# Whisker Sensors Enable Mini AUV Deployment Near Hazards

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*Abstract:* - The design and development of low cost short range and tactile optical fibre sensors for deployment on autonomous underwater vehicles (AUV) in close proximity to marine hazards is described. These sensors enable the operation of AUVs in confined spaces and close to hazards such as the seabed, sea walls, under overhangs, near sea platforms, etc. The paper also reports on the operation of a mini AUV with these sensors in a test pool. The fibre sensors augment the sensory abilities derived from ultrasonic and other sensors. Of particular interest is proximity detection in the "near" (less than 1m) and tactile areas.

*Key-Words:* - Autonomous Underwater Vehicles, Obstacle Avoidance, Marine Optical Fibre Sensors.

## 1 Introduction

The workhorse of sub sea operations for off shore oil and gas and marine survey, up till now has been the remotely operated vehicle (ROV). In ROV operations a human pilot controls the vehicle based on visual information (video relayed to surface for ROV), sonar sensor data along with data from other instruments. Recently the Autonomous Underwater Vehicle (AUV) is coming to commercial maturity, [1]. In the instance of AUVs, an onboard computer controller is responsible for autonomous detection of the vehicle's surrounding environment and must be capable of reacting to the environment appropriately based on sensor input. Reliability of sensor data is all the more important in the absence of a human pilot or operator's ability to react to the unpredicted circumstance. The AUV requires sensors that are capable of detecting objects and obstacles / potential hazards, both at close range and remotely. Vision systems might be thought to be an obvious choice. Due to the variability in water light levels, turbidity, colour, etc., solutions employing artificial vision are difficulty to reliably integrate [2].

Ultrasonic sensor systems have become the system of choice for object detection in the marine environment and they allow detection of objects at significantly greater ranges than video systems, even in clear water conditions. Many AUVs applications use obstacle avoidance sonars and also involve remote sensing pay-load sensor systems such as multibeam, side-scan or sub bottom profiling sonars, etc. In such scenarios the vehicle is flown remote from the bottom and other obstacles. Ultrasonic systems, however, do not lend themselves to all round coverage of autonomous craft in very close proximity to potential undersea hazards. The commercial obstacle avoidance systems used allow scanning of a quadrant or sector to the front of the vehicle. If the AUV is deployed for close up video inspection [3] the controller must be able to detect objects in all directions from the vehicle to allow vehicle control/maneuvering without becoming entangled or snagged. The aim of this work is the development of sensors for the detection of objects within a short (down to 0.1m or less) range in the aquatic environment. A further aim is the testing of AUV deployment with such sensors in close proximity to potential hazards.

## 2 Background

The authors set out to successfully and safely deploy AUVs in close proximity to marine objects for purposes such as filming and inspection, operations commonly carried out by ROVs.

Ultrasonic sensors are commonly used as marine sensors for submersibles and boats for the detection of the seabed and other obstacles and targets such as shoals of fish [4]. There are various classes or types of ultrasonic sensors used in marine robotics including side scan sonar, multi-beam, simple narrow beam echolocation (e.g. altimiter sonars), etc. With the basic echolocation type sensors distance is calculated based on the time delay to reception of reflected ultrasonic pulse. Commercially available marinised ultrasonic sensors are however not useful for detection / resolution of close up objects. Typically quoted minimum detection range for altimeter sonars for example is of the order of 1m (receiver must be blanked or switched off during pulse transmission). Designs for sensors operating at higher frequencies and with narrower 'on' pulse times would allow shorter-range detection. Multiple echolocation sensors could be integrated for proximal detection for vehicle operation in confined spaces but to guarantee all round coverage a significant number or array of these devices would be required. In this scenario cross talk between sensors can be a problem giving incorrect distance measurements. Spurious multi-path distances can result and this is especially so in close up operation or operation in confined spaces. The cost of marine hardened ultrasonic sensor systems is also high. The requirement of many sensors would make for expensive all round obstacle detection.

To enable autonomous craft to operate close to hazards (e.g. drilling platforms, risers, sea cages) or in tight confined spaces (caves or wrecks) development of "near-touch" sensors, which are capable of instantaneous detection of proximal objects within 1m of the craft, is required. The craft can then be given all round coverage with an array of these sensors. With the aim of giving autonomous submersible craft $4\pi$ steradians of solid angle coverage, many sensors are required, even on small craft, so the sensor cost must be low. Optical fibre sensors can provide a cost-effective solution. Many can be used on a craft without a serious weight burden and they are also immune to the relatively hostile marine environment.

