Measurand Inc.

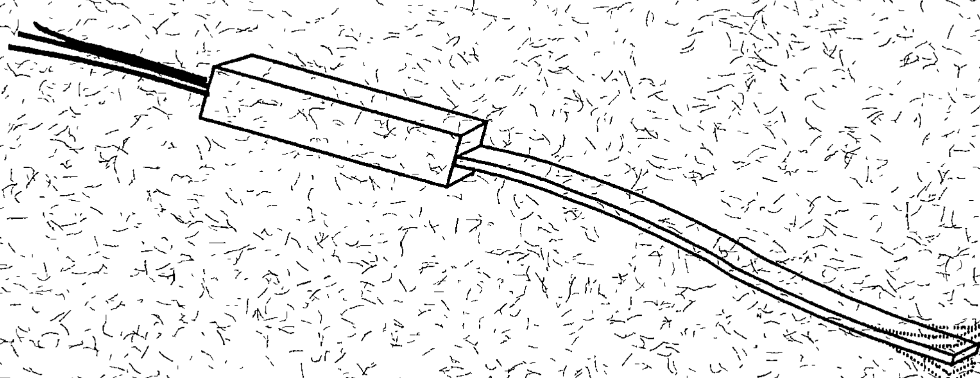
PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]
Internet: danisch@mailserv.nbnet.nb.ca

Patented Measurand fiber optic sensors:

Overview and background information



Lee A. Danisch, P.Eng.
President

Revised May 25, 1995

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]
Internet: danisch@mailserv.nbnet.nb.ca

Patented Measurand sensors:

Overview and background information

[**For a brief overview**, scan the first 22 pages, or at least the one-page description "BEAM© fiber optic curvature sensor," which appears immediately after the table of contents.]

Technologies described in this booklet include:

BEF© (Bend Enhanced Fiber) sensors utilizing straight glass and plastic fibers.

BEAM© (Bend EnhAnced Multicurvature) sensors, which are second generation devices with increased sensitivity and compactness, and which now include all UNE improvements (see below).

UNE (Unitized Nerve Ending) sensors, with third-generation manufacturing and materials improvements, which are now incorporated in the BEAM© line of sensors.

Direct optical liquid level sensors, which utilize treated fibers and optical elements (not BEAM© technology) for continuous liquid level sensing utilizing the interaction of light with liquids **(BEAM© sensors are also used for mechanical liquid level sensing, involving no optical interaction with the liquid).**

Lee A. Danisch, P.Eng.
President

Revised May 25, 1995

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd., Fredericton, NB, Canada E3B 6Z9]

Table of Contents

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]

Company Profile

Measurand holds the exclusive rights to fiber optic sensor technologies developed by Mr. Lee Danisch, including BEF©, BEAM©, and UNE©. Measurand's business is the exploitation of its rights through the manufacture of basic sensor products and the development of associated license agreements, joint ventures, and research and development contracts.

Measurand has facilities for lightguide and optoelectronics manufacture, development and prototyping. In addition, it has onsite access to expertise and facilities for fabrication of miniaturized parts, plastic injection molding, surface mount electronics, electric discharge machining, laser cutting, vibration testing, thermal cycling, stress testing, and salt fog exposure.

Personal Profile

Lee A. Danisch, P.Eng.
President, Measurand Inc.

Lee received a Bachelor of Science degree from George Washington University, and Master of Science degree from the Massachusetts Institute of Technology, both in Electrical Engineering. Honors include election to Sigma Xi, Tau Beta Pi, Phi Eta Sigma, and a National Science Foundation Graduate Traineeship.

His background includes positions at Space Sciences, Inc., Boston University Medical Center Department of Ophthalmic Biomedical Engineering, Process Technology Limited (Vice President of Research and Automation), New Brunswick RPC (Department Head, Electronics). His experience includes development of data acquisition, monitoring, and control systems; eye oximeters and pupillometers; automatic focussing systems; force and torque sensors; chemical vapor deposition systems; plasma gas scrubbers; and capacitance and fiber optic devices for sensing proximity, liquid level, curvature, and displacement. He has authored eight patents.

Lee is 50, married, with two children. He brings 30 years of education, experience, know how and relationship building to helping customers find simple, practical, cost effective solutions to difficult sensing problems.

Business Development

Senada Inc. are responsible for major project financial and business developments for Measurand. Duncan MacDonald, C.A., the C.E.O. of Senada, is an entrepreneur and financier with a broad range of experience in strategic corporate development.

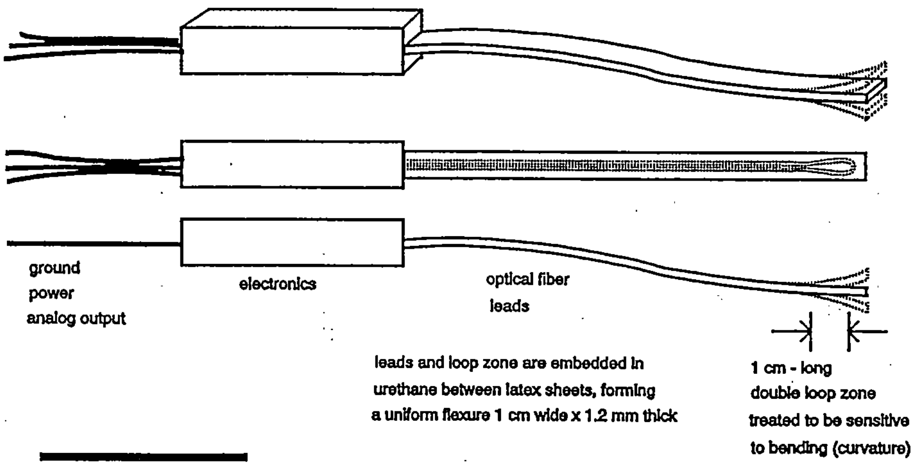
Duncan may be reached at 506-458-8328 (Tel) and 506-459-0518 (Fax). His address is 212 Queen Street, Suite 408, Fredericton, NB, Canada, E3B 1A8.

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]
Internet: danisch@mailserv.nbnet.nb.ca



BEAM© fiber optic curvature sensor

Measurand BEAM© sensors are patented fiber optic devices with a light intensity throughput that is a linear function of curvature over a wide angular range. The sensitive portion is typically 1 cm long. This portion may be affixed to or embedded in a wide variety of materials to sense displacement, flow, pressure, contact, liquid level, and any other physical parameters that interact with the material to cause the BEAM© sensor to change curvature. In a typical application, a BEAM© sensor could be affixed to a thin metal flexure to sense position of the end of the flexure. BEAM© sensors require no transfer of strain, so are not strain gauges. They continue to measure accurately even in the neutral axis of a beam.

The sensor contains treated loops of optical fiber. Each loop is sensitized to lose light on one side, so that if the loop is bent out of its plane one way, more light is lost than if it is bent the other way. The lost light is trapped in an absorptive layer, so that light throughput of the fiber loop is dependent only on curvature. The effect is highly linear over a range of typically ±75 degrees per cm. BEAM© sensors are not microbending sensors; the treated portion is 3000 times more sensitive to bending than an untreated fiber.

In a standard configuration, a BEAM© sensor consists of two nested coplanar loops of plastic fiber facing in opposite directions, so that the throughput during bending increases for one and decreases for the other. Simple analog circuitry performs a difference over sum calculation (sum held constant by a control loop), so that common mode effects such as lead bending, light source ageing, and temperature factors are cancelled. For a 5 VDC supply, the output is a high-speed 0 to 5 V signal, linear with curvature.

Preliminary specifications, BEAM© Model A (subject to change without notice): Supply voltage: 4-16 VDC; Supply current at 5 VDC supply, 15 deg c: ≤5 mA; Analog output:ratiometric with supply, rail-to-rail; Sensitivity at max. gain and 5 V supply: ≥ 1 volt change for 2.5 deg/cm curvature (23 cm radius); Operating temperature for sensor and leads: -40 to +105 deg c, for electronics: -40 to +85 deg c; Sealed flexible lead and sensor structure: 1.2 x 10 x 170 mm nominal; Electronics enclosure: 19 x 19 x 70 mm nominal; Adjustments: gain and offset; Connections: ground, power, analog output.

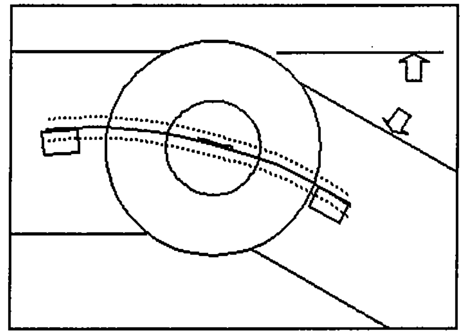
Measurand Inc.

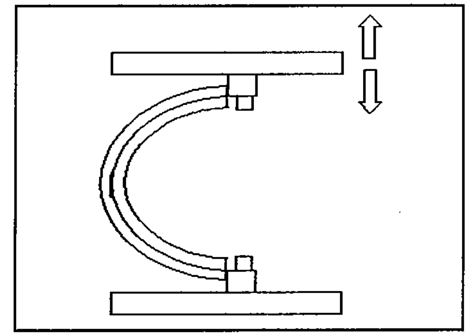
PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd., Fredericton, NB, Canada E3B 6Z9]

Simple solutions to difficult sensing problems...





A simple fiber optic sensor suited to mass manufacture:

Measurand fiber optic BEAM© sensors perform tasks formerly done with strain gauges, LVDT's, encoders, and potentiometers, **but without problems inherent in sliding seals, electromagnetic coils, multiple moving parts, and pivoted mounting systems.** BEAM© sensors can be used to measure a wide variety of parameters including:

- level
- displacement
- force
- angle
- torque
- rotation
- acceleration
- sag
- pressure
- flow...

This is done with the advantages of fiber optic sensing (immunity to EMI, flexibility, light weight), but **without the high cost and complexity normally associated with fiber optic sensors.** Instrumentation normally consists of one quad op amp, one low-power LED, and two photodiodes.

Characteristics:

BEAM© sensors measure curvature in a sensitized zone a few millimeters or centimeters long with a linear range covering over five orders of magnitude, and with sensitivity over 3000 times that of an unsensitized fiber. They can be placed on a substrate, such as a flexible strip of metal. The strip can then be embedded or protected in rubber or other materials and used to sense displacements, joint angles, forces, etc., depending on the fixturing used to attach the strip. For a simple bolt-on sensor, a typical linear range for angles is 40 degrees and for linear displacements is 10 cm, but other sensors with much larger ranges (150 degrees; 60 cm) have been demonstrated. At the other end of the scale are BEAM© sensors measuring in the microradian and micrometer ranges.

Practicality:

Measurand sensors have been tested to over **200,000,000 repeated bends** without any loss of performance. Measurand wheel position sensors have been successfully tested on automobiles. The Measurand simple design and mounting method results in a sensor that withstands hammer blows, that generates no EMI, is completely sealed against contaminants, and has no moving parts or accordion seals. Tested fields of application include robotics, automotive, biomedical, composites, mining, vibration measurement, HVAC, and nuclear.

Improvements:

Measurand sensors have gone through three stages of evolution, from straight glass and plastic fibers (BEF©), to a more sensitive, compact form (BEAM©), to the latest form (UNE©), which is simpler, very well suited to mass manufacture, and has an extended temperature range.

Measurand sensors are protected by patents and patents pending.

Publications and data available on request...

Measurand Inc.
PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]

Brief tutorial on Measurand BEAM© fiber optic curvature sensors

Lee Danisch, P.Eng.
President
September 25, 1994
Revised October 14, 1994
Revised May 25, 1995

These pages form a brief introduction to sensing curvature, and thus displacement, with BEAM© sensors.

Loss zone

Figure 1 shows an optical fiber treated to lose light on one side. When the fiber is bent up (top of figure), most light rays avoid the light loss zone. When the fiber is straight, some rays strike the loss zone and do not travel to the end of the fiber. When the fiber is bent down (bottom of figure), many rays strike the loss zone.

Curvature

Light throughput of the fiber in Figure 1 is a linear function of curvature over a wide range. Curvature of the loss zone, τ, is defined as the angular difference $\Delta\phi$ between two tangent lines drawn to the loss line (i.e. the dotted line in the figure) at the ends of the zone, divided by the arc length s between the ends of the zone. This is the inverse of the radius of curvature r of the loss zone:

$$\tau = \Delta\phi/s = 1/r$$

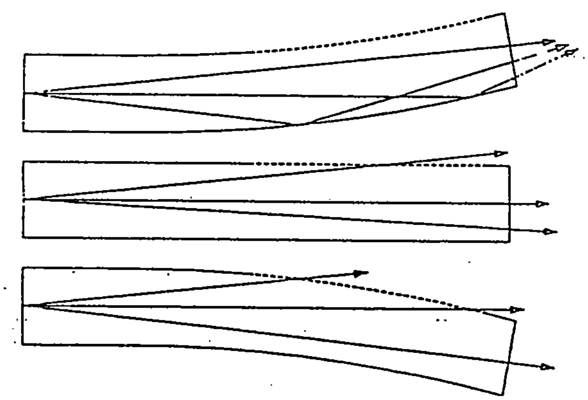


Figure 1

Displacement

Sometimes it is of interest to measure curvature directly. Usually we want to measure linear or angular displacement. This is usually done by placing the fiber on a beam, usually near the built-in or clamped end of a cantilever beam, applying the displacement to the end of the beam, and measuring the resulting curvature of the beam with the sensor system attached to the fiber. Over a large (for our purposes) range, curvature is a linear function of deflection of the end of the beam, according to:

$$\tau = 3Y_{max}X_c/L^3$$

where τ is curvature over the length of the loss zone, Y_{max} is the vertical deflection of the tip, X_c is the position of the center of the loss zone (measured with respect to the tip of the beam), and L is the length of the beam. By mechanically coupling a swinging arm to the beam, angular deflection of the arm can be measured in the same linear fashion, if the coupling is done properly.

BEAM© loops

Figure 2 shows the fiber of figure 1 curved into a tight loop, with the loss zone in the plane of the loop. When the loop is bent out of its original plane (as in the bottom of the figure) the throughput also changes linearly with the curvature of the bend. This is the configuration used in most BEAM© sensors. It allows sensing at the end of a fiber run, allows easy orientation of the fiber, and has some major benefits in terms of throughput and sensitivity that will not be discussed here.

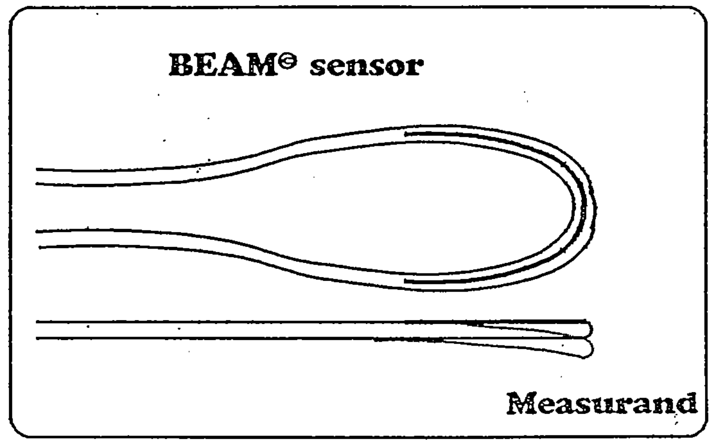


Figure 2

Measurement system

Figure 3 shows a complete measurement system based on two BEAM© loops. Both loops are powered by a light source S (a light emitting diode). The upper loop, which is coupled mechanically to some deflection we wish to measure, is called the sensor loop. The amount of light travelling through it is measured by photodetector D1. The other loop is isolated from the deflection, but otherwise is in the same thermal, aging, etc. environment. Its throughput is measured by D2. An electronic control loop between D2 and S keeps the output of S constant as seen by D2. Since D1 and D2 are in the same thermal, aging, etc. environment, the D1 measurement is independent of these effects.

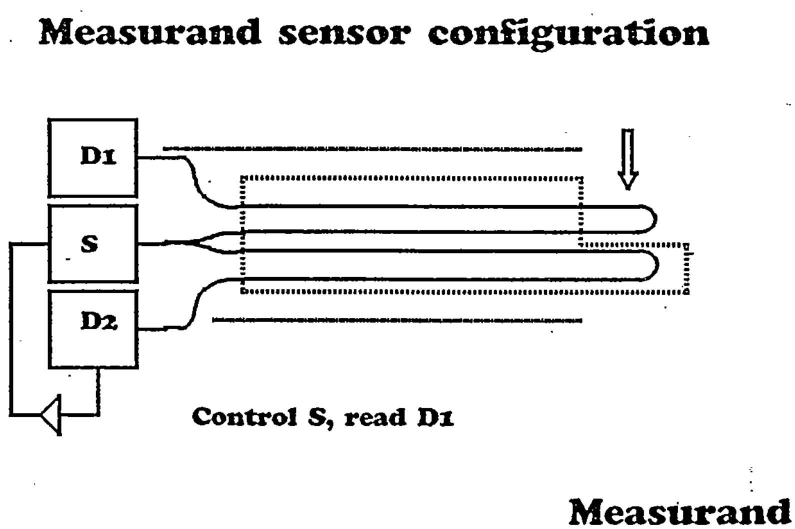


Figure 3

The latest configuration consists of two coplanar nested loops, both of which are in the bending zone. They face in opposite directions, so that during bending, the throughput of one increases while that of the other decreases. A "reference" circuit controls the sum of the throughputs and the sensor circuit measures the difference. This gives improved common mode rejection and a doubling in sensitivity over previous designs.

A practical sensor

Figure 4 shows a practical form of the system of Figure 3, without amplification and control circuits. The fibers are held in armored cable (similar to bicycle brake cable). The reference loop is embedded in a rigid "clamp" zone. The sensor loop is in a flexible "bend" zone. The S, D1, and D2 devices ("optoelectronics") are in a small module at the left, with electrical-only connections to the rest of the electronics. There are no fiber optic connectors. All components except the optoelectronics module are small enough to fit through an 8 mm diameter hole.

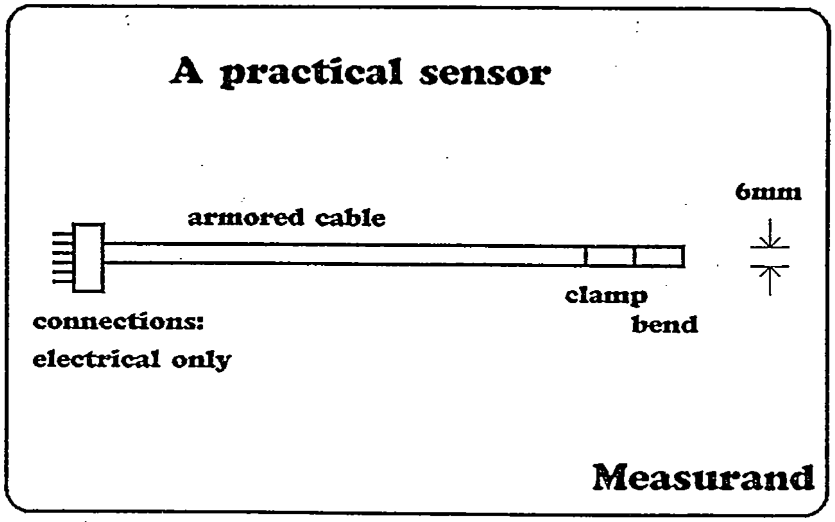


Figure 4

Amplification and control circuits use one quad operational amplifier.

Another version (see preliminary specification sheet) has the loops and leads sealed in a planar flexure, 10 mm wide x 1.2 mm thick.

Materials

Plastic fibers 0.5 mm in diameter are used. These have a polymethyl-methacrylate core, which occupies most of the diameter, and a fluoropolymer cladding a few microns thick. Proprietary materials are used over the loss zone and the cladding to hermetically seal the fiber, prevent light ingress, protect it at high temperatures, and withstand repeated flexing. BEAM© loops have been subjected to over 200,000,000 flexures without any measurable degradation.

Options are available for larger and smaller fibers, glass fibers, and special polymers for higher temperatures.

Applications

BEAM© fiber optic sensors are as versatile as strain gauges, but do not require transfer of strain to the gauge. This allows very large angular (or linear) deflections to be measured, using a long, thin flexure to transfer curvature (or large linear deflection) to the BEAM© loop. It also allows very small linear deflections to be measured, using small flexures, or the loop itself. One of many applications, an angular deflection sensor, is shown in Figure 5. It consists of the sensor system of Figures 3 and 4 incorporated in a long thin structure less than 8 mm in diameter:

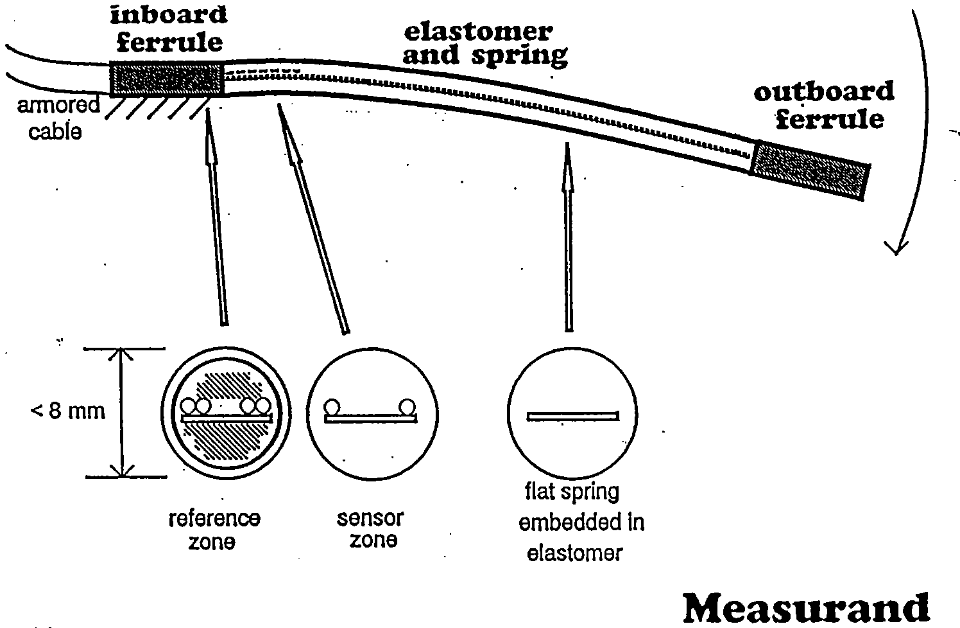


Figure 5

Figure 6 shows a configuration with the leads and loops both in a uniform sealed flexure:

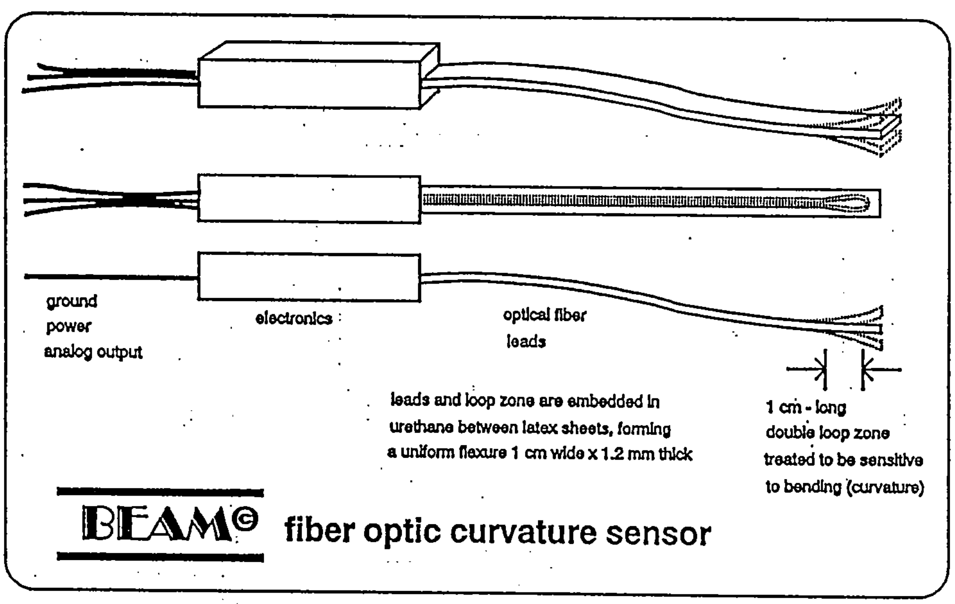


Figure 6

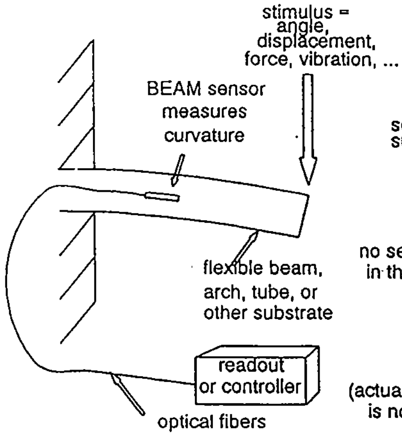
Measurand Inc.

