A Formation of Unmanned Vehicles for Tracking of an Acoustic Fish-Tag

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***Abstract*—In this paper we present a proof-of-concept for an hydro acoustic fish-tag position estimation and tracking system. In our field-tested concept, a formation of Unmanned Surface Vehicles (USV) creates a mobile array of low-cost hydro acoustic fish-tag receivers. The array of receivers is able to estimate fish-tag locations and follow the fish on open waters, significantly increasing capabilities as compared to moored systems. The paper describes the system architecture and components in detail. It also evaluates the proof-of-concept characteristics based on the experience gathered during the field-test.**

I. Introduction

Acoustic fish telemetry has existed for several decades as a fisheries science tool for observing and investigating the behaviour and ecology of migrating fish and other aquatic animals in the marine environment [1]. Today it experiences new and exciting possibilities due to accelerated innovations in the enabling technologies it derives from, such as small end ultra-low power embedded microelectronic systems, digital signal processing and MEMS sensors.

Telemetry experiments normally involve equipping a group of fish with miniature acoustic transmitters (AT) letting them serve as sentinels for the fish population under investigation [2]. At the same time, an array of acoustic hydrophone receivers (AR) are deployed at fixed locations in the geographic area of interest and signals from tagged migrating fish then get picked up, time-stamped and recorded as the fish move within the detection range of the receivers. The signals received typically include a number that uniquely identifies the fish (ID) and readings from sensors the transmitter may contain (e.g. pressure/depth and temperature). This subsequently enables a reconstruction of the approximate fish migratory pattern by "connecting the dots" using source localization algorithms [3] and assess the fish' responses to environmental cues. This method of migration monitoring is, among other, successfully used to track Atlantic salmon juveniles during migrating from their natal streams to the open ocean [4]. However, the quality of data relies heavily on the actual selection of receiver locations, the spatial resolution of the receiver array, and transmitter/receiver performance.

Typical ARs can pick up the AT signals from a distance from a few hundred meters up to a kilometer, a reason why an array is required to contain a substantial number of ARs to cover larger geographical areas. In many cases ARs are standalone data logging units, with no additional communication mechanism. Data from the receivers is retrieved at the end of field campaigns, and often requires support of scuba divers.

In this paper we present a proof-of-concept for a hydro acoustic fish-tag position estimation and tracking system (Fig. 1). In our field-tested concept, a formation of Unmanned Surface Vehicles (USVs) creates a mobile array of low-cost hydro-acoustic fish-tag receivers. The array is able to estimate fish-tag location and follow the fish on open waters, significantly increasing capabilities as compared to moored systems. This paper describes the system architecture and its components. The main contributions of the presented work are:

- A design of a novel system of fish tracking based on a formation of unmanned vehicles and a low cost acoustic system.
- A field validation giving proof-of-concept.
- A discussion on field experiment results.

Section II of this paper describes the Concept of Operations of the proposed system. Section III presents a system proof-of-concept configuration. Section IV describes a field experiment and its results. Section V evaluates system

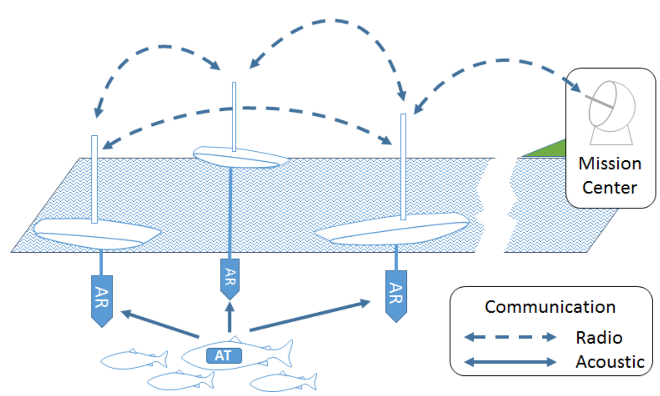

Figure 1: System overview

performance and pinpoints critical aspects of the system.

