Design and validation of a system of autonomous fish tracking vehicles

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***Abstract*—This paper presents the technical design and validation of an autonomous surface vehicle (ASV) system capable of robotic search, localization and autonomous tracking of free-ranging fish carrying acoustic transmitter tags. The system consists of three identical differential-thrust catamaran vehicles equipped with time-synchronized acoustic telemetry receivers capable of accurate timestamping and decoding of signals received from individually coded tags. Multi-vehicle signal receptions allow time-difference of arrival (TDoA) measurements and are used in position estimators to enable collaborative fine-scale tracking and mapping of the movements of individual fish.**

The performance of the system was validated through several sea trials culminating in a deployment over several days in a Norwegian fjord where migrating wild Atlantic salmon smolts and sea-run brown trout had previously been tagged using acoustic transmitters in a nearby river. The three vehicles were able to operate autonomously over the entire deployment, carrying out coordinated searches along shorelines, keeping stations at hot-spot locations, and undertaking formation control while pinpointing fish positions. For the total of 5112 tag detections made during the deployment, 17 unique tag identifiers (fish) were registered at least twice, contributing significantly to the ongoing study of migrating salmonids in the area.

***Index Terms*—Autonomous Surface Vehicle, ASV, Acoustic Fish Telemetry, Robotic Target Tracking**

Fig. 1. The FishOtter ASV.

I. Introduction

Acoustic telemetry is a well-established scientific tool for spatial ecological studies of the movement and migration patterns of fish and other aquatic animals [1] and is usually subdivided into passive and active approaches. While passive acoustic telemetry relies on deploying extensive arrays of moored archival receiver units to detect and log the presence of acoustically tagged animals for retrospective analysis, active acoustic telemetry typically involves manual real-time tracking of tagged animals using a directional receiver from a tracking vessel. Active tracking can potentially provide movement data of high spatial and temporal resolution, but is generally regarded as exceedingly labor intensive and is subject to several practical and operational constraints related to human limitations and fatigue [2]. It thus qualifies as a compelling candidate for a robotic approach where autonomous operation and machine intelligence on-the-edge can push the current operational limits of fish movement studies at sea.

Several robotic fish telemetry systems have been proposed and investigated over the recent years, where different platforms have been employed across a variety of species and environments. These approaches can be classified according to vehicle type, propulsion system, and the telemetry system's mode of transmission (radio, acoustic).

Autonomous underwater vehicles (AUV) are probably the most commonly employed vehicle type for telemetry purposes and have been used to track a variety of species, including leopard sharks [3], [4], sunfish [5], Atlantic Sturgeon [6], Norway lobster [7], and juvenile Chinook salmon [8]. A benefit of using AUVs is their ability to penetrate and observe the underwater environment in the proximity of the animal target [9]. AUVs are however deprived of efficient radio-based communications and positioning systems while submerged, making vehicle operations more complicated.

Unmanned aerial vehicles (UAV) have also been employed as fish telemetry platforms, with mobility as its most prominent advantage allowing them to quickly move between desired listening positions while having continuous access to accurate GNSS positioning and radio communication. As an example, the multi-UAV system reported by [10] was shown to successfully estimate the position of radio-based fish tags using a swarming strategy. This approach, which depends on aerial reception of radio telemetry signals, is however not applicable to the marine environment.

In contrast, autonomous surface vehicles (ASV) have the benefit of simultaneous access to both air and water, which enables them to take advantage of both efficient radio-based communications and positioning systems while maintaining a connection to the underwater environment through a submerged acoustic receiver. In [11], [12], three ASVs carrying acoustic telemetry receivers were collaborating to track an acoustic transmitter carried by a fourth ASV simulating a moving fish. The system employed multilateration in an exogenous Kalman filter to estimate the position of the acoustic tag in combination with a distance-based formation controller [13] that directed the tracking vehicles to positions where subsequent transmissions were likely to be detected in a favorable geometry. In a different study, [14] developed and demonstrated the feasibility of a robotic surface vehicle concept equipped with a directional antenna for detection and localization of radio tagged carp.

Integration of telemetry receivers and acoustic sensors have recently also been accomplished in several types of passively propelled autonomous underwater and surface vehicles, like the buoyancy driven Slocum glider [15], wave propelled vehicles like the AutoNaut [16] and the Wave Glider [17], and the wind driven Sailbuoy [18] and Saildrone [19]. The combination of autonomous operation, energy self-sufficiency and low level of self-generated noise make these platforms highly relevant for long-term acoustic telemetry missions where they can traverse and monitor extensive sea areas with minimal support [16]. However, their inherent dependency on random environmental forces and its implications for maneuverability make them less suited for active fine-scale tracking where agility and tight vehicle formations might be required.

Fish telemetry systems rely on radio or acoustic transmission to broadcast animal data. Traditional radio-based approaches such as the tags and receivers employed in [10] and [14] are suitable for tracking of fish that dwell near the surface in fresh water. In brackish and sea water, radio telemetry suffers severe signal attenuation and has no practical application due to range limitations. Acoustic telemetry is thus regarded as the only viable option in the marine environment, with the exception of large animals that surface often and long enough to transfer telemetry via satellite link. Acoustic telemetry has proved to work satisfactorily in both saline and fresh water environments with detection ranges extending from a few tens of meters to several kilometers depending on the properties of the tag, receiver and the acoustic channel [20].