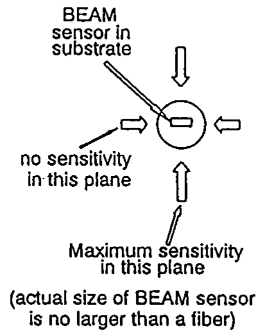
PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

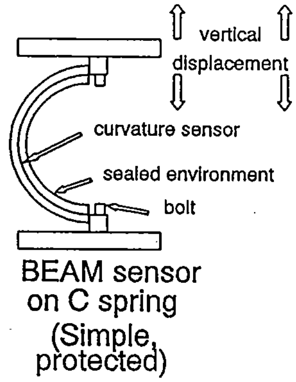
Sensors

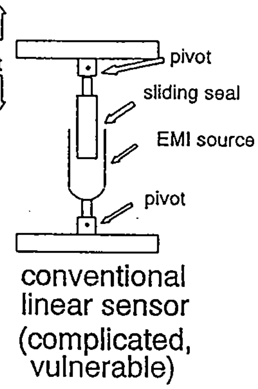
[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]

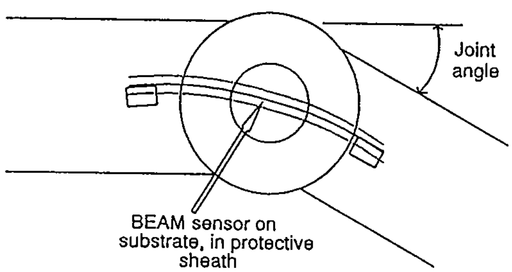
Sketches showing a few of the many applications for Measurand fiber optic sensors

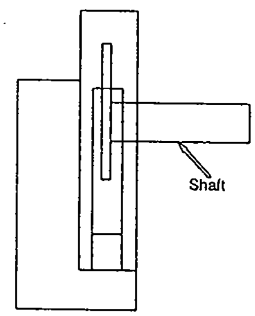


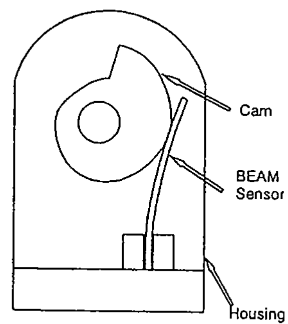


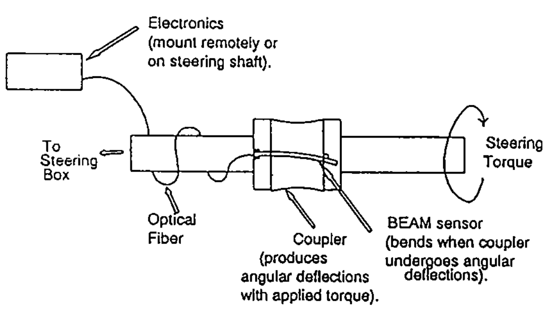


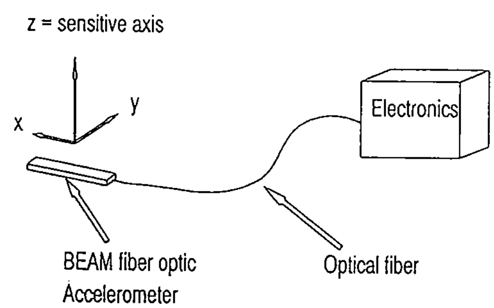


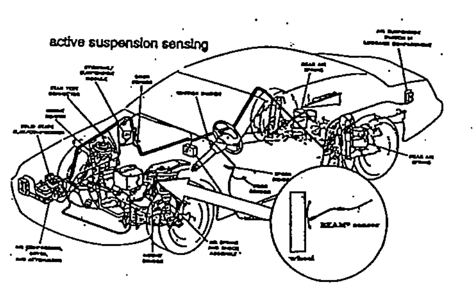




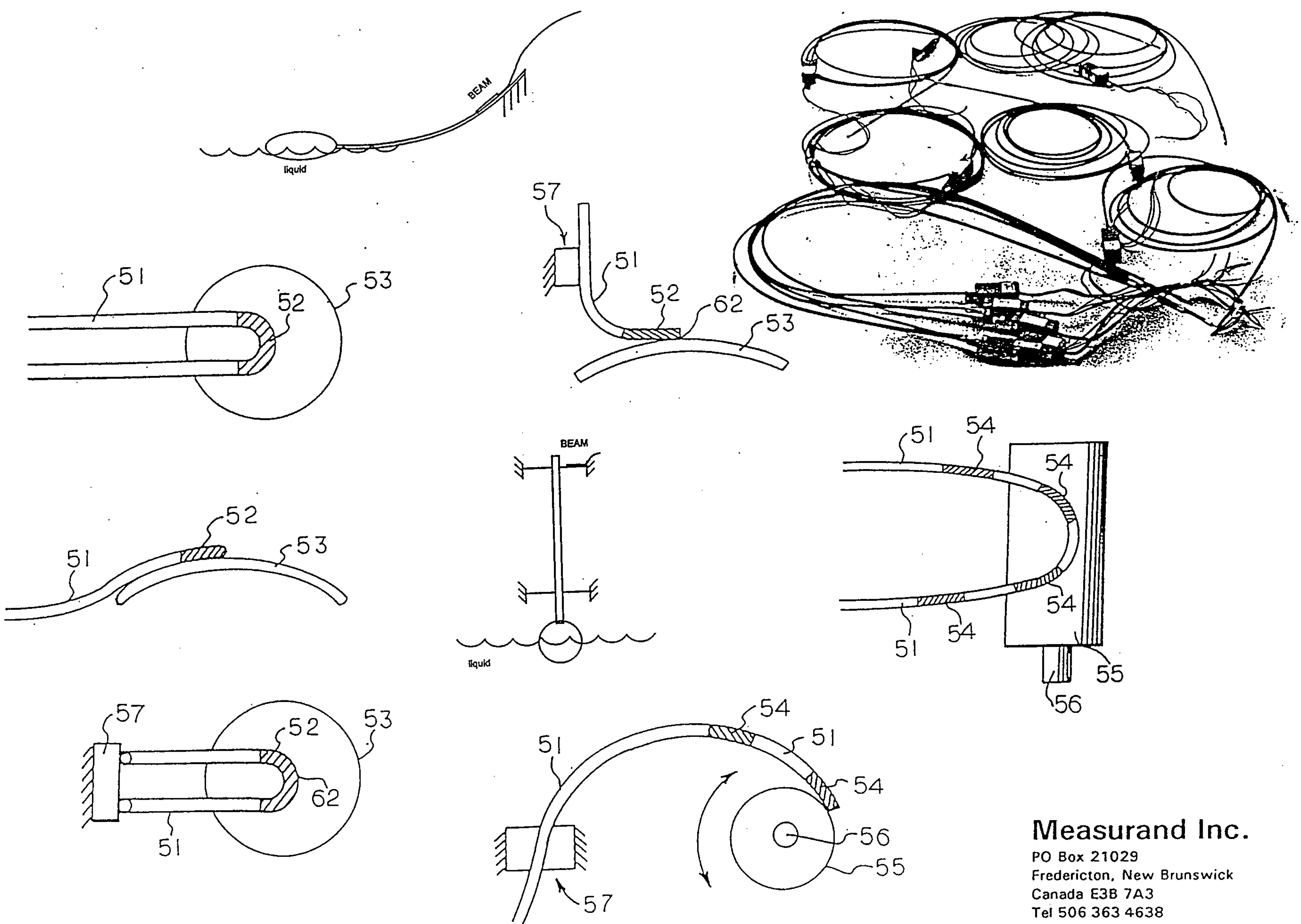




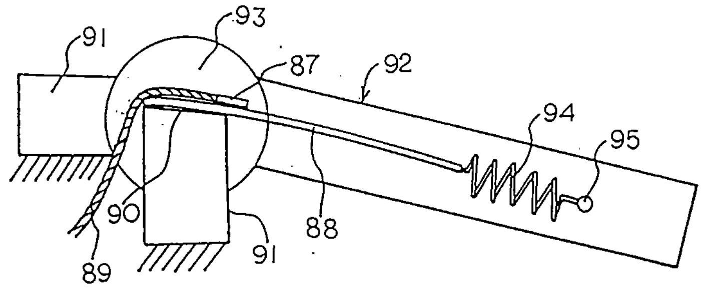


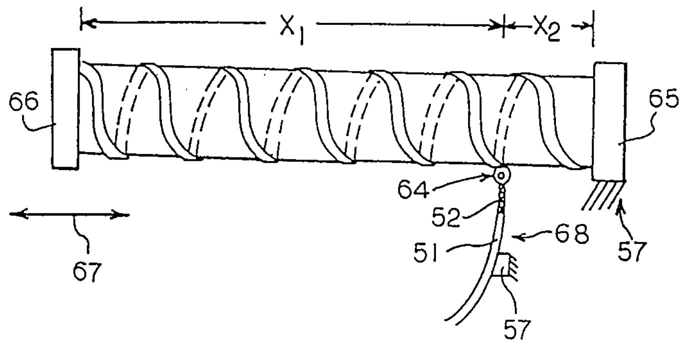


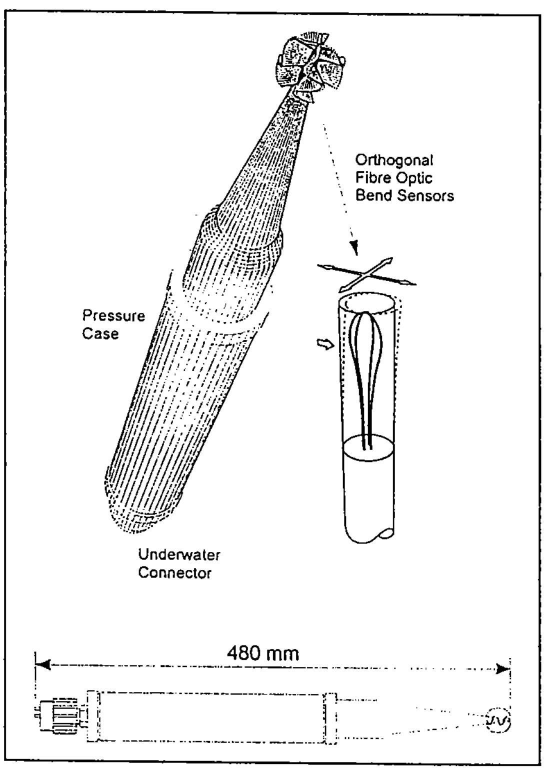
Measurand Inc.
PO Box 21029
Fredericton, New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

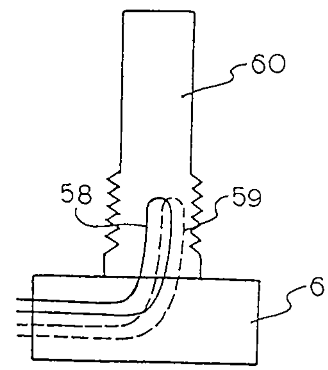


Measurand Inc.
PO Box 21029
Fredericton, New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173



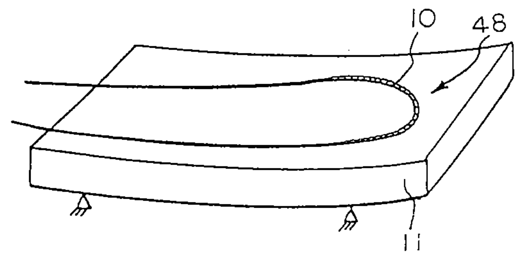




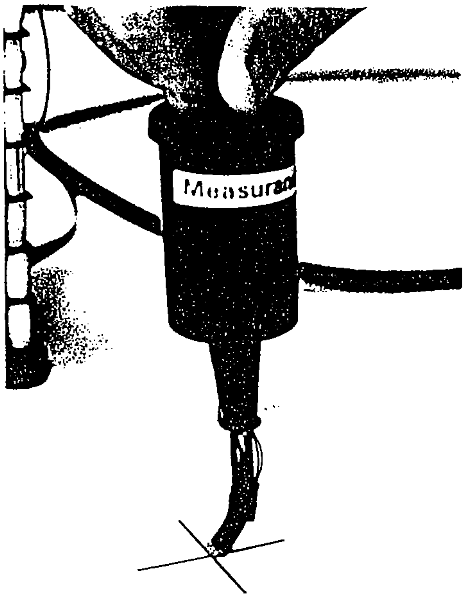


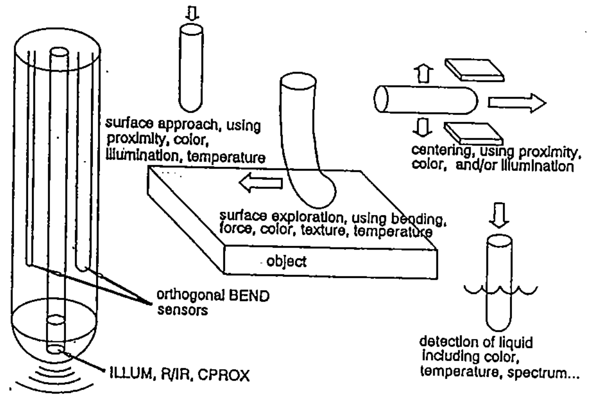
Dalhousie University
Oceanography Dept.
Halifax, Nova Scotia
Canada B3H 4J1

FOCAL
Focal Technologies Inc.
40 Thornhill Drive, Unit 7
Dartmouth, Nova Scotia
Canada B3B 1S1

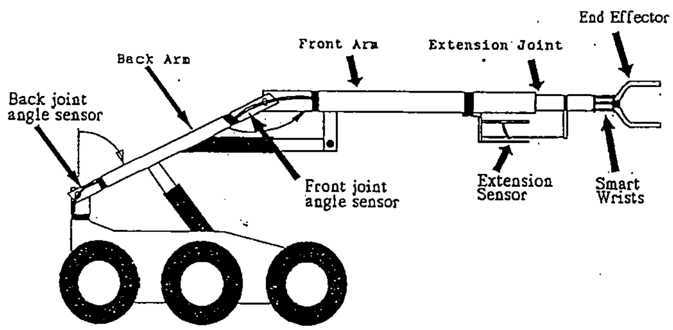


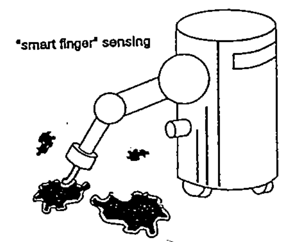
Measurand Inc.
PO Box 21029
Fredericton, New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

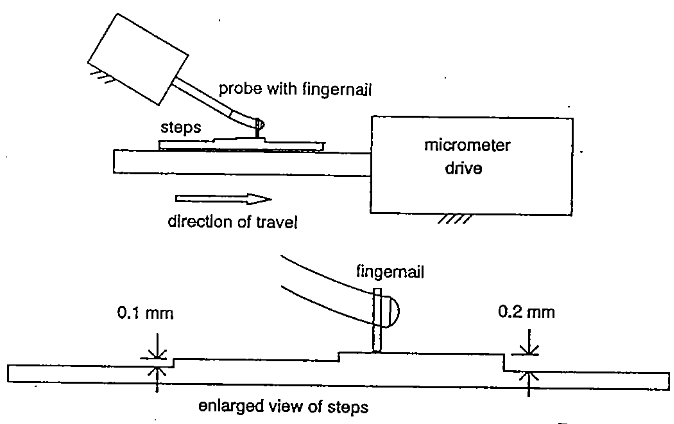




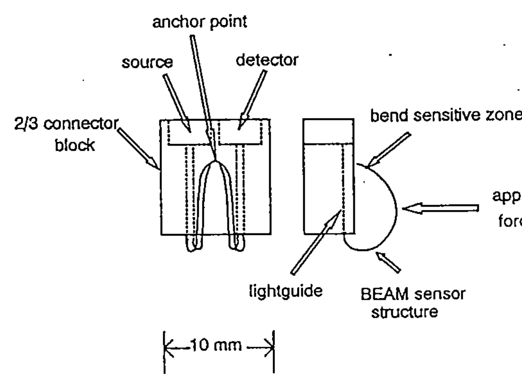
SENSOR	FUNCTION
BEND	2-axis bending texture
ILLUM	illumination
R/IR	red/infrared color discrimination
CPROX	capacitive proximity
above, combined	liquid detection force
others (not implemented)	spectrum temperature







Test setup for moving UNE Array Smart Finger probe over small steps near resolution limit of the "dc" BEND output. Much smaller structures can be seen with the ac TEX output.



Design of displacement sensors for tests in prosthetic arm socket.

Measurand Inc.

PO Box 21029
Fredericton, New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

Simple solutions to difficult sensing problems...

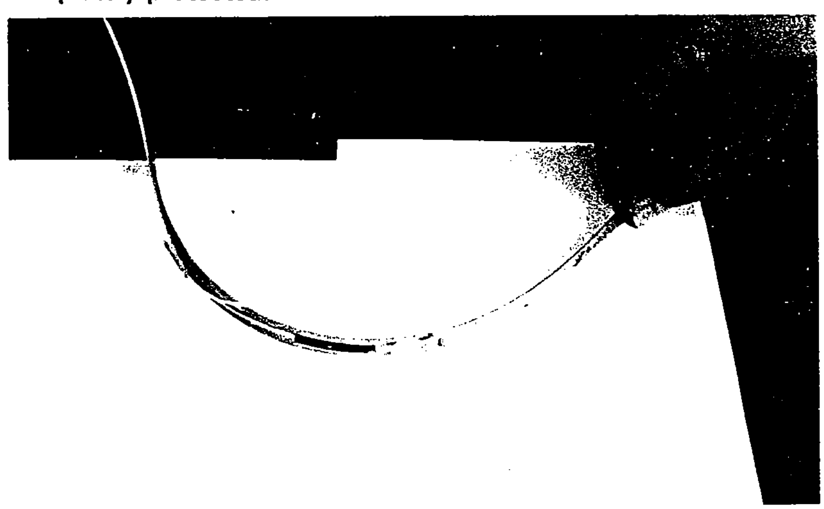
MEASURAND FIBER OPTIC SENSORS:

RELIABILITY THROUGH SIMPLICITY

Measurand sensor systems have been designed for reliability and low manufacturing cost. By using proprietary curvature sensing technology we are able to sense displacements, angles, forces, vibrations, levels, and many other physical parameters with a minimum of moving parts. In most cases, there is only one curving part, such as a simple flexible cantilever beam or arch. This approach eliminates sliding parts, sealed bellows, weep holes, and sealed bearings. Instead, the curvature sensor is embedded in or on the flexible element, where it is completely protected.

Because Measurand curvature sensors are sensitive, and linear over a large range, signal processing is not difficult. Simple analog processing eliminates problems inherent in relative encoders and digital linearization circuits, making our sensors suitable for incorporation in products with a low manufacturing cost and high volume.

At the heart of these measuring systems are BEAM© sensors, which are based on proprietary means of treating optical fibers.

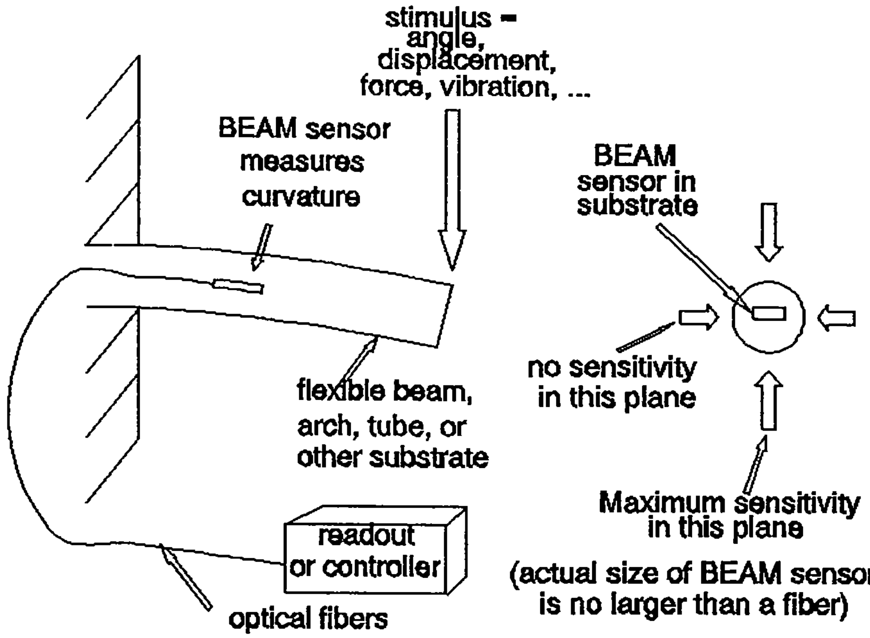


BEAM© sensor mounted on a flexible substrate. This curvature is well within the linear range of the sensor.

BEAM© TECHNOLOGY

BEAM© sensors (patent pending) are optical fibers which have been treated to sense curvature in a highly linear fashion, using simple, inexpensive electronics. Measurand combines BEAM© fiber optic sensors with simple mechanical parts such as curved metal bands to produce systems capable of measuring a wide variety of quantities in real world environments. BEAM© sensors are an improved version of BEF© (Bend Enhanced Fiber) sensors, optimized for maximum throughput and capable of measuring at the far end of a thin beam or other substrate. Another development, called UNE© sensors, package the BEAM© concept in another way that further lowers manufacturing cost and extends the temperature range.

Because of their wide range of application, BEAM© sensors are similar to strain gauges but measure curvature instead of elongation. A typical BEAM© sensor treated to be sensitive to curvature over a 1 cm length is linear over a range of 150 degrees, but can resolve bends of less than 3 arc seconds (a dynamic range of five orders of magnitude). Unlike strain gauges, BEAM© sensors are easy to mount, can measure and withstand large changes in curvature, and can sense curvature even when in the neutral axis of a bending beam. BEAM© sensors have been flexed over 10 million times with no loss of performance.



Concept drawing of BEAM® sensor. BEAM® sensors have a linear response to curvature. Other possible substrates include arch forms, springs, concrete, soil, composites...

BEAM© sensors were developed to be simple and inexpensive to implement in real world systems. They are not based on interferometry or special mode enhanced fibers, and do not use lasers or laser diodes. Instead, a section of multimode fiber is treated to be several thousand times more sensitive to curvature than the untreated portions (so that lead bending does not affect the measurements), and is sensitive only to curvature in a particular plane. Unlike interference sensors, BEAM© sensors are not sensitive to temperature effects. Inexpensive, rugged LED's and photodiodes can be used because light losses in the treated fiber have been carefully minimized. The high light throughput also means that BEAM© sensors can be fast. Response times are typically below 100 microseconds and can be much shorter if required. BEAM© sensors are available in plastic and glass fiber versions.

BEAM© sensors should not be confused with microbending sensors; They have the following properties without any added structural elements (such as serrated plates):

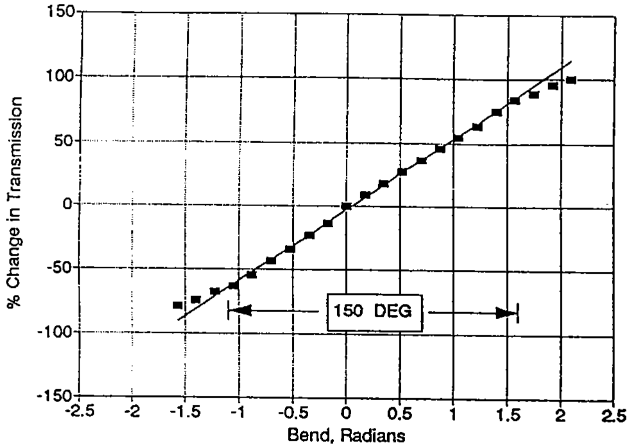
-Linearity: BEAM© sensors respond linearly to curvature over a wide dynamic range.

-Polarity: BEAM© sensors respond positively to curvature in one direction; negatively to curvature in the opposite direction. The response can be tailored so that a straight sensor is in the middle of a monotonic (single slope) range.

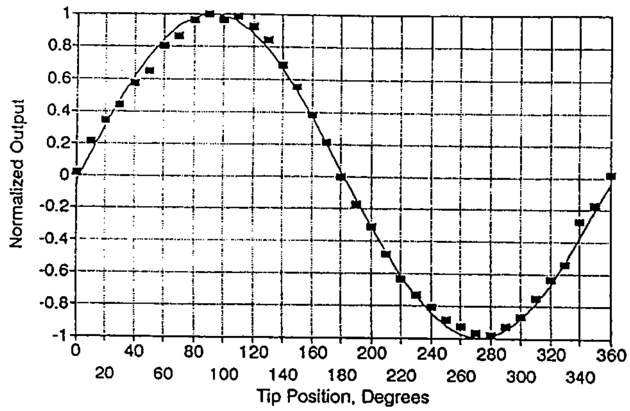
-Directionality: BEAM© sensors respond maximally in a plane of maximum sensitivity (PMS). Response drops off as a cosine function for bends out of the PMS. Thus, multiple sensors mounted in different planes can be used to resolve curvatures with multiple degrees of freedom.

Measurand Inc.

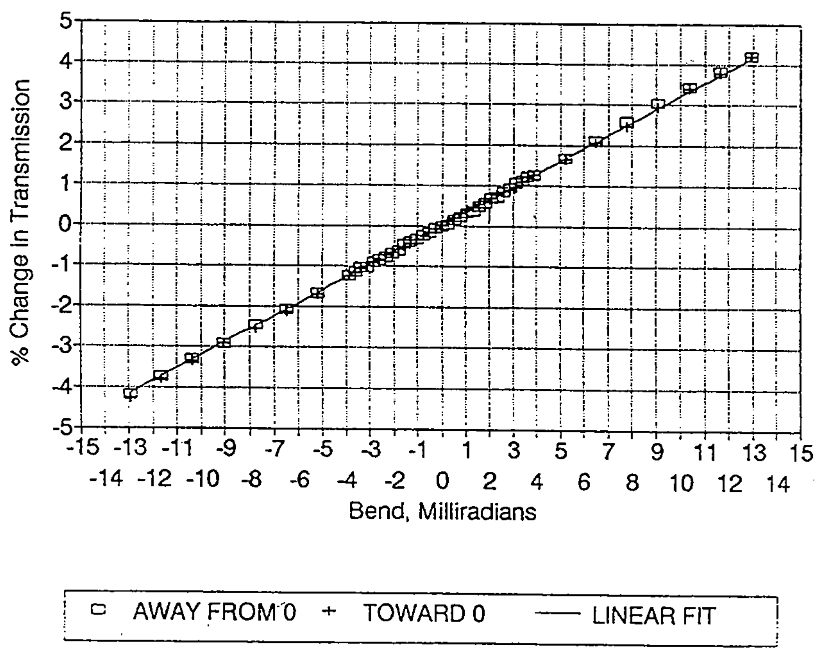
PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173



BEAM© sensors have a large linear range and distinguish between positive and negative curvatures.



BEAM© sensors respond maximally in one plane (90 and 270 deg in the figure). Response in other planes drops to zero as a cosine function.



Fine detail of sensor output near the origin. The sensor began straight, was bent toward +13 mrad, then back through zero to -13 mrad, then back to zero.

