

## Recent advancement in sensor technology for underwater applications

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Underwater environment is the new frontier for major future discovery for the benefits of the world at large. The vastness of the oceans mirrored the vast potentials that lie beneath it. In order for scientist and researchers to explore these vast resources, newer and better sensing technology is pertinent. Of course, any sensor module would not be of any use if there are no reliable platforms to take them to the bottom of the oceans or any water column. Currently, there are underwater robotic platforms that can navigate down to more than 6000 meters. But, there are limitations which need to be addressed. In general, the advancement of sensing technology has always preceded most, if not all, major discoveries in the field of science and technology. The efforts into developing sensors must take into consideration the inherent environmental limitations for underwater applications such as the corrosive nature of sea-water, bio-fouling, limited energy resource module, pressure resistant enclosure, data transfer reliability and the dynamic nature of the ocean itself. The research into producing acceptable sensor system/modules will require close international collaborations. The whole range of potential measurement and sensing requirements also may disrupt the proper development of a robust and reliable sensing system/module. Underwater sensor technology can be divided into the acoustic or non-acoustic based sensing. The major problem of acoustic-based sensors is that they are very prone to noise. Because acoustic signal are mechanically-actuated signal, the dynamic nature of the underwater medium disrupts the signal quality. On the other hand, the non-acoustic sensors are very application-specific, and must be tailored made for specific applications. The utilizations of MEMs-based underwater sensor system are a major future scope of research. MEMs-based sensor will optimize the cost of material and energy, particularly. One other potential dimension of underwater sensor development is the bio-inspired system approach. The existing biological system around us, especially in the oceans, is a rich depository for ideas and solutions to the man-made problems. Bio-inspired sensor system is not just about trying to imitate the living system, but synergize the current available technology with what nature is showing.

### Underwater Sensors: The Importance

Sensors are used to measure many different parameters in terrestrial, air, and marine environments. Underwater sensor applications are still sparsely utilized and relatively expensive which imply the need for long range communication and increase sensors' power usage. Currently, small, robust, cheap and low energy consumption underwater sensor without reducing the sensors performance are needed to assist scientists in various underwater applications especially in rough water environment. Such applications are working on marine environmental in-situ monitoring issue, port security, surveillance, tsunami early detection, and autonomous underwater vehicle navigation.

The prime aspects of the marine environmental monitoring is to be able to detect and quantify the true or in-situ value of the analyze component, rather than collecting and preserving samples and specimens and transporting them to the laboratory for further analysis<sup>1</sup>. While for autonomous underwater

navigation, sensors that can be vastly deployed on the vehicle to provide objects detection from all direction are needed. This will assist the vehicle to operate in hazard environment and close proximity to the detected object and react accordingly<sup>2</sup>. Therefore, large numbers of underwater sensors that can be deployed on the autonomous platform to assist the platform manoeuvring ability or to gather real time data are essential to study the dynamic ocean environment.

### Current Underwater Sensors

#### *Acoustic Sensors*

Acoustic signals propagate better than light and radio waves or any other types of energy in underwater applications. The importance of acoustic for underwater applications is undeniable, and the enabler device is an acoustic sensor. Acoustics are utilized to fulfill the needs of sonar and underwater communications in scientific explorations, commercial exploitations, defense surveillances and environmental protection for many decades. Underwater target detection, object classification and localization, subbottom geological mapping and profiling, ocean topography, bathyvelocimeter, acoustic holography, seismic simulation and measurement, biological noise measurement as well

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as tsunami detection are several applications where acoustic sensor can be found to be used extensively and effectively. Acoustic sensors are also utilized in underwater telephones, telemetry and underwater sensor networks (UWSNs). Acoustic signal generations and detections encounter significant challenges due to the dynamic properties and extreme nature of the ocean. Issues on multi-path propagation, time variation of acoustic channel, nonlinear effects, thermocline, strong signal attenuation, high error rate, limited bandwidth and many more are those already discovered, and are widely-discussed at the theoretical level. Recent acoustic-related system researches works are more likely to focus on the design to improve performances, smaller size and efficient energy consumption. Hence the boundaries in underwater acoustic sensing are widening.