Active tracking requires not only the detection of acoustically tagged fish, but also a means to determine their location. Compared with traditional maritime underwater acoustic positioning systems, transmitters employed in animal studies must comply to far stricter constraints on physical size and weight in order to minimize influence on animal behavior and welfare and are thus relatively simple and limited in energy. Small transmitters in combination with requirements to prolong operational life necessitate use of higher frequencies and implementation of energy saving measures such as extra-long transmission intervals (updates typically exceeding 30 seconds) and strong restrictions on transmission power, which ultimately increase the rate of signal loss. Energy limitations in the tag also inhibits transponder function and thus direct range calculations. Information on time of transmission (ToT) is generally not available to the receiver, limiting position estimators to use time of arrival (ToA) measurements only, along with potential depth measurements that are transmitted by some tags. However, ToA measurements made by multiple spatially distributed and time-synchronized omni-directional receivers enable calculation of time-differences of arrival (TDoA) and pseudo-ranges for use in multilateration-based positioning algorithms.

Uncertainties in clock synchronization and delays, speed of sound and other variables introduce noise to the position estimates. Recursive filters that suppress noise are therefore crucial, along with adaptive sampling strategies that optimize receiver (vehicle) position with respect to geometry and detection probability. Preliminary results presented in [12] and [11] demonstrate the feasibility of this approach with acoustic receivers carried by autonomous surface vehicles. Our goal is to extend this approach and demonstrate its viability even for smaller and less frequently transmitting tags in an uncontrolled environment.

In this paper we thus present a similar system consisting of three autonomous surface vehicles that is designed to search, locate and autonomously track even low-power acoustic transmitters carried by small free-ranging fish and aquatic animals. Through multi-vehicle collaboration strategies, such as dynamic vehicle formations and coordinated search maneuvers, we are moving towards the realization of autonomous system for localization and persistent tracking of coded acoustic transmitter tags that are commonly used in fish movement studies today.

The main contribution of this paper comprises a detailed technical description of an autonomous fish tracking vehicle system, which is based on a commercially available vehicle frame, standard hardware components and an open-source software framework. Our system can be employed separately to autonomously map the presence of tagged fish in a predefined coastal or fjord area, including estuaries and intertidal zones, or engage in fine-scale mapping of the movement of individual fish. It can also be used as a mobile asset in combination with an array of moored passive receivers to augment the array's detection capacity and permit adaptive sampling of hot-spot fish migration events.

We conclude the paper by presenting results and validating the performance of the system through several sea trials that culminate in a search and tracking mission stretching over several days in a Norwegian fjord, targeting migrating wild Atlantic salmon post-smolts and sea-run brown trout which had previously been tagged with acoustic transmitters in a nearby river.

II. System Requirements

The ASV system is planned as a telemetry research tool for carrying out persistent fish search and tracking missions in confined coastal areas such as fjords and archipelagos, in addition to lakes, calm rivers and estuaries. It must be able to operate in wave heights up to a half meter (Sea state two and below [21]) and in water currents up to a meter per second. The vehicles must be able to operate autonomously for at least two full days without replenishment of energy.

The vehicle system must be able to autonomously follow paths by controlling its position, course and speed, and should minimize deviation from desired paths by suppressing disturbances from environmental forces such as wind, waves and currents. It must in addition support special maneuvers for searching, localization and tracking of acoustic transmitters while avoiding surrounding landmass, reefs and other obstacles.

The vehicle control and communications software must provide the operator with situational awareness and enable cooperation between vehicles. This must include real-time telemetry to the operator conveying data from the vehicle motion control system and payload/sensors, including the acoustic telemetry receiver. Inter-vehicle communication must support coordination of collaborative operations, including search formations and fish tracking formations.

Both control system and vehicle hardware should be designed to minimize acoustic noise in order to maximize the detection range of the acoustic telemetry receiver. The telemetry receiver must be able to receive and decode R-coded acoustic tags [20] transmitting in the frequency range 63-77 kHz. The vehicles must be able to assign timestamps to detected tag transmissions and record the vehicle's position where the detections were made. Timestamps must be accurately synchronized to a common system-wide clock and detection data must be available to position estimation algorithms and the operator in real-time. Position estimators must be integrated directly into the vehicle software to support local situational awareness.

III. System Design

This section presents the system design for the proposed ASV, denoted as the FishOtter (Fig. 1), in terms of hardware, software, motion control, communication and acoustic telemetry integration. The three vehicles in the system share the same design and are only differentiated through software configurations.

A. Hardware Components

The vehicle is built upon the commercially available "Otter USV" vehicle frame (Maritime Robotics AS, Trondheim, Norway), which includes two hulls, each equipped with one electric 180 W thruster and support for two 915 Wh Lithium batteries (Torqeedo GmbH, Gilching, Germany), a mechanical frame with a watertight box for electronic components, and a low-level power management and thruster interface. Fig. 2 illustrates the top view of the vehicle, along with approximate locations for the most important hardware components.

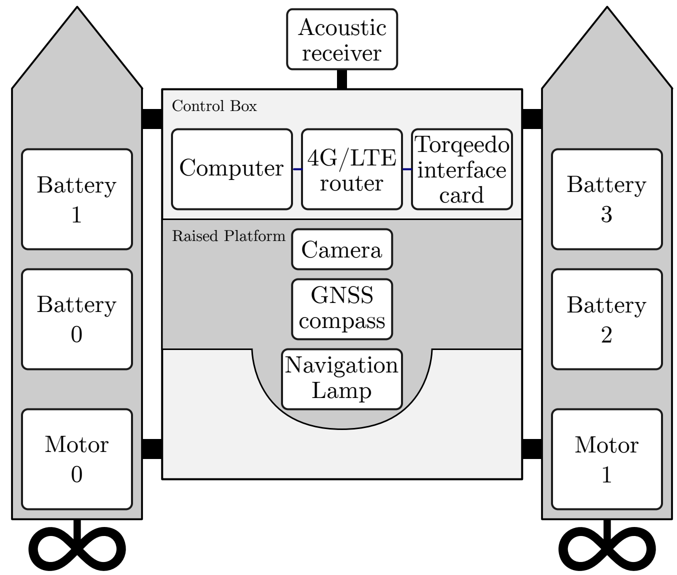

Fig. 2. Hardware Overview.