II. Concept of Operations (CONOPS)

The system proposed in this paper allows to follow a tagged fish outside the limited range of moored arrays of ARs. The concept involves the use of surface vehicles in a formation to move the ARs. The design is scalable and the number of ARs depends on the implemented method of AT position estimation, and can be integrated with various types of unmanned vehicles which can differ significantly in terms of performance and characteristics.

In principle the vehicle system could be used to actively scan the area and search for fish carrying ATs. Alternatively, it could be deployed when a specific event occurs, e.g. when a stationary receiver detects an AT, in a "follow-that-fish" manner. Then vehicles can move in a formation that tracks the fish, providing real-time data about its location. If the system is implemented on long-endurance vehicles, e.g. wave powered, it will enable long-term, long-range monitoring of fish migration.

The successful system needs to meet several functional requirements.

1) Position estimation: The AT position estimation can be calculated using a Time Difference of Arrival (TDOA) localization algorithm [5], [6]. A more advanced, robust estimation algorithms based on a dynamic model and recursive estimation (e.g. Kalman filter) may be applied in order to estimate AT position in situations when only a partial ARs data-set was received.

2) Integration: The system requires integration of various types of vehicles and additional sensors. System components should be able to exchange information and to be controlled using a common set of commands.

3) Situation Awareness (SA): An SA tool that visualize current situation and allow to monitor and control vehicles' maneuvers and paths is required. The software should visualize estimated position of ATs and vehicles. It may also display input from other marine systems, e.g. AIS.

4) Scalability: System scalability depends on the selected tag position estimation method and formation control algorithm. The tag position estimation method may require 1 AR (single beacon problem, depending on relative motion of AR and AT [7]) or in general 3 ARs (if tag transmits information about its depth) or 4 ARs if the depth information is missing.

5) Uniqueness: ARs has to be able to uniquely identify detected tags. This can be achieved by tag ID check.

6) Periodicity: ARs have to be able to distinguish unique messages from fish tags. Since the signal from AT is not equipped with a sequence number, it needs to be transmitted at a sufficiently low rate. Assuming maximum theoretical AT range of 1000 m and speed of sound of 1500 m/s, the messages shouldn't be transmitted more often then every (0.7 + p) s, where p is user defined safety margin.

7) Time synchronization: The position estimation algorithm requires a precise time synchronization of all ARs. The speed of sound in water is higher than in the air and depends on water salinity, temperature and depth. The sound could travel slower than 1480 m/s in fresh water and faster than 1550 m/s in salt water. These values indicate that in a 1 ms time, sound signal travel approx. 1.5 m. To achieve single meter range accuracy the ARs require time synchronization at least to a single-millisecond level, e.g. using GPS time.

8) Acoustic noise: Due to limited power of the acoustic tags, vehicles carrying ARs should not carry other acoustic transducers operating in the same frequency range that may jeopardize system performance, i.e. sonars.

9) Real-Time data-exchange: The information about received AT signals should be subsequently made available to the other nodes in the network in real-time. An application of a scalable network with a dynamic topology can ensure that necessary information is delivered to all endpoints. A Mobile Ad-hoc (WANET) and MESH types of networks may be considered. A low packet delivery ratio between network nodes can significantly affect system performance. For that reason reliable network protocols, e.g. TCP/IP, should be considered for data-exchange.

10)Inter-vehicle communication: A reliable communication method is required for sharing data among surface vehicles. Its range is determined by the maximum potential distance between ARs/USVs. That can be determined by the acoustic tag signal good reception distance, e.g. 1000 m. When two vehicles are on the opposite sides of a centrally located transmitter, the distance between vehicles may reach 2000 m. With 3 vehicles placed with perfect distribution on a circle of 1000 meters radius each vehicle are 1732 m apart. Due to the amount of information exchanged between the vehicles (e.g. telemetry), radio communication may be considered as the most suitable option. However, depending on the technology chosen in the design phase, radio communication may be a system bottleneck too, e.g. if the distance between vehicles exceed license-free ISM radio solutions range.

