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3-dimensional positioning of salmon in commercial sea cages: assessment of a tool for monitoring behaviour

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Abstract

In aquaculture, telemetry may provide a valuable tool for monitoring fish in sea cages non-invasively. A 3-dimensional positioning system was assessed by tracking the movement of commercially farmed chinook salmon (*Oncorhynchus tshawytscha*, Walbaum, 1792) in a sea cage. The accuracy and reliability of the data generated is presented in terms of noise and position precision. Algorithms were used to test the ability of the system to measure and furthermore identify known activity patterns. Differences in night and day activity patterns were picked out by the classifier which was further refined to enable the identification of distinct feeding times in each of three commercial cages.

Introduction

Acoustic telemetry is widely utilised in ecological studies. Archival tags have been used to document seal and whale diving (Le Boeuf *et al*., 2000; Johnson and Tyack 2003) and basic transmitters facilitate real-time tracking of salmonid migration (Thorpe *et al*., 1981; Smith *et al*., 1998). In addition, automated fixed tracking stations can be positioned in arrays to cover specific important areas e.g. salt ponds (Lagardère *et al*., 1990) or marine reserves (Lembo *et al*., 2002).

In aquaculture, telemetry may provide a valuable tool for remotely monitoring fish swimming behaviour in sea cages. Previously, farmers could conduct a basic assessment of health and welfare whilst hand feeding fish. However, the advent of automated feeding systems (e.g. Storvik AS, Norway; Akvasmart, Norway) has resulted in fish feeding lower in the water column (Fernö *et al*., 1995; Hevrøy *et al*., 1997). Hence, cameras are used to assist with feeding and health assessment, but they do not provide information on individuals nor is it known what proportion of the population is viewed at any given time.

To date, aquaculture-based studies have focused on a few individuals in small-scale experimental cages rather than large-scale commercial operations (Juell and Westerberg 1993; Bégout Anras *et al*., 2000). Recently, the accuracy of acoustic positioning systems has been measured and assessed in order to optimise position accuracy (Smith *et al*., 1998; Ehrenberg and Steig 2001; 2003). The described study tested similar technology with replicated groups of fish held under commercial conditions.

As the collection of data is highly automated in fixed array positioning systems, the amount generated can be very large, even over a short time period. This provides problems in processing and analysis. One solution to this is to utilise algorithms to detect interesting features in the data (e.g. McFarlane *et al*., 2004).

The aim of the described study was to assess the use of a 3-dimensional positioning system in tracking the movement of commercially farmed chinook salmon (*Oncorhynchus tshawytscha*) in sea cages. The accuracy and reliability of the data generated was assessed in terms of noise and positioning and algorithms were used to test the ability of the system to measure and furthermore identify known activity patterns.

Materials and methods

Site and Fish

The study was carried out at the Marine Harvest Young Pass sea site (50º36'40N, 125º34'66W) Vancouver Island (BC, Canada) between the 2nd and the 27th of December 2002. During the study the fish were held in three adjacent net cages, 30 m x 30 m, maximum depth 20 m, hanging from a steel frame (Fig. 1). As the cages were in a 2x4 arrangement, cages 2 and 3 were at the end of the system, furthest from the generator and the majority of boat activity, and cage 1 was adjacent to cage 2. The cages were surrounded by a steel walkway, 1 m wide on the outside and 2 m wide in the middle (between cages 2 and 3). The cage system was stabilised and anchored using large buoys situated approximately 1 m from the walkway on the two outside corners of cages 2 and 3.

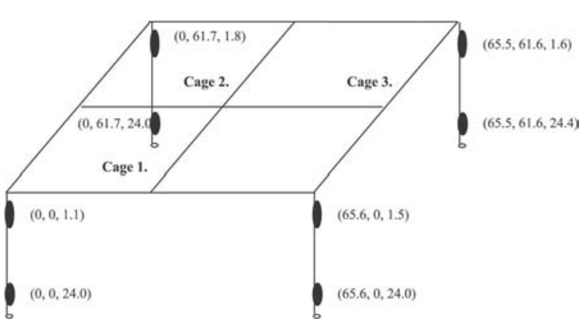

Fig. 1 – Schematic of system, lines are not to scale. Hydrophones are denoted by black ovals, and co-ordinates are displayed in metres.

