Probabilistic swimming pattern of magnetic small fish in underwater magnetic field

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Abstract
The recent aquarium arts simultaneously provide visitors with interest in science technology and fish ecosystems. In particular, some studies on soft robotics develops some fish robots with a feeling similar to reality. These robots have the potential to be a new life that can coexist with human and actual fish. This study aims to develop a soft fish robot that allows people to directly control swimming easily. We introduce 3D printed mold, magnetic soft fish mixed with silicone rubberizing reagent and sand iron. The concept of real fish swarm using magnetic field is proposed on this paper. In this paper, we show a basic follow-up of fish robot and verify soft fish swarm by moving magnetic field. The results reveal that the fish robot follows the magnetic field due to the magnetic change of the sand iron inside the silicon. Refer to the principle of boids, the fish swarm shows that the dynamic mutual interference between fishes by magnetic sand iron can be described as a cohesion of magnetic force, separation of collision and alignment by a water flow.

1 Introduction
Aquarium has been introducing some scientific technologies for fascinating visitors. Sketch Aquarium is one of technologies by image processing [1]. It projects a drawing fish of visitor on a wall. These fishes are freely swimming everywhere on the wall. Although these fish are simple pictures, we presume the movement and fish swarm is the reason for attraction. In a field of artificial life, boids algorithm has been studying for imitating real fish motion as a CG simulation [2]. The boids algorithm is a computational model which has three simple rules (separation, alignment, cohesion). It is also one of the computer simulation technologies that mainly targets fish motion and communication [3]–[8]. Robotics has been developing marine robots that are able to swim in the water. The robot technology imitates a real fish swimming by control theory in a field of mechanical engineering. One of the main roles of these robots is to explore the underwater ecosystem [9]. The robot motion do not threaten marine organisms and the robot collects information for people to understand ecosystem. These robot technologies are also able to be applicable to aquarium art. In particular, soft robotics has attracted attention as a novel framework of underwater robot [10]–[13]. A soft robot is deformed when a pressure is applied. Therefore, such soft reaction via tactile sense gives a close feeling to a person. From the viewpoint of aquarium art, we presume that soft robots will enable new communication via sensory devices.

As one of novel aquarium technologies, we are seeking a way that visitors can easily touch with fishes while keeping the dignity of aquatic creatures. The objective of this study is to develop artificial fish that can coexist with a group of fish bred in an aquarium and can directly communicate with human beings. In addition, we aim to be easy to model the artificial fish like drawing pictures and propose ways to create diverse motion without complicated control mechanism.

In this study, we develop soft artificial fish which swims by magnetic field generated in aquarium. This reason is the following two points. One is that the user who communicates with artificial fish can indirectly control by the magnet from the outside of the aquarium and the other is to give the user a feel like a real fish when directly touching the artificial fish. Magnetic field occurs only by placing a magnet in the environment. A moving magnetic field is generated by moving the magnet at the bottom of aquarium. The moving magnetic field gives drag force and magnetic force into the fish model. Visitors can easily drive the developed artificial fish by embedding the sensor responding to this magnetic force in the fish. The visitors can enjoy the change of motion caused by arranging the artificial fish on the moving magnetic field of a certain pattern.

In this study, we observe the motion which realizes the swimming linearly and curvilinearly in order to consider the fundamental behavior of the developed soft fish. Then we verify the difference between an assumed fish swimming from the given magnetic field and an actual soft fish swimming. Finally, we discuss how a swarm motion of soft fishes emerges on the moving magnetic field. In order to discuss it, we use soft fish model to discuss fish swarm behavior by a moving magnetic field. Sand iron magnetizes in the magnetic field. Therefore, an attractive forces and an repulsive forces are applied between individuals. Moreover, it is inferred that the
Fig. 1: The first step is 3D modeling of handwriting sense by VoxCAD [14]. The second step is to make a mold for 3D printer from 3D modeling data for pour silicone rubberizing reagent. The last step is to build a soft fish with the material corresponding to each part.

magnetic moment of the moving magnet controls the direction of the fish model. Therefore, three rules (cohesion, separation and alignment) in the Boids algorithm are generated in the moving magnetic field and we verified whether fish swarm can be formed in the field.

2 Modeling

This section describes how to develop a magnetically driven soft fish and aquarium with a magnetic field. This model is used as a two-dimensional analysis model of the swimming pattern of soft fish.

2.1 Soft fish including sand iron

First, a series of modeling is shown in Fig. 1 In this study, we create a fish model shown in Fig. 2 (A). This fish model is designed by VoxCAD which is a voxel-based robot simulator [14]. VoxCAD places voxels like drawing a picture on a two-dimensional plane. Then, it creates a 3D model by stacking the two-dimensional plane on which the voxels are drawn. Our artificial fish is made of silicone rubber filled with dry sand iron and buoyant material divided into two layers. The next step is to make a mold corresponding to the designed 3D model with a 3D printer. The mold is divided into three parts which are head, body, and tail. These mold manufacture artificial fish of silicone rubber type by pouring silicone rubber reagent into each mold. EcoFlex Gel is used as a reagent for silicone rubberization. The head part is mixed with sand iron in the reagent. Because the head of fish model only responds to the magnet so as to have directivity facing the magnetic force generation source. A soft fish model is shown in Fig. 2 (B).

