CONTINUOUS REAL-TIME ACOUSTIC SURVEILLANCE
OF FAST SURFACE VESSELS

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Abstract: Passive underwater acoustic sensing technologies applied to mobile autonomous maritime systems allow for minimum environmental impact, coveryness, long endurance, wide area coverage, near real-time, continuous (‘24/7’) monitoring, and the availability of several capabilities, ranging from detection to the classification of acoustic noise sources. Gliders – both as unmanned underwater and unmanned (sea) surface platforms – are particularly appropriate for this kind of application, as their features include persistence, discreteness, portability, scalability and remote control. NATO STO CMRE developed a new low-power passive acoustic system to be hosted on persistent platforms such as underwater gliders and wave gliders. The system is able to detect, track and classify surface vessels by using a compact volumetric array of hydrophones and processing acoustic data in real time, directly on board the gliders, through the application of advanced algorithms. The signal processing chain of the passive acoustic surveillance system has been recently extended to the capability of multitarget tracking by means of a Bayesian tracking algorithm. In this paper, we present post-analysis results, were two fast surface vessels are successfully tracked at the same time.

Keywords: Passive acoustic monitoring, source localization, multitarget tracking, belief propagation, long-endurance low-power platforms.

I. INTRODUCTION

The detection, tracking and classification of surface vessels is of major interest for many civilian and security applications, such as port protection, protection of marine parks, and monitoring of illegal traffic. The presence of large ships can typically be accurately monitored either by radar or via the Automatic Identification System (AIS). However, small vessels, with small radar cross-sections are often missed by these conventional monitoring systems. This motivates the use of passive underwater acoustic arrays for detection, classification, localization and tracking (DCLT) of small and fast surface vessels. Passive hydrophone arrays are particularly attractive as payload on silent low-power mobile autonomous maritime platforms such as gliders since this combination enables covert and persistent wide area

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coverage, and near real-time, continuous monitoring. In this paper, we address continuous acoustic signals, such as ship-radiated noise, as a means for detection. The nature of the noise of interest is broadband, and ranges from a few Hz to several tens of kHz. As small motor boats are targets of major interest, their emitted noise characteristics, mainly dominated by broadband cavitation effects from the propeller, are taken into. This results in a signal processing approach that does not consider any specific narrow-band harmonic component characterizing the signal of interest. In recent years, a variety of passive acoustic monitoring systems have been proposed for ship detection and localization. Most passive monitoring systems based on underwater acoustic measurements are static, either stand-alone [1] or cabled to shore [2]. They can form a network of distributed stations consisting of sensing systems and processing units able to analyse data and communicate results to a central node or to other nodes. In its simplest case, the sensor system may consist of a single hydrophone, see [1] and [3], whereas linear or volumetric arrays (using multiple hydrophones) may be employed in order to be able to estimate target direction of arrival (DOA), to distinguish multiple sources and to perform three-dimensional (3D) localisation [4]. DCLT solutions for maritime surveillance using hydrophone arrays where previously presented based on an underwater glider and a wave glider. Details on the hydrophone array used as an acoustic payload and a preliminary DCLT signal processing chain was previously presented in [5], [6]. In this paper, we introduce an extended DCLT signal processing chain for passive acoustic surveillance system based on a wave glider. The presented extension enables detection localisation and tracking (DLT) of multiple surface vessels simultaneously, by means of a Bayesian tracking algorithms. This new approach to passive acoustic surveillance is evaluated using measurements collected in the gulf of La Spezia, Italy.

II. PASSIVE ACOUSTIC MONITORING SYSTEM

Our passive acoustic surveillance system is based on a wave glider developed by Liquid Robotics Inc. that consists of a ‘float’ that stays on the surface and an underwater body (glider), connected via an umbilical cable. This configuration can use the energy of the waves to generate motion in horizontal direction. The float contains solar panels, antennas for radio frequency communication, and a main payload bay that stores processing units, batteries and electronics. A second payload bay, the ‘tow fish’ is towed underwater. The eight-hydrophone volumetric array introduced in [6] is hosted on the rear of the tow fish (rigidly connected), as shown in Fig. 1. The shape, aperture and number of hydrophones of the array are conceived in a way to better exploit the wide-band nature of boat-radiated noise and have high spatial resolution in distinguishing among closely spaced targets. Details on the acoustic measurement system were presented in [5]. An electro-mechanical cable of about 60 m connects the float to the tow fish.

The most important features of the wave glider featuring a acoustic array are

- detection, classification, 3D localization, and 3D tracking of target boats
- availability of results in real-time
- re-configurability of the array geometry
- adaptivity to different sound-velocity profile conditions
- low-power consumption resulting in ’24/7’ persistence.

