Autonomous Robotic Fish as Mobile Sensor Platforms: Challenges and Potential Solutions
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Autonomous Robotic Fish as Mobile Sensor Platforms: Challenges and Potential Solutions

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ABSTRACT

With advances in actuation and sensing materials and devices, there is a growing interest in developing underwater robots that propel and maneuver themselves as real fish do. Such robots, often known as robotic fish, could provide an engineering tool for understanding fish swimming. Equipped with communication capabilities and sensors, they could also serve as economical, dynamic samplers of aquatic environments. In this paper we discuss some of the major challenges in realizing adaptive, cost-effective, mobile sensor networks that are enabled by resource-constrained robotic fish. Such challenges include maneuvering in the presence of ambient disturbances, localization with adequate precision, sustained operation with minimal human interference, and cooperative control and sensing under communication constraints. We also present potential solutions and promising research directions for addressing these challenges, some of which are inspired by how fish solve similar problems.

Keywords: robotic fish, adaptive sampling, mobile sensing platforms, aquatic sensor networks, water quality monitoring

Introduction

With 500 million years of evolution, fish and other aquatic animals are endowed with a variety of morphological and structural features that enable them to move through water with speed, efficiency, and agility (Lauder & Drucker, 2004; Fish & Lauder, 2006). The remarkable feats in biological swimming have stimulated extensive theoretical, experimental, and computational research by biologists, mathematicians, and engineers, in an effort to understand and mimic locomotion, maneuvering, and sensing mechanisms adopted by aquatic animals.

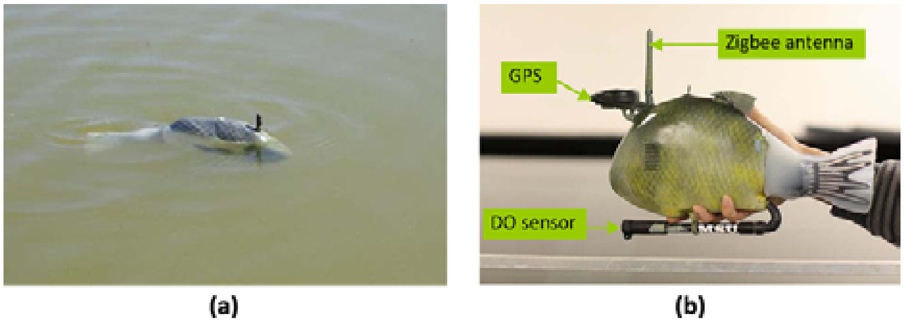
Over the past two decades, there has also been significant interest in developing underwater robots that propel and maneuver themselves like real fish do (Triantafyllou & Triantafyllou, 1995; Kato, 2000; Anderson & Chhabra, 2002; Alvarado & Youcef-Toumi, 2006; Hu et al., 2006; Low, 2006; Epstein et al., 2006; Morgansen et al., 2007; Lauder et al., 2007; Chen et al., 2010; Aureli et al., 2010; Smithers, 2011). Often termed *robotic fish*, these robots provide an experimental platform for studying fish swimming and hold strong promise for a number of underwater applications. Instead of using propellers, robotic fish accomplish swimming by deforming the body and/or fin-like appendages, mostly functioning as caudal fins and sometimes as pectoral fins. Body deformation and fin movements are typically achieved with motors. On the other hand, advances in smart materials have been explored to actuate robotic fish in a noiseless and compact way (Paquette & Kim, 2004; Tangorra et al., 2007; Chen et al., 2010; Aureli et al., 2010). Robotic fish produce wake signatures similar to those of real fish and are thus less detectable than propeller-driven underwater vehicles, which is an important advantage in applications requiring stealth.