Fig. 2: Soft fish model reacting to magnet force based on 3D modeling data

Actually, an individual difference is generated in the fish model created by this method. In this study, the individual differences of models are treated as errors occurring in motion.
2.2 A moving magnetic field

The swimming environment uses a 20.0 cm x 20.0 cm x 10.0 cm cubic acrylic tank. To move the wooden spatula with the neodymium magnet generates a moving magnetic field in the aquarium. The intensity of the magnet used is 2,800 CGS. Four magnets are glued to this wood spatula. This aquarium put a magnet in the inside bottom. A magnet attached to a wood spatula moves the magnet of the aquarium. A flow is generated in the water of this aquarium by sweeping a magnet along the bottom of the aquarium. Therefore, this aquarium gives magnetic power and resistance to fish model. An sample of the created magnetic field tank is shown in fig.3.

3 Experiment

This section conducts three experiments for discussing a communication skill with a user and the probabilistic pattern formation of the swimming behavior of the developed artificial fish. First, we verify fish directivity when the magnet is brought close to the outside of the aquarium. Then, this section illustrates the trajectory until the swimming behavior of a single fish obtained by a given magnetic field shifts to the convergence state. This experiment can show a basic behavior of soft fish. Next, we investigate whether the swimming trajectory of soft fish can be controlled by geometrical arrangement of magnetic cube. Finally, we simulate a motion of fish swarm and discuss how this motion relates to magnetic pattern

3.1 Tactile feel of soft fish

Our fish model is made of material on gel. The body of the fish is easily deformed when lightly pushed with human finger. The head contains sand iron however the deformation is possible. No significant deformation has observed in the fish model by movement underwater. The deformation of the fish is shown in Fig.4

3.2 Basic motion

In order to understand a basic behavior of soft fish, an experiment is conducted to linearly move the magnet spatula. The result this experiment are shown in Fig.5. The red arrow in fig.5 indicates the front direction of the fish, and the black arrow indicates the pulling direc-
Fig. 7: Principle of movement of head sand iron and soft fish by magnetic field. The entire body moves as the head’s magnet attracts. The sand iron grains in the head have magnetic properties. A mechanical change and an equilibrium state occur in the head due to repulsive force and attractive force.

Fig. 8: Follow paths of soft fish swarm. One follows a regular follow-up. The other is irregular trajectory tracking.

Fig. 9: The concept of a magnetic boids of soft fish swarm.

3.3 Soft fish swarm

Using the mechanical properties of the magnetic field, we examine whether we can acquire soft fish swarm behavior generated by the principle similar to boids. Figure 8 shows the experimental environment. In this experiment, five soft fishes are placed in aquarium. Then, the magnet spatula moves along the two paths. The first route has regularity that alternates between linear movement and curve. The second route is a random route. Figure 9 shows the concept of the fish swarm rule by magnets. The attracting power of the magnet reproduces the effect of cohesion of fish swarm. Moreover, a soft fish with a magnetic sand iron head can adsorb another individual. Adsorption based on this principle is also regarded as cohesion. On the other hand, separation is caused by a failure to penetrate the narrow space and a collision with another individual. Alignment is defined as the state in which dynamic action by water flow contributes most to movement. Each route tracking experiment observes whether each rule appears. Additionally, this section discusses the contribution of each rule to the movement from the viewpoint of the moving magnetic field pattern. The result of regular route follow-up is shown in Fig.10. From the experimental results in section 3.2, a single fish model can follow this route. Four groups are placed in this experiments. Contact with the wall and collision with
Fig. 10: Fish swarm behavior by moving magnet along the regular path

Fig. 11: Fish swarm behavior by moving magnet along the irregular path. The irregular path is the S-shape trace at the bottom of the aquarium in this experiment.

another individual cause a separate of the individual from the swarm. Individuals who do not follow the magnets among the separated individuals move along the generated water current. On the other hand, you can also see the aspect of following the magnet while forming the swarm. However, it is found that adsorption of sand iron heads did not occur.

Next, the result of irregular route tracking is shown in Fig. 11. This condition increases the angular displacement of the path in the direction of travel of the individual. Therefore, it is inferred that it is difficult to keep the state of the swarm. The result shows that the swarm forms with the follow-up motion along the vector field generated by the individual adsorbed by the magnet. This principle is similar to alignment of Boids.