The control box serves as a central interconnection hub for the vehicle's electronic components and sensors, and contains the power management system, the communication system and the vehicle computer.

The Torqeedo interface card implements a gateway between the six Torqeedo RS-485 buses (one each for batteries and thrusters) and a CAN interface for communicating with the vehicle computer. It also distributes power from the four batteries to the two motors and contains regulated power supplies for all other components in the vehicle, except for the IP camera, which uses a separate IEEE 802.3af compliant power-over-Ethernet injector. The vehicle power distribution is protected against overcurrent by electronic fuses on the Torqeedo interface card, in addition to a bank of resettable fuses (PPTC) for each power channel.

The communication system uses an LTE/4G router (Teltonika Networks, Kaunas, Lithuania), and provides four Ethernet connections, cellular internet access and GNSS through external antennas, a SMS gateway, and a Wi-Fi connection for future expansions. The external antennas are located on the top of the control box, as seen in Fig. 1. The router's GPS receiver is used as a secondary means of locating the vehicle through an internal SMS interface, and functions independently of both the vehicle computer and the main navigation system.

A GNSS-based compass and positioning system with gyro and tilt aiding sensors serves as the vehicle's main navigation instrument (Tab. II). This instrument has a rated positional error below 1.0 meter for at least 95% of the time, and a heading error less than 2^o rms. An RS-232 serial line to USB converter connects the navigation sensor to the vehicle computer, and adheres to an extended version of the NMEA0183 protocol.

TABLE I
HARDWARE COMPONENTS IN THE VEHICLE COMPUTER

Unit	Model
SOM	Raspberry Pi CM4108032
Carrier board	Waveshare CM4-IO-BASE-B
Storage	Lenovo 4XB1B85886 512 GB M.2
Expansion board	Sfera Labs SPBC12X

The vehicle computer consists of four stacked components: A System on a Module (SOM), a module carrier board, a PCIe SSD and an industrial I/O and power expansion board (Tab. I). The SOM includes the ARM v8 based Broadcom BCM2711 system on chip (SoC), in addition to 8GB of LPDDR4 RAM, 32GB eMMC storage and a wireless module supporting Wi-Fi and Bluetooth. The carrier board connects to the SOM through two 100-pin inter-board connectors and makes the external interfaces available for further use. In addition, the industrial expansion board provides the computer with a robust power supply, CAN bus and RS-485 interfaces and a relay. The relay drives the vehicle's navigation lamp, which is used to indicate the vehicle's operational state through different blink patterns.

The communication interfaces within the control box, and external interfaces to peripheral components are summarized in Fig. 3. All external connections to the control box are furnished with industrial grade connectors with IP67 rating or higher to withstand water intrusion.

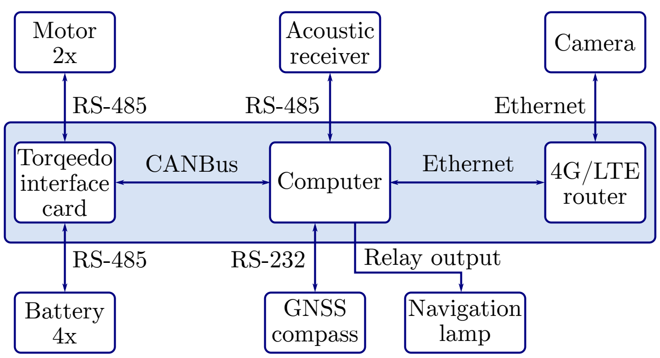

Fig. 3. Communication interfaces within the control box (shaded blue) and to peripheral components.

Tab. II lists components that are peripheral to the vehicle computer. The scientific payload of the vehicle is a TB Live multi-channel acoustic telemetry receiver (Thelma Biotel AS, Trondheim, Norway) for detection and decoding of signals emitted by fish tags. A rigid pole located midship and at the front of the vehicle submerges the receiver below the hulls to a depth of $0.4\,\mathrm{m}$. In addition to the RS-485 interface that connects it to the vehicle computer, it is also directly connected to a pulse-per-second (PPS) signal provided by the GNSS compass that keeps it synchronized with the GNSS clock. This enables accurate and synchronized ToA timestamps across all vehicles to support tag localization by time-difference-of-arrival (TDoA) measurements.

The vehicle's sensor suite also includes an IP camera equipped with a low-light image sensor and an infrared light rated for 30 meters of illumination to support vehicle operators with visual situational awareness both day and night.

TABLE II
HARDWARE COMPONENTS

Unit	Model
LTE/4G router	Teltonika Networks RUT955
Acoustic receiver	Thelma Biotel TB Live
Camera	Hikvision DS-2CD2343G2-I
GNSS compass	Hemisphere GNSS V104S
Navigation lamp	Hella Marine NaviLED 360
Motors	Torqeedo Ultralight 403
Batteries	Torqeedo Battery 915 Wh for Ultralight

B. Software Overview

The vehicle computer runs the Ubuntu Server 20.04 operating system. This Debian based GNU/Linux distribution provides an updated and stable platform for the middleware and other ancillary software, and is similar to the Ubuntu Desktop 20.04 operating system that runs on the operator's computer, except with no graphical user interface (GUI).

Both the vehicle control software and operator interface of the system are based on the open-source toolchain for networked vehicles developed at the Underwater System and Technology Laboratory[1]. The toolchain includes the DUNE middleware for autonomous vehicles, the Neptus graphical command and control interface and the inter-module communication (IMC) protocol for communication between Neptus and DUNE [22].