Recent advances in computing, communication, electronics, and materials have made it possible to create untethered robotic fish with onboard power, control, navigation, wireless communication, and sensing modules, which turns these robots into mobile sensing platforms in aquatic environments. Schools of robotic fish can form wireless sensor networks, which will have numerous promising applications, such as monitoring water quality, tracing oil spills, and patrolling harbors and coasts. Figure 1a shows a prototype of a robotic fish swimming in an inland lake. Figure 1b shows the close-up of another prototype, equipped with a dissolved oxygen (DO) sensor, global positioning system (GPS), and other electronic components, which has been developed for monitoring the DO level in aquafarms. Collected DO information will then be used to control the aerators to maintain a healthy environment for the aquatic animals on the farm.

Autonomous robotic fish schools will provide a competitive alternative

FIGURE 1

Prototypes of autonomous robotic fish developed by the Smart Microsystems Laboratory at Michigan State University: (a) testing in a lake and (b) prototype for dynamically monitoring the DO level in aquafarms.



(a) (b)

to existing sensing technologies for aquatic and marine environments. Manual sampling, sometimes boat or ship-based, is still a common practice in environmental monitoring, which is labor-intensive with difficulty in capturing dynamic phenomena of interest. In-situ sensing with fixed or buoyed sensors or vertical profilers is another approach (Doherty et al., 1999; Reynolds-Fleming et al., 2002). However, these sensors have little freedom to move laterally, and it would require prohibitively many units for capturing distributed, spatially inhomogeneous information. The past decade has seen great progress in the use of robotic technology in aquatic sensing. Autonomous underwater vehicles (AUVs) (Bandyopadhyay, 2005), for example, are being used for hydrographic survey, fishery operations, and environmental monitoring (Hydroid, 2009). Another highly successful technology is autonomous sea gliders, which has remarkable duration for continuous field operation because of highly energy-efficient design (Ericksen et al., 2001; Sherman et al., 2001; Webb et al., 2001; Rudnick et al., 2004). The downside for both AUVs and gliders is their cost, starting at US $50,000 per unit (not including the cost of sensors), prohibiting the deployment of many of them for observing with high spatial resolution, and excluding them from many applications (such as aquafarm monitoring) where cost is critical. The size (meters long) and weight (at the order of 50 kg) of these vehicles also make them cumbersome to handle by a single person.

Small autonomous robotic fish have the potential to address many of the aforementioned challenges. By a *small* robotic fish, we mean one that has length of 50 cm or less, displaces volume of up to 5 liters, and costs no more than US $5,000 (excluding that of aquatic sensors to be mounted). Its low cost, compact size, and light weight would make it affordable and convenient to deploy these robots in groups for versatile applications and various environments, such as ponds, lakes, rivers, and even oceans. Schools of robotic fish could form dynamic, adaptive sensor networks and provide distributed sensing coverage with desired spatiotemporal resolution.

The realization of such a vision, however, is faced with a myriad of challenges. The size and cost considerations put stringent constraints on the robot's locomotion, battery, computing, and communication capacities. The wide adoption of the robotic fish-based sensing technology will hinge on the robots' ability to operate robustly in the unfriendly and often unpredictable environment, with their limited onboard resources and with minimal human intervention. This poses challenges across a wide spectrum, ranging from locomotion and maneuvering mechanisms, to energy-efficient designs, localization and communication schemes, and control and coordination strategies, to name a few. In this paper, we outline some of the most critical challenges and discuss potential approaches or opportunities in research and technology advancement for addressing the challenges.

Maneuvering in Uncertain Environment

As a sensor platform, the robotic fish often needs to survey a given path or hover over a particular region in the presence of ambient disturbances caused by wind, waves, currents, and turbulences. Regardless of its propulsion mechanism, however, a small robotic fish has limited actuation authority to counteract the disturbances. It is thus of great interest to be able to sense the flow and react in the most effective way under the actuation constraints. We can look to live fish for inspiration, because they deal with this very problem on a regular basis and have developed intricate sensing and actuation systems that offer us interesting insight.

