Development of a real-time depth monitoring system for small fishing gear using an acoustic telemetry technique

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Title: Development of real-time depth monitoring system for small fishing gear using acoustic telemetry technique

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Abstract

A system for real-time monitoring of the depth of small fishing gear was developed using acoustic telemetry to improve the efficiency of fishing operations. The system consisted of an acoustic transmitter (pinger), an omni-directional hydrophone with a depressor, and a receiver. Using a pinger equipped with a depth sensor, a fisherman can confirm whether the fishing gear is at the intended depth. The battery of the developed pinger can be replaced easily for repeated use. The performance of the system was evaluated in a field experiment. The accuracy of measured depth was 0.4 m and was constant even if the pinger was moving. In the experiment, the system could successfully monitor the pinger depth every several seconds. The system was implemented in hairtail trolling to examine its effectiveness. The implementation experiments revealed some issues with the system, such as the effect of signal reflections or the installation method of the hydrophone. However, the system could monitor the depth of the fishing gear continuously in real time and it operated successfully without any problem during the fishing operation. Application of the developed system is expected to aid fishermen in adjusting the gear depth easily and accurately.

Keywords: acoustic telemetry, small fishing gear, fishing gear depth, hairtail trolling

Introduction

Understanding the positional relationship between fishing gear and fish is crucial for efficient fishing operations. Acoustic systems have been developed for detecting fish and monitoring fishing gear, and have helped fishermen perform fishing operations [1, 2]. Most fishing vessels are equipped with an echo sounder regardless of the type of fishing because this instrument enables us to know depths of fish and bottom. In addition, the vertical position of fishing gear during capture processes is the most crucial for catch of the detected fish. Fishing gear performances, including the depth of the gear, are measured using wireless acoustic gear sensors attached to the gear. A sonar assembly mounted onto the fishing gear is used to simultaneously monitor the vertical position of the fish and the fishing gear. These systems have been applied to observations of gear geometry and fish behavior in relation to a trawl net [3–7] and have also helped perform net sampling [8–11].

Conventional acoustic systems for monitoring fishing gear are mainly designed and used in trawl and purse seine fisheries. These systems cannot be applied to small-scale fishing such as troll fishing or fishing with hooks and lines owing to their large size and weight. Fishermen who operate such small-scale fishing need to adjust the gear depth by relying only on their experience and intuitions. Therefore, a system for monitoring the depth of small fishing gear would help fishermen perform the fishing operation efficiently.

In order to apply a system for depth monitoring of fishing gear in small-scale fishing, a small yet robust instrument that is attachable to small fishing gear is necessary. Hence, we focused on acoustic telemetry systems developed for behavioral surveys for aquatic animals [12, 13]. This system consists of acoustic transmitters (pingers) attached to target animals and one to several receivers. Since the size of a pinger is limited by the size of the target animal [14], smaller and lighter pingers have gradually been developed [15, 16]. Presently pingers that are small enough to be attached to small fishing gear are available. It would also be necessary to overcome the problem of interference of signals from multiple pingers for the case that small-scale fishing boats with pingers are concentrated in a limited fishing ground. However, the recently studied a pseudo-random noise (PN) code which is assigned to a transmission signals, which enables identification of pingers of the same frequency [17, 18], would help to overcome the problem of signal interference.

In this study, we developed a system that will provide the depth information of small fishing gear in real time to fishermen. We first evaluated the performance of the system in a sea experiment and then implemented it in the trolling of largehead hairtail *Trichiurus lepturus* to discuss its effectiveness.

Materials and methods

System for depth monitoring of small fishing gear

The system for monitoring the depth of small fishing gear was developed based on the acoustic telemetry system by using a transmission signal assigned PN code. The developed system consists of a pinger attached to the fishing gear and a surface unit installed on a fishing boat (Fig. 1).