Both Neptus and DUNE adopt a modular approach capable of running in heterogeneous vehicle systems, and come with a range of modules that can accommodate the requirements of specific operations and vehicles. Which of these modules are used is controlled by configuration files in both Neptus and DUNE, and the configuration files can also contain parameters for each of the modules, which can be changed online. An extensive library of new and modified modules have been created to support the hardware and use-cases of the FishOtter vehicle.

C. Motion Control System

The motion control system architecture of the vehicle is implemented in DUNE, and is organized as shown in Fig. 4. The operator is responsible for creating plan specifications in an IMC defined mission language consisting of maneuvers and transitions between maneuvers.

The maneuvers are the motion primitives of the vehicle and include dynamic controllers and control strategies such as path following, station keeping and loitering.

The maneuver controller further communicates with the path controller with commands for either straight lines or circular arcs and orbits[2]. The integral line-of-sight (ILOS)

[1]LSTS, University of Porto (lsts.fe.up.pt/toolchain)

[2]Circular arcs and orbits are named loiter in the IMC defined mission language.

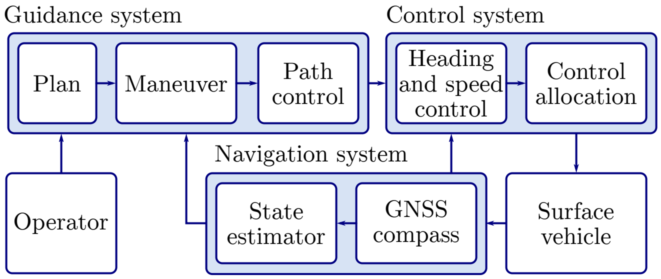

Fig. 4. Motion control system architecture.

guidance law described in [23] is used for straight lines, while the vector field guidance law of [24] is used for circular motion. The desired speed and heading from the ILOS algorithm are subsequently dispatched to the vehicle control system, entering as setpoints for the heading and speed PID-controllers.

The heading and speed control is based on differential thrust control, as there are no rudders on the vehicle. Surge motion is produced from controlling common thrust, and heading rate is controlled through differential thrust, causing a change in heading. Due to the frequent low-speed operations encountered in fish tracking operations, we have opted for heading control over course control, as the noise in course measurements is inversely proportional to speed. The surge controller has been tuned by following the setpoint overshoot method [25], while the heading controller was tuned experimentally. Due to the rather strong directional stability exhibited by the vehicle, the surge controller is deactivated during sharp turns to prevent them from becoming long arches. No control is imposed on sway, roll, pitch and heave motion.

The control allocation takes the desired moments and forces set by the PID-controllers, and subsequently allocates actuation levels on the thrusters based on a curve fitted model from force measurements gathered through a bollard pull test. A saturation stage is also included that prioritizes differential thrust over common thrust, and also ensures that thrust is kept at levels where propeller cavitation is minimized.

D. Communications System

The communicating entities within the system can be classified as: Vehicles, operators, spectators and a computer server. This section will describe the communication between each class, and is summarized in Fig. 5.

LTE/4G is chosen as the primary wireless communication link, which connects the vehicle to a centralized server through an encrypted VPN connection. This simultaneously increases security and ensures that each vehicle is assigned a fixed IP address. The VPN client is integrated in the LTE/4G router, which enables remote access to all connected devices through port forwarding, even if the vehicle computer becomes unreachable.

Using LTE/4G as the primary communication channel limits the system to operate within cellular network coverage,

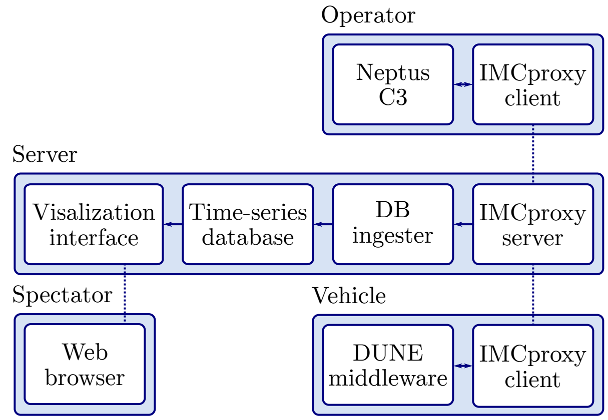

Fig. 5. Communication between the different entity types supported by the system.

which is assumed for the environments outlined in the system requirements.

A secondary communications link to the vehicle has also been implemented using a text-based SMS interface that allows the operator to request telemetry such as position from the secondary GPS, and execute simple commands. This system operates independently of the vehicle computer, providing information in case an emergency recovery is required.

The format for inter-vehicle and operator telemetry and commands is defined by the IMC protocol. With respect to the OSI/ISO model, the protocol resides in the application layer, making it independent of the underlying layers. We have used the default UDP implementation in DUNE to transport the messages, which implements automatic detection of local IMC capable entities through broadcasting. Such broadcasts are restricted to local networks, necessitating the simple WebSocket based IMCproxy that bridges local IMC networks across the Internet.

TABLE III
SOFTWARE SERVICES RUNNING ON THE BACK-END SERVER

Function	Software package
Telemetry visualization	Grafana 8.5
Time-Series Database	InfluxDB 1.8
Database ingester	Modified IMCproxy client
Bridging IMC networks	IMCproxy server/client
VPN server	OpenVPN

A centralized back-end server supporting the vehicle system has been configured to run the services listed in Tab. III. In addition to the VPN for encrypted two-way communication between multiple vehicles and the operator, an online solution for telemetry storage, analysis and distribution has been implemented. This system connects to the IMC network, filters out specified message types and ingests them to a time-series database. An online system for telemetry visualization and analysis can then be accessed by the spectator to view near real-time telemetry from the system, without needing to access the VPN server nor running the Neptus software.