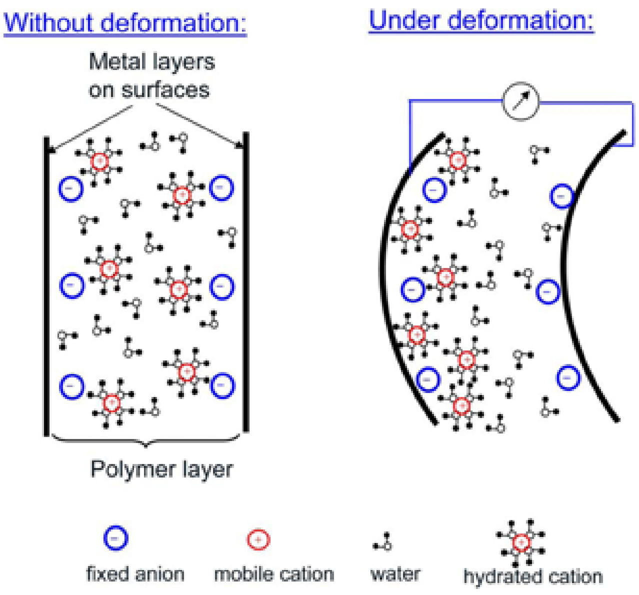
Artificial Lateral Line

Most fish use the lateral line system as an important sensory organ to probe their environment (Coombs, 2001). A lateral line consists of arrays of so called neuromasts, each containing bundles of sensory hairs, encapsulated in a gelatinous structure called cupula. Under an impinging flow, the hairs are deflected, which elicits firing of the hair cell neurons and thus enables the animal to sense the flow field, perform hydrodynamic imaging, and identify new field objects of interest. The lateral line system plays an important role in various fish behaviors, including prey/predator detection, schooling, rheotaxis, courtship and communication.

A lateral line-like sensory module or an artificial lateral line will be very useful for a robotic fish to improve its maneuverability. For example, with feedback from the lateral line, the robot could manipulate vortices in the flow with its actuated fins and exploit the ambient flow energy for locomotion (Beal et al., 2006) or perform station-keeping by responding appropriately to the sensed ambient flow. Artificial lateral line systems, where arrays of beam or hair-like structures are used to measure flow velocities, have been proposed based on various physical transduction principles, including hot wire anemometry (Yang et al., 2006), piezoresistivity (Yang et al., 2010), capacitive sensing (Dagamseh et al., 2010), and encapsulated interface bilayers (Sarles et al., 2011).

FIGURE 2

Illustration of the IPMC sensing principle.

