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System for Real-time Positioning and Monitoring of Fish in Commercial Marine Farms Based on Acoustic Telemetry and Internet of Fish (IoF)

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ABSTRACT

In this study the performance of the Internet of Fish (IoF) concept, a real-time acoustic positioning and fish monitoring system, was assessed in a commercial marine fish farm in Norway. Central to the IoF concept is the Synchronisation and LoRa Interface Module (SLIM), which is a battery operated surface unit that provides distributed time synchronisation and LPWAN support to a submerged digital acoustic receiver. Six SLIM/acoustic receiver pairs were placed inside a fish cage with acoustically tagged fish at a link-length of 200 m from a centralised gateway. All nodes achieved a Packet Error Rate of less than 8% and a position accuracy of 1.5 m.

KEY WORDS: Internet of Fish; LPWAN; acoustic telemetry; TDoA algorithm; marine aquaculture.

INTRODUCTION

Aquaculture is one of the fastest growing food producing industries in the world and is believed to be instrumental in filling the future global supply-demand gap in aquatic food (FAO., 2016). Raising fish in large floating net-based sea-cages have proven as a competitive option due to its flexibility, robustness and cost effectiveness (Føre et al., 2017), despite the generally harsh marine environment and technological and operational challenges it poses to the aquaculture industry. For instance, more than two million tons of Atlantic salmon are produced annually using this farming concept (Liu et al., 2016). The ability to monitor fish behaviour is important, as it is a key element in determining the stress and welfare conditions experienced by the fish in a farm situation (Oppedal, Dempster, and Stien, 2011). In addition, quantifying the movement patterns of fish is critical to understand feeding behaviours, resource utilisation and animal-environment interactions in cages (Espinoza et al., 2011; Biesinger et al., 2013). Acoustic telemetry is fish monitoring concept where individual animals are equipped with miniature electronic devices called transmitter tags that contain sensors and an acoustic modem for wireless underwater data transmission (see Føre, Alfredsen, and Gronningsater (2011) for a more thorough description of the contents of acoustic transmitter tags). This method has been used to observe detailed movement patterns of individual fish by employing source localisation algorithms (Pincock and Johnston, 2012). Previous applications of this approach include tracking of both wild (Espinoza et al., 2011; Biesinger et al., 2013) and farmed fish (Rillahan et al., 2009). Since farmed fish are generally restricted by the confines of the cages, their movement patterns are restricted to be within a much smaller volume than free swimming wild fish. This suggests that it is possible to realise automated positioning systems for aquaculture applications that are more precise than those developed for wild fish monitoring. Considering the large biomass, cage volumes and expected future growth trends in the marine finfish aquaculture industry, a remote monitoring system that can provide input to the day-to-day farm decisions is an essential requirement for realising the benefits and advances of the Precision Fish Farming (PFF) concept (Føre et al., 2017).

In this study, we developed and tested a real-time acoustic positioning and monitoring system for individual fish based on the Internet of Fish (IoF) concept. IoF is a concept similar to the Internet of Things (IoT) that provides real-time access to fish telemetry data by integrating a LoRa based Low Power Wide Area Network (LPWAN) with acoustic telemetry. The proposed solution combines a state-of-the-art submerged acoustic receiver with a surface communication module, hereafter referred to as the Synchronisation and LoRa Interface Module (SLIM), that provides a power-efficient long range wireless radio communication interface for relaying the fish telemetry data collected by the acoustic receiver. Multiple SLIMs were connected in a star topology to form an LPWAN of acoustic receivers, establishing the IoF concept. While the concept in itself provides access to telemetry data in real-time, IoF was extended with a Time Difference of Arrival (TDoA) algorithm to enable localisation in 3D. The system was tested in a commercial fish farm using six SLIM-acoustic receiver pairs placed inside a commercial-scale cage with fish carrying acoustic transmitter tags. The gateway, placed 200 m from the cage, was forwarding the received data to the user via the Internet. Communication quality provided by the IoF concept and position accuracy of the TDoA algorithm were analysed to evaluate the feasibility of an IoF based real-time fish positioning system.

