A Network of Underwater Sensors Estimating Feeding Behavior for Digitizing Optimized Feeding Decisions in Marine Aquaculture

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Abstract

Optimization of fish feeding in marine aquaculture has relied on an expert farmer's decision-making based on subjective experience. This paper presents the development of a network of underwater current, imaging and IMU sensors for estimating fish feeding behavior for digitizing expert feeding decision-making. We constructed the sensor units and deployed them in fish cages and collected measurements during feeding activities. Experiment results indicate that currents were highest at the surface within the duration of the feeding activity.

Keywords: aquaculture, feeding, sensor, network, currents

1. Introduction

Marine aquaculture is one of the largest contributors to fish production in Japan, accounting for around 22% of the country's production volume as of 2019.[1] However, production has remained stagnant over the years. In addition, with higher costs in feeds and fish meal, the average income of farmers has been decreasing. Efficient fish feeding conventionally depends on the fish farmer's judgement of the fishes' feeding behavior, which is based on his/her intuition and subjective experience. This makes efficient feeding more difficult to achieve for less experienced farmers. By applying digital transformation (DX) to experts' knowledge to optimize fish feeding, data from fish cages could help less skilled farmers improve their decision-making, raise more high-quality fishes, and increase their income by reducing the excess feeding costs from uneaten feeds, which also reduces the pollution these feeds release to the environment. This makes the industry more sustainable.

So far, research efforts to digitize expert decision making have been made in recirculating aquaculture systems, applying artificial intelligence on data from water quality and imaging sensors collected in fish tanks.[2,3,4] Such systems have not yet been implemented in open sea cages, where environment conditions are uncontrolled. Measurement of currents generated by fishes has been proposed to estimate their feeding behavior.[5] Although this has already been proposed as part of a monitoring system for marine cages, only simulation of real-world information has been made so far.

This paper presents the development of a modular network of sensors that measures underwater currents, and record fish activities in sea cages during feeding activities. Such data can help less experienced farmers gain further insight on how experts optimally dispense feeds to fish cages, helping them make better feeding decisions in their own cages and improve their farming operations. This paper includes the deployment of the sensor network on fish cages and the results from the measurements during feeding activities.

2. Modular Sensor Network

2.1. *Network Architecture*

The sensor network is composed of one or more sensor units that are attached to the sides of the fish cages (Fig. 1). Each unit consists of a top module and multiple sensor modules. The top module houses the batteries that power the sensor modules as well as the bridge router that relays the data from the sensors to the main router, and then to the user computer, both aboard the feeding boat.

Each sensor module consists of at least two sensors: a modified flow sensor for measuring underwater currents; a network camera to record fish activity underwater. Some of the modules have an inertial measurement unit (IMU) to measure any movement of the sensor frame cause by currents. A microcontroller collects and calculates readings from both the flow sensor and IMU and sends them by serial to a device server.

Both the device server and the network camera in the module connect to an Ethernet switching hub, which forms a daisy chain with the other sensor modules within the unit, connecting to the bridge router. With all sensor unit routers connecting in bridge mode to the main router, the user computer has access to all sensors, collecting data from all of them. With this design, all sensors are well synchronized, with all collected data timestamped more accurately.

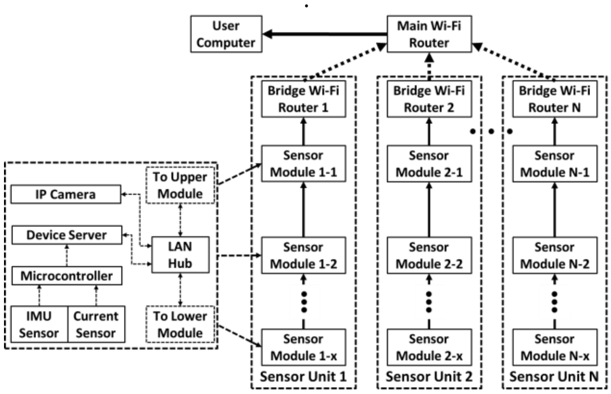

Fig. 1. Topology of the modular sensor network for estimating fish feeding behavior.

2.2. *Prototype Sensor Unit Development*

All electronic components of each sensor module were placed inside a waterproof enclosure mounted on an aluminum frame, except for the current sensor, which was waterproofed and was mounted on the frame above the enclosure. The enclosure featured underwater connectors, to link the power and data of the internal electronics to the current sensor and to the other modules.

Eight sensor modules and four top modules were constructed for the fish cage experiment. Depending on the experiment plan, each sensor unit can have up to three sensor modules. This number was due to the power limitation of constructed cable, although more modules could be connected had a larger gauge been used for the cables' power lines. The unconnected connectors of the lowest sensor modules were sealed.