## 3 Mini AUV for Testing

Testing of AUV deployment close to obstacles and the testing of proximal object detection sensors has been carried out in a 4.5m depth test pool on a mini AUV (see Fig 1.) developed at UL [5].

The single hull mini AUV has been constructed by adapting a radio controlled (RC) model submarine. The RC model used is a Delta Submarine Model (ModellUbootSpezialitäten, email@modelluboot.de, http://modelluboot.de/). Although this craft can never truly be sea hardened and is not capable of carrying anything but miniature payloads it allows testing of sensors and of AUV control.

The hull is made from polystyrene and polyurethane (resin) parts. A 12V 2Ah lead acid gel battery powers the miniature AUV and control electronics. The crafts weight has been adjusted to give slightly positive buoyancy, which can be varied at any time by the ballast system to make the AUV neutrally or negatively buoyant. Propulsion is derived from a single motor driven propeller. Maneuverability of the craft is achieved by means of a servo motor driven rear rudder and a front mounted dive plane.

The mini AUV can be controlled manually by radio control for launch and retrieval and one radio channel has been set aside to enable switching over to the on-board autonomous controller.

Fig. 1 Mini AUV during testing

The mini AUV onboard autonomous controller is provided by a Motorolla 68HC11-based micro-controller board with outputs for four DC motors, 7 analogue inputs and 9 digital inputs. The system incorporates an expansion board providing a further 12 general-purpose analogue inputs, and 8 digital inputs but most importantly the expansion board provides outputs for 6 servomotors.

The approach employed in the control of the developed craft is 'behaviour-based', or 'subsumption' control [6]. This approach equips autonomous robot vehicles with the intelligence needed to allow them to survive when their operating environments change in ways that cannot be predicted in detail, a priori, by the programmer.

In behaviour based architectures a number of behaviours run concurrently. These behaviours can send commands to the actuators simultaneously. To prevent conflicts from occurring, an arbitration function must be implemented. The task of the arbitration function is to select a particular behavioural response from the multitude of possibilities. In subsumption a fixed priority arbitration scheme is used whereby behaviours are layered in a hierarchy according to their relative importance. The output from each of the behaviours is monitored continuously and the arbitration routine decides which behaviour should be active at any given time and there by have control of the actuators. Behaviours critical to the crafts survival such as obstacle avoidance are given highest priority and can subsume control from navigational behaviours or path following behaviours. Experimental work on behaviour based control has been carried out [7,8]. The proximal object detection sensors described in the following sections are used to trigger various obstacle avoidance and maneuvering behaviours.

# 4 Ultrasonic Sensors

Marine acoustic / ultrasonic devices are used for many purposes including navigation, military applications, fishery, physical oceanography, mapping and geology as well as for underwater communications and intervention [4]. Different devices and sensors operate over wide power / intensity ranges, significantly different frequency ranges (few hundred hertz up to kHz and MHz ranges) and utilize a wide range of principals of operation. Acoustic sensors deployed on unmanned underwater vehicles for sensing the surroundings for control would typically include; obstacle avoidance sonars (mechanically rotating or electronically scanning), simple narrow beam echolocation (for depth, height off bottom and for obstacle detection), Doppler velocity logs and positioning /navigation sonar systems (long base line, short base line and ultra short base line systems) etc. For the purpose of visualising the vehicle surroundings ROV pilots would also use side scan and multibeam sounders.

Obstacle detection and avoidance uses narrow beam echolocation type sensors or scanning sensors, which scan over an angular sector. In both cases distance is calculated based on the time delay to reception of reflected ultrasonic pulse. Scanning sensors give direction as well as distance information. Commercially available obstacle avoidance sonars typically detect obstacles at ranges up to hundreds of meters from the vehicle. Commercial available examples include systems from companies such as; Tritech, Seaking, etc. These commercially available marinised obstacle detection sensors are however not useful for detection / resolution of close up objects. Typical minimum detection range for narrow beam sonars and scanning obstacle avoidance sonars is of the order of 1m or in some czses down to 0.5 m.

