Development of a mobile robot to study the collective behavior of zebrafish

Frank Bonnet, Philippe Rétornaz, José Halloy, Alexey Gribovskiy and Francesco Mondada

Abstract— **A robot accepted by animals as conspecifics is a very powerful tool in behavioral biology, particularly in studies of gregarious animals. In this paper we present a robotic zebrafish designed for experiments on the collective animal behavior. The robot consists of two modules: a replica fish fixed on the magnetic base and a miniature mobile robot guiding the replica fish from below the experimental tank. The size of the mobile robot is 45x15x73 mm that makes it possible to use it in a group of robots forming a dense artificial fish school. The experiments showed that the robot can reach speed and acceleration maximums reported for zebrafish, thus its parameters satisfy the conditions necessary for the next step that will be interaction tests with the zebrafish.**

I. INTRODUCTION

Mechanisms of interactions between animals have always been one of the long-standing interests in behavioral research. It was shown in [1] that animal communication can be based on rather simple signals and that it is possible to interact with animals by making specifically designed artifacts that generate and exploit only a part of signals relevant for social behavior. At that time, the level of technology was not high enough to use real robots for this purpose. The rather simple mock-ups were used instead, each of those usually served to study only one specific behavior. Naturally, these devices could not support complex interaction and did not possess any adaptive capabilities. Recently, technology became more advanced and affordable, and such simple tools were replaced by robotic devices, capable of sending cues to the animal, of sensing the response and of adapting its behavior to it. This made it possible to test animal response to various signals very precisely as every element of the robot behavior can be individually controlled including the signals emitted. For social animals, such systems should be able to deal with groups of animals and not only be limited to one-robot-to-one-animal interactions.

Nowadays, we observe a growing number of research projects that address this type of scientific question. One of the examples is the Leurre project [2], where a mixed society consisting of cockroaches and mobile robots was created, where robots were able to interact with cockroaches, and, as members of the society, they could participate in social decisions. In fishes, a robotized model of the three-spined sticklebacks was used to study collective behavior in [3]. The honeybee dance communication system is another interesting research topic that was addressed in the RoboBee project, where the aim was to build a honeybee robot imitating a honeybee dance [4] to study effects and importance of various signal combinations. A bio-inspired robotic rat presented in [5] was designed as an experimental tool to study social interactions between rats and robots. Finally, in our previous work we developed a mobile robot PoulBot to study collective behavior in domestic chicken [6]; we demonstrated that the robot can be successfully socially integrated into the animal group, thanks to the imprinting mechanism, that is confirmed by the following behavior demonstrated by imprinted animals.

In this paper, we present first results on development of the robotic zebrafish. The goal again is to make a robot that can be socially integrated into a fish school, that is, accepted by animals as a member of the group and able to interact with the animals by using relevant communication channels. An intended purpose of such a robot is to be a tool in studies of social and collective animal behavior that demand 'insider' capabilities, that is, the use of artificial agents considered by the animals as group-mates. We chose the zebrafish (*Danio rerio*) as a model animal, since it is one of the most important vertebrate model organisms in genetics, developmental biology, neurophysiology and biomedicine [7].

The paper is organized as follows: Section II provides a specification that we used to design the robot; in Section III we describe a hardware design of the robot: actuators used, mechanical design and electronics; and Section IV gives an overview of the control system of the robot. Section V presents experimental results and, finally, Section VI concludes this paper.

II. SPECIFICATION

The design of a robot dedicated to experiments with animals have to originate from relevant sensory modalities and behaviors of the animal under study [8]. Hence, a good understanding of animal biology and behaviors, both on the individual and collective levels, must precede the robot design process.

The zebrafish (Fig. 1) is a social species that prefer to swim in groups (to shoal). Individuals rarely exceed 40 mm standard length (from the tip of the snout to the origin of the caudal fin) [7]. The shoaling behavior is believed to be innate, it commences soon after hatching. Shoaling decisions

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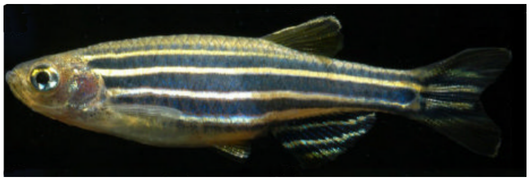

Fig. 1: An adult wild type zebrafish [12]

in fishes often depend on the phenotypic characteristics of group members (such as body size or color) [9], [10]; for the zebrafish, experimental results demonstrated that individuals show preference towards their own conspecifics, with the color, body shape and stripes playing an important role [11], [12].