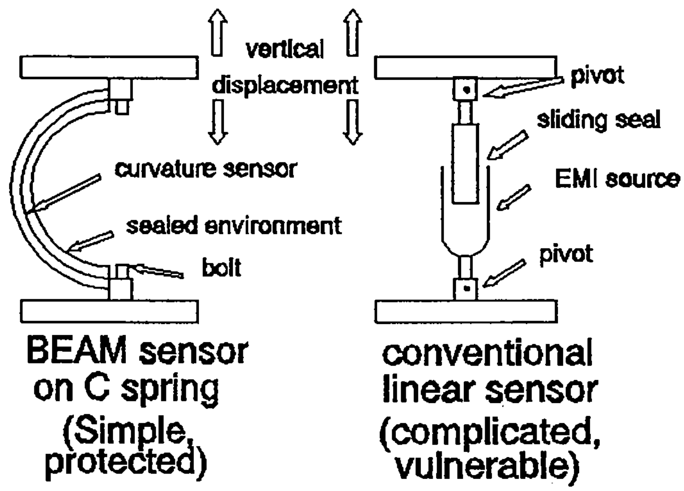
Measurand Inc.

PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173

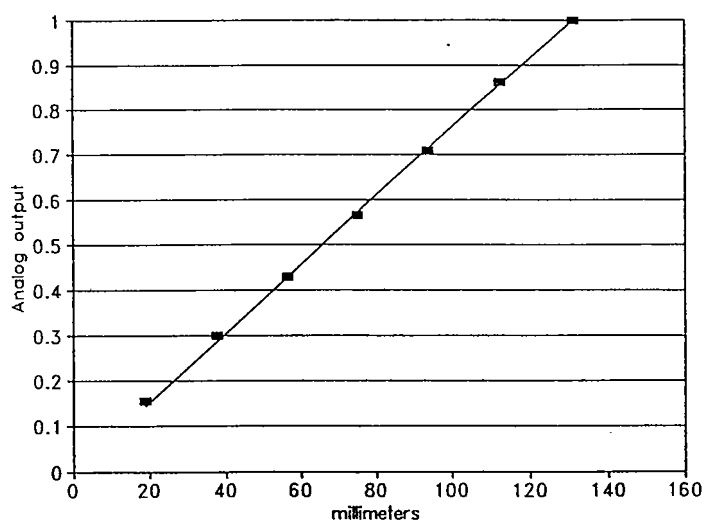
PRACTICAL APPLICATIONS

BEAM© sensors have been used in many practical applications, some of which are listed here:

-Position sensing: BEAM© sensor systems with no moving parts except a bending arch form are being used to measure the positions and motions of vehicle components, robot arms, and end effectors. Typical linear ranges are ± 50 mm, with submillimeter resolution. Advantages include insensitivity to side forces, impacts, and motions outside the plane of the arch:



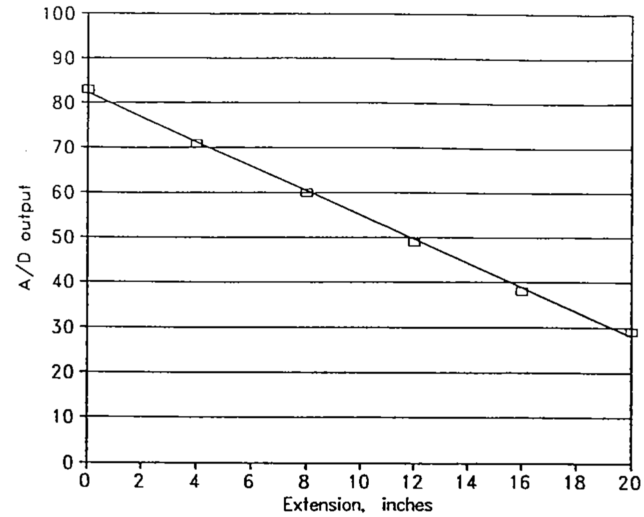
Comparison of BEAM© and conventional approaches to sensing displacement. The curvature sensor uses fibers (no EMI) sealed into an environment that curves with no moving parts.



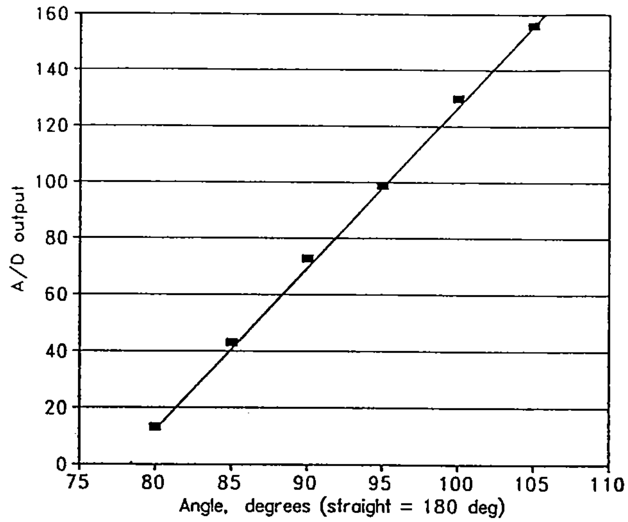
Response of an arch-mounted displacement sensor over a 100 mm range.

Measurand Inc.
PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173

-Large deflections/extensions: BEAM© sensors were used with a spring linkage to measure large deflections (50 cm or more) between mechanical parts. This method has been applied to sensing the position of an extendable robot end effector.

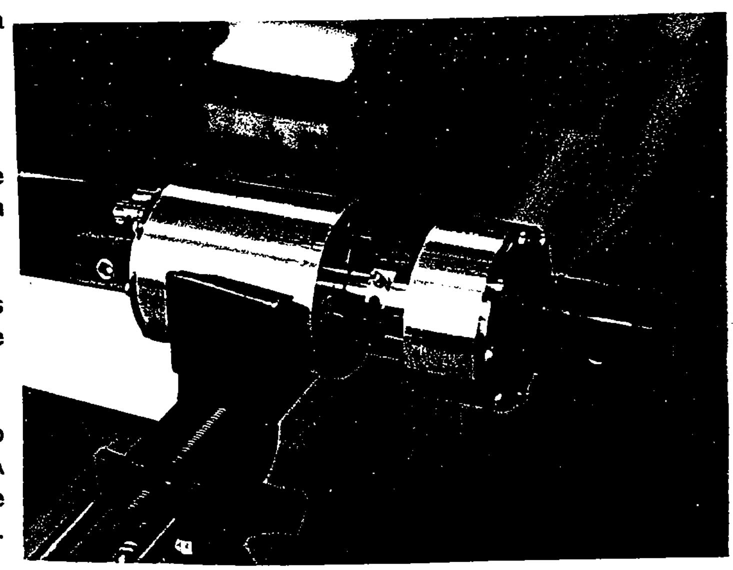


Output of extension sensor with a linear range of over 50 cm. A spring linkage was used.



Output of BEAM© joint angle sensor mounted on a robot arm.

-Joint angles: BEAM© sensors mounted on flexible metal strips ("C" springs) were used to measure joint angles on a Pedsco robot. Sensor output was linear with joint angle over a wide range (over 40 degrees), and was used to display a moving stick figure of the teleoperated robot on a computer screen.



Wrist with composite bones used to sense vertical and horizontal force components by means of integral BEAM© sensors.

-Pressure: BEAM© sensors were used to measure deflection of a flexible membrane due to application of forces and pressures.

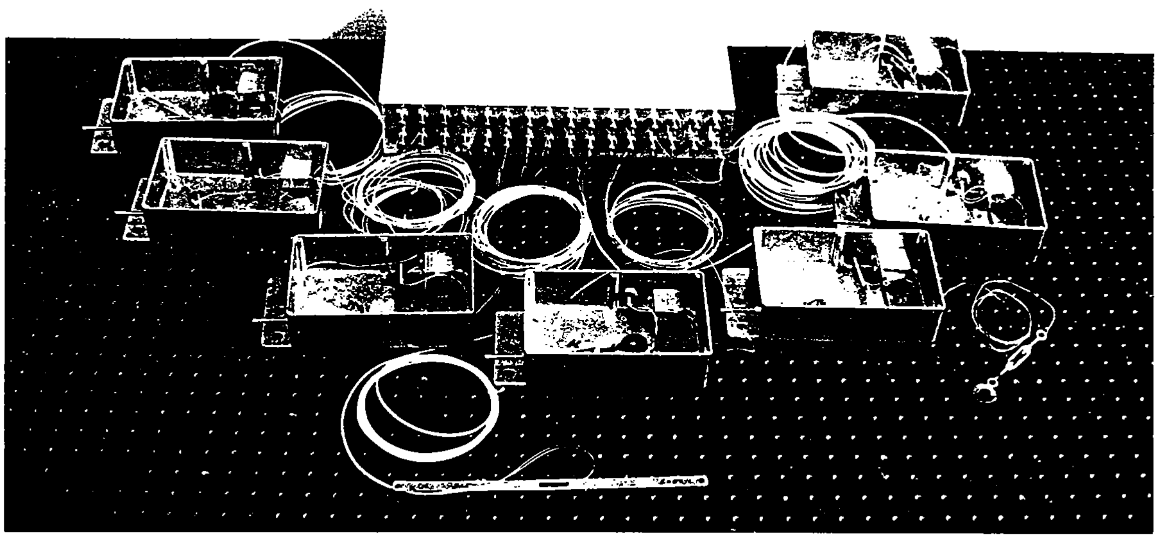
-Pipeline sag: A probe with a BEAM© sensor was developed to measure small changes in curvature along a pipeline, indicating sag or tilt of the pipe.

-Switches: BEAM© sensors are very sensitive to curvature changes and can be used as switches. A small deflection of a sensorized lever can produce a change in light throughput of 50 percent or more.

Measurand Inc.
PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173

-Force vector: Multiple BEAM© sensors were used to resolve horizontal and vertical force components applied to a robot wrist. The sensors were mounted to composite "bones" in a wrist. Forces on an end effector produced minute bends in the bones. The BEAM© outputs were calibrated to indicate forces, and these were displayed on a computer screen as a vector. The range was ±50 pounds for each component.

-Gearbox deflections: A large gearbox on a coal dragline was fitted with eight BEAM© sensors arranged to sense sub-millimeter movements between various portions of the gearbox case. This system was used to diagnose a gear tooth breakage problem.



Eight-channel BEAM© instrumentation system for measuring small deflections at remote points.

Measurand Inc.

PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173

PROCEEDINGS REPRINT
SPIE–The International Society for Optical Engineering

Reprinted from

Fiber Optic and Laser Sensors X

8-11 September 1992
Boston, Massachusetts

SPIE PROCEEDINGS SERIES

Volume 1795

Bend-enhanced fiber optic sensors

Lee A. Danisch

(New Brunswick Research and Productivity Council,
Fredericton, NB, Canada, E3B 6Z9)

ABSTRACT

Developments in sensor technology have enabled measurement of strain in composite materials by means of embedded fiber optic interferometric sensors. Often the intent is to measure and then actively control vibration and position. This paper describes novel Bend Enhanced Fiber (BEF) sensors used to make continuous, linear, real-time measurements of curvatures, which often relate more directly than strains to the control of vibration and position. BEF sensors are made by treating optical fibers to have an optically absorptive zone along a thin axial stripe a few millimeters long. Light transmission through the fiber past this zone then becomes a robust function of curvature, three orders of magnitude more sensitive to bending than in the untreated fiber. Directionality and polarity of curvature are preserved in the transmission function, over a linear range covering 5 orders of magnitude, centered about zero curvature. Thus, BEF sensors are curvature-measuring optical analogs of elongation-measuring resistance strain gauges, with similar sensitivity. BEF sensors add little or no thickness to the fiber, can be instrumented with simple analog electronics, and have been successfully embedded in composites. Results of dynamic curvature measurements are included, along with characterization data for BEF sensors made with plastic and silica fibers as small as 125 microns.

1. INTRODUCTION

Most recent work on smart skin sensors for mechanical parameters has been for development of optical strain gauges based on interferometry. These sensors can be used to measure very small strains and are suitable for embedment in composite structures.[1-3]

Often bending is of more direct interest than axial strain. This should be the case for composite robot arms, structural members that are not in pure tension (cantilevered structures or structures under dynamic load), and aircraft lift surfaces that are subjected to dynamic moments from flutter and high-G maneuvers. Direct measurement of bending can avoid some of the drawbacks of strain gauge (optical or electrical) measurement, including the necessity to achieve strain transfer to the gauge, and measurement on opposite sides of a beam to infer changes in curvature. Direct measurement of curvature permits mounting the gauge in the neutral axis, where strain gauges would be useless, and dynamic measurement of very large curvatures, where strain gauges would be likely to delaminate.

This paper describes a type of sensor suitable for embedment, which directly measures curvature. It is an analog intensity-modulated device, with an output that is a continuous linear function of curvature. Sensitivity appropriate to this type of device has been achieved by treating a small portion of the fiber to be very sensitive to bending. This permits the use of simple electronics, multimode fiber, and low-cost LED light sources.

Bend-Enhanced Fiber (BEF) sensors should not be confused with microbending sensors,[4-6] which depend on mode shifts as the fiber is bent at an angle. Because large angular deflections are necessary to produce measurable loss of light in an untreated fiber, corrugated plates are often used to translate applied force into a series of microbends. With such plates, microbend sensors can detect very small (Approximately 0.1 micron[6]) deflections perpendicular to the fiber. However, they are not well suited to embedment. One form suitable for some applications employs a spiral-wrapped wire, which deflects the cladding under axial strain, and has been used successfully to measure large strains when embedded in concrete.[7] The presence of a steel wire adds considerably to their weight and diameter and makes them less than desirable for embedment in lightweight composite structures.

Untreated fibers can be embedded in composites to measure transmission changes during curing and tension testing.[8] The measurement is presumably due to microbending of the fiber by adjacent structural plies in the composite, but the method is not directly applicable to measurement of bending.

 0-8194-0974-X/93/$4.00

2. DESCRIPTION OF BEND ENHANCED FIBERS

2.1 Treated Strip

BEF's are based on methods of treatment first used to produce elongate emitter and detector fibers for liquid level sensors.[9-10] Similar methods of treatment can be used to create fibers sensitive to bending. The BEF's are treated to lose light along a thin strip oriented axially along one side of the fiber.[11] On plastic fibers this can be accomplished by embossing a serrated pattern on one side of the fiber, as shown in Fig. 1.; on glass fibers, selective removal of cladding is appropriate. Typically, from 5 to 30 degrees of the circumference is treated, resulting in a light loss of approximately 50 to 90 percent for an unbent, treated fiber compared to an unbent, untreated fiber. Response of sensors to bending is measured as a change in the percentage of light transmitted by an unbent treated fiber. Sensitivity to bending is greatest in the axial plane containing the treated strip. This is called the Plane of Maximum Sensitivity (PMS).

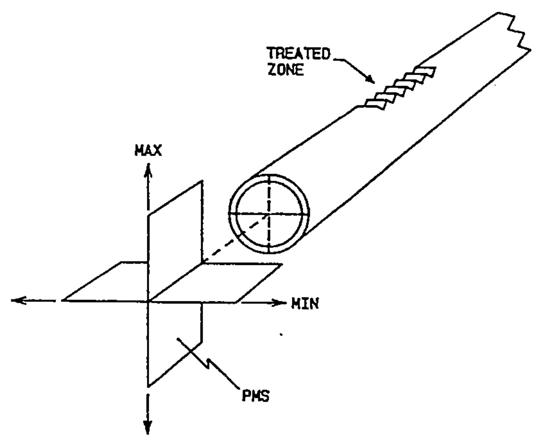


Figure 1: Plastic fiber with a treated strip. Planes of maximum and minimum sensitivity are indicated.

2.2 Bends in the PMS

Operation of BEF sensors can be visualized according to the following model: In Fig. 2, a length of step index multimode fiber treated to be a BEF sensor is shown for three cases of curvature in the PMS. For simplicity, the cladding is not shown in the drawing. In each case, three rays of light are shown emanating from a single point within the fiber, at angles that would normally propagate in the core. The dotted line indicates the portion of fiber treated to lose light.

If the fiber is bent upward, the three rays reach the end of the fiber either directly or by total internal reflection. When the fiber is straight, only one ray is lost through the treated portion. If the fiber is bent downward, two of the rays are lost.

This model can be extended to show that for any number of rays contained within the core, more are lost for downward bends than for upward bends, and that the straight fiber represents an intermediate case. If all the cladding were removed, upward bends would be indistinguishable from downward bends, and the sensor would not be useful when straight, the most likely position for embedded fibers.

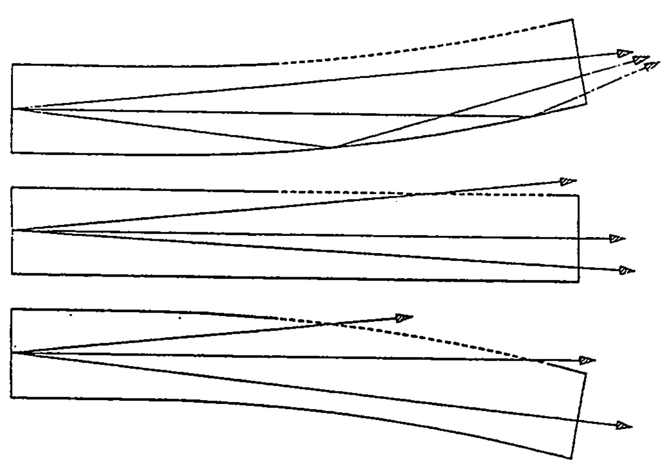


Figure 2: Ray tracing for BEF sensors. The dotted line represents the section treated to lose light. For upward bends in the PMS, the rays miss this section. For downward bends, more rays strike this section.

2.3 Bends outside the PMS

For bends orthogonal to the PMS, the rays encounter no more loss zone than for the straight fiber shown, so losses are equal to those for the straight fiber. From experiments, it has been learned that for bends in planes intermediate between the PMS and the plane orthogonal to it, the light lost is a cosine function of the angle between the plane of bend and the PMS.

2.4 Sensor structure

A complete analysis of the characteristics of BEF's requires consideration of the numerical aperture of the fiber, the length of the treated zone, and geometry of the fiber. Further, for a practical sensor, rays that leave the fiber through the treated zone must be absorbed so that they cannot re-enter elsewhere, due to reflection, refraction, or scattering from the surrounding media. This can be done by applying a light-absorbing coating after treatment. A suitable material is graphite-filled epoxy, which is compatible with most composite materials.

Fig. 3 includes photos of a BEF sensor made from 200/230 micron fiber, a similar sensor attached to a flexible metal strip, and a diagram of the internal structure of a BEF sensor. Typical 200/230 micron BEF sensors include an 8 mm-long zone treated to lose light and a covering of graphite-rich epoxy designed to absorb light and protect the loss zone from damage during installation.

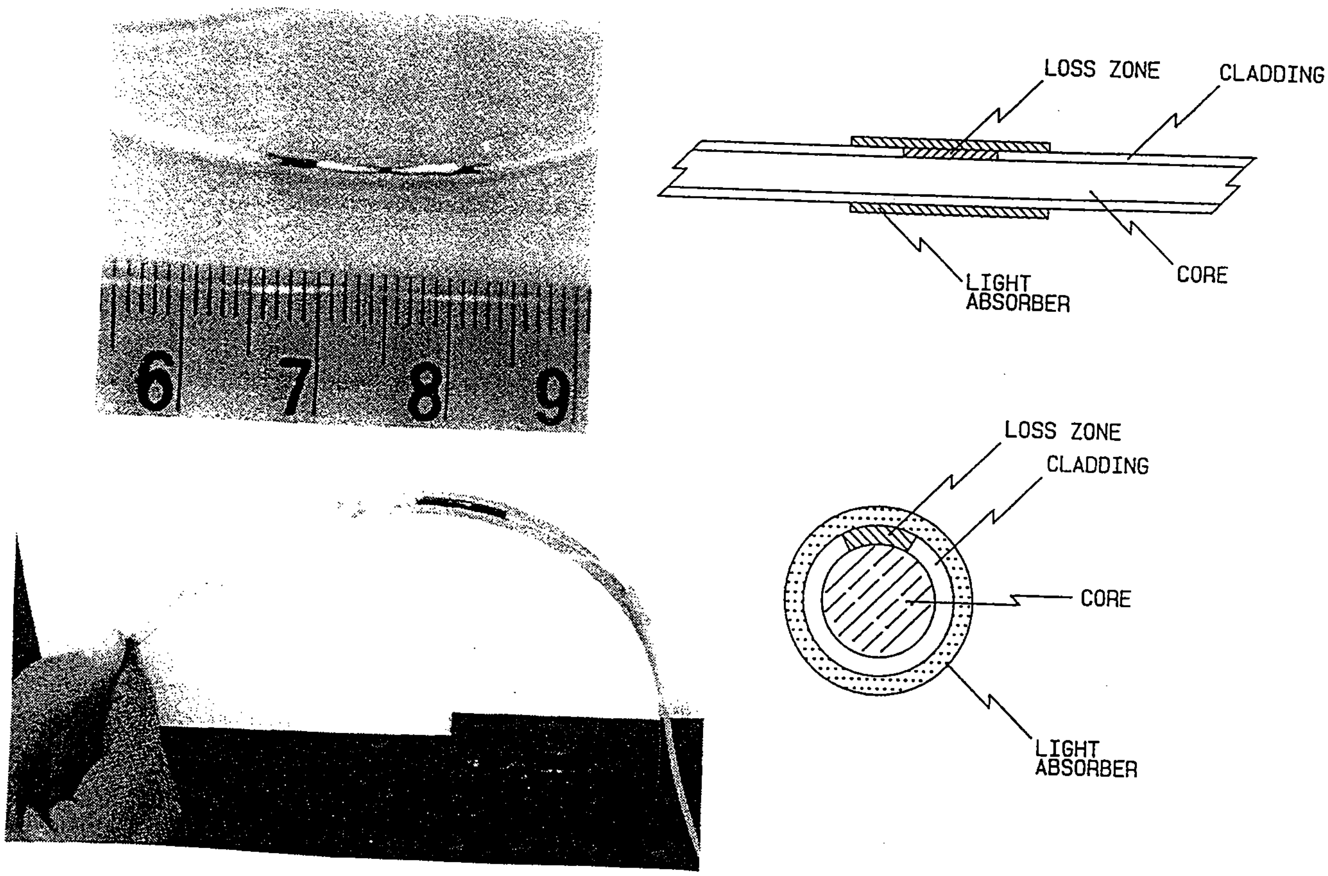


Figure 3: Examples of BEF sensors. Upper left: 200/230 micron BEF, coated with black epoxy over treated zone (scale marks: cm); Lower left: A BEF sensor attached to a thin metal substrate can be bent over large angles.; Right: construction of BEF sensor.

2.5 BEF characteristics

BEF sensors have four important characteristics:

-Sensitivity: Compared to untreated fibers, BEF sensors are over 3 orders of magnitude more sensitive.

-Polarity: "Upward" bends in the PMS increase the throughput of light, and are distinguishable from "downward" bends, which decrease the throughput.

-Linearity: Sensor output is linear for curvatures over a range covering approximately 5 orders of magnitude.

-Directionality: Bends in the PMS produce maximum output. Bends in the plane orthogonal to the PMS produce no output; intermediate bends follow a cosine law.

These characteristics result in important features:

-Sensitivity: BEF sensors are relatively unaffected by bending of the leads.

-Polarity: BEF sensors are near mid-range when straight (the most convenient configuration for embedded fibers).

-Linearity: BEF sensors have a very large useful range.

-Directionality: BEF sensors can be used in multiples, with PMS's arranged at different angles, to completely describe the three-dimensional state of curvature of an object.

They are curvature-measuring analogs of elongation-measuring optical or electrical strain gauges.

3. EXPERIMENTAL PROCEDURE

BEF sensor characteristics were measured in a simple setup. An LED illuminated one end of a treated fiber, a PIN photodiode and transimpedance amplifier were used at the other end to measure light loss due to bending. Measurement wavelength was 850 nm for the experiments reported here (650 and 1300 nm have been used with equal success in other experiments). In some cases a reference fiber was used. This was either an untreated fiber, or another treated fiber arranged "upside down" so that losses increased in one fiber and decreased in the other. The reference fiber was instrumented with a separate LED, photodetector, and amplifier, but signal and reference fibers were maintained in close proximity as much as possible. Partial correction of common-mode effects was performed by subtracting the amplified reference and signal voltages using a differential amplifier. Bandwidth could be changed by means of capacitors from approximately 100 Hz to over 10 kHz. Low-cost operational amplifiers were used throughout.

Large-angle bends were produced by attaching fibers to a hinged fixture, which allowed the fiber to flex along a circular path (Small-diameter fibers were attached to a 0.25 mm-thick steel band, then to the large-angle bending fixture).

Small-angle bends were generally studied with BEF's (usually 200/230 micron glass fibers) bonded to or embedded in beams clamped at one end. In this case curvatures were determined from tip deflections according to the classical small-deflection cantilevered beam equation, which, for a known deflection of the tip, reduces to:

$$\Gamma = \theta/S = 3Y_{max}X_c/L^3 \qquad (1)$$

Where Γ is curvature, θ is the angle of bend (the difference in angular position of the two ends of the sensitized section, which is assumed to be in a circular arc), S is the length of that section, Y_{max} is the vertical deflection of the tip, X_c is the position of the center of the sensitized section (measured from the tip), and L is the length of the beam between tip and clamp.

Response to bending at angles outside the PMS was studied by bonding a 200/230 micron BEF sensor to a 3 mm-diameter steel rod, clamping one end, and moving the other end in a circular pattern concentric with the long axis of the rod.

4. RESULTS OF EXPERIMENTS

4.1 Sensitivity and Polarity

Fig. 4 compares the responses of a BEF to those of an untreated fiber and a fiber with cladding removed from its entire circumference. Data are for 1 mm plastic fibers. The sensitized zones were 30 mm long.

The response of the untreated fiber is virtually zero for all angles of bend up to ±0.35 rad at which points it begins to lose some light to cladding modes. The BEF sensor maintains reasonable linearity up to approximately the same ±0.35 rad degree limits. Beyond that, it loses additional light, probably due to a combination of its BEF response and normal bending losses. Its sensitivity in the linear zone is approximately 86 percent per radian, or 1.5 percent per degree.

The completely declad fiber is more sensitive, but imparts no polarity (up vs. down) information.