We need to consider the following specifications of the pinger: size; weight; battery life; source level, which is related to the possible propagation distance of the acoustic signal; and the transmission interval, which is related to the interval of data display. A conventional pinger that transmits signals encoded by the PN code, for example, AquaSound Inc., model AQPX-1030-60P (http://aqua-sound.com/products/pinger-aqpx-1030.html “Accessed 9 Nov 2015”.), is 9.5 mm in diameter and 36 mm in length, and weighs 1.6 g in water. The battery life of the pinger is 2 days if the pinger transmits the signal every 1 s. While conventional pingers are disposable since it is attached an aquatic animal and is not collected, a pinger that can be used repeatedly is needed for application to fishing gear. We chose a lithium CR15H270 battery (3 V, 850 mAh, 15.6 mm diameter and 27 mm length) for transmitting signals with the power, intervals, and duration that are required in order to conform to most small-scale fishing operations. As a result of pinger development, the source level of the pinger was 155 dB re 1μPa at 1 m, which implied that the signal could propagate for about 500 m. The frequency of the pinger is 62.5 kHz. Its battery life is about 1 month if it transmits the signal every second, although a longer transmission interval can be set. The battery can be replaced by fishermen themselves for repeated use. The pinger dimensions are 24 mm (diameter) × 100 mm (length), and it weighs 77 g in air and 31 g in water.

The surface unit consists of an omni-directional hydrophone with a depressor, a cable, and a processing and display apparatus (receiver). The hydrophone with the depressor is towed in the shallow water layer to prevent communication failure caused by air bubbles and to also prevent collision with the propeller. The hydrophone is 45 mm in diameter and 150 mm in length. The receiver is placed in the cabin of a fishing boat and is 170 mm × 100 mm with a height of 40 mm. The depth information is displayed on an LCD panel. During fishing, the system operates without any setting so that a fisherman can use it by oneself. The time of signal detection and the depth information can be recorded by a PC through a USB cable. Table 1 presents the specifications of the pinger and the surface unit.

The acoustic signal from the pinger consists of two consecutive pulses for the transmission of the depth information (Fig. 2). The receiver calculates the pinger depth from the interval of the two pulses, which changes in proportion to the pinger depth. The depth resolution is approximately 0.5 m if the maximum depth is set to 250 m. To prevent the interference of signals between plural users in the limited area, each pulse is assigned one of 32 PN codes. Since the receiver identifies the pinger by two PN codes, approximately 1000 identifications can be used (32 × 32). Additional sensors such as a water temperature sensor can be added according to the intended purpose. If one sensor is added, the number of pulses increases to three and the additional information is calculated from the interval between the second and the third pulses.

Evaluation experiment of system performance

A field experiment was conducted for evaluating the performance of the developed system. The accuracy of the measured depth was estimated by a comparison with data acquired by a depth data logger (DEFI-D20HG, JFE Advantech Co., Ltd.; range: 200 m, resolution: 0.02 m). The pinger and logger were tied onto a rope connected to the fishing line. The transmission interval of the pinger was set to 1.27 s, and the logger recorded its depth every 1 s. The depth of the instruments was adjusted using an electrical reel, which displayed the paid-out length of a line. During the measurement, a research boat drifted in the water of 100–150 m deep. Two measurements with a different vertical moving pattern were tested to evaluate the effect of the vertical velocity of the pinger on the accuracy of the measured depth. As the first measurement, we lowered the instruments down to a depth of about 100 m, and then wound up 10 m of the line and waited for about 1 min until the paid-out length of the line was 20 m. In addition to this movement, the line was also wound up to prevent the pinger from touching the sea bottom. As the second measurement, the instruments were shuttled between the surface and near the bottom (about 140 m) at maximum velocity. The vertical velocity was then calculated from the variation of depth per time as measured by the logger.