11)Formation control: In order to maximize system performance, vehicles involved in the operation should maneuver in a coordinated manner. To keep autonomous vehicles in a desired relative position to the fish, and to follow the fish, a formation control algorithm needs to be implemented. The formation controller has several objectives. The controller should keep the geometry of vehicles and AT constellation, in a way that minimize error of the position estimation algorithm. Moreover, it should keep all vehicles within a radio and acoustic communication ranges. The formation control mechanism shall be able to keep formation of vehicles with different motion characteristics and maneuverability, and be able to track both stationary and moving fish/ATs. It shall also be scalable to handle an task-specific number of vehicles. A system operator should be able to start/stop the controller through the user interface (e.g. SA software) and set its parameters during operation.

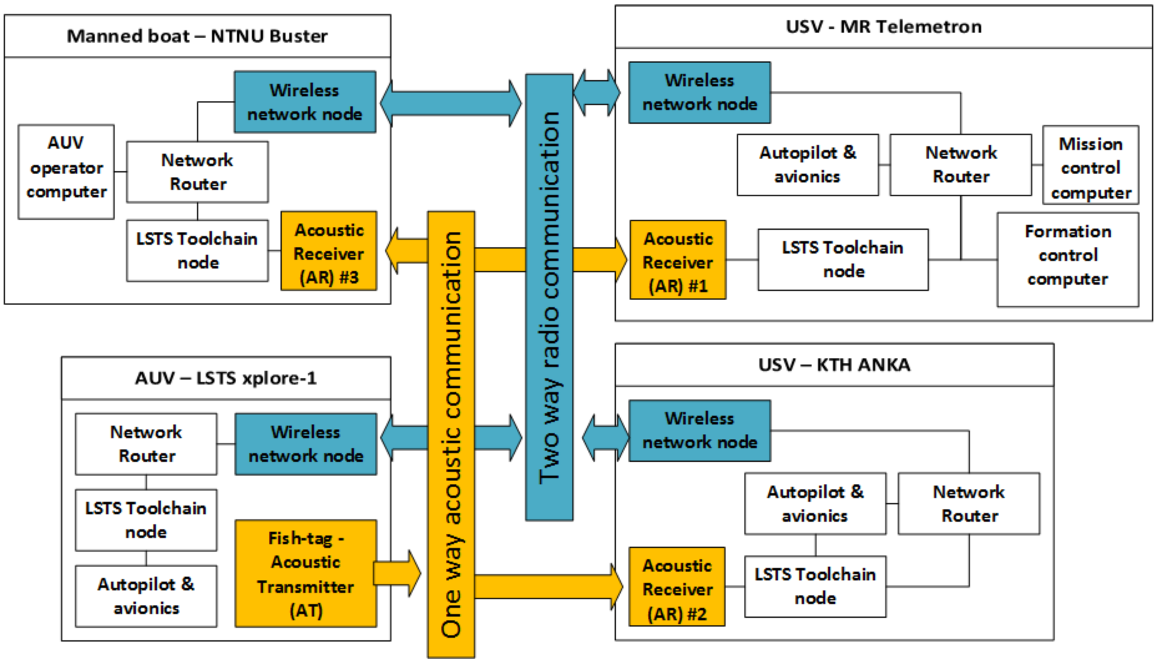

Figure 2: System architecture for test configuration

III. Proof-of-concept Configuration

The system architecture, of the configuration that was experimentally tested, is presented in Fig. 2. In addition, the main instruments and vehicles has been shown in Fig. 3, these are:

1) Acoustic Transmitter (AT): Acoustic transmitters (Fig. 3a) are designed for tracking wild fish movement and behaviour (Thelma Biotel AS [8]). These can transmit data such as: ID, pressure/depth, temperature, acceleration, tilt, dissolved oxygen, conductivity, and salinity. The smallest ID tag diameter is 7.3 mm, length is 18 mm, and mass is 1.2 g. Larger tags are able to transmit up to about 1000 m, while the smaller size tags might be limited to 200 m. However the actual range varies strongly with environmental conditions, e.g. sea state. In the field experiment a depth reporting tag ADT-16 was used.