MATERIALS AND METHODS

System Requirements

Link-length, bandwidth and battery operated end devices are three dimensioning requirements of the IoF concept. The end-to-end extent of a typical Atlantic salmon marine farm may be larger than 1 km, indicating that the minimum link-length supported by the IoF concept should exceed this distance. The minimum data transmission capacity/bandwidth is another important dimensioning parameter for the IoF concept, and is determined by the overall acoustic message rate and the size of a single acoustic message received by the SLIM from the acoustic receiver. In this study, 33 acoustic tags (Thelma Biotel AS, Trondheim, Norway) with a time interval between consecutive transmissions varying from 30 s to 90 s were used, roughly corresponding to an overall acoustic update rate of 10 acoustic messages per minute for the system as whole. After being interpreted by the acoustic receivers used in this study (TBR-700-RT, Thelma Biotel AS, Trondheim, Norway), a single telemetry message consisted of 11 bytes of information. The SLIMs were set up to transmit one radio packet per minute meaning that a packet size of at least 110 bytes was required to be able to include all telemetry messages received since last transmission. A final requirement for the IoF concept is that the end devices should be battery operated as electrical power may not be easily available and because cables are preferably avoided out of safety and practical reasons in floating sea-cages.

The aim to determine the fish position using a TDoA algorithm introduces additional system requirements due to the fact that acoustic messages from a single tag then need to be received by three or four acoustic receivers to achieve positioning in 2D or 3D, respectively. The TDoA algorithm also requires that the internal clocks of all acoustic receivers are synchronised (Juell and Westerberg, 1993; Grothues, 2009; Pincock and Johnston, 2012).

Internet of Fish (IoF) and LPWAN

The IoF concept (Hassan et al., n.d.) is based on LPWAN which is an emerging communication technology that addresses the unique requirements of IoT devices and that exploits the sub-gigahertz unlicensed Industrial, Scientific and Medical (ISM) radio bands. LPWAN provides large area coverage combined with low power consumption at the end-devices by utilising efficient modulation and duty-cycled transmission/reception schemes (Raza, Kulkarni, and Sooriyabandara, 2017). However this comes at a cost of very low data rates, which are in order of a few kilobytes per second (kbps) for a typical LPWAN (Centenaro et al., 2016; Raza, Kulkarni, and Sooriyabandara, 2017). Low data rates combined with duty-cycled operation yields low data throughput (in order of few bytes per second). Acoustic fish telemetry systems share many of these properties as end devices tend to rely on battery operation and have low power requirements and intrinsically low data throughput. This makes the combination of LPWANs and acoustic telemetry systems a reasonable approach for providing real-time user access to telemetry data. This is realised in the SLIM by providing LoRa based LPWAN support to extend an acoustic receiver with a radio interface for real-time access to the data.

The IoF concept used in the present study (Fig. 1) is made up of three layers and conforms to the architecture presented in Talavera et al., 2017. The first layer is the perception layer that contains end-devices that are typically distributed geographically/spatially. The second layer is the network layer and consists of a centralised network gateway which communicates with all end-devices in the perception layer. The third layer in this representation is the application layer which features a server and a database that together function as a system back-end and front-end for presentation of data to the user. The TDoA algorithm in the current study is implemented in the application layer and executes on the server.

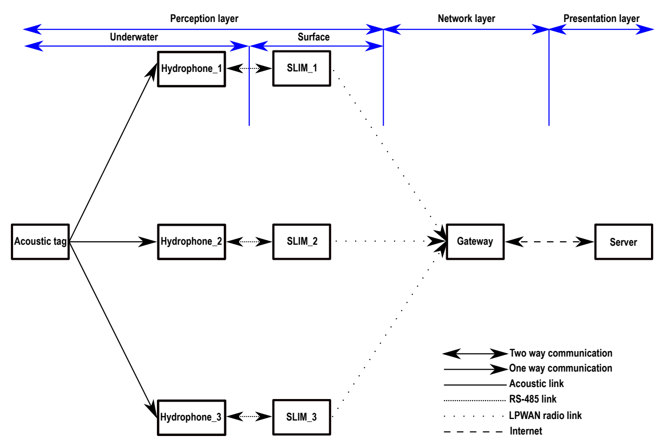

Fig. 1 Layered view of the IoF concept and modules used in different layers

Perception Layer: Synchronisation and LoRa Interface Module (SLIM)

