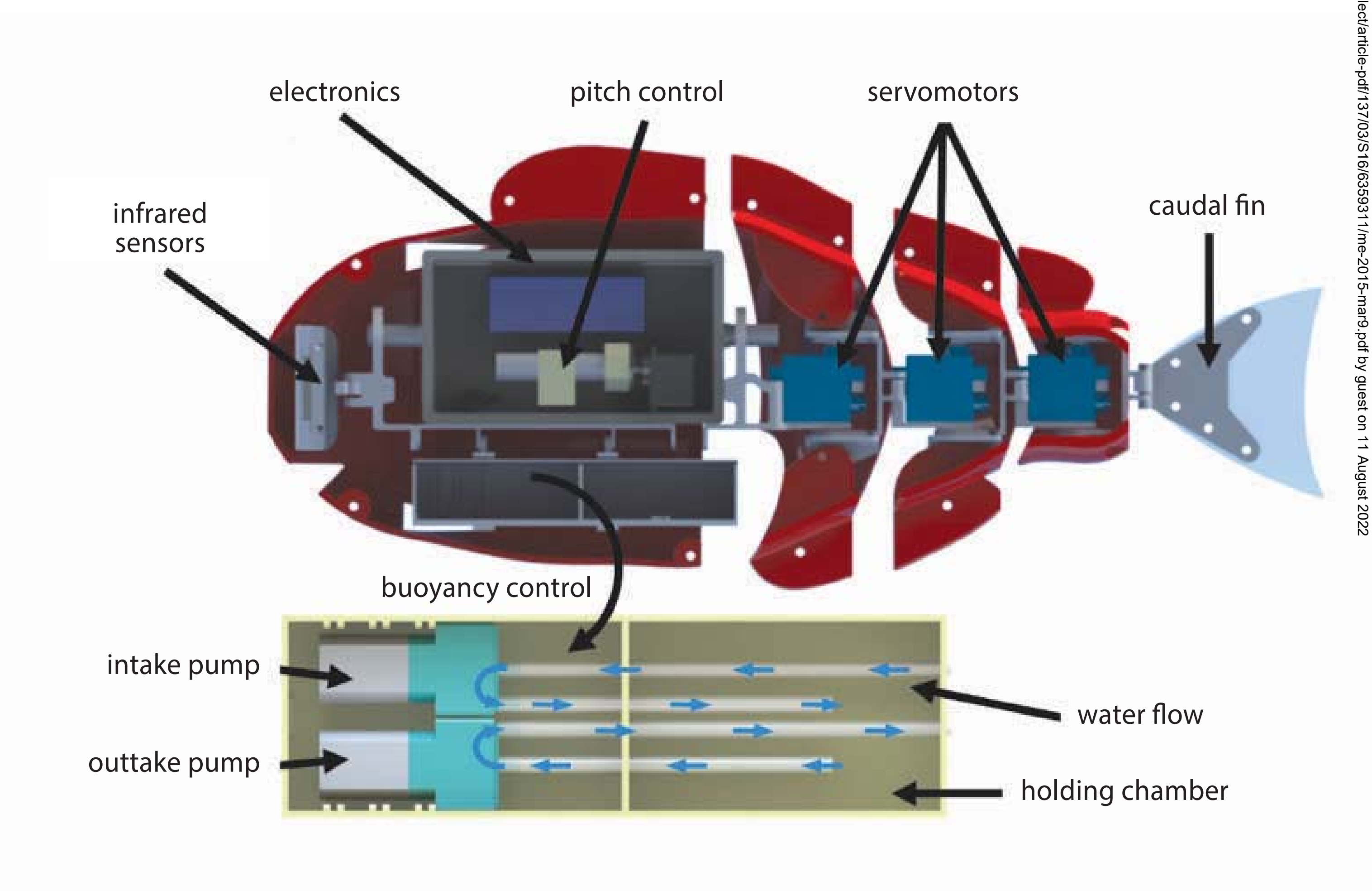
