Review of Bio-inspired Sensors for Underwater Vehicle Path Finding

Candidate number: 13140

Word count excluding Abstract: 2497

Abstract

With increased exploration of oceans and waterways the demand for underwater vehicles capable of path finding has become increasingly important. The key metric of improvement has been in the sensors used to achieve this. By looking at how marine life's sensory organs work biomimetic sensors were classed into three categories based on the properties they measure to achieve information for path finding (electrical, light, and mechanical). The leading electric solution of the electric camera resulted in a 2D electric image and an error rate of 0.5% during object localisation. For the light sensors the simplistic polarised linear sensor achieved basic linear object localisation but could not achieve true vision and the compound eyes achieved an image 1280x720p, dynamic range of 62dB, signal-to-noise ratio maximum of 48dB, and quantum efficiency of 30% making it suitable for depths below 200m. Mechanical sensors offered the most robust method for mid to far field path finding. Covering ultra-low-frequencies of 20-500Hz and mid to high frequencies of around 20kHz. Suggestions are made on the best combination for current UV technologies for all operating conditions.

Introduction

Path planning is a crucial aspect of underwater robotics, allowing the underwater vehicle (UV) to determine its position, orientation, and velocity in the underwater environment. Accurate path planning is essential for the UV to successfully accomplish its mission, whether it be exploration, inspection, or monitoring. To achieve this, UVs are equipped with various sensors and algorithms that enable them to navigate and map their surroundings. All the different classes of UVs have progressed substantially with their capabilities and data collected contributing immensely to our understanding of the oceans[1].

Bio-inspired sensors for path planning are those that are inspired by the sensory systems of aquatic animals. These sensors mimic the mechanisms used by animals to orient themselves and navigate in the underwater environment. Bio-inspired sensors for path planning have several advantages over traditional sensors[1], such as being energy efficient, robust, and capable of operating in extreme environments.

Sensors for path planning can be categorised by the properties measured. Within marine organisms 3 main properties are used to detect and map surroundings: electrical (electroreception), light (photoreception), and mechanical (baroreception). Evolution has caused organisms to adapt sensory organs and mechanisms to match their environments becoming very efficient and effective navigators. Path finding is an essential mechanism for navigation of both know and unknown environments. Path Finding involves identifying characteristics and objects within the environment and deciding the most beneficial path[2]. This can be to avoid collisions or to pick the most energy efficient path. To achieve this object localisation and environmental characterisation must be undergone. This can be sense actively or passively.

None of the sensors and techniques presented in this review are total solution to the challenges of underwater path planning. In practice it is most common for systems to use a combination of methods, with the specific selections depending on a variety of factors. These factors include, but not limited to; depth, range of sensing, update rate of measurements, and precision[3].

This report will explore the various bio-inspired sensors for path planning that have been developed for use on UVs. This report will discuss the different types of sensors and the animals that they are inspired by, as well as their characteristics, advantages, and limitations. It will also review the current state of the art in this field, including the latest research and development efforts. Finally, we will discuss the potential future directions and applications of bio-inspired sensors for path planning in underwater robotics.

Review of Engineering Solutions

Electrical Sensors

Sensors to generate electric images of objects and environments have relied mostly on amplitude modulation of a local electric field on a sensory mosaic Zupanc et al. [4]. Studies by Emde et al.[5] and Solberg et al.[6] have used weakly electric fish to study the merit of evaluating time waveforms of local stimulus to generate electric images of object. Emde's study concluded that evaluating time waveforms gave considerable improvement by method increasing the capacities of electro-sensory channels, while Solberg's showed that a 2 probe with a slender cylindrical body, one emitter, and a single receiver application (Figure 1) was capable of object detection but could not provide sufficient discrimination for object avoidance. Subsequent investigation by Lebastard et al.[7] built on the methods of Solberg by increasing the number of probes used to from 2 to 3 or more and using 2 receivers (Figure 1). This helped them solve the issue of discrimination for object avoidance as it gave multiple electric images however this was only true within an enclosed field with walls. Without a large enough distribution of receivers, resulting in 1D static imaging. In a study by Boyer et al.[8] a recommendation was made that use of a passive sensor, which considers electromagnetism through the combination of the electrical and magnetic fields, would result in more robust object avoidance capabilities (Figure 1). This method however is only capable of following external electric fields and is passive in nature. These configurations are summarised in Table 1.

