An Autonomous Robotic Fish for Mobile Sensing
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Abstract
In this paper an innovative approach to robotics education is reported, where hands-on learning is integrated with cutting-edge research in the development of an autonomous, biomimetic robotic fish. The project aims to develop an energy efficient, noiseless, untethered swimming robot for mobile sensing purposes. The robot is propelled by an ionic polymer-metal composite (IPMC) actuator and equipped with a GPS receiver, a ZigBee wireless communication module, a microcontroller, and a temperature sensor for autonomous navigation, control, and sensing. The two phases of the development are operation compared to traditional motors. These include shape memory alloy actuators [5], [6], piezoelectric actuators [3], and electroactive polymer actuators [7]–[10], to name a few. Ionic polymer-metal composites (IPMCs) are a particularly promising class of actuation materials for underwater robots [7]–[11], since they produce large bending motions under low voltages (1 – 2 V), work well in water and other fluids, and are flexible and biocompatible [12], [13].

In this paper the development of an IPMC actuator propelled, autonomous robotic fish is presented. In this the integration of power, navigation, control, communication, and sensing units, all inside the robotic fish are kept. Although a frequency modulator and a microcontroller were used in the robotic tadpole for remote control of actuation frequency and duty cycle by Kim et al [10], ZigBee1, an increasingly popular wireless described, emphasizing both the technical approaches and the learning paradigms. The developed robotic fish will be further used as a research tool for investigating multi-robot collaborative sensing.

I. INTRODUCTION
Biomimetic swimming robots have wide (potential) applications, ranging from ocean sampling [1] and defense [2] at the meter scale, to pipe inspection at the centimeter scale [3], to micro-surgery at the millimeter to micrometer scale [4]. For millimeter to centimeter-size robots, smart material actuators have been explored for propulsion due to their higher energy conversion efficiency and quieter communication protocol for sensor networks, is implemented in this paper for communicating general information (user commands, sensing data, etc.) and (in the future) for forming fish networks. A GPS receiver and a digital compass, together with the navigation and control algorithms, will allow the robot to autonomously execute missions such as reconnaissance in hostile waters and environmental monitoring.

The appealing nature of the project provides ideal hands-on learning and research opportunities for a wide spectrum of students, from high-school students to graduate students. An emphasis of this paper is to share our experiences in engaging diversified, cross-disciplinary undergraduate teams in research. Two novel approaches are reported, which were adopted during the first two phases of the development of the robotic fish, respectively. These approaches, to be briefly discussed next, have proven effective in boosting
students’ interest in engineering and sciences, and in particular, in the field of robotics.

The first generation of the wireless robotic fish was developed by a team of six students, supported by the Diversity Programs Office at Michigan State University (www.egr.msu.edu/dpo). The makeup of the team was highly diversified: one high-schooler, one freshman, one sophomore, one junior, and two seniors. Among the undergraduate students, three were from Electrical and Computer Engineering and two from Mechanical Engineering. Furthermore, the majority of the team members came from underrepresented groups: two were females, and three were minority students (African American or Hispanic). The structure of the team enabled students to gain research experiences at early stages of their study, to teach each other thus facilitating learning, to appreciate the importance of an interdisciplinary perspective, and to develop the respect for a multi-culture work environment. Starting from scratch, the team successfully built a working prototype that could be remotely controlled through a radio controller.

The second phase of the development has been carried out as a Capstone design project by a group of five senior students in Electrical and Computer Engineering. Taking the first prototype as a starting point, the group has made a number of improvements in navigation, communication, control, sensing, and packaging, thus bringing the fish much closer to the envisioned mobile sensing applications. In addition, a Graphical User Interface (GUI) has also been developed, which allows one to monitor and control the robot via a PC or PDA device.

The remainder of the paper is organized as follows. The development of the first prototype is described in Section II. Section III presents the implementation details of the second prototype. Concluding remarks and future work are discussed in Section IV.