Based on this data in the beginning of this project we draw up the following specification for the robot: dimensions of the robotic fish have to correspond to the dimensions of the real fish: total length 45 mm, maximum body height 10 mm, maximum body width 5 mm. The robot has to be designed taking into account that it will be used in the multi-robot experiments, where robots can approach one another considerably close (1-2 cm). The robot has to provide wireless communications and the following speed capabilities: maximal speed 0.5 m/s and acceleration 2 m/s^2. The speed and acceleration parameters were selected based on the available experimental results [13] and on several experimental videos available by the start of the project.

III. HARDWARE DESIGN

If we look at the specification from the previous section it becomes clear that the main limiting factor is the size of the robot. There are already several robotic fishes built around the world but they model the relatively big fishes [14], [15]; to make a biomimetic autonomous underwater robot of a size of zebrafish poses serious technological challenges. That is why in our work following ideas presented in [3] we decided to decouple the active (sensing and actuating) robotic part from the biomimetic passive lure. In [3] a replica fish made from a mold of a dead three-spined stickleback and painted to match the color pattern of the fish was fixed on the magnetic base those movement was guided by the electromagnet under the tank. The electromagnet was mounted on the a pulley system, attached to two stepper motors providing a movement along the width and the length of the tank. The drawback of this design is that only one robotic fish can be used per experimental setup, thus behavior experiments including several robots are not possible. Our goal is to go beyond this limitation by using an autonomous mobile robot as a locomotion base guiding the mockup fish.

The prototype of the robot is presented on Fig. 2, it consists of two parts: a mobile robot that moves under the aquarium and a replica fish module with a mockup fish attached to it that moves in the aquarium. The advantage of using the miniature mobile robot as a locomotion means for the replica fish is that several robots can act on the same setup thus making possible experiments on mixed groups of robots and animals. In this section we present the hardware of the robot – its electronics and mechanical design.

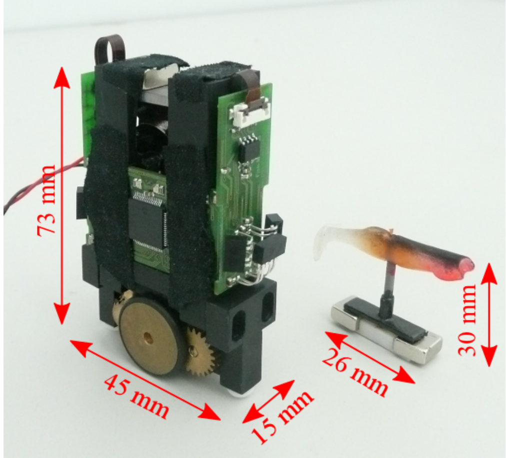

Fig. 2: The overall view of the robotic fish: a mobile robot module on the left and a passive mock-up fish module on the right. Here we use an artificial fish used in fishing that will be further replaced by a zebrafish replica.

A. Actuators determination

For the mobile robot we selected a two-wheel differential-drive configuration with two additional ground contact points used for stability. Such a configuration allows to achieve high maneuverability as the robot can spin on the spot.

To select suitable motors we estimate the required rotation speed ω_m and torque T_m as

$$T_m = \frac{F_r R_w}{2r}, \tag{1}$$

$$\omega_m = \frac{r V_r}{R_w}, \tag{2}$$

where F_r is the force needed to accelerate the robot at the maximal acceleration (2 m/s^2), R_w is the radius of the wheels, r is the reduction and V_r is the maximal speed (0.5 m/s).

The forces acting upon the system when the robot accelerates are represented on Fig. 3, hence the force F_r needed to accelerate the robot is

$$F_r = Ma + F_{f,b} + F_{f,r} + F_{d,m} + F_{d,b}, \tag{3}$$

where M is the mass of the robot and the mockup fish module together ($M \simeq$180g). The friction forces ($F_{f,b}$ and $F_{f,r}$) have been estimated using the static friction formula $F_f = \mu_s P$, where P is the weight of the body and μ_s the static friction coefficient. The drag forces ($F_{d,m}$ and $F_{d,b}$) on the fake fish and the mobile have been computed as

$$F_d = C_d A \left(\frac{\rho V_0^2}{2}\right). \tag{4}$$

Here A, ρ and V_0 note the drag area, fluid density and free-stream velocity measured relative to the object respectively.

