Aquaculture 293 (2009) 49–56

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

A self-contained system for observing and quantifying the behavior of Atlantic cod, *Gadus morhua*, in an offshore aquaculture cage

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ARTICLE INFO

Article history:
Received 5 January 2009
Received in revised form 31 March 2009
Accepted 2 April 2009

Keywords:
Offshore aquaculture
Ultrasonic telemetry
Atlantic cod
Gadus morhua
Fish behavior
Daily rhythms

ABSTRACT

A self-contained data collection system is described that was used to investigate the behavior of Atlantic cod (*Gadus morhua*) in an offshore net pen (Sea Station 3000) located 13 km off the coast of New Hampshire, USA. The entire system was housed inside a modified U.S. Coast Guard (USCG) navigational buoy that was retrofitted for this purpose. Power was provided by a combination of eight 12 V batteries, two solar panels and a wind generator. The behavior of the population of cod as a whole, during daylight hours, was monitored using four waterproof cameras connected to a four channel digital video recorder. The behavior of 4–12 individual fish implanted with ultrasonic transmitters was continuously recorded, during each of four study periods, using a HTI model 291 ultrasonic telemetry system. Laboratory studies showed no influence of transmitter implantation on swimming or feeding behavior. Transmitters were programmed to “ping” at intervals between 1.7 and 3.3 s and they typically lasted for about one month. The system successfully detected and plotted 84.9 ± 6.0% of transmissions, resulting in an average of 1283.4 ± 252.5 positional fixes for each animal, during each hour of the study. This preliminary evaluation of cod behavior in a net pen demonstrated that they are diurnally active and have a tendency to mill about, rather than school. Cod predominately used the lower half of the cage, except when rising to the feeding area during periods when feed was delivered. The system that was developed proved to be ideal for investigating the behavior of fish within a net pen, and it can be used by both inshore and offshore farms to gather behavioral data that can lead to improvements in the efficiency of aquaculture operations.

1. Introduction

Global aquaculture is a $63.3 billion dollar industry, yielding 45.5 mmt of seafood/year (FAO, 2006). While aquaculture continues to grow at a compounding growth rate of 8.8%/year (since 1970; FAO, 2006), scientific and public concerns have arisen about the sustainability and environmental impacts of the industry. Recent publications have highlighted several factors of concern, including aquaculture's dependence on wild fish products, eutrophication from animal waste and uneaten food, and escapement of genetically altered farming stock (Naylor et al., 2000; Powell, 2003; Naylor and Burke, 2005). While federal governments continue to embrace the growing industry, most aquaculture legislation highlights the need for continued research to reduce environmental impacts (e.g. Dept. of Commerce Aquaculture Policy, 1999; U.S. Ocean Action Plan, 2004; National Offshore Aquaculture Act, 2007).

One way to alleviate some of the issues described above is to use information regarding the behavior of farmed fish to design operations that reduce escapement and optimize feed utilization. For example, Juell and Westerberg (1993) used telemetry to study the behavior of farmed salmon and they found that the fish they tracked did not participate in 74.9% of the feeding bouts; suggesting that an alternative feeding schedule might be more effective. Additional behavioral studies have revealed stress responses in farmed animals, due to environmental disturbances, farming operations or high stocking densities (Begout and Lagardere, 1993; Cooke et al., 2000; Begout and Lagardere, 2004; Chandroo et al., 2005). These types of behavioral data, if available, can be used by fish farmers to optimize operations, improve fish welfare and produce a better product.

While the aforementioned studies illustrate the practical implications of obtaining behavioral data about farmed fish, the difficulty in gathering such data in the field has impeded progress, especially with respect to offshore aquaculture operations. While monitoring fish behavior with video systems is fairly routine, and easy to implement, it has many disadvantages: 1) it is almost impossible to keep track of individual fish; 2) video cannot be used effectively at night, especially with marine fish, because seawater rapidly absorbs infra-red light; and 3) quantifying fish behavior from video is both challenging and time-consuming.

The use of biotelemetry can overcome some of the pitfalls of video technology. A major benefit of telemetry is the ability to monitor the

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doi:10.1016/j.aquaculture.2009.04.003

activity of individual fish despite lighting or visibility conditions. In addition, because of the nature of the data obtained, it is possible to quantify many aspects of the behavior of the animal in question, such as swimming speed, periods of the day when it is most active, and spatial distribution in the cage. Unfortunately, telemetry systems also have their drawbacks: 1) they are expensive, and more difficult to use than video systems; 2) fish have to be implanted with transmitters, and this can limit the size of the fish that can be used; and 3) most telemetry systems are not capable of collecting data at a high enough speed, with a good enough resolution, to be practical in typical aquaculture settings. Due to these constraints, most studies to date using ultrasonic telemetry have focused on medium-scale (10 s of meters to km) movements of animals and data has primarily been used to calculate home ranges and determine habitat use (see Bjorn et al., 2009 for a recent example with cod).