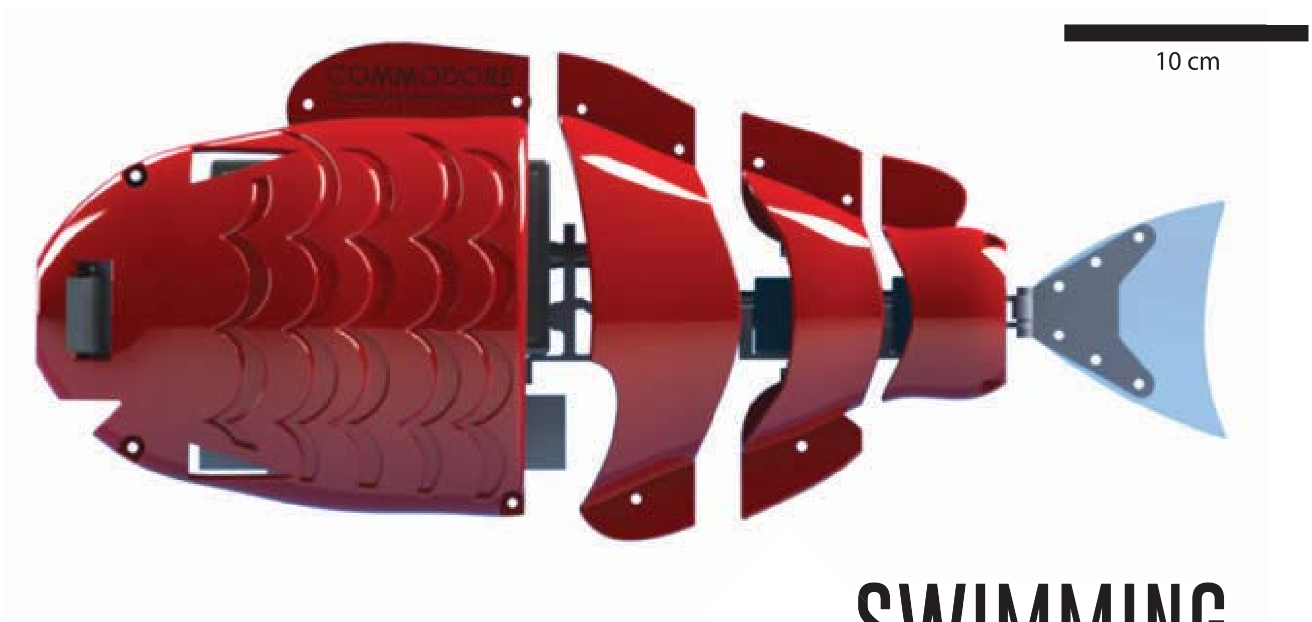
ROBOTIC FISH

