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

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10

11 Abstract

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

24

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

26

27 **Introduction**

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

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

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

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

55

56 **Materials and methods**

57 *System for depth monitoring of small fishing gear*

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

61 We need to consider the following specifications of the pinger: size; weight; battery life; source level, which is
62 related to the possible propagation distance of the acoustic signal; and the transmission interval, which is related to
63 the interval of data display. A conventional pinger that transmits signals encoded by the PN code, for example,
64 AquaSound Inc., model AQPX-1030-60P (<http://aqua-sound.com/products/pinger-aqpx-1030.html> “Accessed 9 Nov
65 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
66 days if the pinger transmits the signal every 1 s. While conventional pingers are disposable since it is attached an
67 aquatic animal and is not collected, a pinger that can be used repeatedly is needed for application to fishing gear. We
68 chose a lithium CR15H270 battery (3 V, 850 mAh, 15.6 mm diameter and 27 mm length) for transmitting signals
69 with the power, intervals, and duration that are required in order to conform to most small-scale fishing operations.
70 As a result of pinger development, the source level of the pinger was 155 dB re 1 μ Pa at 1 m, which implied that the
71 signal could propagate for about 500 m. The frequency of the pinger is 62.5 kHz. Its battery life is about 1 month if
72 it transmits the signal every second, although a longer transmission interval can be set. The battery can be replaced
73 by fishermen themselves for repeated use. The pinger dimensions are 24 mm (diameter) \times 100 mm (length), and it
74 weighs 77 g in air and 31 g in water.

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

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

91

92 *Evaluation experiment of system performance*

93 A field experiment was conducted for evaluating the performance of the developed system. The accuracy of the
94 measured depth was estimated by a comparison with data acquired by a depth data logger (DEFI-D20HG, JFE
95 Advantech Co., Ltd.; range: 200 m, resolution: 0.02 m). The pinger and logger were tied onto a rope connected to
96 the fishing line. The transmission interval of the pinger was set to 1.27 s, and the logger recorded its depth every 1 s.
97 The depth of the instruments was adjusted using an electrical reel, which displayed the paid-out length of a line.
98 During the measurement, a research boat drifted in the water of 100–150 m deep. Two measurements with a
99 different vertical moving pattern were tested to evaluate the effect of the vertical velocity of the pinger on the
100 accuracy of the measured depth. As the first measurement, we lowered the instruments down to a depth of about 100
101 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
102 addition to this movement, the line was also wound up to prevent the pinger from touching the sea bottom. As the
103 second measurement, the instruments were shuttled between the surface and near the bottom (about 140 m) at
104 maximum velocity. The vertical velocity was then calculated from the variation of depth per time as measured by
105 the logger.

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

$$108 \quad \text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (D_{P_i} - D_{L_i})^2}{N}} \quad (1)$$

109 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-Li}), and N is the
110 number of data items. The correlation coefficient (r) of D_{Pi-Li} with the vertical velocity was examined for evaluating
111 the tracking performance. The absolute values were used in the calculation of the correlation coefficient.

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

$$115 \quad P_R = \frac{N}{N_T} \times 100 \quad (2)$$

$$116 \quad N_T = \frac{T}{I} \quad (3)$$

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

123

124 *Outline of hairtail trolling*

125 We applied the developed system to hairtail trolling in western Japan. Specifically, we considered trolling in the
126 Bungo Channel, which lies between Kyushu and Shikoku islands in Japan. The fishing gear used in this experiment
127 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
128 desired depth, a nylon main line, and branch lines (Fig. 3). About 90 branch lines were connected to the main line,
129 and each branch line had a baited or lure hook; however, a few branch lines were connected to floats to stabilize the
130 gear depth. The approximate length of the branch lines was 3 m, the main line between the two branch lines was 4 m,
131 and the line connecting the wire and the sinker was 2 m. The gear was towed by a fishing boat with a gross tonnage
132 of less than 5 t.

133 The main target of this fishing is largehead hairtail, but other fish species can be caught too, such as
134 Japanese Spanish mackerel *Scomberomorus niphonius* or Japanese amberjack *Seriola quinqueradiata*. While towing

135 the gear, the fisherman has to adjust the gear depth to the layer in which the target fish is distributed, which is
136 observed using an echo sounder (this process is called “tana-dori”). The gear depth is estimated from the ratio of the
137 paid-out length of the wire at which the sinker touches the bottom to the water depth measured with the echo
138 sounder. To determine this ratio, the fisherman has to let the sinker touch the bottom several times during a fishing
139 operation. However, years of experience and intuition are required for tana-dori because the ratio changes in a
140 complex manner depending on the current. The accuracy of tana-dori is one of the factors affecting the catch. We
141 attempted to apply the developed system to trolling with the aim of making tana-dori easier.