Thirty-nine chinook salmon (mean ± s.e: 826.41 g ± 24.75) were obtained during routine transfer from one pen to another. All fish on the farm were female. The subjects were fitted internally with CAFT 11-3 acoustic tags (11x46 mm, 8.4 g in air, 4.2 g in water). Before undergoing surgery, individuals were anaesthetised in clove oil at 60 ppm until the operculum rate became slow and irregular. During surgery, the gills were irrigated with clove oil at 30 ppm to maintain anaesthesia. Each individual was weighed and measured and a 2 cm mid-ventral incision was made, anterior to the pelvic girdle, to allow insertion of the acoustic tag into the body cavity. The incision was then closed using 3 separate absorbable monofilament sutures (3-0 Ethicon). Surgery took no longer than 3 minutes and the entire procedure including anaesthetisation, a maximum of 7 minutes. Individuals were then held in a 1 m^2 tank until equilibrium and normal swimming behaviour were recovered and 13 fish placed in each of three cages. The fish were divided equally into 3 pens containing an average of 6000 fish in each resulting in a density of 3.7 kgm^{-3}. There was no significant difference in the weight of tagged fish placed in each cage (Kruskal-Wallis: χ^2=0.720, d.f.=2, p=0.698, median: cage 1=815 g, cage 2=755 g, cage 3 =820 g)

During the study the fish were fed on commercial regimes; each cage was fed in turn for 30 minutes with 10 minutes in between. Feeding times were as follows (24 hour clock): Cage 1: 10:40-11:10, cage 2: 12:00-12:30, cage 3: 12:40-14:10. Due to the layout of the farm, there was a longer delay between feeding in cages 1 and 2 than there was between cages 2 and 3.

Positioning system

Positioning data were collected using 8 Lotek LHP_1 hydrophones (bandwidth 20-80 kHz), arranged in rectangular array suspended by four ropes, each with a 7 kg weight attached (Fig. 1). The hydrophones were suspended from the outer buoys of the farm in order to minimise transmission error (Ehrenberg and Steig, 2001). The acoustic tags emitted a coded pulse sequence (76.8 kHz, 86 dB) every 5 seconds. The information regarding the identity and the time that this signal was received by each hydrophone was transmitted via cable to the MAP_500 receiver. The signal was then digitally processed in order to remove noise, find acceptable codes and record the times that individual hydrophones received these codes. This information was transferred to a computer twice daily using 80 Mb flashcards.

Data were collected and stored continuously by the MAP system once tagged fish were placed in the cages. In order to reduce possibility of spurious behaviour due to recovery from surgery, data from the first 10 days following surgery has been omitted from the present study.

Setup and accuracy of system

Following deployment of the hydrophones, a reference tag was submerged at various important positions in the array to ensure that tag signals could be detected throughout the array and to set the receiver offset and gain values. Using this, the receiver gain and offset were adjusted to maximise the total number of received signals whilst minimising the number of spurious data points. The desired ratio of one spurious data point to 10 accurate points was achieved at a gain of 70 and an offset of 65.

In order to assess the position accuracy of the system, a stationary reference tag was anchored at the centre of the array (x=34.5 m, y=31.0 m, z=5.0 m) for the duration of the study. In addition, acoustic interference in the transmission of signals was determined by measuring the intervals between received tag signals for each tag. Data collected at the end of the study (December 26th) was used for these analyses as any technical errors in the tags would be present to the greatest extent at this point.

Data Processing

Files collected by the MAP 500 system were processed using the BioMAP program (Lotek Wireless, St Johns, Canada) to provide raw positioning data. These data were then filtered to remove extraneous and unreliable data points. Initially, fish positions recorded on fewer than 4 hydrophones were removed (the minimum for a three-dimensional position), as were positions outwith the physical boundaries of the cages. Subsequently, points of poorer accuracy were identified using a reliability index and geometric diffusion of precision (GDOP). Since the MAP system calculated positions from hyperbolae of possible points from each receiver, the degree that these hyperbolae overlap, and therefore the degree of noise/error was related to the geometry of the receivers (Smith *et al*., 1998 and Ehrenberg and Steig, 2003 for discussion). The GDOP calculated the area of error that occurred as a result of the geometry of the hydrophones and was set at 0.3; data with a value greater than this were rejected.