The logger depth was treated as the true value, and the accuracy of the measured pinger depth was estimated from the root-mean-square-error (RMSE), given by

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(D_{\mathrm{P}i} - D_{\mathrm{L}i})^2}{N}} \tag{1}$$

where D_{Pi} is the pinger depth, D_{Li} is the logger depth ($D_{Pi} - D_{Li}$ in Eq. (1) is referred to as $D_{Pi\text{-}Li}$), and N is the number of data items. The correlation coefficient (r) of $D_{Pi\text{-}Li}$ with the vertical velocity was examined for evaluating the tracking performance. The absolute values were used in the calculation of the correlation coefficient.

To evaluate the continuity of the data, the reception ratio P_R (%), which is the ratio of the number of transmissions from the pinger (N_T) to the number of depth data values obtained (N in Eq. (1)) during the experiment, was calculated as follows:

$$P_R = \frac{N}{N_T} \times 100 \tag{2}$$

$$N_T = \frac{T}{I} \tag{3}$$

where I is the transmission interval of the pinger, and T is the duration of the experiment. There is a possibility that the reception ratio was affected by the Doppler frequency shift due to the position variation of the pinger. On the basis of the results of the second measurement, the effect of the Doppler frequency shift was evaluated using the correlation coefficient between the reception ratio and the vertical velocity. We did not consider the error of the sound speed in this analysis because the frequency shift was affected much more by the position variation of the pinger.

Outline of hairtail trolling

We applied the developed system to hairtail trolling in western Japan. Specifically, we considered trolling in the Bungo Channel, which lies between Kyushu and Shikoku islands in Japan. The fishing gear used in this experiment consisted of a wire with ellipsoid-type small sinkers (i.e., a long radius of 1 cm), a sinker for setting the gear to the desired depth, a nylon main line, and branch lines (Fig. 3). About 90 branch lines were connected to the main line, and each branch line had a baited or lure hook; however, a few branch lines were connected to floats to stabilize the gear depth. The approximate length of the branch lines was 3 m, the main line between the two branch lines was 4 m, and the line connecting the wire and the sinker was 2 m. The gear was towed by a fishing boat with a gross tonnage of less than 5 t.

The main target of this fishing is largehead hairtail, but other fish species can be caught too, such as Japanese Spanish mackerel *Scomberomorus niphonius* or Japanese amberjack *Seriola quinqueradiata*. While towing the gear, the fisherman has to adjust the gear depth to the layer in which the target fish is distributed, which is observed using an echo sounder (this process is called “tana-dori”). The gear depth is estimated from the ratio of the paid-out length of the wire at which the sinker touches the bottom to the water depth measured with the echo sounder. To determine this ratio, the fisherman has to let the sinker touch the bottom several times during a fishing operation. However, years of experience and intuition are required for tana-dori because the ratio changes in a complex manner depending on the current. The accuracy of tana-dori is one of the factors affecting the catch. We attempted to apply the developed system to trolling with the aim of making tana-dori easier.

Implementation experiments

Two implementation experiments were conducted in the Bungo Channel (100–200 m depth): one on November 21, 2013, and the other on March 11, 2014 (Fig. 4). A pinger was attached to the part of the line connecting the wire and the sinker (Fig. 5). The transmission interval of the pinger was set to 1.27 s. Under the assumption that the hooks were floated by being towed, the pinger was attached at a distance of 1.5 m from the sinker so that the pinger would be at approximately the same depth as the hooks of the gear. The hydrophone was towed from the stern of the boat with the depressor. The receiver was deployed near an echo sounder placed in the cabin so that the fisherman could check the water depth and the pinger depth at the same time. The fisherman conducted fishing while monitoring the depth of the pinger. A PC was used to record the time of signal detection and the depth data. In the second experiment on March 11, 2014, movies of the echo sounder were recorded using a digital camera in order to obtain the water depth information during the fishing operation. The towing speed was also measured by a GPS logger (M-241, Holux). We checked whether the system could be used without any interruption to the fishing operations. After the experiments, we received some feedback from the fisherman that is discussed later.

