Chasing Fish: Tracking and control in a autonomous multi-vehicle real-world experiment

José Pinto, Margarida Faria, João Fortuna,
Ricardo Martins, João Sousa
Faculdade de Engenharia da Universidade do Porto
Email: {*zepinto, mfaria, jfortuna, rasm, jtasso*}*@fe.up.pt*

Nuno Queiroz
Research Center in Biodiversity and Genetic Resources
Porto, Portugal
Email: *nuno.queiroz@gmail.com*

Frederic Py, Kanna Rajan
Monterey Bay Aquarium Research Institute
Moss Landing, USA
Email: {*fpy, Kanna.Rajan*}*@mbari.org*

***Abstract*—This paper describes scientific and engineering efforts towards remote sensing, tagging and continuous tracking of sunfish specimens (*Mola mola*, world largest bony fish) in the open sea.**

This ongoing experiment is done in the context of a collaboration between MBARI and Porto University and bridges biology, fisheries research, autonomy and control with use of satellite tags, autonomous aerial, surface and underwater vehicles, as well as new software tools for remote asset control and situational awareness.

Here we describe technologies and overall architecture of the experiment and results from initial deployments.

I. Introduction

The increasing threat to bio-diversity in our oceans have impacted fish stocks many of which have collapsed altogether. Overfishing is one obvious culprit; yet anthropomorphic inputs in the coastal ocean are also likely to have had a substantial impact on fish populations. Tracing the various reasons of such depletion requires sustained observations and frequent sampling of the water column to determine what and where the fish ingest. Yet such behavioral studies are expensive and challenging; tagging fish provides some evidence of the spatial scales of residence and migration. However, additional contextual information is necessary to understand not only their behavior in the water-column, but also the *context* of their activity in space and time.

The Faculty of Engineering, Univ. of Porto (FEUP) and MBARI along with colleagues at the Research Center in Biodiversity and Genetic Resources (CIBIO), will be carrying out a novel experiment which bridges biology, fisheries research, autonomy and control with the use of autonomous aerial, surface and underwater vehicles to track sunfish (*Mola mola*), the world largest bony fish.

A. Engineering Objectives

Mola mola popping-up behavior is well known among the scientific and fishing communities. Sunfish specimens typically stay afloat around one hour per day, in average. In our experiment, we exploit this behavior by tagging a number of sunfish with electronic tags that, whenever at surface, send their current location through satellite communications.

Sunfish locations are disseminated to two different teams: one staying on the shore and another aboard a ship in the proximity of predicted sunfish pop-ups. The team on the ship uses unmanned vehicles (AUV, ASV, UAV) in order to acquire more information about these specimen in near real-time and about the environment selected by this fish for surfacing.

The engineering objective is to ensure that AUVs can systematically track the fish over a number of hours as long as they are on the surface by making upper water column surveys around the fish. Aerial platforms function as spotters to determine the approximate locations of at-surface fish and to reacquire these targets should they dive for extensive lengths of time. We are also testing using both aerial and water surface vehicles as data mules, transferring information acquired underwater from AUV to the ship.

B. Scientific Objectives

Previous research [1] [2] on sunfish provided the first information available anywhere on behavior and seasonal

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movements in the northeast Atlantic. Tagged sunfish displayed a diel diving pattern occurring near the surface at night and deeper during the day, including repeated dives below the thermocline, suggesting sunfish were following vertically migrating prey. We also found evidence that sunfish optimize search behaviour for patchily distributed prey in different environments. Horizontal movements of sunfish were consistent with seasonal migration patterns to high latitudes and subsequent return south in response to shifts in sea surface temperature.

The scientific objective for this experiment is to better understand the behavior of this species and, by having in-situ observations, determine what drives this fish to stay at these locations.