The overall goal of this investigation was to develop an integrated telemetry and video system that could be used to investigate the fine-scale movements of cod that are being raised by the UNH Open Ocean Aquaculture project (www.ooa.unh.edu) in a net pen located 13 km off the coast of NH, in the Gulf of Maine. This involved adapting a high frequency (307.2 kHz) telemetry system, initially developed for tracking fish in a freshwater habitat, for use in a marine environment, as well as modifying existing video surveillance technologies for our specific applications. Moreover, due to the offshore location of the study site, all systems had to be powered from batteries, supplemented with a wind generator and solar panels. In this manuscript, we describe our final product and present some representative data. Two manuscripts in review will provide more detailed analyses of behavior. The final system is based on a HTI (Model 291, Hydroacoustic Technologies Inc., Seattle, WA) biotelemetry system that uses four hydrophones, hard-wired to a receiver, to track fish implanted with very small transmitters, in three dimensions. Positional fixes were obtained about every 2 s, making it possible to very accurately calculate swimming speeds and investigate fine-scale movements. It was possible to use this high frequency system, rather than the lower frequency (50–100 kHz) ultrasonic telemetry systems typically used in the marine environment, because the net pen kept the fish in a small enough area that attenuation of the high frequency signals by seawater was not a problem.

2. Methods

2.1. Study site

The UNH Open Ocean Aquaculture study site is located 13 km off the coast of New Hampshire and 1.5 km south of the Isle of Shoals (www.ooa.unh.edu). The site has a submerged grid system capable of mooring up to four submerged cages and their associated surface support buoys. Atlantic cod (*Gadus morhua*) are being raised in a 3000 m^3 Sea Station cage (25 m wide × 15.5 m deep; Net Systems Inc., Bainbridge, WA). One cohort (~30,000) of cod was raised in the submerged cage from September 2003 to February 2006 and the other cohort of 50,000 juvenile cod (~50 g) was transferred to the site for grow out in April of 2006 (data presented in this paper were only obtained from the second cohort).

The exposed nature of the site required the design of a system to house the electronics while facing high seas (8+ m), high winds, and ice. An independent self-contained system was created within a refurbished USCG, 6 × 20 LR navigational buoy (Fig. 1) moored at 2-points to the submerged grid network. The advantage of having an independent buoy system was that it could be moored in a central location, giving researchers the ability to monitor multiple cages, while also being small enough so that it could be disconnected from the site and towed into more protected waters during large storms. The disadvantage of this independent system was that the size of the infrastructure required to handle the sea conditions, and provide sufficient power, greatly surpassed the actual size of the electronics.

2.2. Monitoring equipment

The Hydroacoustic Technologies Inc. (HTI) Model 291 Portable Acoustic Tracking System (Seattle, WA) was used to track fish in this study. This system was chosen for several reasons: 1) it uses fixed hydrophones connected directly to the receiver so the position of the fish can be very accurately (sub-meter resolution) and rapidly (0.2–16 s/location) tracked; 2) the system is able to simultaneously track and plot the position of multiple fish (thousands) in three dimensions; and 3) the required transmitters are small enough so that they can be easily implanted in juvenile cod. The HTI system uses small, high frequency (307.2 kHz), transmitters designed for freshwater environments and in seawater these signals are significantly attenuated. However, because the signals travel ~200 m in seawater, and because fish were confined within a 25 m diameter net pen, signal loss was not a problem.

A four hydrophone array was fixed to the netting forming the net pen enclosure (Fig. 2). Hydrophones were hardwired, via 153 m cables, to the surface buoy. A Dell Inspiron 600 m laptop computer running AcousticTag software (Version 4, HTI) controlled the system and logged data.

Video recordings of fish in different areas of the net pen were obtained using a four channel digital video recorder (DVR; ID-400CD-SN, Compulan Centers Inc., Dallas, TX) linked by cables to three underwater cameras and one surface camera. Data were stored on an onboard hot-swappable 240 GB hard disk, that was sufficient to store a week's worth of video data. The DVR was scheduled to record only during daylight hours to avoid unnecessary use of power or disk storage space.

A 2D-ACM acoustic current meter (Falmouth Scientific Inc., Falmouth, MA) was placed within the cage to monitor current speed and direction. It was hardwired to the surface buoy and data were stored on the laptop computer. HOBO temperature and light loggers (Onset Computer Inc., Bourne, MA) were placed within the cage to monitor light intensity and temperature. A wireless router (Linksys Co.) provided a close-range link between the on-board computer and DVR, and the research vessel used during the study. This allowed for

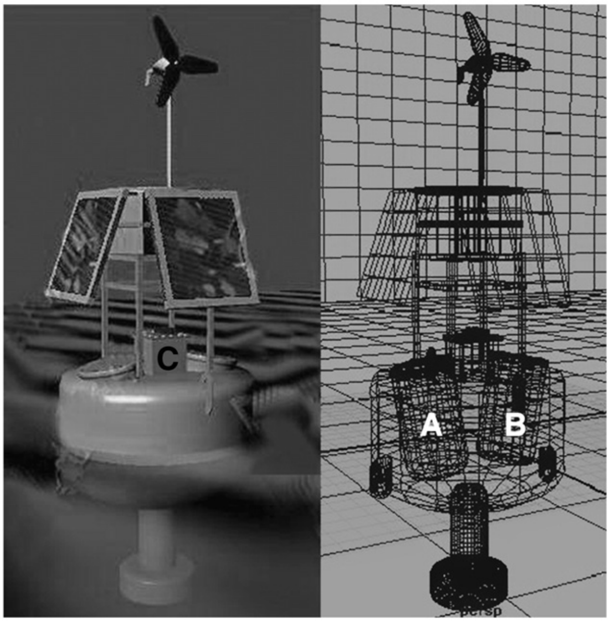

Fig. 1. USCG navigational buoy refurbished to serve as an instrumentation buoy for monitoring fish behavior. Instrument cables from the fish cage were plugged into a waterproof junction box (C). Additional cables transferred information between the instrumentation (A) and battery (B) silos. Solar panels and a wind generator charged the batteries located in silo B.