During the last many decades, scalar-type sensor that only measures pressure component of acoustic field is utilized extensively, in field of oceanography. Recently, vector-type sensor starts to replace conventional scalar sensor in various sonar applications. It measures both scalar (pressure) and vector (wave velocity) components of acoustic field. Currently, there are two types of vector sensor namely inertial and gradient vector acoustic sensor. Inertial type directly measures the velocity by responding to acoustic medium motion. Gradient type on the other hand employs finite difference approximation to estimate the velocity. Usually this type of acoustic sensor consists of more than two velocity hydrophones working together with pressure hydrophone. As the result, four channel vector acoustic sensors not only are smaller in dimension, but also allow narrower beams to be generated with a smaller number of sensors over a smaller foot-print than can be obtained from a scalar acoustic sensor. Latest application of vector-type acoustic sensor is for target localization with full manoeuvrability in elevation in addition to azimuth<sup>3,4</sup>. Recently, more advanced two dimensional direction-finding algorithms and simulation have been developed for coherent acoustic signal<sup>5</sup>. This will widen the exploration windows for more complex design of vector-type acoustic sensor. Future work in this area is expected to focus on overcoming irregular beam-forming patterns problem. When smaller and compact vector sensor was not small enough to fit several applications, enormous efforts took place to shrink the size down to micro-level. Owing to microelectronics

technology and advanced computer aided design, both capacitive type and piezoelectric type acoustic sensors have been successfully miniaturized for underwater applications<sup>6-8</sup>. In comparison however, development of micro-acoustic sensor for underwater used is relatively slow compared to airborne applications. Micro acoustic sensors suit for light weight platforms such as portable diver device, ROV and UUV as well as acoustic modem and underwater sensor nodes. Even micro-acoustic sensors have gained popularity recently, researches and studies of macro-size and classical design acoustic sensors still ongoing. For example studies on new designs and applications of *tonpilz* piezoceramic sandwich sensor are yet carried out. One of the latest studies is to understand sensor properties at low resonance frequency<sup>9</sup>, and exploring new applications of long distance underwater acoustic transmission<sup>10</sup>.

Optical fiber based acoustic sensing which utilizes light beam in generating acoustic pulses has become an active research area recently. Researcher already started looking for optical-based devices as an alternative technology for higher sensitivity and better immunity from electromagnetic interference. Fiber-optic based hydrophone also found to be very convenient for multiplexing. One of the latest fiber-optic hydrophone was developed with novel mechanical antialiasing interferometric features<sup>11</sup> to encounter signal aliasing in existing design. Another research has been carried out to evaluate plastic optical fiber (POF) as pressure sensor<sup>12</sup> and the results are stunning. Another advantage of POF is it comes in a cheaper package than silicon technology. However, application for these types of sensors still limited due to low resonant frequency issue.

Recent advancement also takes place in sensor arrays. Undoubtedly, studies on underwater acoustic sensor arrays are still popular within underwater research community. Instead of focusing on novel shape of array, active researches is now working on enhancing existing array performances for broader applications. Planar and triplet arrays of hydrophones are one of those being studied recently to overcome weaknesses which exist in the commercial Multibeam and Sidescan sonars<sup>13,14</sup>.

Mutual coupling effects exist between array elements and became a puzzling problem in practical array of acoustic sensors. Existing mutual coupling understanding is still relying on electromagnetic waves extended model. Specific mathematical

interpretation is actually needed since acoustic waves are longitudinal, not transverse. Recent study that focuses on this particular area has been discussed and new understanding in mutual coupling sonar array is achieved<sup>15</sup>. This interpretation had resulting in more accurate analyses and physical meaning in underwater acoustic study.