II. A RADIO-CONTROLLED SWIMMING ROBOT

As illustrated in Fig. 1, the design task was first divided into electrical modules and mechanical modules, and then all components are integrated into a working prototype.

![Fig. 1. Sub-modules in the robotic fish development.](image)

A. **Onboard Power, Communication, and Control Circuitry**

The mobile nature of a swimming robot excludes the possibility of powering the robot through wires from off robot sources. It would be nice if the robot can be powered wirelessly or through energy scavenging. Although inductive coupling has been demonstrated to power IPMC-based toy fish [14], this is only applicable to confined environments with limited ranges, such as a fish tank. Power harvesting from ambient sources (such as vibrations) is of special interest with the advances in sensors and networking technologies [15]. However, the power harnessed through IPMC materials is at the order of nanowatts [16], far below the power...
required for operation of an IPMC-propelled robotic fish (order of 100 milliwatts). Therefore, the only viable option for power is onboard batteries. Both lithium coin cell batteries and conventional alkaline batteries (AAA and AA) were explored. The lithium ones had an excellent capacity-to-size ratio and were chosen in the final prototype considering the size constraints. The output voltage of 3 V could generate enough bending in the IPMC actuator while limiting the power consumed in electrolysis.

Remote control of the robot was the primary goal for the first-generation prototype. Instead of seeking a general communication solution (which was later achieved in the second generation), a radio remote was adopted to send four different commands, Fast Forward, Slow Forward, Left Turn and Right Turn. The radio receiver from a Zip Zaps™ toy car decoded the command, which was then used by a microcontroller PIC12F509 for generating appropriate output signals. Since the microcontroller could only source 25 mA on any output pin while the IPMC actuator could draw as much as 300 mA at the peak, a pair of MOSFETs (International Rectifier F7307) was placed following the microcontroller outputs to provide sufficient current. Metallic clamps for the IPMC actuator (Environmental Robots, Inc., Albuquerque, NM) would also function as heat sinks once the circuit is sealed. The microcontroller board and the radio receiver board were placed back to back for efficient use of space inside the robotic fish (see Fig. 2).

Fig. 2. The radio receiver circuit, the microcontroller board, and the radio remote.

B. Fish Body Design and Packaging

It is desirable for the swimming robot to have a real fishlike appearance. In addition, a packaging scheme needs to be developed to protect all electronics onboard, yet leaving easy access for battery replacement. Although the initial design of the fish body and waterproof packaging was not very successful, the development effort will be described next since it provides valuable lessons for later improvement.

The original design had three components, going inward from the outermost layer: a flexible, waterproof, fish-shaped outer layer as skin, a light inner filler to support the skin, and a structure to hold the controller/receiver board in place. Latex Rubber, manufactured by Woodland Scenics R_2, was chosen to be used as the skin material. The rubber comes as a liquid stored in a plastic bottle, and it solidifies after painted on a surface and left to dry for about an hour. Multiple layers can be painted to obtain the desired thickness. A mold was fabricated from a rapid tooling machine (CNC mill) for painting the rubber to make the skin follow a fish shape, as shown in Fig. 3. RenShape
R_3, a polyurethane/epoxy board, is a desired mold material since it provides a nice rough surface for the latex rubber to grip to while in its liquid form. The circuit board was placed inside an insulation tube (typically used for copper pipes), and the open ends were sealed using a silicone adhesive. An expanding foam, Great Stuff TM from Dow Chemical Company was then used as a filler material based on its ability to expand in an enclosed area and harden, creating a firm yet lightweight supporting structure.

