Robotic Fish

Design and Characterization of an Interactive iDevice-Controlled Robotic Fish for Informal Science Education

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In this article, we present the design, development, and characterization of a biomimetic robotic fish remotely controlled by an iDevice application (app) for use in informal science education. By leveraging robots, biomimicry, and iDevices, we seek to establish an engaging and unique experience for free-choice learners visiting aquariums, zoos, museums, and other public venues. The robotic fish incorporates a three-degree-of-freedom tail along with a combined pitch and buoyancy control system, allowing for high maneuverability in an underwater three-dimensional (3-D) space. The iDevice app implements three modes of control that offer a vividly colored, intuitive, and user-friendly theme to enhance the user experience when controlling the biomimetic robotic fish. In particular, the implemented modes vary in the degree of autonomy of the robotic fish, from fully autonomous to remotely controlled. A series of tests are conducted to assess the performance of the robotic fish and the interactive control modes. Finally, a usability study on elementary school students is performed to learn about students' perception of the platform and the various control modes.

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Robotic Fish Exhibits

Technology facilitates learning and expression in both academic and nonacademic environments [1], [2]. In particular, the use of robotics in university-level classes and museums has been shown to effectively excite and educate students and free-choice learners [3], [4]. In the context of underwater robotics, various robotic fish have been developed and displayed for the entertainment and education of the general public in exhibits at aquariums [5], expositions [6], and water gardens [7]. Although these robots have generated considerable interest from onlookers, none of the exhibits offered opportunities for people to directly interact with the robotic fish.

Interactivity in exhibits is a crucial part of science learning in informal settings, whereby interactive components are recognized to improve subject retention and enhance both sociability and curiosity in participants [8], [9]. To this end, smart devices have become increasingly popular as a tool for enhancing education through the use of interactive applications [10], [11]. Young participants have been shown to prefer the use of smart devices over traditional mediums, and better educational outcomes are attained with this growing technology [12]. To actively engage participants, museums, galleries,

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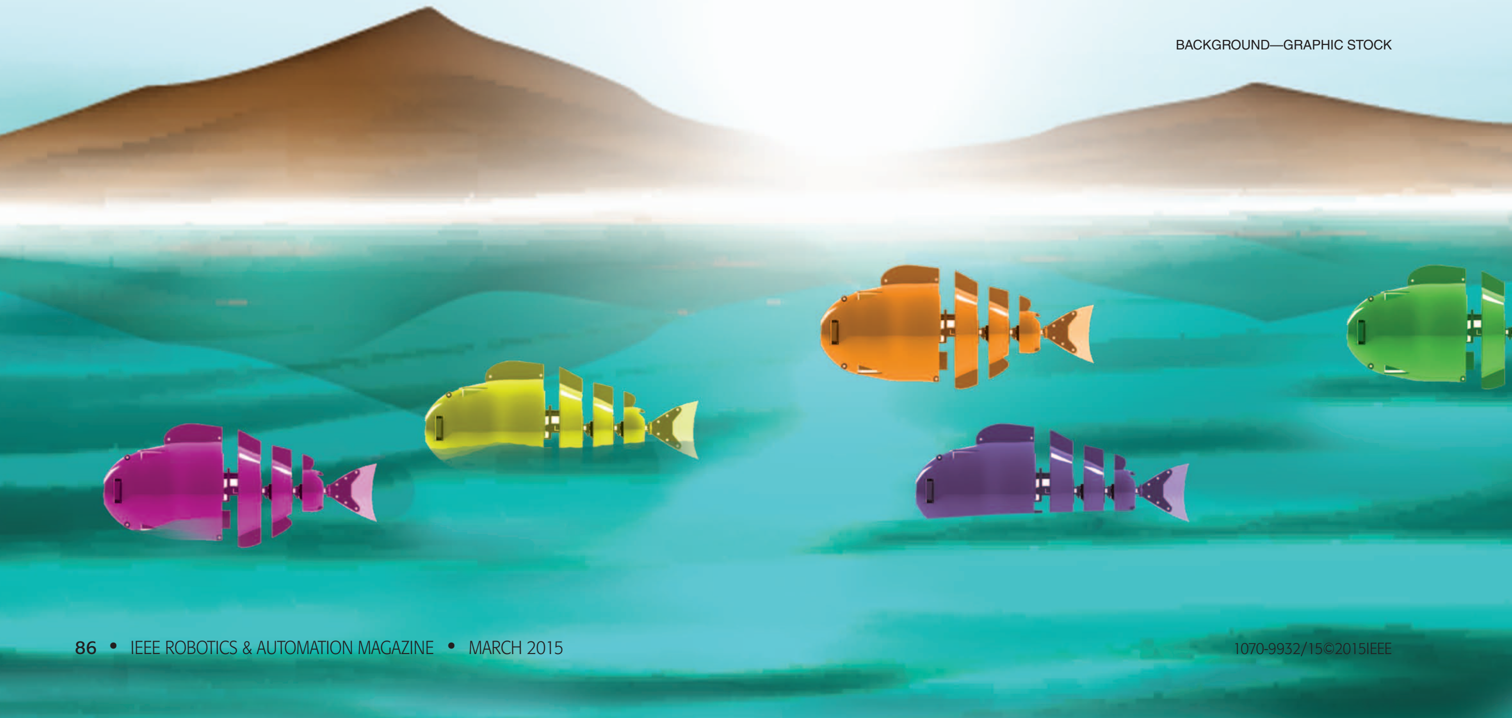

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and zoos have started incorporating touchscreen tablets and smart devices into their displays [13]–[15]. These experiences allow free-choice learners to interact through their smart devices with images and animations in information kiosks or projected displays [13]–[15].

While the integration of interactive smart devices with the state-of-the-art robotics in informal science education is still untapped, our group has demonstrated the feasibility of increasing the engagement of young participants in a formal robotics-based program through the smart devices [16]. The program takes place at the New York Aquarium, where small classes of young students are first given a tour of the aquarium to learn about fish swimming and then tasked with designing the caudal fin of a robotic fish based on what they have observed [17]. Students are ultimately given the chance to drive their robotic fish with a remote control in races with their colleagues, which serves as a validation of the students' bioinspired design. In a series of events, participants indicated an increased interest in science, technology, engineering, and mathematics careers after the program [17], and, similar to the utilization of touchscreens in the classroom [12], they showed a preference for touchscreen devices over traditional controllers for remotely controlling their robotic fish [16]. In this study, students also found the interface of touchscreen devices to have a higher usability as compared with a traditional remote.

Here, we leverage these findings toward the design and development of a biomimetic robotic fish remotely controlled by an iDevice app for use in informal science education. We specifically envision the deployment of this platform in informal science venues in which free-choice learners can interact with the robotic fish in a series of activities through their smart device. The robotic fish builds on the work of [5] and [18] and incorporates a three-degree-of-freedom tail, a pitch control system, and a buoyancy control system to enable 3-D underwater servomotors that are individually controlled to simulate fish undulation. The novelties in the robotic fish design include the implementation of a combined pitch and buoyancy control system for 3-D locomotion, the independence between the robotic fish shape and its waterproofed electronics, and the inclusion of biomimetic swimming patterns.