The SLIM is a microcontroller (SiLabs EFM32GG842 32-bit ARM Cortex M3) based battery operated standalone module designed to provide LoRa radio interface to an acoustic receiver. In the LPWAN system, each SLIM has a unique ID and is a basic transmission device. A block diagram of the physical components in the SLIM is shown in Fig. 2. The SLIM was designed to interface with a Thelma Biotel TBR-700-RT acoustic receiver that was set up to forward all acoustic data received onto an RS-485 link, sending the decoded acoustic telemetry messages to the SLIM continually as they arrive. Radio communication was realised through a Serial Peripheral Interface (SPI) based LoRa module (RFM95W, HopeRF), and a Global Positioning System (GPS) module (u-blox, NEO-7P) was included to provide the receivers connected to the SLIM units with a system for distributed time synchronisation. The SLIM was designed using low power design techniques, and had a current consumption of 20 mA during normal operation (i.e. registering and storing messages received from the acoustic receiver), and 50 mA during radio transmit mode (lasting for very short duration). Power was provided through a 3.6 V, 35 A h Lithium primary cell which allows the SLIM to operate for approximately 2 months.

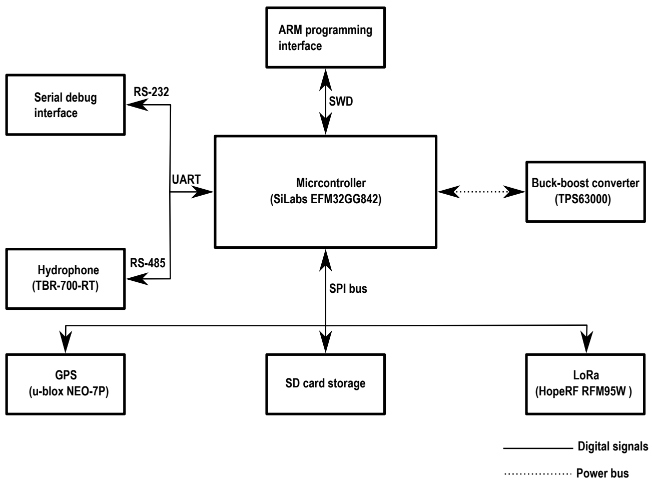

Fig. 2 Block diagram of the SLIM showing its peripherals

LoRa has previously been identified as the best candidate for IoT applications in agriculture (Adelantado et al., 2017; Talavera et al., 2017), and was used here as a physical (PHY) layer to realise the LPWAN in the IoF concept due to its relatively large coverage area and energy efficiency features. LoRa offers a coverage area of 5-15 km, thus satisfying the link-length requirement of the IoF concept. It also offers a payload up to 250 bytes, data rates up to 37.5 kpbs and a very low power consumption at the end-devices, thereby satisfying the system requirements associated with bandwidth and battery operated end devices (Goursaud and Gorce, 2015; Augustin et al., 2016; Adelantado et al., 2017; Raza, Kulkarni, and Sooriyabandara, 2017). The internal clocks of the acoustic receivers were synchronised using the Pulse Per Second (PPS) signal of the GPS chip of the SLIM, satisfying the TDoA-specific requirement of synchronisation of the acoustic receivers. In the European region (EU), LPWAN/LoRa modulation uses the 868 MHz ISM band with a maximum allowed duty cycle of 1%, which gives each end device a maximum time-on-air of 36 s per hour (Adelantado et al., 2017). The SLIM were programmed to comply with these duty cycle regulations, and use a spreading factor SF7, a coding rate of 4/5, a bandwidth of 125 kHz and a transmit power of 14 dBm. For a payload of 111 bytes, time-on-air for a single radio packet transmitted by the SLIM was 187.65 ms, or 11.259 s for 60 transmissions over a period of one hour. The firmware of the SLIM was developed in the C programming language using Silicon Lab's Simplicity Studio Integrated Development Environment (IDE), and was based on IBM's LMiC library which implements the LPWAN stack. Firmware operation was based on timer and PPS signal interrupts with an Interrupt Service Routine (ISR) being executed every 10 s, performing synchronisation and other radio transmission related tasks. Operation of the firmware is explained in the flow diagram shown in Fig. 3.

Network and application layers

The network layer includes the gateway, which works as a centralised node for all end devices (SLIMs) and is responsible for forwarding all incoming messages from nodes with authorised IDs to a server. A MultiConnect Conduit (MTCDT-H5-210L, Multi-Tech Systems, Inc.) which is a Commercially Off The Shelf (COTS) module, was used as the gateway in this study. The gateway was equipped with a Radio Frequency (RF) antenna to receive data from nodes via the LoRa radio link, and an Ethernet connection for transmitting all received data to the server. The gateway was communicating with the application layer using the Message Queuing Telemetry Transport (MQTT) protocol. MQTT is a subscribe/publish-based protocol often used in IoT applications, and that follows software client/broker architecture (Light, 2017).