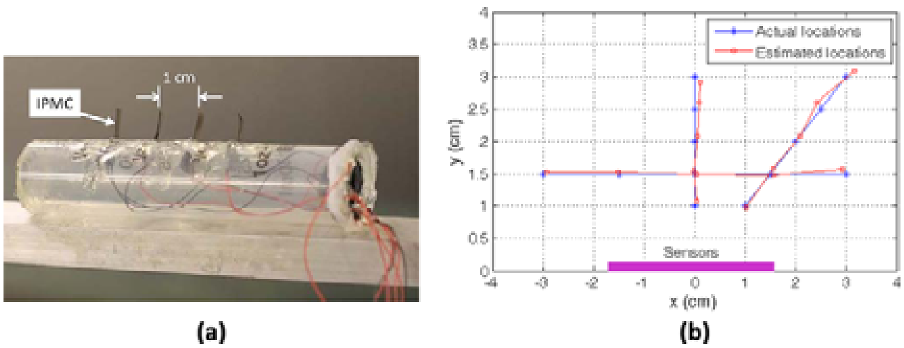


Recently, we have exploited the intrinsic mechanosensory property of ionic polymer-metal composites (IPMCs) to construct artificial lateral lines (Abdulsadda & Tan, 2011; Abdulsadda et al., 2011). As illustrated in Figure 2, an IPMC consists of three layers, with an ion-exchange polymer membrane (e.g., Nafion) sandwiched by metal electrodes. Inside the polymer, (negatively charged) anions covalently fixed to polymer chains are balanced by mobile (positively charged) cations. An applied mechanical stimulus, such as a flow impinging on the IPMC, redistributes the cations inside and produces a detectable electrical signal (typically open-circuit voltage or short-circuit current) that is correlated with the mechanical or hydrodynamic stimulus (Chen et al., 2007). Conversely, an applied voltage across an IPMC leads to the transport of cations and accompanying solvent molecules, resulting in both differential swelling and electrostatic forces inside the material, which cause the material to bend and hence the actuation effect (Shahinpoor & Kim, 2001). Figure 3a shows a prototype of an artificial lateral line consisting of four IPMC sensors.

While the physical construction of robust and sensitive artificial lateral lines remains an active research area, it is of equal importance to make sense out of the data collected by the lateral line. Existing studies on biological and artificial lateral lines have

FIGURE 3

Experimental results on localization of a dipole source with unknown location and vibration amplitude: (a) prototype of IPMC-based lateral line, consisting of four IPMC sensors, and (b) localization results along three different tracks, based on solving a model-based nonlinear estimation problem (Abdulsadda et al., 2011).



(a)

(b)

mostly focused on the problem of localizing a vibrating sphere, known as a *dipole*, which is used to emulate periodic tail beating or other appendage movement of aquatic animals. Several approaches to signal processing have been reported, which include exploitation of the characteristic points (e.g., zero-crossings, maxima, etc.) in the measured velocity profile (Dagamseh et al., 2010), matching of the measured data with preobtained templates (Pandya et al., 2006), beamforming techniques (Yang et al., 2010), and artificial neural networks (Abdulsadda & Tan, 2011). We have further considered a source localization problem where both the source location and its vibrating amplitude are unknown. The posed problem is interesting, since a source far away but with large vibration could produce a signal that has similar amplitude as a signal produced by a source nearby but with small vibration. By formulating and solving a nonlinear estimation problem based on an analytical model for dipole-generated flow, we are able to resolve both the source location and the vibration amplitude simultaneously (Abdulsadda et al., 2011). As shown in Figure 3b, experimental results on an IPMC-based lateral line prototype (Figure 3a) have confirmed the effectiveness of the model-based estimation approach.

Other than the dipole source localization problem, there are a few interesting directions for the signal processing of artificial lateral lines. The first is the detection and localization of multiple, more sophisticated moving sources (including vortices). With the sources moving, the resulting-flow is no longer at a steady state, and the processing algorithm needs to localize the sources with minimal latency. Another major problem to consider is the information processing for a lateral line that is mounted on a robotic fish, where the motion of the robot itself and its fins adds significant "noise" to the lateral line signal. Biological fish deal with these problems effectively through biomechanical filtering for enhanced signal-to-noise ratio and through dynamic filtering in the central nervous system to remove the unwanted signal components (Coombs & Braun, 2003; Bodznick et al., 2003). For example, dynamic neural mechanisms have been identified for suppressing self-generated noise (Coombs & Braun, 2003). Such biological insight will prove valuable in devising the mechanical, electrical, and digital filtering mechanisms for solving complex processing problems faced by artificial lateral lines.