II. Related Work

Previous GPS-enabled tag deployments on sunfish [1] [2] have been successful and represent the first demonstration of long-term ($>$ 170 days) GPS tracking of a large pelagic fish. More importantly, sunfish GPS tracking yielded the highest spatial resolution tracks yet achieved for a fish. That allowed the application of robust track shape analysis, and therefore, the description of movement and behaviour at much finer scales than previously possible. Despite these important findings, there is still the need to link specific behaviors of tracked fish with their immediate environment.

In [3], the authors also use AUVs in order to track and follow fish. In this case the fish (tiger shark) tag includes an acoustic pinger that allows AUVs to estimate the relative angle between AUV and fish while underwater. This angle is used by the onboard controller to follow the fish. In our work, however, we are required to minimize perturbation to the fish which otherwise will dive to great depths.

The control architecture used in this experiment bridges the work by [4] and [5]. In the former, the authors use the T-REX/EUROPA onboard planer to generate and execute Lagrangian survey plans around a moving drifter in a similar way to what is done around sunfish. In the latter, the authors integrated T-REX/EUROPA into the existing LSTS control toolchain [6] which makes it compatible with both AUVs and UAVs from Porto.

III. Implementation

Two teams are involved in the experiment. A supervisor team stays on shore with fast internet access as well as some global situational awareness of the experiment: updated fish and asset positions, upcoming surveys, meteorological forecasts. The team at the ship is responsible for driving the assets (ship and unmanned vehicles) in a way that optimizes scientific relevance of the acquired data. For this, they must take into account all constraints coming from a real-world deployment: those expected like fuel, speed and communications range limitations as well as any other unpredicted problems. Moreover, only the team on the ship will have access to AUV survey data so they can make for informed decisions on what to do next.

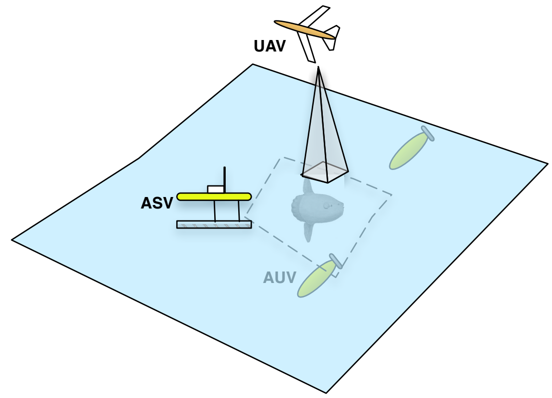

Fig. 1: Proposed concept of a Lagrangian experiment akin to [7], [4] using sunfish as targets and the use of a WaveGlider and aerial platforms.

Fig. 1 illustrates the concept of operations for the unmanned vehicles surveys. Within the survey,the AUV uses a saw-tooth (yoyo) vertical pattern to provide information on the variability in the water column within the bathymetric limitations of the area. The survey pattern itself, could potentially start with a large 1km $\times$ 1km pattern and could then be reduced successively after due observation of the fish's reaction to the propelled AUV.

The UAV is used for spotting the fish after receiving updates from satellite tag and to retrieve acquired data. The AUV data is relayed into the ASV (when surfacing periodically) and then forwarded to the UAV that functions as a data mule.

In the following subsections, we decompose this high-level description into its several subsystems, concluding with control and communications architecture.

A. Sunfish Tags

The fish tags (Fig. 2) have been developed in-house with reduced price, which allows simultaneous tagging of many fish. The tags are slightly buoyant devices (100 g of buoyancy) that are able to detect when they are submerged or at surface via a salt-water switch.

Whenever the tags are at the surface, a GPS sensor is turned on to acquire a position that gets updated and transferred periodically. Globalstar simplex (one-way) satellite communications are used for sending position

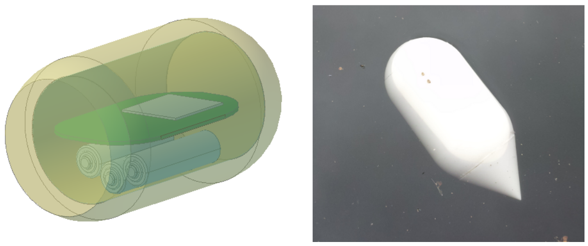

Fig. 2: Sunfish tags. 3D model (left) and first tested prototype (right).