Nearly half of century ago, parametric acoustic array<sup>16</sup> is discussed and proved about half century ago. Ever since, the study on parametric effects has never stopped. Recent research trend are more likely to focus on utilizing and characterize commercial parametric sonar for various applications. For example, TOPAS acoustic source has been installed on AUV for studies of seafloor scattering and sub-bottom imaging<sup>17</sup>. Buried objects detection and classification in multipath environment have been successfully achieved. With various selection of highly sensitive parametric sonar in the market, many new applications are expected to be explored.

The applications of highly directive, conical and omnidirectional acoustic sensors are emerging in underwater communication applications. One example is underwater sensor nodes for underwater sensor networks (UWSNs). It composes of omnidirectional and compact acoustic sensor as a receiver. Various research groups and industry players have successfully developed underwater modem for underwater communication and sensor networks<sup>18</sup>.

## **Non-Acoustic Sensors**

### *Optical Sensor*

Underwater sensor applications are governed by an acoustic sensor system for AUV object detection in the marine environment. However, due to their high manufacturing cost, a mass sensor deployment is not feasible. Recently, optical fibers-based sensors have increasingly become an important part of sensor technology. The fiber-optic sensor systems have many advantages such as smaller in size, low costs, distributed measurement over a long distance, and eliminate cross talk problem associated when using multiple ultra-sonic sensor<sup>2</sup>. It has been reported that, fiber optic sensor is a powerful sensors for many parameter measurements including temperature, pressure, strain, salinity, mass flow rate and rotation position<sup>2,19</sup>. Their usage as a probe or as a sensing element is growing not only in measuring the marine chemical and physical environmental components but also in AUV platform.

During an AUV application, due to the payload and energy storage constraints, optical sensors designed and developed for AUVs must be made to be smaller, lighter and require minimal power consumption. In addition, the AUV systems themselves might not always be recoverable. Hence the manufacturing cost is to be low. A development of optical fiber sensor as proximal object and hazard detection sensor is a proof of using optical fiber in underwater sensor application<sup>2</sup>. The sensor which made from plastic optical fiber is cheap, consumable and light, it also has good respond sensitivity and proven to be immune to harsh marine environment. It is able to detect objects in a short range with proximity detection less than 1 meter. This ability allows the AUV to operate close to hazard, in a confined space, or close to the sea bed.

Underwater chemical environmental components consists the presence of oxygen, nutrients such as nitrate, phosphate, silicate and iron for optimum growth of marine organisms. The nutrient concentration is measured by a very mature second generation system called Spectrophotometric Element Analysis System (SEAS II)<sup>19</sup>. SEAS II is an accurate, high resolution instruments that incorporates both fluorescence and colorimetric techniques. The high resolution criterion is highly important especially in oligotrophic marine environment where the contents of dissolved nutrients salts are in short supply. The ability of SEAS II to measure the low concentration of nutrients is achieved by applying a long-path-length cell and multi wavelength spectrometer<sup>19</sup>. Before, it is impractical to have a long path length, but current advances in material research allow the construction of flexible optical cells with complete internal reflection. This in return make it possible for the cell to be wound inside a case<sup>20</sup>. A development of attaching real time communication capabilities into SEAS II with reduce-cost system for long-term deployment is in plan. It can be used for monitoring carbon system parameter which will provide better explanation in the impact of increasing carbon dioxide with current climate change

Optical sensor is proven to be an alternative for acoustic-base sensors. However; biofouling are the limiting factors for measurement accuracies and deployment longevity. This is especially true for moored optical sensor deployment where they typically degraded with several weeks to at most a

few months due to biofouling. Copper can significantly reduce marine fouling for long-term optical sensor deployment in marine environment<sup>21</sup>. Studies on copper application for optical sensor which less toxic than chemical antifouling, can be employed on all three types of optical sensor; open, closed and semi-closed, and shuttered. It can be deployed for open and closed system more than 60 days, while shutter system has an extended deployment period of 400 days and longer without any sign of biofouling<sup>22</sup>.

