Proximal object and hazard detection for autonomous underwater vehicle with optical fibre sensors


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Received 28 November 2003; received in revised form 28 August 2005; accepted 13 September 2005

Available online 27 October 2005

Abstract

This paper describes short range and tactile optical fibre sensors for marine applications. The sensors are designed for obstacle avoidance on unmanned underwater vehicles (UUVs) operating in confined spaces, but have other possible applications. The fibre sensors augment the sensory abilities derived from ultrasonic and other sensors employed for marine proximity measurement. Of particular interest is proximity detection in the “near” (less than 1 m) and tactile areas. The paper describes the basic principle of operation and alternative sensor configurations. Results are given based on laboratory tests and deployment on a mini autonomous submersible in a test pool.

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Keywords: Autonomous underwater vehicles; Optical fibre sensor; Obstacle avoidance; Behaviour-based control

1. Introduction

In the realm of submersible technology, the autonomous underwater vehicle (AUV) is coming to maturity. Up till now the workhorse for offshore oil and gas operations and marine survey has been the remotely operated vehicle (ROV). In the case of both ROVs and manned submersibles, a human pilot controls the vehicle based on visual information (video and sonar images relayed to surface) and sonar sensor data. A major disadvantage with this technology is cost-of-use due to the requirement for a surface support vessel and human pilot for every mission. Still, ROV technology is used extensively by the offshore oil and gas industry in the inspection and maintenance of sub-sea oil and gas plant such as pipelines and risers. For an AUV an onboard controller interprets sensor input and delivers commands to robot actuators to implement mission objectives. Key to the success and effectiveness of the navigation and control scheme employed by the onboard controller are vehicle sensors. Advances in navigation, guidance, obstacle classification/avoidance, and control of AUVs are necessary before AUVs overtake the ROV as the offshore oil and gas industry’s work-vehicle of choice. However, over the last number of years the number...
of AUVs being used for offshore surveys and other tasks has been increasing at a rapid pace. Currently, AUVs are being deployed for tasks such as sub-sea cable laying [1], naval mine detection and marine science survey work [2–5]. In these reconnaissance and survey scenarios the complexity of the AUV control problem is lessened because the AUV is flown at a distance from the bottom where difficult terrain need not be negotiated, a low degree of manoeuvring (other than mission course) is required, and a fast speed of response to sensor stimuli is not critical. Conversely, for up close intervention work with an AUV the sensor requirements and the control challenge increase considerably because exposure of the vehicle to potential hazards increases significantly. The new era of AUV for up-close and intervention operations requires an adaptation and a re-design of a range of sensors currently used in ROV offshore operations as well as the development of completely new sensors [6]. In the event of deploying AUVs for operation close to hazards or near to the seabed, sensors that can detect in the proximal range from 0.1 to 1 m are a requirement. Vision systems might be thought to be an obvious choice to meet this purpose. However, due to the variability in water turbidity, colour and light levels, developing solutions employing artificial vision is not straightforward [7]. Moreover, any vehicle coming close to the bottom may raise a cloud of sediment in which instance visibility may fall to near zero.

Ultrasonic/acoustic sensor systems have become the system of choice for object detection in the marine environment for UUVs [8] and allow detection of objects far beyond the range of video, even in clear water conditions. Current commercially available ultrasonic systems, however, do not lend themselves to all round coverage of autonomous craft in very close proximity to potential undersea hazards. If an AUV is to be deployed for close up video inspection, the controller must be able to detect objects in all directions from the vehicle to allow vehicle control/manoeuvring without becoming entangled or snagged. The aim of this optical fibre sensor development work is to develop a sensor suitable for the detection of objects within a short (1 to <0.1 m) range in the aquatic environment. A principal objective is to construct a sensor that allows an AUV to detect objects close to it and react accordingly, e.g. by stopping or turning to avoid collision.

2. Background

For most current AUVs, real-world operations are confined to remote hydrographic and scientific survey applications in open uncluttered water. In these scenarios, robots follow predefined transects at hazard free altitudes while detecting the bottom, water surface and other significant objects with long range sonars. A goal of the authors is to extend the operational capabilities of AUVs for intervention work close to hazards and in proximity to sub-sea structures. Investigation, test, and evaluation of suitable control sensors and strategies is being carried out on two submersible robot platforms that have been developed at University of Limerick for this purpose. One vehicle, designed for control experiments in test tanks, is of a small mono hull design (Fig. 1) while the second AUV is a larger multi-thruster open frame vehicle (Fig. 2), designed to operate in the open sea.
The control software for these robots uses a behaviour-based scheme [9] namely, the Subsumption architecture as described in [10]. The scheme employed is similar to that used by other research groups in the field [11,12] and has been described in detail in [13]. The effectiveness of the individual behaviours within the control system and hence the success of the entire control scheme depend on the availability and quality of data from vehicle sensors. A wide range of sensors are currently in use for marine observations on remotely operated vehicles (ROVs), AUVs and on fixed buoys [14]. Commercial off the shelf (COTS) sensors are available for positioning and navigation, scientific observation of seawater properties, seabed mapping and geological survey as well as for underwater communications and intervention [15]. However, advances made in other branches of science and technologies such as optics have yet to be fully exploited in the design of AUV specific sensors. With few exceptions, currently available COTS sensors for AUV control are adaptations of sensor systems designed for deployment on ROVs or instruments designed for bathymetric survey. The dimensions, weight, power consumption, etc. of such sensor systems are not optimal for AUV applications and are often unsuitable for use in close proximity to the sea-bed and other hazards. The principle sensing approaches employed by such UUV COTS sensors are discussed in the following sections.