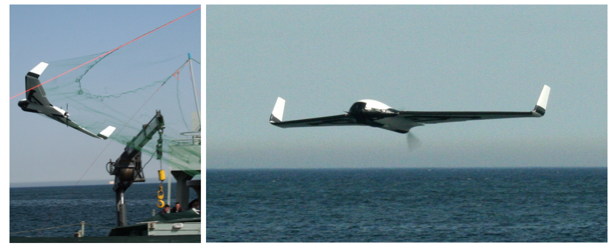

Fig. 3: X8 UAV used for the experiment. Landing (left) and fre-flying (right)

data to Globalstar. These positions can then be accessed through a web service.

The tags were required to withstand pressures in the order of 60 bar since sunfish are known to dive up to 600 meters of depth. This is the main reason for the round shape of the polyurethane encasing (more evenly distribute the pressure around the device). Several tests were done to these tags to verify that they can go as deep as sunfish and also that they transfer GPS positions as quick as possible (after surfacing).

The battery endurance for these tags is now estimated at 30 days (fish surfacing one hour per day and sending a position update every 5 minutes) but autonomy will vary according to programmed frequency of position updates and fish surfacing times.

B. Vehicles

In this experiment we use 3 types of vehicles: LAUV AUVs, X8 UAVs and the Wave Glider ASV. AUVs and UAVs share most of the control architecture (LSTS toolchain) while the ASV uses a proprietary control system from Liquid Robotics that can be commanded via a web interface.

1) X8 UAVs: The X8 UAV is based on a commercial RC-plane airframe and a COTS ArdupilotMega autopilot. Onboard the airframe there is an IGEPv2 ARM CPU which runs DUNE (LSTS onboard software) and also provides Wi-Fi communications with the base station.

For sensing, the X8 carries a fixed optical camera that supports both video streaming to the base station and still image capturing. Since communications with the base station are limited some frames may be dropped. However, all video is simultaneously recorded to disk onboard the plane for later retrieval after landing.

One of the requirements for this experiment is to be able to launch and recover the UAV from a ship out at sea. We have developed a new catapult launch mechanism based on elastic ribons and used a net for capturing the vehicle safely when landing.

These UAVs can fly up to 45 minutes with the necessary payloads which is enough for flying safely 8 Kms away and back to the ship. By using two UAVs and doing battery swapping, it is possible to fly continuously. Taking off requires a certified pilot that initially controls the UAV towards a safe altitude and only after this altitude is reached (100 meters) the autopilot becomes active.

Landing is done in a similar fashion. The UAV is commanded to go to a nearby location autonomously and then the control is overridden by the human pilot that controls it to fly against a net onboard the ship (Fig. 3 on the right) with low speed.

While operated autonomously, UAVs are typically commanded to go to a remote location and then do a (spiral) search pattern around a point of interest while recording video.

2) LAUV AUVs: For this experiment we use two LAUV-class vehicles, the LAUV-Xtreme-2 (XT2) and LAUV-Noptilus-1 (NP1). These LAUV vehicles are human-portable torpedo-shaped vehicles rated for 50 meters of depth and nominal speeds of 1.5 m/s. Battery endurance is up to 8 hours with CTD payload.

These 2 vehicles are equivalent with the exception of some sensor payloads. Both vehicles carry front-looking echo sounders, sidescan sonars and CTD. XT2 additionally carries an underwater optical camera and led lightning. NP1, instead of the camera payload, carries a multi-beam sonar sensor. Both multi-beam and camera sensors are turned off in the context of this experiment since this data is not of practical scientific relevance.