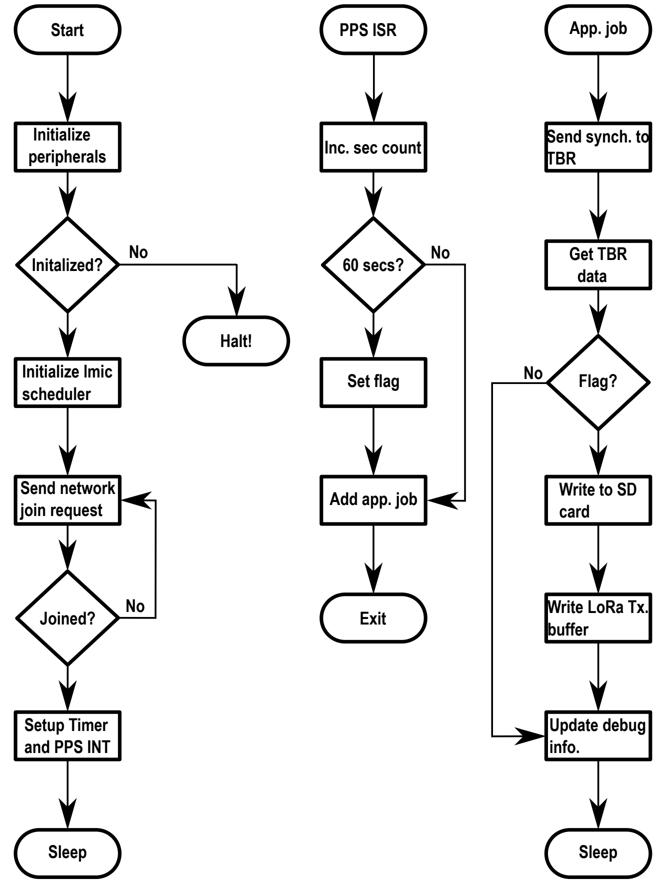

Fig. 3 Flowchart explaining firmware operation of the SLIM

A computer with Internet access was assigned the role as the server in the application layer. The server was responsible for receiving data from the gateway, storing the data locally on its hard drive, executing the TDoA algorithm for tag positioning and presenting the resulting data to end users. HBMQTT, which is an open source implementation of the MQTT protocol was used to implement the broker and client applications on the server, with the broker being set up to accept connections and receive data from the publisher-client running on the gateway, while the client was set up to subscribe to and store all received messages on the local hard drive in text files, acting as a database. A MATLAB script was continually executed on the server to run the TDoA algorithm to derive positioning data. This application enabled the user to select an array of SLIM nodes based on their IDs and plot associated fish position data in real-time.

Positioning Algorithm

The TDoA positioning method provided by Fang (1990) was used in this study. 2D position i.e. in the xy-plane, was achieved by using three acoustic receivers. Combined with the depth information provided by the on-board pressure sensor in the acoustic tags (Skilbrei et al., 2009; Føre, Alfredsen, and Gronningsater, 2011) the fishes' position in 3D could be determined. This method establishes an xyz-coordinate system (Euclidean space) which is defined with respect to the known 3D placement of the acoustic receivers. In this coordinate system, the position of the first acoustic receiver (A) was used as the origin $(0, 0, 0)$, the second receiver (B) was placed along the x-axis $(b, 0, 0)$, while the third receiver (C) was placed inside the xy-plane $(c_x, c_y, 0)$ having non-zero x- and y-coordinates. The placement of receivers and their coordinates are shown in Fig. 6. While Fang (1990) provided detailed equations for source localisation based on TDoA algorithm, equations are reproduced here for the purpose of clarity.