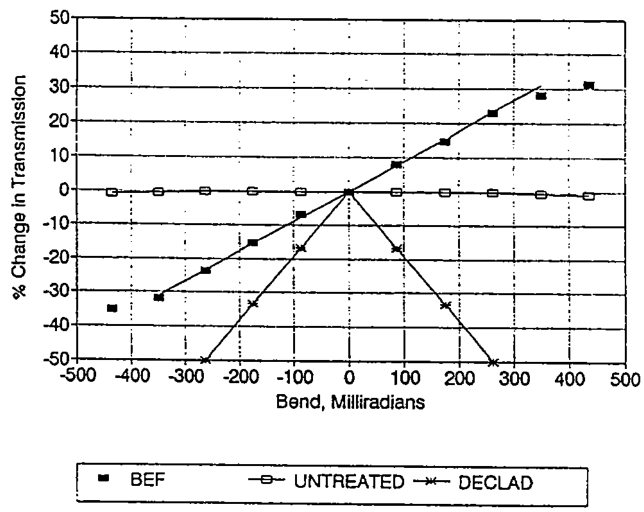


Figure 4: Comparison of responses to bending of BEF-treated, untreated, and declad (cladding removed from entire circumference) fibers.

To test more quantitatively the sensitivity of the treated region of a BEF to that of an untreated region, an untreated 200/230 micron lead going to a 200/230 micron BEF was subjected to a bend of 18 mm radius over a 10 mm length (equal to the length of the sensitized region) by holding it against a cylinder. The sensitized region (attached to a cantilevered beam) was then moved until the output signal changed by the same amount. The radius of curvature applied to the untreated pigtail fiber was 18 mm, below the recommended minimum bend radius for the fiber. The same change in light transmission was caused by a 57 m radius bend of the sensitized region (sensitivity approximately 0.35 percent per mrad) of the same fiber. Thus, the treated section was over 3000 times more sensitive to bends than an untreated fiber.

Sensitivity of BEF sensors varies from about 0.5 %-mm/mrad to about 3 %-mm/mrad. Sensitivity is a function of the length and width of the treated zone, the diameter of the fiber, and the method of treatment. More than 250 sensors have been made, including some with 50/125 micron diameter fibers. The 50/125 micron fibers are the most difficult to treat, but sensitivity of these sensors was in the 2 to 3 %-mm/mrad range.

4.2 Linearity

The response to large bends of a BEF sensor made from 200/230 micron fiber is shown in Fig. 5. The treated zone was 8 mm long. The linear range is approximately 2.7 radians, or 150 degrees.

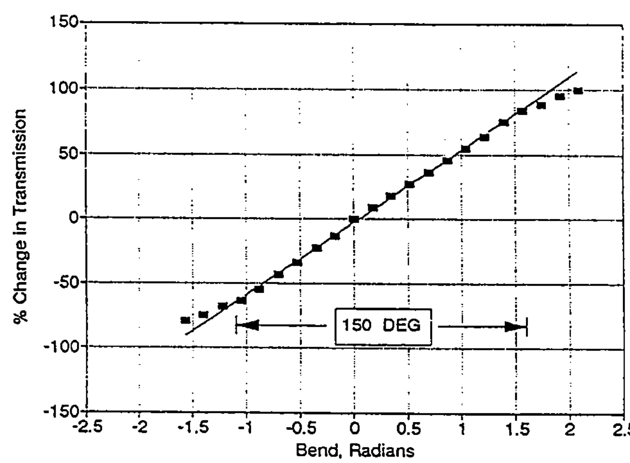


Figure 5: Linear range of a 200/230 micron sensor with a treated length of 8 mm.

A small deflection sensor was made by embedding (with epoxy) two BEF sensors in a flexible plastic tube (approximately 2 mm outside diameter and 1 mm inside diameter). The sensors both had sensitive regions 10 mm long, placed at the center of the tube axis. The tube was 40 mm long. The sensors were arranged with PMS's in the same plane but of opposite polarity. This allowed the use of a simple differential amplifier to reduce common-mode lead sensitivity and drift. This sensor was clamped in a vise at the end of the sensitized zone, with its PMS vertical. 21 mm down the tube from the clamp (11 mm beyond the other end of the sensitized zone), a small loop of stiff wire was wrapped around the tube and affixed to a stage driven in a vertical direction by a manual micrometer drive. The small tube sensor is shown in Fig. 6.

The bending function of this sensor is shown in Fig. 7, where the line shown is a linear fit to the data points, which include all points for moves away from and back toward the origin in both directions. The co-linearity of all these points indicates a very low hysteresis. The sensor is linear over a larger range, but the stage movement was limited.

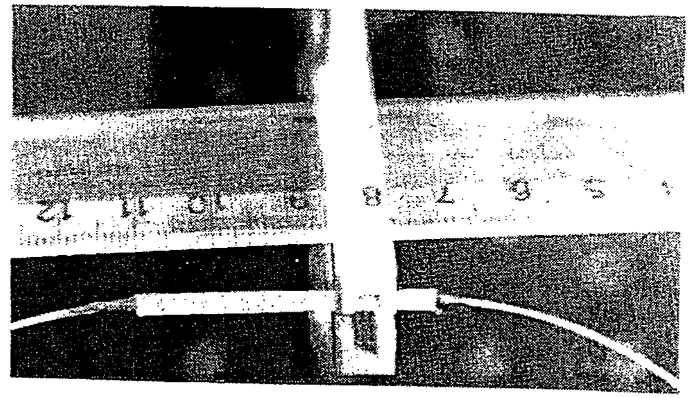


Figure 6: Sensor pair mounted in small plastic tube (2 mm outside diameter). Scale markings are in cm.

4.3 Directionality

Fig. 8 shows the variation in sensitivity of a single BEF to changes in the direction of bend (directionality property). In this test the BEF sensor was affixed with epoxy to a 3 mm-diameter steel rod, 295 mm long. The rod was clamped at one end, 43 mm from the sensor; the other end was moved in a 25 mm-radius circle concentric to the axis of the rod when straight, and readings of BEF response were taken every 10 degrees.

The response is a sine function of the angle between the plane of bend and the plane of minimum response (zero degrees in the graph), or a cosine function of the angle between the plane of bend and the plane of maximum sensitivity. For bends orthogonal to the PMS, the response is very nearly zero.

4.4 Resolution

In the chart recording shown in Fig. 9, another sensor bonded to a cantilevered metal beam made of feeler gauge stock (0.25 x 13 x 63 mm beyond clamp, sensor centered 23 mm from tip) is being bent back and forth with a hand-driven micrometer stage by ±125 microns, corresponding to a curvature change of ±170 microradians over 8 mm. An untreated reference fiber was used with this sensor.

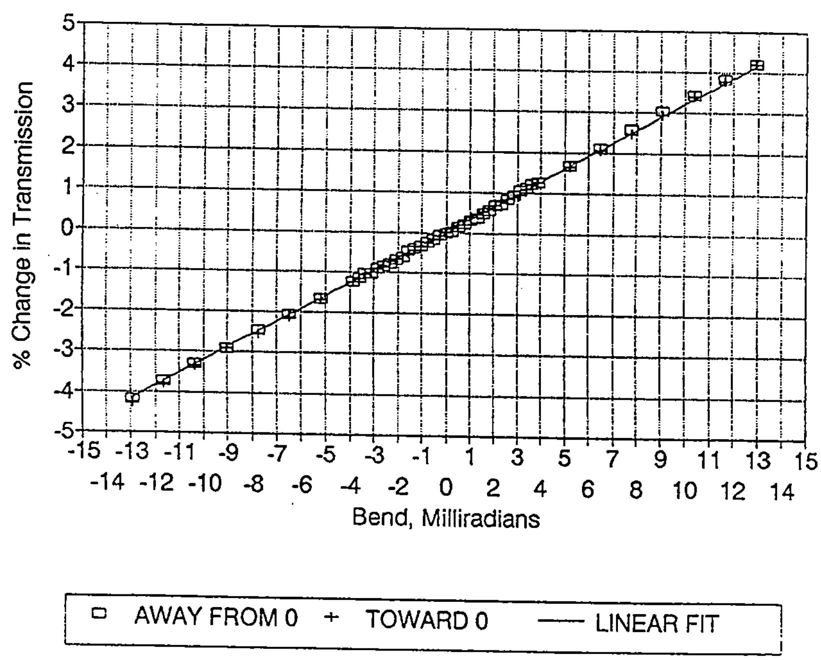


Figure 7: Response of sensor pair in small tube to bending. The tube began straight, then was bent toward +13 mrad, then back through zero to -13 mrad, then back to zero.

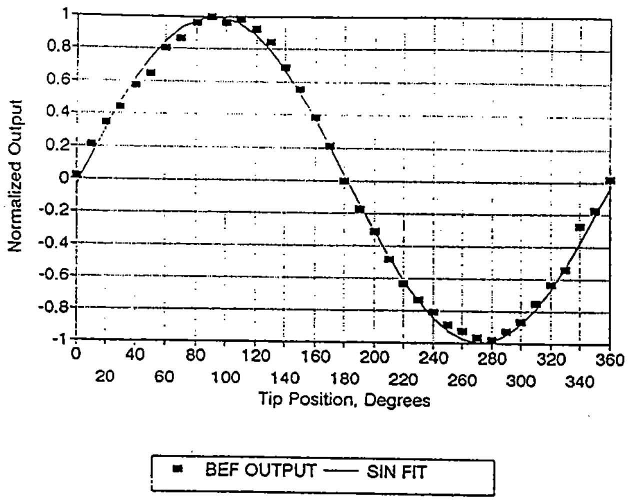


Figure 8: Response of BEF sensor on cantilevered rod when tip is moved in a circle. BEF response is normalized to unity at maximum output (PMS was at 90 degrees). The line is a sinusoid fitted to the data points.

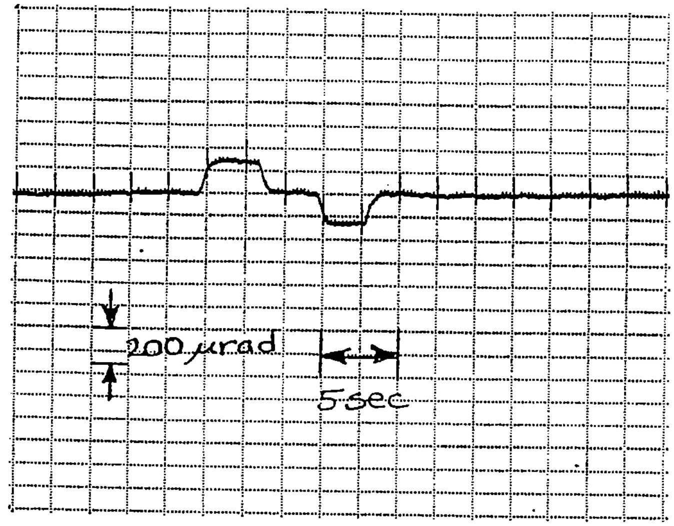


Figure 9: Response of BEF sensor bonded to a cantilevered beam made of feeler gauge stock, undergoing bends of ±170 microradians.

Response to very small deflections of the sensor on the feeler gauge stock is shown in Fig. 10. It was being moved ±13 microns, producing variations in curvature of ±17 microradians.

Similar data is shown in Fig. 11 for a 200/230 micron BEF fiber embedded in a pultruded carbon composite rod (9.5 mm diameter, clamped 14 cm from the tip, sensor centered 4.5 cm from the tip). The 8 mm-long sensor was being bent by ±16 microradians. No reference fiber was used.

For these small deflection tests, the bandwidth of the amplifier was limited to approximately 100 Hz.

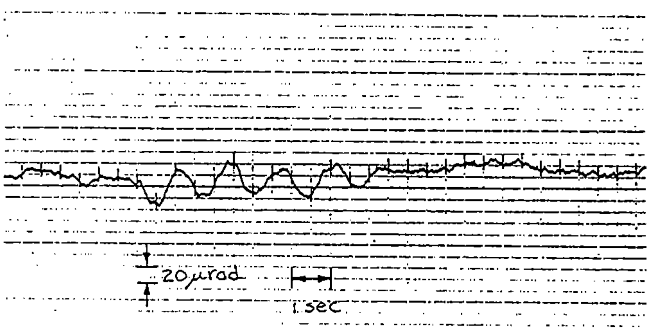


Figure 10: Response of BEF sensor bonded to feeler gauge stock when bent by ±17 microradians.

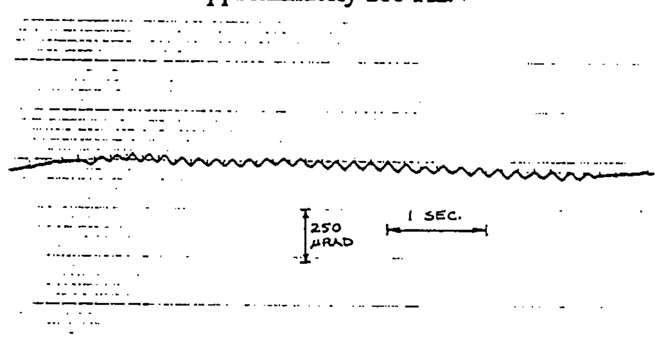


Figure 11: Response of BEF sensor embedded in pultruded carbon composite rod when bent by ±16 microradians.

4.4 Dynamic Response

Dynamic response of the sensor in the 2 mm tubing is shown in Fig. 12. The tubing was being tapped with a small screwdriver to produce rapid bends of a few milliradians (1 percent change in light transmission for this sensor corresponds to approximately 3 milliradians per 10 mm sensor length). Note the clear change in polarity of output signal for bends of opposite polarity in the PMS.

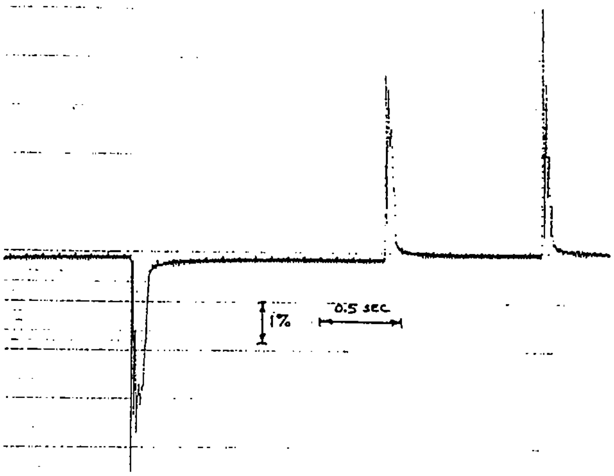


Figure 12: Dynamic response of the BEF sensor pair mounted inside 2mm plastic tubing. The tubing is being tapped with a small screwdriver from opposite sides, in the PMS.

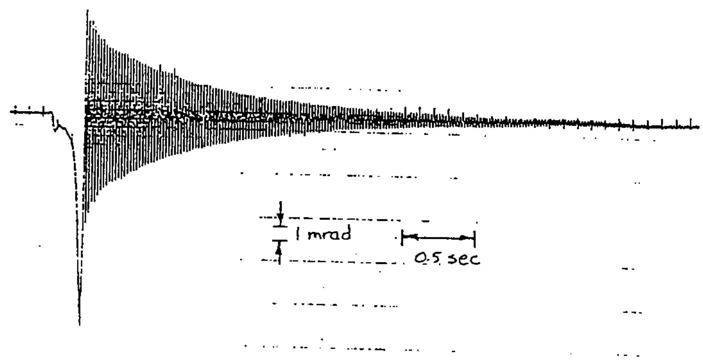


Figure 13: Dynamic response of BEF sensor bonded to cantilevered beam made of feeler gauge stock. The beam was deflected by hand and then released.

Dynamic response of the sensor mounted on the feeler gauge stock is indicated in Fig. 13. It was deflected by hand and then rapidly released (plucked). The resulting damped vibrations have a frequency of approximately 50 Hz. In this run, the amplifier had a frequency response of approximately 10 kHz.

5. DISCUSSION

Important properties of polarity, directionality, and linearity were demonstrated. These, and the elimination of mechanical fixturing to transform deflections into bends, differentiate BEF sensors from microbending sensors.

Detailed measurement of small and large bend angles for BEF sensors demonstrated good sensitivity, low hysteresis, reasonable drift, and excellent linearity over a wide range.

Sensitivity of BEF sensors (which measure angular change per sensor length) is not directly related to that of strain gauges (which measure axial displacement per sensor length). In the presence of other strains, measurement of curvature with strain gauges requires attachment to both sides of a beam, and no measurements can be taken at the neutral axis, where there is by definition, no strain. On the neutral axis, BEF sensors are sensitive down to the zero strain level.

To make a more practical comparison, for homogeneous beams of uniform cross section undergoing circular curvature, strain is given by:

$$\epsilon = y\theta/S \tag{2}$$

Where y is the radial distance of the measurement point from the neutral axis, θ is the angle of curvature of the sensitized section, and S is the length of that section. If we place a BEF sensor 5 mm away from the neutral axis, and take its dynamic resolution limit to be 10 microradians per 10 mm, this is equivalent to a measurement of 5 microstrain.

Lead bending and drift are concerns for any intensity-based sensors. BEF sensors are relatively free from lead bending effects because the treated sensitivity is more than three orders of magnitude greater than that of the leads. When a reference fiber is used, and is subjected to the same lead bends as the sensor fiber, lead bending is even further reduced.

Drift is attributable to changes in LED output and photodetector sensitivity, and decreases considerably when a reference fiber is used in differential mode (reference path amplitude is subtracted from signal path amplitude). With differential measurement, drift is less than 0.3 mrad per hour for an 8 mm-long sensor. Currently, this sets the limit for absolute curvature measurements. Below about 1 mrad, measurements are only meaningful in dynamic mode (i.e. relative changes over a short timescale), where the noisefloor is of the order of 10 microradians. Dynamic measurements can still be very useful for control applications, including flutter reduction.

The relatively large throughput of BEF sensors (approximately 10 to 50 percent of the light that would pass through an untreated fiber is passed on to the photodetector) is a significant advantage. This allows the use of relatively low-power LED's and special amplification is not required to achieve high bandwidth.

6. APPLICATIONS AND FUTURE PLANS

6.1 Applications of BEF Sensors

Embedment of BEF sensors and the use of BEF sensors to measure other modalities (torsion, axial strain, tactile stimuli) have been shown to be feasible.[12] Examples include sensors embedded in pultruded carbon fiber/epoxy rods where the the processing temperature exceeded 180 deg c, and sensors embedded in prosthetic arms produced by an acrylic resin layup technique. This work was carried out by a team including the New Brunswick Research and Productivity Council, Atlantic Nuclear Services, University of New Brunswick Institute of Biomedical Engineering, and Focal Technologies Inc. The same team, with the addition of Process Technology Limited, is now doing more embedment and system development work. This includes preliminary experiments with thin-film deposition to replace the current epoxy light-absorbent coating.

As an example of the practicality of the technology in its present state of development, an eight-gauge, 32-connector (8 BEF's, 8 reference fibers) instrument has been successfully built and used on a coal dragline to measure sub-millimeter deflections under severe conditions of vibration and temperature. The instrument and its deflection gauges are shown in Fig. 14.

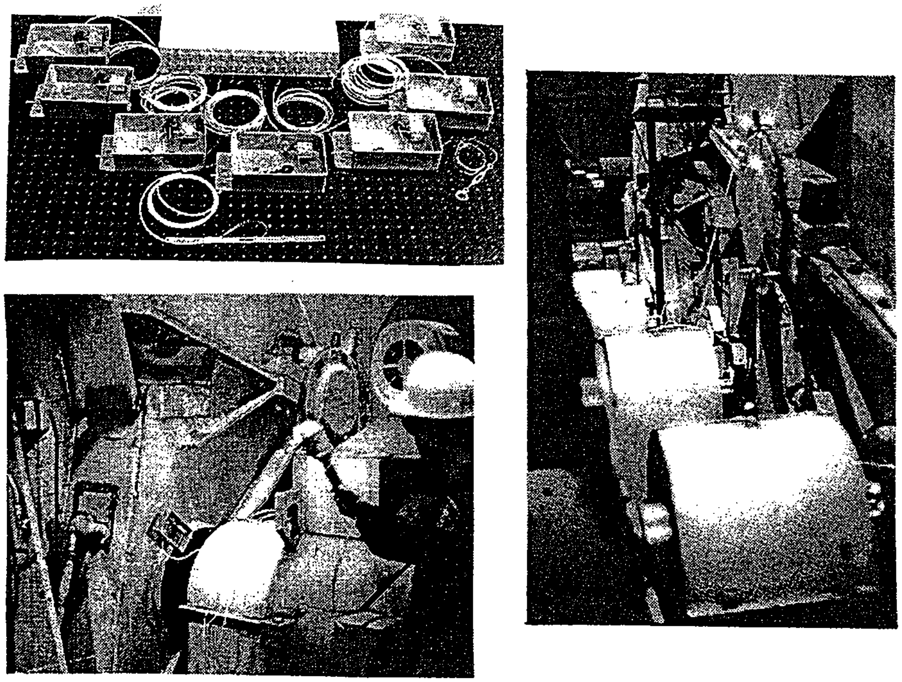


Figure 14: Practical application of BEF sensors used to measure deflections on a coal dragline. Upper left: interface box and eight sensor units; Lower left and Right: sensors installed on dragline.

6.2 Goals for the Future

Further reductions in drift are expected. In theory, differential correction can eliminate common-mode mechanical perturbations but cannot eliminate the effects of LED and photodetector sensitivity changes. Drift will be reduced compared to a differential method, if the signal path amplitude is divided by the reference path amplitude, as is commonly done in optical instruments.[13,14] This technique can in theory eliminate the effects of LED and photodetector changes in sensitivity, including changes due to ageing.

Even after applying division techniques, the problem of connectors remains for sensor instrumentation using separate emitters and detectors for the two paths. This is not a severe problem if resolution of a few milliradians or relative measurement of dynamic changes are adequate. For other applications requiring absolute DC accuracy in the microradian range, it is preferable to use a single emitter and detector. A promising method which includes in-situ calibration is now under evaluation.

Another goal is to produce single-ended sensors, which would eliminate the loop-back of fiber from the distal end of the sensor to the photodetector. This will be accomplished by using a mirrored distal end and a directional coupler at the proximal end.

7. CONCLUSIONS

BEF sensors have been shown to be capable of making real-time measurements of curvatures, and are suited for embedment in composites. The simplicity and potential low cost of the sensors and their attached instrumentation makes it likely that they will be used in a wide variety of practical applications where optical fibers are preferable to electrical sensors.

8. ACKNOWLEDGEMENTS

A "Smart Bone" project closely related to the work reported here[12] was supported by the Canadian Space Agency and the Province of New Brunswick under a cooperative agreement with the Atlantic Canada Opportunities Agency. This support is gratefully acknowledged. The author is indebted to "Smart Bone" team members W. Thompson and A. Djordjevich of Atlantic Nuclear Services Ltd.; E. Biden, R. Caldwell, and Z. Wedderburn of the University of New Brunswick Institute of Biomedical Engineering; J. Snow and K. Bowers of Focal Technologies Inc.; and R. St-Laurent, T. Patterson, B. Lee, B. Bell, A. Jaskielewicz, J. Carter, and G. Mallory of RPC. Pultrusion expertise was provided by G. Murphy of General Composite Technologies.

9. REFERENCES

1. Measures, R.M., "Fiber Optics Smart Structures Program at UTIAS," SPIE Vol. 1170 Fiber Optic Smart Structures and Skins II, Boston, Mass., pp. 92-108, 1989.

2. Measures, R.M., "Smart Structures with Nerves of Glass," Progress in Aerospace Sciences, Vol. 26, No. 4, pp. 289-351, 1989.

3. Grossman, B., et. al., "Fiber-Optic Sensor and Smart Structures Research at Florida Institute of Technology," SPIE Vol. 1011, Fiber Optic Sensors III, Hamburg, pp. 123-135, 1988.

4. Krohn, D.A., "Intensity Modulated Fiber Optic Sensors Overview," SPIE Vol. 718, Fiber Optic and Laser Sensors IV, pp. 2-11, 1986.

5. Bruinsma, S.J.A., "Review of Fiber Optic Methods for Strain Monitoring and Non-destructive Testing," SPIE Vol. 1011 Fiber Optic Sensors III, Hamburg, pp. 122-129, 1988.

6. Lagakos, N., and Bucaro, J.A., "Optimizing Fiber Optic Microbend Sensor," SPIE Vol. 718, Fiber Optic and Laser Sensors IV, pp. 12-20, 1986.

7. Wolff, R., "The Monitoring of Bridges with Optical Fiber Sensors," Smart Structures Research Institute Inaugural European Seminar, Paris, 1991.

8. Udd, E., et. al., "Microbending Fiber Optic Sensors for Smart Structures," SPIE Vol. 1170, Fiber Optic Smart Structures and Skins II, pp. 478-482, 1989.

9. Danisch, L.A., "Fiber Optic Liquid Level Sensor," U.S. Patent 4,880,971, 1989.

10. Danisch, L.A., "Removing Index of Refraction Constraints in the Optical Measurement of Liquid Level," also presented at this conference.

11. Danisch, L.A., Fiber Optic Bending and Position Sensor, U.S. and Canadian Patent applications.

12. Danisch, L.A., "Smart Bone," Final Report for Canadian Space Agency Contract 9F006-1-0006/01-OSC, RPC Report No. ELR/92/22S (General Distribution Volume), 24 pp., June, 1992.

13. Laing, R.A., Danisch, L.A., and Young, L.R., Non-invasive Multichromatic Eye Oximeter, NASA CR No. NAS12-2018, October 1969.

14. Laing, R.A., Danisch, L.A., and Young, L.R., The Choroidal Oximeter: An Instrument for Measuring Oxygen Saturation of Choroidal Blood in vivo, IEEE transactions on Biomedical Engineering, pp. 183-195, 21 March 1975.

Preprint of "SMART WRIST" paper presented at 1993 SPIE Conference:

Danisch, L., Thompson, W., Ele, A., Lovely, D., Hudgins, B., Biden, E., Caldwell, R., Snow, J., MacKay, I, and Aite, K., "Bend enhanced fiber optic sensors in a teleoperation application," SPIE Technical Conference 2070: Fiber Optics and Laser Sensors XI, Optical Tools for Manufacturing and Advanced Automation, Boston, 13 pp., Sept. 7-10, 1993.

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

Lee A. Danisch, SM, P.Eng., President

BEND ENHANCED FIBER OPTIC SENSORS IN A TELEOPERATION APPLICATION

Lee Danisch;[a] Walter Thompson, Abraham Ele;[b] Dennis Lovely, Bernard Hudgins, Edmund Biden, Robert Caldwell;[c] Jim Snow, Ian MacKay,[d] and Kamel Aite[e]

(a) New Brunswick Research and Productivity Council, Fredericton, NB, Canada E3B 6Z9 (Tel. 506-452-1373); (b) Atlantic Nuclear Services Limited, Fredericton NB, Canada E3B 5C8; (c) Institute of Biomedical Engineering, University of New Brunswick, Fredericton, NB Canada E3B 5A3; (d) Focal Technologies Incorporated, Dartmouth, NS, Canada B3B 1S1; (e) Process Technology Limited, Oromocto, NB, Canada E2V 2H5.