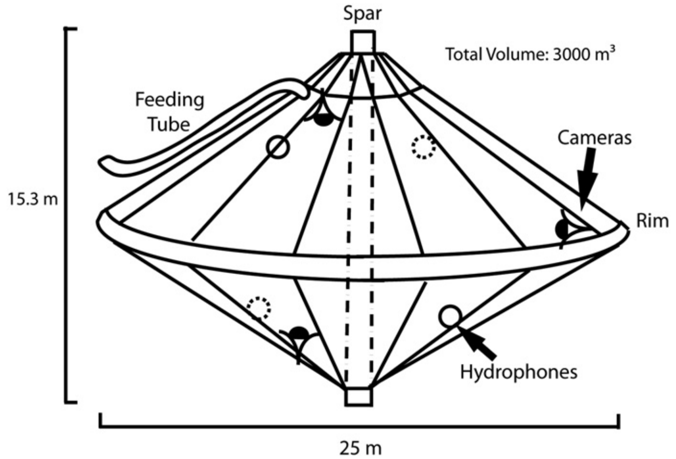

Fig. 2. Placement of cameras, hydrophones and the feeding tube on the Sea Station 3000 net pen. The Sea Station consisted of a 15.3 m central steel spar and surrounding steel rim (diameter: 25 m). Rope stays and spectra net panels maintained the nets rigid structure. The net was equipped with 3 video cameras located on the top, middle and bottom of the cage (eye icons) and four hydrophones (circles) positioned 10–13 m apart.

system configuration, verification and data downloading without having to board the buoy.

2.3. Power

The system was designed to autonomously collect video, telemetry and environmental data for approximately one week. To meet the power requirements of the electronics, a rack of eight, 110-Ahr batteries were installed in a separate battery silo of the buoy (Fig. 1). Four solar panels and a wind generator were installed on the buoy tower to supplement the battery power; however the demand of the system was much greater than the power they yielded. Therefore, every seven days batteries were swapped out with fresh batteries, and brought to shore to be charged. Finally, a power conditioning system controlled the flow of power within the system. A low voltage disconnect protected the batteries from excessive drain by turning the system off when battery levels dropped below nine volts and a fuse block and voltage regulator protected the electronics from current and voltage spikes.

2.4. Surgical procedure

At the offshore site, sentinel fish were captured from the submerged net pen, slowly decompressed by bringing them to the surface at a rate of 5 m/h, and brought on board the research vessel for surgery. Fish were anesthetized using MS-222 (50 ppm) and a small incision was made on the ventral side, posterior to the pectoral fins. An ultrasonic transmitter was then implanted into the abdominal cavity of the fish and two sutures were used to close the incision. HTI F-tags (9 mm × 21 mm; 2.2 g in air, 1.1 g in freshwater; duration ~24 days) were used for smaller cod and HTI G-tags (11 mm diameter × 25 mm length; 2.4 g in air; duration ~30–40 days) were used for larger cod. Tags did not exceed 2.5% of the body weight as recommended in the literature (Baras and Lagardere, 1995; Jepsen et al., 2002). Fish were held in onboard tanks until fully recovered from surgery (~30 min) and then were returned by divers to the net pen. Fish were continuously monitored for the duration of the tag life, about one month. Cote et al. (1999) demonstrated that in juvenile cod implanted transmitters did not influence swimming, growth or mortality and that proved to be the case in this study. We had no incidences of infection or tag rejection and mortality during tagging only occurred during one early trial when a strong thermocline (~10 °C) caused additional stress during decompression and surgery. To minimize this stress, the decompression schedule was adjusted for longer decompression times below the thermocline, followed by an abbreviated decompression above the thermocline. In addition an on-board chiller was used to create a cooler water bath for fish once in the boat. These adjustments eliminated further mortalities.

2.5. Influence of transmitters on locomotion

To determine the possible effects of surgery or transmitter implantation on fish behavior, the behavior of 12 fish was investigated in the laboratory before and after tag implantation. Cod (length: 25.89 ± 0.37 cm, weight: 145.6 ± 9.9 g; all averages here and elsewhere are mean ± SEM) were decompressed and transferred from the offshore site to the University of New Hampshire's Coastal Marine Laboratory, where they were maintained in a flow-through seawater system from March through April of 2006 (water temperature: 4–5 °C). Cod were hand fed to satiation every other day.

Four experimental trials were conducted in a shallow rectangular (2 m × 1 m × 0.5 m) tank containing three 1 m diameter circular "racetracks". The tank was surrounded by opaque plastic sheeting to isolate animals from visual disturbances, and the enclosure was kept on a 12:12 light:dark photoperiod. Low light infrared video cameras were installed above each circular raceway to monitor fish activity, and a digital video recorder was used to store video data on hot-swappable hard disks.