2.1. Acoustic sensors

Acoustic energy is attenuated in sea water as a function of depth, frequency, temperature, pH, and dissolved salts [16]. Nevertheless, the propagation characteristics of sound in water are greatly superior to those of light or electromagnetic waves generally [17]. Acoustics have thus long been exploited in the design of marine sensors, allowing detection of objects at significantly greater ranges than video systems, even in clear water conditions. Types of sonar system used for obstacle detection and avoidance include:

- Narrow beam echolocation type sensors, which detect objects in only one dimension (range, at the pointing angle of the sonar) and cannot be used to classify an object.
- Fan-beam scanning/imaging sonars that can detect objects only in two dimensions (bearing and range) and are of limited usefulness due to their slow scan rate.
- So-called forward looking sonars (with pencil beam forming) that provide high resolution, fast sector scan rates and can detect objects in three dimensions (range, bearing and altitude) but can cover only a limited sector.
- Bathymetric sonars; side scan and multibeam sounders used by ROV pilots for the purpose of visualising the vehicle surroundings [18].

Lower frequency acoustic waves suffer less attenuation in sea water than higher frequencies, however range resolution for echo sounder and image resolution for imaging sonars are better at higher frequencies. The frequency of single beam sonars depends on the application but they range from 12 kHz for deepwater (long range) models up to 200, 400 and even 700 kHz for shallow water (short range) models [15]. Minimum detection range, for commercially available narrow beam sonars and scanning sonars, is inter-related with frequency of operation and maximum range rating [19]. Beam width also affects sonar maximum range. Lower frequency sonars suffer less absorption and thereby give larger maximum sonar ranges but require longer pulses to increase the instantaneous acoustic power available at reception. This implies they have larger minimum detection ranges also. Typical pulse duration varies between $10^{-4}$ and $10^{-3}$ s [19]. Minimum detection ranges quoted are usually in the range 0.5–1 m.

With ROV operations, the sonar returns from scanning obstacle avoidance sonars are often displayed visually in Plan Position format for interpretation by a human operator. Although such obstacle avoidance sonars give direction as well as distance information, incorporation of these systems into an AUV control system is difficult and significant hardware and software systems integration is required. Obstacle avoidance sonar suppliers do not offer comprehensive ‘turn-key’ solutions for autonomous vehicle control. Certain research groups are using COTS obstacle avoidance systems (OAS) but they have undertaken considerable system development to facilitate integration on a dedicated AUV [20–22]. As a result many AUVs use simple narrow beam sounders such as Altimeters for obstacle avoidance. These are sufficient for survey AUVs flying remote from the seabed where the demands on the OAS are not so great. For torpedo like vehicles the objective
of obstacle avoidance is not to stop the vehicle from hitting objects but rather to ensure the vehicle never enters a circumference which will result in collision [23]. Performing close-quarters inspection/maintenance tasks autonomously, for example, a sub-sea platform or pipeline places significant demands on the OAS of an AUV such as a short-range detection requirement, high resolution and the ability to discriminate separate objects. A number of single beam (higher frequency) echolocation sensors could be integrated for proximal detection for vehicle operation in confined spaces but to guarantee all round coverage a significant number or an array of these devices would be required. To give an AUV $4\pi$ sr of solid angle coverage with $15^\circ$ beam width sonars requires a large number of sonars. The solid angle coverage, $\Omega$, of one sonar is given by:

$$\Omega = \frac{\text{area of cone on surface}}{(\text{sphere radius})^2} = \frac{2\pi R^2}{\int_0^\theta 2\pi R \sin \theta R d\theta} = 2\pi (1 - \cos \theta)$$

For $\theta = 7.5^\circ$ (beam-width/2), $\Omega = 0.0538$ sr. $4\pi$ sr coverage therefore requires 234 sensors. To give an AUV $4\pi$ sr of solid angle coverage using sensors with $45^\circ$ beam width sonars requires 26 sensors. With multiple sensors, cross talk between sensors can be a problem, giving spurious multi-path distances to objects. This is especially so in close-up operation or operation in confined spaces. Potential multi-path errors could be avoided by designing and using higher-frequency ultrasonic devices operating in separate bands, (useful range of ultrasonic sensors falls off with range to the fourth power of frequency). The cost of marine-hardened ultrasonic sensor systems is high so the requirement of many sensors would make for expensive all round obstacle detection.