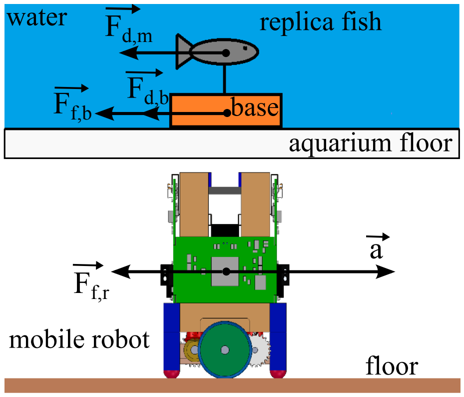

Fig. 3: Diagram of forces acting upon the mobile robot and the mockup fish module when the robot accelerates. Drag forces $F_{d,m}$ and $F_{d,b}$ act upon the mockup fish and upon its base, and friction forces $F_{f,b}$ and $F_{f,r}$ are exerted by the tank floor on the base of the mockup fish module and by the floor on the ground contact points of the mobile robot.

The drag coefficient C_d has been estimated using engineering tables from [16].

Two Maxon DC motors were preselected thanks to their small diameter (8 mm) and a high nominal torque (0.616 mNm) (article number 347725 in the Maxon catalog). Magneto resistive encoders of these motors (Maxon encoder MR Type S 100CPT (334910)) provide 6400 position readings per wheel's round, which guarantees a good precision for speed and position control. Maxon 1:16 gears (Maxon Planetary Gearhead GP 8A 16:1 (370420)) were combined with the motors to multiply their torque and a wheels' diameter of 20 mm was chosen in order to obtain the best trade-off between the torque T_m and the rotational speed ω_m of the wheels. As it is shown on Fig. 4, bevel and spur gears were used to transmit the motion to the wheels. Once all the component were selected, we did an estimation of the final torque taking into account yield and inertia of the transmission in order to validate the choice of motors, gears, wheels diameters and transmission. We use the following relation between the torque, inertia and angular acceleration of the wheels:

$$T = I_{fW}\alpha_w \tag{5}$$

Here the inertia seen from the wheel (I_{fW}) is computed using all inertia and yield of the transmission

$$I_{fW} = I_w + \eta_R\eta_b\eta_s r^2 I_m + \eta_R\eta_b\eta_s r^2 I_R + \eta_b\eta_s I_b + \eta_s I_s, \tag{6}$$

where I_w, I_m, I_R, I_b, and I_s are the inertia of the wheel, motor, gear, bevel gear and spur gear and η_R, η_b, and η_s are the yield of the gear, bevel gear and spur gear and r the reduction. We assume here that the robot's wheels don't slip on the ground. We can then find the angular acceleration α_w of the wheels:

$$\alpha_w = \frac{r\eta_R\eta_b\eta_s T_m - T_w}{I_{fW}}, \tag{7}$$

where T_m and T_w are the torque of the motors and wheels.

This estimation shows that the mobile robot can theoretically move the mockup module with a maximum speed of 0.87 m/s and acceleration 5 m/s^2 at the motor nominal voltage of 6V, thus validating the choice of motors and the transmission.

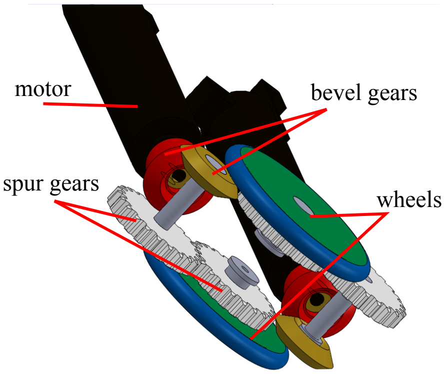

Fig. 4: Overview of the design of the transmission of the mobile robot. Bevel gears are used for the transmission between motors and axes and then spur gears are used to transmit the motion to the two independent wheels.

B. Mechanical design

The mechanical design of the mobile robot is presented on Fig. 5, its length 45 mm and width 15 mm are defined by the specification. The height of the robot is 73 mm. The robot is composed of two principal parts: a chassis (Fig. 5(c)) holding the axes of the wheels and gears and a main body (Fig. 5(a)) on which the motors, magnets, electronics and two adjustable skates are mounted.

The chassis is made of Polyoxymethylene (POM), while the wheels and axes are made of brass. Since the friction between POM and brass is very low, no bearing are used for the rotation of the axes. The O-rings are used to increase the friction between the wheels and the ground.