Modular metal frames were designed and constructed especially for the sensor modules for flexibility in the arrangement of sensors in the fish cages. Each sensor module is fixed in a modular frame in such a way that when multiple frames are attached, the modules would be properly spaced as desired. Each sensor unit has one frame with a sensor module and a top module.

A video management software (VMS) was used in the user computer to display and record the views from the cameras. Data from the current sensors and the IMUs were recorded by accessing the device servers via Telnet using a terminal emulator with logging function, storing accurately timestamped data into files for later analysis.

3. Fish Farm Experiment

3.1. *Overview*

In November 2021, a two-day experiment was made using this sensor network in three fish cages in the town of Shin-Kamigotō, in Nagasaki prefecture. On the first day, two sensor units with three sensor modules each were deployed, one each for two fish cages. Both units were attached to the center south side of the cages. On the second day, four units with two modules each were deployed in one cage, two on the north side and two south side. Two units were mounted on the center of opposite sides. The other two were supposed to be mounted on the center of the east and west sides of the cage, but these are where the feeding boat would dock on. Therefore, they were attached to the northwest and southeastern corners instead.

The sensors were deployed on 11.7 x 11.7 m^2 square cages with depth of five meters, as shown in Fig. 2. All cages contained Japanese amberjack (*Seriola quinqueradiata*) that have been raised for around half a year. There were 11,000 fishes in each of the two cages on the first day, all caught from the wild as fries. They were fed from the boat using a dispensing machine. The cage on the second day contained 8,000 fishes raised from an artificial hatchery. They were fed manually by the farmer from the platform on the center of the cage.

At the start of each data collection, the farmer was requested to wait for five minutes before starting to feed the fishes. This was done to get baseline data before feeding began. The sensors were made to collect until five minutes had passed from the end of the feeding activity to get data when the fishes returned to the same state prior to feeding.

The sensor units were attached to the fish cages on the afternoon of the day before the measurement, as feeding was performed in the morning. It was decided by the research group to fix all modules two meters apart from each other, with the topmost sensor module positioned 0.5 m from the surface. The lower sensors were therefore fixed at 2.5- and 4.5-meter depths.

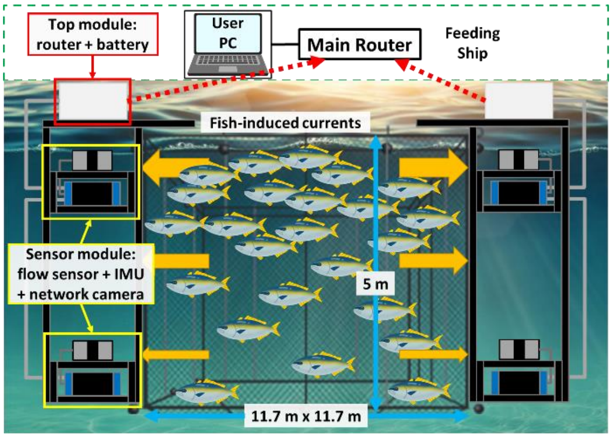

Fig. 2. Side view of the fish cage experiment with two sensor units fixed on opposing sides. This setup was made on the third cage on the second day.

The starting and ending times of dispensing feeds were noted for all measurements. The feeding activity in the third cage was also recorded on video, from which the progression of the amount of feed given was estimated. For easier analysis of data, moving averages of current and IMU measurements within 15 seconds were calculated to reduce the noise, thus smoothening the plot. Noted events during feeding and observations from the underwater cameras were compared with the sensor data.

3.2. *Results and Discussion*

3.2.1. *First Day Measurements*

In the first cage, measurements were collected only at 0.5 and 2.5 m, as connection with the sensor module at 4.5 m could not be made due to internal loose connection. Data at all three depths in the second cage was collected.

The feeding in the first cage lasted around nine minutes, as shown in Fig. 3a. Before feeding started, cameras did not capture fishes swimming at 0.5 m. Feeds were immediately dispensed continuously at the start. At around this time, cameras recorded fishes swimming very fast towards the surface to feed. View at 0.5 m started to blur a minute after due to the bubbles flowing towards the camera.

Although vigorous splashing was already present, surface current measurements did not start to rise above 4 cm/s until around the fourth minute. Current peaked at the sixth minute at around 21 cm/s, which gradually declined. At the end of feeding, current was at 12 cm/s.

Video recordings showed that fishes started going down to the bottom of the cage and surface gradually became as calm and clear as before feeding started. Current dropped to zero in less than a minute. Despite presence of fishes during feeding, only zero readings were collected at 2.5 m.

Shown in Fig. 3b, feeding in the second cage lasted around seven minutes, starting gradually for a minute before dispensing feeds continuously. Even before feeding began, surface currents up to around 10 cm/s was already measured. Some fishes could be seen at the bottom of the video from 0.5 m. Although most of the fishes could be seen from the cameras at 2.5 and 4.5 m around this time, current measurements were very small.