Fig. 6 shows an example dashboard of visualizations from the system which provides an overview of the vehicle state during a mission. Other dashboards have been created for specific tasks such as visualizing the locations of fish tag detections and position estimates.

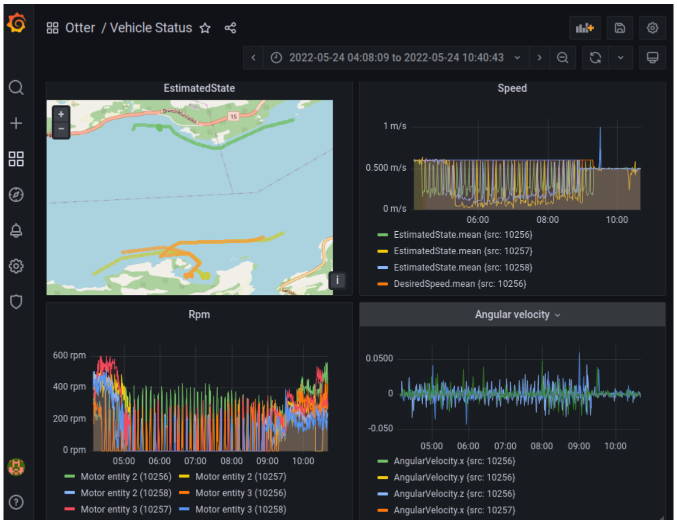

Fig. 6. Online telemetry visualization system.

E. Acoustic Telemetry Integration

The acoustic telemetry receiver communicates through a NMEA0183 inspired text-based protocol, and provides two kinds of messages by default: tag detections and sensor messages.

- The sensor message contains the current water temperature along with average and peak acoustic noise measurements, and is reported at 60 second intervals.
- The tag detection message contains a UNIX timestamp divided into seconds and milliseconds, transmitter ID, protocol, transmitter data, frequency and the signal to noise ratio (SNR), and is reported once a transmission has been processed.

These messages are read and parsed by a custom DUNE module, and distributed through the IMC network. This module also buffers IMC messages containing navigational data, and pairs the detection with the receiver's position at the time of detection, as illustrated in the upper part of Fig. 7.

The temperature measurements from the sensor messages are read by a module that estimates the speed of sound in water using Leroys first formula [26]. Salinity and pressure are based on either fixed module parameters or provided through the IMC network from a compatible vehicle such as the AutoNaut [16]. The estimated speed of sound is then published to the IMC network for use in the position estimators.

The tag detection and speed of sound messages are read by a position estimator module specifically designed for the FishOtters. The module stores a buffer containing the latest detections made by all vehicles in the IMC network, and activates position estimators for acoustic receivers dynamically as more detections become available. This provides the system with four modes of tag positioning:

1) *Single vehicle, single tag reception*: The tag is in the vicinity of the vehicle and located within a sphere centered at the acoustic receiver, with radius limited by the current acoustic transmission conditions.
2) *Single vehicle, multiple tag receptions*: The transmission interval of the targeted tags is pseudo-random with one second resolution. With two subsequent detections of a tag, the interval in seconds can be found, and a single TDoA estimate can be calculated. With at least three subsequent detections, multilateration with two synthetic baselines can be used for position estimation. The accuracy of this method is highly dependent on minimizing the dilution of precision by placing the receiver (vehicle) at favorable positions for each transmission. Given further receptions, a Kalman filter is launched to estimate and reduce the measurement noise in the position estimate.
3) *Three vehicles, single tag reception*: With three detections of the same tag transmission, along with a depth measurement from the tag, the 3D position of the tag can be calculated based on the TDoA equations. This results in a single position estimate without noise mitigation.
4) *Three vehicles, multiple tag receptions*: With subsequent receptions from the same tag on at least three vehicles, a recursive filter can be employed to estimate position and mitigate measurement noise.

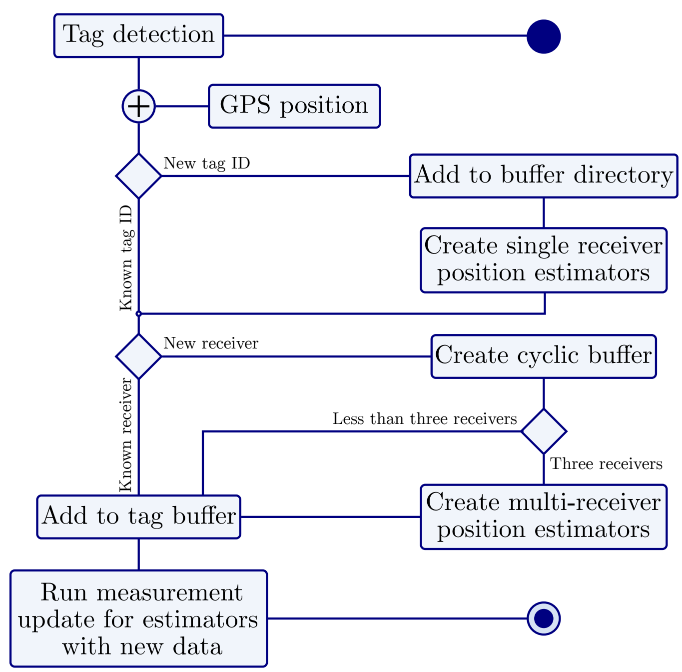

Fig. 7. Activity diagram for tag detections.

The dynamic change between the positioning modes is shown in Fig. 7. The position estimators are implemented as C++ classes, each using a standardized interface inherited from a base class. The system currently contains options for position estimators based on extended, unscented, square-root unscented and exogenous Kalman filters.