Identification of known activity patterns

Initially, behavioural characteristics such as column position and absolute velocity were calculated from the data and assessed by eye for differences in night and day activity. This determined the occurrence of trends in activity and identified key behavioural characteristics. Following this, a fuzzy K-Means classifier (Duda *et al*., 2001) was used to distinguish trends in fish activity levels with respect to night and day and feeding times.

Twenty-two behavioural characteristics that were likely to indicate broad changes in activity were derived from the position time series data. They consisted of means and standard deviations of 11 measurements (Table 1). One behavioural characteristic was created for each fish within a specified time window by averaging the data available for that interval to create a single datum. This moving window was used to provide a smoothing effect to facilitate the identification of clusters as the data were often erratic.

The classifier provided a degree of membership (from 0 to 1) for each feature in a predetermined number of classes, chosen as an input parameter to the algorithm. The sum of the degree of memberships was 1, similar to a probability distribution. Naturally occurring clusters were identified within these behavioural characteristics using an iterative process that calculated the metric distance from the centre of each of the classes to each of the behavioural characteristics. The degree of membership of each behavioural characteristic to each class was then used to adjust the class centre until it no longer moved; thus identifying a naturally occurring cluster.

Classifications were initially performed on all the behavioural characteristics using all fish and time data. Naturally occurring classes were identified, and the data was deconstructed into its original order, by time and fish number. Following the initial classification the classifier was refined in order to minimise variation in behaviour between cages and between night and day. The classifier was run individually for each cage using only daylight hours. In addition, the number of behavioural characteristics was reduced to 6; the mean and standard deviation of radial position (distance from cage centre), absolute velocity (speed, regardless of direction) and column position (distance to the water surface).

Table 1 – Description and formulae for calculation of the parameter vectors used for classification

Name	Description	Formula
Absolute Velocity	Speed, regardless of direction.	$AbsVel = \sqrt{\left(\frac{\Delta X}{\Delta t}\right)^2 + \left(\frac{\Delta Y}{\Delta t}\right)^2 + \left(\frac{\Delta Z}{\Delta t}\right)^2}$
Absolute Acceleration	Fish acceleration regardless of direction	$AbsAcc = \sqrt{\left(\frac{\Delta(\Delta X)}{\Delta t}\right)^2 + \left(\frac{\Delta(\Delta Y)}{\Delta t}\right)^2 + \left(\frac{\Delta(\Delta Z)}{\Delta t}\right)^2}$
Radial Position	Fish distance from cage centre	$AbsAcc = \sqrt{(X_{fish} - X_{centre})^2 + (Y_{fish} - Y_{centre})^2}$
Radial Velocity	Rate of change of the distance from cage centre	$AbsAcc = \sqrt{\left(\frac{\Delta(X_{fish} - X_{centre})}{\Delta t}\right)^2 + \left(\frac{\Delta(Y_{fish} - Y_{centre})}{\Delta t}\right)^2}$
Radial Acceleration	Rate of change of speed with respect to the cage centre	$AbsAcc = \sqrt{\left(\frac{\Delta(\Delta(X_{fish} - X_{centre}))}{\Delta t}\right)^2 + \left(\frac{\Delta(\Delta(Y_{fish} - Y_{centre}))}{\Delta t}\right)^2}$
Column Position	Distance to the water surface	$AbsAcc = Z_{fish}$
Column Velocity	Rate of change of the distance to the water surface	$AbsAcc = \sqrt{\left(\frac{\Delta Z_{fish}}{\Delta t}\right)^2 + \left(\frac{\Delta Z_{fish}}{\Delta t}\right)^2}$
Column Acceleration	Rate of change of speed with respect to the cage centre	$AbsAcc = \sqrt{\left(\frac{\Delta(\Delta Z_{fish})}{\Delta t}\right)^2 + \left(\frac{\Delta(\Delta Z_{fish})}{\Delta t}\right)^2}$
Arc Length	The angular distance with respect to the centre of the cage	$\sqrt{(X_{fish} - X_{centre})^2 + (Y_{fish} - Y_{centre})^2} \cdot \arctan 2((X_{fish} - X_{centre}),(Y_{fish} - Y_{centre}))$
Angle Velocity	Rate of change of angular position to the cage centre	$\frac{\Delta\left(\sqrt{(X_{fish} - X_{centre})^2 + (Y_{fish} - Y_{centre})^2} \cdot \arctan 2((X_{fish} - X_{centre}),(Y_{fish} - Y_{centre}))\right)}{\Delta t}$
Angle Acceleration	Rate of change of angular velocity with respect to the cage centre	$\frac{\Delta\left(\Delta\left(\sqrt{(X_{fish} - X_{centre})^2 + (Y_{fish} - Y_{centre})^2} \cdot \arctan 2((X_{fish} - X_{centre}),(Y_{fish} - Y_{centre}))\right)\right)}{\Delta t}$