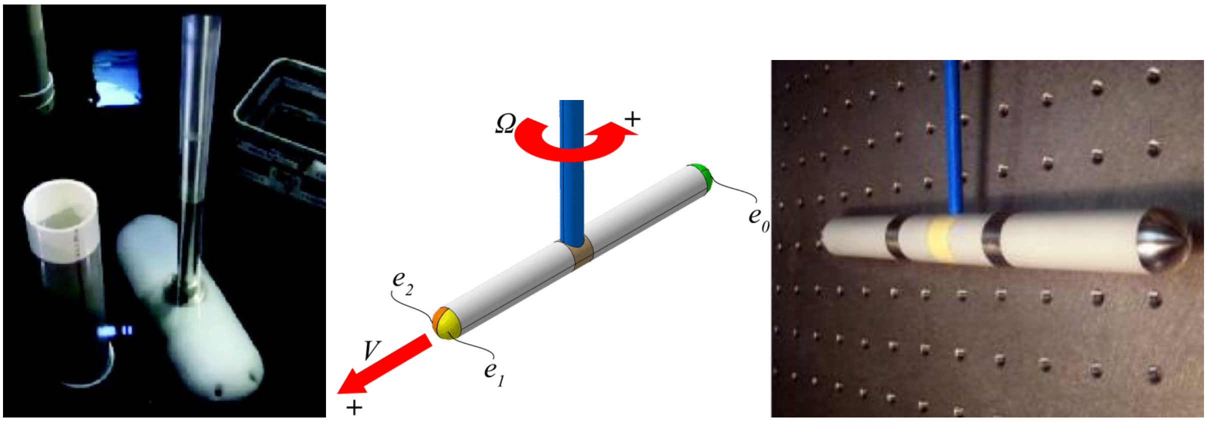


Figure 1: (Left) Solberg 2 Probe Electroreception Sensor, (Middle) Lebastard 3 Probe Electroreception Sensor, (Right) Boyer 4 Probe Electroreception Sensor[6,7,8]

Table 1: Electroreception Sensors

Name	Passive or Active	Number of Probes	Capable of Object Detection	Capable of Object Avoidance	Reliable Range (number of sensor lengths)	Error (mm) Mean
J. Solberg et al. (2008) [6]	Active	2	Yes	No	~1	3%
V. Lebastard et al. (2013)[7]	Active	3+	Yes	Yes	~3	Below 1%
F. Boyer et al. (2015)[8]	Passive	2+	Yes	Yes	~3 to 5	0.5%

A newer “electric camera” method was proposed in a further study by Gottwald et al.[9] which actively capture electric images by processing object-evoked field modulations resulting in an average error of 0.5%. This solution used a 7x7 set of gold electrodes in receiver array combined with grounding electrode and emitter either side (Figure 2). This camera relied on the variation of electrical peak-to-peak amplitude or peak amplitude ratio of waveform and produced electric colours and outlines of objects within range. This camera produced an image within a 2D space. This gives an extra dimension by which path finding algorithm can calculate reducing assumption biases typically introduced with 1D sensing for path navigation.

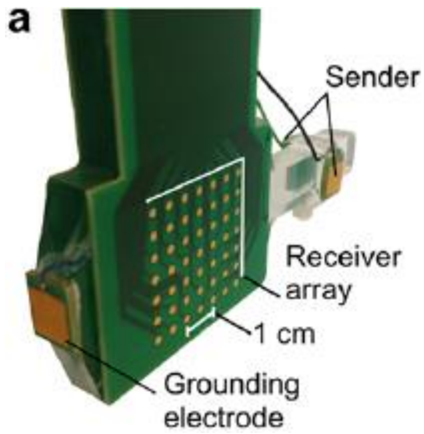


Figure 2: Electric Camera[9]