In addition to such robotic advancements, we introduce a spectrum of user-friendly touchscreen applications that are created to engage free-choice learners in control of the robotic fish while delivering salient educational content on robotics and biology. An iDevice, specifically the Apple iPad mini, is selected as the appropriate hardware for this app due to its widespread usage as well as its portability, wireless networking capacity, and high-resolution graphics. The general public's familiarity with and interest in these devices are expected to contribute to more natural interactions with our exhibit platform. The novel app affords three modes of control, which vary in the degree of autonomy of the robotic fish. Beyond the remote control of the robotic fish [16], we propose two additional modes of control in which the robotic fish is either prescribed a route to follow by the user through real-time video

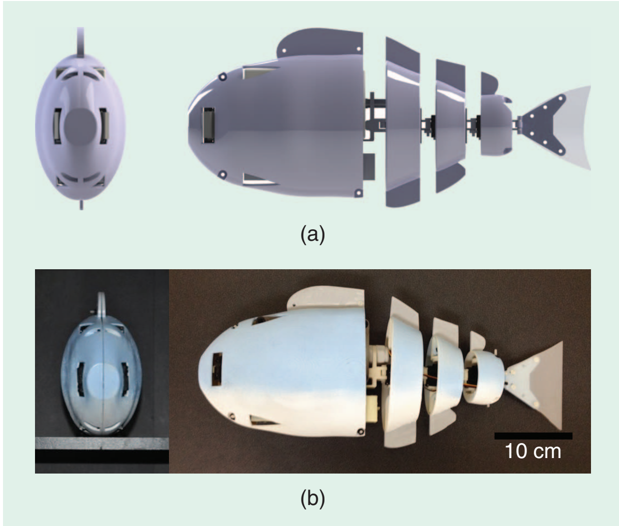

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Figure 1. The front and side views of the (a) computer-aided design (CAD) and (b) physical prototype of the robotic fish.

feedback, similar to [23], or is tasked to autonomously navigate the environment through infrared (IR) sensors. To demonstrate the feasibility of the platform, we perform a usability study on elementary school students.

Hardware Description

The robotic fish developed in this article is shown in Figure 1. The mechanical design consists of a motorized tail, an electronics housing, a pitch control system, and a buoyancy control system. This design is selected for its implementation simplicity, ability for underwater swimming in 3-D, and decoupling of the hardware from the aesthetics. Tail beating allows for swimming in two dimensions (2-D), while the pitch and buoyancy control system, located in the head of the fish along with the electronics housing, are utilized for diving. The cover of the robotic fish is designed in SolidWorks, taking inspiration from a scup fish, *Stenotomus chrysops* [24], and built out of solid-packing acrylonitrile butadiene styrene (ABS) material printed from a Stratasys rapid prototyping machine. Finally, the cover is painted using nontoxic colors inspired by the natural color pattern found in scup fish [24]. The robotic fish measures 46 cm in length, 19 cm in height, and 10 cm in width and weighs 1,170 g. The servomotors and electronics are individually waterproofed to improve the durability of the robot and facilitate variations of its aesthetics.

Electronics Housing

The electronics housing contains the power elements, the control unit, and the mechanical pitch control system [see Figure 2(a)]. The electronics housing is a polycarbonate waterproof Bulgin box enclosure with two mounting holes that are used to connect to the remainder of the assembly. The primary electronic components include an Arduino Pro Mini microcontroller, a RFM22B radio transceiver, and a 2,200 mAh 7.4 V Traxxas LiPo battery. The microcontroller is selected for its size, simple interface, and limited cost. The RFM22B radio transceiver, which communicates at an

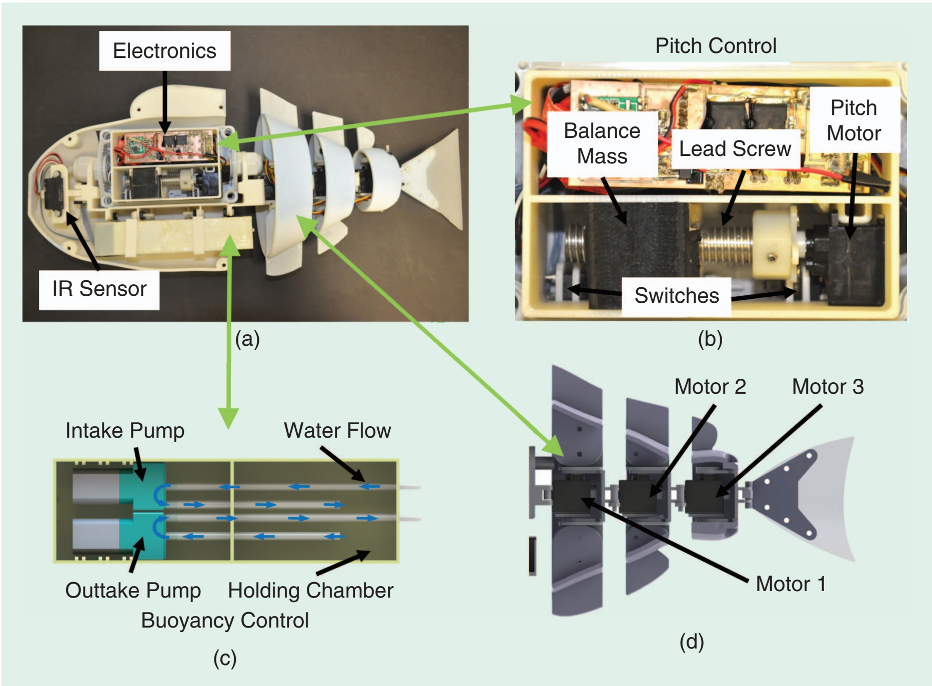

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Figure 2. (a) The waterproof housing displaying the exposed electronics, sensors, and pitch control system. (b) The pitch control motor, lead screw, balance mass, and limit switches. (c) A CAD illustration of a cutaway top view of the buoyancy control tank, water pumps, and holding chamber. (d) A CAD illustration of a cutaway view of the robotic fish tail including the servomotors, links, and caudal fin.

ultrahigh-frequency of 434 MHz, provides a greater range of transmission though water, as compared with a direct Wi-Fi connection at 2.4 GHz [25], which is effective only for a few centimeters. A printed circuit board (PCB) is designed using Eagle PCB software and fabricated in-house on an LPKF ProtoMat circuit board plotter to connect the electronic components. In addition, a battery charge sensor, composed of a voltage divider utilizing two 10-kΩ resistors, is included to measure the battery power level, which is read by the Arduino using an analog-to-digital conversion of the output voltage. The robotic fish is powered by the 2,200-mAh battery, which lasts 2.5 h while swimming continuously.

The PCB is connected internally to the pitch control system and externally to the tail, two Sharp GP2Y0A21YK0F IR sensors, and the buoyancy control system. At the mounting holes, the wires to the external electronics are fitted through a 3-D printed tube and sealed with rubber silicone. For navigation, the sharp IR sensors, pointing 120° apart, are attached to the front of the robotic fish to detect the distances to walls or other obstacles. The circuits of the IR sensors are waterproofed with a layer of general-purpose epoxy. Rapid-prototyped parts are fabricated from ABS material to hold the electronics, sensors, and battery in place.

Pitch Control

The pitch control system is used in conjunction with the buoyancy control system to regulate the depth of the robotic fish. The design implements a pitch control system similar to [26], whereby a known mass is shifted to change the center of gravity of the robotic fish. Unlike other robotic fish prototypes that employ the anal fin [27], pectoral fins [28], and glide wings [29] for 3-D swimming, the implementation with the balance mass decouples the mechanics of diving from the robotic fish cover. Herein, a tungsten mass is used rather than a battery pack as in [26] [see Figure 2(b)]. The pitch of the robotic fish is controlled using a Hitec HS-65MG servomotor, modified for continuous rotation by severing an internal physical stop connected to a 12-mm-diameter lead screw. When the servomotor is actuated, the lead screw linearly shifts a tungsten mass of 165 g within the electronics housing. To constrain the travel of the tungsten mass, two limit switches are integrated at opposite ends of the lead screw. When the balance mass collides with a limit switch, the microcontroller sends a command to the pitch control servomotor to stop further movement in the direction of the pressed switch. The balance mass is designed with a 2.2-cm travel length. A sequence of three steps is used to reach the center position of the travel length. First, the pitch mass is shifted to contact the limit switch in the direction of the head; second, it is moved to the second limit switch while being timed; and, third, it is returned to the center based on half of the time measured in the second step.

The shifted mass is used to control the center of gravity of the robotic fish with respect to the center of buoyancy, thus tilting the robotic fish upward or downward. When the robotic fish is close to neutral buoyancy and the tail is commanded to undulate, the pitch control provides the capability for rising or diving.