The interval of data display required for tracking the fishing gear was estimated from the characteristics of the trolling. We calculated the reception ratio by Eq. (2) for each operation and checked whether the data were displayed at the required interval. Since the interval of the data display was changed depending on the reception ratio and the transmission interval of the pinger, the appropriate transmission interval was also discussed from the calculation results of the reception ratio.

Results

Evaluation experiment

We obtained the pinger depth and the logger depth simultaneously in the evaluation experiment (Fig. 6). The overall RMSE value was 2.6 m. However, most absolute $D_{\mathrm{P}i\text{-}\mathrm{L}i}$ values were less than the RMSE value (Fig. 7) and this result was affected by some $D_{\mathrm{P}i\text{-}\mathrm{L}i}$ values that were more than 2 m as clearly indicated in the bottom graph of Fig. 6. These $D_{\mathrm{P}i\text{-}\mathrm{L}i}$ values were defined as "erroneous data" by detection of a wrong signal that was probably caused by multi-path effects. The percentage of the erroneous data was calculated as

$$P_{\mathrm{E}} = \frac{N_{\mathrm{E}}}{N} \times 100 \tag{4}$$

where N_{E} is the number of the erroneous data items and N is the total number of depth data items. The erroneous data accounted for 19.7 % of the all depth data. The overall RMSE value excluding the erroneous data was 0.4 m. A comparison of results for the two measurements revealed that the RMSE value of the first measurement was 0.3 m and that of the second measurement was 0.7 m (Table 2). The relation between the $D_{\mathrm{P}i\text{-}\mathrm{L}i}$ value excluding the error and the vertical velocity of the pinger was examined for each measurement (Fig. 8), and no correlation between the $D_{\mathrm{P}i\text{-}\mathrm{L}i}$ value and the vertical velocity was observed in the case of both the measurements (r = 0.10 in both the measurements). However a weak correlation was observed overall (r = 0.37).

The reception ratios calculated by Eq. (2) for the first and second measurements were 72.0% and 92.0%, respectively (Table 2). The overall reception ratio was 75.3%. The reception ratio for the second measurement was divided into three cases according to the vertical velocity of the pinger: (1) vertical velocity in the range of -0.2 to 0.2 m/s (stop or slow), (2) vertical velocity less than -1.5 m/s (velocity during descent), and (3) vertical velocity more than 2.0 m/s (velocity during ascent). The reception ratios for these three cases were 91.7%, 90.3%, and 98.5% respectively. These were almost constant and no effect of the Doppler frequency shift on them was observed.

Implementation experiments

The fisherman could operate the developed system alone without any problem during the fishing operations. The depth of the fishing gear was obtained in seven operations each in the two implementation experiments (Fig. 9), i.e., a total of 14 operations. The summary of results of these implementation experiments is presented in Table 3.

The developed system monitored the gear depth continuously in real time. However, some data obviously deviated even when the fisherman did not change the gear depth. These data interrupted the monitoring when they were generated frequently, as was observed in operation No. 12. To identify the deviating data, we used the vertical velocity of the gear that was calculated from the variation of the measured depth. The vertical velocity ranged from 1.4 m/s to 1.9 m/s on average until the time at which the sinker touched the bottom at the beginning of the operation. We assumed that vertical velocity at that time was the maximum value, and we extracted depth data that instantaneously exceeded 2.0 m/s as the erroneous data. For each operation, the percentage of the erroneous data was calculated by Eq. (4). The percentage was significantly higher in the second implementation experiment (15.8% ± 10.9%) than in the first one (5.9% ± 4.8%) (Mann–Whitney *U*-test, $p < 0.05$).

The reception ratio calculated by Eq. (2) was 39.7% overall. However, comparison of the results of the two experiments revealed that the condition of reception was significantly better in the second experiment (Mann–Whitney *U*-test, $p < 0.05$). The reception ratio in the first experiment was 24.8% ± 6.2%, and that in the second experiment was 54.6% ± 20.1% on average. The reception ratio excluding the erroneous data was down to 23.5% ± 6.7% in the first experiment and 46.5% ± 19.2% in the second experiment.