142

143 *Implementation experiments*

144 Two implementation experiments were conducted in the Bungo Channel (100–200 m depth): one on November 21,
145 2013, and the other on March 11, 2014 (Fig. 4). A pinger was attached to the part of the line connecting the wire and
146 the sinker (Fig. 5). The transmission interval of the pinger was set to 1.27 s. Under the assumption that the hooks
147 were floated by being towed, the pinger was attached at a distance of 1.5 m from the sinker so that the pinger would
148 be at approximately the same depth as the hooks of the gear. The hydrophone was towed from the stern of the boat
149 with the depressor. The receiver was deployed near an echo sounder placed in the cabin so that the fisherman could
150 check the water depth and the pinger depth at the same time. The fisherman conducted fishing while monitoring the
151 depth of the pinger. A PC was used to record the time of signal detection and the depth data. In the second
152 experiment on March 11, 2014, movies of the echo sounder were recorded using a digital camera in order to obtain
153 the water depth information during the fishing operation. The towing speed was also measured by a GPS logger (M-
154 241, Holux). We checked whether the system could be used without any interruption to the fishing operations. After
155 the experiments, we received some feedback from the fisherman that is discussed later.

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

161

162

163 **Results**

164 *Evaluation experiment*

165 We obtained the pinger depth and the logger depth simultaneously in the evaluation experiment (Fig. 6). The overall
166 RMSE value was 2.6 m. However, most absolute D_{Pi-Li} values were less than the RMSE value (Fig. 7) and this result
167 was affected by some D_{Pi-Li} values that were more than 2 m as clearly indicated in the bottom graph of Fig. 6. These
168 D_{Pi-Li} values were defined as “erroneous data” by detection of a wrong signal that was probably caused by multi-path
169 effects. The percentage of the erroneous data was calculated as

170
$$P_E = \frac{N_E}{N} \times 100 \quad (4)$$

171 where N_E is the number of the erroneous data items and N is the total number of depth data items. The erroneous
172 data accounted for 19.7 % of the all depth data. The overall RMSE value excluding the erroneous data was 0.4 m. A
173 comparison of results for the two measurements revealed that the RMSE value of the first measurement was 0.3 m
174 and that of the second measurement was 0.7 m (Table 2). The relation between the D_{Pi-Li} value excluding the error
175 and the vertical velocity of the pinger was examined for each measurement (Fig. 8), and no correlation between the
176 D_{Pi-Li} value and the vertical velocity was observed in the case of both the measurements ($r = 0.10$ in both the
177 measurements). However a weak correlation was observed overall ($r = 0.37$).

178 The reception ratios calculated by Eq. (2) for the first and second measurements were 72.0% and 92.0%,
179 respectively (Table 2). The overall reception ratio was 75.3%. The reception ratio for the second measurement was
180 divided into three cases according to the vertical velocity of the pinger: (1) vertical velocity in the range of -0.2 to
181 0.2 m/s (stop or slow), (2) vertical velocity less than -1.5 m/s (velocity during descent), and (3) vertical velocity
182 more than 2.0 m/s (velocity during ascent). The reception ratios for these three cases were 91.7%, 90.3%, and 98.5%
183 respectively. These were almost constant and no effect of the Doppler frequency shift on them was observed.

184

185 *Implementation experiments*

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

189 The developed system monitored the gear depth continuously in real time. However, some data obviously

190 deviated even when the fisherman did not change the gear depth. These data interrupted the monitoring when they
191 were generated frequently, as was observed in operation No. 12. To identify the deviating data, we used the vertical
192 velocity of the gear that was calculated from the variation of the measured depth. The vertical velocity ranged from
193 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.
194 We assumed that vertical velocity at that time was the maximum value, and we extracted depth data that
195 instantaneously exceeded 2.0 m/s as the erroneous data. For each operation, the percentage of the erroneous data
196 was calculated by Eq. (4). The percentage was significantly higher in the second implementation experiment (15.8%
197 \pm 10.9%) than in the first one (5.9% \pm 4.8%) (Mann–Whitney *U*-test, $p < 0.05$).

198 The reception ratio calculated by Eq. (2) was 39.7% overall. However, comparison of the results of the two
199 experiments revealed that the condition of reception was significantly better in the second experiment (Mann–
200 Whitney *U*-test, $p < 0.05$). The reception ratio in the first experiment was 24.8% \pm 6.2%, and that in the second
201 experiment was 54.6% \pm 20.1% on average. The reception ratio excluding the erroneous data was down to 23.5% \pm
202 6.7% in the first experiment and 46.5% \pm 19.2% in the second experiment.