These vehicles can be tele-operated while at surface, pre-programmed to follow a scripted plan or additionally can carry a T-REX executive for onboard deliberative planning and execution. In the communications front, these vehicles are connected at surface via Wi-Fi, GSM/HDSPA and Iridium. While underwater they can use the acoustic modem for exchanging small data packets.

3) Wave Glider ASV: For this experiment a Liquid Robotics Wave Glider (WG) will also be used for sampling and as a communications relay between AUV

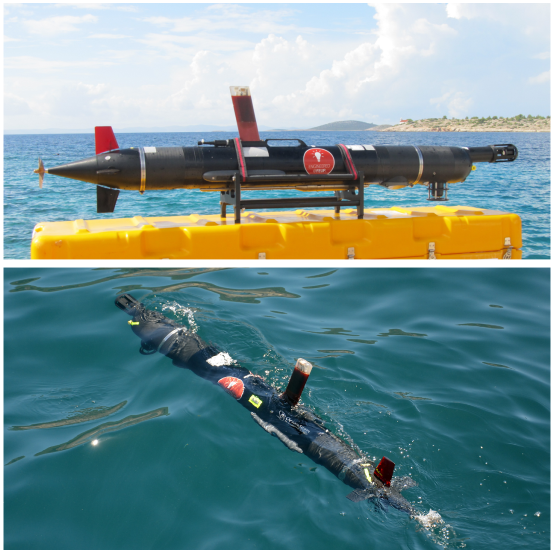

Fig. 4: LAUV-Xtreme-2 AUV

and other vehicles. For this, we developed a new communications device to be added to the WG. This communications device consists in two long range Wi-Fi antennas and an embedded computer that downloads/uploads data automatically from/to selected network peers.

Currently, the only way we are able to control the WG is through a web-based interface to which the team in the ship may not have access. For this reason a simple communication infrastructure was put in place that is able to send high-level commands through Iridium to the shore base station. On the shore, there will be a responsible for actually commanding the WG to the position desired by the other team. This is a simple addition to the situational awareness infrastructure described in the following section.

C. *Situational Awareness Infrastructure*

Since the operations take place mostly at open sea, internet access is expected to be very limited or inexistent. For this reason, a major requirement for the situational awareness infrastructure is to be capable of disseminating information without relying on Internet access.

The cornerstone of the communication infrastructure is a central web service (called *HUB*) that receives information from various sources (web, Iridium, GSM), stores this information, provides the information and optionally pushes information actively to subscribers (web, Iridium).

HUB provides a REST API that allows continuous access to updated asset position information. Examples of assets are sunfish tags, unmanned vehicles, ships and some virtual assets like target asset positions (current waypoint) and desired position (position where other team would drive the asset).

The AUVs use their Iridium communications module to send SBD messages with position and other state updates and receive messages with new objectives and commands.

On the ship, all asset updates are received through a Iridium-capable communications gateway (Manta). The Manta gateway onboard the ship is used to send commands to AUVs and to inform other team about target AUV survey destinations and desired WG position.

On the shore, the *HUB* REST API is polled to download all updates periodically and display them on a map (using Neptus CCU [6]).

D. *Control Architecture*

The control architecture for this experiment is based on 4 main components: DUNE onboard software, T-REX executive, EUROPA planner and Neptus CCU.

DUNE [6] is onboard software that allows abstracting of vehicle hardware through an execution environment composed by a configurable set of asynchronous tasks. Each task has a known message interface for communication with other tasks. These message interfaces are divided into different layers of control (from low-level drivers to high-level plan executives).

T-REX executive, currently developed at MBARI, is a framework that allows creating situated agents composed by different modules (reactors) that, despite executing synchronously with each other, are allowed to have different planning windows. Reactors expose observations and request goals that potentially become observations sometime inside the planning window of the reactor where the goal was requested.