ABSTRACT

Bend enhanced fiber (BEF) sensors, described in detail previously,[1,2,3] are curvature-measuring optical analogs of elongation-measuring resistance strain gauges. They are made by treating optical fibers to have an optically absorptive zone along a thin axial stripe a few millimeters long. Light transmission through the fiber past this zone then becomes a robust function of curvature, three orders of magnitude more sensitive to bending than in the untreated fiber. Directionality and polarity of curvature are preserved in the light transmission function, over a linear range covering five orders of magnitude, centered about zero curvature. This paper describes a project[4] in which BEF sensors were used to improve teleoperation of a small mobile robot, by instrumenting joint angles, an extension, and four forces. The operator, who formerly had only a televised view from a camera on the robot, now has additional information on a computer screen showing these parameters in graphical form. This information, provided entirely from fiber optic sensors, makes it considerably easier to manipulate the robot. The project also included demonstrations of a multiplexing system for larger BEF arrays, use of BEF sensors in prosthetics, and plasma enhanced chemical vapor deposition of a light absorptive coating on BEF sensors.

1. DESCRIPTION OF PROJECT

This project was designed primarily to demonstrate the ease with which simple intensity modulated Bend Enhanced Fiber optic sensors may be used to instrument a small mobile robot. This is made possible by use of sensors which measure curvature directly over a large linear range, making it possible to use the same type of sensor to measure joint angles, displacements, and forces. Seven parameters were measured on a Pedsco robot, which normally provides no feedback to the operator except front and back television views. The robot is shown in Fig. 1. It has two parallel "forearms," one of which is extendable.

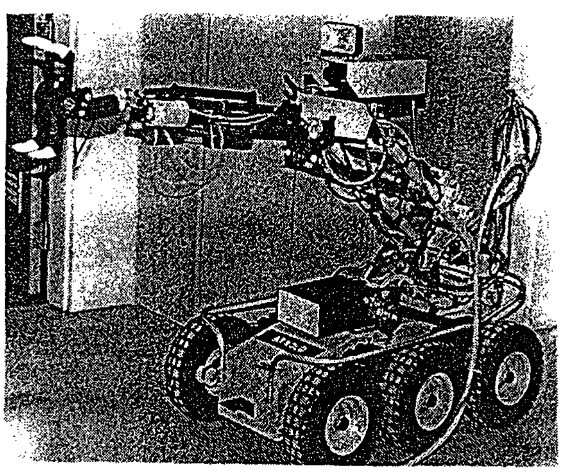


Figure 1: Teleoperated robot used as a testbed for BEF sensors.

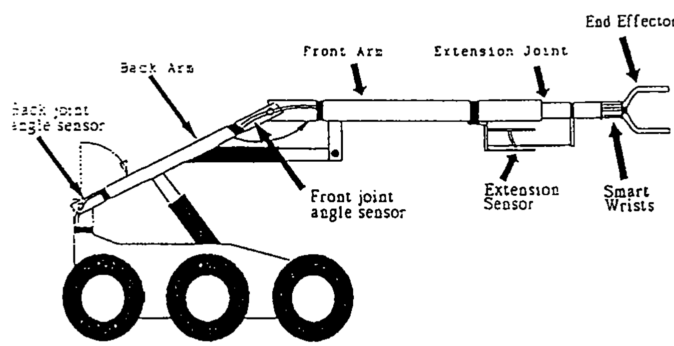


Figure 2: Two joint angles and an extension instrumented on the robot. The "smart wrists" were used to measure forces on the end effectors.

Control switches, a joystick, and a television monitor on a console (not shown) are connected to the robot through an umbilical cord. The robot is designed for use in police, environmental cleanup, and nuclear work.

Fig. 2 shows two joint angles and an extension on the robot that were instrumented with BEF sensors. "Smart wrists," also using BEF sensors, were added at the ends of the "forearms" to measure vertical and horizontal components of forces applied to various end effectors.

Sensor signals were used to provide the operator with a computerized viewscreen showing a stick figure elevation of the robot which changes as two motorized joints and an extensor move under teleoperated control. Another part of the display shows forces exerted on the end effectors and displays a forward tipping moment.

The project team also investigated related aspects of BEF sensor implementation, including optoelectronic multiplexing of signals from many fibers, use of BEF sensors to instrument prosthetic arms, and a plasma enhanced chemical vapor deposition alternative to epoxy coating of sensors.

2. DESCRIPTION OF SENSOR SYSTEM FOR ROBOT

All sensors use the same Bend Enhanced Fibers which were made by treating 200/230μm Ensign Bickford HCS fiber to have a loss zone along a thin axial strip 5mm to 10mm long, overcoated with an optically absorptive layer of graphite-rich epoxy. A typical transmission curve for a BEF sensor is shown in Fig. 3.

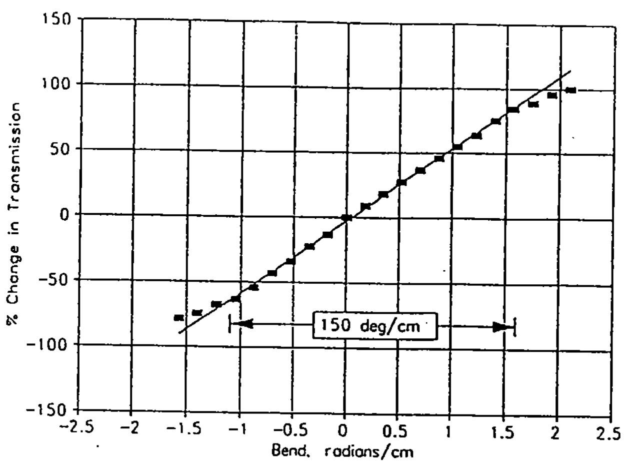


Figure 3: Transmission curve for BEF sensor mounted in hinged fixture to produce a wide range of curvatures.

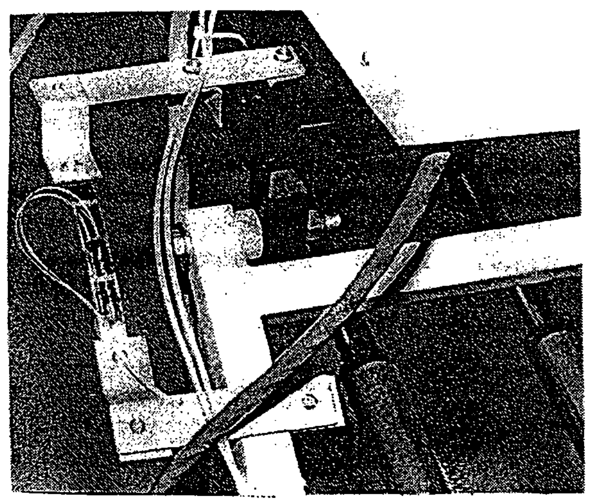


Figure 4: Joint angle sensor (arch form at left of figure) attached with brackets to two sections of robot arm.

2.1 Joint Angle Sensors

As seen in Fig. 3, curvature is measured linearly by the BEF sensors over a range of approximately ±75 deg/cm of treated length, centered about zero degrees (a straight fiber). These sensors were mounted with flexible adhesive to thin flexible strips of metal 0.25mm x 13mm x 30mm long. Each strip was formed into an arch with the sensor at the apex and attached to a movable joint of the robot using spacer brackets, as shown in Fig. 4. Because of the way curvature at the apex changes with joint angle, the sensors are well within their linear range for large variations in joint angle, and are relatively immune to attachment variations and forces out of the plane of the joint.

2.2 Extension Sensor

The extension sensor was used to measure a 50cm motor-driven axial movement of a distal segment of one of the robot "forearms" holding a claw shaped end effector. This was done with a BEF sensor mounted to a short (4cm) piece of the same kind of metal strip used to measure joint angles. In this case, the strip was mounted as a cantilevered beam, so that displacement of the end of the beam over a ±5mm range produced a curvature of approximately ±50mrad/cm in the sensor, which was mounted near the midpoint of the unclamped beam length. In order to use this relatively small displacement range to sense the large extension, the end of the beam was mounted between two helical springs, one spring being attached to the robot arm, the other to the extensible claw assembly. Spring constants were such that the beam displacement range was used to represent the full extension range. The extension sensor is in the cylindrical housing at the lower left in Fig. 5. A long helical spring can be seen extending to a bracket inboard of the rightmost "smart wrist" holding the claw. A shorter spring and the small cantilevered beam are inside the housing.

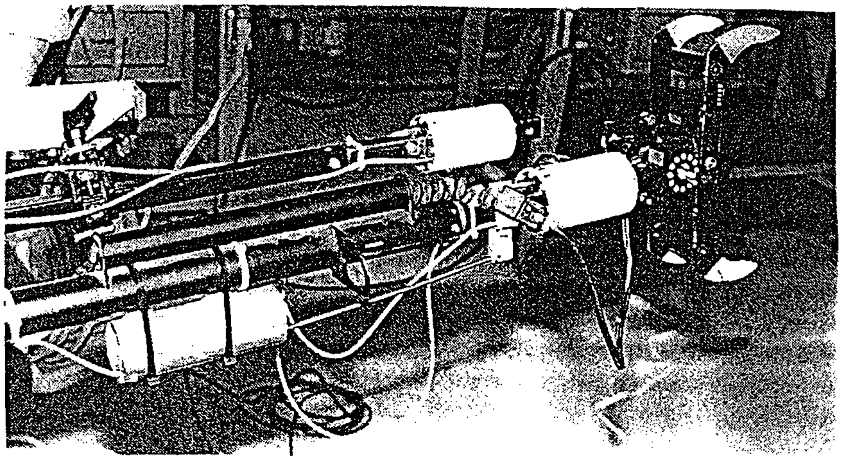


Figure 5: Extension sensor (in cylindrical housing at lower left) mounted on robot. Two smart wrists, one holding a claw end effector, appear at the right.

2.3 Force Sensors

"Smart Wrists" (See Fig. 6) were made with two flanges separated by four carbon composite "bones" designed to bend slightly under deflection of the outboard flange. The bones are hollow tubes with an outside diameter of 6mm, wall thickness of 1mm, and a length between the flanges of 5cm. They undergo a double curvature, so the flanges remain nearly parallel under load, preventing droop of loads cantilevered outboard of the wrists. Deflection of the outboard flange is approximately 500μm under a 222N (50 pound) horizontal or vertical load. A torsion-resisting cylindrical outer skin of cross-woven carbon fibers in resin was developed so each wrist could be used singly. However, they are normally used in pairs to lift a large object using a custom end effector held by both "forearms" of the robot, so are constrained not to twist. A BEF sensor was attached inside the wrist so that opposite ends of the sensitized zone move with each flange, while the sensitized zone is unsupported and free to bend. This produces a significant change in curvature over the load range of each wrist (±222N vertical and horizontal).

To correct a problem with failure of the adhesive used to cement the bones into the flanges, small metal rods were used in parallel with the bones to resist axial forces on the bones. These rods have no other effect, as they are too small in cross section to affect the bending forces on the bones. Although rated at ±222N, the wrists are capable of supporting ±900N singly and include two levels of mechanical stops for forces over ±900N.

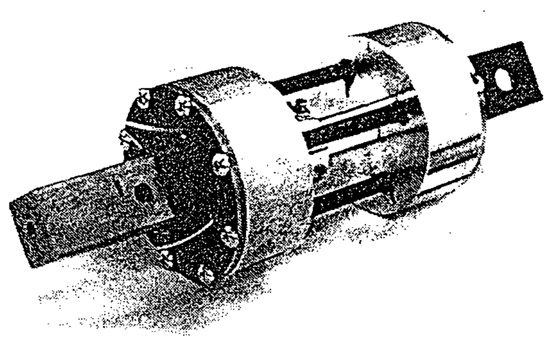


Figure 6: Smart wrist (shown without its cover) used to measure vertical and horizontal forces. Carbon composite "bones" connect the two flanges and surround a central safety stop assembly.

2.4 Optoelectronic Interface

All the BEF sensors were instrumented the same way. Leads up to 3m long from each of the seven "gages" were covered in teflon tubing and brought into an optoelectronic interface unit (IU), shown in Fig. 7. The tubing for each gage also contained leads from a "reference" made of untreated fiber, which ran next to each gage fiber. A foam-covered guillotine door on the IU prevented pulling of the leads at the ST connectors, which were inside the IU. Each fiber was illuminated by a separate 850nm LED, and light output was detected by a PIN photodiode and transimpedance amplifier. Gage signals were divided by reference signals using an analog divider. Offsets and gain for each channel were adjustable. A 68hc11 microprocessor was included to perform 8-bit analog to digital conversion, multiplexing, and serialization. The serial stream was sent over the umbilical cord to a personal computer (PC) near the robot control console.

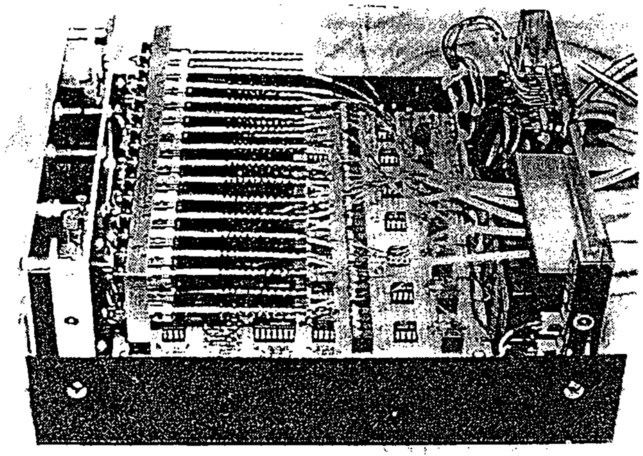


Figure 7: Optoelectronic interface unit for BEF sensors on robot.

2.5 Operator Interface

The PC was programmed to display a stick figure of the robot and other information shown in Fig. 8, all of which is updated approximately every second. The vector indicates horizontal and vertical components of forces applied to the end effectors. The bargraph at the bottom of the display indicates the tipping moment about the front axle as a percentage of the moment required to upset the robot. Numbers indicate outputs from individual sensors calibrated in degrees, pounds and inches of extension, but the pictorial information is designed to be the main focus of the operator's attention.

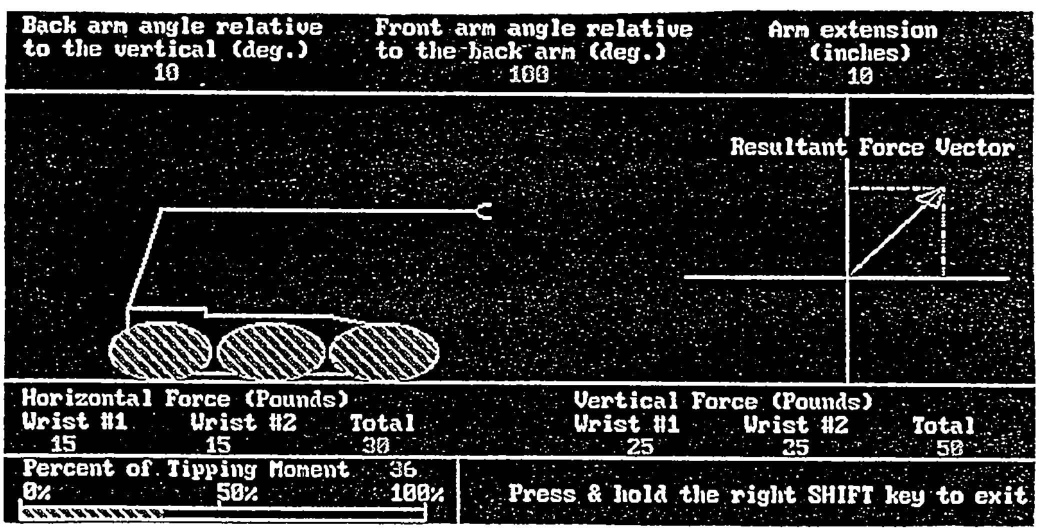


Figure 8: Example of computer screen providing feedback to aid operator in controlling the robot.

2.6 Transmission Curves

The sensors were calibrated on a test fixture designed to simulate the actual robot. Transmission curves for each type of sensor are shown in Fig. 9. Transmission was measured as an 8 bit number resulting from division by the reference signal, scaling, and A/D conversion. Transmission curves are included for: joint angle sensors over their normal ranges of operation; the extension sensor; the horizontal component of one wrist as a digital signal and as measured with a micrometer on the outboard flange; and combined downward vertical components of two wrists used together to support a large end effector. The data for the vertical wrist components is from three runs, the third being after the sensors were used for a week, disconnected, transported 200 km by car, and reconnected without any readjustment or calibration. The force data, which was taken starting at zero force, includes extra points for a return to zero force after each run, indicating worst-case hysteresis data (which always occured near the origin).

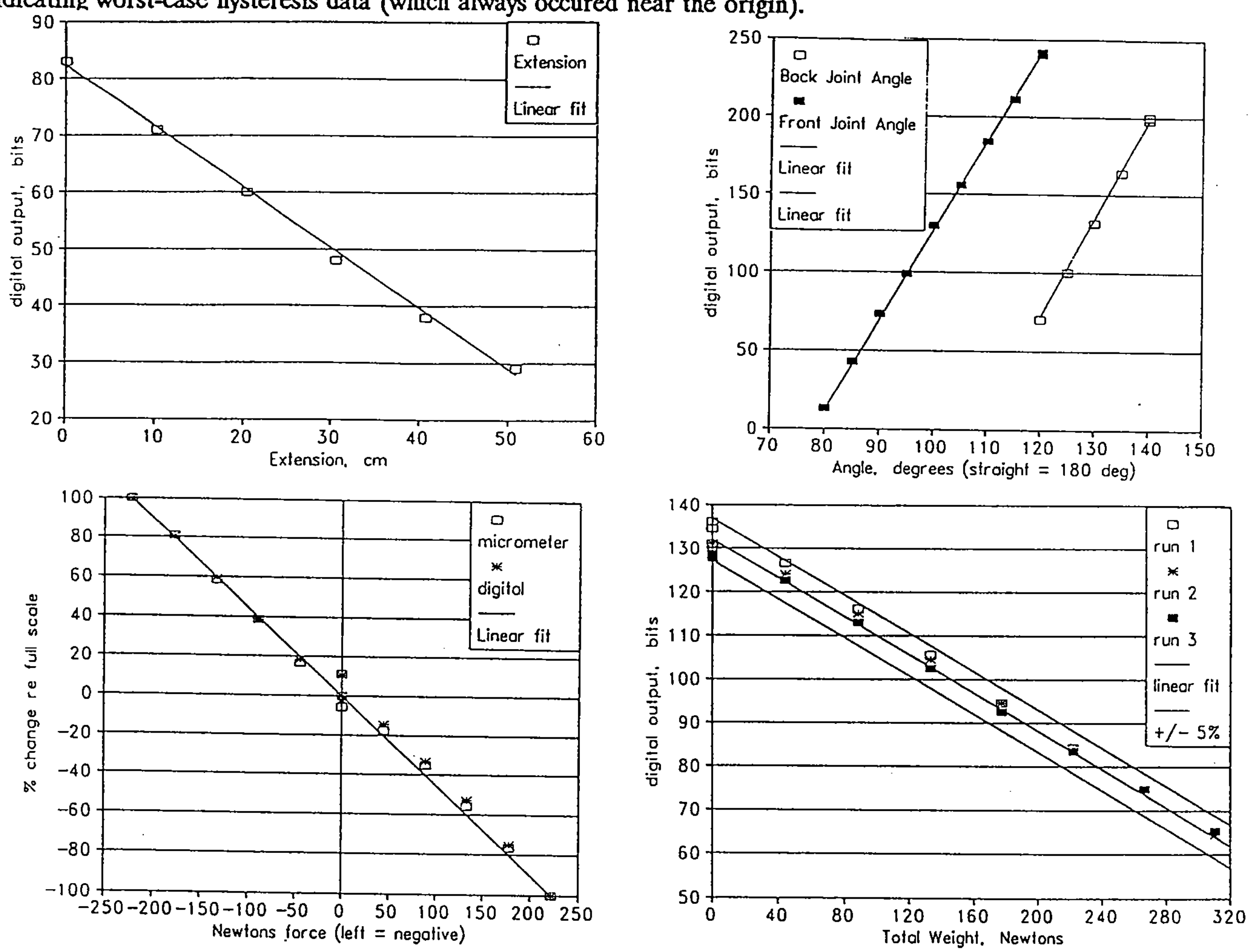


Figure 9: Transmission curves of sensors: Upper left: joint angles; Upper right: extension; Lower left: horizontal component of one wrist (with micrometer comparison); Lower right: combined downward responses from 2 wrists.

2.7 Nonlinearity and Drift

Nonlinearity is attributable mainly to the mechanical portions of each sensor path. Joint angle sensors properly represent the curvature of the apex of the arch used to support them, which is a linear function of joint angle over a wide range. The extension sensor output depends on a linear bending function of its cantilever beam and the difference between two linear functions for the helical springs, so it is linear over its range of use. The wrist outputs depend on a combination of linear deflection functions for the bones and attached BEF sensors. These sensors showed considerable hysteresis for small forces, probably reflecting the physical nature of the carbon composite bones. The hysteresis was also visible in the deflection data measured directly with a micrometer. The wrist sensors also deviated slightly from linearity near full load, but this was also visible in the data taken with a micrometer, indicating that the nonlinearity did not originate with the BEF sensors. All BEF measurements met the ±5 percent accuracy goal for the project, which is more than sufficient to provide improved control cues to the operator.

Drift of the full system (including A/D conversion) was measured over a 30 hour period, including temperature excursions of 10 deg c. Five of the seven sensors drifted less than ±1 percent of range. The front angle sensor was within ±1.7 percent and the extension sensor was within ±1.5 percent. Data shown earlier in Fig. 9 from three runs of the wrist sensors, the third taken after more than a week including reconnection of the fibers, indicates a stability of ±5 percent over a longer term, including effects of hysteresis and connector repeatability.

2.8 Field Test

After calibration on a test fixture, the sensor system was installed on the robot at a nuclear generating station and used by the maintenance team at the station to perform a variety of teleoperated tasks. Installation and checkout required less than a day, most of it being required to change some brackets for the joint angle sensors because mounting holes were somewhat different than in the drawings.

Station personnel reported that the sensors provided much needed information not available from the on board cameras. The horizontal load information is particularly valuable, as it allows the operator to know when an object being manipulated is stuck during insertion or removal, or has encountered an obstruction during transport.

2.9 Robot System Performance

The sensor system demonstration illustrated the following points:

- -The same BEF sensors were used to implement force, angle, and extension measurements.
- -The ±5 percent accuracy goal was met.
- -Installation was rapid.
- -Simple sensors can improve considerably on the information available from a televised view alone.

3. IMPLEMENTATION OF INTENSITY BASED SENSORS IN LARGER SYSTEMS

3.1 Addressing, Multiplexing and Connecting

Any fiber optic sensor network, whether it uses BEF or other sensors, requires some form of multiplexing and addressing of the signals. Although individual connection of fibers and simple electronic multiplexing were appropriate for the above project, other approaches will be required for systems with more than one or two dozen sensors, particularly if the sensors are embedded in composites. In larger systems, reduced size and cost will be essential to practical implementation.

Dakin provides an extensive review of multiplexed and distributed transduction techniques for use with optical sensors[5]. With intensity based sensors like the BEFs, wavelength, frequency and time division multiplexing schemes are not generally practical. The overall desire for a compact inexpensive sensor system is quickly defeated or simply not feasible due to flux budget limitations. However, separate fiber paths for each sensor or "spatial multiplexing" has a number of attractive characteristics: it is simple in concept, it provides a good power budget, it has low crosstalk performance and it is relatively fault tolerant. The main disadvantage is the high cable and connector cost as well as bulk. However, these can be reduced by bringing all fiber ends to a common location and eliminating connectors. This requires an optoelectronic interface capable of directing light to and collecting light from the fiber ends. Ultimately this would take the form of a multisensory mapped video (MSMV) system capable of illuminating and collecting from hundreds of fibers without individual connectorization. As a step in this direction, it was decided to build a simple prototype system demonstrating some aspects of MSMV.

3.2 Requirements for Prototype MSMV

Design requirements for the prototype were taken to be: up to 100 fiber end connections (25 sensors), with a sensor accuracy of ±0.04% (0.002 dB) and dynamic range of 35 dB. The sampling rate was assumed to be at least 1 kHz to measure dynamic loading. This allows a typical optical sensitivity of better than -80 dBm for PIN photodiode detectors based on rise time performance.

3.3 Design Alternatives for MSMV

Various source and detector combinations were considered along with an intermediate scanning element in some cases. Each was evaluated in terms of size, cost, reliability, optical power budgets and sensitivity, long term stability, and whether sensor access would be sequential or simultaneous. Scanning elements considered were piezoceramic devices, mechanical rotary devices, and liquid crystal display matrices. None of the mechanical devices were found to be adequate for analog measurements of less than 0.1 dB. The favored design was based on a single source, which coupled to a bundle of sensor and reference fibers, and a photodiode array detector.

3.4 Demonstration MSMV System

A sixteen fiber demonstration system suitable for eight sensors was built and tested. The source was a 660nm LED (Archer 276-087). The bundle consisted of sixteen 200/230 Ensign Bickford HCS fibers. The detector was a UDT A2V-16 sixteen element linear photodiode array, connected to transimpedance amplifiers. The fiber bundle at the source end was terminated in a modified FC bushing using an epoxy-polish technique. Fiber location was not critical and up to 127 fibers could be accommodated. An aluminum block was drilled to accept the sixteen fibers such that they would line up with the diode array elements. These connector-like fixtures are depicted in Fig. 10. Here and in the robot demonstration, the most effective connector scheme for use elsewhere in the system was the conventional ST type.

3.5 Performance of MSMV Prototype

In this non-optimized case, up to 3μW was launched into each fiber. Coupling 1μW into each of 100 optical fibers would not be unreasonable for readily available LED's, e.g. Hamamatsu L2656. The crosstalk was measured to be less than -30 dB and occurred mainly at the detector between adjacent diodes. Using simple transimpedance amplifier schemes it was found possible to achieve a sensitivity of 0.5%. AC detection schemes would give the desired order of magnitude improvement.