IV. Results/System Validation

This section presents experimental data chosen to demonstrate fulfillment of the previously stated system requirements. The underlying data were gathered through numerous sea trials designed to validate the hardware integration and motion control system, and characterize self-generated acoustic noise and tag detection capability. In addition, selected data from two field deployments in the Norwegian fjord Nordfjord (Vestland, Norway) is presented. The field deployments were executed in May, targeting the predicted migration of ocean-bound Atlantic salmon post-smolts while simultaneously observing local sea-run brown trout. In total, 5112 detections were recorded with 31 distinct identifiers, and 17 were received at least twice, making them less likely to be false detections.

The presented data was collected using a logging module in DUNE for archiving IMC messages, and was subsequently extracted using the mission review and analysis tool in Neptus.

A. Motion Control System

The overall performance of the motion control system was assessed through the plan shown in Fig. 8. The vehicle started just outside the fourth waypoint, and traversed the four waypoints in ascending order. The desired heading and speed along with the measured actuation levels gathered from the experiment are shown in Fig. 9.

The environmental disturbance from ocean currents, wind and waves during the trial was found experimentally by letting the vehicle drift until speed and attitude reached a steady state. The steady state drift speed was measured to $0.2\,\mathrm{m\,s^{-1}}$ in a south-westerly direction.

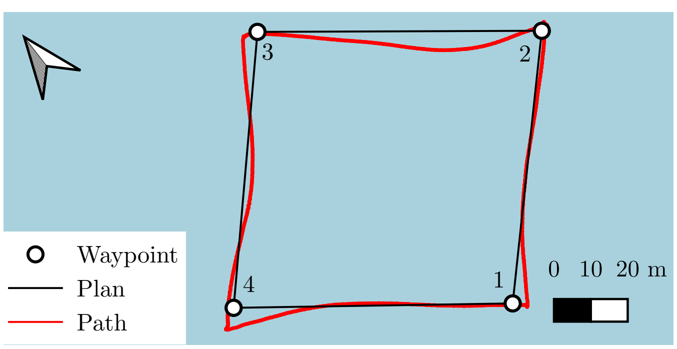

Fig. 8. Vehicle path (red) autonomously traversed according to a pre-specified plan (black), numbers indicating the waypoint order.

B. Acoustic Noise Generation

The self-generated noise of the vehicle was measured by fixing a broadband hydrophone adjacent to the acoustic telemetry receiver, and running a spectrum analysis on the recorded data. One-minute-long waveforms were collected and analyzed at different actuation levels, producing the spectra shown in Fig. 10.

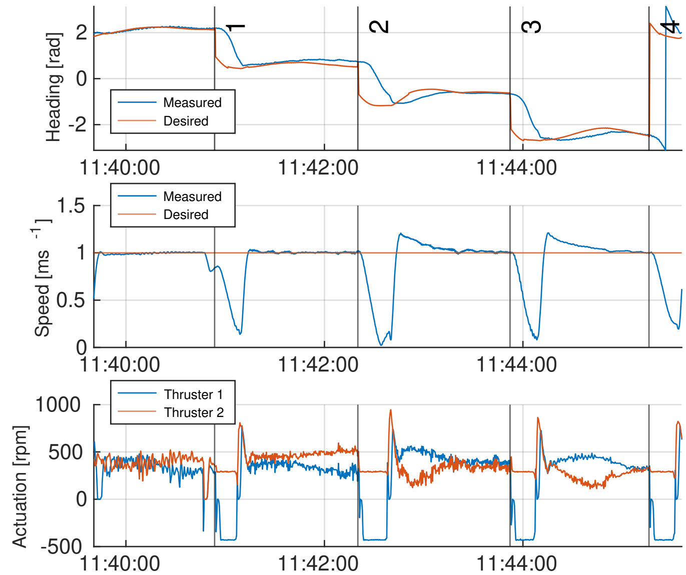

Fig. 9. Heading, speed and resulting actuation for the tracks in Fig. 8. The numbered horizontal lines indicate waypoint changes corresponding to the numbers used in Fig. 8.

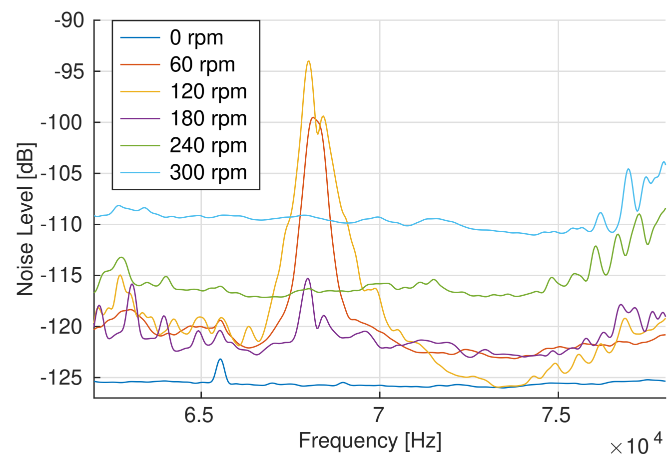

Fig. 10. Acoustic noise spectra at different actuation levels.

C. Tag Detection Range Model

The probability of detecting an acoustic tag transmission depends on the terms of the passive sonar equation [27]. Besides self-generated noise, detection probability is influenced by a range of complex physical mechanisms that can be difficult to quantify. Assuming that all other factors stay unchanged during an experiment, we can however establish probabilistic detection functions based on empirical range test data obtained at different actuation (rpm) levels. For this, we consider each tag transmission as a Bernoulli trial, and use the ratio of detected transmissions to calculate the probability at each range. As previously shown [28], a logistic approach can provide a simple yet realistic model of such relationships.

Data for the model was collected by conducting a field experiment with a periodically transmitting acoustic transmitter submerged at 2 m depth from a floating dock. The FishOtter vehicle was then driven away from the submerged receiver at fixed actuation levels, and turned around when no further detection was made.