EUROPA-PSO planner has been integrated into T-REX as a specialized reactor. The EUROPA reactor is configured with a domain model that specifies how actions lead into observations. When this reactor is requested a goal, it will calculate a set of actions that need to be requested to other reactors in order to achieve the desired goal. Using such type of planners allows users to specify multiple high-level objectives instead of individual sequences of actions. It is the duty of the planner to generate valid (according to the domain model) sequences of actions that have the desired outcome.

Neptus CCU [6] is what human operators use to interface the vehicles. From here they can monitor the state of the entire system (connected vehicles, iridium updates, weather forecasts, etc) and can also command new behaviors. Until recently, Neptus would only allow commanding vehicles through scripted plans but, with

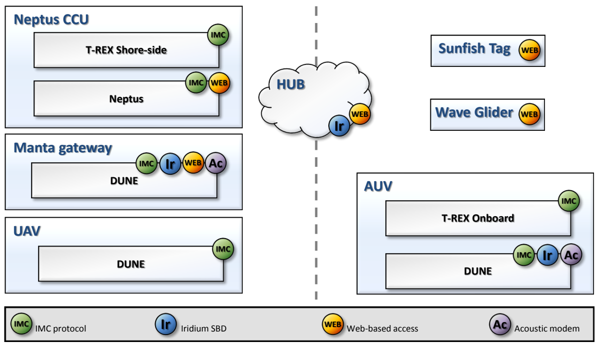

Fig. 5: Experiment components and their available communication means. Assets disconnected from ship are on the right.

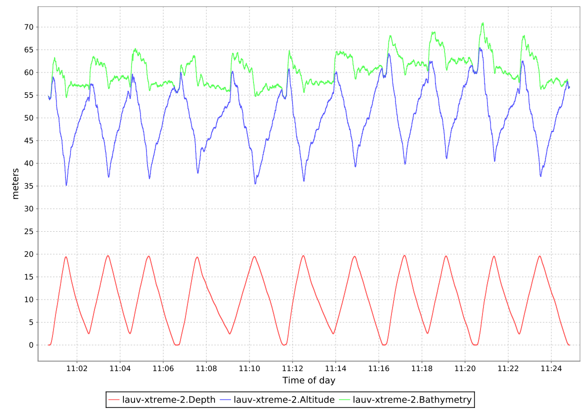

Fig. 6: Vertical profile of an AUV survey from 2 to 20 meters of depth and box side length of 400 meters.

the addition of T-REX to the architecture [5], it is now possible to request high-level objectives to T-REX instances that will result in plans generated at the base station (shore-side T-REX) or onboard the vehicles.

In the context of this experiment, human operators select a tag from the list of currently visile tags (at surface) and Neptus generates a high level objective that is sent to T-REX running onboard the AUV. As a result, T-REX will generate a survey pattern around the moving tag. After the survey is complete, T-REX sends an Iridium message with the result (success / failure) of the survey and waits for further objectives.

IV. Field Deployment Results

This experiment was planned to take place from 19th to 25th July 2013. Unfortunately, due to a heat wave that struck Portugal in mid-July, sunfish specimen were scarce and the few that were captured succumbed to high ammonia in the water due to the heat. The actual experiment thus had to be postponed to May 2014. However, the engineering aspects of the experiment were put to test at sea from 9th to 18th July, off the coast of Sesimbra, in Portugal.

The tests were made during the Rapid Environmental Picture (REP) event. REP is an annual event, organized conjointly by Porto University and Portuguese Navy for testing ocean observation technologies and operational concepts from all participating institutions.

The aim of this experiment was to provide a readiness report of the entire system and thus the different components were tested individually and together in a simulated experiment (tracking a drifting tag instead of a sunfish).

The sunfish tags were tested in two sunfish at the same time of the deployment (but not co-located). Both tags reported positions after one day but one of the fishes was captured (despite this being illegal to sell this fish). The reported tag positions were nonetheless accurate enough for Maritime Police to recover the tag and notice the fisherman.

