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Frank Bonnet · Francesco Mondada

Shoaling with Fish: Using Miniature Robotic Agents to Close the Interaction Loop with Groups of Zebrafish *Danio rerio*

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Many men go fishing all of their lives without knowing that it is not fish they are after.

—Henry David Thoreau

Foreword

Robotics is undergoing a major transformation in scope and dimension. From a largely dominant industrial focus, robotics is rapidly expanding into human environments and vigorously engaging in its new challenges. Interacting with, assisting, serving, and exploring with humans, the emerging robots will increasingly touch people and their lives.

Beyond its impact on physical robots, the body of knowledge robotics has produced is revealing a much wider range of applications reaching across diverse research areas and scientific disciplines, such as: biomechanics, haptics, neurosciences, virtual simulation, animation, surgery, and sensor networks among others. In return, the challenges of the new emerging areas are proving an abundant source of stimulation and insights for the field of robotics. It is indeed at the intersection of disciplines that the most striking advances happen.

The *Springer Tracts in Advanced Robotics (STAR)* is devoted to bringing to the research community the latest advances in the robotics field on the basis of their significance and quality. Through a wide and timely dissemination of critical research developments in robotics, our objective with this series is to promote more exchanges and collaborations among the researchers in the community and contribute to further advancements in this rapidly growing field.

The monograph by Frank Bonnet and Francesco Mondada is based on the first author's doctoral thesis. It effectively brings together concepts from robotics and biomimetics. Novel tools are introduced that can integrate shoals of zebrafish and characterise their collective behaviours. Bio-inspired controllers are designed for the robots to mimic fish locomotion underwater.

Rich of examples developed by means of extensive experimentation on mixed groups of fish and robots, this volume was the co-winner of the 2018 Georges Giralt Ph.D. Award for the best doctoral thesis in Europe. A very fine addition to the STAR series!

Naples, Italy
February 2019

Bruno Siciliano
STAR Editor

Acknowledgements

This work was part of a multidisciplinary project involving many people from different fields for several years, and its achievement would not have been possible without their contributions.

First and foremost, I would like to thank my supervisor Francesco Mondada. Francesco taught me how to manage such a multidisciplinary project with many partners from different backgrounds. He offered me the freedom in my work, while orienting me during the harder times. He gave me the opportunity to teach at the university level during the time of this thesis, and provided me with a great research environment, with dynamic people and enriching discussions, which improved a lot the quality of this work.

This thesis would also not have been possible without the work, help and friendship of Alexey Gribovskiy. Alexey is the person who first hired me for a semester project that involved the first design of one of the robots that is presented in this thesis, and he is the one who first convinced me of doing a Ph.D. He also contributed to the project proposal that financed my thesis, and, finally, advised and contributed largely to this work. Alexey was always a great motivator and his expertise in this field was very precious.

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also invested a lot of energy to design various parts of the robots and experimental setup, and for that I am very grateful. Dany and Norbert also brought a lot of positive atmosphere in the open space, which made every work day a pleasure to be there. I also would like to thank Philippe Rétornaz for his precious advices and coding capacities that accelerated the development of the project in its early phase. Thanks go to Christophe Barraud who replaced me during the first phase of the project and realized progress on the robotic design, and to Marcelo Elias de Oliveira for his contribution on the software side. I am grateful to Manon, Léa and Maria for their designer expertise that improved the presentation of this work. I thank also the rest of the group with which it was a pleasure to work with: Anne, Claudia, Vincent, Fanny, Florian, Stefan, Gordana, Morgane, Yui, Olguta, Hadi, Mariza, Michael, Ehsan, Stéphane and Martin.

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This work would not have been possible without the support of my family and friends. I am deeply grateful to my parents, Michéle and Jean-Luc, for their support and encouragements during my life, and especially throughout my studies. Thanks also to my sister Sandra for helping me sorting my Legos during my childhood, and to my grandparents, Janine and Robert for their continuous support and lifestyle example. I have some gratitude also to my family-in-law, especially to Anna and Sergei, for always welcoming me well during my trips to Moscow and for interesting conversations.

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Finally, I would like to thank all the zebrafish that participated in my experiments and with which we have shared some difficult moments. Making experiments with animals taught me also lessons on how to respect and admire more the animal world that surround us, and that, most of the time, the capacities and intelligences of these organisms are neglected by us. I hope that these fish also enjoyed their time in our laboratory and the company of our robotic fish.

Lausanne, Switzerland Frank Bonnet
March 2017

About This Book

Robotic animals are nowadays developed for various types of research, such as bio-inspired robotics, biomimetics and animal behavior studies. The miniaturization of technologies and the increase in performance of embedded systems allowed engineers to develop more powerful, sophisticated and miniature devices. The case of robotic fish is a typical example of such challenging design: the fish locomotion and body movements are difficult to reproduce and the device has to move autonomously underwater. More specifically, in the case of collective animal behavior research, the robotic device has to interact with animals by generating and exploiting signals relevant for social behavior. Once perceived by the animal society as conspecific, these robots can become powerful tools to study the animal behaviors, as they can at the same time monitor the changes in behavior and influence the collective choices of the animal society.

In this work, we present novel robotized tools that can integrate shoals of fish in order to study their collective behaviors. This robotic platform is composed of two subsystems: a miniature wheeled mobile robot that can achieve dynamic movements and multi-robot long-duration experiments, and a robotic fish lure that is able to beat its tail to generate fish-like body movements. The two subsystems are coupled with magnets which allow the wheeled mobile robot to steer the robotic fish lure so that it reaches very high speeds and accelerations while achieving shoaling. An experimental setup to conduct studies on mixed societies of artificial and living fish was designed to facilitate the experiments for biologists. A software framework was also implemented to control the robots in a closed-loop using data extracted from visual tracking that retrieved the position of the robots and the fish. We selected the zebrafish *Danio rerio* as a model to perform experiments to qualify our system. We used the current state of the art on the zebrafish social behavior to define the specifications of the robots, and we performed stimuli analysis to improve their developments. Bio-inspired controllers were designed based on data extracted from experiments with zebrafish for the robots to mimic the zebrafish locomotion underwater.

Experiments involving a robot with a shoal of fish in a constrained environment showed that the locomotion of the robot was one of the main factors to affect the collective behavior of zebrafish. We have also shown that the body movements and the biomimetic appearance of the lure could increase its acceptance by fish. Finally, an experiment involving a mixed society of fish and robots qualified the robotic system to be integrated among a zebrafish shoal and to be able to influence the collective decisions of the fish. These results are very promising for the field of fish-robot interaction studies, as we showed the effect of the robots in long-duration experiments and repetitively, with the same order of response from the animals.

Keywords Animal-robot interaction • Collective behavior • Mobile robotics • Biomimetic robots • Underwater robotics • Visual tracking • Multi-agent system • Zebrafish

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