2.2. Vision systems

Video camera systems are an integral part of most, if not all, ROV platforms. Since these systems are tele-operated, a pilot at the helm controls the vehicle based on the visual image of the robot’s environment provided by its onboard camera. In an AUV context, [24–26] describe the development and use of vision systems for pipeline tracking, station keeping, positioning and motion estimation. However, underlying practical difficulties exist with the use of any vision-based sensor system on an AUV:

- The requirement for a light source is a drawback on an AUV with limited energy.
- The fact that useful range varies depending on the translucency/turbidity of the water.
- Light absorption and the diffraction of longer wavelengths results in underwater images being monochromatic.
- In shallow waters, time of day, depth and tide alter the light gradient of the baseline background image making object classification a challenge.
- clouds of sand/sediment generated accidentally by a vehicle manoeuvre or other motion can render a vision system temporarily ‘blind’ for the duration of the disturbance.

In the absence of a human pilot to interpret sensor data from high-resolution video (or high definition imaging sonar), the control system of the AUV must interpret the data stream from the camera system. This involves image processing for object/hazard recognition and feature extraction. These difficulties mean that camera systems are not a reliable control sensor solution. Backup systems relying on more simple robust sensors are required for vehicle control tasks such as obstacle avoidance, tracking, station keeping, etc. For operation close to hazards (e.g. drilling platforms, risers, sea cages) or in tight confined spaces (caves or wrecks) a “near-touch” sensor is required, which is capable of instantaneous detection of proximal objects within 1 m of the craft. Although some researchers are investigating vision system solutions for near-quarter operation [24–26], reliable ‘ready-to-go’ vision solutions for AUVs are not yet available.

2.3. Proximal object detection sensor requirements

For autonomous craft operating close to hazards (e.g. drilling platforms, risers, sea cages) or in tight confined spaces (caves or wrecks) a “near-touch” sensor is required, which is capable of instantaneous detection of proximal objects within 1 m of the craft. For all round $4\pi$ sr of solid angle vehicle coverage, many sensors would be required, even on small craft, so the sensor cost must be low. Optical fibre sensors can potentially
provide a cost-effective solution and alternative to high frequency ultrasonic devices. Many optical fibre sensors could be used on a single craft without a serious weight burden. The sensors must be immune to the relatively hostile marine environment and again optical fibre sensors readily fulfill this requirement. In terms of military applications an advantage of optical fibre proximity sensors over ultrasonic sensors would be that of stealth.

3. Optical fibre sensor design for proximal object detection

Various configurations of optical fibre extrinsic sensors (fibre used only as a conduit to guide the light), and intrinsic sensors (light propagating through the optical fibre is modulated indirectly by optical path changes within the fibre), have been developed and investigated. Some of these configurations transmit light pulses from the end of the fibre/wave-guide and rely on reflection and back scattering of light energy by the target (extrinsic type), see Fig. 3. In other configurations, the pulsed light is not transmitted into the water but is contained within the fibre. In these configurations, deformation of the wave-guide has a detectable effect on the light within the fibre, (intrinsic type), see Fig. 4.

3.1. Simple open-end whisker configuration

As illustrated in Fig. 3, pulsed light reflected off a target and coupled back into the whisker can be detected. The following fibre optic ‘Whisker’ configurations have been investigated:

(i) A three fibre whiskers with a third fibre used for sensor correction/normalization for ambient light levels—as illustrated in Fig. 5(a).

(ii) A two-fibre whisker sensor with separate transmit and receive fibres—as illustrated in Fig. 5(b).

(iii) A Single transmit/receive fibre whisker sensor with integral coupler/splitter at emitter/receiver end—as illustrated in Fig. 5(c).

The results of these investigations have been reported previously in [27,28].

Of primary interest is the detection of proximal objects, which have relative motion with respect to the submersible. Consider relative motion between the whisker sensor and the target such that they approach each other at constant velocity. As the obstacle approaches the whisker, sensor output varies/increases with falling distance until the whisker bumps. Neglecting backscatter due to water turbidity and light loss in the water (absorption small over short distance), returned light intensity is inversely proportional to...
the fourth power of the sensor-obstacle distance (i.e. $I \propto \text{range}^{-4}$). The actual intensity of returned light coupled back into the fibre depends on many parameters, most of which cannot be controlled a priori. Examples of parameters affecting the intensity include water turbidity, target size, target colour, target surface smoothness, target geometry, etc. The expected returned light intensity for a given target distance cannot therefore be predetermined. Nevertheless, variations in these various parameters will affect the sensor response and will give a family of similar curves of sensor output versus time/distance (Fig. 6). Each of the curves will show a similar discontinuity at the point of contact.