Bioinspired Fin

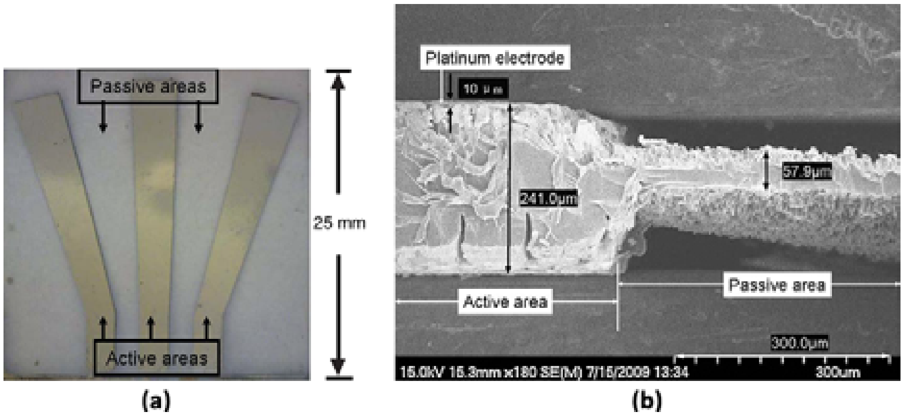
Achieving high-maneuverability hinges on the ability to manipulate the fluid in a delicate manner. Fish often use their pectoral fins to perform sophisticated maneuvers (Drucker & Lauder, 2001, 2003). These maneuvers involve complex conformational changes of the fins, involving cupping, twisting, and bending motions. Robotic fish fins, on the other hand, often use rigid foils (Kato, 2000; Morgansen et al., 2007). Recently, advances in soft actuation materials, e.g., IPMCs, have led to the exploration of these materials as flexible propulsors (Paquette & Kim, 2004). However, the resulting robotic fins typically have simple deformation modes, e.g., bending only (Chen et al., 2010; Aureli et al., 2010), and fall short of emulating the complex deformation of biological fins.

Understanding of the morphology and mechanics of fish fins has spurred effort on mimicking these features (typically at a higher level) in designing robotic fins (Lauder et al., 2007). In particular, the complex shape change of fish fins is enabled by multiple muscle-controlled, relatively rigid, bony fin rays that are connected via collagenous membrane (Lauder & Madden, 2006). Coordinated movement of individual fin rays results in conformational changes of the fins desired in maneuvers. On the engineering side, by patterning electrodes of IPMC materials, one can expect to produce complex deformation by applying different voltage inputs to different electrode areas. The patterning can be achieved with masking during electroless plating or by selective removal of electrodes post-IPMC fabrication using laser or machining (Kim et al., 2011). Inspired by the pectoral fins of bluegill sunfish, we have developed a lithography-based monolithic fabrication process for creating IPMC actuators capable of sophisticated shape changes (Chen & Tan, 2010). As shown in Figure 4, the fabricated sample consists of multiple active IPMC regions, coupled through much thinner passive regions. By phasing the voltage inputs to different active regions, we can realize various deformation modes including bending, twisting, and cupping (Figure 5). For example, a peak-to-peak twisting angle of 16° is achieved with actuation voltages of 3 V (Chen & Tan, 2010).

While the progress made in biomimetic fins is encouraging, significant further advances in both material fabrication and fin control are needed, before robotic fish are capable of manipulating the flow in a manner close to what their biological counterparts do. In particular, the materials need to be improved so that they can produce much larger deformation with reasonable bandwidth (a few Hz). On

FIGURE 4

Monolithically fabricated IPMC sample inspired by fish fins: (a) top view and (b) SEM picture of the cross section, showing that the passive area is much thinner than the active area (Chen & Tan, 2010).



the control side, we need to model and understand the deformation and its hydrodynamic consequences of a given input by combining observation of kinetic patterns of fish fin movement, nonlinear elasticity modeling, computational fluid dynamics modeling, and experimental flow measurements using digital particle image velocimetry.

Energy-Efficient Sustained Operation

For the robotic fish-based sensing technology to gain widespread adoption, these robots will have to be able to work continuously in the field with minimal human intervention. In particular, they need to operate for at least weeks, if not for months, before returning for battery recharge and other manual maintenance. Power is arguably the most crucial factor that limits the operational time. While fuel represents a potential energy source with high power and energy density, it is unclear when fuel-based propulsion will become feasible for small underwater robots. Therefore, battery is expected to be the primary power source for robotic fish, for at least the next 5–10 years.