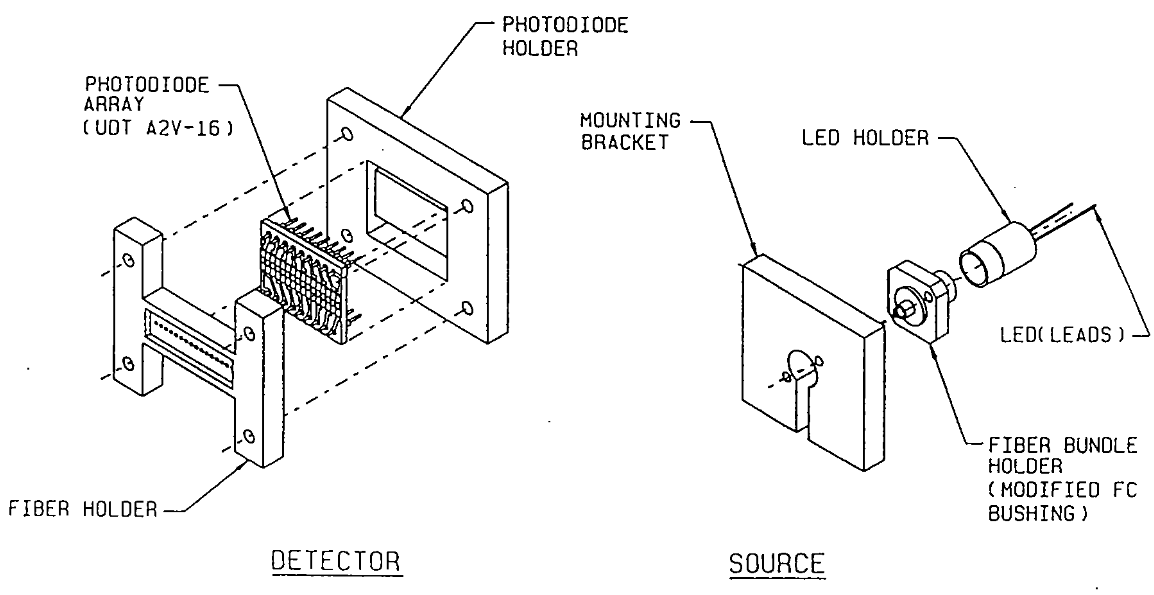


Figure 10: Mechanical detail of spatial multiplexing demonstration.

4. PROSTHETIC APPLICATION OF BEF SENSORS

In this part of the project, BEF sensors were investigated as input devices for control of prosthetic arms.

4.1 Input Device Requirements

Powered prosthetics have become the accepted method of replacing limb function lost by traumatic or congenital amputations.[6] The control of these devices is accomplished by either mechanical switches or by switches based on the level of myoelectric activity. Although both approaches provide excellent solutions, there are problems inherent with mechanical and myoelectric control (MEC). Because the mechanical switches used in the prosthetic industry must be small, they lack durability and often fail. For myoelectrically controlled systems a total contact socket is required to minimise the effects of motion artifact and to allow continuous detection of the myoelectric signal (MES). This is often difficult to obtain and leads to signal contamination by 60 Hz interference. Furthermore, perspiration disrupts normal myoelectric signal detection leading to a loss of control.

4.2 BEF Sensors as Input Devices

At the Institute of Biomedical Engineering, UNB, a preliminary investigation is under way into methods by which a prosthetic control signal can be derived from pressure changes within the socket using a bend-enhanced fibre (BEF) optic sensor. A contraction of the stump musculature causes a small deformation in the socket. By using a BEF mounted within the socket, this deformation can be transduced into a control signal which reflects the pressure exerted by the stump on the socket. In a manner analogous to myoelectric control, a system based on signal amplitude or signal rate of change can then be constructed.

One of the major advantages of using BEFs as sensing elements is in the simplicity of the processing necessary to derive the control signal. In a myoelectric system an electrode pair placed over an active muscle will transduce the underlying ionic current flow in the muscle into an electrical signal. This low amplitude signal is contaminated with 60 Hz interference and must be differentially amplified and processed through a suitable nonlinearity and filter to extract a control signal.

The BEF sensor, on the other hand, is a complex transducer requiring an LED light source and photodetector. The sensor must be mounted on a structure which exhibits an angular displacement with applied force. Because of the microradian sensitivity of the sensor, the magnitude of the displacement can be very small. Due to the nature of the BEF signal, post processing is simplified, requiring no nonlinear element.

4.3 Description of Experiments with Input Devices

It was thought useful to compare the control signal available from a conventional myoelectric setup and that attainable from the BEF transducer. Areas for investigation were the speed of the transducer and its sensitivity.

A plastic cuff was manufactured using conventional prosthetic materials which was used to house the BEF based pressure sensor. This was fastened to the inside surface of the cuff using double sided tape. The cuff was positioned over the bulk of the biceps muscle in a non-amputee volunteer subject and secured in place using a velcro strap. A pair of passive stainless steel electrodes were also located close to the sensor so that a comparison could be made between the myoelectric signal and pressure signal for the same contraction level.

The passive electrodes were connected to a conventional differential amplifier with a gain of 40,000 to provide the raw MES. This signal was further processed using an RMS converter (non-linearity) to provide a signal whose level reflects the degree of muscle contraction. Two RMS converters were used in parallel so that a comparison between time constants could be made. The BEF sensor was interfaced to an amplifier with a much reduced gain, X20 with no additional signal processing.

The subject was instructed to perform a series of contractions of the biceps muscle while the signals from the electrodes and BEF sensor were recorded simultaneously. A brief study of more complex muscular activity involving rotation of the forearm was also performed.

4.4 Results of Experiments with Input Devices

The experimental results of this preliminary research have been published elsewhere,[7] consequently only a summary of the more important findings are given here. In Fig. 11, the output from the sensor is compared with the processed MES obtained for the same sequence of contraction patterns. The graph shows the effect of 50 ms and 200 ms time constants for the MES processing along with the direct signal from the BEF sensor. The correlation between all three traces is immediately obvious. While the 50 ms MES signal responds the quickest, the time constant of the BEF sensor is estimated to be of the order of 100 ms. This compares favorably with typical time constants in commercial myoelectric controls.

The most novel feature of the new sensor is shown in Fig. 12. The output is truly bipolar - responding to pressure changes in both directions. As the BEF sensor is bent in the direction of the treated region, the transmission loss decreases. The signals in Fig. 12 show the effect of medial and lateral rotation of the upper arm. While the processed MES shows distinct muscle activity, discrimination between the two movements cannot be made. However, the bipolar nature of the BEF signal makes this discrimination trivial. Consequently, the use of this sensor for multi-function control is a distinct possibility.

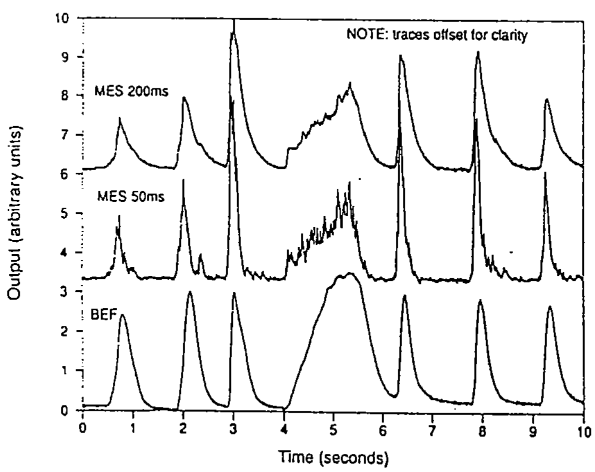


Figure 11: Comparison between BEF signal and processed MES.

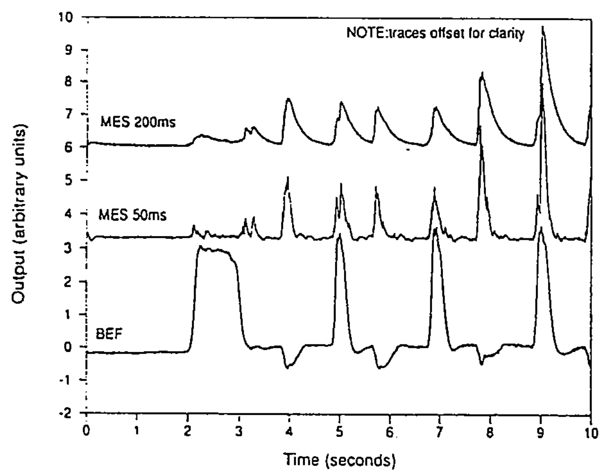


Figure 12: Medial and lateral humeral rotation.

4.5 Prosthetic Application and Future Work

On the basis of these early results a 3-state hand control using a BEF sensor has been implemented. The signal was processed using a circuit similar to that which is presently used in the UNB 3-state myoelectric control system. This level coded system was briefly evaluated using a normal limbed volunteer. Control of the hand with the BEF control system was easily achieved and required a strategy on the part of the user not unlike that used for myoelectric control.

The mounting of the sensor in this preliminary work is definitely not suitable for clinical trials. Consequently, further work has been targeted towards other mounting methods. A possible scheme is to laminate one or more sensors within the socket wall. This would reduce wear on the sensor during use.

5. PECVD COATING OF BEF SENSORS

BEF sensors used in this project were made by treating 200/230μm Ensign Bickford HCS fiber as described previously[1]. The light loss zone on the fiber must be overcoated with light absorptive and protective material so that the core remains structurally sound and light in the core does not interact with the environment outside the cladding layer. Normally, the coating used is graphite-rich epoxy, which is applied manually to a thickness of approximately 100-200μm. In this portion of the project, an alternative plasma enhanced chemical vapor deposition (PECVD) method was explored, aimed at volume production.

5.1 Requirements for Light Absorptive Coating

A candidate coating system must provide good adhesion to fibers inside and to composite materials outside, mechanical strength, long term stability, and over 85 percent light absorption. The 85 percent goal is somewhat arbitrary, but assumes that no bright light sources are present externally, so that the coating must be able to prevent light which leaves at the sensor loss zone from re-entering the fiber. This amount of absorption ensures that only about 2.25 percent of light that fully leaves and re-enters will again reach the core. Further goals set for the system included a target thickness of 10μm or less and zero damage to cladding and buffer materials already on the fibers. The latter requires process temperatures no greater than approximately 200 deg c. Samples of the fiber were able to withstand 200 deg c for at least 30 minutes. At 250 deg c, the tefzel buffer and the cladding were found to fail rapidly.

5.2 PECVD System

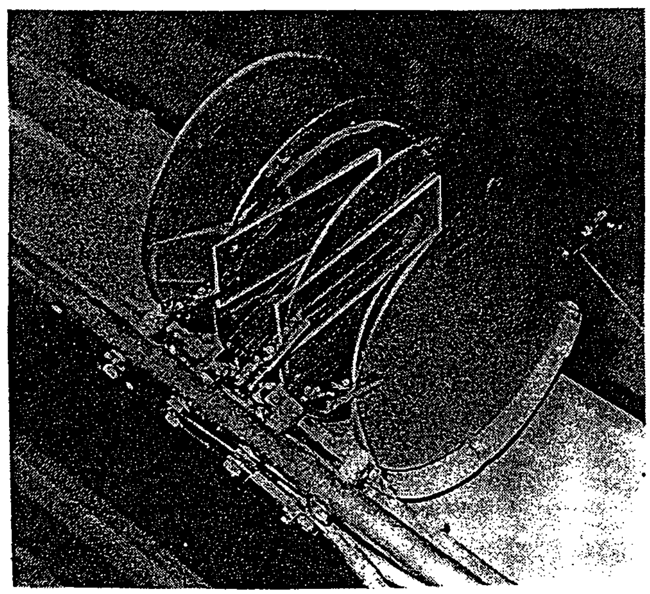


Figure 13: PECVD electrode array used in coating the fibers and glass substrates. Glass and fiber components are clipped to the wafer-shaped metal electrodes.

Because of the low process temperatures required, PECVD was chosen as a means of depositing the light absorptive coating. PECVD films can be applied at temperatures of less than 100 deg c, and deposition rates are well above those achievable with thermal CVD at higher temperatures. Deposition was done with a new type of PECVD reactor and electrode system[8] designed primarily for processing semiconductor wafers, with more than ample space for the small number of sample fibers treated. Temperature, pressure, and gas flow in the quartz reactor chamber of a PTL horizontal hot wall CVD system were independently controlled by a digital processor, automatic throttle valve, roots blower, roughing pump, and mass flow controllers. Radio frequency power was supplied by an Advanced Energy Inc. model PEP1250 power supply capable of 1250W output at 55kHz. This power was delivered through an automatic matching network and feedthroughs to four stainless steel electrodes in a quartz boat on a silicon carbide paddle. Deposition was performed on small glass plates (microscope slides) and treated fibers, both of which were held on the electrodes with alligator clips as shown in Fig. 13. The glass plates were cleaned before deposition to promote adhesion of the films, and adhesion was tested just after deposition using a Scotch Tape pull test.

Light absorption testing was performed by measuring transmission loss through the glass plates and collecting light lost from fibers with a small reflective structure. Both measurements were comparative, the standard in each case being an uncoated plate or fiber.

5.3 Candidate Films for Deposition

Light in the 600-800nm range is strongly absorbed in a 1 to 2μm thick film of amorphous silicon[9], although absorption falls rapidly with increasing wavelength. This led us to choose it as a candidate material for the absorptive layer, for BEF sensors operating at 650nm. Silicon nitride films were also tried, because of their well known protective qualities.[10]

During the trials, silicon nitride as well as amorphous silicon films were deposited onto glass substrates and optic fibers at temperatures varying from room temperature to 225 deg c. The experimental conditions were varied to obtain silicon nitride films from near stoichiometric to highly silicon-rich compositions. Even thick silicon nitride layers (>2um) could absorb substantially less light than the amorphous silicon films, so were rejected early in the experimental trials as candidates for an absorptive layer. However, silicon nitride was used as a final capping layer.

5.4 Effects of Process Parameters

Our preliminary experiments were carried out at room temperature. The resulting films showed a poor quality with a polymer-like structure. The films could be easily removed from the substrate just by rubbing the surface with a finger which turned black in the case of amorphous silicon films. However, these films had qualitatively good light absorption characteristics.

It is well-known that discharge-produced amorphous silicon films contain a considerable amount of hydrogen in the range of 10-50 at.% and that most of the hydrogen is bonded to silicon atoms.[11,12] Amorphous silicon (a-Si:H) films deposited at substrate temperatures below 200 deg c contain significant amounts of dihydride and possibly trihydride groups, as well as short polymer chains which cause high defect densities.[13]

Increasing the deposition temperature improves film quality, so more trials were performed at 200 deg c.

The film quality started to degrade at pressures higher than 350mTorr due to increasing polymerization or gas-phase nucleation in the discharge.

5.5 Discussion of PECVD Results

Optimum conditions of deposition as well as the essential characteristics of the best quality a-Si:H films obtained during our experiments are summarized in Table 1.

Reactants	90 sccm of SiH_4
RF power (continuous mode)	85-95W
Frequency	55 +/- 1kHz
Pressure	275mTorr
Temperature	200deg c
Deposition rate	>40nm/min
Refractive index	Close to crystalline silicon, i.e. 3.45
Adhesion	Good
Appearance	Dark
Light absorption	97% absorption for a thickness of 1-2μm as tested on BEF sensors

Table 1: Deposition conditions and characteristics of a:Si-H films.

Some BEF sensor fibers coated with the amorphous silicon films are shown in Fig. 14.

BEF sensors coated with amorphous silicon were found to have the same linearity, sensitivity, and range as their counterparts coated with graphite rich epoxy. Although they do not achieve 100 percent absorption like the epoxy versions, 97 percent is more than adequate for most applications, and this is achieved with films an order of magnitude less thick than a manually applied epoxy layer.

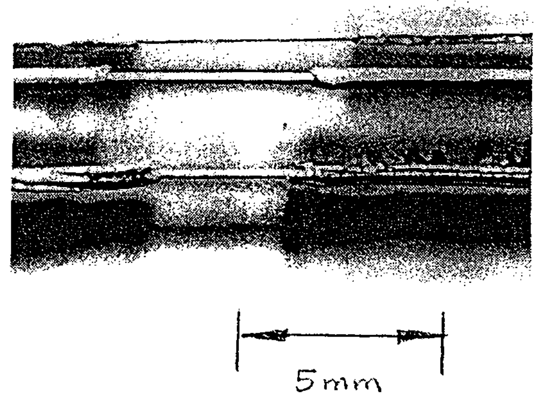


Figure 14: BEF sensor fibers coated with amorphous silicon by PECVD process.

6. CONCLUSIONS

BEF sensors were shown to provide a simple means of instrumenting teleoperated robots. The same basic sensors were used to measure forces, joint angles, and an extension. Instrumentation was not complex and the complete sensor system could be installed on site in a matter of hours. Overall accuracy and stability were in the ±5 percent range, which is more than adequate for assisting an operator to achieve better control. Most inaccuracy was attributable to mechanical aspects of the sensor system rather than the BEF sensors themselves.

A prototype system for addressing, connecting, and multiplexing larger sensor systems was built and tested. It was shown to have characteristics suitable for more compact and economical implementation of larger arrays.

BEF sensors were investigated as possible input devices for the control of motorized prosthetic arms. Potential advantages were noted including a bipolar response that could be used to control more than one function from a single site, freedom from the effects of perspiration which can affect myoelectric electrodes in warm climates, no moving parts, and insensitivity to 60Hz interference.

A prototype process for coating BEF sensors with a light absorptive film was developed, using plasma enhanced chemical vapor deposition. This process could be used in volume manufacture of the sensors.

7. ACKNOWLEDGEMENTS

This work was supported in part by the Canadian Space Agency and the Provinces of New Brunswick and Nova Scotia under a cooperative agreement with the Atlantic Canada Opportunities Agency. This support is gratefully acknowledged. The authors are indebted to RPC team members B. Bell, J. Carter, A. Jaskielewicz, B. Lee, T. Patterson, and R. St-Laurent for their contributions to the project, and to G. Murphy of General Composite Technologies for supplying the carbon composite tubing.

8. REFERENCES

1. Danisch, L.A., "Bend-enhanced fiber optic sensors," SPIE Vol. 1795, Fiber Optic and Laser Sensors X, pp. 204-214, 1992.

2. Danisch, L.A., "Fiber optic bending and positioning sensor," Patents pending.

3. Danisch, L.A., "Smart bone," Final Report for Canadian Space Agency AC STEAR Contract No. 9F006-1-0006/01-OSC, Vol. 1: General Distribution, 24pp., 1992.

4. Danisch, L.A., "Smart wrist," Final Report for Canadian Space Agency AC STEAR Contract No. 9F006-2-0010/01-OSC, Vol. 1: General Distribution, 63pp. + Appendices, 1993.

5. Dakin, J.P., "Multiplexed and distributed optical fibre sensor systems," Journal of Physics E: Scientific Instruments, Vol. 20, pp. 954-967, 1987.

6. Parker, P.A. and Scott, R.N., "Myoelectric control of prosthesis," CRC Critical Reviews in Biomedical Engineering, Vol. 13, Issue 4, pp. 283-310, 1986.

7. Lovely, D.F., Hudgins, B., Danisch, L., Caldwell, R., Daly, J.A. & Biden, E., "Control of powered prosthetics using bend-enhanced fibre optic sensors," UNB Myoelectric Control Symposium, MEC '93, pp. 93-97, Aug. 1993.

8. Aite, K., DesBrisay, R.B. and Danisch, L.A., "Plasma Enhanced CVD Processing," US Patent 5,225,375, 1993.

9. Sze, S.M., "Semiconductor Devices, Physics and Technology," John Wiley & Sons, p. 257, 1985.

10. Kern, W., "Dielectric Materials," in Microelectronic Materials and Processes, R. Levy (ed.), Kluwer Academic Publishers, pp. 247-273, 1989.

11. Brodsky, M.H., Cardona, M., and Cuomo, J.J., Phys. Rev. B16, p. 3556, 1977.

12. Zanzucchi, P.J., Wronski, C.R., and Carlson, D.L., J. Appl. Phys. 48, p. 5227, 1997.

13. Knights, J.C., Bull. Am. Phys. Soc. 23, p. 295, 1978.

Removing index of refraction constraints
in the optical measurement of liquid level

Pre-print of paper presented at
OE/Fibers '92 Conference of
SPIE: The International Society for Optical Engineering
Boston, Sept. 8-11, 1992

Presented by:
Lee A. Danisch
Department Head, Electronics
RPC
921 College Hill Road
Fredericton, New Brunswick
Canada E3B 6Z9

Tel: 506-452-1373
Fax: 506-452-1395

Measurand Inc.
PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173
Sensors

Removing index of refraction constraints in the optical measurement of liquid level

Lee A. Danisch

(New Brunswick Research and Productivity Council, Fredericton, NB, Canada, E3B 6Z9)

ABSTRACT

Continuous and discrete liquid level measurements made with fiber optic sensors generally depend on refraction of light in the liquid to be measured. Problems, including erratic or incorrect readings, arise when the index of refraction of the liquid is near that of the outer surface of the optical probe. This is often the case for common optical probe materials and many organic compounds including fuels and lubricants. This paper describes a continuous liquid level sensor which operates over a wide range of indices. The lower limit of the range is determined by an intermediate optical material in the probe, rather than the material of the outer surface; there is no upper limit. The liquid being measured may have any index equal to or greater than that of the intermediate material. Water is used as the intermediate material in the sensor to be described; it surrounds a lambertian fiber optic emitter and detector pair. The sensor is linear within +/- 5 percent over a five-inch measurement span, for liquids of any index equal to or greater than 1.33, even though the outer surface of the probe is fused quartz, with an index of 1.46. Since most liquids have an index greater than that of water, and many liquids of interest have an index near that of quartz or glasses, this method greatly extends the range of liquids that can be measured with a given sensor.

1. INTRODUCTION

Optical liquid level sensors capable of making single-level[1-5] and continuous[6,7] measurements of the liquid-air interface have been described. These sensors rely on measuring or detecting light lost to the liquid because of a change in the critical angle when air surrounding a transparent optical element forming the outer surface of the probe is replaced by a liquid. When air surrounds the probe, most of the light incident on the probe/liquid interface will be refracted because it encounters the relatively low index of refraction of air. When liquid having an index of refraction greater than that of the probe surrounds it, all light incident on the probe/liquid interface is free to escape. Problems can be encountered when the liquid has an index less than that of the probe, in which case little or no light is lost to the surrounding medium, leading to incorrect readings, or necessitating re-calibration when different liquids are used.

Partial solutions to the problem have been suggested. In one variation,[8] a continuous probe with an index higher than that of the liquid is used. In this case, the outer surface of the probe has grooves which optimize the angle of incidence of light at the probe/surround interface, so that the amounts of light lost to air and liquid are significantly different. In another variation,[9] different probe constructions are suggested for three cases of liquid index: greater than, equal to, or less than that of the probe. These probes have grooves or indentations on the outer surfaces, which increases the cost of manufacture and can lead to fouling problems.

In some cases it is desirable to ignore the presence of some liquids. A hydrocarbon-detection probe has been described[4] which can have a surface with index intermediate between that of water and oil, so that water is ignored and oil is detected. A variation uses a coating that melts away in the presence of, for example, hydrocarbons but not water.

This paper describes a continuous probe[10] with the following features:

-No re-calibration is required for different liquids.

-The outer probe material may have virtually any index of refraction.

-The outer surface is smooth.

2. SENSOR DESCRIPTION

A probe was developed to measure the level in a flask containing liquid reagents used in processing semiconductor wafers. These liquids are of "triple-nines" purity and must be maintained in that condition. Quartz (fused silica) is one of the few materials suitable as a containment. Because of its clarity, quartz might seem to be an ideal material for the walls of a liquid level probe. However, fused quartz has an index of approximately 1.46 at near-infrared wavelengths, which are preferred for level measurement (because scattering from foreign particles is minimized). This is an unfortunate index of refraction, because many organic compounds used as reagents and dopants in the semiconductor industry have indices in the range of 1.4 to 1.5. Measurement errors would occur if different mixtures were measured with a probe requiring indices either higher or lower than that of its quartz walls.

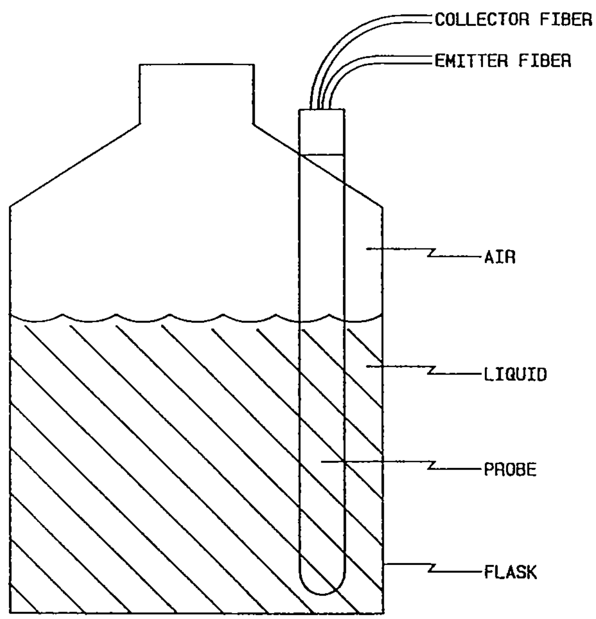


Figure 1: Overall view of liquid level probe in flask. The collector and emitter fibers are connected to an interface box.

The probe was designed instead to be independent of the index of its walls, but dependent on the index of an intermediate material contained within the probe. In this case the intermediate material was chosen to be water, which has an index of approximately 1.33. Virtually all liquids have an index equal to or greater than 1.33.