The rate of change of the intensity signal can be used for detection of object proximity as against using intensity alone for detection. Use of rate of change of intensity overcomes one potential problem with the sensor system. Detection would be made independent of the "colour" or absorption and reflection characteristics of the target. If the sensor system relied on intensity alone for range measurement it would give different readings as the submersible approached two different targets made of different material. However, the rate of change of intensity signals for two targets of the same geometry and dimensions but differing "colour" should be independent of target absorption/reflection characteristics. Sensor output would be dependent on the range rate and the size (solid angle of the target) (a family of similar curves).

By differentiating the intensity signal and comparing the differentiator output with a threshold level the sensor system can be set up to give a switched output for a given target distance. Sampling and storing intensity values allows further signal processing to be applied in order to yield additional information about the target, e.g. target velocity relative to the submersible (useful in the instance of moving targets).

At the point where the whisker hits the target, the sensor will exhibit a detectable discontinuity in the intensity versus time signal. This discontinuity provides the opportunity to fabricate a very simple micro-switch type device. This "micro-switch" type device gives a fail-safe sensor output in the event that the more complex signal processed output is not wholly reliable. In this scenario of bump detection, the otherwise smooth intensity curve has a very distinct discontinuity. For example, in a two-fibre whisker (separate transmit and receive fibres), if the sensor fibre ends are cleanly blocked off by the target the received light intensity rapidly falls to near zero. If the surface characteristics of the target are such as not to cleanly block the fibre ends there will nevertheless be a distinct discontinuity in the received intensity signal. These abrupt changes can be used to derive a level change in output signal indicating whisker collision.

Sensor output versus distance beyond the bump point depends on the way the whisker bends while in contact with a target and is thereby not wholly repeatable. The output depends on the direction of motion of the sensor relative to target. It depends on the angle of the fibre to the surface at the point of contact. It also depends on the surface smoothness and whether the fibre skates smoothly across the surface or not.

Various electronic detector circuits have been built and tested to investigate the most reliable characteristics of the output versus distance trace for distance/proximity measurement. The simplest detector circuit detects the discontinuity at the point of whisker contact, while more complex sensors rely on analysis or processing of sensor output.

Whisker length and stiffness can be varied for a given UUV application. A given craft will have a minimum stopping distance and thus whisker length and stiffness will need to be varied to suit. If the fibre whisker is flexible and of sufficient length it should allow the sensor end to collide with obstacles while still allowing the submersible craft time to slow down and come to a halt or safely execute an avoidance manoeuvre. Sensors to the side of the craft, where lateral motion velocities are much less than surge motion velocities, would typically utilise shorter whisker lengths than sensors forward and aft (Fig. 7).
Collision avoidance on the vehicle can comprise of remote object detection (using target reflected/back scattered light) complimented by a collision sensor functionality based on sensor characteristic discontinuity. This complimentary approach to detecting the target allows smooth reaction to obstacles based on remote detection (not wholly reliable) backed up by a failsafe collision detection system.

### 3.2. Loop sensor configuration

In the loop sensor, which is an intrinsic sensor configuration, the light is contained within the fibre and not propagated into the surrounding aquatic environment. This has the distinct advantage of making a loop sensor immune to the parameters of the aquatic environment that affect the whisker sensor described in the previous section. In particular this approach mitigates the effects of unfavourable sensing conditions such as detection in murky or turbid water and poor target absorption/reflection characteristics.

The loop sensor operates in the following manner. A light emitting diode launches a signal into the fibre/waveguide which is transmitted through the fibre loop to a photo-detector located at the receiving end. It is well established that optical fibres suffer radiation losses at bends or curves on their paths due to energy loss in the evanescent field in the cladding along the bend [29].

Such radiation losses are experienced in the fibre loop sensor due to the gross deformation or bending of the fibre when it hits an obstacle in the aquatic environment. The photo-detector is capable of detecting the resulting changes in transmitted light intensity within the core.

In early experiments with simple receiver circuitry, it was found that gross bending (>70°) over short ~5 mm sections of the fibre were necessary for reliable detection. With improved detector circuits the losses due to much smaller bends can be detected. By stiffening or reinforcing the fibre along much of its length, by pre-stressing the fibre to certain bend angles, and by controlling the length of fibre bend zones the sensor can be designed to give the required detectable response over short contact distances. The sensor can also be fabricated by coiling the fibre thus giving many short bend zones (Fig. 8).