There are a number of ways one can potentially extend the run time of battery-powered robotic fish. For example, many onboard devices can be put to the sleep mode to save energy, when they are not active. Photovoltaic films can be mounted on the robot to harvest solar energy and replenish the battery, when the robot is on the water surface. Wave energy could be another source to tap into, but how to harvest it on an untethered and often goal-oriented robotic fish remains a challenge.

While all the aforementioned approaches could stretch the mileage per battery charge to some extent, they are not game-changers. Design of energy-efficient locomotion mechanisms will be critical in realizing long-duration field operation, since locomotion is the biggest source of energy expenditure for autonomous robotic fish. To this end, we are currently developing a novel class of underwater robots, called *gliding robotic fish* (Figure 6a). Such a robot will represent a hybrid of underwater glider and robotic fish; for example, it will have wings for gliding and fins for maneuvering and assistive propulsion. Consequently, a gliding robotic fish is expected to possess both high energy efficiency and great maneuverability.

Figure 6b further illustrates the gliding principle and why a gliding robotic fish will be energy-efficient. Under the combined influence of gravity and buoyancy, the body will experience vertical (up or down) motion. When the glider is properly pitched, the lift generated during buoyancy-induced vertical motion will enable horizontal travel. Through the control of pitch direction and buoyancy, one can switch between the descent/ascent gliding motion, resulting in a sawtooth-shaped trajectory. Since buoyancy

FIGURE 5

Examples of deformation modes demonstrated by the fabricated IPMC fin: (a) bending and (b) twisting.

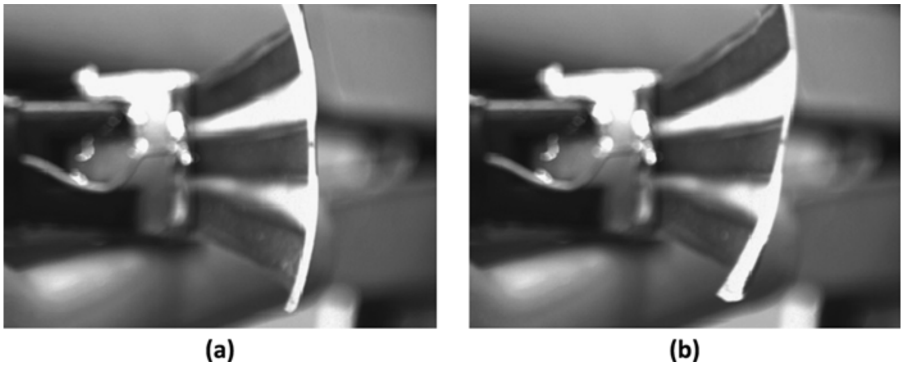
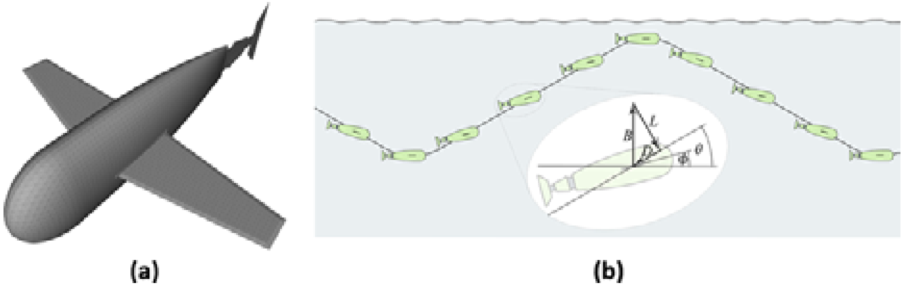


FIGURE 6

Energy-efficient gliding robotic fish: (a) the concept of a gliding robotic fish with a hydrodynamic gliding body and a caudal fin and (b) illustration of the gliding principle.



control and pitch control are the major sources of energy expenditure and take place only during ascent/descent switching, the motion is very energy-efficient, especially if the dive depth is relatively large.