Paul Phamduy and Maurizio Porfiri
Department of Mechanical and Aerospace Engineering
New York University Polytechnic School of Engineering





SWIMMING OUTSIDE THE SCHOOL TO AID INFORMAL SCIENCE EDUCATION

Informal science education is the process of scientific learning that takes place outside of the classrooms and academic institutions [1, 2]. It is the most predominant form of learning across life-long education, is spontaneous in nature, and has practically unlimited opportunities [1, 2]. Informal learning can occur through visits to museums and galleries, participation in science festivals, and even watching educational programs [1].

For visitors to informal science venues, robotics has been shown to be an effective tool to elicit their interest, as it often affords several elements of novelty [3]. Further, robotics offers quick feedback for participants to test new ideas or reinforce preexisting knowledge [4, 5]. Thus, a number of robotics-based exhibits, such as the exploratory rover [6], robotic dolphin [7], and remotely-controlled miniature boats [8], have been designed to increase visitors' interest in robotics, while delivering important topics in science, like space exploration [6] and environmental mapping [8].

Biologically-inspired robotic fish have been found to be particularly engaging [7, 9, 10], likely due to the additional connections to the natural world they can offer [11]. Thus, a few robotic fish exhibits have been deployed to engage and educate visitors in public aquariums and expositions [9, 10]. However, such exhibits are often limited in the level of interactivity they afford, which is known to be a key factor in informal science education [12, 13].

FIGURE 1 *(Above)* **The robotic fish, Commodore.**

FIGURE 2 *(Left)* **Exposed view of electronics, sensors, pitch control, buoyancy control, and robotic fish tail.**

A novel interactive robotic fish exhibit has been developed at the Dynamical Systems Laboratory of New York University (NYU) Polytechnic School of Engineering to address this gap [14]. The exhibit features Commodore (Figure 1), a robotic fish based on a multi-link design with a pitch and buoyancy control system for three-dimensional biologically-inspired swimming. An ad hoc iDevice application with three control modes varying in the level of robot autonomy provides visitors with a unique experience to control the robotic fish swimming.

BIOLOGICALLY-INSPIRED ROBOTIC FISH

Commodore is designed with inspiration from the Atlantic scup fish, *Stenotomus chrysops*. The cover of the robotic fish is fabricated through a rapid prototyping machine from solid-packing acrylonitrile butadiene styrene plastic. Its mechanical design includes a three degree-of-freedom motorized tail, electronics housing, and pitch and buoyancy control systems (Figure 2). The undulation of the tail enables the robotic fish to swim in two dimensions, and the pitch and buoyancy control systems allow the fish to dive and surface. The robotic fish measures 48 cm in length, 19 cm in height, and 10 cm in width.

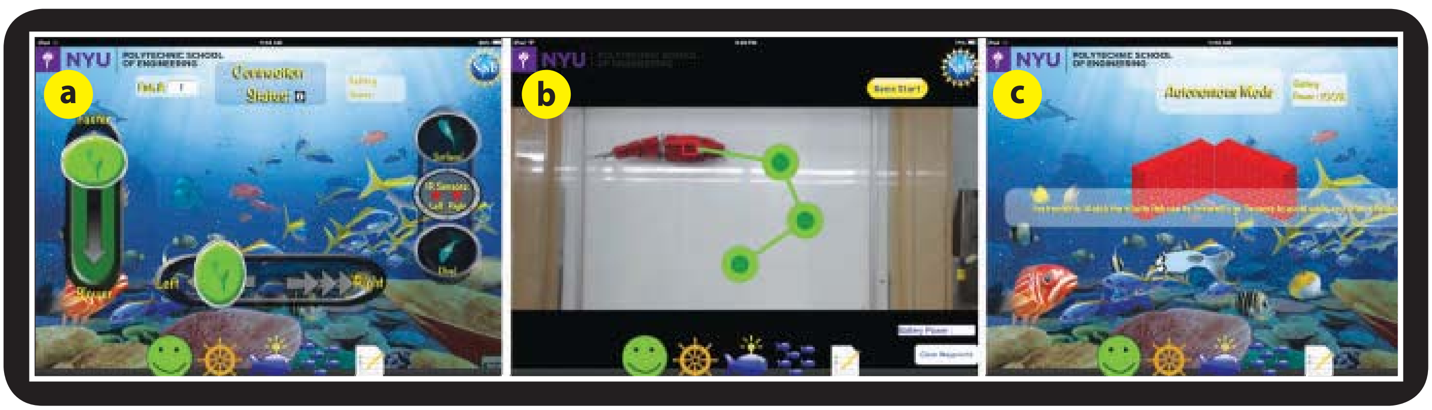
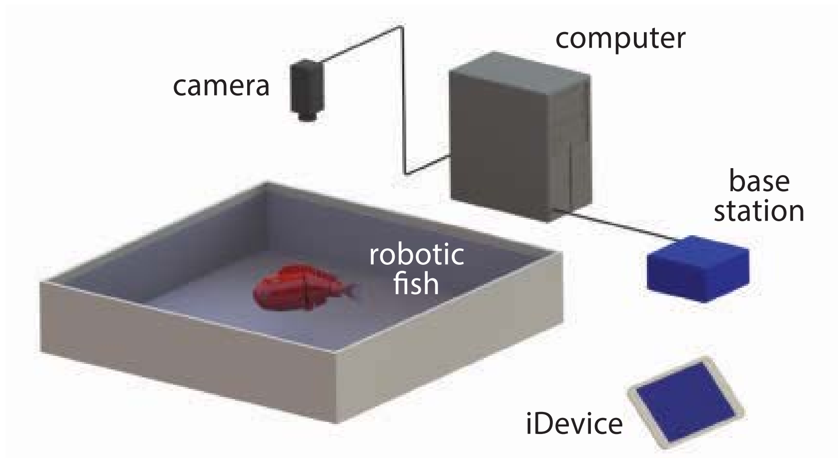