Two NdFeB magnets (8x8x4 mm) are fixed on an iron plate on top of the main body in such a way that one magnet has the north pole on its top side and the other magnet has it on the bottom part. The magnetic field is very well conducted by the iron and does not perturb the encoders or electronics of the robot. The magnets can easily be changed depending on the strength required that depends on the distance between the mobile robot and the replica fish module.

C. Electronics design

The control circuit board of the robot is presented on the Fig. 6. It consists of three boards soldered together at 90 degrees angle to guarantee a stable connection between them. The central board carries the microcontroller DSPIC33 by Microchip and a Bluetooth module, while the motor drivers were put on the side boards. The nominal motors voltage is 6V, but in order to increase the capacities of the prototype it is possible to increase the voltage up to 10V. To guarantee a

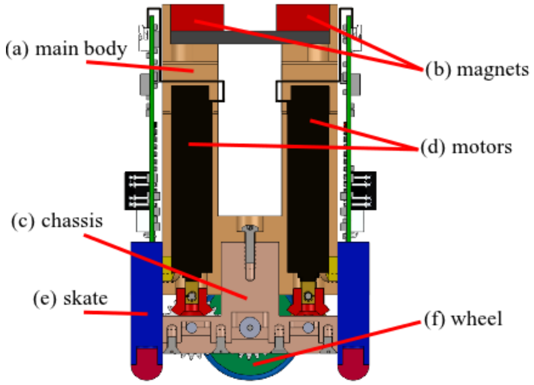

Fig. 5: The side view of the mobile robot. The chassis is fixed with the main body by a screw. Skates on the front and back of the robot can be adjust using screws. The magnets are fixed to a iron plate on the top of the robot.

safe displacement in the multi-robot experiments the robot is equipped with six infrared sensors TCRT1000, three in front of the robot and three in the back. One sensors is oriented straight and the two others are oriented with a 45 degrees angle. The sensors can detect obstacles up to 5 cm. The Bluetooth device LMX 9838 is used to communicate with the robot using UART. It is protected by the main body of the robot and can be removed as it is only plugged with connectors.

The current prototype of the robot is powered by a wire, while the next version will have a power supply more suited for the multi-robot experiments.

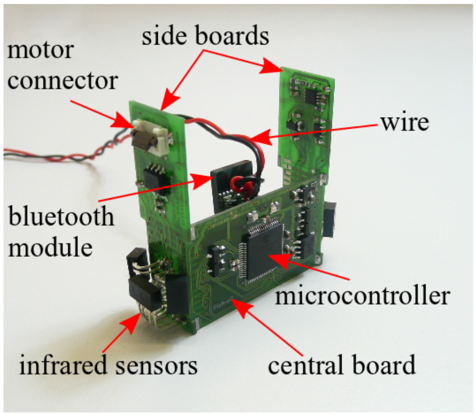

Fig. 6: Overview of the control circuit board. It composed of three boards, the main board with a DSPIC33FJ128 microcontroller and a Bluetooth module, and two boards with motors drivers and infrared sensors.

D. *Fish replica module*

The replica fish module (Fig. 7) consists of the mockup fish fixed on the base. The base is made of Polytetrafluoroethylene that guarantees a low friction with the aquarium floor. An iron plate is screwed to it holding the magnets that have the same orientation configuration as the magnets on the mobile robot, thus both the robot and the replica fish module always have the same orientation. The mockup fish is attached to the thin rode soldered on the iron plate. Thanks to this configuration, various types of mockup fishes can be used in the experiments thus making the developed robot an universal experimental tool. On the current prototype a Orka fish lure is used. It has approximately the same dimensions as the zebra fish. For the experiments with the fishes the base will be painted in white color to make it less visible by animals.

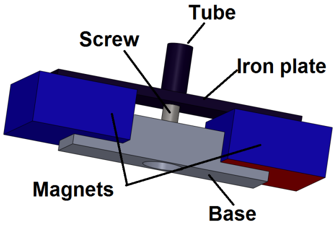

Fig. 7: Design of the mockup fish module.