2) Acoustic Receiver (AR): TBR-700 Realtime acoustic receiver (Fig. 3b) is designed to operate at 69 kHz, however it supports full multi-frequency reception in the 60-80 kHz band [8]. The device can store 1 500 000 tag-recordings in an internal memory. Maximum operational depth is 500 m. The device dimensions are 75 mm diameter, 230 mm long, and mass is 1140 g. The battery life is 8-9 months. Data can be uploaded using a wired RS485 line, used during the experiment, or wireless Bluetooth link. The ARs internal clock can be synchronized with a reference time source, e.g. GPS, by a custom synchronization protocol over the RS485 interface. The AT data transmission requires hundreds of milliseconds to complete, however AR compensates it, and reports the AT detection time which matches arrival of a first bit of the message.

3) KTH Anka: The ANKA Version 2 is an electric USV designed to operate in calm waters (Fig. 3c). Its length is 1.65 m and draught 0.4 m. Dryweight is 50 kg, and it can carry payload of 49 kg. ANKA's endurance is between 8 and 10 hours.

4) MR Telemetron: The Maritime Robotics Telemetron is an USV designed for sea operations (Fig. 3d). Length is 8.45 m and the vehicle is powered by a combustion engine [9]. The boat's top-speed is about 37 knots, and the mass is 2400 kg.

5) NTNU Buster: A manned motorboat (Fig. 3e)

6) LSTS xplore-1: The LSTS xplore-1 is a Light AUV (LAUV) allowing for 8 hours long underwater surveys on depths down to 100 m. The length is 1.1 m and its mass is 18 kg.

During the field-experiments the AT was carried by the Autonomous Underwater Vehicle (LSTS xplore-1). At the same time the three surface vehicles were equipped with ARs. Two ARs were carried by Unmanned Surface Vehicles KTH Anka and MR Telemetron. The third AR was attached to the manned motorboat (Buster). Vehicles were connected using high-performance WiFi nodes, and static TCP/IP network configuration.

All components have been integrated under the open-source LSTS Toolchain [10], which provides a set of necessary software. Three main elements of the Toolchain were used: (1) NEPTUS – SA software, (2) DUNE – unified navigation environment running on-board the vehicles, (3) IMC – Intermodule communication protocol. The position estimation algorithm has been implemented as a DUNE task. The formation controller has been implemented as a plug-in to NEPTUS.

(a) Thelma Biotel AS tag [8]

(b) Thelma Biotel AS TBR-700 receiver [8]

(c) USV - KTH ANKA

(d) USV - MR Telemetron

(e) Manned boat - Buster

(f) AUV - LSTS xplore-1

Figure 3: Main instruments and vehicles

On-board the vehicles DUNE tasks are controlling vehicles' behavior and encapsulating ARs data into IMC messages. These messages are being shared between network nodes. An additional DUNE instance, at the operator station, is listening for ARs messages. When a complete set of data from all ARs is received, the task computes an estimated AT position. That estimation is visualized in the NEPTUS software and is used as an input for the formation control plug-in.

The mathematics behind the formation controller is described in full in [11]. In this design, vehicles are kept at a desired radius, circulating about the estimated fish location. They are kept apart by calculating an angle between vehicles with respect to the estimated fish position and trying to maximize it. This means that if three vehicles are controlled, it tries to keep them at a 120° angle apart. When a vehicle is outside the radial tolerance it changes behavior to get the vehicle to approach the desired radius faster. An operator is able to monitor current situation using the NEPTUS, which also allows to control the vehicles and activate/deactivate formation controller.

IV. Field Experiment Results

The field test took place in the area of Agdenes in Norway in September 2016.

In the first stage of the field-trial the AT was attached to the AUV and deployed at the experimental site. Then USVs and manned motorboat took positions in the area around the AUV and started moving in an uncoordinated manner. At the same time, the fish tag position was computed based on information arriving from the receivers.