### 3.3. Optical fibre selection

It is possible to sub-divide the various types of optical fibre waveguide currently available today into three main groups, by the construction process used to manufacture them. These types are as follows:

- **Silica–silica (all glass fibre)**, where both the optical fibre core and optical fibre cladding are manufactured using silica glass.
Plastic-coated silica fibre (PCS), where the optical fibre core is manufactured from silica glass and the cladding is made from plastic.

All-plastic fibres, where the entire fibre structure (both core and cladding) is made from plastic material; a popular combination being a core of polymethyl methacrylate (PMMA, \( n = 1.495 \)) with a cladding of fluoroalkyl methacrylate (\( n = 1.402 \)).

Taking into consideration the advantages of plastic fibres for this application, including increased flexibility, ease of coupling, lower cost, and the relatively large differences between core and cladding refractive indices (resulting in higher numerical apertures allowing for easier coupling of light into the fibre), it was decided to implement the fibre optic proximity sensor using an all plastic fibre.

Although the basic causes are the same, plastic core fibre has higher losses associated with it when compared to silica core fibres, it is important to note that the lengths of fibre associated with the sensor design are relatively small, and as such, the fibre material related transmission losses associated with the use of plastic fibres are negligible.

4. Optical fibre sensing mechanism

4.1. Back scattering/reflection from aquatic target

The attenuation and the backscatter of light within an oceanic environment, are determined by a number of parameters such as absorption by water and suspended pigments, scattering by molecules and particles, turbulence, and the wavelength of the light being utilised. The absorption as a function of wavelength has been widely reported in literature [30].

Although blue light is absorbed the least, with red light absorbed most strongly, the choice of a 950 nm source in the whisker sensor design is based on the aim to utilise readily available off-the-shelf components and hence develop inexpensive sensor solutions. To compensate for the higher rate of absorption a pulsed operation is implemented and is discussed in detail in Section 5 of this paper.

The attenuation experienced in water per unit distance is proportional to the radiance:

\[
\frac{df}{dx} = -cI
\]

where \( x \) is the distance along the beam, \( c \) is an attenuation coefficient (Fig. 9, Source: [31]), and \( I \) is radiance. Radiance is the power per unit area per solid angle, and describes the energy in a beam of light coming from a particular direction. If the absorption coefficient is constant, the light intensity decreases exponentially with distance for a plane wave front, as stated in the Beer–Lambert law:

\[
I_2 = I_1 \exp(-cx)
\]

where \( I_1 \) is the original radiance or irradiance of light, \( I_2 \) is the radiance or irradiance of light after absorption and \( c \) represents the absorption coefficient.

For \( \lambda = 950 \) nm, the light will be absorbed over a short distance (2.5 cm approximately) from the end of...
the sensor. This implies that the active region for a whisker sensor is within 2.5 cm from the whisker end. As the sensor is to be employed much as a micro-switch is often employed on wheeled robots, 2.5 cm active region is adequate. With light absorption over a short distance the absorption effect is dominant over other effects such as backscatter of light in the water [31].

By using shorter wavelengths in the visible spectrum, resulting in a significantly smaller absorption coefficient, the active range of the whisker sensor could be extended considerably and the effects of backscatter should then also be taken into account, see [32,33].

4.2. Evanescent wave

To provide a general understanding of the evanescent wave in optical fibre waveguides, the evanescent field and its attenuation properties in the cladding are briefly discussed in this subsection. A more detailed treatment can be found in [34,35].

Standard optics theory describes how an incident ray meeting a boundary between media with higher and lower refractive indices at a large enough angle of incidence may be totally reflected—these rays being referred to as bound rays.

However, light is not abruptly reflected when it reaches the core-cladding interface, but penetrates to some extent into the optically rarer cladding. More precisely, the amplitude of the electric field does not drop abruptly to zero at the boundary but has a ‘tail’ that decreases exponentially in the cladding in a direction normal to the interface (boundary). This wave is an evanescent wave and is illustrated in Fig. 10.

This wave propagates along the core-cladding interface, matching the guided wave within the core, while the amplitude decays exponentially in the cladding (y-direction). The exponential decay constant $\alpha$ is the inverse of the penetration depth $\xi$, which is given by

$$\xi^{-1} = \kappa \left( \frac{n_{cl}^2}{n_{co}^2} \cos^2 \theta_1 - 1 \right)^{1/2}$$

from [34,35], where $n_{co}$ and $n_{cl}$ represent the refractive index of the core and cladding respectively, $\theta_1$ represents the angle of incidence the propagating ray of light makes to the core-cladding interface, and $\kappa$ is represented by

$$\kappa = \frac{2\pi n_{co}}{\lambda}$$

where $\lambda$ is the wavelength of the light propagating within the fibre.