One cod was placed in each raceway and allowed to acclimate for two weeks prior to tagging. Animals were fed five pellets (~2% B.W.) every other day. Following the acclimation period, animals were surgically implanted with a transmitter using the same protocol previously described. Fish were then returned to the raceways and their behavior and feed intake was monitored for one week after tagging.

Activity was determined by counting the number of laps an individual fish swam around the racetrack during the first 15 min of every hour. To determine the effect of implantation, activity was quantified for five days prior to tagging (during the acclimation period), and five days after tagging. To evaluate the potential effect of implantation on feeding, the feeding regime previously described continued throughout the experiment. Five pellets were hand fed to each fish on alternating days. Uneaten food was removed 3 h after feeding to determine daily food consumption. Feed intake was monitored for one week before and after tagging. A paired Student's *T*-test was used to compare pre-implantation activity and food consumption, to post-implantation activity and food consumption.

2.6. Data collection and analyses

The monitoring buoy was deployed at the UNH Open Ocean Aquaculture site in July 2006. Twenty-two cod were tagged between July 31st, 2006 and November 2nd, 2006 to test system performance. Four groups of fish were tracked sequentially (three cod in August, four in September, six in early October and nine in mid-October). All fish were continuously tracked for the duration of the transmitter life, 10–30 days. Due to the nature of signal processing within the HTI telemetry system, each transmitter had to be programmed with a unique pulse period because that is how the "ping" from each individual fish was identified. In this study the transmitters were programmed to "ping" at intervals ranging from 1.7–3.3 s.

Raw acoustic files were processed using a two step procedure within the HTI software suite. First, the noise was manually filtered with the MarkTag software (Version 4.0) by isolating repetitive signals based on the pulse periods of individual transmitters. Second, the data were imported into AcousticTag (Version 4.0) where signals from each hydrophone were examined. A three dimensional triangulation algorithm was applied to achieve a positional fix. Two restrictions were applied to the algorithm to reduce erroneous locations. First,

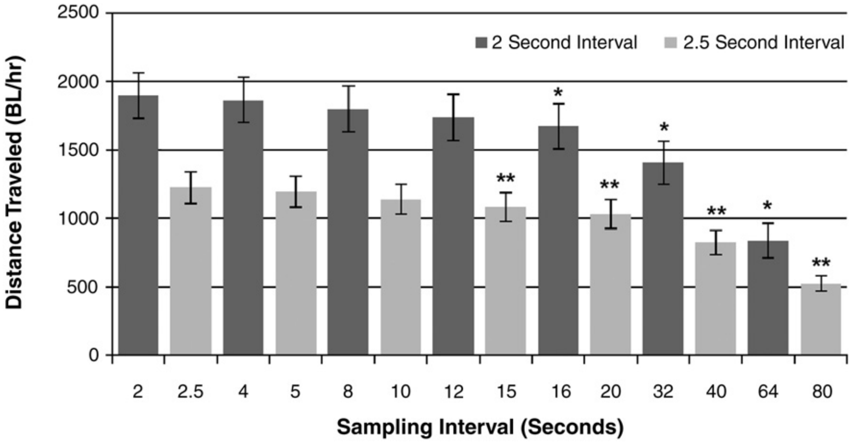

Fig. 3. The impact of sampling interval on calculations of distance traveled. Data were obtained from six cod originally tracked using sampling intervals of 2 and 2.5 s. Artificially removing points and thus increasing the sampling interval resulted in underestimations of distance traveled. Asterisks represent statistically significant reductions in distance traveled compared with the baseline sampling interval of 2 or 2.5 s. Statistically significant reductions in distance traveled occurred when the sampling interval was increased to greater than 10 s.

locations were locally restrained within a grid surrounding the cage. Second, locations were restrained based on excessive speed of travel (locations were omitted if subsequent positions yielded swimming speeds >1.5 m/s; ~5–6 BL/s). The software was also designed to linearly interpolate gaps in the data set, if the gap was less than 30 s. Interpolated values were marked and examined for validity and quantity after processing. The resultant data, consisting primarily of a time stamp and *X*, *Y*, *Z* coordinates, were exported to a Microsoft Access database for further analyses.

Previous studies (Begout and Lagardere, 1993; Lokkeborg et al., 2002) have demonstrated a negative correlation between the duration of the interval between successive positional fixes and calculations of swimming speed. That is, the longer the interval the more likely that the true path of the fish was not tracked, and thus distance traveled will be underestimated. In order to test this theory we calculated the distance traveled by a subset of the fish, while systematically removing points to simulate different sampling intervals. Swimming speed and distance traveled were calculated within a 1 h sample of data for six individual cod (three with a true pulse interval of 2 s, three with a true pulse interval of 2.5 s). The data set was then systematically reduced to evaluate swimming speed and distance traveled at theoretical sampling intervals ranging from 2–80 s. Five replicates from each individual were examined at the same time of day. A Tukey–Kramer multiple comparison test was performed