Light Sensors

Underwater conditions are much more varied [10] than that experienced in atmospheric conditions. More specifically water has an increased absorption and refraction of light making visual path planning difficult at lower depths. Light sensors for path planning aim to achieve 'true vision' by detecting spatial structure in a scene (forming an image). Polarised light-based navigation sensors are the standard practice for mobile robots. Primary success was achieved by Chu et al.[11] and Shashar et al.[12] for the purpose of inertial navigation systems (Figure 3). These sensor systems comprised of a substantial number of differential equations prone to large errors arising from uncorrected signals when unchanged for long periods of time. Fan et al. achieved an improved solution by assisting the polarised light method with geomagnetism and GPS. This solution only provided a system capable of judging short range linear distance but could not achieve 'true vision', as no image was formed, and was prone to failure to capture accurate data in low light conditions.

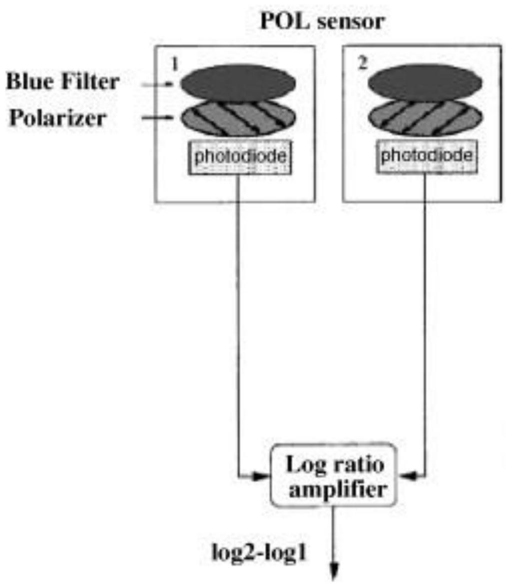


Figure 3: Polarised Light Sensor (Chu)[11]

For true vision, scotopics inspired by the eyes found in nature are most effective. Lie et al.[13], inspired by the elephant nose fish's eyes, designed an artificial 'eye' that guided light rays through an enclosed structure of polydimethylsiloxane (PDMS) ($R = 12.5$ mm, thickness $t = 300$ µm) as seen in Figure 4. By doing this, the sensor was less prone to imperfections within the optical element resulting in successful superposition for the imager giving true vision but not improving range. In addition, this was a solution that could be used in low light conditions with an identifiable wavelength range of $\lambda = 400–780$ nm.

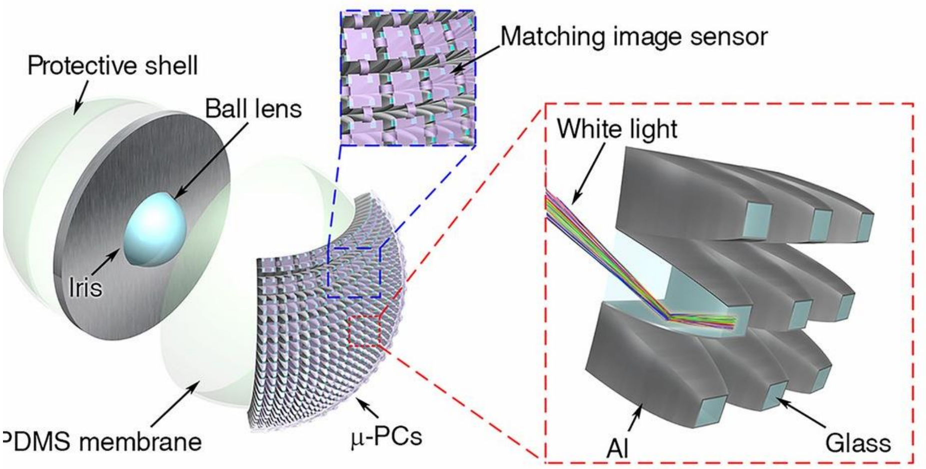


Figure 4: Artificial Eye (Lie)[13]

A major source of error was the wall reflection of UV light on the enclosed PDMS distorting the image plane on boundary spectral channels. M. Garcia[14] instead used a compound eyes reflecting the structure of mantis shrimps where the sensor focuses on capturing co-registered colour and polarisation information. This sensor uses nanowire polarisation filters with vertically stacked photodetector (Figure 5) to achieve an image 1280x720p, dynamic range of 62dB, signal-to-noise ratio maximum of 48dB, and polarisation extinction rate of ~40 for each spectral channel. Most importantly, it produced a quantum efficiency 30% beyond visible light spectrum making the sensor capable of interpreting beyond the visible spectrum reliable assisting path planning at depths below 200m.