It is worth noting that the evanescent wave can penetrate a significant distance into the cladding of an optical fibre, (penetration of the order of a wavelength).

4.3. Bending loss

It is well established that optical fibres suffer radiation losses due to bends or curves on their paths due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding [35]. This occurs when, in order for a wave-front perpendicular to the direction of propagation to be maintained, the part of the mode which is on the outside of the bend is required to travel faster than that on the inside. As it is not possible for the part of the mode in the cladding to travel faster than the velocity of light in that medium, the energy associated with this part of the mode is lost through radiation. This is illustrated diagrammatically in Fig. 11.

5. Sensor experimental test results

Bench tests and experimental tests on a small AUV have been carried out for both extrinsic whisker sensors and intrinsic loop sensors.
5.1. Whisker sensor experiments

The fibre used in these whisker sensor experiments was 1 mm core diameter (2.2 mm sheath outer diameter) plastic optical fibre, which gives the advantages of ruggedness, flexibility, ease of assembly or alignment with fibre transmitters and receivers and inexpensive sensor components. The whisker fibre length used was 300 mm. The light source used in the sensor was the Infion SFH450 infrared surface emitting LED (light emitting diode) with peak wavelength at 950 nm. For reasons of increasing the instantaneous light intensity for the sensor the emitter was pulsed with currents up to 1 A as permitted by the SFH450 with appropriate pulse duty cycle. The detector circuits used an Infion SFH250 PIN photodiode with appropriate buffering and signal amplification.

Various configurations of whisker sensors with one, two and three fibres have been fabricated and tested in the laboratory to date. In some of these experiments, a third fibre was used to increase the amount of target reflected light gathered for detection by the receiver. In other tests, a third fibre was used to enable ambient light level compensation in the receiver circuitry.

The single-fibre whisker requires a coupler/splitter for connection to both the transmitter and the receiver and this coupler/splitter proved a source of significant technical difficulty. With this configuration tested with the whisker approaching normal to a flat surface, the sensor output as expected grew to a maximum value at the collision point. With the target removed or remote, the sensor ‘dark’ output was higher than with other two- and three-fibre configurations. This was due to some emitter light passing directly back to the receiver from the coupler and from reflections at the end of the fibre whisker. See Fig. 12.

The two whisker fibres proved significantly easier to fabricate and did not suffer from the characteristic response variation from sensor to sensor due to the coupler. Sensor output as expected grew as the sensor approached the collision point. However, due to the non-zero diameter of the fibres resulting in the receive fibre being 2.2 mm displaced from the transmit fibre, maximum sensor response occurred some few millimetres away from the collision point. Inside this distance from the target the falling overlap of the transmitted light cone and the cone of acceptance of the receive fibre resulted in sensor response decreasing up to the collision point (see Fig. 12). The response of the sensor was improved by removing the cladding such that the fibre cores could be brought closer together. This results in improved overlap between the transmit cone and the receive fibre cones of acceptance.

A sensor with a second receive fibre (two fibres to increase collection of reflected light) was tested and gave improved response. This points to the possible benefit of using some means such as lenses for gathering more target reflected light into the receive fibre.

In the bench tests with one-, two- and three-fibre whisker sensors, it was found that the two- and three-fibre sensors give a more repeatable response. Of these two sensor types, the three-fibre sensor, gave the better response. To improve the light coupling into the receive fibres, the outer sheath of the three fibres was removed for a 20 mm section at the end of the whisker. This
allowed the three fibres to be brought closer together and resulted in peak sensor response occurring at 2 mm from contact (rather than 4 mm from contact as shown in Fig. 12). The next set of experiments was carried out to investigate the effect on whisker sensor output if the target is moved towards the sensor beyond the contact point. A single-fibre (with integral coupler) whisker sensor was tested. This test is not appropriate for two- and three-fibre sensors as the light coupled into the receive fibres is cut off at the contact point and hence bending loss cannot be measured at the receiver. With a long fibre allowed to bend freely the output variation with move distance was found to be of little use. The whisker was strengthened along most of its length leaving a 40 mm section free to bend and Fig. 13 shows sample sensor output traces versus target distance for some of these laboratory tests. Notice the distinct trace discontinuity at the whisker touch point. With each experiment the output beyond the contact point varied from the last. This was due to the fact that the manner in which the flexible part of the fibre bent was different for each experiment.

5.2. Loop sensor experiments

Loop sensors of various configurations have been tested. Loop sensors, which are intrinsic sensors, only give detectable output after contact. The light source used in the sensor in these experiments was again an Infineon SFH450 infrared surface emitting LED (light emitting diode). The fibre used was 1 mm core diameter plastic optical fibre. Early tests were carried out with a continuously powered LED with 15 V circuit power rails and Fig. 13 shows sample sensor output traces versus target distance for some of these laboratory tests. Notice the distinct trace discontinuity at the whisker touch point. With each experiment the output beyond the contact point varied from the last. This was due to the fact that the manner in which the flexible part of the fibre bent was different for each experiment.