The relation between the gear depth and the water depth was obtained in three operations (Fig. 10). The gear was essentially set 10–20 m above the bottom, but if the water depth was more than 200 m, as was the case in operation No.13, the fisherman fished without tana-dori owing to insufficient wire length. The fisherman had to adjust the gear depth several times in one operation while keeping the depth to the bottom unchanged.

Discussion

From the results of the evaluation experiment for each measurement, the accuracy of the measured gear depth was found to be almost constant without any correlation with the vertical velocity of the pinger. However, a weak correlation was observed overall. It was affected by the imperfect time synchronization of the pinger and the logger that would cause the increasing of the $D_{\mathrm{P}i\text{-}\mathrm{L}i}$ values when vertical velocity was high, and there seemed to be no indication that the accuracy deteriorated with increasing vertical velocity. The tracking performance was ensured to be sufficient to apply the developed system to fishing operations in which the gear depth is changed at a velocity of less than 2.0 m/s, including hairtail trolling. The developed system measured with an overall RMSE of 0.4 m in the evaluation experiment. The RMSE value corresponded to the accuracy of measurement of the water depth in shallow water (< 20 m) by a general echo sounder used in fishing operations [19]. Fishermen would use the gear depth measured by the developed system simply by comparing this gear depth with the echogram of depth including the bottom and fish schools.

The reception ratios differed between the evaluation experiment and the implementation experiments. This was probably due to a higher ambient noise level in the implementation experiments. In particular, interference might occur between the signals of the pinger and the echo sounder because the frequency of the echo sounder was 50 kHz, which was close to the frequency of the pinger (62.5 kHz). The reception ratio also significantly varied between both the implementation experiments. The difference in wind force levels would have an effect on the variation of the reception ratio. The wind is one of the factors that causes considerable changes in the ambient noise level in the ocean [20, 21] and its influence is much higher when a hydrophone is near the surface than when it is submerged at a large depth [21]. The wind speed data for each operation that was obtained from the data archive of the Japan Meteorological Agency (observation station: Seto, Ehime prefecture) indicated that the wind-related noise was lower in the second implementation experiment than that in the first one (Table 3). For the application of the developed system to small-scale fishing, the first experiment was conducted in the maximum allowable wind condition for the fishing operation. We considered the reception ratio on that day as being the lowest value for the developed system. The depth of the trolling gear, excluding the erroneous data, could be monitored every 4 to 9 s in the first experiment and every 2 to 6 s in the second experiment. The display interval was short enough to monitor the gear depth when the gear was towed at a fixed depth. During tana-dori, however, there were some instances in which the system could not track the gear depth. The maximum vertical velocity of the gear depth during tana-dori was 1.3 m/s, except at the beginning of the operation. Since the gear was maintained at a distance of 10–20 m from the bottom, it takes 7.7 s (= 10 m / 1.3 m/s) at the shortest to let sinker touch the bottom. We considered the required display interval to be less than 7 s for tracking of the gear depth. To monitor the depth at 7 s intervals with certainly, the transmission interval should be less than 1 s instead of the present interval of 1.27 s, for the case when the reception ratio excluding the erroneous data is the lowest (14.2% in the operation No. 5).

We also attempted to monitor the depth of the hooks in hairtail trolling with one pinger that was attached to the line connecting the wire and the sinker. This approach was considered adequate for the monitoring because the boat speed was constant and lower than the other general trolling speed of 4.5 knots [22], and the variation of the overall gear depth with the boat speed might be relatively less. In this study, however, the actual hook depth was not measured. A more appropriate installation position of the pinger could be selected by using hook depth data obtained by smaller pingers or data loggers.