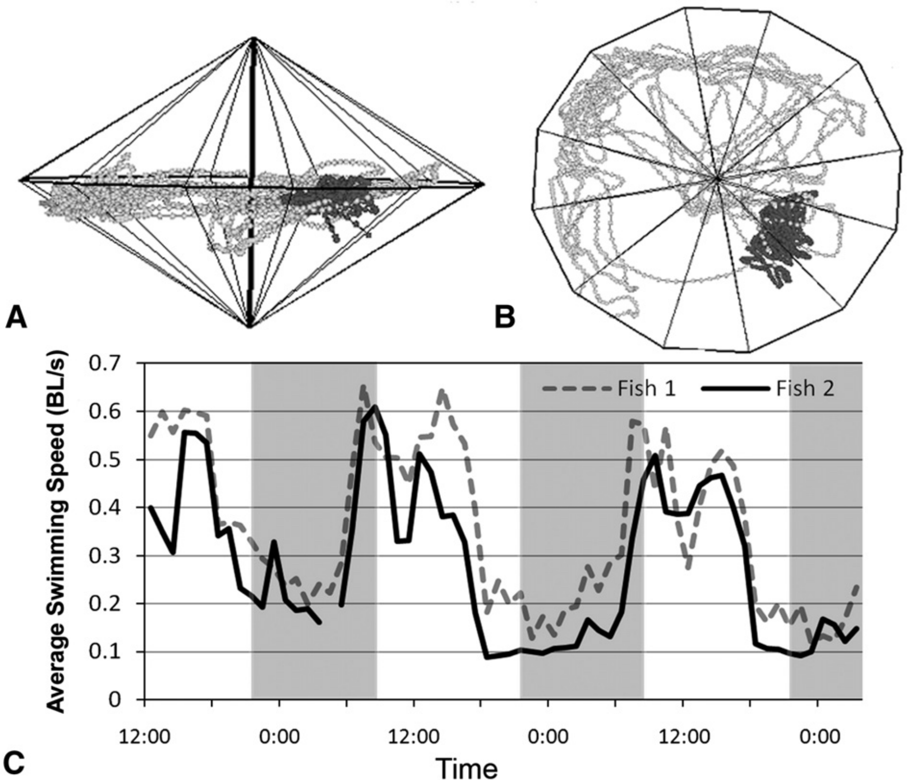

Fig. 4. Diurnal pattern of activity expressed by two cod between August 24th and August 27th. The top two panels (A,B) show locations obtained in the day (gray) vs. the night (black). Note how night activity is very reduced in both fish. The bottom panel (C) is a plot of swimming speed over the course of several days. There was a significant difference between swimming speeds recorded during the day (0.48 ± 0.12 and 0.40 ± 0.16 BL/s) in comparison to the night (0.23 ± 0.08 and 0.16 ± 0.07 BL/s) ($P = 0.014$; Student's paired *T*-test), in both fish.

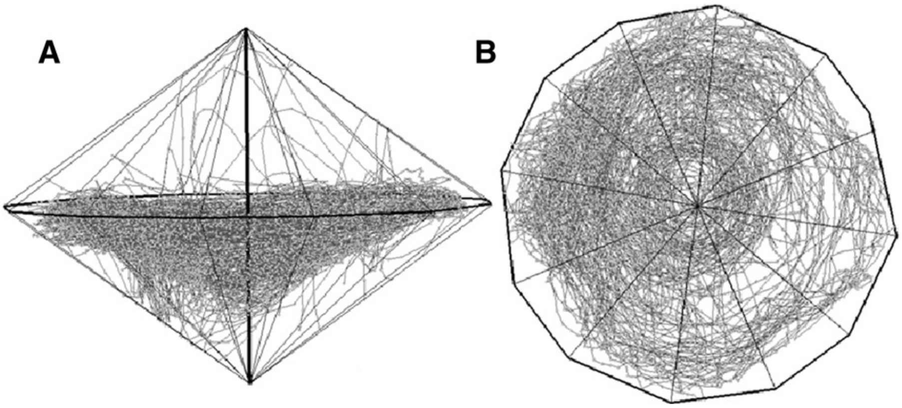

Fig. 5. Combined tracks of eleven cod that were simultaneously tracked, for one hour, between 11:00am and 12:00pm, demonstrating full use of the cage below the rim, but sparse excursions to the upper half of the net pen.

to determine if there were statistically significant differences between the swimming parameters calculated using different inter-pulse time intervals.

Activity data (swimming speeds) were plotted to determine if cod had a tendency for higher activity in the day vs. the night (data from one hour before to one hour after sunset and sunrise were eliminated from the data set). Selected periods of data were also visualized in 3D using Tecplot (Version 10, Tecplot Inc., Bellevue, WA) to determine spatial use of the cage during feeding and resting periods of the day or night. Finally, to test the performance of the system data files were analyzed for the number of locations obtained per hour, number of interpolated values and transmitter life span. To estimate signal loss, the number of locations obtained per hour was compared with theoretical estimates of the number of “pings” the transmitter should have produced in that hour.