Communication and Localization

Robotic fish need to communicate with a base station to receive commands and send back the collected environmental information. They also need to communicate with each other for information relay and motion coordination. Underwater communication, however, is particularly challenging for small robotic fish that have stringent power and size constraints. Radio frequency (RF) signals attenuate quickly in water, severely limiting the achievable communication range and data rate. Light communication is possible (Verzijlenberg & Jenkin, 2010), but again the range and data rate are very limited and it does not work in a turbid environment. Acoustic and sonar communication underwater has been studied for many decades and was recently explored for communication among robotic fish (Science Daily, 2008). However, the associated power and hardware required to achieve reasonably large communication distance and data rate are typically not affordable by small robotic fish. For these reasons, the most viable solution would be to communicate when the robot surfaces, in which case low-power, low-cost RF communication protocols such as ZigBee can be readily used. Unlike the Bluetooth protocol, which is intended for eliminating cables between electronic devices, the ZigBee protocol is built on top of the IEEE 802.15.4 standard and it targets specifically wireless sensor network applications. For wider range communication, cellular networks could also be employed if such networks are available.

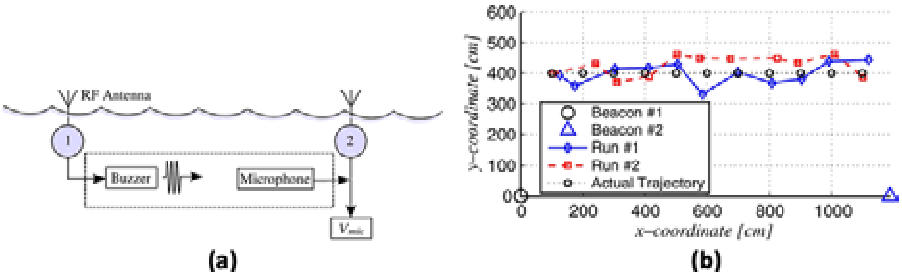
Limiting the communication to the water surface entails additional challenges in robotic fish coordination, control, and networking. For effective networking, we need to have a sufficient number of nodes on the surface. This can be achieved through joint motion planning and control. For example, we can hold robotic fish on the surface until a network with adequate density and coverage is formed and completes data transmission.

Localization is another challenge in robotic fish-based sensor networks. For small robotic fish, having onboard localization capability is essential for successful navigation of the robot and for effective coordination of robotic fish networks. Accurate localization is also critical for tagging the sensed information so that the data collected by robotic fish are associated correctly to the physical location in water. While the GPS is readily available and does not take up much space, its typical precision of 5–10 m is inadequate for many applications of robotic fish due to their small size and relatively low speeds (50 cm/s or less). In addition, the GPS may take a few minutes to lock satellites every time the robot emerges from underwater, which severely limits the networking and control performance. More agile and precise localization technology is needed.

We have developed an efficient localization scheme for small robotic fish (Shatara & Tan, 2010). As illustrated in Figure 7a, the scheme is based on

FIGURE 7

Underwater acoustic ranging-based localization: (a) schematic of the ranging protocol and (b) localization performance in a pool test (Shatara & Tan, 2010).



acoustic ranging, which measures the time it takes an acoustic signal to travel from one node to the other. For example, node 1 simultaneously sends an RF packet and an acoustic pulse to node 2. When node 2 starts its onboard timer when it receives the RF packet and then stops its timer when it detects the acoustic pulse. Since the RF signal travels much faster than the acoustic signal, we can estimate the distance between the two nodes based on the timer reading. The scheme involves simple hardware, a buzzer and a microphone, for each node. A sliding discrete Fourier transform algorithm, implemented on a digital signal controller, is employed for the detection of arrival of the acoustic signal. Figure 7b shows the results from experiments in a swimming pool, where a small robotic fish was towed across the deep side of the pool (about 13 m long) while its distances to the two beacon nodes mounted on the pool wall were measured through acoustic ranging. The resulting localization error was less than 1 m for the entire tested range, which was a significant improvement over the precision of a commercial GPS.