If the arrival times of an acoustic signal transmitted from a position (x, y, z) at acoustic receivers A, B and C are denoted by T_a, T_b and T_c respectively, T_{ab} denotes difference of arrival time between receivers A and B and T_{ac} denotes difference of arrival time between receivers A and C, giving the equations:

$$T_{ab} = T_a - T_b$$

$$T_{ac} = T_a - T_c \tag{1}$$

If the sound speed in water is denoted as c, and the distance of the acoustic tag from acoustic receivers A, B and C are denoted by R_a, R_b and R_c respectively, the difference of time equations can be written in terms of range difference equations using the distances between receivers A and B (R_{ab}) and receivers A and C (R_{ac}):

$$R_{ab} = T_{ab} * c$$

$$R_{ac} = T_{ac} * c \tag{2}$$

Using the geometry of the acoustic receiver setup, the distance of a tag placed at coordinates (x, y, z) from the three acoustic receivers is given by:

$$R_a = \sqrt{x^2 + y^2 + z^2}$$

$$R_b = \sqrt{(x - b)^2 + y^2 + z^2}$$

$$R_c = \sqrt{(x - c_x)^2 + (y - c_y)^2 + z^2} \tag{3}$$

These distances can be written in terms of difference of range with respect to acoustic receiver A using:

$$R_{ab} = \sqrt{x^2 + y^2 + z^2} - \sqrt{(x - b)^2 + y^2 + z^2}$$

$$R_{ac} = \sqrt{x^2 + y^2 + z^2} - \sqrt{(x - c_x)^2 + (y - c_y)^2 + z^2} \tag{4}$$

Squaring and simplifying Eq. (4) yields:

$$R_{ab}^2 - b^2 + 2 * b * x = 2 * R_{ab} * \sqrt{x^2 + y^2 + z^2}$$

$$R_{ac}^2 - (c_x^2 + c_y^2) + 2 * c_x * x + 2 * c_y * y = 2 * R_{ac} * \sqrt{x^2 + y^2 + z^2} \tag{5}$$

When R_{ab} and R_{ac} are non-zero, Eq. (5) can be written in parametric form in terms of x- and z-coordinates by eliminating y as:

$$z^2 = d * x^2 + e * x + f \tag{6}$$

where parameters are d, e, f, g and h are given by:

$$d = -1 * \left\{1 - (b/R_{ab})^2 + g^2\right\}$$

$$e = b * \left\{1 - (b/R_{ab})^2 - 2 * g * h\right\}$$

$$f = (R_{ab}^2/4) * \left\{1 - (b/R_{ab})^2 - h^2\right\}$$

$$g = \{R_{ac} * (b/R_{ab}) - c_x\} / c_y$$

$$h = \left\{c_x^2 + c_y^2 - R_{ac}^2 + R_{ab} * R_{ac} * (1 - (b/R_{ab})^2)\right\} / 2 * c_y$$

Similarly, tag's y-coordinates can be written in terms of x-coordinates using:

$$y = g * x + h \tag{7}$$

Depth (z) information is provided by tag's on-board depth sensor, whereas R_{ab} and R_{ac} can be calculated by the arrival time of the acoustic signals (Eq. (2)). Once R_{ab} and R_{ac} are known, parameters d, e, f, g and h can be calculated. Afterwards, x- and y- coordinates can be found by using equations Eq. (6) and Eq. (7), respectively. Cases when R_{ab}, R_{ac} or both are zero are solved trivially. For example when $R_{ab} = 0$, the x-coordinate of the tag is given by $b/2$. Similarly, when both $R_{ab} = 0$ and $R_{ac} = 0$, x- and y-coordinates of the tag are at an equal distance from all three acoustic receivers (Fang, 1990).

Experimental Setup

A series of dry tests in the lab were first conducted to test the general functionality of the IoF concept and the TDoA positioning algorithm separately, before testing a single integrated system that combined both functions. A field trial at a commercial marine fish farm in Norway was then conducted to test the use of the LoRa-based LPWAN for real-time acoustic tag positioning in the real setting. Six nodes and one gateway were used in the field test. Each node consisted of a surface mounted SLIM connected to a submerged TBR-700-RT acoustic receiver. The nodes were set up in a redundant configuration (Fig. 4), but only three nodes were used by the positioning system. The nodes were installed in an equilateral triangle configuration in a fish cage, with the antennas 0.8 m above sea level and with a link-length of 200 m from the gateway (Fig. 5). Acoustic receivers were placed 3 m below the sea-surface, firmly fixed to the cage structure to maintain the receiver geometry during the experiment. All nodes were set to transmit one radio message over the LPWAN every minute where the size of the radio messages varied depending on the number of acoustic messages received during the past minute. Three acoustic test transmitter tags (R-MP9L Thelma Biotel AS, Trondheim Norway) were deployed in the water at fixed known locations with varying depths inside the fish cage for 12 h to benchmark the communication quality of the LPWAN and determine position accuracy of the positioning system. After collecting the benchmarking dataset, the system was used to monitor 30 fish carrying acoustic tags with acceleration/activity and depth sensors (AD-MP9L, R-MP9L and D-LP7 Thelma Biotel AS, Trondheim Norway). The tags were divided into three groups transmitting at different acoustic frequencies to reduce acoustic interference (69 kHz, 71 kHz and 73 kHz) inside the cage. Although only the depth data values were used for fish positioning, the data from the activity sensor was also sent over the radio link. The gateway was placed inside the fish farm's feed barge with an RF antenna mounted inside the barge approximately 8 m above sea level to ensure line of sight communication with the nodes. The gateway was connected to the Internet via an Ethernet port on a standard network router installed on the barge. The relative locations of the nodes and the gateway are shown in Fig. 5. The server was placed in an office environment.