An overall view of the probe in the flask is shown in Fig. 1. The probe is less than half an inch in diameter, and approximately six inches long. It is roughly the shape of a test tube. The interior of the probe is shown in Fig. 2. Emitter and detector fibers extend down the middle. They are 1 mm diameter plastic fibers treated to emit and collect light along a strip running lengthwise along each fiber and occupying about 90 degrees of the circumference. The inner portion of the probe is completely filled with an intermediate material, which in this case is water. The fibers are separated from each other by a central reflector strip, and are covered with light-absorbing material within a "fiber end structure" designed to minimize internal back-reflection of light at the tips. A light-diffusing layer of teflon tubing (not shown) covers the central fiber and reflector structure. A simplified drawing of a fiber treated to emit or collect light along its length is shown in Fig. 3. The fibers are treated by pressing them onto a platen which produces facets similar to those shown in the figure. Fibers treated in a similar way have been used to make bending and position sensors in which bending causes a variable amount of light to be lost through the treated region.[11-13] For liquid level sensing, the fibers are held straight and serve as non-varying collectors and emitters.

Both fibers extend to an interface box, which contains a light source and photodetector. The electronic interface is designed for simplicity and low cost. The emitter fiber is illuminated by an 850 nm LED; the collector fiber returns light to a PIN photodiode. The LED output is pulsed, and synchronous detection is used in the photodiode amplifier circuit to reject the effects of ambient light. A decrease in the liquid level outside the probe causes the amount of collected light to increase in a manner described later. The electronic circuit is designed to respond linearly to the amount of light collected. The linear signal is offset and scaled with operational amplifiers, so that an LCD display indicates the liquid level in inches. Trimpots on the interface box permit adjustment of offset and gain, which are slightly different for each probe. However, since almost total extinction of light is achieved when the probe is totally covered with liquid, normally only the gain adjustment needs to be changed if probes are interchanged on the same interface box.

The major source of drift in this type of instrument is the LED output power as a function of temperature. Stability of the measurements is achieved by automatically controlling the temperature of the LED and photodetector circuits to 40 ± 1 deg c. Good control at room temperatures up to 30 deg c can be achieved with simple circuitry.

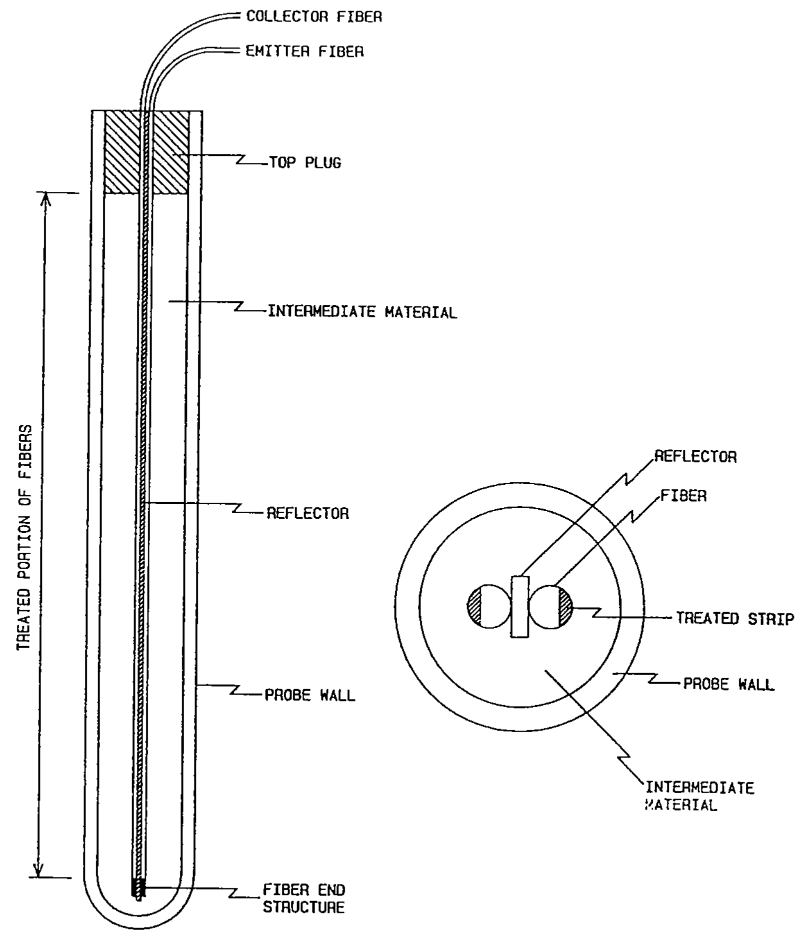


Figure 2: Interior views of the probe. The intermediate material in this example is water, which completely fills the probe.

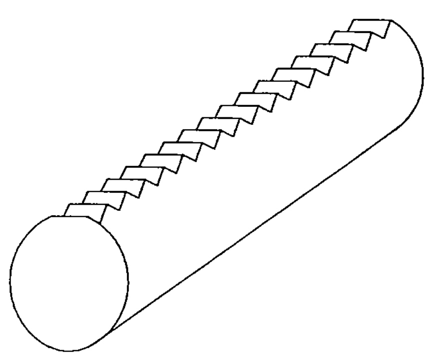


Figure 3: Optical fiber treated to emit or collect light along its length. In this simplified drawing, the facets enable light to leave or enter.

3. PRINCIPLE OF OPERATION

The fibers in the probe emit and collect light along their treated sides. Microscopically, their treated surfaces contain many facets. For the emitter fiber, this permits emission of light into the intermediate fluid (water) in which they are immersed, even though the fiber core and cladding both have indices larger than that of water. Similarly, the facets on the collector fiber allow entry of light from water to fiber core.

Because the probe wall is of quartz, which has an index greater than that of water, light is free to enter the wall. The behavior of the light in the probe wall depends on whether the surrounding medium is air or the liquid to be measured. For simplicity, in this description the gas covering the liquid in the flask will be called air, although in actuality it would be an inert gas. Operation of the probe would be the same because the index of any gas likely to be used is near unity.

Fig. 4 indicates the behavior for air and liquid surrounding the probe. In the figure, n1, n2, n3a and n3b are indices of refraction:

-n1: Intermediate material (in this case water).

-n2: Probe wall.

-n3a: Air (or gas) surrounding the probe.

-n3b: Liquid surrounding the probe.

Five rays (A through E) are shown emanating from two points on the emitter fiber, for the two cases of interest: liquid surrounding the probe and air surrounding the probe. In both cases rays pass easily from the faceted emitting surface of the fiber into the intermediate material (water in the probe).

When air surrounds the probe (upper part of drawing), Rays A and B pass through the water and wall to enter the air outside the probe because they strike the wall/air interface at angles below the critical angle. Rays C and D strike the wall/air interface above the critical angle and are reflected back through the wall and water to return to the fibers at the center of the probe. Ray E is above the critical angle for the wall/air interface and also for the wall/water interface, so that it remains trapped inside the wall, which behaves as a waveguide carrying it toward the tip of the probe. The waveguide conditions are satisfied because the index of the quartz wall (approximately 1.46) is higher than that of either the air outside (1.00) or the water inside (1.33). Most of the Ray E light never finds its way back to the fibers but is instead lost at the curved surface at the bottom of the probe (the probe is also designed to "extinguish" rays traveling to its upper end).

The lower part of the figure indicates the behavior of the same set of rays when a liquid surrounds the probe. Rays A and B leave the probe as before, but now Rays C and D also depart because the index of the liquid outside the probe is relatively high. Ray E remains trapped in the probe wall as before. None of these rays return to the fibers at the center; they are either lost to the outer liquid or remain trapped in the wall. Note that this is true regardless of whether the outer liquid is of index higher or lower than that of the quartz wall. If, for instance, the index of the outer liquid is very high, then more rays tend to be refracted out into the liquid. If it is low (lower than that of quartz) then more rays tend to remain in the wall waveguide, trapped by total internal reflection, and to pass out of the probe at the ends. As long as the outer liquid is of index equal to or greater than that of the inner medium (in this case, water), none of the rays in the wall can re-enter the inner water, as they did when air surrounded the probe (Upper part of the figure).

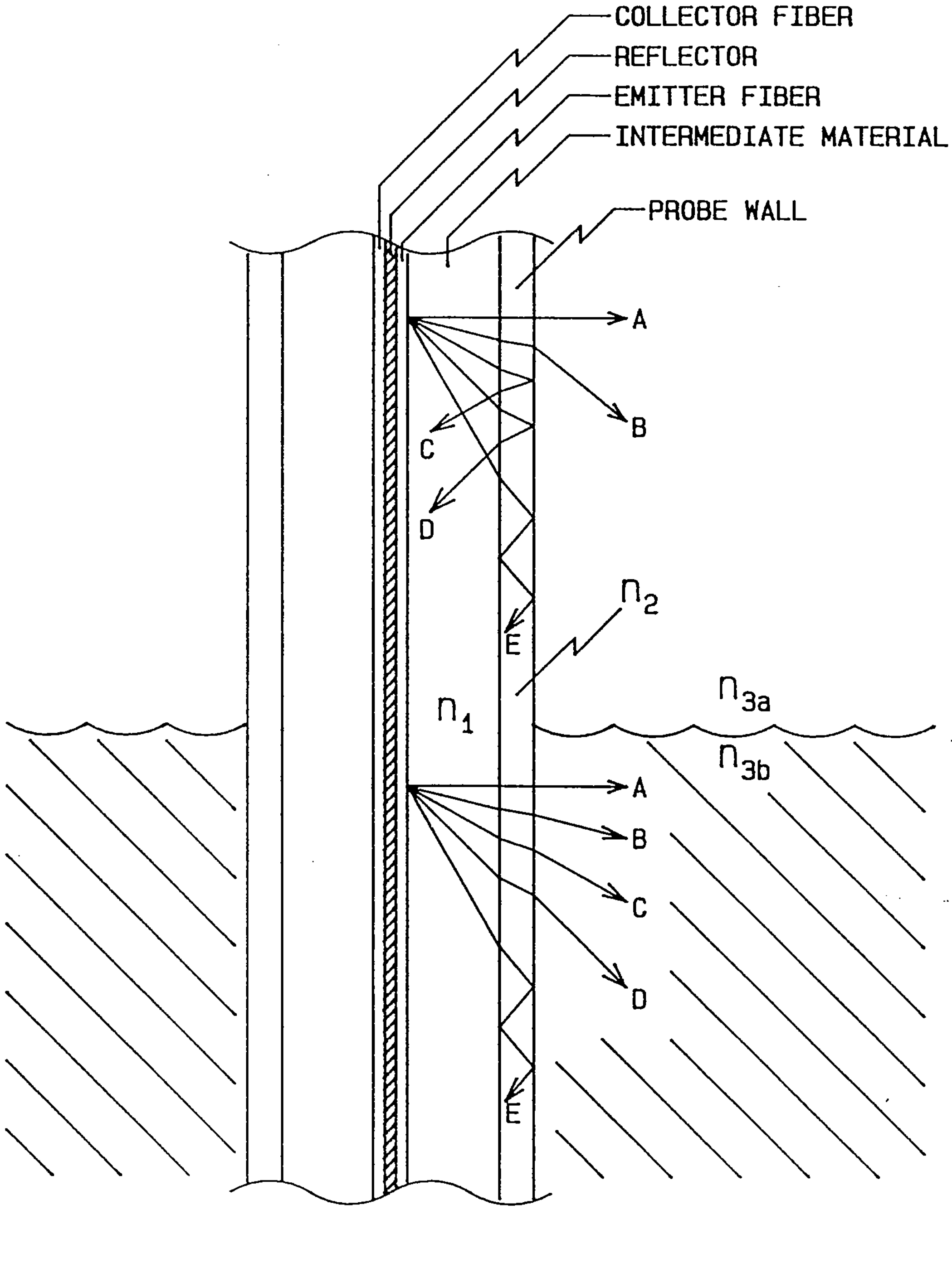


Figure 4: Tracings for five rays. Upper: rays when air surrounds the probe; Lower: rays when liquid surrounds the probe. n_1: index of intermediate material; n_2: index of wall; n_3: index of surrounding medium (a: air; b: liquid).

These qualitative arguments can be expressed mathematically in the following way. The critical angle a_{co} at the outer probe/liquid interface is larger than a_{ci}, the angle at the inner probe/water interface. These two critical angles for light in the wall waveguide are given by:

$$\sin(a_{co})=n_3/n_2 \tag{1}$$

$$\sin(a_{ci})=n_1/n_2 \tag{2}$$

Rays internally reflected from the outer wall/liquid interface at a given angle will strike the inner wall/water interface at the same angle. Therefore, for any wall rays to reach the inner water, they must reflect internally from the outer wall/liquid interface at an angle that is less than the critical angle (a_{ci}) at the inner wall/water interface. This is equivalent to requiring that

$$a_{co} < a_{ci}, \tag{3}$$

or that:

$$\sin(a_{co}) < \sin(a_{ci}), \tag{4}$$

which implies that:

$$n_3/n_2 < n_1/n_2. \tag{5}$$

multiplying through by n_2, we obtain the requirement that

$$n_3 < n_1. \tag{6}$$

However, we have already chosen $n_3 \geq n_1$, so that eq. 6 is never satisfied, and no rays re-enter the water when the liquid is outside the probe.

4. EXPERIMENTAL PROCEDURE

The flask, which has transparent quartz walls, was fitted with a transparent ruler so that the level of the meniscus could be read from the outside. A bucket and siphon were used to fill and empty the flask at a rate slow enough that readings of the liquid level could be taken from the scale and from the LCD display of the fiber optic liquid level sensor at half-inch intervals, before the liquid level changed by more than 0.05 inch (1 percent of full scale, which was 5 inches). Graphs were then prepared showing level sensor reading (from the LCD display) vs. inches measured visually from the ruler, with zero inches corresponding to the tip of the probe. The LCD display is meant to indicate "1.00" for a full flask (5 inches), and "0.00" for an empty flask (level below bottom of probe). Readings above 5 inches are not expected to be accurate, as the probe meets the sloped wall of the top of the flask at 5.5 inches.

During most of the tests, water was used as the liquid surrounding the probe, which itself was completely filled with water. To check performance with a liquid of different index, a saturated sugar-water solution was prepared.

Seven probes (numbered 201 through 207) made by hand in a series, were tested to indicate variations to be expected in production. An eigth probe, number 102, was tested for insensitivity to index of refraction of the liquid in the flask. The same interface box was used with all the probes. For each probe, the gain trimpot was adjusted so that zero scale (empty flask) would read the same. This reading corresponds to the maximum amount of light returning to the collector fiber. Only the gain trimpot was changed to make this adjustment. The offset trimpot remained in the same position for all probes, as virtually all light leaves the system at full scale.

5. RESULTS OF EXPERIMENTS

The response curve of a typical probe (202) is shown in Fig. 5. The straight lines are ±5 percent limits based on a full scale reading of 5 inches.

The most linear (205) of the series of seven probes is shown in Fig. 6.

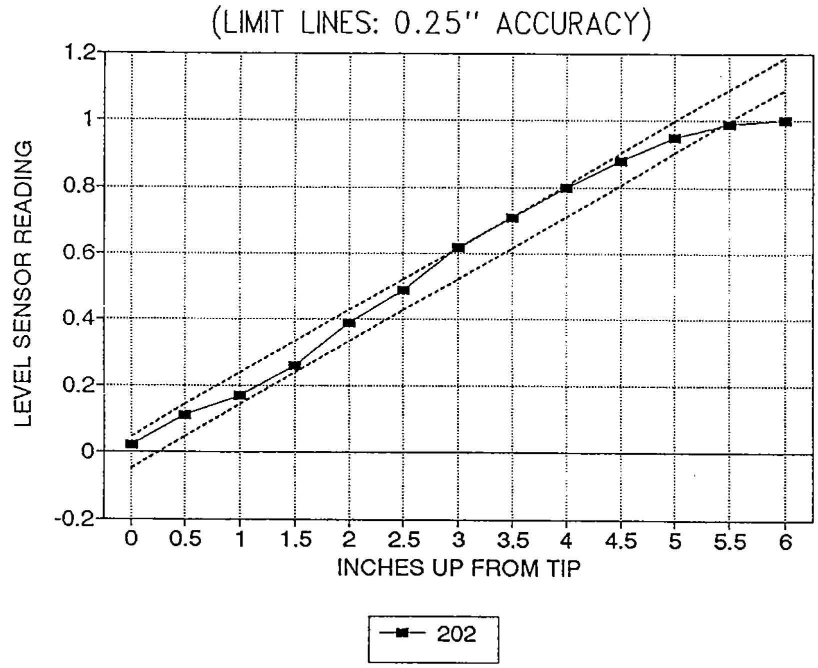


Figure 5: Response of typical probe (number 202). The straight lines indicate limits of ±0.25 inches, or ±5% of full scale (5 inches).

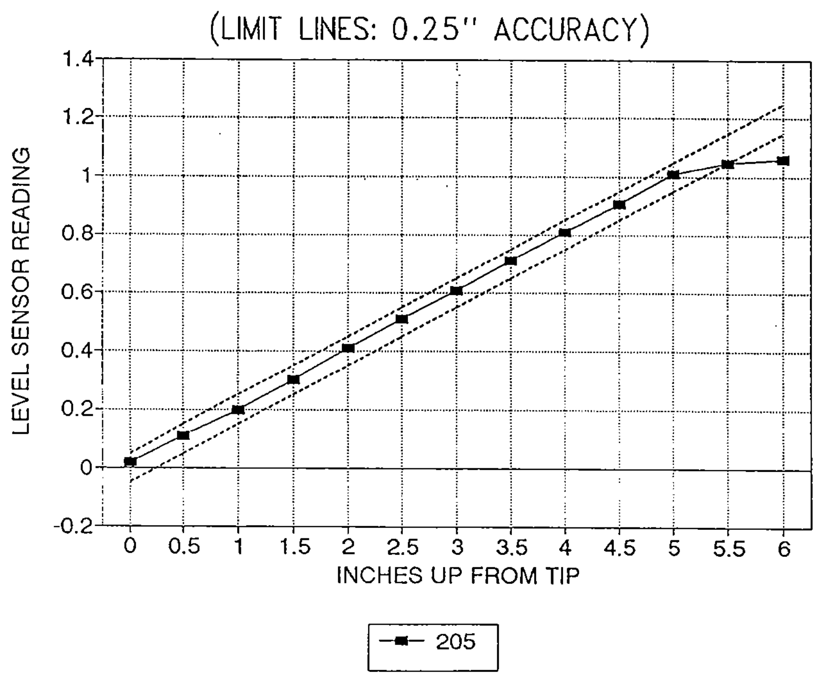


Figure 6: The most linear of a series of seven probes.

All seven probes in the series are shown in Figs. 7 and 8. The slopes of the ±5 percent error lines are slightly different for the two groupings of probes.

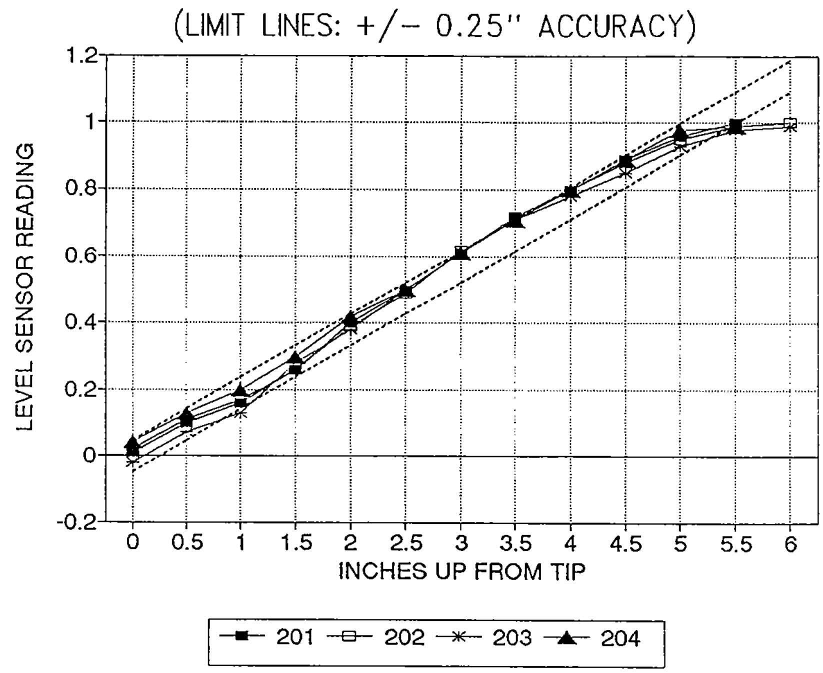


Figure 7: Responses of four probes (201 through 204) plotted together.

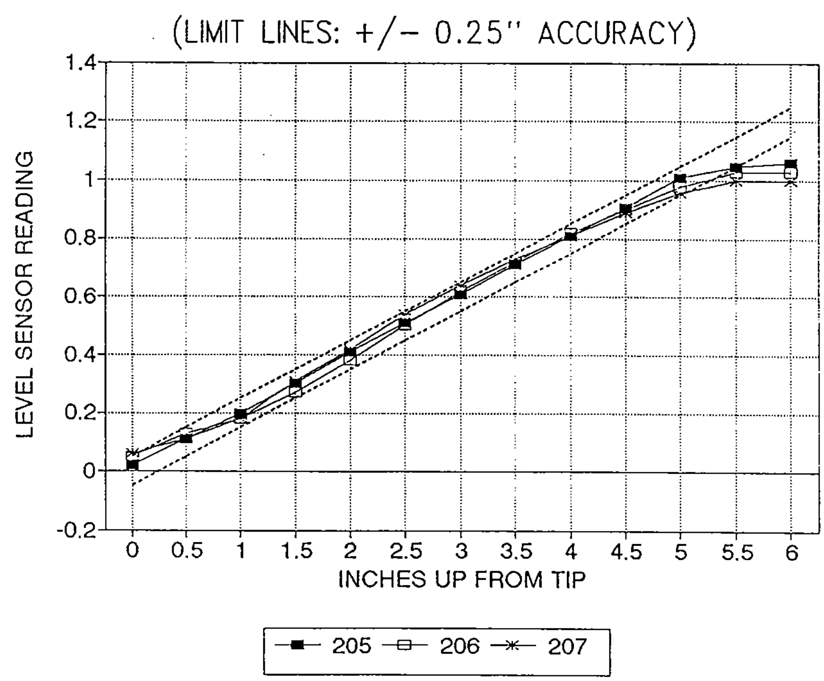


Figure 8: Responses of three more probes (205 through 207) plotted together.

Repeatability of one probe (204) is shown for four separate runs (labelled 204A through 204D) in Fig. 9. The runs were performed as follows:

-204A: Measured for rising liquid.

-204B: Repeat, rising liquid.

-204C: Repeat, falling liquid.

-204D: Measured for rising liquid after removing probe from bubbler, and optical fibers from interface box, then replacing without recalibration.

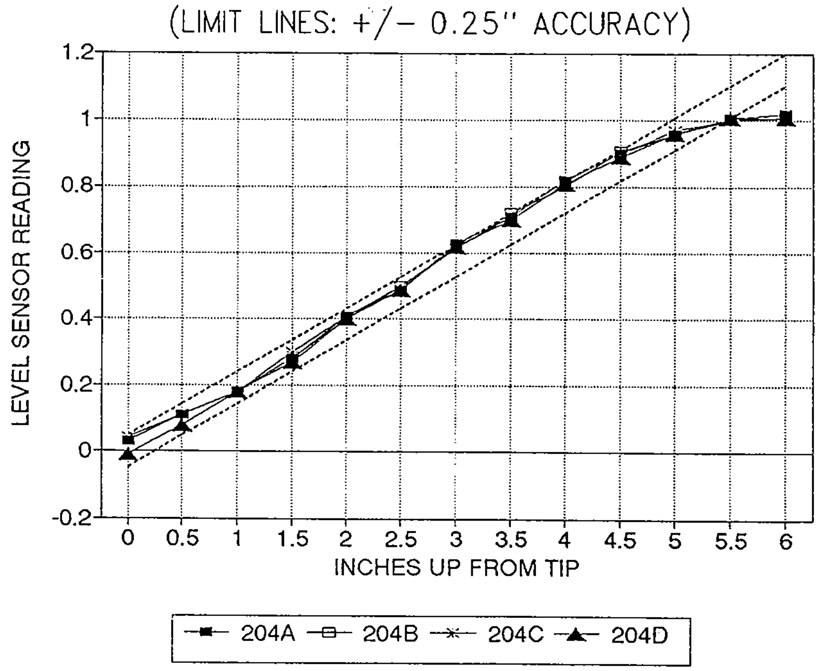


Figure 9: Runs A through D of a single sensor (number 204). See text for run conditions.

A probe was operated for two months continuously. Drift was less than ±2 percent of half-scale reading.

Hysteresis was observed to be less than ± 1.5 percent at half scale, when measurements were made on rising and falling liquids. Variations in sensor output appeared to correlate with variations in the shape of the meniscus where it meets the probe.

Condensation on the outer probe wall causes errors of up to 3 percent (rise in LCD readout at half scale). If the flask is tilted to wash off the condensation, the readings return to normal.

Accuracy is unaffected by reasonable amounts of stray light. A transitory change, followed by a return to normal readings occurs for the following stray light sources:

-A 60 Hz, 75 Watt incandescent lamp with reflector 30 inches from the flask.

-A dual 40 Watt fluorescent fixture with reflector 30 inches from the flask.

Fig. 10 shows the response of probe 102 to a large change in index of refraction. The probe was first tested with water (index 1.33); then with a sugar/water solution of index 1.40.

In another test, probe 102 was immersed to its mid-point in water and then in motor oil (index approximately 1.5). The sensor indication changed by less than 1 percent.

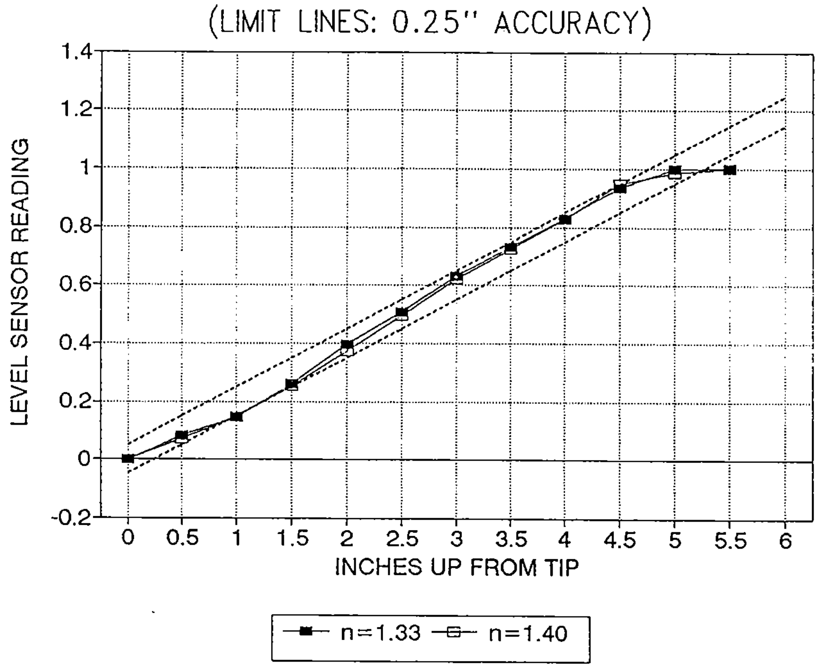


Figure 10: Probe 102 measuring liquids of different indices of refraction: 1.33 and 1.40.

