle inspection. Conventional EC systems require cleaning to bare metal so that the lift-off can be kept constant.

5.4 Advancement in EC Inspection Under SIM

The EC system (Ref. 5) developed in SIM has resolved the permeability variation problem by developing a rectangular matrix array probe of 16 eddy current coils that maps the variation of metal properties under the array. This technique can determine if the variations in permeability from one location to another is the cause of gradual changes in metal properties or a crack indication. A 16-element array prototype is approximately 3/4-inches square with 16 1/16-inch diameter coils arranged in a square matrix. The development of a 16-element array required the development of new computer aided instrumentation for probe excitation and sensing, switching and data storage and analysis.

The system has a lift-off sensor in the probe that provides a graphic indication of lift-off in the instrumentation. It is important for the operator to know that the probe is within acceptable limits because the magnetic field strength, and therefore the crack detection, will be affected. The lift-off for the present probe is 3/16-inch. Another approach to insure correct lift-off on surface of irregular shapes is to configure the probe so that it conforms to the surface. This can be done for welds and other shapes. This is an objective of the current SIM project.

6.0 INTELLIGENT MANIPULATOR PROJECT (IMP)

6.1 Uses

The IMP is developing a robotic manipulator for cleaning and NDE of welded tubular joints in offshore structures without the use of divers or other substantial human intervention (Ref. 6). This technique has application to the inspection of the mooring chains and terminations on floating facilities, and tension leg platforms that will be moored in deep water for many years.

6.2 Theory of Operation

To accomplish cleaning and inspection tasks in deep water, the manipulator will be mounted on an ROV or an ROV-transported platform and attached to the structure adjacent to the welded tubular joint to be cleaned and inspected (Figure 6). After the manipulator is secured to the structure and its location determined from a reference mark, the manipulator begins a computer-driven routine in which the manipulator determines its precise location with regard to the tubular members making up the joint to be inspected. To accomplish this, the manipulator is extended until it touches one of the tubular members. The computer records the location in space of that contact point. The manipulator then retracts and extends until it touches another point near the first point; the location of that point in space is recorded. This procedure is repeated to establish the location of several "patches" in space; a patch is a small area on the surface of the tubular defined by three or four points that the manipulator has located. The computer then proceeds to locate other patches on the other tubular members in the same manner as the first. Having located several patches on the adjacent tubular members, the computer routine calculates where the two members meet, and therefore, where the weld is. Having determined the location of the welded joint, the manipulator goes back and traces the same path with a cleaning device to expose the weld, and repeats the process with an NDE probe to locate and size cracks.