The surgical protocol for implanting acoustic tags in the fish followed the general recommendations given by Mulcahy (2003) and Cooke, Thorstad, and Hinch (2004). Approval was granted by the Norwegian

Animal Research Authority (ID 15491). All surgical equipment was sterilised before use, and care was taken to maintain conditions as aseptic as possible. A well-documented protocol for anaesthesia, analgesia and surgery described by Urke et al. (2013) was used. The total length L_T of the fish was recorded. Total handling time was around 2 min, per fish. Immediately after surgery, the fish were transferred to a recovery tank and closely monitored. Fish regained balance ability and showed active swimming behaviour within 0.5 min-2 min of recovery. After a recovery period of 10 min, the fish were released into the cage.

Fig. 4 SLIM nodes installed in redundant configuration on cage structure

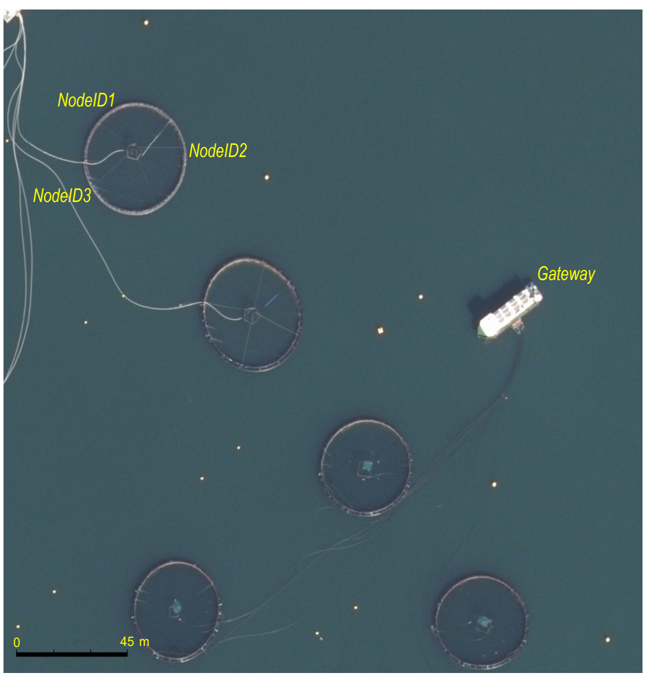

Fig. 5 Map showing position of nodes and gateway in the fish farm

RESULTS

The overall performance of the nodes during the experiment satisfied all system requirements specified for the system. The benchmark dataset was used to evaluate system performance in terms of the communication quality provided by the IoF concept and the accuracy bounds of the positioning algorithm.

Packet Error Rate (PER) of the IoF Concept

PER is defined as ratio of packets lost in transmission from nodes to server and was used to evaluate the performance of the IoF concept and quality of communication provided by the radio interface (LPWAN). PER includes two types of losses due to the radio interface and an additional loss of packets from gateway to the server i.e. loss over the Internet. The first type of radio loss includes those acoustic messages that were successfully received and processed by a SLIM node but did not arrive at the gateway, whereas the second type of radio loss includes radio packets that were received at the gateway and successfully transmitted to the server but which were based on corrupted acoustic data. Mathematically, PER is defined as:

$$PER = 1 - \frac{uncorrupted\ messages\ received\ at\ server}{total\ messages\ transmitted\ by\ a\ node} \quad (1)$$

Table 1 shows the total number of messages transmitted (Packets Tx), uncorrupted messages received at the server (Packets Rx) and PER values of the nodes for the benchmark dataset. All nodes achieved a PER of less than 8%.