3. Results

3.1. Equipment performance

Twenty-two cod were tagged between July 31st, 2006 and November 2nd, 2006 to test system performance and gather preliminary behavioral data. Transmitters lasted from 10–29 days, and variation in battery life did not appear to correlate with any known variables. Pulse intervals of the transmitters were programmed between 1.7 s and 3.3 s, yielding a maximum of 1090 to 2117 locations/h. The system detected and plotted 84.9 ± 1.2% of the maximum possible number of “pings”, yielding a mean of 1278.1 ± 53.8 locations/h for each transmitter (range: 866–1770), depending on the pulse interval. Periods of time when detections were low were typically correlated with high levels of ambient noise, often due to boat depth sounders and high winds. Interpolated values averaged 3.8 ± 2.7% of the data calculated.

Over four weeks of video data were obtained from the four cameras. However storage and processing of so much data proved to be difficult. The power consumption of the system allowed for data to be collected for ~5 days (3.5–8 days) depending on supplements from the solar and wind generators. Longer system running times correlated with periods of time when wind speeds were high, demonstrating that the wind generator provided more supplemental power than the solar panels.

3.2. Impact of tags on fish behavior

Laboratory studies demonstrated that implantation of transmitters had no significant effects on swimming activity ($N = 10$, $P = 0.949$, Student's paired *T*-test). Prior to implantation animals traveled 49.08 ± 0.76 m/h in the day and 46.97 ± 1.11 m/h at night, while following implantation they traveled 47.71 ± 1.03 m/h (day) and 48.91 ± 1.15 m/h (night), respectively. Implantation of transmitters also had no influence on food consumption. Cod consumed 2.86 ± 0.35 pellets/individual/feeding event prior to implantation compared with 2.81 ± 0.30 pellets/individual/feeding event post-implantation ($N = 12$, $P = 0.848$, Student's paired *T*-test).

In the field, tagged animals resumed “normal” behavior ~20–30 min after being returned to the cage, as determined by watching tracks of their movements and from diver observations. No significant

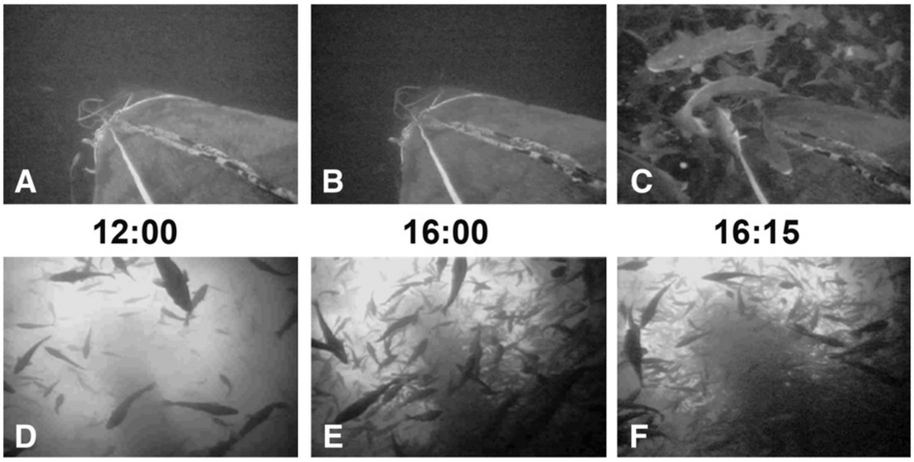

Fig. 6. Two video perspectives on a feeding event at that took place at 16:15. A camera mounted on the bottom of the cage, looking up (D–F) revealed fish moving into the water column as feeding time approached. However, the camera near the top of the cage, looking down (A–C), did not capture any fish until food was presented.

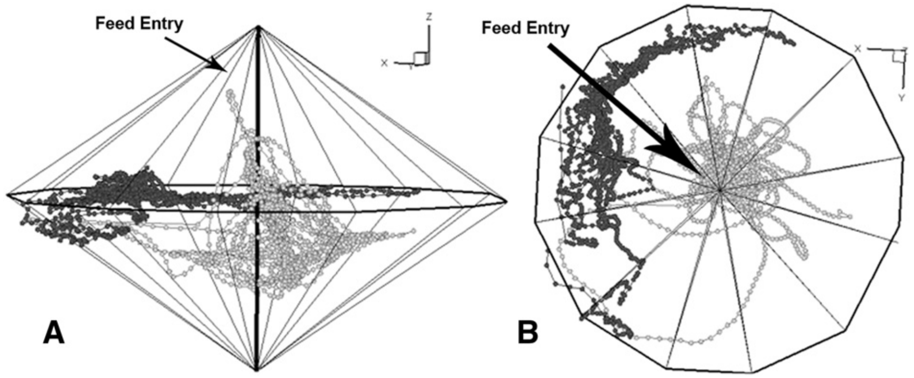

Fig. 7. Tracks showing the movements of two fish during one feeding event. Fish one (light gray) made several feeding loops into the feeding area and maintained a position within the center of the cage, where the feed fell, while fish two (dark gray) remained along the rim of the cage, separated from any feeding activity. Occasional positional fixes that appear to be "outside" of the net pen are due to a small error in merging an image of the cage with positional fixes of the fish.

difference was observed in the distance fish traveled on day 1 (post-implantation) and day 7 ($N = 10$, $P = 0.12$, Tukey–Kramer multiple comparison test), day 1 and day 14 ($N = 10$, $P = 0.995$), or day 7 and day 14 ($N = 10$, $P = 0.222$). None of the tagged animals died during the course of the experiment.