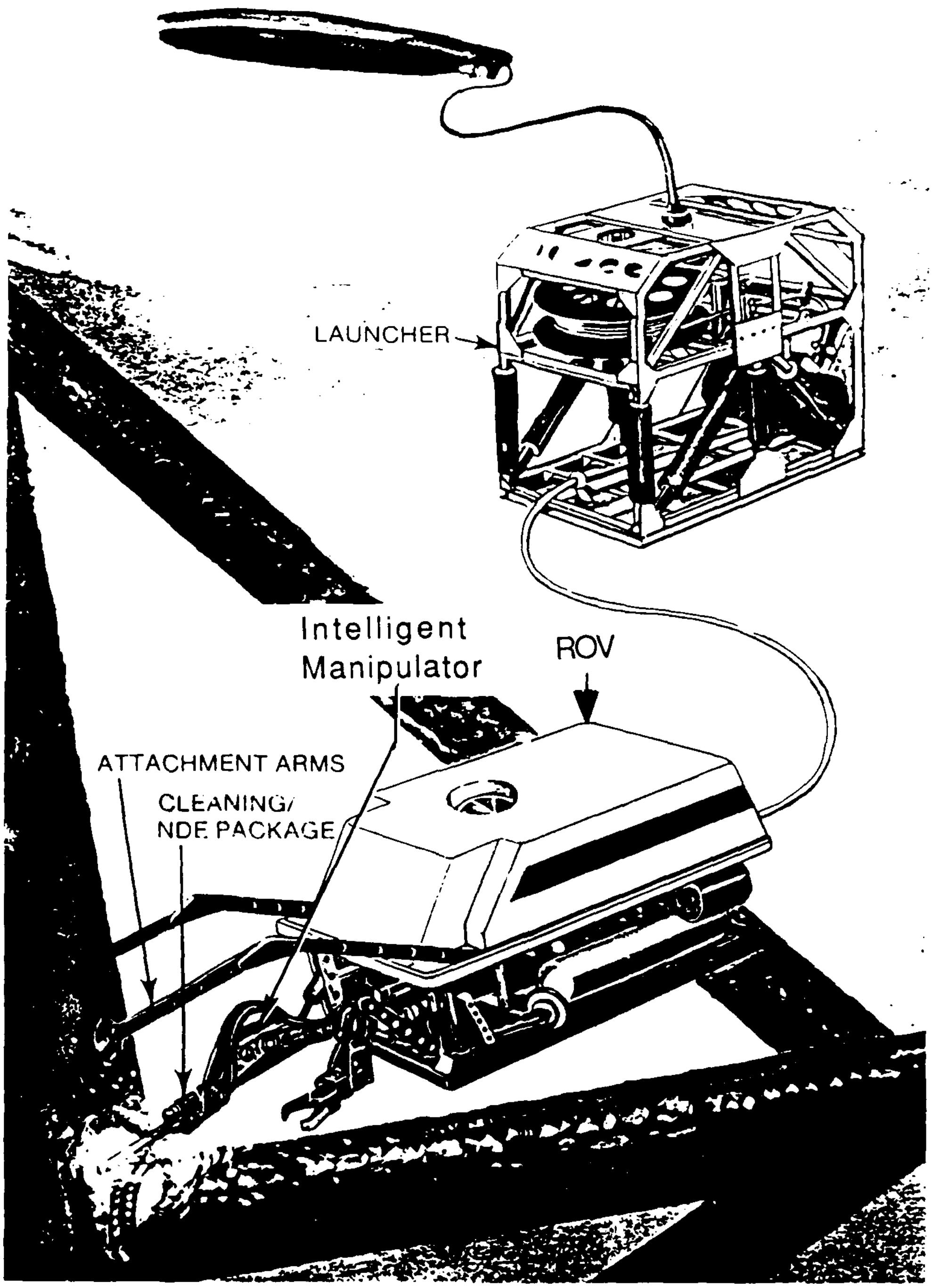


Figure 6
Intelligent Manipulator on ROV

During the scanning of the NDE probe over the weld, the manipulator control system is recording the location of the NDE probe. If a defect is indicated, the manipulator controls record the location. That allows the manipulator to return to the same location on subsequent inspections to determine if the crack is growing.

6.3 Current Capabilities

Current applications of manipulators in underwater inspection and cleaning tasks use the master/slave configuration of control. The person operating the manipulator is located on the structure or support vessel and views the work site over closed circuit television (CCTV). He sits on a device that has an arm (called the master) much like the manipulator (called the slave) at the underwater work site. The control circuit links the master and slave so that the slave mimics the motion of the master. The operator, viewing the work site on the CCTV, moves his master arm as if he were at the work site and the manipulator is his arm. Feedback systems in the slave add resistance to the master arm so that the operator can feel that the slave is against an immovable object. This gives the operator some sense of touch through the manipulator.

The master/slave system is slow because the operator views the work site through CCTV which is a two dimensional representation of a three dimensional situation. This requires a high level of concentration by the operator; most operators can work only 2-4 hours before requiring relief. Three-dimensional viewing systems have been developed that improve depth perception but cause eye strain and headaches in many operators.

The positional accuracy of conventional manipulators is adequate for visual inspection, cleaning and magnetic particle inspection. However, for EC, ACPD and other more precise NDE techniques, a more precise manipulator is required so that the probe is moved across the weld bead with greater accuracy and the crack can be relocated in subsequent inspections. This requires development of both sensors (to determine distances) and control system (i.e., software) routines to compute positions.

6.4 Advancements in Manipulators Under SIM

The general advancements in manipulator technology by SIM are largely described in the Theory of Operation section above, because of the uniqueness of this project. Manipulator technology has advanced from master/slave operation into the field of semi-automatic operation for this specific application.

In addition to the computer control system algorithms, major developments of this project that have increased the precision are the tactile sensors and laser range techniques. The tactile sensors are used during the "patch" process in which the tubular member surfaces are being located. Greater accuracy in the tactile sensor provides greater accuracy in the tubular joint mathematical model in the computer control system. Tactile sensors are configured to penetrate light marine fouling.

The introduction of laser ranging devices is increasing the precision of the manipulator by giving it real time up-dates of the distance from the manipulator to the surface. This can be compared with the distance calculated by the control system algorithm and a correction applied. The laser ranging technique is also being utilized to trace the shape and location of the weld bead. This allows the control systems to key on the shape of the weld bead for tracking purposes.

7.0 OPTICAL FIBER CRACK MONITORING DEVICE

7.1 Uses

A fiber optic crack monitoring device is a witness technique that continually monitors a crack to indicate when the crack has propagated beyond a specified point (Ref. 7).