4 Discussion

the artificial fish is disturbed by the water current generated by itself and the attitude is not stable, but the resistance due to the water current slowly declines with time. When the water resistance decreases, the artificial fish turns attract motion closing to the position of magnets at that time. Therefore, the user’s interference gives a new mechanically stable position of the artificial fish. In comparison with the experimental result of Section 3.2, the developed soft fish has a superior water resistance in all areas. In order to control the fish by attractive force of magnetic force, it is necessary to keep the magnetic field for a time width in which the vector of resistance decreases. Additionally, from the results of the swimming behavior experiment based on the pattern of the magnetic field in section 3.3, the artificial fish probably swims over the magnetic field with disturbance from the initial position, and it stays in contact with another individual or in a mechanically stable magnetic field region. This suggests that even if the magnetic field is slightly changed, the artificial fish is an unstable system showing a large change Therefore, it is presumed that the fish swarm by the magnetic field changes a physical equilibrium between cohesion and separation by strengthening the content of sand iron embedded in the fish and the magnetic flux density of the moving magnet.

Moreover, the fish swarm observed in this experiment shows a swarm behavior in which a leader and a follower relationship. This swarm behavior emerges leader and follower individuals. The leader individuals generally receive dynamic influences from the environment and have a control mechanism of autonomous behavior. The fish model of this experiment has no autonomous control mechanism, however the individual with the closest distance to the magnet has the quickest swimming speed. The water flow generated by this individual swimming and the contact to leader individual create a follow-up motion for other individuals. The individuals getting a follow-up movement can be regarded as follower individuals. Leader individual always is transferred by changing the position of moving magnets. However, since an area of the water flow generated by the swimming of the leader individual is very small, an area where the leader individual generates the follower individual is narrow. Additionally, the adsorption area of the model due to the magnetic field is narrow. Therefore, it is seen that the magnetic swarm behavior proposed in this paper causes a community collapse due to a slight external force to water. In order to model more controllable magnetic swarm behavior based on these principles, it is necessary to strengthen the magnetic flux density of the moving magnet and a body mechanism capable of converting water pressure by disturbance into autonomous swimming.
5 Conclusions

This study develops a soft fish with a soft tactile feel. This robot development can be created with modeling that draws pictures and does not require assembly of complex electronic components. It can be easily driven with an inexpensive magnet. In addition, we propose fish swarm behavior resembling the principle of Boids in a moving magnetic field. This experiment shows only specific swimming patterns that can be observed from magnets and fish robots with specific mechanical and chemical parameters.

This experiment is limited to actual verification. It becomes possible to describe stochastic behavior model of actual robot by comparing actual motion with numerical calculation. In the future, the mathematical model can be expected to be applied to easily reproduce realistic fish behavior.

References

[1] Sketch Aquarium, http://seoul.teamlabworld.com/en/park/park05.html (accessed 2018-10-17)

[2] Reynolds, C. W., Flocks, herds and schools: A distributed behavioral model. In ACM SIGGRAPH Computer Graphics, volume 21, pages 25–34. ACM

[3] Momen, S. and Amavasai, B. P. and Siddique, N. H., Mixed species flocking for heterogeneous robotic swarms, EUROCON, The International Conference on "Computer as a Tool, pp.2329–2336, 2007

[4] Witkowski, O. and Ikegami, T., Emergence of swarming behavior: foraging agents evolve collective motion based on signaling, PloS one, Vol. 11, No. 4, pp.e0152756, 2016

[5] Pitcher, T. and Partridge, B., Fish school density and volume. Marine Biology, 54(4):383–394.

[6] Su, H., Wang, X., and Lin, Z., Flocking of multi-agents with a virtual leader. Automatic Control, IEEE Transactions on, 54(2):293–307.

[7] Yu, W., Chen, G., and Cao, M., Distributed leader-follower flocking control for multi-agent dynamical systems with time-varying velocities. Systems and Control Letters, 59(9):543–552.

[8] Tomine K, Noguchi W, Iizuka H, Yamamoto M, Discriminating Social Behavior of Guppy Swarm by Convolutional Neural Network, Proceedings of the First International Symposium on Swarm Behavior and Bio-Inspired Robotics, pp. 414-417

[9] Zereik, E., Bibuli, M., Mišković, N., Ridao, P., Pascoal, A., Challenges and future trends in marine robotics, Annual Reviews in Control, 2018

[10] Marchese, A. D., Onal, C. D, Rus, D., Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators, Soft Robotics, Vol. 1, No. 1, pp. 75–87, 2014

[11] Katzschmann, R. K., Marchese, A. D., Rus, D., Hydraulic autonomous soft robotic fish for 3D swimming, Experimental Robotics, pp.405–420, 2016

[12] Jusuﬁ, A., Vogt, D. M., Wood, R. J., Lauder, G. V., Undulatory swimming performance and body stiffness modulation in a soft robotic ﬁsh-inspired physical model, Soft robotics, Vol. 4, No. 3, pp. 202–210, 2017

[13] Wen, L., Ren, Z., Di Santo, V., Hu, K., Yuan, T., Wang, T., Lauder, G. V., Understanding Fish Linear Acceleration Using an Undulatory Biorobotic Model with Soft Fluidic Elastomer Actuated Morphing Median Fins, Soft robotics, 2018

[14] Hiller, J., Lipson, H., Dynamic simulation of soft multimaterial 3d-printed objects, Soft robotics, Vol. 1, No. 1, pp. 88–101, 2014