FIGURE 4 iDevice application screens (a) manual, (b) semi-autonomous, and (c) autonomous.

Electronics

The primary electronic components of Commodore include an Arduino-based microcontroller, a radio transceiver, and a 2200 mAh 7.4V lithium polymer battery. A battery charge sensor, composed of a voltage divider, is incorporated to assist with monitoring the battery power level. Two infrared (IR) sensors, facing 120° apart, are mounted on the front of the robotic fish to provide navigational information when walls or obstacles are detected.

FIGURE 3
Communication protocol between the robotic fish and iDevice.



Pitch and Buoyancy Control

The combination of the pitch and buoyancy control systems is used to adjust the depth of the robotic fish. Specifically, the buoyancy control system heuristically sets the robotic fish to neutral buoyancy by adjusting the water content within a rigid volume tank.

The pitch angle is regulated by shifting a balance mass with a 2.2 cm travel length. This mass is used to control the center of gravity of Commodore with respect to the center of buoyancy, thus tilting it upwards (positive pitch) or downwards (negative pitch). When Commodore is close to neutral buoyancy, adjusting the pitch angle while beating the tail allows rising and diving.

The buoyancy system comprises a rigid enclosure, fabricated using rapid prototyping, which contains two separate chambers (Figure 2). One chamber encases two motors, pumping water between the second holding chamber and the environment through airline tubing, while the other chamber simply holds the water. Commodore can reach neutral buoyancy as the water in the latter holding chamber is varied.

Fish Tail

The tail of the robotic fish consists of three servomotors connected by rigid plastic links and a rubber silicone caudal fin. Coordinating these three motors causes the tail to undulate and the Commodore to swim. A simplified model for carangiform fish swimming [15] is used to mimic the swimming pattern of a real scup fish.

COMMUNICATION AND IDEVICE APPLICATION

A communication network is developed to operate Commodore from a custom iDevice application (Figure 3). In the network, a user datagram protocol (UDP) is utilized to communicate between the base station, a desktop computer, and the iDevice for delivering important messages, such as the control mode and its key parameters. The base station comprises a microcontroller, a radio shield, an Ethernet shield, and a wireless router, and is used to translate commands from UDP to radio signals for Commodore.

The three control modes have separate screens on the iDevice application (Figure 4). i) In the manual mode, the user has the option to use sliders and buttons to directly control the robotic fish, including the tail-beat frequency, steering, diving, and surfacing. ii) In the semi-autonomous mode, the user can generate a waypoint path for Commodore to follow, by tapping on the iDevice screen that shows a real-time bird's-eye view of the tank through an overhead webcam. The robotic fish then automatically swims along the prescribed path by implementing a proportional-integral-derivative (PID) controller on its orientation, using feedback from the webcam. iii) In the autonomous mode, an animated fish is displayed on the screen, offering the user a visual representation of the swimming decisions of Commodore. When one of the IR sensors detects an object within its vicinity, the user observes a red brick wall appearing in front of the animated fish, and the robotic fish and its animation both react to turn away from the obstacle.