The system accuracy can be measured by comparing the GPS location of the AUV and the estimated position of the AT attached to it. However, this is valid only for the moments when the AUV was on the surface which was the case for 86 samples. During that time USVs were moving around the AUV on a radii ranging from about 50 to 150 meters. The smallest difference between estimated position of an AT and GPS readings of the AUV was 0.77 m, while the biggest difference was 23.87 m. A histogram of recorded results is presented in Fig. 5. Median error was 4.7 m, while average error was 6.34 m.

In the second stage of the experiment, the formation control algorithm was controlling the USVs in order to track the position of the simulated fish. Unfortunately, due to time constrains and limited resource availability the formation control was not evaluated against the performance of the acoustic positioning system. Still, results and experience gathered during the field-work provide a host of valuable information. The two autonomous vehicles used in this trial differs greatly in characteristics. ANKA is able to operate at speeds in the range of 0-1.5 m/s, whilst the Telemetron requires the speed to be at least 3 m/s to behave well. For the controller to be able to keep the angle between the vehicles

Figure 4: Tag position estimation under various constellations of moving vehicles

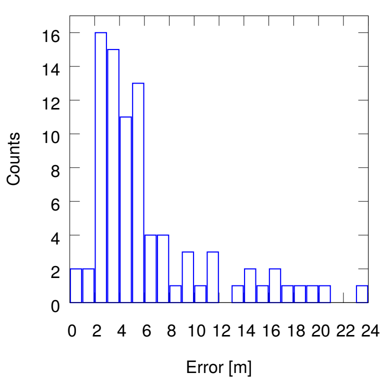

Figure 5: AT position estimation accuracy histogram

they were therefore given different radii to circulate at. This would keep them at about the same angular speed.

V. Discussion

During the test, the following observations were made.

- Before the field-trial one of major concerns was noise generated by the propeller and traveling hull of MR Telemetron. In practice the system worked satisfactorily if the boat travels at speeds up to 3 knots.
- In the field trial, the AT detection range was much lower than expected and previously observed. Reasons for that could be intensive rain showers and fresh water run-off that created a layer of fresh water on the surface of the sea, which affected acoustic wave propagation since the AUV was operated very close to the sea surface. This influenced the number of samples collected when the AUV was at the surface so the GPS position could be compared with the estimated tag location.
- The same phenomenon caused that AT message were often received by only one or two AR. In that case, due to the use of a simple localization algorithm, no AT position was computed. However a more advanced algorithm could be used to estimate AT location in such cases.
- The depth of an AR has significant influence on reception. The AR on approx. 0.4 m depth picked up 14% less data then the AR submerged to approx. 1 m, even though the vehicle carrying it was traveling closer to the AT.
- Radio communication caused 39% loss of all transmitted AR data between the vehicles.

Several factors influenced the localization accuracy. First of all, comparison of acoustic location with GPS is not ideal, due to a certain level of GPS position error. Other factors contributing to the position error are:

- Geometry of ARs constellation with respect to the true AT position.
- Timestamp of the acoustic data – the acoustic data are transmitted with low speed, therefore a data frame transmission time should not be neglected.
- Sensor depth measurement accuracy – during the experiment information about depth was provided by the AT. Accuracy of that measurement directly influence localization results.
- Distance between the GPS antenna on the AUV and the AT.

VI. Conclusions

Underwater localization finds its use in numerous applications. One of these is fish tracking. Knowledge about fish behaviour and migration is an important topic of marine biology, fishery and aquaculture research. Nowadays, systems allowing migration monitoring are usually based on arrays of moored acoustic receivers, with no near-real-time feedback. In this paper we present a system for tracking of an acoustic fish-tag using a formation of unmanned vehicles. A proof-of-concept has been tested in a field-experiment providing median localization error of 4.7 m, and average accuracy of 6.34 m. The work continues and a second version of the system is expected to be tested in 2017.

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