#### *Electrochemical Sensor*

Electrochemical based sensor is widely used in marine environmental monitoring. The success in miniaturization technology has led to the development of real time in situ chemical sensor with high sensitivity that robust for routine applications. Electrochemical sensor system includes potentiometry, amperometry, and voltammetry<sup>22</sup>. Potentiometry, an ion selective electrodes have the capability to measure the chemical component up to (sub)-nanomolar levels. Amperometry is a sensor that measures the applied current between the working and reference electrode while Voltammetry, uses three electrode (reference, working, and counter) where electrode potential is applied between working and reference electrode and current is measured between counter and working electrodes<sup>23</sup>. The fact that most underwater substances provide different applied potentials, which in return provide different current measurements, make Voltammetry a versatile electrochemical sensor for addressing security and environmental problem. Recently, efforts have been focused on developing carbon fiber based Voltammetric sensor to detect the presence of underwater explosive residues such as trinitrotoluene, a yellow, crystalline, water-insoluble, flammable solid<sup>24</sup>. Besides monitoring the marine environment, the fiber based Voltammetric sensor can also provide security from the increasing terrorist activity.

#### **Challenges**

Underwater systems aiming for data collections and assessments, equipped with sensors, housing and other support structures are expected to be put on the long-term measurements, and face very short term biofouling effect and corrosion. Biofouling and corrosion can disrupt measurement quality and many approaches have been taken to counter the problem especially for long term deployment system. The

protection of the sensing area of the sensor is the most urgent so that workable data can be produced continuously. Mechanically protected sensing area using wipers or copper screen is no longer practical. The usage of chemical biocide such as *Tributyl Tin* (TBT) is prohibited worldwide since 2008. One of the possible solutions is using localized chlorine generation<sup>25</sup>.

Challenges also appear in the form of environmental awareness of worldwide marine research community. Generation of high intensity sound at certain frequency for long-range underwater sonar and communication are found to be affecting the marine cetaceans<sup>26</sup>. A novel approach to transmit low intensity sound at long range should be established, especially, for power sensitive underwater platforms. Other challenge is on the design of the platform. Acoustic sensor especially vector-type sensor appears to be very sensitive when rigidly mounted on the moving platforms such as ROV and AUV. The effort should be made to support the development of mounting system to provide isolation from platform vibration without reducing the sensitivity of operating acoustic sensor. Another challenge is when operates the sensor. For example, micro-size acoustic sensor design promises smaller housing. Small housing or encapsulation should allow the water to flow past it without causing turbulent. Turbulent issue is crucial for shallow immersed transducer unit since air could easily separated from the water in the form of bubbles. Reflected acoustic signals by bubbles sometimes causing serious interfere, especially during high speed operations. Thus, most acoustic transducer design should be tailed with proper encapsulation and housing development.

Sensor design itself facing a lot of challenges. Deeper operation of acoustic sensor will expose the sensor to underwater pressure which can results in large deflection of thin diaphragm due to the nature of acoustic sensing that requires cavity for diaphragm deflection. Large deflection however, will force sensor to function in saturation region and reducing the resolution of the sensor. Recent work to overcome large deflection is conducted by reinforcing the design using double thin-thick diaphragm combination<sup>6</sup>. This design however only suits for static pressure measurement application due to low sensitivity and operating range. In transmitter design, micro-machined thick film piezoelectric sensor array has

been developed<sup>7</sup>. Thicker transduction material however has sacrificed the bandwidth and sensitivity of the sensor. Recent challenge in acoustic micro-sensor design is to minimize the size or completely remove the cavity without compromising performances.