C. Integration and Testing

It was discovered later that the body design and packaging had a problem. The latex rubber allows water to enter and fill the gaps between material strands, and is therefore not waterproof. A lesson learned here, which has been applied to the second-generation fish, is that the outer surface of the fish does not need to be waterproof as long as the circuit itself is protected by a watertight layer. For testing of the robotic fish, the circuit board was finally sealed off with a silicone adhesive and placed in a Easter egg shell, and the motion of the fish was successfully controlled via the radio remote (Fig. 4). The robot measured 4.3 × 4.3 × 12 cm. It was found that the geometry of the IPMC actuator could be further optimized. Although a plate-like tail has a larger area for thrust than a beam-like tail, it does not produce as much forward-thrust bending as the beam-shaped tail does since the upper and lower edges also bend towards each other.

III. A ROBOTIC FISH-BASED MOBILE SENSING PLATFORM

The development of the first-generation prototype provided valuable groundwork for the design and implementation of the second-generation robotic fish. Named NEMO (Navigating EAP-Controlled Module with Onboard Resources), it was envisioned to carry out mobile sensing tasks by incorporating advanced navigation, communication, and control capabilities.

A. Design Overview

Fig. 5 illustrates the overall design. The robot is equipped with a GPS and a digital compass for navigation. It can communicate wirelessly with a PC through the ZigBee protocol to receive instructions and send sensor data. Temperature sensing is used as an example application. A microcontroller, as a central coordinator on the robot, performs multiple essential functions related to control, navigation, sensing, and
B. Implementation Details

1) Communication: ZigBee™ is a wireless communication protocol built on top of IEEE 802.15.4. It has advantages such as low power consumption, large transmission range (over 100 m), and capability of mesh networking. This makes it more suitable for sensor network applications than other wireless alternatives (e.g., Bluetooth™ or Wi-Fi™). Two XBee™ modules from Max Stream were used, one on the PC side (through a serial port) and one on the robot. The adoption of the ZigBee technology makes it straightforward to establish communications among a group of robotic fish in the future.

2) Navigation: Navigational capability becomes necessary if a robot needs to conduct operations autonomously in a possibly unknown environment, e.g., in surveillance, search and rescue, or environmental monitoring. Considering future outdoor applications, GPS (Global Positioning System) was adopted as the main navigation solution for the robotic fish. Having access to the location information about the robot at any time instant would be useful in a number of ways. It would allow the robot to maneuver to desired target locations or come back to the base without human interventions, to tag interesting events or sensed information (temperature, chemical concentration, etc.) with specific locations, and to coordinate with other robots in collaborative missions. Using GPS, however, puts a constraint on the robotic fish: it needs to stay on the water surface or at least close to the surface so that the GPS antenna is above water. Although the current robot was designed to have the upper portion of the body above the surface, buoyancy control components can be added later on (see, e.g., [9]) to enable the robot to perform underwater missions. In that case it will need to surface periodically to get an update on its new location through GPS. A 12-channel Laipac PG-31 GPS receiver (30.6 × 28 × 9.8 mm) was used in the robot, as shown in Fig. 6(a). To further enhance the navigation, a digital compass (Dinsmore 1490 sensor)
with eight outputs (S, W, E, N, NE, NW, SE, SW) was also integrated into the robot. Shown in Fig. 6(b), the compass measures about $12 \times 12 \times 18$ mm.

3) Temperature sensing: A temperature sensor (National Semiconductor LM335 AZ) was used to demonstrate the mobile sensing applications of the robotic fish. As a mobile sensing platform, the robot is expected to house a variety of sensors (such as pH, pressure, chemical, and biological sensors) in the future.

4) Control: A microcontroller (Microchip PIC16F688) handles coordination of different modules on the robot. It can control the bending of the IPMC actuator in either open loop or closed-loop manner. In open-loop control, one can adjust the frequency, the duty cycle, and the polarity (for turning purposes) of the actuation pulses remotely on a PC. In closed-loop control, the actuation voltage will be computed based on the target coordinates and the actual coordinates decoded from the GPS receiver. The dimensions of the IPMC actuators are $50 \times 10 \times 0.3$ mm. As the brain of the robot, the microcontroller also interfaces with the sensor, the GPS, and the digital compass. Through the XBee module, the microcontroller establishes communication with the PC.