Buoyancy Control

The buoyancy control system allows the robotic fish to be set at neutral buoyancy by adjusting the density within a rigid volume tank [Figure 2(c)]. The system consists of two Haiper GS-V1412N water pumps encased in a rigid volume enclosure fabricated using rapid prototyping. The tank contains two chambers, with one chamber encasing the motors and the second holding water. The water pumps in the first chamber are waterproofed by filling the chamber with a petroleum-based gel. The buoyancy control system utilizes the first motor to pump water into a 74.4-ml holding chamber and the second motor to pump water out of the holding chamber. The motors pump water between the holding chamber and the surrounding environment using airline tubing. Both motors are controlled by the microcontroller in the electronics housing. Neutral or slightly negative buoyancy is achieved when the robotic fish dips below the water surface as the pump is taking in water. This procedure is conducted heuristically to calibrate the system before starting the app. The response time for the buoyancy control system alone to dive or rise is on the order of 15–20 s.

Fish Tail

The propulsion of the robotic fish is generated by the undulation of the tail, which comprises three Hitec HS-82MG servomotors and a rubber silicone caudal fin. The servomotors actuate three rigid links at three joints, while a rubber silicone fin is affixed to the last link in the tail [Figure 2(d)]. The maximum allowable angle at each joint is 31°, 41°, and 30° for motor 1, motor 2, and motor 3, respectively, based on the design of the cover. The caudal fin is cut from a 2.5-mm-thick rubber silicone sheet into a bioinspired shape. The covers for the tail servomotors, fabricated with a rapid prototyping machine, are designed to be spaced 2.1 cm apart to allow for sufficient clearance during the tail undulation.

For the robotic fish to mimic the locomotion of a scup fish, its movement is based on a simplified model for carangiform fish swimming [30], [31]. This model is often used to characterize the motion of live fish as well as to implement the same motion into bioinspired robotic fish [19], [30], [32], [33]. The sinusoidal amplitude, period, and phase offset parameters for each servomotor are derived from this model and then programmed into the microcontroller inside the robotic fish. The tail beating, that is, the lateral deflection of the tail mid-axis, of carangiform swimming y^{model} is defined by the wave number k, the tail-beat frequency f, and the shape envelope of the undulation c_1 and c_2 [30] by the following equation:

$$y^{\text{model}}(x,t) = \left(c_1 x + \frac{c_2}{2}x^2\right)\cos(kx - 2\pi f t), \tag{1}$$

where t is the time variable and x is a coordinate along the fish's body, with its origin located at the first servomotor joint (for convenience, the fish's body length is scaled to unit length). Figure 3(a) displays a typical tail undulation produced by carangiform swimming. Following [18], such undulation is replicated by considering 30 samples in an oscillation period and interpolating the model shape using three rigid links for each time sample, as shown in Figure 3(b). All of the computations are performed in MATLAB. The link lengths are measured using a CAD model of the robotic fish, which yields lengths of 2, 2, and 3 cm from the first servomotor to the fin. Figure 3(b) shows the interpolation along with the angles θ_1, θ_2, and θ_3 that should be imposed at the joints of motors 1, 2, and 3 [Figure 2(d)]. Ultimately, the 30 samples of each servomotor angle are fitted using a MATLAB nonlinear regression method to a sinusoidal function whose amplitude and phase are stored and tabulated for input to the robotic fish [Figure 3(c)].

Software Description

Interaction with the robotic fish is enabled through an app for the iDevice offering three modes of control: 1) manual, 2) semiautonomous, and 3) autonomous. The modes differ in the degree of autonomy of the robotic fish, spanning from full autonomy to remote control by the user. At one extreme, the robotic fish is able to swim on its own without the need for user commands, while, at the other extreme, it is completely maneuvered by the user. In between is a mode in which the user controls the robotic fish via commanded waypoints. These modes are implemented through custom-developed software and a packet-based communication protocol.

Communication Protocol

The robot is controlled through a custom app running on an iDevice [Figure 4(a)]. The main nodes of the communication protocol are the robotic fish, base station, iDevice, and computer. The base station comprises an Arduino Uno microcontroller, an RFM22B radio shield, an Arduino Ethernet shield, and a Netgear wNR1000 wireless router. When the iDevice

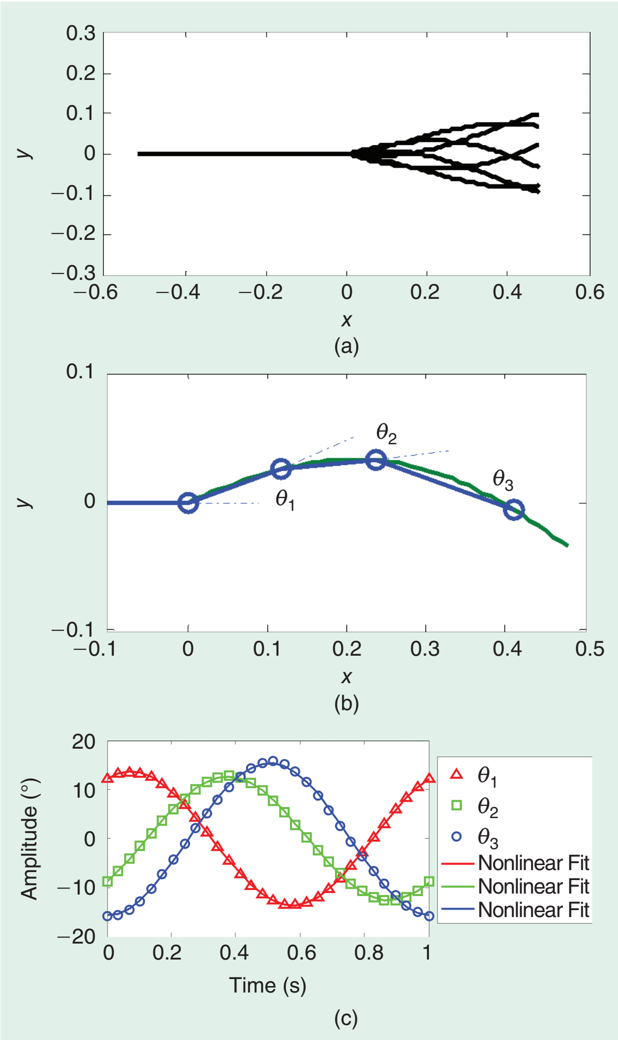

Figure 3. (a) The biomimetic model of a fish tail beating at various time instants. (b) The robotic link interpolation for a fixed time. (c) A nonlinear fitting of the time traces of the servomotor angles for $c_1 = 0.25$, $c_2 = -0.15$, $k = 4$, and $f = 1.0$ Hz. The required angles at various time instants are indicated by the red triangle markers (motor 1), the green square markers (motor 2), and the blue circle markers (motor 3). The nonlinear fittings for the motors are shown in their respective colors.

communicates to the robotic fish, the commands are relayed through the base station. The commands are first sent as packets through Wi-Fi to the wireless router in the base station using the user datagram protocol (UDP). Within the base station, the router forwards the commands to the microcontroller. The microcontroller then translates the commands using an RF22 library for Arduino and transmits a signal through the RFM22B radio transceiver to the transceiver located in the robotic fish. In other words, the base station converts the UDP commands from the app into a radio signal transmitted to the robotic fish.

While no additional hardware is required for the implementation of both the autonomous and the manual modes, an external computer and a Web camera are employed for real-time tracking and control in the semiautonomous mode. A Microsoft LifeCam Web camera is installed above the water surface in a setup similar to [34] and connected to a computer running Ubuntu 12.04 on an Intel Core i5 Processor. The computer is set to stream video at 15 frames/s to the wireless router in the base station utilizing a motion JPEG (MJPG)-streamer video library. Within the app, the GStreamer open-source library is used to receive and display the video stream from the Wi-Fi signal. Figure 4(b) shows the communication flow of this system. Two-way communication between the robotic fish and iDevice is achieved through this setup. The iDevice app is written in the Objective-C programming language using the Apple Xcode development environment.

iDevice App and Robot Control

A separate screen of the iDevice app is used for each mode of control, and a menu bar allows the user to switch between the modes. Figure 5 displays the three separate screens along with the welcome screen displayed upon activation of the app.