Surface current temporarily dropped to zero during gradual feeding. Fish activity was still the same, as seen in Fig. 4. And then, fishes started swimming upward very fast at around this time to feed. This current drastically rose to peak at around 37 cm/s when continuous feeding started. Video started blurring from the flowing bubbles at around this time.

Fewer fishes could be seen at 4.5 m during feeding as most were at the surface. Peak surface readings gradually decreased as time progressed. Substantial currents, reaching to 10 cm/s, were measured at 2.5 m towards the end of feeding. By the time feeding was stopped, surface reading was at around 14 cm/s and eventually declined to zero within the same minute. At around this time, surface became calm again, and fishes started gathering at the bottom of the cage.

The amount given to the fishes in the first cage was 240 kg while only 230 kg was given to the fishes in the second cage, as 10 kg of feed remained when the farmer decided to stop the feeding machine. The farmer assessed that the fishes were feeding less actively compared to those in the first. However, surface measurements from both cages seem to suggest that feeding activity was greater in the second cage.

3.2.2. *Second Day Measurements*

For the third cage on the second day, due to physical connection problems, no data was collected at 2.5 m on the northeast corner while incomplete data was collected at the same depth on the southwest corner. IMU data was available from the other three modules at 2.5 m. Most of the sensor data from the units at the corners were negligibly small. Therefore, the focus of discussion will be on the data from sensors on the center north and south sides.

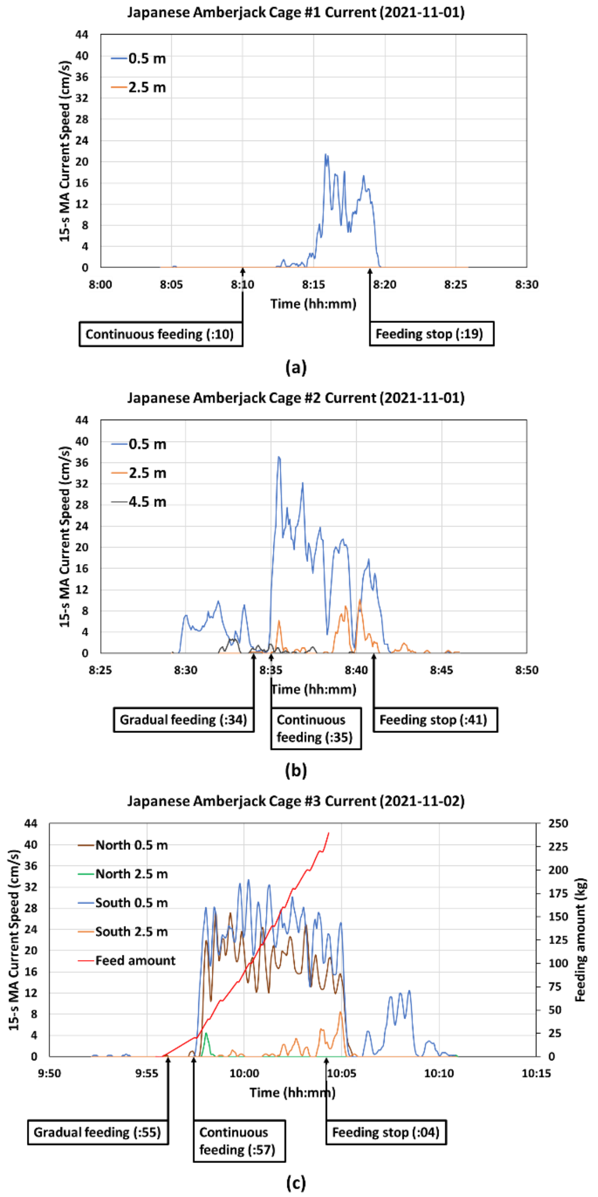

Fig. 3. Current measurements from the first (a) and second (b) fish cages on the first day, and from the third fish cage on the second day (c).

Feeding in the third cage lasted nine minutes, same as in the first cage, as seen in Fig. 3c. Readings were at zero before feeding. Like in the first cage, cameras at 0.5 m captured no fishes at surface. At 2.5 m, while no fishes were seen on the south side, they were seen swimming on the north side. Around the time gradual feeding started,

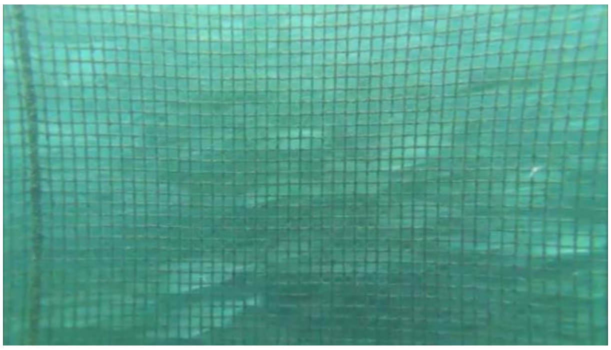

Fig. 4. Camera view at 4.5 m at the second cage during gradual feeding. They were still schooling at the bottom of the cage.

fishes started swimming to the surface fast, like those in the previous cages. At 2.5 m of north side, small readings were detected after feeding started.