IV. CONTROL SYSTEM

Each motor's torque is controlled by a PI controller running at 1KHz which is itself controlled in speed by a PID controller using the motor encoders (Fig. 8). A infinite impulse response (IIR) filter with the same time constant as the motor thermal time constant is run on the microcontroller. By controlling precisely the current inside each motors, based on the estimated power dissipation from the IIR filter, we are able to ensure that we never overheat the motor. Such control architecture enables to use the motors with a higher than manufacturer-specified nominal voltage thus providing a higher torque for a short period of time; this can be particularly useful when building a robot for experiments with fishes, as fish movements are composed of shorts burst of acceleration followed by a slow deceleration. The control is done separately for each motor.

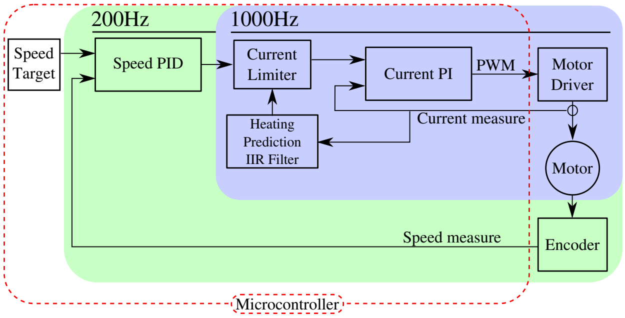

Fig. 8: Motors's control architecture.

At a higher level, a joystick is used to remotely control the robot to make it follow certain specific trajectories. A Matlab script is getting information from the joystick and sends those information to the robot using a serial communication. The robot automatically stops when it detects an obstacle using its six infrared sensors.

For now, a simple ASCII-based communication protocol is implemented between the control PC and the robot. We will implement an Aseba [17] control system in the near future. This will help to improve the control strategies of the robot by being able to dynamically change the behavior of the robot. Moreover as shown in [18], this enable interesting cooperation possibilities in multi-robot experiments.

V. PERFORMANCE EVALUATION

To evaluate the technical performance of the robot, to verify that the speed and acceleration that it is able to achieve correspond to the specification, we carried out a series of experiments.

A. *Experimental setup*

The experimental setup is presented on Fig. 9, it is composed of the following components: a wooden frame holding a test tank and a wooden plate used as a floor for the robot, an overhead camera and a stand alone PC. A test tank is an aquarium 1x1x0.25 m. A sheet of a gray paper is placed under the aquarium to provide a homogeneous background and thus to simplify the tracking task. The PC runs the vision system and records experimental video. To track robot displacements we use the Scout Gigabit Ethernet color camera scA1000-30gc by Basler Vision Technologies It takes images of the setup (1032 x 778 pixels) with a frame rate 15 fps.

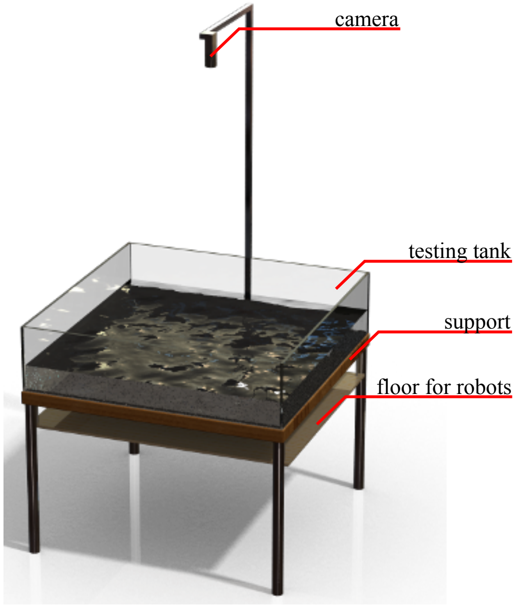

Fig. 9: An overview of the experimental setup.

The image processing is performed by the custom written tracking software that relies on the OpenCV computer vision library [19] for image processing. The mockup fish can be detected by subtracting the background image and binarizing the result with a predefined threshold. All positions and distances are measured in the real-world coordinates thanks to the calibration routine based on the well known Tsai's calibration technique.

B. *Results*

Before the whole system was tested in the tank, we had measured the performance of the mobile robot. The robot steadily achieved speed of 0.75 m/s and acceleration of 2.81 m/s^2; the tracks were used to guarantee that the robot goes straight and thus to have reliable measurements.

Then we ran a series of tests in the experimental tank. Results of a sample test are presented on Fig. 10-12. Noise on data has been decreased using a Savitzky-Golay filter. In this test, the goal was to try to reach the speed of 0.6 m/s. As we can see from Fig. 11-12 the robot was able to achieve a speed of 0.57 m/s with the peak acceleration equal to 1.8 m/s^2.