3.3. Influence of sampling interval on swimming speed and distance traveled calculations

Systematic increases in the sampling interval demonstrated that activity (i.e. distance traveled in body lengths/hour) was negatively correlated with sampling interval (Fig. 3). As the modeled inter-pulse interval was increased from 2 s to 80 s, calculations of distance traveled significantly decreased, beginning at intervals longer than 10–12 s. Increases in sampling intervals resulted in an 8.4–55.8% decrease in the calculated distance traveled when going from 2 sec intervals to 64 sec intervals. These data indicate that appropriate sampling intervals are necessary to accurately track the movements of swimming fish. In this study, because our sampling rate was about five times higher than necessary to obtain accurate data, and because we typically obtained 85% of the maximum possible number of detections from each tag/hour, there was no correlation between number of locations/hour and either distance traveled or average swimming speed. Therefore, sampling interval was not a source of error in our study.

3.4. Behavior of cod in the net pen

In general, at the stocking density used (~3–5 kg/m^3), cod within the net pen did not school and the movements of individual cod did not appear to be strongly influenced by other cod. Cod were more active, and used more of the cage, during the day than the night (Fig. 4). In general, except for when they were feeding, they had a strong tendency to distribute themselves in the bottom half of the cage and around the perimeter of the net pen (Fig. 5).

Daily video from two locations in the net pen demonstrated that many of the cod had a tendency to move from the bottom of the net into the water column near the feeding tube when food pellets were delivered. Such movements to the top of the cage were limited to times when food was presented (Fig. 6). Telemetry data of individuals matched that of the video; however the telemetry data also demonstrated that not every cod fed during a given feeding period (Fig. 7). Movements expressed during feeding had a distinct pattern. Cod would swim vertically to the feeding tube then descend back to deeper water before making another feeding loop. Feeding loops were distinct from one another and were probably associated with ingestion of individual pellets.

4. Discussion

The autonomous video and telemetry system we developed for investigating the behavior of fish in an offshore aquaculture setting provided us with data that was previously unattainable. Traditionally, ultrasonic telemetry, using tags transmitting at frequencies in the range of 70 kHz, has been used to study the movements of marine species because frequencies in this range travel almost a kilometer underwater, while higher frequency signals are rapidly attenuated. While these systems are optimal for tracking large-scale movements of a variety of mobile species, they are of limited use for examining the small-scale, rapid movements, of fish in a net pen for two main reasons. First, due to the size of the transducer required and the batteries needed to drive the transducers, it is difficult to build tags that are small enough to use in juvenile fish. Secondly, to our knowledge, no commercially available ultrasonic telemetry system can track with the precision and speed required to accurately quantify the movements of fish in a net pen. The heart of the system we developed was a HTI acoustic telemetry tracking system that was originally designed for use in the freshwater environment. However, due to the restricted area of a large offshore aquaculture net pen, the higher frequencies employed and the necessity to hard wire the hydrophones to the receiver were not a problem. As a result, this system proved to be an effective solution for the study of fish behavior under these conditions. Although the net pen we used (3000 m^3) was much smaller than typical commercial salmon cages (>20,000 m^3), the system we developed should work on these larger cages because the acoustic tags can be detected by the hydrophones at a distance of ~200 m in seawater. We have also employed the same system to investigate fish behavior in much smaller (90 m^3) enclosures located near shore and the results have been equally good.

Our analysis of the types of errors that can result when positional fixes are not obtained at a high enough rate further emphasizes the need for high speed telemetry when investigating the fine-scale movements of fish. Previous studies have demonstrated that sampling intervals can influence the accuracy of swimming speed calculations; however, the sampling intervals used were longer than in our investigation (15–17 s; Begout and Lagardere, 1993; Lokkeborg et al., 2002). Lokkeborg et al. (2002) demonstrated, in field studies of cod swimming, that increasing the sampling interval from 17 s to 34 s, and then to 68 s, resulted in a 30–50% decrease in calculated swimming speeds. Similar virtual increases in sampling intervals, from 12 s to 32 and 64 s, in our study, resulted in comparable reductions in swimming speeds of between 19% and 51%. In contrast, using a sampling interval of 12 s resulted in only an 8% reduction in swimming speed calculations compared to using 2 sec intervals. Thus, for cod, using a sampling interval of 10–12 s could extend tag life and still provide enough resolution to calculate accurate swimming speeds, assuming no loss of data.

In general, it is recommended that the sampling interval be adjusted to the swimming behavior of the species in question, as well as the type of information that is desired. For example, the milling behavior typical of cod (Figs. 4 and 7) is characterized by random directional swimming, which may yield a higher degree of error at larger sampling intervals, due to the increased likelihood of missing frequent loops within the track. In addition, low sampling intervals may reduce the likelihood of capturing fine-scale events, like feeding, prey capture, or predator avoidance. When examining feeding behavior in wild cod, Lokkeborg et al. (2002) documented how longer sampling intervals showed cod swimming straight to the food source, whereas higher resolution data illustrated cod moving through the odor plume in a zigzag search pattern. Finally, longer sampling intervals will often miss brief accelerations and speed changes. Because burst swimming has been documented to have exponential energetic consequences (Brett and Groves, 1979; Jobling, 1985; Webber et al., 1998), loss of these events could lead to underestimations of the metabolism of freely swimming fish.