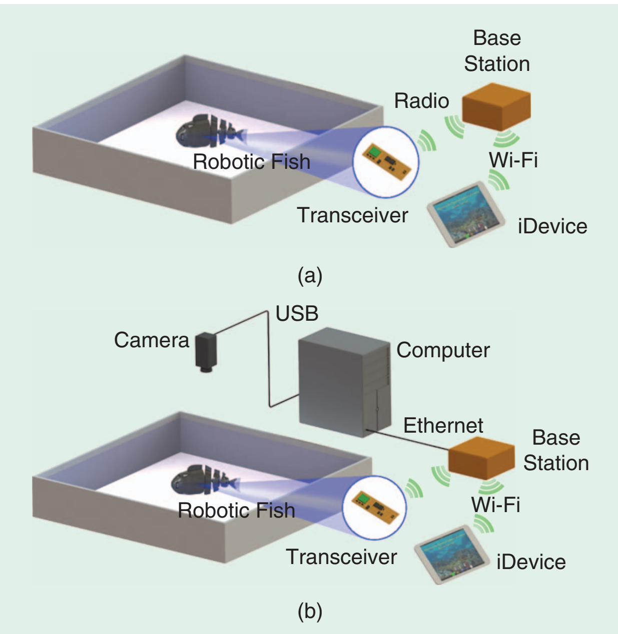

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Figure 4. A schematic representation of (a) the communication protocol between the robotic fish and the iDevice for the manual and autonomous modes and (b) the additional components required for the experimental setup in the semiautonomous mode.

Manual Mode

In the manual mode, a screen with sliders, buttons, and indicators is presented to enable direct control of the robotic fish. The buttons and sliders are clearly identified with a label to indicate their function. The available functions are the speed control, steering, diving, and ascension of the robotic fish. Indicators are displayed for the connection status, battery level, IR sensors, and an identifier for the robotic fish in the event that multiple robotic fish are in the water tank. To have a consistent biomimetic locomotion, the robotic fish is set to follow a wave pattern of constant k, c_1, and c_2 values. To control the speed of the robotic fish, a slider located on the left of the screen acts as a throttle for varying the propulsion. In particular, the throttle controls the robotic fish's speed by adjusting the tail-beat frequency. Steering the robotic fish is possible by sliding the steering button located at the bottom-center of the screen, which generates an offset angle for each of the sinusoidal functions transmitted to the servomotors.

Such an offset, in turn, produces a turning maneuver similar to the methodology proposed in [35]. In particular, by sliding the steering button to the maximum rightmost position, an offset angle of 18° is added to each of the sinusoidal functions transmitted to the servomotors. When the slider is in the neutral position, the offset angle is zero.

The diving of the robotic fish is controlled through a button labeled *Dive!* located toward the bottom-right of the screen, while the rising of the robotic fish is controlled through a button labeled *Surface!* located toward the top-right of the screen. Pressing the diving or the rising buttons causes the robotic fish to rise or dive for 25 s before leveling off by modulating its pitch.

In addition to control of the robotic fish, the manual mode graphically displays the feedback from the IR sensors between the dive and rise buttons. The microcontroller is programmed to set the threshold value of both sensors to 15 cm. Each sensor indicates to the microcontroller if there is any obstacle within 15 cm in front of that sensor. When the IR sensors are clear of obstacles, the indicator displays two green smiley icons. When one of the IR sensors detects an obstacle, the corresponding smiley icon changes into a red frowning icon, indicating danger ahead.

On the top-left of the screen, a textbox indicates which robotic fish the iDevice is currently controlling, providing a way to maneuver multiple robotic fish located in the same water tank. On the top-middle of the screen, the connection status between the robotic fish and the iDevice app is indicated with a green icon being displayed when the connection is stable and a red icon when the connection is unavailable. Finally, the battery status is displayed as a percentage of remaining battery power on the top-right of the screen.

Semiautonomous Mode

In the semiautonomous mode, the user is shown an overhead view of the fish tank through a Web camera. On this screen of the app, a red box is drawn on top of the robotic fish as a tracker to aid the user in visually identifying the robotic fish.

The user is instructed to create waypoints by tapping the screen, toward which the robotic fish is tasked to automatically swim in the order they are given. This created path is drawn on the screen using green circles and lines to distinguish it from the background video. The waypoints are programmed to remain inside the borders of the app and to not overlap with other waypoints by finding the closest valid position relative to the original position tapped by the user.

In the semiautonomous mode, the position and orientation of the robotic fish are controlled by a feedback algorithm implemented off board on a computer to minimize the relative error between the current and desired orientations. The computer utilizes image processing on the live video feed and MATLAB computer vision libraries to track the position of the robotic fish, which is then fed into a Kalman filter to obtain the current orientation using a method similar to [34]. Once the current orientation is known, a proportional-integral-derivative (PID) controller implemented in the same MATLAB script minimizes the error between the current and desired orientations, similar to [20]. The error is calculated as the projection on the plane perpendicular to the camera view of the cross product of the current orientation vector and the desired orientation vector. The error in pixels is then fed into the PID controller, which produces an offset angle as an output. This output is constrained in the MATLAB script to limit the maximum offset angle to 18° for each servomotor to avoid damage to the robotic fish. Finally, turning is implemented in the same method as the manual mode, whereby the offset angle is added to the sinusoidal functions at each servomotor.

Autonomous Mode

In the autonomous mode, the user is presented with a screen showing an animated fish swimming straight. The animated fish offers the user a visual representation of the swimming decisions of the robotic fish while in the autonomous mode. When only one IR sensor detects an object within its vicinity, a red brick wall appears in front of the animated fish on the corresponding side detected by the IR sensor. The animated fish then rotates to turn away from that wall. When both IR sensors detect an object, two red brick walls appear in front of the animated fish. The animated fish then makes a u-turn on the screen and swims away from the walls. The animated fish is reset to look forward and swim straight if objects are no longer detected by the IR sensors.

The animations on the screen are coordinated to the robotic fish swimming in the autonomous mode. In general, the robotic fish will swim straight until it detects an obstacle on either or both sensors. In the event that an object is detected within the threshold, the robotic fish performs a preprogrammed sharp turn maneuver, whereby the tail contracts