Separate echolocation sensors could be integrated for proximal detection for vehicle operation in confined spaces but to guarantee all round coverage a significant number or array of these devices would be required. Cross talk between sensors can also be a problem, giving spurious multi-path distances to objects and this is especially so in close up operation or operation in confined spaces. Potential multipath errors could be avoided by designing and using higher frequency ultrasonic devices (since useful range of ultrasonic sensors falls off with range to the forth power of frequency) The cost of marine hardened ultrasonic sensor systems is high. The requirement of many sensors would make for expensive all round obstacle detection.

Commercially available marine narrow beam echo sensors which are designed to give distance readings from 1m to 100m + are of necessity of a size which makes them unsuitable for deployment on the mini AUV used in this work. Sensors designed to operate for close up object detection with out range requirements of 100m would be of lower power rating and much smaller devices but as stated such devices are not readily commercially available as marine hardened sensors.

# 5 Optical Fibre Sensors

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.

Various configurations of both fibre optic extrinsic (where the fibre is used only as a conduit to guide the light), and intrinsic (where the light propagating through the optical fibre is modulated indirectly by optical path-length changes within the fibre), sensors have been built and tested. The extrinsic configurations transmit light pulses from the end of the fibre/wave-guide and rely on reflection and scattering of light energy by the target, see fig. 3. In other loop configurations the pulsed light is contained within the fibre and deformation of the wave-guide has a detectable effect on the light pulses within the fibre, see fig. 3 (intrinsic type). The fibre used in these whisker sensor experiments is 1mm 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 light source used in the sensors is the Infinion SFH450 infrared surface emitting LED (light emitting diode) with peak wavelength at 950nm. In some sensor configurations for reasons of increasing the instantaneous light intensity, the emitter is pulsed with currents up to 1 Amp as permitted by the SFH450 with appropriate pulse duty cycle. The detector circuits use an Infinion SFH250 PIN photodiode with appropriate buffering and signal amplification.

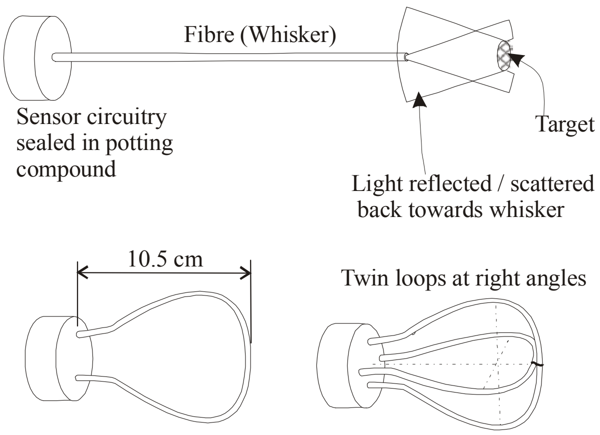


Fig. 3. Whisker and loop sensor

## 5.1 Open End Whisker

As illustrated in fig. 3, pulsed light reflected off a target and coupled back into the whisker can be detected. Various configurations of such a "whisker" were experimented with; (a) whisker with separate transmit and receive fibres, (b) three fibre whisker with third fibre used for sensor correction/normalization for ambient light levels, (c) single transmit/receive fibre with integral coupler/splitter at emitter/ receiver end. The results of this experimental work have been reported in [9,10] and fig. 4 shows sample sensor output versus distance traces for the single fibre configuration.

The primary interest is in detecting proximal objects with relative motion with respect to the submersible. Consider relative motion between the sensor and the target such that they approach each other at constant velocity. As the obstacle approaches, the sensor output varies or increases with falling distance until the whisker impacts.

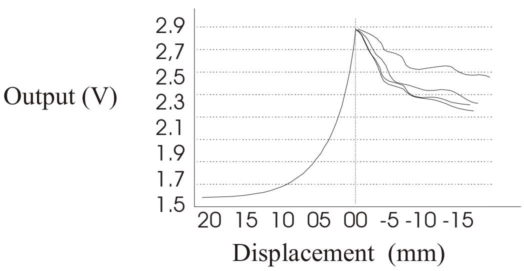


Fig. 4. Whisker sensor output versus distance.

The intensity of returned light coupled back into the fibre depends on many parameters, most of which cannot be controlled a priori. Examples of such parameters include water turbidity, target colour, target surface smoothness and geometry, etc. The expected returned light intensity for a given target distance cannot therefore be predetermined. Nevertheless variations in these various parameters give a family of similar curves of sensor output versus time/distance. Each of the curves will show a similar discontinuity at the point of contact.