Fig. 13. Sample output vs. target distance traces.

LED at higher instantaneous currents). Subsequently the circuits were altered to 5 V rail circuits to match the available voltages with the input/output stage of the controller of the Minisub used for pool testing of the sensors. The detector circuits used the Infineon SFH250 PIN photodiode with appropriate buffering and signal amplification.

Initial bench tests were carried out with the loop approaching a flat surface target normally or at 90°. For these tests, loops with the same dimensions were used, i.e. fibre length—30 cm with an assembled loop length of 10.5 cm, see Fig. 14.

A single loop sensor was first tested and a sensor output plot for this test is given in Fig. 16. The sensor output voltage reduces as the loop is pushed towards the target due to increased fibre bending. At 5.5 cm from the target the sensor output increases again which might seem unexpected. The reason for this is that at this point the sensor did not continue to deform normal to the surface but rather the sensor loop slid obliquely across the target resulting in overall less acute fibre bending with less energy loss to the evanescent field in the cladding.

As a means of overcoming this oblique slippage and giving repeatable stable bending, tests were carried out with two loops at 90° to each other (see Fig. 14). Test results for two loop sensors are also shown in Fig. 15. Tests were carried out with both loops active (i.e. sensor with two transmitters and two receivers) and with one active/one passive loop (sensor with smaller component count and simpler detector circuitry). The twin active loop sensor gives the most desirable response with a decrease in sensor voltage output from 3 V at 10 cm down to 0.7 V at 2 cm from target collision. For this two loop configuration, with loop length of 10.5 cm, the response becomes unreliable due to repeatability problems relating to how the fibre bends for target distance less than 2 cm.

Fig. 14. Loop sensors 10.5 cm long tested.
Fig. 15 also shows a plot of a double loop experiment (with one active and one passive loop) in which the target surface is at 45° to the sensor axis. This sensor does not give a very good response and is therefore not very effective for detection of oblique surfaces. This is due to the fact that the sensor loops slide over the surface rather than being compressed. For target surfaces at angles between the head on surface and 45° the response varies between the responses plotted in Fig. 15. Reinforcing the fibre using planar reinforcement to restrict the manner in which the fibres bend (see Fig. 16) gives the possibility of improving the response over a range of target surface attitudes to the sensor but detailed tests with this adaptation have yet to be carried out.

The active range at which a target can be detected can be varied for a given active loop dimensions by including a rigid reinforced fibre extension to the loop as shown in Fig. 17. Such sensors were tested with extensions of up to 15 cm. Sensor response characteristics in this scenario depend on the active loop dimensions and are independent of the rigid section length. The semi rigid reinforced section is considerably less flexible than the active loop but never the less should be flexible enough to bend or deflect if the vehicle fails to stop forward motion within the sensor active length.

5.3. Sensor testing on the mini submersible experiments

Separate simple tests were carried out with two-fibre whisker sensors and twin loop sensors mounted on the Minisub AUV (see Fig. 18). The sensor electronics were sealed in potting compound. The tests were carried out in each case with a single sensor mounted on the front of the vehicle. The sensors were interfaced to the onboard Handyboard (Motorolla 68HC11-based) controller.

In the case of the whisker sensor, two simple obstacle avoidance behaviours were programmed. The first
was set up as a simple “Threshold level” behaviour, which was set to trigger at approximately 15 mm from whisker contact by static trial and error tests. In the event that this collision avoidance behaviour failed to stop the craft before whisker contact a second behaviour was programmed to monitor sensor output for the collision point trace discontinuity. In order to be able to visibly distinguish the activation of these two collision avoidance behaviours, the angle to which the rudder control surface was driven differed for the threshold triggered and the contact point triggered behaviour. At all but the lowest of speeds the second contact point behaviour was triggered in these pool tests. So, in effect, the sensor was acting as a physical deflector or bumper as well as a sensor. With the intention of the fibre acting as a bumper, sensor stiffness could be varied to give stiffness appropriate for a given craft travelling at a certain velocity in the event the vehicle thruster control is unable to guarantee non-collision of the vehicle/whisker. Stiffening the fibre sufficiently to act as a bumper, though, can effect the sensitivity of the device, so an alternative is to include a separate ‘bumper’ structure with a less stiff more sensitive sensor. This is in effect what the sensor with a stiffened fibre section is.

In the case of the loop sensor, a simple threshold level was set corresponding to a 10% drop in sensor output (due to loop bend losses). Whenever the sensor output dropped below this threshold a simple obstacle avoidance behaviour was activated within the vehicle behaviour-based control and the vehicle was programmed to reverse thrust and drive the rudder control surface over in this behaviour.