While the PER values of the nodes describes the overall quality of the communication system, the positioning system requires the successful reception of a single acoustic message on all three receivers and that this message is transferred from at least three SLIM nodes to the server over the radio link. Table 2 shows the number of messages received for each tag ID (Tag ID) in the benchmark dataset that were detected by all three SLIM modules and thus were usable for the positioning algorithm (Message triplets), the average number of messages for each tag ID received by the individual SLIM units (Average messages received) and the percentage of the average number of messages that were part of a message triplet (Percent usable). More than 90% of the received messages were used by the position algorithm for each tag ID.

Accuracy of the Positioning Algorithm

The accuracy of the positioning algorithm is affected by geometry, variations in position and uncertainties/bias in the clocks and timestamping accuracy of the acoustic receiver array (Juell and Westerberg, 1993). Errors related to array geometry and acoustic receiver positions were minimised in the field experiment by mounting the nodes at known position on the cage structure. The PPS signal of the GPS chip was used to synchronise the acoustic receivers, thus minimising the impact of clock difference as an error source. Acoustic receivers (TBR-700-RT) timestamped the incoming acoustic signals with a resolution of 1 ms, setting an upper bound of 1.5 m on to the position resolution of the algorithm. Fig. 6 shows the calculated positions of reference tags, whereas Fig. 7 shows a histogram of radial error ($\sqrt{x_{error}^2 + y_{error}^2}$) for the benchmark dataset. A Circular Error Probability (CEP) of 1.37 m, 1.49 m and 1.22 m were achieved for tag ID 90 (depth 3 m), tag ID 91 (depth 2 m) and tag ID 92 (depth 1 m), respectively.

Table 1 PER values of individual nodes, with number of packets transmitted by nodes and received at server.

Node ID	Packets Tx by node	Packets Rx at server	PER
1	1446	1381	4.5%
2	1386	1276	7.94%
3	1381	1368	1%

Table 2 Benchmark data set tag IDs, number (average) of messages received at server and number of messages usable for positioning algorithm.

Tag ID	Average messages received	Message triplets	Percent usable
90	462	419	90.69%
91	423	392	92.67%
92	446	411	92.15%

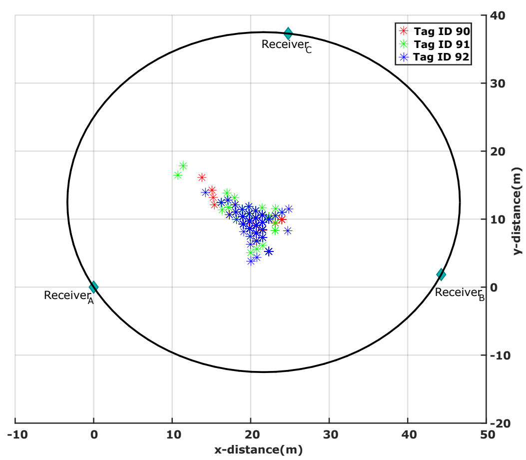

Fig. 6 Horizontal placement of acoustic receivers inside the cage (all receivers at 3 m depth). TDoA calculated positions for the benchmark data set are shown in the middle of cage.

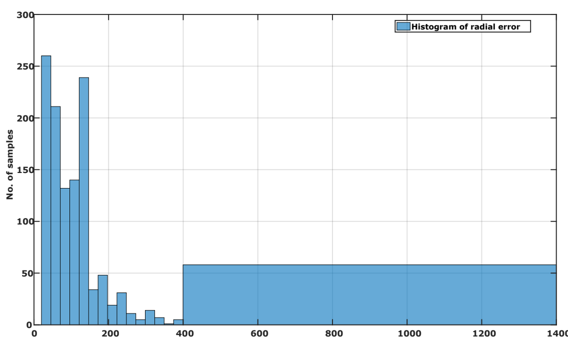

Fig. 7 Radial error distribution ($\sqrt{x_{error}^2 + y_{error}^2}$) of the TDoA calculated tag positions based on the benchmark dataset. The dataset includes a total number of 1222 message triplets.