Rate of change of the intensity signal can be used for detection of object proximity rather than using intensity alone. Use of rate of change of intensity overcomes one potential problem with the sensor system. Detection is made less dependent on the "colour" (i.e., absorption and reflection characteristics) of the target. A sensor system relying on intensity alone for range measurement would give different readings as the submersible approached two different targets made of different material. The rate of change of intensity signal, however is largely independent of the absorption/ reflection characteristics of the target (a family of similar curves).

Differentiating the intensity signal and comparing the differentiator output with some threshold level allows the sensor system to be set up to give a switched output for a given target distance. Sampling and storing the intensity signal allows further more complex signal processing possibilities potentially yielding extra 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 exhibits a distinct discontinuity in the intensity versus time signal. This discontinuity enables the fabrication of 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.

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.

Whisker length and stiffness can be varied for a given AUV application. A given craft will have a minimum stopping distance and thus whisker length and stiffness need to be varied to suit a particular craft. If the fibre whisker is flexible and of sufficient length it allows the sensor end to bump off obstacles while still allowing the submersible craft time to slow down and come to a halt safely. Sensors to the side of the craft, where lateral velocities are much less than forward and reverse motion velocity, would typically be much shorter than sensors forward and aft (see fig 5).

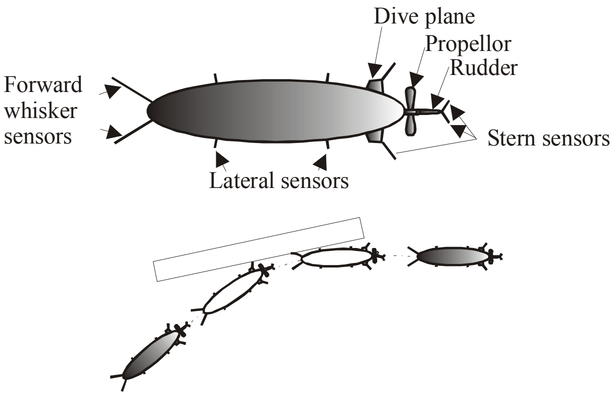


Fig. 5 AUV detecting and turning from an obstacle

## 5.2 Loop sensor configuration

In the loop sensor configuration the pulsed 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.

The loop sensor operates in the following manner. Light from a light-emitting-diode is transmitted from the launch end of the fibre/wave-guide loop to a photo-detector located at the receiving end. It is well established that optical fibres suffer radiation losses due to bends or curves on their paths due to energy in the evanescent field at the bend exceeding the velocity of light in the cladding [11]. Such radiation losses are experienced in the fibre loop sensor due to the deformation or bending of the fibre when it hits an obstacle in the aquatic environment and further the losses increase as the loop deformation increases. The photo-detector is capable of detecting the resulting changes in transmitted light intensity within the core. Fig. 6 shows sensor output versus distance for a loop sensor with two active fibre loops at 90˚.

By stiffening or reinforcing the fibre along most 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 active bend zones.

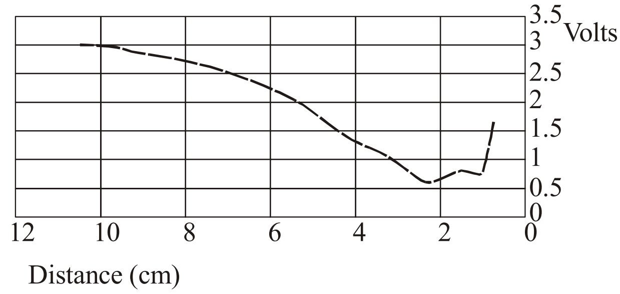


Fig. 6 Loop sensor output versus distance

## 5.3 Sensor testing on mini AUV

Separate simple tests were carried out with whisker sensors and twin loop sensors (see fig. 6) mounted on the mini sub AUV. 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 mini AUV onboard controller.

In the case of the whisker sensor two simple obstacle avoidance behaviours were programmed. The first was set up as a simple level threshold 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.

Fig. 6. Mini sub pool testing with loop sensor

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 control and the vehicle was programmed to reverse thrust and drive the rudder control surface over.

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

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.

## 6 Conclusions

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 within the minimum operating range of commonly available commercial marine sensors. The sensors will therefore enable the operation and control of vehicles close to potential marine hazards and in cluttered and confined spaces where other sensor systems fail. The sensors are cheap, rugged and reliable. 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 sensor cross-talk problems associated with using multiple ultrasonic sensors are much less of a problem.

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