6. DISCUSSION

Departures from linearity are attributable to two different mechanisms. At the low end of the probe (0 to 1 inch) the fibers sometimes are beginning to lose significantly more light per unit length than at the upper end, leading to a relative increase in the level reading (less light in collector = higher reading). At the high end, the departure from linearity is attributable to the geometry of the probe in the flask. Even for probe 205, the most linear probe (see Fig. 6), there is a departure from linearity when liquid covers the upper end of the probe (5.5 and 6 inches). These measurement points correspond to the least amount of light being returned to the collector fiber. The amount of light is near zero above 5 inches (this has been confirmed by measuring the output of the photodetector directly, before offset voltages are applied). The response curves are nonlinear at this end because the probe meets the flask wall at 5.5 inches.

Improved linearity in the intended range of the sensor (0 to 5 inches) could be achieved with automated treatment of the fibers. Probe 205 (Fig. 6) indicates that this is possible. In these experiments, the objective was to achieve ±5 percent linearity over a five-inch range, for which hand construction methods are appropriate.

In the experiments, only the gain trimpot was adjusted for each probe. This was sufficient for all seven probes to meet the ± 5 percent linearity criterion, but the error lines had slightly different slopes for two different groupings of probes. The use of more calibration points or automated manufacture of the probes would probably lead to considerably improved linearity and matching of probes.

Repeatability was very good. The only significant variation occured when the probe was completely disconnected, then reconnected without recalibration (not a recommended procedure). Even then, the only difference was at the two lowest points on the curve (Fig. 9), and was still within the ±5 percent limits.

Although drift was within ±2 percent over a two-month period, greater variation might be expected for very long term measurements due to ageing of the LED. This could be compensated for by controlling the LED luminance to remain constant.

The use of pulsed light and synchronous detection makes the probe very insensitive to stray light.

When the index of refraction of the liquid being measured was changed from 1.33 to 1.40, there was no significant difference in the sensor response at any of the 12 measurement points. In another test at a single point, the output varied by less than 1 percent when the probe was immersed to its mid-point in water and then motor oil (index approximately 1.5). Insensitivity to index is further indicated by the almost total extinction of return light when the probe is covered with liquid (5.5 and 6 inch measurement points). This happens in spite of the fact that the index of the probe wall is higher than that of the surrounding liquid, a condition which would normally be expected to return some light to the collector fiber. These observations confirm the insensitivity of the probe to changes in index of refraction.

7. CONCLUSIONS

A fiber optic liquid level sensor has been described which has reasonable linearity, drift, and repeatability. It is made with inexpensive materials and uses simple circuitry. The sensor has important properties which include:

-The probe walls are smooth, without notches or grooves.

-The probe walls may be made of a wider variety of materials since the wall index does not affect the range of indices that can be measured.

-The liquid to be measured can have virtually any index. The index must be equal to or greater than that of the intermediate material (usually water, of index 1.33).

8. APPLICATIONS

Although the probe described was designed for semiconductor processing, the method used is applicable to other level measurement tasks. Natural candidate applications would include measurement of the level of fuels and lubricants.

Another application would be measurement of the level of cryogenic liquids. These are the only liquids of commercial interest with indices lower than that of water. It should be possible to use the probe to measure the level of liquified gases such as nitrogen or oxygen. This would require that the probe be filled with the same liquid as that being measured.

By application of the method shown here, optical liquid level sensors with different light emission and collection systems could also be improved in terms of reliability and accuracy.

9. REFERENCES

1. Jeans, E.L., "Liquid Level Sensor," U.S. Patent 4,353,252, 1982.

2. Oberhansli, J., Stalder, E., Bulgheroni, W., and Penasa, J., "Optical-Electrical Liquid Probes," U.S. Patent 4,039,845, 1977.

3. Evans, M., Kirkendall, J.H., "Fluid Level Detector and Probe Assembly," U.S. Patent 4,038,650, 1977.

4. Tsunoda, A., "Apparatus for Detecting Oils and the Like," U.S. Patent 4,159,420, 1979.

5. Krohn, D.A., "Intensity Modulated Fiber Optic Sensors Overview," SPIE Vol. 718, Fiber Optic and Laser Sensors IV, pp. 2-11, 1986.

6. Snow, J.W., Colbourne, P.D., Woodside, S.H., and Paton, B.E., "A Continuous Liquid Level Sensor Using Fluorescent Fibre," in Optical Fiber Sensors, Springer Proc. in Physics 44, H.J. Arditty, J.P. Dakin, and R.Th. Kersten, eds., pp. 222-226, Springer-Verlag, Berlin, 1989.

7. Wostl, W.J. and Heintz, J.A., "Liquid Level Detector," U.S. Patent 3,448,616, 1969.

8. Merz, K.M., "Liquid Level Sensing Means," U.S. Patent 4,311,048, 1982.

9. Christensen, D.A., "Method and Apparatus for Optically Measuring Fluid Levels," U.S. Patent 4,745,293, 1988.

10. Danisch, L.A., "Fiber Optic Liquid Level Sensor," U.S. Patent 4,880,971, 1989.

11. Danisch, L.A., Fiber Optic Bending and Position Sensor, U.S. and Canadian Patent applications.

12. Danisch, L.A., "Smart Bone," Final Report for Canadian Space Agency Contract 9F006-1-0006/01-OSC, RPC Report No. ELR/92/22S (General Distribution Volume), 24 pp., June, 1992.

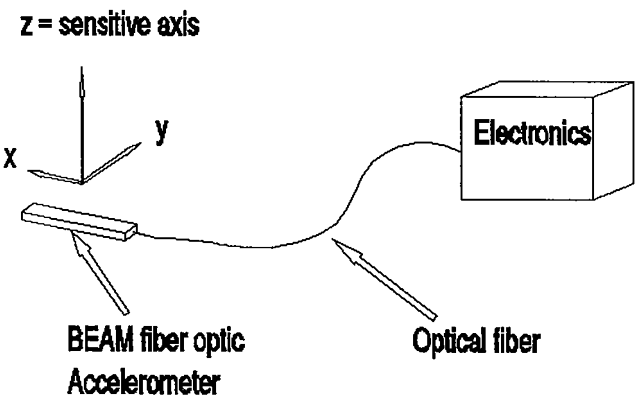
13. Danisch, L.A., "Bend-enhanced Fiber Optic Sensors," also presented at this conference.

Measurand Inc.

PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd., Fredericton, NB, Canada E3B 6Z9]



BEAM© Fiber Optic Accelerometers

Acceleration may be measured by sensing curvature of an optical fiber to which a tiny mass is attached. Normally, this measurement would either be very insensitive or would require expensive interferometric techniques. Measurand has made practical fiber optic accelerometers possible by treating a section of the fiber to be unusually sensitive to curvature. Light loss through the fiber is measured by very simple means, to yield an output voltage which automatically has the linearity, polarity, directionality, and frequency response desired in accelerometers.

BEAM© curvature sensors

Measurand BEAM© curvature sensors make many fiber optic measurements possible, including measurements of acceleration, displacement, force, pressure, and many others. BEAM© curvature sensors are optical fibers that have been treated to sense curvature over a short sensitized zone. BEAM© sensors have properties including:

-Sensitivity: BEAM© sensors can measure curvatures down to 10 microradians per centimeter of treated length.

-Linearity: Output voltage is linear with curvature over angles of up to 150 degrees (per cm of treated length).

-Polarity: Center of linear range is at zero curvature. Polarity of curvature (i.e. "up" vs. "down") corresponds to polarity of output voltage.

-Directionality: Maximally sensitive to curvature for bends in a plane of maximum sensitivity (PMS). Output is zero for bends at right angles to the PMS.

-Small size and flexibility: The sensitized zone may be a few millimeters long; the fiber may be 250 μm in diameter. Plastic fibers may be used.

-Ease of installation: The sensitized zone may be on a tiny loop at the end of the fiber run, so that no reflective structure is required (simplicity) and no light leaves the treated fiber (no degradation of sensitivity over time).

-Low cost: Optical and electronic components for interfacing to the sensor are very simple and low in cost, suitable for mass manufacturing even in the automotive market. Typical instrumentation for a sensor includes no more than one quad operational amplifier, an LED, and photodiodes.

-Durability: BEAM© fiber optic sensors have been tested for more than 200 million flexures without degradation. They are completely enclosed, embeddable structures.

These properties are ideal for making fiber optic accelerometers with frequency response from DC up to approximately 1 kHz.

BEAM© accelerometer characteristics

BEAM© fiber optic accelerometers may be tailored in terms of size, volts/g, damping, and resonant frequency.

Fiber optic accelerometers allow measurement with minimal effects from temperature, freedom from electromagnetic interference at the sensor site, and with great mechanical simplicity. Typical preliminary specifications for BEAM© fiber optic accelerometers include:

-Accelerometer package size 3x7x20 mm.

-Accelerometer package weight less than 3 grams.

-Electronics package size less than 50 $cm.^3$

-Resonant frequency greater than 300 Hz.

-Output voltage of 10 mV per g, 50 g full scale.

-Off-axis sensitivity of less than 3 percent.

-Sensor operating temperature of -55 to +105 deg c without electronic drift.

BEAM© fiber optic technology may be used to measure acceleration:

-With excellent speed, directionality and resolution of acceleration levels.

-With tailoring of damping.

-Without interference from electric and magnetic fields.

-Without being affected by large temperature swings.

-In a small, low-mass package size.

-In flammable and explosive environments.

Measurand Inc.
PO Box 21029
Fredericton
New Brunswick
Canada E3B 7A3
Tel 506 363 4638
Fax 506 363 5173

Sensors

[Shipping/Courier: 921 College Hill Rd.,
Fredericton, NB, Canada E3B 6Z9]

Resumé

LEE ALLEN DANISCH, SM, P. Eng.

President, Measurand Inc.

PROFESSIONAL REGISTRATION

Registered Professional Engineer, Association of Professional engineers of New Brunswick

Member, Institute of Electrical and Electronic Engineers

Member, SPIE-The International Society for Optical Engineering

TECHNICAL EDUCATION

Massachusetts Institute of Technology, Master of Science degree, Electronic Engineering, Cambridge, Massachusetts, 1968.

George Washington University, Bachelor of Science degree, Electrical Engineering, Washington, D.C., 1967.

University of California, Electrical Engineering, Santa Barbara, California, 1962-1963.

HONORS

Sigma Xi Research Honorary, Tau Beta Pi Honorary, Phi eta Sigma Honorary, National Science Foundation Graduate Trainee, G.W.U. Honors Student and Trustees' Scholarships.

EMPLOYMENT

President, Measurand Inc., Fredericton, New Brunswick, May 1993 - present.

Department Head, Electronics, Research and Productivity Council, Fredericton, New Brunswick, April 1988 - February 1994.

Senior Electronic Engineer, Research and Productivity Council, Fredericton, New Brunswick, December 1986 - March 1988.

Vice President, PTL Research Ltd., Oromocto, New Brunswick, November 1985 - December 1986.

Director, PTL Research Ltd., Oromocto, New Brunswick, June 1985 - November 1985.

Manager, PTL Research Ltd., Oromocto, New Brunswick, January 1985 - May 1985.

Project Coordinator, New Product Development, Process Technology Limited, Oromocto, New Brunswick, June 1984 - January 1985.

Engineering Consultant to Process Technology Limited, Oromocto, New Brunswick, March 1984 - June 1984.

Microelectronics Consultant to WMB Manufacturing Limited (microprocessor-based coin handling systems), Sussex, New Brunswick, 1983.

Director, Autonomics, (microprocessor-based systems design, energy management, remote data acquisition, alternate-energy implementation), Sussex, New Brunswick, 1978 -1984.

Engineering Consultant, Boston University Medical Centre, Department of Ophthalmic Biomedical Engineering (electro-optical systems design, biomedical engineering), Boston, Massachusetts, 1978 - 1980.

Senior Biomedical Engineer, Boston university Medical Centre, Department of Ophthalmology (electro-optical systems design, biomedical engineering), Boston, Massachusetts, 1972 - 1973.

Research Engineer, Biosystems Division, Space Sciences Inc., Waltham, Massachusetts, 1969 - 1970.

Instructor, Electrical Engineering and Rural Electrification, University of the Philippines College of Agriculture, 1968 - 1969.

Acoustical Consulting Engineer, Polysonics, Acoustical Engineers, Washington, D.C., 1963 - 1967.

Technician, University Sound, Goleta, California, 1962 - 1963.

EXPERIENCE

Mr. Danisch's background in electronics, biomedical research, and engineering has been applied to a varied array of problems in optics, semiconductor equipment design, plasma physics, flow control systems, chemical processing, robotics, medical research, space engineering, fiber optics, psychophysics, acoustics, power engineering, and electronic control systems. Mr. Danisch's involvement in projects has extended well beyond the confines of electronics to encompass eye research, mechanical design, and production techniques.

MANAGEMENT EXPERTISE

At RPC, Mr. Danisch was responsible for all technical, project management and funding functions for a group of eight engineers and technicians, including management of subcontractors and joint development project activities.

At Process Technology Limited, Mr. Danisch was responsible for all scientific and administrative activity of a staff of 50 scientists, engineers, technicians, and administrative personnel, making up two subsidiary companies of Process Technology Limited. In addition to having hired and trained most of the research staff, he was responsible for setting up computerized management information systems and purchasing systems for PTLR.

PROJECTS

Projects for which Mr. Danisch has had direct responsibility include:

-Development of production processes for fiber optic sensors.

-Development of fiber optic flow sensors.

-Development of patented fiber optic sensors, including bending, position, and liquid level sensors.

-Development of a smart probe including sensing of color, optical and capacitive proximity, texture, bending, presence of liquid, and force.

-Development of tactile and proximity sensors based on capacitance sensing.

-Development of a compliant six degree of freedom force and torque sensor.

-A patented gas-plasma post reaction chamber which removes toxic effluents from a low-pressure chemical deposition system (in production; over 100 systems sold, in over 7 countries).

-A digital control system for semiconductor furnaces.

-A robotic loading system for semiconductor furnaces.

-An automated system for introducing liquid reactants to a semiconductor furnace.

-Design and implementation of a completely automated semiconductor furnace system, involving a multiplicity of robots (prototype demonstrated).

-Design of quartzware for automated semiconductor processing.

-Design and construction of an energy management and data acquisition system.

-Automatic control systems for power-generation equipment.

-Design of commutated-SCR and power-FET load diverters.

-Design and construction of digital pyrometers, charge regulators, and integrating energy meters.

-Computer-controlled optical systems for eye-motion emulation.

-Design, testing, and production of an infrared pupillometer.

-Laser, photographic, and photoelectric studies of ocular circulation.

-In-vivo laser absorption studies in blood using Argon and Helium-Neon lasers.

-Brain research using microsurgical techniques.

-Analysis of control systems for paraplegics.

-Design and construction of automatic focusing systems for fundus cameras.

-Spectrofluorometric analysis of blood.

-Noise and vibration analysis; spectral response, decay times, transmission loss, absorption.

-Design and analysis of vibration-isolation systems.

-Design and analysis of architectural acoustics.

PUBLICATIONS

Danisch, L.A., "Organization of the motor nucleus of the facial nerve in rats," S.M. Thesis, Massachusetts Institute of Technology, June, 1968.

Laing, R.A., Danisch, L.A., and Young, L.R., "Non-invasive multichromatic eye oximeter," NASA CR No. NAS12-2018, October 1969.

Danisch, L.A., "Rapid detection and measurement of lead poisoning by spectrofluorometric analysis of porphyrins in whole blood," Space Sciences, Inc., TR No. SSI-P-598-01, January 1970.

Laing, R.A., Danisch, L.A., and Young, L.R., "The choroidal oximeter: an instrument for measuring oxygen saturation of choroidal blood in vivo," IEEE transactions on Biomedical Engineering, 21 March 1975.

Danisch, L.A., "An objective focusing fundus camera," H.E.W. Final Report, June 1979.

Danisch, L.A., "An optimized small-scale hydroelectric plant," Small-Scale Conservation and Renewable Energy Demonstration Program, Final Report, June 1983.

Danisch, L.A., "A centralized energy control and monitoring system for commercial spaces," Small-Scale Conservation and Renewable Energy Demonstration Program, Final Report, January 1985.

Danisch, L.A., Jenkins, G., Wallingford, E., and Moharir, Y., "A plasma post reaction chamber for removal of toxic and pyrophoric effluents," U.S. patent application, February, 1987.

Danisch, L.A., "Fiber optic liquid level sensor," U.S. Patent 4,880,971, November, 1989.

Danisch, L.A., "Investigation of electro-osmosis and its applications," Canadian Electrical Association 716 U 629, 1989.

Danisch, L.A., "Sensor fusion-other sensors," in Autonomous Robotics, Part A Report, Dynacon Report 28-904/0401, K.A. Carroll, for Canadian Space Agency, Contract No. 02SW.31098-9-2026, pp. 1-19, 34-46, 1989.

Danisch, L.A., "Proportional control system for forced-air electric furnaces," Canadian Electrical Association 649 U 587, January 1990.

Danisch, L.A., Jenkins, G.M., Wallingford, E.E., Moharir, Y.E., "Treatment of Reaction Gases by Radio Frequency Plasma," Canadian Patent 1,282,732; April, 1991.

Danisch, L.A., "Smart bone," Final Report for Canadian Space Agency AC STEAR Contract No. 9F006-1-0006/01-OSC, Vol. 1: General Distribution, 24pp., 1992.

Danisch, L.A., "Smart bone," Final Report for Canadian Space Agency Atlantic Canada STEAR Contract No. 9F006-1-0006/01-OSC, Vol. 2, 79 pp. + appendices, 1992.

Danisch, L.A., "Bend-enhanced fiber optic sensors," SPIE Vol. 1795, Fiber Optic and Laser Sensors X, pp. 204-214, 1992.

Aite, K., DesBrisay, R.B. and Danisch, L.A., "Plasma Enhanced CVD Processing," US Patent 5,225,375, 1993.

Danisch, L.A., "Fiber optic bending and positioning sensor including a light emission surface formed on a portion of a light guide," U.S. Patent 5,321,257, 1994.

St-Laurent, R., Golla, D.F., Danisch, L.A., Carroll, K.A., and Milgram, P., "Tactile and proximity sensors project," Vol. 1: Final Technical Report (Phase I), Dynacon Report 29/290/1002, for Canadian Space Agency, Contract No. 02SW.9F006-2-0413, 319 pp., 1993.

Danisch, L.A., "Smart wrist," Final Report for Canadian Space Agency AC STEAR Contract No. 9F006-2-0010/01-OSC, Vol. 1: General Distribution, 63pp. + Appendices, 1993.

Lovely, D.F., Hudgins, B., Danisch, L., Caldwell, R., Daly, J.A. & Biden, E., "Control of powered prosthetics using bend-enhanced fibre optic sensors," UNB Myoelectric Control Symposium, MEC '93, pp. 93-97, Aug. 1993.

Danisch, L.A. "Fiber optic curvature and displacement sensor," Canadian Patent application, June, 1993.

Danisch, L., Thompson, W., Ele, A., Lovely, D., Hudgins, B., Biden, E., Caldwell, R., Snow, J., MacKay, I, and Aite, K., "Bend enhanced fiber optic sensors in a teleoperation application," SPIE Technical Conference 2070: Fiber Optics and Laser Sensors XI, Optical Tools for Manufacturing and Advanced Automation, Boston, 13 pp., Sept. 7-10, 1993.

Danisch, L.A., and Lee, B., "Technical feasibility study of an optoelectronic drum input system," RPC Report ELR/93/68, Nov. 8, 1993.

Danisch, L.A., Mikaelian, H.M., Key, T., and Walker, S., "Light flicker due to short duration supply voltage fluctuations," Canadian Electrical Association Report 9134 U 861, 100 pp., August, 1994.

Danisch, L.A., "Unitized nerve ending (UNE) project," STACI Contract 9F028-3-1714/01-OSC, 82 pp. + appendices, 1994.

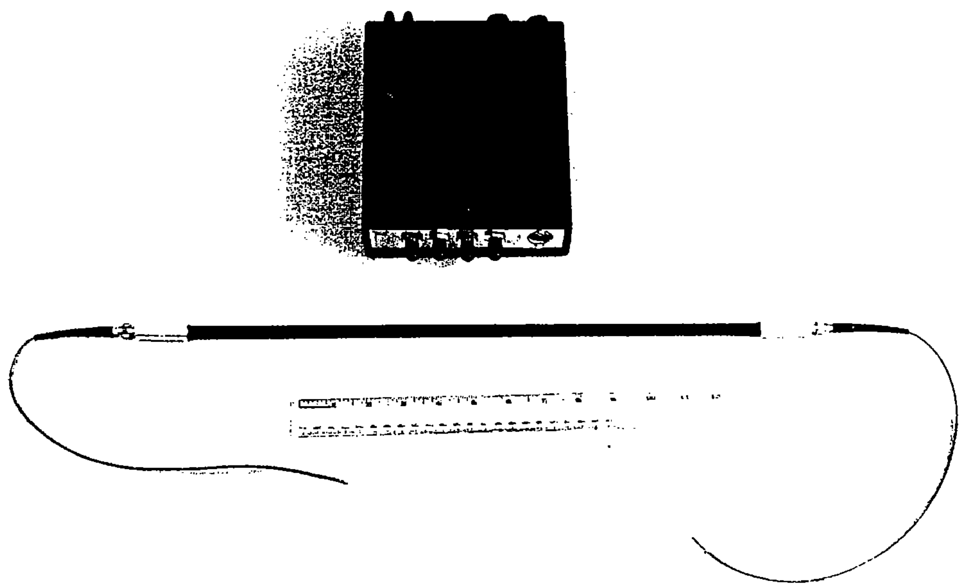
Danisch, L.A., "Fiber optic bending and positioning sensor," PCT/CA94/00314, International PCT application, published 1995.

-Direction of bend: Circularly symmetrical cantilever rods fitted with multiple BEAM© sensors with planes of maximum sensitivity oriented at different angles were used to determine the direction in which the beam was bent, and the amount of bend.

-Embedded in composites: BEAM© fibers have been embedded in pultruded carbon epoxy composites to measure tiny dynamic deflections with a 0.5 kilometer bend radius.

-Vibration: BEAM© sensors embedded in composite rods were used to measure vibrations along the rods. Also, tiny accelerometers (miniature BEAM© sensor with a proof mass) have been demonstrated, sensitive from DC to 500 Hz.

-Flow: BEAM© sensors have been fitted to indicate airflow in HVAC systems.



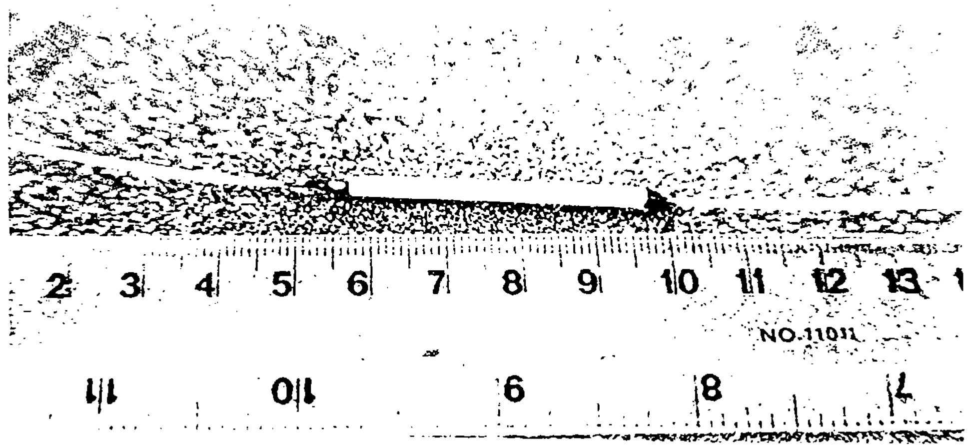
BEAM© sensor mounted in composite rod, with analog processing module used to observe deflections below 20 microradians.

Many other applications are possible, including measurement of:

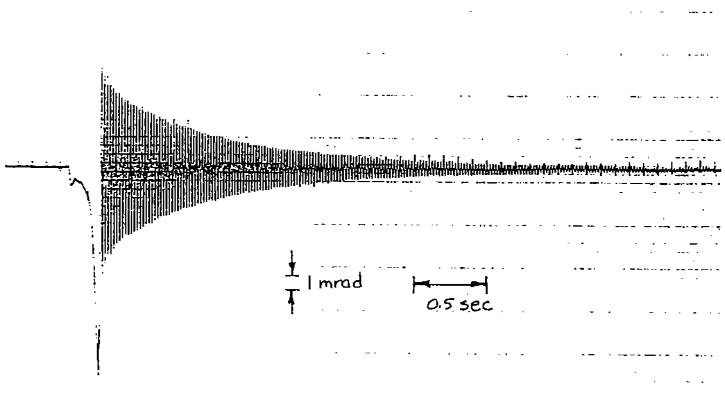
- -Wing flutter.
- -Biomedical measurements.
- -Motion in magnetic fields.
- -Flexure or cracking of concrete bridges, buildings, and dams.
- -Soil movement, including frost heaving.
- -Contact forces.
- -Fluid flow due to flexure of vanes.
- -Aircraft wing flutter.
- -Forces and deflections on or in sports equipment.

Measurand Inc.

PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173



BEAM© sensor mounted in small plastic tube, used to measure vibrations and small deflections.



Typical dynamic response of BEAM© sensor.

The attached papers give more detail on the theory and characteristics of Measurand fiber optic sensors and include bibliographies for further reading.

Measurand Inc.

PO Box 21029 Fredericton, NB, Canada E3B 7A3
Tel 506 363 4638, Fax 506 363 5173