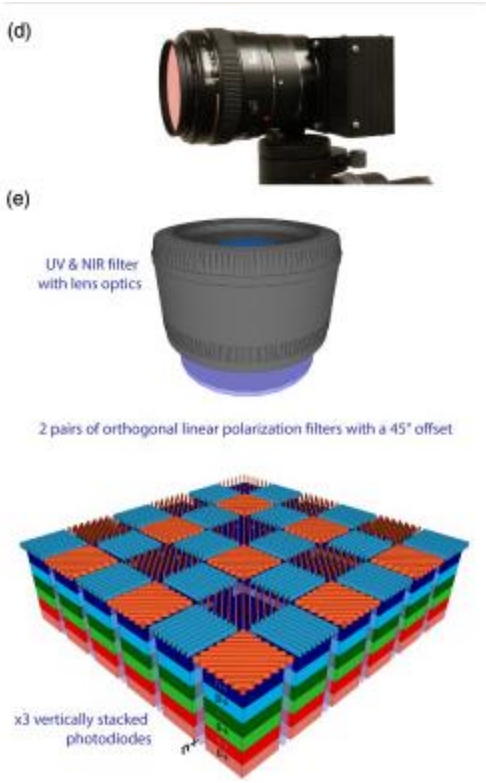


Figure 5: Compound Eye Inspired Imager (Garcia)[14]

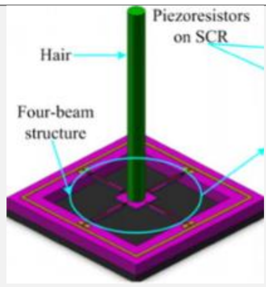
Mechanical Sensors

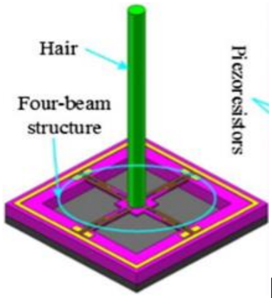
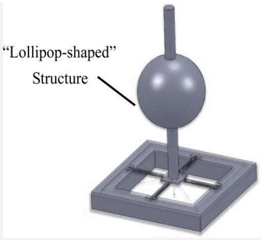
Mechanical bio-inspired sensor for planning can be split into two subcategories that both rely on baroreception: flow sensing and sound sensing[15]. Flow sensing aims at establishing a vector image of flow within the surrounding environment of the sensor, while sound sensing aims at generating an image of specific sound waves within the environment. The key difference between the two is within their respective frequency bands. Ultra-low-frequency and DC detection concern flow sensing, and AC and medium-to high frequency band concern sound sensing[16].

Flow Sensing

Artificial piezoelectric hair sensors are one method to achieve sensing of flow through the deformation of the cilium at the sensing base[17]. There are three established configurations, typically encapsulated in either parylene, stress centralized MEMS vector hydrophone (SCVH G. Zhang et al.[18]), conventional micro-silicon four-beam vector hydrophone (CFVH C. Xue et al.[19]), or Lollipop-shaped vector hydrophone (LVH Y. Liu et al.[20]). See Table 2.

Table 2: Piezoelectric Hair Sensor Configurations

CONFIGURATION	RECEIVING SENSITIVITY (DB)	WORKING FREQUENCY BAND	MAIN ADVANTAGE	DIAGRAM
SCVH	-183	20-500Hz	Greater measurable stress in piezoresistor	 [18]

CFVH	-200.2	20-500 Hz	Miniaturisation capability	 [19]
LVH	-190.6	20–500 Hz	Perfect Parylene insulation	 [20]

Compared to the LVH and CFVH the SCVH is 3.4 and 8 times more receptive in low frequency environments when sensing sound underwater.