The *HUB* was tested successfully in that all device updates were sent through Iridium to the web, allowing situational awareness from any Neptus CCU. The *HUB* was also used to track in real-time the positions of sunfish tags that were drifting.

The behavior of the AUVs was defined to be a Lagrangian box around a moving reference. The side length of the box is decided by an operator and the yo-yo pattern is generated onboard the AUV. In order to decrease navigation errors, the vehicle actively popped up at every corner of this box (see Fig. 6). This is because in the high sea no bottom lock is expected and thus the navigation is more prone to compass and current errors. We tested executing surveys both with and without DVL with results which are more than acceptable for this experiment at less than 5% of travelled distance (see Fig. 7 for an example). The CTD data (Fig. 8) is also promising in that it is possible to observe the thermoclime (water surface stratification).

The UAVs have been successfully controlled using a TREX instance running on the ship and video was transmitted in real time up to 7 Km from the ship (with dropped frames). The videoquality is good enough to spot fishing net marker buoys at water surface and potentially sunfish (see Fig. 9). Due to the flare from sun reflecting in the ocean, the areas of interest needed to be filmed from specific angles. In the experiment, the area of interest will in fact be pictured from all angles since the autonomous behavior corresponds to a series of circles around the point of interest.

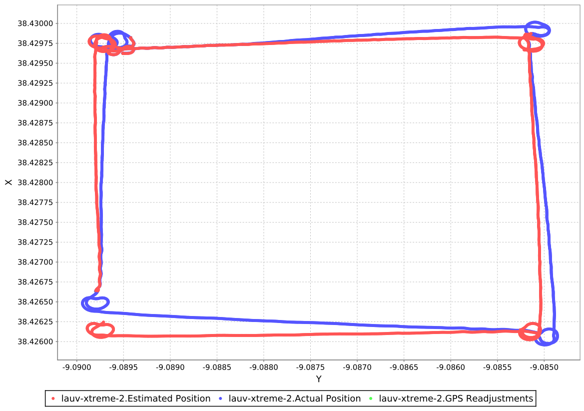

Fig. 7: Estimated position (red) and actual position (blue) for 400×400 m yo-yo survey

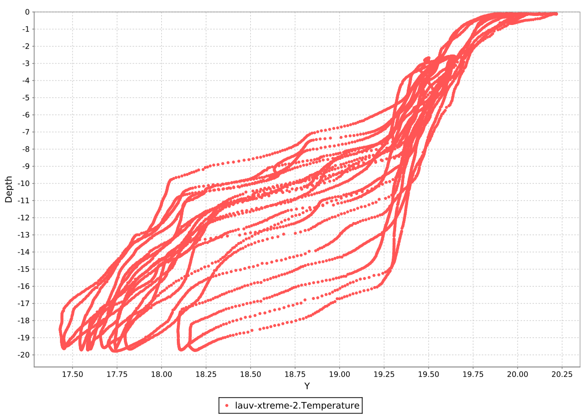

Fig. 8: CTD temperature data plotted against depth.

Fig. 9: Aerial imagery extracted from realtime video feed. Plume (on the left) and ship used for experiment (on the right)

V. Conclusions and Future Work

With the exception of the ASV, all remaining assets were tested successfully. The control and communications infrastrucutre was flexible in the sense that it allowed controlling AUVs using both wi-fi and Iridium communications and we were able to execute TREX onboard the AUVs and onboard the ship, controlling the UAVs. All deployments, operation and data analysis was done onboard the ship.

We still have to test the operational concepts for coordinating two teams at remote locations with very limited communication with each other and data muling using an ASV has not yet been tested in the ocean.

We have described and field-tested the technological aspects required for tracking sunfish in the ocean. Despite not being able of testing these technologies to track actual fish targets, we are confident based on the results that the system is ready for the next opportunity window on May 2014.

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