When a crack is located by an inspection technique, a fiber optic crack monitoring device can be placed across the crack. As loading conditions increase and the crack begins to grow, the crack monitoring device is fractured by the crack and causes an indication in the instrumentation on the platform. This type of crack monitoring is most effective in locations on a structure where diver observation is not possible until after the extreme loading conditions subside or perhaps until the next scheduled inspection or maintenance occurs. This is the case, for example, on offshore structures that are normally inspected in the summer months when the weather is better. Cracks can be monitored during the winter months between inspections.

7.2 Theory of Operation

The essence of fiber optics is the transmission of light through a small glass fiber with very low attenuation. This characteristic is used as a witness device, that is, to indicate if a known condition has been exceeded (rather than to measure a condition). In a fiber optic crack monitoring device, the fiber transmits light until a condition is exceeded and the fiber breaks interrupting the light path.

A fiber optic crack monitoring device is a very simple system which has as its sensing element a fiber optic "package." The "package" is analogous to a strain gage that is placed on a location where the indication is required. It is an optical fiber embedded in a resin matrix to give it rigidity. The matrix is cemented to the steel surface over the crack tip that is being monitored.

In practice, the light source transmits light down the fiber optic cable through the package and back up the cable to the instrumentation where a light sensor is located. The light path through the package to the light sensor remains intact and there is no indication in the instrumentation (Figure 7a). When the loading conditions have caused the crack to grow and open, the optical fiber in the package breaks and the light transmitted through the package is substantially reduced (Figure 7b). That reduction causes the light sensor in the instrumentation on the platform to sound an alarm.

Fiber optic crack monitoring devices have the advantage that there is no interpretation of data required by the operator on the platform; it is a go/no-go system. Fiber optic systems are not sensitive to electrical noise as are other types of sensitive measurement systems because no electric cables are routed around the structure where they are subject to a wide variety of extraneous electrical noise. All signals in fiber optic systems are transmitted by light through fiber optic cables which are unaffected by electricity.

Once placed over a crack on the structure, a fiber optic crack monitoring device requires no further maintenance. Marine fouling can grow over it with no effect.

7.3 Advances in SIM

This project takes advantage of existing fiber optic technology as much as possible. Mass production of fiber optic cables, terminations, instrumentation and other components for the telecommunication industry has reduced cost and increased availability. The area of package development and adhesion is the primary area of technical advancement made in this project.

Optical fiber has a breaking strain of approximately 5-7%. For a fiber to be sensitive to the growth of small crack openings, the breaking strain must be reduced to 0.5-1.0%. Several techniques were developed in SIM that degrades the fiber in a chemical solution and reduces the strain at failure. This process produces notches uniformly distributed on the fiber surface which act as stress raisers. The degraded fiber is then assembled in a resin matrix that comprised the crack monitoring device "package". Techniques were developed to produce packages that are as thin as possible yet rugged because efficient transfer of strain from the steel surface to the fiber is essential for good sensitivity. In a package applied to a flat surface, the fiber is approximately 0.5mm from the surface.

Tests on flat surfaces indicate that crack openings of 50 micrometers can be sensed and that the crack tip may be 10mm past the package before it fails. Monitoring weld toe cracks will reduce the sensitivity of the fiber optic crack monitoring device because the uneven surface of the weld profile must be made flat with resin before the package is affixed. Tests have showed that every 1mm increase in resin halves the package