Results

System Accuracy

The median pre-programmed time for tag transmission was 5 seconds. However, the overall average time between received signals on December 26th was 17.3 seconds. This ranged from an average of 7.4 to 491.0 seconds for each tag.

The reference tag provided an index of positioning accuracy. From this, it was determined that the overall standard deviation of the noise in the position measurement was 74.6 cm. Thus, 99.7% of the position points are within 2.2 m of the actual position overall. The depth plane has the largest affect on position accuracy as the standard deviation of this plane is 2.6 m compared with 0.5 m and 0.7 m on the X and Y planes respectively.

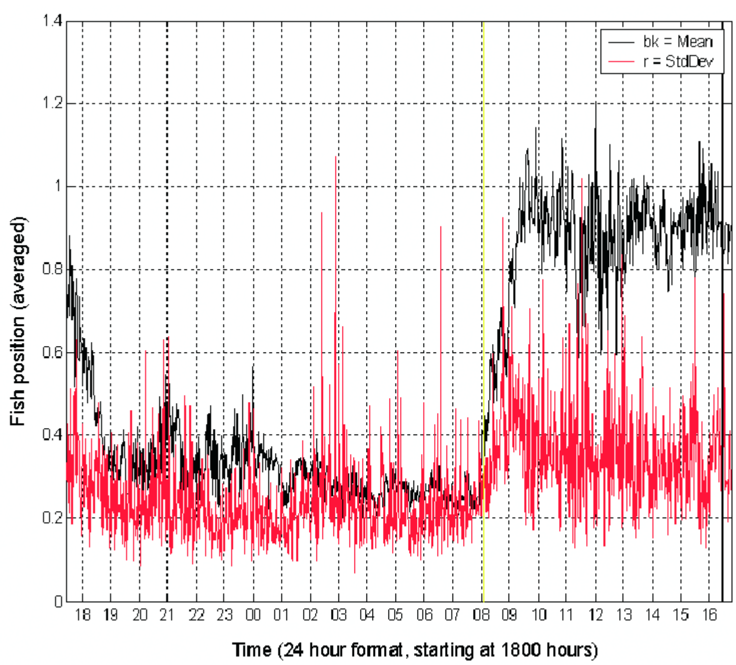

Fig. 2 – Fish position (averaged for all fish) over one day.

Detection of activity patterns

Initially, the mean and standard deviation of the behavioural characteristics were calculated, normalised and filtered (see methods). Differences between day and night were evident in mean and standard deviation of absolute velocity, absolute acceleration, angular velocity, mean radial velocity and radial acceleration, standard deviation of angular acceleration, column acceleration and column velocity. These differences were most pronounced in column position (Fig. 2); the fish were much lower in the water column during daylight (from 08:00 h to 18:00 h) than during darkness. Three-dimensional positions for each individual enabled tracks to be plotted showing the distribution of fish in the cage over time (Fig. 3).

Classification was then performed using one day of data and all behavioural characteristics. The behavioural characteristics were normalized and the Euclidian metric distance was calculated. Overall, a general trend was apparent, with the majority of fish classified into same class at any given time. However, the occurrence of differential class membership is indicative of small differences in individual behaviour.