DISCUSSION

In this study, the server got updates from the nodes every 60 s and the positions of fish carrying tags would therefore face a worst case delay of

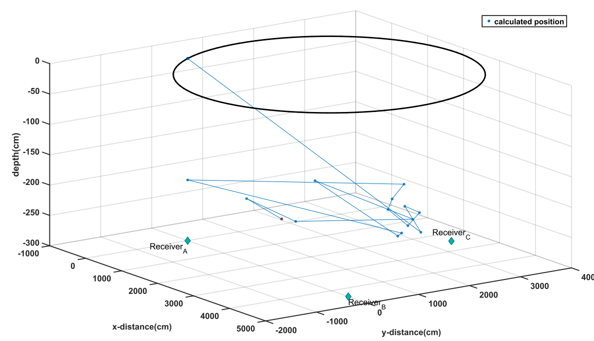

Fig. 8 A trajectory of a tagged fish (tag ID 102) tracked in real-time with an average sampling time of 3 minutes. Acoustic receivers are placed at a depth of 3 m inside cage.

60 s. Since the system was designed to be a real-time system for monitoring applications, as opposed to a critical industrial control system, a worst case delay of one minute seems acceptable. The CEP values for the tags used in the benchmark data set suggests that the positioning error stayed within the bounds of the expected resolution of about 1.5 m (i.e. the distance sound travels in sea water in 1 ms). This confirms that the accuracy of the positioning system is limited by the minimum resolution of the timestamp provided by the acoustic receiver, which for a TBR-700-RT is 1 ms. When a tag is placed close to an acoustic receiver, the error in calculated position may increase thus leading to lower position accuracy. It is also possible that the algorithm cannot find a valid position solution in such a scenario. The position resolution of the IoF based real-time positioning system can be increased by using acoustic receivers with finer timestamp resolutions, or by using the Signal to Noise Ratio (SNR) value when a tag detection is close to one of the acoustic receivers. The TBR-700-RT already provides the SNR value for each received acoustic signal, making the latter of these algorithm improvements relatively easy to achieve. There exist several acoustic positioning systems using TDoA algorithms to calculate positions, including both wired (e.g. Vemco VPS, HTI Inc) and wireless (e.g. Vemco VRAP, Lotek inc Wireless WHS 3060 MAP) systems (Espinoza et al., 2011; Biesinger et al., 2013). In wired system, cables are used to provide real-time access and may also be used to synchronise the acoustic receivers making them generally more precise in terms of positioning than wireless systems (Andrews et al., 2011). However, wired systems suffer from coverage areas issues, are labour intensive with respect to retrieving telemetry data and can only be used in

near-shore applications (Espinoza et al., 2011). Moreover cables in and around fish farms and cages are also seen as a liability issue by the farmers, rendering wired systems impractical for applications in the marine environment. Wireless positioning systems typically use radio interfaces to provide real-time access to the telemetry data. However, commercially available wireless systems are typically not designed to use modulation schemes such as LoRa and LPWAN protocols, and may therefore suffer from issues such as limited range, inferior scaling (i.e. number of acoustic receivers served) and too low energy efficiency of the end devices (Espinoza et al., 2011). These systems tend to be more expensive than wired position systems (Andrews et al., 2011). The LoRa/LPWAN based IoF concept does not suffer from these shortcomings in having long range and low power end devices. This is achieved at the cost of low data transmission rates for the end-devices. Since data rates in acoustic telemetry and similar applications are inherently low, the benefits in range and power consumption of using LPWAN-based solutions for the wireless components in such systems outweigh the disadvantage of reduced data rates.

The field experiment for real-time tagged fish position monitoring was planned for 4 months. The LPWAN system proved the feasibility of real-time fish monitoring in a commercial aquaculture farm. Fig. 8 shows a sample trajectory track of a tagged fish (tag ID 102) over a 45 min duration, illustrating a typical output and the capability of the IoF based positioning system. However, the fish behaviour data of the experiment is not studied in this paper.

CONCLUSIONS

In this study, the IoF concept was extended with a TDoA positioning algorithm for real-time estimation of acoustic tags positions in marine aquaculture farms. The results of the experiment affirm that the IoF and TDoA positioning can be used to provide real-time positions of acoustic tags in marine aquaculture monitoring applications. An average PER of 4.48% was achieved for all nodes used in the experiment, which proves that the system was able to upload field telemetry data in real-time to a server in a reliable manner. Furthermore, the TDoA algorithm was able to achieve a resolution/CEP of 1.5 m, which can be further improved by using acoustic receivers with finer timestamp resolution. The SLIM units developed in this study can potentially operate for months on a single battery with sufficiently long link-lengths to cover any configuration of a commercial marine aquaculture fish farm. In summary, this demonstrates that the IoF positioning system developed in this study was able to provide users with real-time access to position data for acoustic tags in sea-cages without suffering from the challenges faced by existing commercially available cabled or wireless real-time positioning systems.

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