## Future Potential Solutions

### *Bio Inspired Sensors*

Animals display a great variety of sensory system that easily outperforms existing sensors generated by human. Getting inspiration from learning and mimicking nature always serve new design approaches that push current information technology to a new paradigm. New discoveries in neurosciences and advances in recent technologies such as MEMS, neuro-interfacing, biocompatible materials, low power computing and communications devices are among the driving forces behind today's development of bio-inspired information technology<sup>27</sup>. Biologically inspired approaches have successfully proved major breakthrough in a wide variety of problems<sup>28</sup>. A more recent trend is to explore applicability of bio inspired approaches into underwater technologies. This new adaptation will enhance the future development of underwater sensor in many ways. The box jellyfish behavior imitation will help create cheap underwater sensor platform for mass sensor deployment, while plankton photoluminescence ability to produce light at a visible wavelength that scattered less as compared to radio wave inspired new way of data communication that provide an alternative to acoustic system.

It is known that jellyfish has inspired scientists to mimic their biological behavior to create a covert network of widely distributed underwater sensors network<sup>29,30</sup>. The sensors will be attached to the artificial jellyfishes, and passing through information from one sensor to another while the artificial jellyfishes maintaining their respective places in the water. Currently, a study on understanding the behavior of the jellyfish and creating an inexpensive platform that made of simple and acoustically transparent materials is actively done. Recent finding on box jellyfish swimming ability shows that at a slower flow current the box jellyfish will swim both with and against current, but when the current flow increase they are more likely to move with the current and, in fact, their travelling rate also increases<sup>31</sup>. The data collected is concluded that the box jellyfish

posses the ability to swim against the current but they do so until the current reaches at certain velocity. At this velocity, it is either they are no longer able to move against the current or the energetic cost required to move against the current outweighed the benefits. Therefore a future study on understanding the behavior of box jellyfish is an important aspect of this project. While jellyfish provides new inspiration for inexpensive underwater network platform, underwater living organism and plankton prompt the development of *Smart Plankton*, a new generation of underwater wireless sensor network<sup>32</sup>. By adopting "*smart dust*" project which already applied in terrestrial wireless sensor network, the observation on marine organism and plankton help ease the transferring process of the mature terrestrial system to their underwater counterpart. Photo-luminescent plankton's drifter ability in real current and their light production with visible wavelength that scattered less as compared to radio wave becomes the anchor of this new finding<sup>33</sup>. The smart plankton will communicate wirelessly using flashing LEDs to send messages and will release in a group to drift through to track a water condition at a wide area.

### *MEMS Based Sensors*

The advancement of MEMS technology has enable scientist to miniaturized sensors on a dimensional scale of microns<sup>34</sup>. Recently, the achievements in MEMS technology help to realize the adaptation of new sensor design approached inspired by animal behavior into a 'functional' biologically inspired underwater sensor. For example the development of MEMS flow sensor is the fundamental of superficial neuromasts (hairs) sensor development that used for navigation in some fish<sup>35,36</sup>. This new generation of sensor will help augment or provide better alternative to current acoustic system. Another example is the blind cavefish which rely on their hair to sense obstacles, predators, and prey. Their ability to detect underwater objects and navigate blindly in complex underwater environment inspired a group of researches to mimic their hairs structure. This artificial haircell is fabricated using MEMS flow sensor encapsulated with hydrogel cupula<sup>35,37</sup>.

## Future Works

Underwater sensor has gone through a remarkable development. However many of the develop sensors especially chemical sensors are still at the prototype stage, and lack investments necessary to turn them

into robust and reliable Commercial Off-The-Shelf (COTS) sensors<sup>38,39</sup>. Current investigation shows that tremendous effort has been put to produce a simple, robust, real-time and in-situ sensor system. But still there is room for future challenges in producing robust and reliable sensors which could be routinely deployed in the marine environment on autonomous platforms. Possible future challenges on underwater sensor development are standard interface with plug and play capabilities across a range of sensors and data feeds/types, higher stability and more robust with possible utilization of MEMS-based and Bio-inspired approaches.

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