The distance between the submerged transmitter and the logged detections was calculated based on GPS positions, and divided into 25 m bins. The detection ratios were then calculated and fitted to a logistic model using the MATLAB® function *glmfit*[3]. The results are shown in Fig. 11.

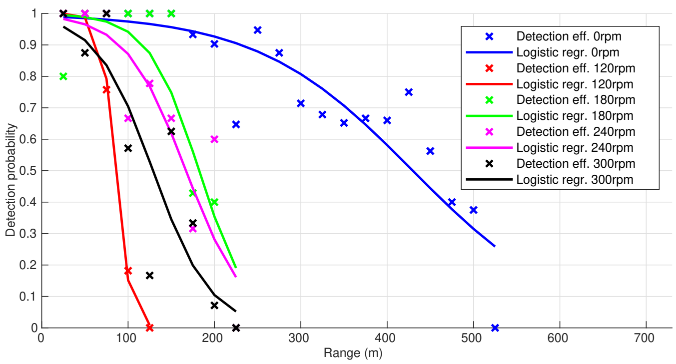

Fig. 11. Empirical detection probabilities established for a 7 mm, 69 kHz acoustic tag (R-LP7, Thelma Biotel AS) at different actuation levels.

D. Search Formation

When searching for acoustically tagged fish, it is desirable to let the three vehicles sweep an area as large as possible, while simultaneously keeping them sufficiently close together to allow a fast transition into a tracking formation as soon as a tag is detected. This can be achieved by creating a V-shaped formation where the vehicles are separated by distances determined by the detection range probabilities established in Fig. 11. Accordingly, a basic control solution was implemented by defining a leading vehicle and commanding the other two to trail the leading vehicle with an offset in distance. Based on the two most recent positions of the leading vehicle, the trailing vehicles independently calculate and navigate towards their desired relative positions.

During the field trial in Nordfjord (Vestland, Norway), a plan consisting of an 18 km long path was configured for the leading vehicle, while the trailing vehicles were given a trailing offset of 100 m to each side and 50 m behind the leading vehicle. An excerpt from this path, as measured by the vehicle's onboard GNSS receiver, is shown in Fig. 12 where the leading vehicle (yellow) is traveling westwards, with the port (orange) and starboard (green) trailing vehicles attempting to track its path with the defined position offset.

E. Endurance

During the deployment in the outer parts of Nordfjord, a 30 km long shoreline search, as shown in Fig. 13, was traversed at a target speed of $0.5\,\mathrm{m\,s^{-1}}$ under environmental conditions that can be regarded as representative for such missions. Intermittent station keeping maneuvers at strategic

[3]The MathWorks, Inc.

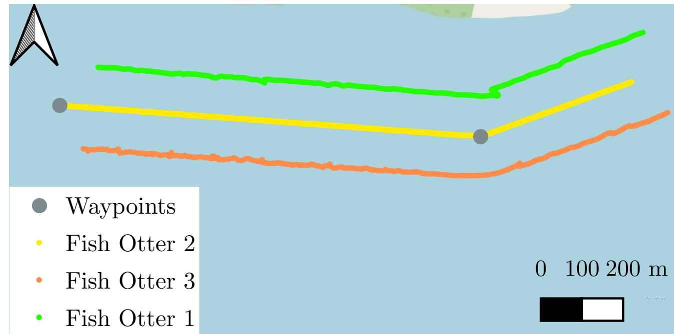

Fig. 12. Observed paths navigated by FishOtters searching in V-formation in a Norwegian fjord.

locations along the shoreline was also included in the path plan, extending the search to a total of 25.5 hours. The vehicle was supplied with four fully charged batteries at the start of the mission. At the end of the mission batteries reported 67% remaining capacity, amounting to a gross energy expenditure of $1208\,\mathrm{kW\,h}$, or an average power consumption of $47.4\,\mathrm{W}$.

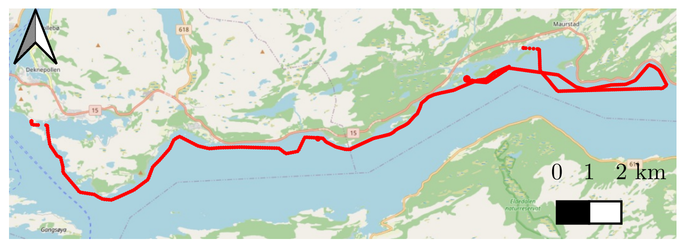

Fig. 13. 30 km track made while autonomously searching for tagged fish along a Norwegian fjord. (Basemap: ©OpenStreetMap contributors [29]).

F. Tag Localization and Autonomous Tracking Formation

The field trials in Nordfjord (Vestland, Norway) culminated in an active tracking event where a migrating juvenile salmon (Tab. IV) was detected by all three vehicles while station keeping in the Stryn river estuary. The tag was also detected by an online receiver buoy located in the river outlet verifying that the transmitter had recently migrated from the river. A multi-receiver extended Kalman filter position estimator (see Fig. 7) was automatically started upon detection and provided tag position estimates once the tag was received by all vehicles. The position controller described in [13] was subsequently activated to keep the positions of the three vehicles in formation around the tag at a nominal distance of 25 meters.

The position of the vehicles at all detections and the measured SNR of the detections are shown in Fig. 14, along with the tag position estimates. The vehicles and position estimates move from south to north, and the longest distance between any received transmissions was 520 m.

After the mission, the online buoy receiver kept receiving tag messages where depth measurements indicated active fish movements for four days. After this, the depth measurements became highly correlated with the tidal levels in the area, indicating a stationary transmitter and possible fish mortality.

TABLE IV
INFORMATION ON TRACKED TAG.