203 The relation between the gear depth and the water depth was obtained in three operations (Fig. 10). The
204 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
205 operation No.13, the fisherman fished without tana-dori owing to insufficient wire length. The fisherman had to
206 adjust the gear depth several times in one operation while keeping the depth to the bottom unchanged.

207

208 **Discussion**

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

218 depth measured by the developed system simply by comparing this gear depth with the echogram of depth including
219 the bottom and fish schools.

220 The reception ratios differed between the evaluation experiment and the implementation experiments. This
221 was probably due to a higher ambient noise level in the implementation experiments. In particular, interference
222 might occur between the signals of the pinger and the echo sounder because the frequency of the echo sounder was
223 50 kHz, which was close to the frequency of the pinger (62.5 kHz). The reception ratio also significantly varied
224 between both the implementation experiments. The difference in wind force levels would have an effect on the
225 variation of the reception ratio. The wind is one of the factors that causes considerable changes in the ambient noise
226 level in the ocean [20, 21] and its influence is much higher when a hydrophone is near the surface than when it is
227 submerged at a large depth [21]. The wind speed data for each operation that was obtained from the data archive of
228 the Japan Meteorological Agency (observation station: Seto, Ehime prefecture) indicated that the wind-related noise
229 was lower in the second implementation experiment than that in the first one (Table 3). For the application of the
230 developed system to small-scale fishing, the first experiment was conducted in the maximum allowable wind
231 condition for the fishing operation. We considered the reception ratio on that day as being the lowest value for the
232 developed system. The depth of the trolling gear, excluding the erroneous data, could be monitored every 4 to 9 s in
233 the first experiment and every 2 to 6 s in the second experiment. The display interval was short enough to monitor
234 the gear depth when the gear was towed at a fixed depth. During tana-dori, however, there were some instances in
235 which the system could not track the gear depth. The maximum vertical velocity of the gear depth during tana-dori
236 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
237 the bottom, it takes 7.7 s ($= 10 \text{ m} / 1.3 \text{ m/s}$) at the shortest to let sinker touch the bottom. We considered the required
238 display interval to be less than 7 s for tracking of the gear depth. To monitor the depth at 7 s intervals with certainly,
239 the transmission interval should be less than 1 s instead of the present interval of 1.27 s, for the case when the
240 reception ratio excluding the erroneous data is the lowest (14.2% in the operation No. 5).

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

246 obtained by smaller pingers or data loggers.

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

258 Some erroneous data were generated in the field experiments. The presumed cause of the erroneous data
259 was the detection of the pulse that was reflected from the sea surface or the bottom (Fig. 11). The arrival time of a
260 reflected pulse is later than that of a direct pulse. If the hydrophone detects only a direct pulse and a reflected pulse
261 for the detection of a signal, the interval of the pulses is shorter (when the first pulse is the reflected pulse) or longer
262 (when the second pulse is the reflected pulse). The delay time of the reflected pulse was determined by the
263 difference in the propagation distance between a direct pulse and a reflected pulse. If pulses are reflected at the
264 surface, the difference in the propagation distance depends on the hydrophone depth. In that case, the delay time and
265 the error value of the depth should be almost constant in one operation owing to just a slight change in the
266 hydrophone depth. On the other hand, if pulses are reflected at the bottom, the error value should change with a
267 change in the distance of the pinger from the bottom that is caused by the change in the water depth or the gear
268 depth. We calculated the error values from the depth difference between erroneous data and other data around the
269 erroneous data when the gear was towed at a fixed depth (Fig. 12 and Table 4). The histogram shows similar
270 tendencies of the positive and negative error values. The absolute value of the error almost ranged from 8 to 20 m,
271 and three modes were observed at 13, 15, and 17 m. The appearance of the three modes was caused by the change in
272 the error value for each operation, and the error values were almost constant in one operation. Therefore, we
273 concluded that the cause of the incorrect signal detection was the reflected pulse at the surface. The number of

274 erroneous data items was considered to vary depending on the condition of the surface. According to the wind speed
275 in the experiments (Table 3), it can be said that a larger amount of erroneous data can be generated when the sea
276 state is better. Adding directivity to the hydrophone to detect only direct pulses is one way to solve this problem.
277 The problem could also be solved by deploying the hydrophone at the bottom of the boat as described above,
278 because the reflected pulses were found to be blocked by the boat.

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

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

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

296

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302

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