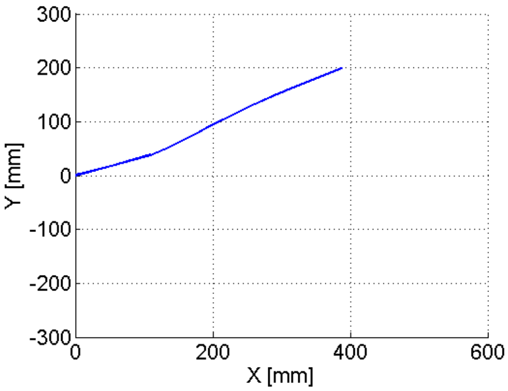

Fig. 10: A sample experimental trajectory of the robotic fish.

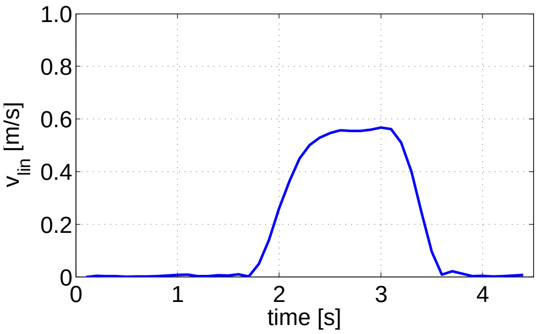

Fig. 11: The speed profile of the robotic fish, corresponding to the trajectory on Fig. 10.

The demonstrated values are very close to the ones of the real zebrafish, and, as we see, the achieved speed even exceeds the specification requirements. In the same time the acceleration value is 10% lower than defined by the

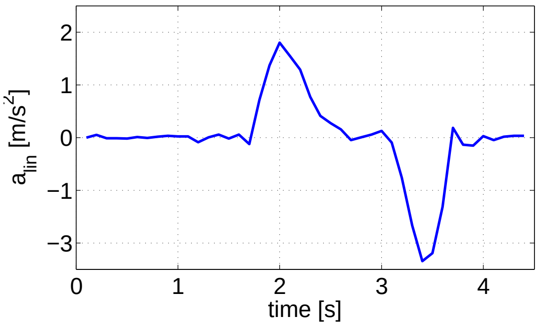

Fig. 12: The acceleration profile of the robotic fish, corresponding to the trajectory on Fig. 10.

specification. This is due to the current settings of the motor controllers that limit the maximum current in the motor to prevent overheating. However they can be tuned to allow a higher current for a short period of time, thus providing higher acceleration. Also we can see on Fig. 10 that at the maximal speed the trajectory of the robot slightly deviates from the straight line; this is due to the fact that when the robot is accelerating with the maximum motor torque one motor can go faster than the other because of small friction differences between the two motors. Thus a more advanced control strategies has to be put on top of the current motor control that would include a saturation-based limitation mechanism making the motors to run at the slowest pace of the two.

VI. CONCLUSIONS AND FUTURE WORKS

Robotic devices are becoming a common tool in experimental biology, thanks to the possibility to test in an automatic way the animal reaction to various isolated or multimodal stimuli. The aim that we pursued in this work was to develop an autonomous robotic zebrafish that can be used in experimentation on the collective behavior. We selected zebrafish as a model animal since it is one of the most important vertebrate model organisms in genetics, developmental biology, neurophysiology and biomedicine.

The robot that we developed consists of two modules: a mockup fish fixed on the magnetic base and a miniature mobile robot guiding the mockup fish from below the aquarium. The compact size of the robotic part (45x15x73 mm) makes it possible to have a group of robots forming a dense school. It is also equipped with infrared sensors to detect obstacles and provides the Bluetooth connectivity. We experimentally showed that by using the developed system we are able to guide a mockup fish in the experimental tank with a speed and an acceleration comparable with the ones of the zebrafish.

In further work, for a power supply we will use another solution, more suitable for the multi-group experiments such as a sliding contact or a battery. The motor control will be also improved to achieve better acceleration and speed synchronization of two wheels as explained in V-B; performance of the new controller will be tested on examples of recorded trajectories of real fishes. Moreover the Aseba framework will be used to program the robot. Also the part of the future work will be to build a realistically looking replica fish. Finally, the developed solution will be validated in the experiments with the zebrafish.

In the long term, we believe that our system will help in the study of fundamental social mechanisms and advance our understanding of collective animal behavior.

VII. ACKNOWLEDGMENT

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