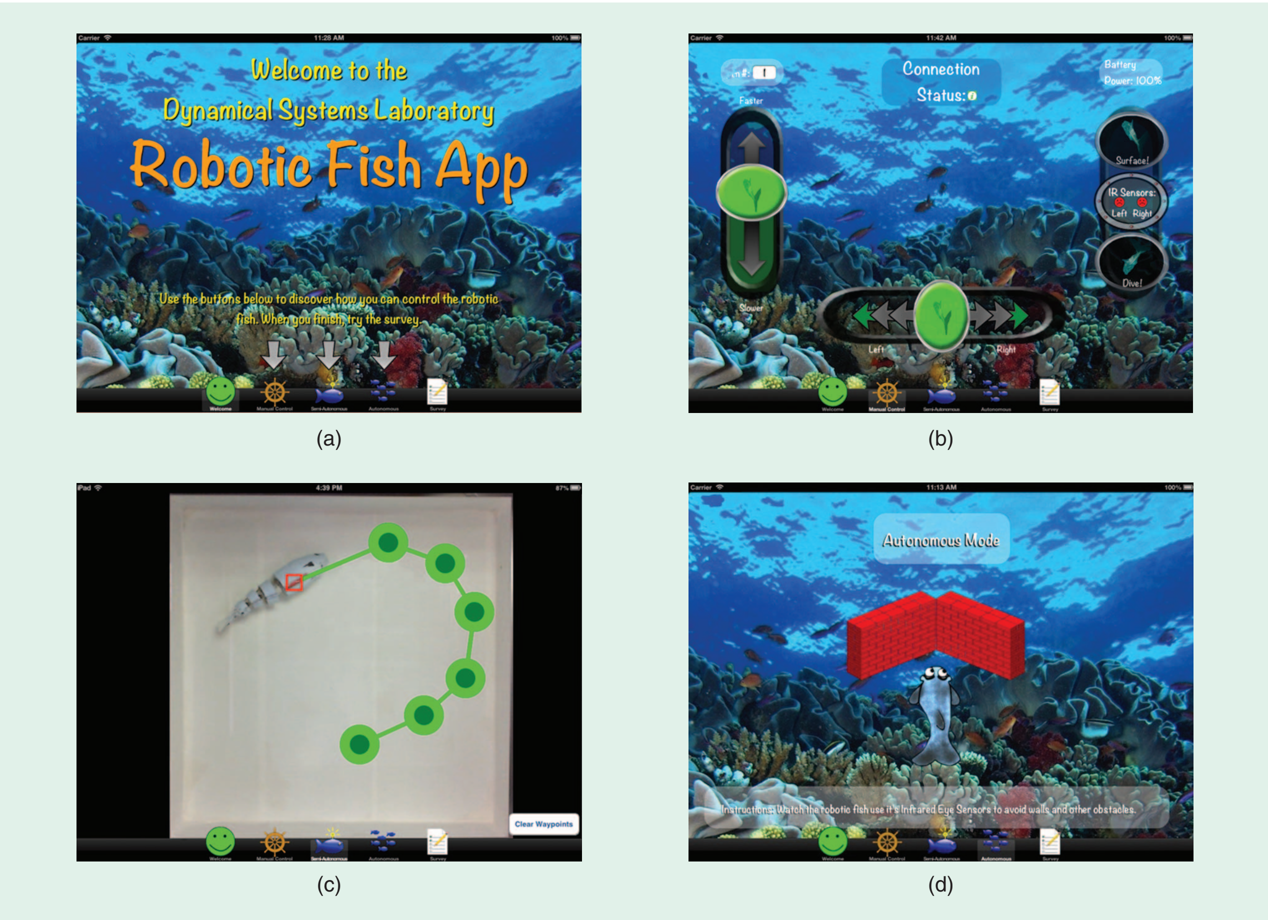

Figure 5. Screenshots of the iDevice app showing the (a) welcome screen, (b) manual mode, and (c) and (d) autonomous mode.

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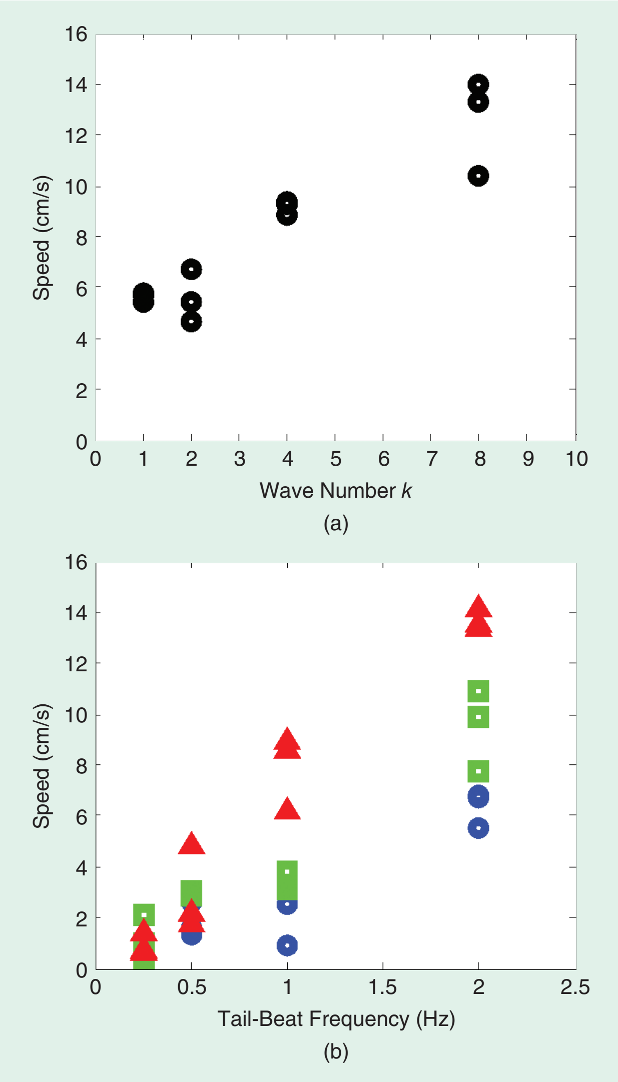

Figure 6. (a) The speed performance for various wave numbers and (b) the various amplitudes and frequencies. The conditions for amplitude 1 are indicated by the blue circle markers, while amplitude 2 is indicated by the green square markers, and amplitude 3 is indicated by the red triangle markers.

and expands rapidly to move away from the direction of the detected object, following [36]. In particular, when the tail contracts, each servomotor is sequentially commanded, starting from motor 1, to an angle offset of 30° in 1.1 s, and, when the tail uncurls, each servomotor's angle offset is returned back to zero in 0.45 s. The servomotors are commanded to increase the angle offset linearly with time. This turning implementation is selected to reduce the likelihood that the robotic fish will spend excessive time in a corner while swimming. When both IR sensors detect an object, the robotic fish activates a right-turn maneuver in an attempt to avoid the obstacles. The robotic fish continues to make turning maneuvers until no obstacles are detected.

Methods

To characterize the performance of the robotic fish, experiments are conducted in both the manual and semiautonomous modes. In the manual mode experiment, the performance of the robotic fish in the manual mode is assessed through a set of swimming tests conducted in a large swimming pool, a pitch test performed in a small tank, and a diving test conducted in the same large swimming pool used for the swimming tests. In the semiautonomous mode, an instrumented water tank with an overhead camera is used instead to demonstrate its feasibility.

Manual Mode

All swimming tests are conducted in a 3.8-m deep swimming pool at the New York University Coles Sports and Recreation Center. Therein, the speed of the robotic fish is measured as its swims according to the carangiform model [19], [30], [32], [33]. In particular, in a sequence of conditions, the model parameters $(c_1, c_2, k,$ and $f)$ are varied to determine the influence of the wave number, tail-beat amplitude, and tail-beat frequency on the robotic fish's speed, similar to [37]. For a given condition, trials are repeated to obtain an accurate measurement of the robotic fish's speed. For each trial, the robotic fish is recorded using a Canon Vixia HF R300 video camera while swimming in a straight trajectory alongside a measured length of 137 cm near the edge of a swimming pool. The motion of the robotic fish is recorded starting from rest to its terminal speed. A 10-s interval in which the robotic fish swims at its terminal speed is extracted from each recorded video and is separately analyzed through the motion tracking software ProAnalyst.

To determine the influence of the wave number on the robotic fish's speed, the parameters $(c_1 = 0.25, c_2 = -0.15,$ and $f = 1\,\text{Hz})$ are held constant while trials are conducted for four wave number conditions, $k = 1, 2, 4,$ and 8, with three trials per condition. To isolate the role of the tail-beat amplitude from the tail-beat frequency on the speed of the robotic fish, we also vary the values of the tail-beat amplitude: there are three different tail-beat amplitudes of 1.63, 3.26, and 4.89 cm, referred to as *amplitudes 1, 2, and 3*, respectively. Such amplitudes are obtained by selecting the following parameter sets: 1) $(c_1 = 0.083,\ c_2 = -0.05)$, 2) $(c_1 = 0.167,$ $c_2 = -0.10)$, and 3) $(c_1 = 0.25, c_2 = -0.15)$. For each of these parameter sets, trials are conducted with a wave number $k = 4$ and at the tail-beat frequencies $f = 0.25, 0.5, 1$ and 2 Hz with at least two trials per condition. In total, four conditions are executed when the wave number is varied, and 12 conditions are executed when the tail-beat amplitude and the tail-beat frequency are varied.

The static pitch test is conducted in a $51\,\text{cm} \times 32\,\text{cm} \times 26.5\text{-cm}$ water tank. When the robotic fish is set to neutral buoyancy, the pitch is controlled by the position of the balance mass inside the electronics housing. The maximum downward pitch angle is obtained when the balance mass is shifted toward the front of the robotic fish, while the maximum upward pitch angle is obtained when the balance mass is shifted toward the back of the robotic fish. The pitch angle is recorded using the Canon camera and measured from digital still images of the recording.