Surface measurements started to rise drastically only after continuous feeding started, as measured by sensors on both sides almost at the same time. These peaked at 33 cm/s, with the following peak currents declining until the end of feeding, at which they dropped to zero simultaneously on both sides. After feeding stopped, currents up to 12 cm/s were still read by the sensor on the south side. On the south side at 2.5 m, a pattern of currents like that from the second cage was seen towards the end of feeding. Fish activity from then onward was same as in the beginning.

3.2.2. *IMU Measurements*

Due to a flawed design decision, only four out of the eight sensor modules had an IMU included. Therefore, it was decided to deploy two modules with IMU at 2.5 and 4.5 m in the first cage (although no connection at 4.5 m), and at 0.5 and 4.5 m in the second cage. In the third cage, all IMUs, except for the one on the northeast unit, collected at 2.5 m.

Offsets were evident in the acceleration and rotation data in various axes, as shown in data from one of the sensor modules in Fig. 5, because the IMUs were uncalibrated when they measured data. While fluctuation patterns in acceleration and rotation could be seen within the feeding duration, these changes were at very small scales. Such was the case for all collected IMU data. Accelerations were less than 0.1 m/s^2 (Fig. 5a & 5b), while rotations were less than .01 rad/sec or around 0.6 degrees (Fig. 5c). Data suggest that movement in frames were very small even during fish activities, although further analyses are needed.

4. Conclusion

In this paper, a network of sensors was developed to estimate fish feeding behavior, which could be useful for optimizing feeding control. It consisted of current sensors, cameras and IMUs, collecting data at different depths and sides of a fish cage. This system was deployed in three fish cages and collected measurements during feeding activities. Experiment results suggest that changes in current measurements are related to the fish feeding behavior, as recorded. However, data needs to be analyzed further to understand these relationships better.

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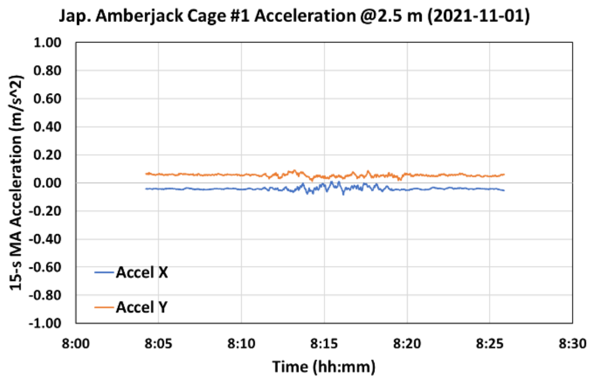
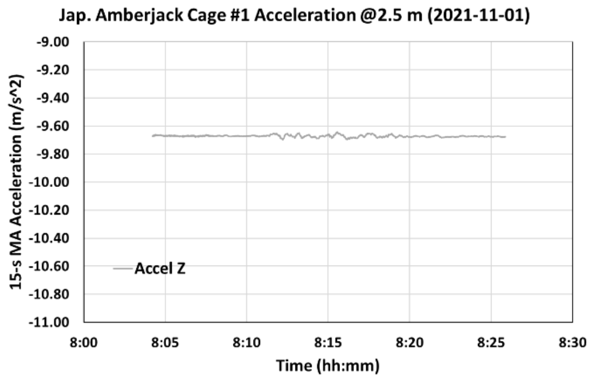


(a)



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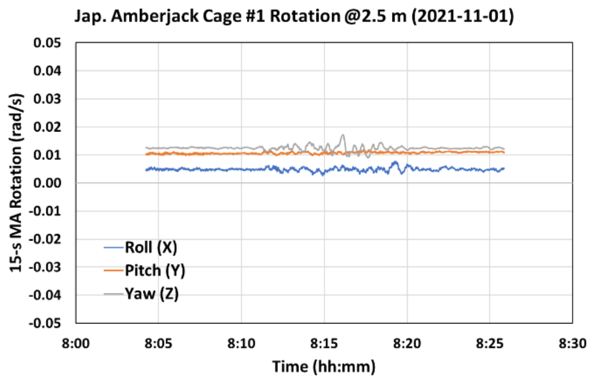

(c)

Fig. 5. Acceleration measurements at X and Y axes (a) and at Z axis (b), and rotation measurements at all axes (c) at 2.5 m in the first cage.

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