The developed system was successfully operated without any problem and was sufficiently manageable for a fisherman to operate it alone. We received some feedback from the fisherman, including a remark that the system made adjustment of the gear depth easier because he could monitor it in real time. This feedback indicated that the system provided the expected level of support to the fisherman. However, there were some issues with the system. One was the additional effort required for retrieving the hydrophone from the stern of the boat when trolling was suspended to change the fishing ground. Accidents may be incurred by forgetting to recover the hydrophone. This issue can be overcome if the hydrophone is deployed at the bottom of the boat to prevent its handling. Another issue was the method of displaying data. The depth displayed on the receiver was too small to be observed from outside the boat cabin. The receiver should be improved to make the displayed data more clearly visible. For example, the pinger depth is displayed using LED, but it is more effective to display the gear depth graphically as shown in Fig. 9 because a user would be able to distinguish the erroneous data in the graphical presentation.

Some erroneous data were generated in the field experiments. The presumed cause of the erroneous data was the detection of the pulse that was reflected from the sea surface or the bottom (Fig. 11). The arrival time of a reflected pulse is later than that of a direct pulse. If the hydrophone detects only a direct pulse and a reflected pulse for the detection of a signal, the interval of the pulses is shorter (when the first pulse is the reflected pulse) or longer (when the second pulse is the reflected pulse). The delay time of the reflected pulse was determined by the difference in the propagation distance between a direct pulse and a reflected pulse. If pulses are reflected at the surface, the difference in the propagation distance depends on the hydrophone depth. In that case, the delay time and the error value of the depth should be almost constant in one operation owing to just a slight change in the hydrophone depth. On the other hand, if pulses are reflected at the bottom, the error value should change with a change in the distance of the pinger from the bottom that is caused by the change in the water depth or the gear depth. We calculated the error values from the depth difference between erroneous data and other data around the erroneous data when the gear was towed at a fixed depth (Fig. 12 and Table 4). The histogram shows similar tendencies of the positive and negative error values. The absolute value of the error almost ranged from 8 to 20 m, and three modes were observed at 13, 15, and 17 m. The appearance of the three modes was caused by the change in the error value for each operation, and the error values were almost constant in one operation. Therefore, we concluded that the cause of the incorrect signal detection was the reflected pulse at the surface. The number of erroneous data items was considered to vary depending on the condition of the surface. According to the wind speed in the experiments (Table 3), it can be said that a larger amount of erroneous data can be generated when the sea state is better. Adding directivity to the hydrophone to detect only direct pulses is one way to solve this problem. The problem could also be solved by deploying the hydrophone at the bottom of the boat as described above, because the reflected pulses were found to be blocked by the boat.

In this study, we designed a system for monitoring small fishing gear in real time and implemented it in a hairtail trolling operation. The results of the experiments showed that the system could monitor and visualize the gear depth, although some issues were faced that need to be solved. Application of the system could assist fishermen in adjusting the gear depth easily and accurately without having to rely on their experience and intuitions. It may also help to change the method of fishing and the fishing operation to achieve higher efficiency. In the case of hairtail trolling, for example, the process of letting the sinker touch the bottom for tana-dori could be skipped by monitoring the gear depth continuously.

The developed system is capable of supporting various small-scale fisheries, especially, for fishing methods in which the depth information is essential. For example, the system could be utilized for fishing with hooks and lines because the relative depth between the hook and fish is also important information for this kind of fishing. The system is effective for small-scale trawl or purse seine boats for the same reason as the use of conventional systems in large-scale boats. For specific target uses, the transmission interval can be adjusted so that the sampling interval and battery life can be optimized for the monitoring duration.

The developed system can also be used in net sampling in fisheries and in oceanography studies. Additional sensors such as a temperature sensor can be mounted on the pinger according to the intended purpose. At the moment, we have not incorporated the data recording function in the system itself, but if this function is incorporated, collected data will contribute to more efficient fishing operations.

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