The diving test is performed in the same swimming pool used for the swimming tests. Therein, the robotic fish is set to

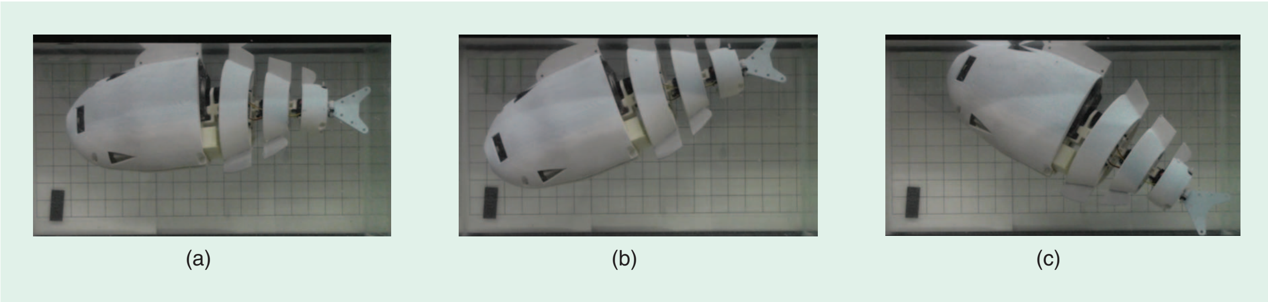

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Figure 7. The pitch performance for the robotic fish. The robotic fish can be set to (a) neutral pitch, (b) maximum downward pitch, or (c) maximum upward pitch.

neutral buoyancy with maximum downward pitch and commanded to swim with the parameters ($c_1 = 0.25$, $c_2 = -0.15$, $k = 4$, $f = 2$ Hz) corresponding to one of the conditions considered in the swimming tests. The robotic fish is recorded using the Canon camera as it dives from the surface of the pool to the bottom. The dive rate of the robotic fish is calculated from the time the robotic fish takes to reach the bottom of the pool, measured with a stopwatch.

Semiautonomous Mode

The semiautonomous mode experiment is conducted through a test in a laboratory setting at the New York University Polytechnic School of Engineering. The setup consists of a 120 cm × 120 cm × 20-cm water tank with each surface covered with white contact paper to provide a consistent background, similar to [34]. In this case, the water depth is maintained at 18 cm throughout the test and the Microsoft LifeCam Web camera is placed 142 cm above the water surface so that the image resolution is 2.76 mm/pixel. The PID controller is set with gains of $K_p = 5.25$ (°/pixel), $K_i = 7.5 \times 10^{-3}$ [°/(pixel × s)], $K_d = 7.5 \times 10^{-4}$ (°×s/pixel) corresponding to the proportional, integral, and derivative terms, respectively. The robotic fish is initially placed next to a wall of the water tank and tasked with tracking a circular path constructed by sequentially assigning 24 waypoints with a radius of 96.8 cm through a MATLAB script. In this test, the parameters are ($c_1 = 0.25$, $c_2 = -0.15$, $k = 4$, $f = 1.0$ Hz), corresponding to one of the conditions considered in the manual mode swimming tests.

Results

Manual Mode

The effect of varying the wave number on the robotic fish's speed performance is shown in Figure 6(a). Therein, we find that the terminal speed of the robotic fish increases as the wave number increases. Notably, a low wave number indicates a motion similar to thunniform or carangiform, while a high wave number indicates a motion similar to subcarangiform or anguilliform [31]. Thus, our results suggest that when the tail beating is set to resemble subcarangiform or anguilliform swimming, the robotic fish swims faster.

The effects of varying the tail-beat frequency and the tail-beat amplitude on the robotic fish speed are shown in Figure 6(b). The dependence of the speed on the tail-beat amplitude is more evident at higher tail-beat frequencies, whereby increasing the tail-beat amplitude from amplitude 1 to 3 produces an increase in the average speed of 7.4 cm/s for a tail-beat frequency of 2 Hz, while only a modest increase of 0.1 cm/s is found for a tail-beat frequency of 0.25 Hz. This result is in line with findings on other robotic fish designs, whereby a speed increase can be achieved by increasing the tail-beat frequency [18], [21] or tail-beat amplitude [37]. Furthermore, when the model parameters are set to ($c_1 = 0.25$, $c_2 = -0.15$, $k = 4$, $f = 2$ Hz), the robotic fish exhibits an average speed of 13.7 cm/s, or 0.30 body lengths per second (BL/s), which is comparable with the speed of other robotic fish designs based on caudal fin propulsion, ranging from 0.17–1.2 BL/s [38].

In the static pitch test, when the robotic fish is set to neutral buoyancy and the balance mass is at the center of its travel length, the robotic fish is pitching neither upward nor downward, as shown in Figure 7(a). On the other hand, Figure 7(b) shows that the robotic fish pitches downward at −17.4° with respect to the horizontal plane when the balance mass is shifted to the front. Similarly, Figure 7(c) shows that the

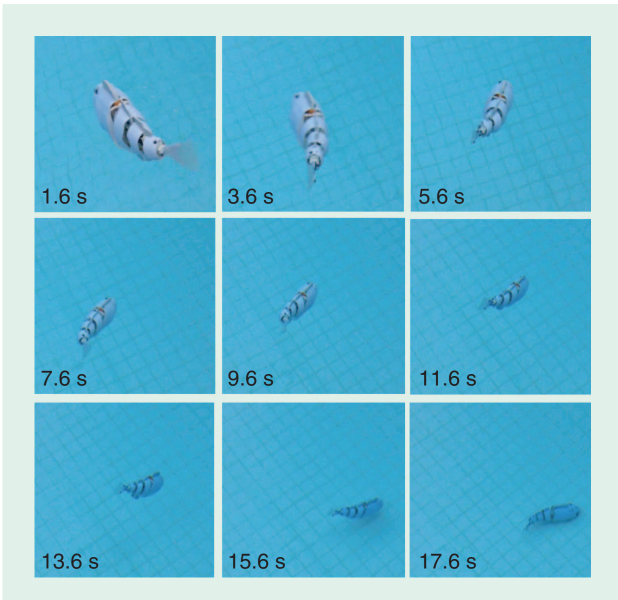

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Figure 8. A sequence of snapshots of the robotic fish during the diving test.

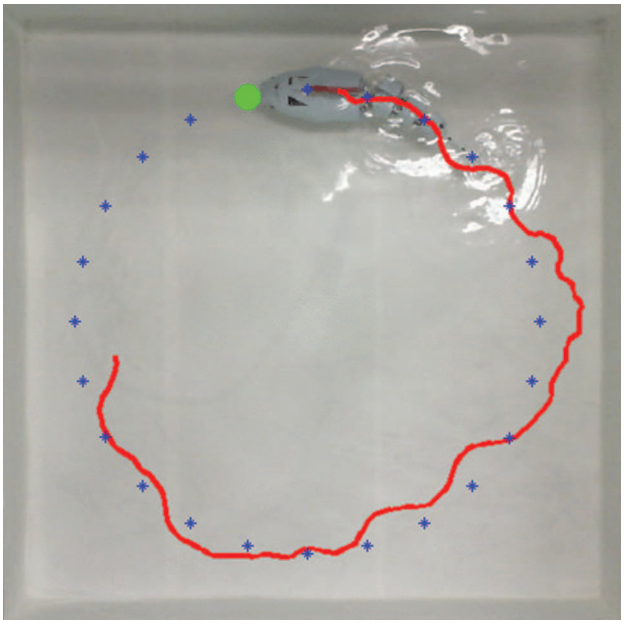

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Figure 9. The robotic fish swimming in a circular path utilizing a PID controller algorithm. The waypoints are indicated by the blue diamond markers. The next waypoint in the snapshot for the robotic fish is indicated by the green circle marker. The path taken by the robotic fish in 30 s is indicated by the red line.

robotic fish pitches upward to an angle of 31.5° when the balance mass is shifted toward the back. Thus, the total pitch range of the robotic fish is then 48.9°.