Note that the above localization scheme works only when the robot surfaces, since it involves RF communication. The location of a robot when it is underwater can be inferred using dead reckoning. The scheme in Figure 7 does require beacon nodes (whose locations are known) to obtain the absolute location of a node. In the absence of such beacon nodes, the scheme can be used to get relative locations among nodes, which is of interest in coordinating schools of robotic fish. There are many other in-air localization schemes for wireless sensor networks, e.g., ranging based on received signal strength. While these schemes can be adapted for robotic fish-based aquatic networks, care must be taken to address the challenges associated with noises, disturbances, and signal attenuation at the air/water interface.

Autonomous Control and Coordination

With onboard communication, navigation, control, and sensing devices, robotic fish are desired to operate autonomously, as individuals and as schools, to carry out envisioned monitoring tasks. A few challenges arise in the control and coordination of these robots. A robotic fish needs to handle multiple functions subject to environmental uncertainties and resource constraints. In particular, the functions could include sampling the environment, processing and transmitting the measured data, maintaining network connectivity, and controlling its motion. There are various uncertainties that interfere with these functions, examples of which include motion perturbations due to waves and turbulences, imperfect sensor measurements, and localization error and communication packet drops. Furthermore, all of these functions compete for limited onboard computing and power resources. This is a classic multi-objective, multi-constraint optimization problem, and it demands a systematic approach to the joint consideration of control, networking, and sensor fusion. Evolutionary algorithms (Deb, 2001), which codify basic principles of genetic evolution, can offer a promising solution to this multi-objective optimization problem.

Another challenge lies in coordinating a school of robotic fish. It is intriguing to deploy groups of robotic fish that cooperatively perform sensing tasks. In that case, it is often desirable not to use centralized control, because the centralized paradigm would entail prohibitive cost in communication, and it would paralyze the whole network if the command node fails. Therefore, individual robotic fish are expected to communicate only with their local neighbors and make decisions in a distributed manner. Animals including fish often exhibit coordinated collective movement facilitated by only local interactions, which has inspired great interest from the controls community in analyzing and synthesizing control laws for groups of unmanned vehicles. Significant progress has been made in this area, even with some demonstrated success in adaptive sampling using underwater gliders (Leonard et al., 2007). While these accomplishments can provide a sound starting point for the control and coordination of robotic fish schools, we need to recognize many new and subtle difficulties faced by the latter. For example, a robotic fish can only communicate with its peers when it surfaces, which renders communication and feedback intermittent and asynchronous. This again points to the need to jointly consider control, communication, and networking issues.

Other Challenges

As sensor platforms, the potential of robotic fish in environmental sensing will be ultimately limited by the availability of versatile sensors that are compact and easy to interface with. Most commercial sensors available today are not amenable to integration into small robotic fish, since sensor manufacturers have mostly been targeting handheld, fixed, or buoyed sensors where miniaturization is not critical. It is expected that, with the development of robotic fish and wireless networking technologies, manufacturers will see the growth opportunities in robotic fish-enabled aquatic sensing and start investing in the development of compact, economical, and robust aquatic sensors.

There are other engineering challenge, one example of which is biofouling, where microorganisms and other organisms accumulate on the surface of robotic fish and their sensors, degrading movement and sensing performance. Periodic cleaning is an option; thanks to the mobility of robotic fish, access to these robots is relatively easy. Another possibility is to apply anti-fouling coatings.

Conclusion

In this paper, we have explored the potential of small robotic fish as mobile sensor platforms for aquatic and marine environments. Realization of this vision poses a rich set of challenges across a wide spectrum of areas, such as actuation/sensing materials, mechanism design, communication, control, and packaging. We have reviewed some of the major challenges and discussed possible routes to overcome them. The list of challenges outlined in this paper is by no means exhaustive, but even partial success in addressing them could have far-reaching impact on aquatic environmental monitoring and other engineering applications.

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