In order to minimise the variation in behaviour between cages and between night and day, the classifier was refined. The resulting class membership is illustrated in Fig. 4 over a seven day period. Similar

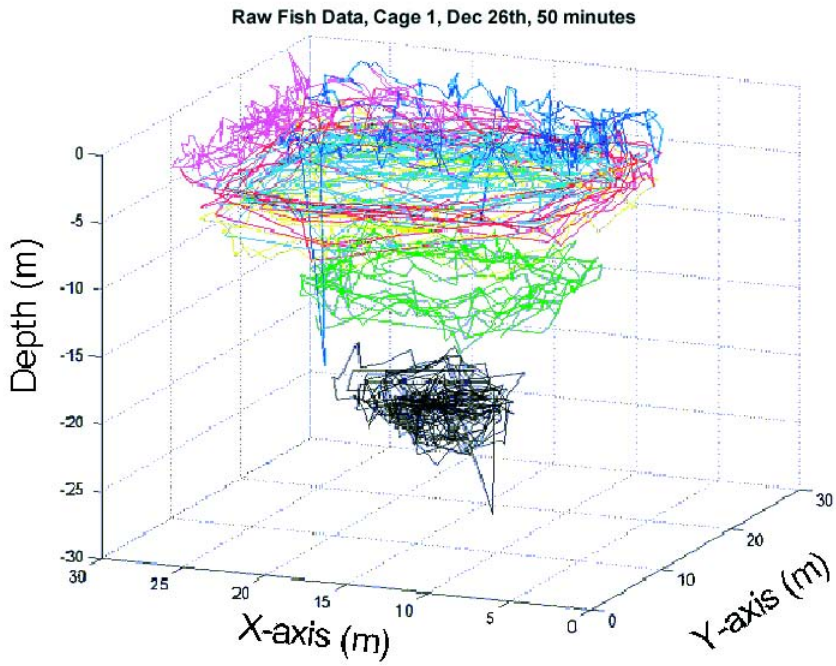

Fig. 3 – Raw data illustrating 50 minutes of fish position data for many individuals in one cage.

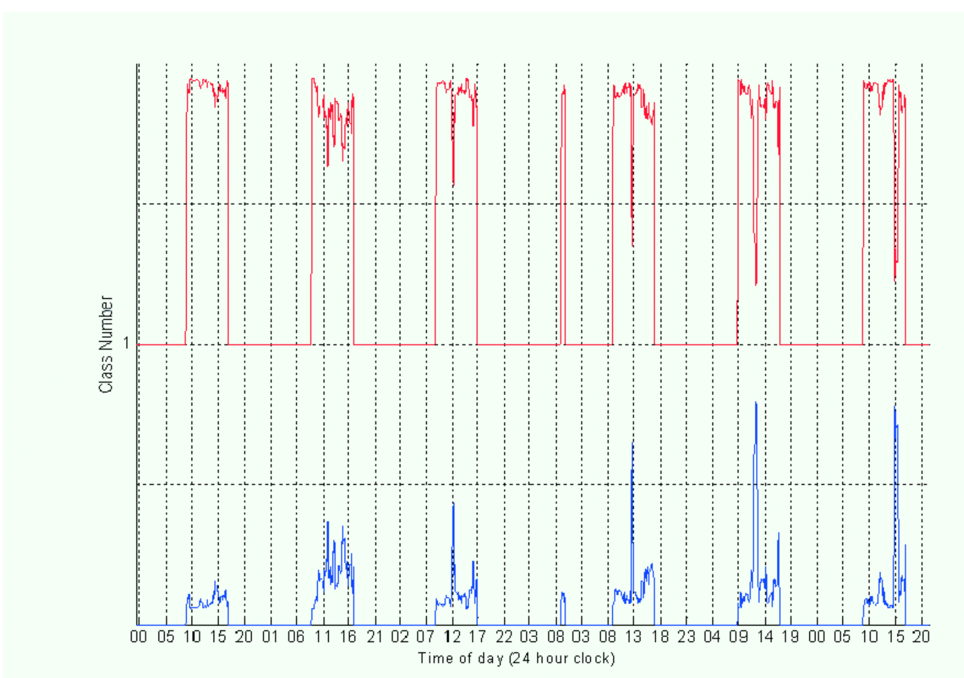

Fig. 4 – Graphical representation of class membership (0 or 1) of one cage of fish over seven days. The x-axis is labelled with the first two digits of the 24 hour clock in five-hourly intervals.

classification patterns were present each day although there was some variation between days. However, there was a spike in class 0 (the lower class) around the same time everyday which corresponds to the time that the fish were fed. This time was different in each tank, no tank had an overlap in the timing of the spike and they occurred in the same order as the cages were fed on the farm.