The combination of the pitch adjustment and the tail-beat undulation determine the ability of the robotic fish to dive in the swimming pool. In particular, Figure 8 suggests that the dive rate of the robotic fish is 21.6 cm/s, which corresponds to 0.47 BL/s. This value is highly comparable with the speed of the robotic fish for in-plane locomotion, thus offering indirect evidence for the ability of the robot to effectively maneuver in a 3-D environment.

Semiautonomous Mode

In the semiautonomous mode test, the robotic fish is commanded to follow a circular path for 5 min. As the robotic fish follows this path, it maintains an average speed of 9 cm/s. Figure 9 compares the path taken by the robotic fish to the circular path approximated by the waypoints. To quantify the accuracy of the waypoint tracking, we measure the radial error as the difference between the current position of the robotic fish and the nearest point on the desired circular path. The radial error is continuously calculated throughout the entire test at 12 frames/s for 300 s, and the average is calculated to be 1.05 cm with a standard deviation of 4.23 cm. In other words, as the robotic fish follows the circular path, 95% of the time it will remain within a range from 9.45 to −7.35 cm of the desired circular path. This test demonstrates the feasibility of utilizing the semiautonomous mode to accurately track 2-D trajectories prescribed by the user.

Table 1. The results of the response to usability and enjoyment survey questions.

Response to Usability	Manual Mode (Number of Students)	Semiautonomous Mode (Number of Students)
Easy	9	11
Medium	7	4
Difficult	1	2
Response to Enjoyment	**Manual Mode (Number of Students)**	**Semiautonomous Mode (Number of Students)**
a (smiley face)	15	15
b (neutral face)	2	2
c (frowning face)	0	0

Usability Study

As a demonstration of the potential of the proposed platform in aiding informal science education, a preliminary usability study is designed and conducted. The goal of this article is to assess the level of engagement of children and the degree to which they find the platform usable. The manual and semiautonomous modes are chosen for their interactive components. The survey is conducted at the New York University Polytechnic School of Engineering and includes 17 elementary school students with an average age of 9.2 years, without prior experience using the robotic fish.

The study is conducted as follows. First, the students are given a short lecture by a trained biologist from our group about the research on robotics and biology performed in our laboratory. Following this, the students are individually shown the robotic fish and given the iDevice app. The students are then encouraged to use both modes for at least 1 min per mode. Nine students are randomly assigned the manual control mode first, and eight students are given the semiautonomous control mode first. (The setup for the semiautonomous mode is analogous to that described in the "Methods" section.) Once the student is satisfied with controlling the robot, she/he is administered a survey asking for her/his opinion on usability, preferred mode of control, and enjoyment while interacting with the robotic fish.

To learn about the perceived usability of the platform, a student is asked the following question: for each of the following modes of control, please circle the word that describes how easy it was to control the robotic fish. The possible responses are easy, medium, and difficult. To learn about the students' enjoyment of the platform, the student is asked the following question: for each of the following modes of control, please circle the letter under the face that describes how much you like to use that mode of control. The possible responses are *a* for a smiley face, *b* for a neutral face, and *c* for a frowning face. To clearly identify which mode the student feels is easier to use, the student is asked the following question: please circle the mode that is easier for you to use. Similarly, to clearly identify which is the preferred mode, the student is asked the following question: please circle the mode that you prefer to use. For the responses to each of these questions, the student is given a binary choice between the manual and semiautonomous modes. Finally, to qualify the overall experience of the student and understand her/his level of enjoyment, the student is asked the following questions:

- Did you enjoy spending time today interacting with the robotic fish?
- Would you like to learn more about how the robotic fish was created?
- Would you like to learn more about how live fish swim?

For each question, the student can then respond with either yes, not sure, or no. The results from the survey are shown in Table 1.

To test the significance of students' opinions of the ease of use and enjoyment for the two modes, Cochran's Q tests [39] are utilized and calculated through the statistical software R (version 3.0.2) with a significance level of 0.05. The survey results indicate that the options for usability (easy, medium, and difficult) are not equally chosen by students in both manual (Cochran $Q = 6.11,\ p = 0.047$) and semiautonomous modes (Cochran $Q = 7.88,\ p = 0.019$). Only one student found the manual and two students the semiautonomous modes difficult to control the robotic fish. Similarly, the survey results indicate that the options for enjoyment (smiley, neutral, and frowning face) were not equally chosen by students in both the manual (Cochran $Q = 23.41,\ p < 0.001$) and semiautonomous modes (Cochran $Q = 23.41,\ p < 0.001$), whereby the vast majority of students enjoyed both modes. When comparing the modes, the students did not find one mode easier to use (Cochran $Q = 2.88,\ p = 0.089$) or more enjoyable (Cochran $Q = 0.52,\ p = 0.47$) than the other. The students were also found to positively respond to the robotic fish and the iDevice system. In particular, in response to the question, did you enjoy spending time today interacting with the robotic fish?, 100% of students indicated *yes*. Furthermore, 88% of students stated that they wanted to learn more about how the robotic fish is created. In addition, 76% of students responded *yes* to wanting to learn more about how live fish swim.

As expected from our previous work on iDevice-controlled robots [16], the users indicated that the robotic fish is easy to control and that they enjoyed interacting with both the tested modes. As discussed in [16], these findings should be attributed to the students' familiarity with touchscreen devices. As suggested by [12], children in fact demonstrated an increased mastery with repeated use on touchscreen devices. Another notable yet unexpected finding of this study is that students did not prefer one control mode over the other. It is likely that this may relate to the different learning styles of the relatively small group of students involved in this article [40]. In particular, active learners who rapidly understand the functions of the buttons and indicators may have chosen the manual mode, whereas reflective learners who engaged in the observation of the robotic fish swimming in the video feedback may have chosen the semiautonomous mode.

Conclusions

In this article, we have presented the design and development of a platform featuring a biomimetic robotic fish capable of 3-D underwater locomotion and remotely controlled by a custom iDevice app. The design of this platform is primarily motivated by the need to encourage the interaction of free-choice learners with exhibits at aquariums, zoos, museums, and other such informal science venues.

The novelties in the robotic fish design include the combination of the pitch and buoyancy control, custom-fabricated electronics, and biomimetic locomotion. The communication protocol between the iDevice, base station, and robotic fish through Wi-Fi and ultrahigh-frequency radio is also a novel feature of this platform. As such, the iDevice app enables the control of the robotic fish using ubiquitous smart devices through an original graphical user interface that offers three levels of autonomy. While more extensive usability studies for larger populations and users from different age groups are needed, our preliminary results indicate the feasibility of enhancing engagement in robotics and promoting curiosity in science and engineering through the unprecedented integration of robotic fish and iDevices in informal science learning.

Ultimately, this platform is expected to be integrated into informal science learning venues in New York City. In this direction, ongoing work is focused on devising techniques for operating the platform for several consecutive hours and testing the use of multiple robotic fish by different users.

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References

[1] T. Lauwers, E. Hamner, and I. Nourbakhsh, "A strategy for collaborative outreach: Lessons from the CSbots project," in *Proc. Technical Symp. Computer Science Education*, Milwaukee, WI, 2010, pp. 315–319.

[2] I. Nourbakhsh, E. Hamner, B. Dunlavey, D. Bernstein, and K. Crowley, "Educational results of the personal exploration rover museum exhibit," in *Proc. IEEE Int. Conf. Robotics Automation*, Barcelona, Spain, 2005, pp. 4278–4283.

[3] T. Lauwers, I. Nourbakhsh, and E. Hamner, "CSbots: Design and deployment of a robot designed for the CS1 classroom," in *Proc. Technical Symp. Computer Science Education*, Chattanooga, TN, 2009, pp. 428–432.

[4] T. Shibata, K. Wada, and K. Tanie, "Subjective evaluation of a seal robot at the national museum of science and technology in Stockholm," in *Proc. IEEE Int. Workshop Robots Human Interactive Communications*, 2003, pp. 397–402.

[5] H. Hu, "Biologically inspired design of autonomous robotic fish at Essex," in *Proc. IEEE SMC UK-RI Chapter Conf.*, Sheffield, U.K., 2006, pp. 3–8.