The typical net pens used for aquaculture are too large to permit video observation of the entire space within the enclosure, even when visibility is exceptional. Therefore, multiple cameras are necessary and, based on our experience, strategic placement of cameras is essential and must be closely linked to the research or farm management objectives. For example, when studying feeding, two opposing cameras provided different details relevant to feeding behavior. The camera placed on the top of the net pen, next to the feed tube, provided video relevant to feeding intensity (Fig. 6, A–C), while the camera on the bottom of the net pen, showed cod moving off the bottom prior to feeding, illustrating possible feeding anticipatory activity (Fig. 6, D–F). Finally, while obvious, it is important to consider the fact that video data are difficult to obtain at night, it is almost impossible to keep track of changes in the behavior of individual fish, and, if using a DVR to collect the data, long-term digital storage issues must be addressed.

In this study cod predominately occupied the bottom surfaces and outer edges of the net pen, most likely due to their benthic nature. The extent to which the bi-conical shape of the Sea Station cage influenced the behavior and distribution of the fish is unknown, but it is likely that these would differ in a cylindrical gravity cage. In this study, cod preferred the area of greatest diameter, which also had a nearby ‘substrate’ (netting) both above and below (Fig. 5). We hypothesize that cod would be found near the cage walls in cylindrical cage, and that their vertical distribution would be expanded. Feeding also influenced distribution of the fish. When food was presented, they moved toward the top of the net pen, a distance of 5–10 m. As fish became satiated, they reduced the frequency of their upward movements, and eventually returned to the bottom half of the cage. Identical behavior has been shown in salmon, where it was used as a metric for measuring in-situ hunger levels (Juell et al., 1993). We have successfully used customized software to digitize videotapes, like those shown in Fig. 6, and quantified feeding intensity based on the number of fish in the proximity of the feeding tube. We have also extracted similar data from the tracks provided by the telemetry system. Thus, it is possible that either video or telemetry data could provide instantaneous biological feedback of fish feeding activity and satiation, which could help aquaculture managers optimize feeding regimes, while minimizing food waste.

Although behavioral studies have been limited in full-scale aquaculture operations, it is hoped that the evolution of new technologies, such as those described in this paper, will enable researchers to gather real-time information about fish behavior, energetics, health and welfare. Such studies will allow for the development of fish rearing technologies that take advantage of subtle differences in the feeding behavior and activity patterns of different fish species. In addition, knowledge about the manner in which different fish utilize the space within a net pen and interact with the net itself, could lead to improvements in cage design that will maximize production and minimize escapement. While the system described in this paper is expensive at the present time, it is likely that in a few years it will be cost effective enough to be considered in large fish farming operations.

5. Conclusions

We have used commercially available technologies to build an autonomous telemetry and video system that can be used to investigate the behavior of fish in either offshore or inshore aquaculture net pens. The telemetry part of this system is based on a HTI acoustic telemetry system that differs from telemetry systems typically used in the marine environment because it utilizes small, high frequency, tags and four hydrophones that are hard wired to a receiver. These features, and the associated software, make it possible to obtain positional fixes from juvenile fish every 2 s, and plot the position of these fish in three dimensions with a resolution of about 10 cm. As a result, it is possible to obtain very accurate and continuous information about fish swimming behavior for many days at a time.

The preliminary data we obtained using this system demonstrated its usefulness. Using a combination of batteries, solar panels and a wind generator, we were able to continuously record telemetry data and video images from four cameras for 5–7 days. The data obtained showed that cod did not school within the net pen, they were strongly diurnal, and they tended to spend most of their time in the bottom half of the net pen. When food was presented, most, but not all the fish, made repeated movements up to the feeding tube. This initial investigation was very revealing and additional studies of fish behavior that take full advantage of the tracking and video systems described in this manuscript are currently underway.

Acknowledgements

We are very thankful to the many specialized personnel required to construct and conduct an experiment of this size, including all the talented people who are part of the UNH Open Ocean Aquaculture project. Thanks go out to boat captains Forbes Horton, Tim McClare, and Gita George; divers Rob Love, Gunnar Ek, Graham McKay, Dan O'Grady, Caleb Thiebault and Liz Kintzing and engineers Stanley Boduch and Rob Cinq-Mars. Special thanks to Glen Rice who provided solutions to many unforeseen problems. Additional thanks are due to the U.S. Coast Guard for the donation of the buoy used in this experiment and to Steve Handler for the welding required to modify the buoy. Mark Timko and HTI provided advice and technical help, and Nate Rennels at the Coastal Marine Lab aided us during the lab studies. We also would like to thank Darren Scopel for his advice and Heather Moulton for her illustrations and support. Finally, the manuscript was improved as a result of the comments and suggestions provided by three anonymous reviewers and we would like to acknowledge their help. All animals were handled in full compliance with IACUC protocol (#061202) through the University of New Hampshire. This study funded by a grant from NOAA to the Atlantic Marine Aquaculture Center.

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