FIGURE 5 *(Above)* **Robotic fish platform deployed at the World Science Festival.**

FIGURE 6 *(Right, below)* **Robotic fish platform and educational materials at the Brooklyn Children's Museum.**

APPLICATIONS IN INFORMAL SCIENCE

The robotic fish platform was deployed in various informal science events and venues, in April 2014 at the USA Science and Engineering Festival, in May 2014 at NYU Polytechnic School of Engineering Research Expo, and in June 2014 at the World Science Festival (Figure 5). All events were open and accessible to the general public, whereby thousands of visitors interacted with Commodore over the course of the summer of 2014.

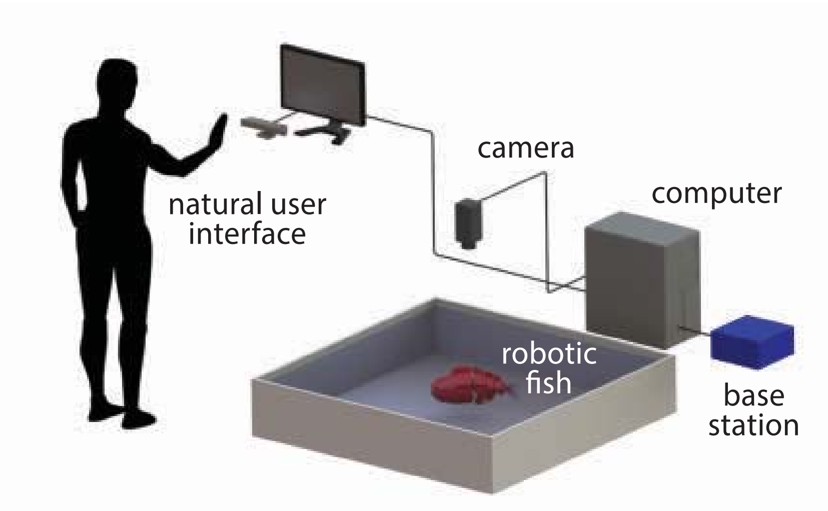


FIGURE 7 Natural user interface for controlling a robotic fish.

At these events, data from 224 visitors were recorded: users spent on average 85 seconds in the manual mode, 69 seconds in the semi-autonomous mode, and 5 seconds in the autonomous mode. Due to the nature of the events, the popularity of the exhibit amongst youngsters, and the high visitor traffic, when opportunity arose to use the iDevice application, visitors were inclined to select an interactive control mode over the autonomous, passive mode.

An optional questionnaire was administered to visitors after controlling the robotic fish, to acquire feedback on the usability of the platform and learn their thoughts on pertinent environmental issues. Users indicated that the experience was enjoyable, rating the exhibit on average 4.6 out of 5 stars, and identified marine pollution, overfishing, and climate change as the most pressing environmental issues we are currently facing.

To allow visitors additional time to interact with the platform and to examine uninterrupted interactions with Commodore, the platform was customized to operate in a 1000 liter tank (Figure 6) and demonstrated to the public in New York City, at The River Project from August 19, 2014 to September 22, 2014 and at the Brooklyn Children's Museum from October 9, 2014 to January 19, 2015. In this platform, the robotic fish was presented alongside educational material that was created based on the usability studies and interactions with education professionals.

OUTLOOK ON FUTURE RESEARCH

To further expand on the degree of interactivity of Commodore, we are exploring natural user

REFERENCES

1 H. L. Ainsworth and S. E. Eaton, *Formal, Non-formal and Informal Learning in the Sciences*. Calgary, Canada: Onate Press, 2010.

2 J. Banks, K. Au, A. Ball, P. Bell, E. Gordon, K. Gutiérrez, *et al.*, "Learning in and out of school in diverse environments: Life-long, life-wide, life-deep," The LIFE Center, Seattle, WA2007.

3 J. H. Falk and J. D. Balling, "The field trip milieu: Learning and behavior as a function of contextual events," *J. Educ. Res.*, vol. 76, no. 1, pp. 22-28, 1982.