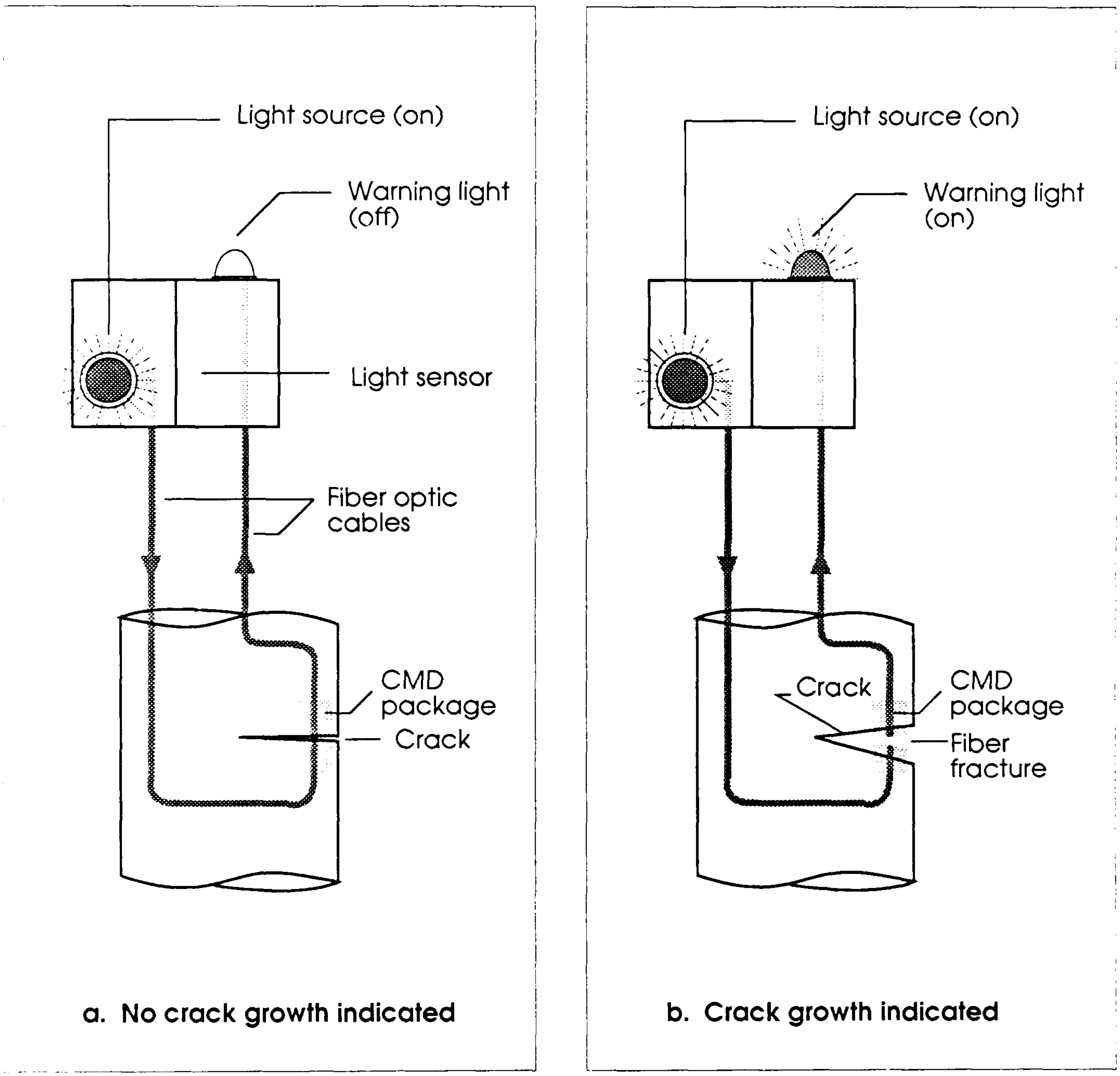


Figure 7
Fiber Optic Schematic

sensitivity. Because of this, some of the tubular joints in offshore structures will have a limited number of locations that cannot be monitored.

The technique of applying the package underwater was developed in SIM. A high viscosity underwater epoxy was utilized that can be applied to vertical or overhead surfaces without the epoxy running before the package is applied. One of the biggest problems in the underwater application of the package is non-uniformity in the thickness of the epoxy layers used either to create a flat surface for the package or excess adhesive between the package and the surface. This lack of control decreases the sensitivity of the package. This area is under continuing development.

8.0 CONCLUSIONS

SIM provides a window on the development of future underwater water inspection and NDE systems that will be used on ships and MODUs (to reduce the high cost of dry dock for inspection), and offshore floating facilities as oil production moves into deeper water. Given the rudimentary state of underwater inspection systems in general, the technology developed in this program represents a significant portion of all new information in this field.

SIM is a technology building program. While the development of some of these inspection systems requires years, the reports and exposure to the program provides technical input for the evaluation of inspection plans that are being submitted now for TLPs and other floating facilities that will remain on station for many years. Current program involvement provides a means of assessing what is possible now and where the technology will be in five or ten years. Participation also indicates the types of procedures that should be undertaken to estimate system performance in a scientific manner so that the results are creditable.

Participation on the Steering Committee provides an insight to the thought process and viewpoint of the industry that is developing and using these systems. While the research and development of these systems is executed by academic researchers, the Steering Committee is composed of commercial operators and oil companies expecting to implement this technology profitably. Participation provides exposure to industry views which is considered in Coast Guard regulatory activities. An appreciation of industry viewpoints helps the Coast Guard meet its intent of not over-regulating the industry.

SIM provides a significant quality and quantity of research and development at a very nominal cost to the Coast Guard. Access to $850K of research costs the Coast Guard $11K per year.

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