Discussion

The mean interval between received signals was much greater than the interval between signal transmission. This reflects the extent of noise in the environment; preventing the signal from reaching the hydrophones or slowing it down. Random noise can make an extensive contribution to the errors encountered in tracking positions of individuals (Smith *et al*., 1998). The present study was carried out upon a commercial farm where noise in the data can potentially result from boats, generators and automatic feeders in addition to noise inherent to the seawater environment.

Overall, the positioning accuracy of the system was lower than similar studies; Chapman *et al*. (1975) documented an error of ± 1 m when tracking Norway lobster and Juell and Westerberg (1993) estimated an error of 0.1 m in the centre of a sea cage. Ehrenberg and Steig (2003) quoted standard deviations of 0.16 m, 0.14 m and 0.26 m on the X, Y and Z planes, respectively using a similar sized hydrophone array. These are 4 times lower than those quoted in the present study for X and Y co-ordinates and 10 times lower for the Z co-ordinates. Smith *et al*., (1998) used an array approximately seven times larger than that described here, however the average position accuracy of 5 tags was also seven times greater (3.3 m). In the present study the reference tag was suspended in the water with no weight attached, potentially giving a lower accuracy of positioning than from the subjects themselves. Unfortunately, it was not possible to increase the accuracy of the data further using the GDOP or Reliability index. Other data filtering techniques such as Kalman filtering, which uses information available about noise to determine the actual position of a target, given consecutive position measurements, may improve the accuracy. However, this level of filtering is outwith the scope of the present paper.

In the described study, the hydrophone array was positioned to surround the cages, but this resulted in the depth plane being shorter than the rest so the formation was not a true cube shape with sides of equal length. This has been shown to result in a larger position error in the centre of the cage, especially in the depth plane (Ehrenberg and Steig, 2003). Therefore, in order to improve accuracy, hydrophone arrays should be positioned in a cube formation wherever possible.

The data analyses performed did not utilise absolute points, but rather scanned large sections of data for trends. This method is less likely to be affected by inaccuracies in positioning. The clear differences in diel behaviour that were documented have also been exemplified in farmed Atlantic salmon (e.g. Bégout Anras *et al*., 2000; Oppedal *et al*., 2001) and are likely to be influenced by feeding and surface light avoidance (Fernö *et al*., 1995).

In addition to diel patterns, differences in activity were identified in relation to feeding times. Although these trends were picked out by the classifier, there was a great deal of variation between individuals and between days. For example, the spikes that indicate abrupt changes in class membership at feeding times are not always present to the same degree if at all (Fig. 4). This could be a result of particular sets of circumstances replicating the feeding spikes or more likely, some external stimulus affecting the fish behaviour. The classifier was run in multiple iterations, meaning that different starting points give different end clusters whilst naturally occurring clusters are identified. In the present study, extraneous clusters may occur in the data as a result of sunrise or sunset, watercraft, predators, or environmental anomalies. However, the appearance of similar membership spikes over multiple days does indicate a re-occurring phenomenon.

In conclusion, the classifier was able to identify known changes in activity that occurred in commercial sea cages. Daytime swimming activity was differentiated from that at night and distinct membership patterns indicative of feeding were identified in each of three commercial cages. Therefore, this system could provide a valuable tool for farmers to monitor their stock. Automation of this system could potentially provide a tool that would monitor feeding activity daily and pick out differences as they occur, warning farm staff that there is a problem in terms of disease or predation.

The ability to quantify swimming behaviour of farmed fish in sea cages has widespread implications. There are many unanswered basic questions such as the issue of social interactions in the large, high-density groups found in aquaculture. Furthermore, recent documents and legislation on the welfare of farmed fish (e.g. FSBI, 2002) call for a greater understanding of the basic behaviour of caged fish in response to husbandry stressors and routine procedures such as feeding.

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