4 C. Wilkinson, K. Bultitude, and E. Dawson, "Oh yes, robots! People like robots; the robot people should do something: perspectives and prospects in public engagement with robotics," *Sci. Commun.*, vol. 33, no. 3, pp. 367-397, 2010.

5 D. P. Miller, I. R. Nourbakhsh, and R. Siegwart, "Robots for education," in *Springer Handbook of Robotics*, ed Berlin, Germany: Springer, 2008, pp. 1283-1301.

6 I. Nourbakhsh, E. Hamner, E. Ayoob, E. Porter, B. Dunlavey, D. Bernstein, *et al.*, "The Personal Exploration Rover: Educational assessment of a robotic exhibit for informal learning venues," *Int. J. Eng. Educ.*, vol. 22, no. 4, pp. 777-791, 2006.

7 J. Yu, M. Wang, M. Tan, and J. Zhang, "Three-dimensional swimming," *IEEE Robot. Automat. Mag.*, vol. 18, no. 4, pp. 47-58, 2011.

8 J. Laut, S. Wright, O. Nov, and M. Porfiri, "Gowanus Voyage: Where mechatronics, public art, community members, and environmental science meet," *IEEE Control Syst.*, vol. 34, no. 1, pp. 60-64, 2014.

9 Y. Terada and I. Yamamoto, "An animatronic system including lifelike robotic fish," *Proc. IEEE*, vol. 92, no. 11, pp. 1814-1820, 2004.

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

11 J. H. Falk, E. M. Reinhard, C. Vernon, K. Bronnenkant, J. E. Heimlich, and N. L. Deans, *Why zoos & aquariums matter: Assessing the impact of a visit to a zoo or aquarium*. Silver Spring, MD: Association of Zoos & Aquariums, 2007.

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

13 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.

14 P. Phamduy, R. LeGrand, and M. Porfiri, "Design and characterization of an interactive iDevice-controlled robotic fish for informal science education," *IEEE Robot. Automat. Mag.*, accepted for publication, 2015.

15 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.

16 H. M. J. Hsu, "The potential of Kinect in education," *Int. J. Inform. Educ. Technol.*, vol. 1, no. 5, pp. 365-370, 2011.

17 T. M. Alisi, A. Del Bimbo, and A. Valli, "Natural interfaces to enhance visitors' experiences," *IEEE Multimedia*, vol. 12, no. 3, pp. 80-85, 2005.

18 K. Johnson, J. Pavleas, and J. Chang, "Kinecting to mathematics through embodied interactions," *Computer*, vol. 46, no. 10, pp. 101-104, 2013.

19 B. Lange, C. Y. Chang, E. Suma, B. Newman, A. S. Rizzo, and M. Bolas, "Development and evaluation of low cost game-based balance rehabilitation tool using the Microsoft Kinect sensor," in *Proc. Ann. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Boston, MA, USA, 2011.

interfaces. Such interfaces have been shown to be effective tools for enhancing user engagement and learning [16-18]. A proposed platform to control a robotic fish with a natural user interface is illustrated in Figure 7. This system can possibly involve a mini-game, such as to collect water temperature, to further encourage user engagement [19].

In a parallel research effort, we are also investigating a new autonomous charging station for the robotic fish to minimize maintenance by museum personnel. A proposed platform for enabling continuous use of an untethered robotic fish through a direct contact approach is sketched in Figure 8.