Model	Thelma Biotel D-LP6, 6 mm, 69 kHz
Transmission	ID 197, depth sensor, interval 30-90 s
Fish species	Atlantic salmon, 13.9 cm, 25.4 g
Tagging date	2022-04-07
Tracking date	2022-05-12
First detection	Moored buoy 02:10:24, FishOtter 04:03:34
Fish tracking start	20:38:17

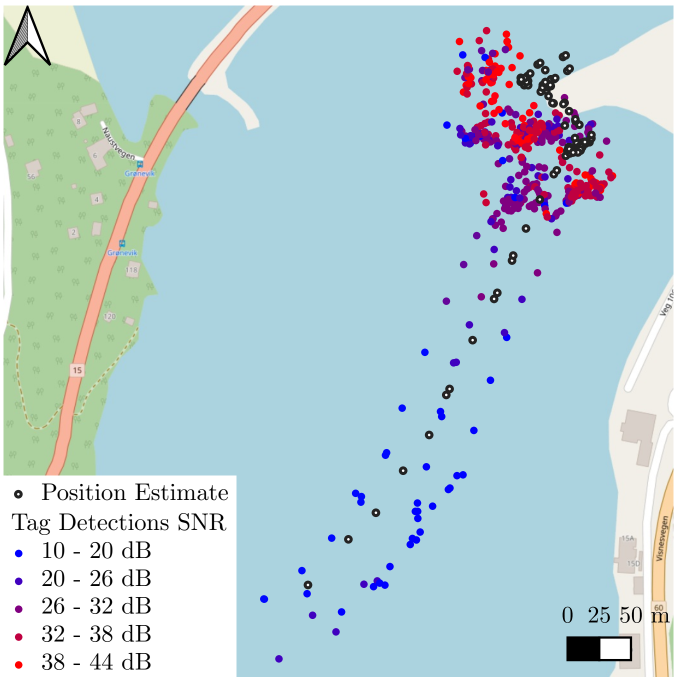

Fig. 14. Positions of vehicles at tag detections (colored according to SNR) and corresponding position estimates (black rings) for tag ID 197 during the tracking event. The landmass in the upper right corner was submerged by the tide at the time. (Basemap: ©OpenStreetMap contributors [29]).

V. DISCUSSION

The four step responses shown in Fig. 8 demonstrate an acceptable path following performance for typical fish telemetry operations, where tight operations close to shore and other obstacles can be avoided. The maximum cross-track error is well below 10 m at all times, indicating that operations with vehicles in compact formation (20 m) can be accomplished without collisions even when subject to moderate environmental disturbances. Fig. 13 shows that these results are applicable also to long-range missions in open and uncontrolled fjord environments.

Based on battery measurements from the mission shown in Fig. 13, the maximum traversed distance that can be attained by the vehicle under those conditions is approximately 90 km, corresponding to around 75 hours of operation, before battery recharging/replacement.

The actuation levels in Fig. 9 show that the motion control system is currently not optimized for reduced noise generation, with high actuation levels needed to make sharp turns. Specialized controllers for fish tracking that operate at more optimal actuation levels as suggested by Fig. 10 and 11 are therefore currently being explored. Reducing vehicle noise generation is of interest in all search and tracking scenarios, and particularly during active tracking events like Fig. 14, where it is desirable that all vehicles receive every tag transmission while maintaining longer baselines for improvement of the position estimates and keeping a good distance to the fish.

During the experiments, the motion control system had no active obstacle avoidance system, neither for mapped elements like land and shallows, nor for unknown elements such as ships or semi-permanent installations. Obstacle avoidance has not been a major priority of the system, as the low weight and forces produced by the vehicle are assumed to have limited damage potential. A system based on electronic navigational charts has been implemented, but has yet to be experimentally validated. In addition, web-based AIS-services provides positions that could contribute to avoiding collisions with larger boats such as cruise ships and fishing vessels.

The fish tracking mission from Fig. 14 provides proof of concept both with respect to the system's motion/formation control and the acoustic telemetry integration. It should however be noted that although the vehicles appear to be tracking a moving acoustic transmitter, this may just be the position estimator slowly converging to the correct location of a stationary tag. Should this be the case, the detection range during the tracking had to be significantly better than the ranges attained during the range tests (Fig. 11). The area is situated in the estuary of the Stryn river, making the water more brackish compared to the conditions experienced during the range test, which is known to reduce signal attenuation. On the other hand, the fish carried a tag with 2 dB lower transmission power than the tag used in the range test (137 vs. 139 dB Re 1 μPa at 1 m [30]). Nevertheless, the high SNR readings where most of the tag detections were received definitively show that the vehicle system was able to collaboratively position a genuinely small acoustic transmitter tag in an uncontrolled environment. Compared with the results presented in [11] and [12], the power of the tracked transmitter was 21 dB lower (137 vs. 158 dB Re 1 μPa at 1 m [30]), and was transmitting with significantly longer update intervals (30 s - 90 s pseudo-random interval vs. 7 s fixed interval).

Additional experiments are needed to verify the limit at which faster moving targets can be persistently tracked, in addition to a controlled experiment where position of a submerged tag with a accurately verified position is estimated to assess estimator performance and errors.

VI. CONCLUSION

In this paper we have presented the design and validation of the FishOtter system of autonomous surface vehicles designed to perform robotic search, localization and autonomous tracking of fish that carries small acoustic transmitter tags.

The acoustic properties of the vehicle were characterized experimentally along with the detection probability of a representative fish tag across different ranges and actuation levels. Through field tests conducted in a Norwegian fjord that were aligned with an ongoing telemetry study targeting migrating Atlantic salmon and sea-run brown trout, the system's ability to search, locate and actively position an acoustic tag was demonstrated.

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