A study by Wang[21], inspired by mimicking the whiskers on seals, improved upon the CFVH by adjusting the mechanical properties of the cantilevers of the cilium (Figure 6), increasing the operating bandwidth but with limited returns compared to SCVH. A key improvement is the mirroring of the undulating structural morphology of the whisker for the cilium and its rubber diaphragm attached to 4 bending sensors. This offers a structure capable of supressing vortex induced vibrations which increases the signal-to-noise ratio of the sensing whisker with working frequency of 20-23300 Hz. Similarly, this sensor can determine environmental vector field, making it idea for object localisation and object avoidant sensing.

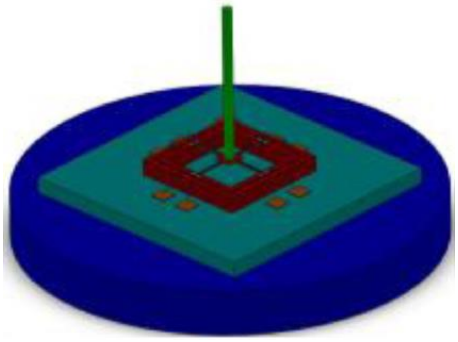


Figure 6: Whisker CFVH (Wang)[21]

Sound Sensing

This is almost solely found in the form of active sonar, which offers long range path planning through active sensing. This is the oldest sensor type with the ASDIC system, developed in 1938[22], and having an operating frequency of 14-22 kHz. Active sonar has come a long way in improving the bands in which this path finding sensor can operate at, as well as increasing range. Traditional sonar systems struggle with decreasing range to achieve applications like that of echolocation. This difficulty is exasperated by noise introduced by bubbles between the sensor and linear targets. In turbulent/effervescent conditions a new sensor structure BiaPSS[23] which utilises physical matched filters for addition and subtraction to enhance and cancel specific nonlinear and linear components giving a clear acoustic image of environment as seen in Figure 7. BiaPSS allowed for path finding at lower peak frequencies improving the efficiency of this process.

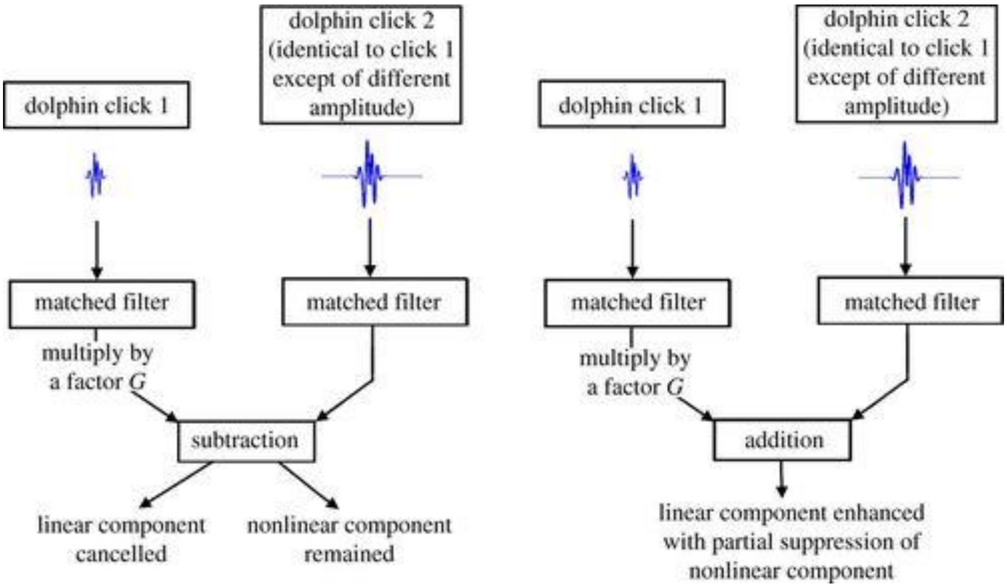


Figure 7: BiaPSS Filtering Schema [23]