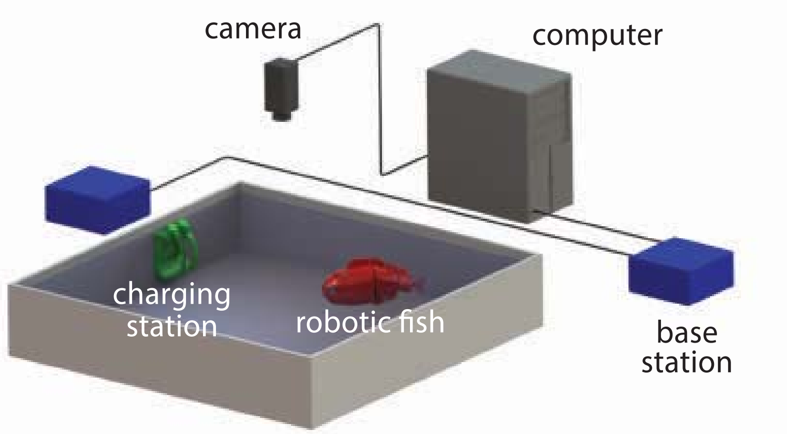


FIGURE 8 Autonomous charging station for a robotic fish.

CONCLUSIONS

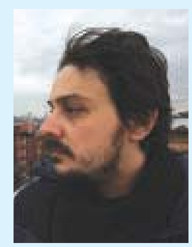
An interactive robotic fish exhibit was developed to aid informal science learning. The platform has been well received by visitors and has contributed to increasing their interest in robotics. Integrating natural user interfaces and autonomous charging into the exhibit is expected to further enhance the visitor experience and strengthen the feasibility of robotics-based informal science education. ■

ACKNOWLEDGEMENTS

The authors would like to thank Drs. Mary Leou and Catherine Milne for important feedback on the informal science education aspects of the platform; Raymond LeGrand and Chengxing Zhang for the implementation of iDevice applications; Jayhwan Cheong, Mauro DeBellis, Chengxing Zhang, and Chun Hsien-Wu for assistance with hardware development; Jeffrey Laut and Tiziana Bartolini for help with planning and implementing the events; The River Project and the Brooklyn Children's Museum for graciously hosting Commodore; and all the visitors for their valuable feedback. This research was supported by the National Science Foundation under grant nos. CMMI-0745753, DGE-0741714, and DRL-1200911.

ABOUT THE AUTHOR

Paul Phamduy was born in Lowell, Massachusetts in 1988. He received B.Sc. and M.Sc. degrees in mechanical engineering from the University of Massachusetts, Lowell, in 2010 and 2012, respectively, and is working toward a Ph.D. degree in mechanical engineering at New York University. His doctoral research, supported by the National Science Foundation, focuses on biologically-inspired robotics with application to animal behavior and informal science education. Since 2012, he is a recipient of a National Science Foundation GK-12 fellowship in the Applying Mechatronics to Promote Science program.



Maurizio Porfiri was born in Rome, Italy in 1976. He received M.Sc. and Ph.D. degrees in engineering mechanics from Virginia Tech, in 2000 and 2006; a laurea in electrical engineering (with honours) and a Ph.D. in theoretical and applied mechanics from the University of Rome "La Sapienza" and the University of Toulon (dual degree program), in 2001 and 2005, respectively. From 2005 to 2006 he held a post-doctoral position with the Electrical and Computer Engineering Department at Virginia Tech. He has been a member of the faculty of the Mechanical and Aerospace Engineering Department of New York University Polytechnic School of Engineering since 2006, where he is currently a professor. He is engaged in conducting and supervising research on dynamical systems theory, multiphysics modeling, and underwater robotics. Maurizio Porfiri is the author of more than 150 journal publications and the recipient of the National Science Foundation CAREER award (dynamical systems program) in 2008. He has been included in the "Brilliant 10" list of *Popular Science* in 2010 and his research featured in all the major media outlets, including CNN, NPR, *Scientific American*, and Discovery Channel. Other significant recognitions include invitations to the Frontiers of Engineering Symposium and the Japan-America Frontiers of Engineering Symposium organized by National Academy of Engineering in 2011 and 2014, respectively; the Outstanding Young Alumnus award by the College of Engineering of Virginia Tech in 2012; the ASME Gary Anderson Early Achievement Award in 2013; and the ASME DSCD Young Investigator Award in 2013.