[6] iTersNews. (2012, Feb. 15). SRC Inc. of Korea eyes growth potentials of Korea's robot market. [Online]. Available: http://itersnews.com/?p=16838

[7] T. Ichiklzaki and I. Yamamoto, "Development of robotic fish with various swimming functions," in *Proc. IEEE Symp. Underwater Technology Workshop Scientific Use Submarine Cables Related Technologies*, 2007, pp. 378–383.

[8] B. Schneider and N. Cheslock, *Measuring Results: Gaining Insight on Behavior Change Strategies and Evaluation Methods from Environmental Education, Museum, Health, and Social Marketing Programs.* San Francisco, CA: Coevolution Institute, 2003.

[9] S. Allen, "Designs for learning: Studying science museum exhibits that do more than entertain," *Sci. Educ.*, vol. 88, no. S1, pp. S17–S33, 2004.

[10] M. S. Lewis, J. Zhao, and J. K. Montclare, "Development and implementation of high school chemistry modules using touch-screen technologies," *J. Chem. Educ.*, vol. 89, no. 8, pp. 1012–1018, 2012.

[11] J. A. Frank and V. Kapila, "Development of mobile interfaces to interact with automatic control experiments [focus on education]," *IEEE Control Syst. Mag.*, vol. 34, no. 5, pp. 78–98, 2014.

[12] L. J. Couse and D. W. Chen, "A tablet computer for young children? Exploring its viability for early childhood education," *J. Res. Technol. Educ.*, vol. 43, no. 1, pp. 75–98, 2010.

[13] T. Geller, "Interactive tabletop exhibits in museums and galleries," *IEEE Comput. Graph. Appl.*, vol. 26, no. 5, pp. 6–11, 2006.

[14] P. F. J. Pazmino, B. L. Silva, B. Slattery, and L. Lyons, "Teachable mo[bil] ment: Capitalizing on teachable moments with mobile technology in zoos," in *Proc. Conf. Human Factors Computing Systems*, Paris, France, 2013, pp. 1–6.

[15] N. Haywood and P. Cairns, "Engagement with an interactive museum exhibit," in *Proc. Human Computer Interaction*, London, U.K., 2006, pp. 113–129.

[16] N. Abaid, J. Bernhardt, J. A. Frank, V. Kapila, D. Kimani, and M. Porfiri, "Controlling a robotic fish with a smart phone," *Mechatronics*, vol. 23, no. 5, pp. 491–496, 2013.

[17] N. Abaid, V. Kopman, and M. Porfiri, "The story of a Brooklyn outreach program on biomimetics, underwater robotics, and marine science for K-12 students," *IEEE Robot. Automat. Mag.*, vol. 20, no. 2, pp. 31–39, 2013.

[18] J. Yu, M. Tan, S. Wang, and E. Chen, "Development of a biomimetic robotic fish and its control algorithm," *IEEE Trans. Syst. Man Cybern. B*, vol. 34, no. 4, pp. 1798–1810, 2004.

[19] P. V. Alvarado and K. Youcef-Toumi, "Design of machines with compliant bodies for biomimetic locomotion in liquid environments," *ASME J. Dyn. Syst. Meas. Control*, vol. 128, no. 1, pp. 3–13, 2006.

[20] V. Kopman, J. Laut, F. Acquaviva, A. Rizzo, and M. Porfiri, "Dynamic modeling of a robotic fish propelled by a compliant tail," *IEEE J. Oceanic Eng.*, vol. 40, no. 1, pp. 209–221, 2015.

[21] V. Kopman and M. Porfiri, "Design, modeling, and characterization of a miniature robotic fish for research and education in biomimetics and bioinspiration," *IEEE ASME Trans. Mechatron.*, vol. 18, no. 2, pp. 471–483, 2013.

[22] J. Wang, P. K. McKinley, and X. Tan, "Dynamic modeling of robotic fish with a base-actuated flexible tail," *ASME J. Dyn. Syst. Meas. Control*, vol. 137, no. 1, p. 011004, 2014.

[23] D. Lopez, J. A. Frank, and V. Kapila, "Comparing interface elements on a tablet for intuitive teleoperation of a mobile manipulator," in *Proc. ASME Biennial Conf. Engineering Systems Design Analysis*, Copenhagen, Denmark, 2014, pp. 25–27.

[24] S. Luna. (1990, Jan. 15). Stenotomus chrysops. [Online]. Available: http://www.fishbase.org/summary/Stenotomus-chrysops.html

[25] X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong, "Re-evaluation of RF electromagnetic communication in underwater sensor networks," *IEEE Commun. Mag.*, vol. 48, no. 12, pp. 143–151, 2010.

[26] A. Alessi, A. Sudano, D. Accoto, and E. Guglielmelli, "Development of an autonomous robotic fish," in *Proc. IEEE RAS EMBS Int. Conf. Biomedical Robotics Biomechatronics*, Rome, Italy, 2012, pp. 1032–1037.

[27] K. H. Low, "Locomotion simulation and system integration of robotic fish with modular undulating fin," *Int. J. Simulation*, vol. 7, no. 8, pp. 64–77, 2008.

[28] M. Malec, M. Morawski, and J. Zając, "Fish-like swimming prototype of mobile underwater robot," *J. Autom. Mob. Robot. Intell. Syst.*, vol. 4, no. 3, pp. 25–30, 2010.

[29] F. Zhang, T. John, C. Thon, and X. Tan, "Miniature underwater glider: Design and experimental results," *IEEE ASME Trans. Mechatron.*, vol. 19, no. 1, pp. 394–399, 2014.

[30] D. S. Barrett, M. S. Triantafyllou, D. K. P. Yue, M. A. Grosenbaugh, and M. J. Wolfgang, "Drag reduction in fish-like locomotion," *J. Fluid Mech.*, vol. 392, no. 1, pp. 183–212, 1999.

[31] M. Sfakiotakis, D. M. Lane, and J. B. C. Davies, "Review of fish swimming modes for aquatic locomotion," *IEEE J. Oceanic Eng.*, vol. 24, no. 2, pp. 237–252, 1999.

[32] G. Polverino, P. Phamduy, and M. Porfiri, "Fish and robots swimming together in a water tunnel: Robot color and tail-beat frequency influence fish behavior," *PLoS One*, vol. 8, no. 10, p. e77589, 2013.

[33] J. Yu, L. Wang, and M. Tan, "Geometric optimization of relative link lengths for biomimetic robotic fish," *IEEE Trans. Robot.*, vol. 23, no. 2, pp. 382–386, 2007.

[34] S. Butail, T. Bartolini, and M. Porfiri, "Collective response of zebrafish shoals to a free-swimming robotic fish," *PLoS One*, vol. 8, no. 10, p. e76123, 2013.

[35] J. Liu, I. Dukes, R. Knight, and H. Hu, "Development of fish-like swimming behaviours for an autonomous robotic fish," in *Proc. Control*, Bath, U.K., 2004, pp. 1–5.

[36] J. Liu and H. Hu, "Mimicry of sharp turning behaviours in a robotic fish," in *Proc. IEEE Int. Conf. Robotics Automation*, Barcelona, Spain, 2005, pp. 3318–3323.

[37] Q. Yan, Z. Han, S. W. Zhang, and J. Yang, "Parametric research of experiments on a carangiform robotic fish," *J. Bionic Eng.*, vol. 5, no. 2, pp. 95–101, 2008.

[38] D. T. Roper, S. Sharma, R. Sutton, and P. Culverhouse, "A review of developments towards biologically inspired propulsion systems for autonomous underwater vehicles," in *Proc. Institution Mechanical Engineers, Part M: Journal Engineering Maritime Environment*, London, U.K., 2011, pp. 77–96.

[39] W. J. Conover, *Practical Nonparametric Statistics*. New York: Wiley, 1999.

[40] R. M. Felder and L. K. Silverman, "Learning and teaching styles in engineering education," *Eng. Educ.*, vol. 78, no. 7, pp. 674–681, 1988.

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