Discussion

With the current solutions capable of near field high resolution measurement, despite most water conditions, electrical sensors for path finding are best suited for murky or contaminated water applications of UVs[24]. These sensors have also shown that they are unsuitable for mid to long range path finding as electrical signal energy dissipation is too great across distances to warrant the energy consumption required to compensate. The most comprehensive study by Gottwold in the review section demonstrated a 2D electric image capable of object recognition and that increasing probes or sensing array will increase sensitivity. While this is more information dense this also puts a larger strain on the controller within UVs, as greater image processing and informational storage is necessary compared to simpler approaches of 1D. There is a trade-off between data size of measurement and power/informational requirements of the UV system to handle the measured data from the sensor. Studies have shown there are two ways to solve this, compression techniques using neural networks, or using the systems controller or behaviour to influence when measurements are taken[25]. Bai et al.[26] presented an algorithm capable of processing this 2D electric image and extracting shape, material and position data of object. S Bazeille[27] presented demonstrated that with these electrical sensors the measured data can be learned from egocentrically like Bai's study, or allocentrically to reduce the necessary data size of measurement by increasing the retention of data.

Light sensors are the fastest of the three sensor types available. They are further affected by depth as well if no external light source is provided by the UVs as only higher energy visible light can penetrate further within water. Light sensors are particularly prone to obscuration of the visible field and is unable to map around objects. While Garcia’s artificial compound eyes showed high resolution and reliable operations at increased depths of beyond 200m, they were not effective when it comes to autonomous path finding. This solution collects too much redundant data and is more useful for UVs piloted by people as this feedback is the easiest to interpret or to better classify objects in a field. If a light sensor path finding solution was to be used, Shashars simplistic polarised linear sensor as this produces less object localisation redundant environment data for path finding, increasing the efficiency of the process while.

Both flow and sound sensing use sound making them the slowest sensors of the three main categories. However, the key advantage these solutions have are their ability to sense beyond direct line objects that can obscure the other sensor types due to the refraction and reflection of sound waves. Another advantage is that this the best long-range solution of the three main types for far field path finding. The ability to sense flow and objects provide the most comprehensive solution to path planning as they both identify objects and operating conditions of the environment making it possible to more efficiently path plan reducing the overall energy consumption of a UV. The leading solution within the industry is the LVH configuration for flow sensing even though the SCVH has shown better simulated performance. This is due to a lack of testing and application data for industry confidence. Research could greatly benefit by seeing how the SCVH can integrate with current UVs.

Current literature suggests that a standard UV looks to use a multimodal sensing method for path finding with one system focused on near field and another on far field. This typically comes in the form of mechanical sensing (particularly acoustic sensing) for the far field and optical or electric sensing for near field[28]. The most promising state of the art research argues for electrical sensing as it gives more points of data on key aspects during object detection for decisions on path finding while also avoiding obscuration factors[29]. To better understand the performance of these sensors research must be conducted on how much redundant instantons data from sensor measurements are produced, and the general efficacy of path planning agnostic of specific control systems. A potential experiment would recreate a robust field similar to that of Boyer and mathematically reduce information channels of sensors to identify the redundant data. This can be gauged by the change in the systems ability to effectively path plan from a given baseline performance of a unimodal system.

Conclusions

In this report, a review of the existing literature around biomimetic sensors for UV path finding has been conducted. It has outlined 3 main categories of sensors for UV path finding of electrical, light, and mechanical. It was shown that electrical based sensors were able to achieve the most information per measurement and generate 2D electrical images of the near field. This was best achieved through increasing sensing nodes (electrodes) in a sensing array. Electrical sensor image generation is a preferred use in murky waters. Light sensors were the fastest, capable of 30% quantum efficiency making the application suitable for lower depths for near field but an inferior option to the electrical sensor when not piloted by a human. Mechanical sensors offered the only robust method for far field path finding. SCVH while currently under researched has the best simulated performance for medium ranged object localisation and should be explored for use on UVs when the cilium is adjusted to a wavy structure. Through the integration of BiaPSS the missing bands of the far field can be achieved giving the closest unimodal method for path finding sensors. Electrical sensor image generation combined with mechanical sensor is a lesser researched area where further study should be aimed at. The combination would give UVs the ability to navigate murky and volatile waters with both near and far field object recognition and path planning at a reasonable update rate and sensitivity.

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