5) Power and packaging: A toy fish from Swim ways Corporation8 was utilized for housing the electronics and for providing a fish-like looking. The original motor unit was taken out to create the space for the circuit board. The fish body itself was not waterproof, so the circuit board was completely sealed off with silicone adhesive except for the power wires and the interface for reprogramming of the microcontroller. A special clamp was manufactured to provide secure and flexible mounting for the IPMC actuator.

Two rechargeable lithium batteries (3.6 V, 750 mAh) were used to provide sufficient power for the electronics and the IPMC to keep the robot running continually for at least one hour without recharging. A steady 3.3 V voltage, required for the operation of the circuit and the actuator, was produced through a voltage regulator. The batteries were safely housed in the battery compartment of the original fish body.

6) Graphical User Interface (GUI): A user-friendly GUI was developed to allow convenient remote monitoring and control of the robotic fish through a PC or a PDA (see Fig. 7). Basic functions include display of sensor data, GPS/compass readings, and XBee signal strength, and open-loop motion control of the robot. One can also enter the target coordinates through the GUI so that the robot can navigate to specified locations.

C. Integration and Testing

Fig. 8 shows the assembled circuit board inside the robot, and Fig. 9 shows the circuit box for the XBee module at the PC side. The final prototype measures $23 \times 13 \times 6.5$ cm and weighs 295 g. The communication,
sensing, and open-loop control functions were successfully tested in a tank (Fig. 10). Fig. 11 shows the measured swimming speed of the robot under different actuation frequencies when pulses of ±3.3 V are applied to the actuator. A peak speed of 6.3 mm/s is achieved at 2 Hz. The trend of frequency-dependent speed is consistent with typical observations [9], [10]: the speed initially increases with the frequency, and then drops with the latter due to the limited actuation bandwidth of IPMC actuators. Although the achieved speed will not be sufficient for envisioned applications, the performance compares reasonably with reported results in the literature. For instance, Guo et al achieved 5.21 mm/s for a robotic fish with dimensions 4.5 cm × 1 cm and weight 0.76 g [9], and Kim et al achieved 23.6 mm/s for a robotic tadpole with size 9.6 × 2.4 × 2.5 cm and weight 16.2 g [10]. Ongoing research is focused on autonomous navigation with GPS and compass information, and improvement of the swimming performance through geometry optimization of the IPMC actuator and the fishbody.

Fig. 7. GUI for remote monitoring and control of the robotic fish.

Fig. 8. Assembled circuit board for the robotic fish.

Fig. 9. The circuit box for the XBee module at the PC side.
IV. CONCLUSION AND FUTURE WORK

In this paper the development of a robotic fish for mobile sensing applications was reported. The robot used an IPMC actuator to generate swimming motions. Compared to other IPMC-based robotic fish in the literature, this swimming robot has integrated communication, navigation, and sensing capabilities in addition to the motion control. Another contribution of this paper is on innovative approaches to robotics education. In particular, two paradigms of engaging undergraduate students (or even high school students) in robotics research were introduced. Learning through hands-on research proved particularly effective. The students involved in these projects had good appreciation of the interdisciplinary nature of robotics, and were exposed to a broad spectrum of subjects, including smart materials, circuit design, mechanical design, dynamics and control, and communication systems. The implementation details provided in the paper are expected to be useful for faculty and students who are interested in adapting and/or adopting the robotic fish in their robotics curricula. The future work on the educational and outreach side will be to adapt the robotic fish into appealing educational kits of varying complexity levels, and to develop accompanying instructional materials suitable for K-12 students. These kits will be used in the pre-college programs hosted by the Diversity Programs Office and by the Recruitment and K-12 Outreach Office at Michigan State University to inspire young students’ interest in science and engineering in general, and in robotics in particular.