While these tests are in some senses contrived, in that they only protect the vehicle from obstacles dead ahead, they prove that the sensors worked on the vehicle and that the vehicle can reliably initiate a programmed response on obstacle detection. All round obstacle avoidance requires multiple fibre sensors and significant work in tuning the sensor length, stiffness and control behaviour response for these multiple sensors. Depending on which sensor is activated the vehicle would variously, turn, pitch, slow down, or reverse thrust and drive rudder and elevator control surfaces, etc., to avoid collision.

More complex sensor configurations employing advanced signal processing techniques are yet to be tested. With further sensor development it is expected that the useful detection range of the whisker sensor before contact can be extended, possibly through a combination of increasing pulsed light intensity, improved reflected light gathering and more sensitive detection circuitry and signal processing.

The whisker and loop sensors have not undergone accelerated life testing nor have they been tested to failure. Definitive statements about the sensor reliability can therefore not be made at this point. The extrinsic whisker sensor is potentially prone to end fouling which will affect sensor response over time. With cleaning, the sensor response can be maintained. The intrinsic or loop type sensor should be less susceptible to changes in response over time, e.g. due to fouling, as the active sensor is protected by the fibre sheath. Repeated bending of sensors may lead to degradation over time. As the sensors are fabricated from low cost components they may be considered as consumable items, which are regularly replaced.

6. Conclusions and future work

Optical fibre proximal object and hazard detection sensors have been fabricated and tested with good results for marine submersible vehicles. These sensors complement the array of marine sensors which can be utilised on submersible vehicles for the purpose of sensing the aquatic surroundings and enabling deployment/operation of marine unmanned underwater vehicles (both AUVs and ROVs). In particular the optical fibre sensors give good response sensitivity to proximal objects at ranges below the minimum operating range of commonly available commercial marine sensors. The optical fibre sensors are also significantly smaller and lighter than marinised and depth rated sonars. The sensors will therefore enable the operation and control of AUVs close to potential marine hazards and in cluttered and confined spaces where other sensor systems fail. The sensors are cheap. Being fabricated from plastic optical fibre material with the simple electronics protected in potting compound, the sensors should be rugged and reliable. They should give some distinct advantages over sonar sensors. They are not limited in terms of minimum range, or the number, which can be employed in an array, as are sonar sensors. Sensor cost will allow many to be deployed on a single craft and allow the
sensors to be considered as consumable items which can be regularly replaced as needed. Sensor cross-talk problems associated with using multiple ultrasonic sensors are not a problem with the optical fibre sensors.

Various configurations of both extrinsic and intrinsic sensors have been fabricated and tested with variations such as: reinforced segments; whisker extensions allowing active zone distance from craft to be varied; one-, two- and three-fibre whisker sensors; sensors with continuous light; sensors with higher instantaneous pulsed light levels; single and twin loop sensors; twin loops with 1 and two active loops; whisker sensors with an extra fibre for ambient light compensation. While testing explored some combinations of these sensor variations, significant type testing has not been carried out to date to allow full evaluation of all combinations of these various options.

Both extrinsic/whisker and intrinsic/loop sensors have been tested and each type has advantages and disadvantages when compared to the other. In the extrinsic whisker, light is transmitted from the sensor end, reflected and received back through the receive fibre at a detector. Problems relating to response can occur with whisker end fouling and chipping or wear due to repeated contact. This fouling and wear and tear problem could be accommodated by the including a suitably sealed and marinised fibre connector allowing the easy replacement of the plastic fibre.

The extrinsic sensor has the advantage of providing target information both before and after contact. Before contact and with appropriate signal processing information such as the relative speed of the target with reference to the craft can be elucidated. A simpler alternative is to set a threshold response level. In any event, the sensor output discontinuity or peak at the contact point allows a very simple programmed sensor response to be guaranteed.

One potential hazard in employing the intrinsic loop sensor is that the loop may snag in the underwater environment. Loop sensors have the advantage of simplicity. Intrinsic sensors have an advantage over the extrinsic whisker form as the light is contained within the sensor and thus sensor response is independent of aquatic conditions such as ambient light level, turbidity and surface and colour characteristics of targets. Sensor end fouling, chipping, wear and tear and other problems relating to the sub-aqua environment are avoided with the intrinsic sensor, which can be protected with protective covering material.

Both types of sensor have been tested on a mini submersible and integrated into its control system with good results. These tests allowed the vehicle to successfully and reliably detect obstacles such as the pool sides. The test vehicle, however, was equipped with a single forward sensor for the purpose of testing appropriate sensor response and behaviour-based controller reaction. To guarantee ability to detect proximal objects all round the vehicle requires a network of the optical fibre sensors with the appropriate programmed behaviour response to the various sensor stimuli.

References

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