The underwater payload in the tow fish consists of a single-board-computer (SBC) that hosts the data analysis process, devoted to target detection and feature extraction for classifi-
In particular, array processing algorithms provide time-difference-of-arrival (TDOA) measurements of potential target. Whenever a detection is made, it is communicated along with the orientation and depth of the tow fish to the processing unit in the main payload bay in the float of the wave glider (at 1Hz). When the signal excess is sufficiently high, also a set of numerical features needed for classification are computed and sent to the processing unit in the float (where the actual classification processing takes place). The surface payload consists of a GPS receiver, and a SBC. This SBC performs a further real-time data processing step for (i) geo-referencing the target trajectory through GPS, (ii) launching a classification process, and (iii) transferring output results to shore. Data communication between underwater payload and surface payloads is through Ethernet. The surface payload communicates the DCLT output either via a radio link or via a satellite communication to shore lab. Each message contains a time stamp, the target position, and possibly – depending on the target signal-to-noise ratio (SNR) – the vessel class and the level of confidence for the classification result. The output rate depends on the communication bandwidth. A dedicated software tool handles the arrival of email messages, parses the message content and makes the output results available to a graphical interface in a standard format, so that target trajectories can be displayed on a cartographic map, together with wave glider position.

### III. The DCLT Signal Processing Chain

In order to obtain location information of non-cooperative targets with unknown waveforms, signals at the hydrophones of the array are compared pairwise. More specifically, for each hydrophone pair \((k, l)\) the signal of hydrophone \(k\) and the signal of hydrophone \(l\) are correlated and time delays related to peaks in the resulting cross-correlation function are extracted (see a general block diagram in Fig. 2).

These time delays \(r_{kl}^{(m)}, m = 1, \ldots, n_{kl}\) are referred to as a TDOA measurements [7]. We used \(n_S = 6\) hydrophone pairs of the passive acoustic sensor to obtained TDOA measurements. For each of these hydrophone pairs, signals with a duration of one second were used to calculate the generalised cross-correlation function following the so-called smoothed
coherent transform (SCOT) approach [8]. Then, a simple energy detector [9] is applied to
the generalised cross-correlation function in order to extract TDOA measurements using
a threshold that is adaptive to the background noise level. These TDOA measurements
are used as input for the Bayesian multitarget tracking algorithm discussed in what follows.
Depending on the in-situ environmental conditions a machine learning algorithm based
on feature extraction and a relevance vector machine (RVM) can provide vessel class and
course information (see [10] for details)

Each TDOA measurement is related to a possible target location along a hyperboloid. For
hydrophone pair \((k, l)\), at time \(t\) the random TDOA \(r_{t,kl}^{(m)}\) that was originated by target \(j\) is
modelled as

\[
    r_{t,kl}^{(m)} = \frac{1}{\nu} \left( \| p_t^{(j)} - q_t^{(k)} \| - \| p_t^{(j)} - q_t^{(l)} \| \right) + z_{t,kl}^{(m)},
\]

where \(p_t^{(j)}\) is the position of target \(j\), \(q_t^{(l)}\), is the position of hydrophone \(l\), \(\nu\) is the speed of
sound and \(z_{t,kl}^{(m)}\) is the measurement noise which is zero-mean Gaussian with variance \(\sigma_z^2\) and
statistically independent across \(m\) and \((k, l)\) pairs. The dependence of a measured TDOA
\(r_{t,kl}^{(m)}\) on the location \(p_t^{(j)}\) of the generating target \(j\) is described by the likelihood function
\(f(r_{t,kl}^{(m)} | p_t^{(j)})\) that can be directly obtained from the Equation (1). With \(r_{kl}^{(m)}\) observed and
thus fixed, this likelihood function describes target position information on the surface of a
hyperboloid. TDOA position information related to different hydrophone pairs is expected to
intersect in the vicinity of true target positions.

The algorithm used for multitarget was developed in a Bayesian random finite set (RFS)
setting. A random quantity \(X\) whose realizations \(X = \{x^{(1)}, \ldots, x^{(n)}\}\) are finite sets of \(n_x\)-
dimensional vectors \(x^{(1)}, \ldots, x^{(n)} \in \mathbb{R}^{n_x}\) is referred to as a RFS. Both the number \(n = |X|\),
\(n \in \mathbb{N}_0\) of vectors in the set (the cardinality of \(X\)) and the vectors \(x^{(i)}\) are chosen randomly.
Thus, \(X\) consists of a random number \(n = |X|\) of random vectors \(x^{(1)}, \ldots, x^{(n)}\). In a Bayesian
RFS setting, multi-object estimation of the RFS state \(P_t\) relies on the marginal posterior
PDF \(f(P_t | R_{1:t,n_x})\) which involves RFS measurements \(R_{1:t,n_x}, R_{1,1:n_x}, \ldots, R_{t-1,n_x}\). For every
time step \(t\), \(f(P_t | R_{1:t,n_x})\) can be calculated from \(f(P_{t-1} | R_{1:t-1,n_x})\) by means of a prediction
and an update step. The update step is employees the non-linear single-target, single sensor
likelihood functions \(f(r_{t,kl}^{(m)} | p_t^{(j)})\) (see [7] for details).

In the presented post-analysis, we use a variant of the RFS based localization algorithm
previously presented in [7] with the following extensions: (i) We employ a state-transition
model to allow targets to be mobile. (ii) We consider a pseudo-3D scenario, where hydrophones are not on the same plane as the target. (The state of the target however consists of the 2D position and the 2D velocity since only surface vessels are considered.)

IV. POST-ANALYSIS OF EXPERIMENTAL RESULTS

In the conducted experiment, a small fast motorboat crossing orbiting the wave glider served as the main target. The target was equipped with a GPS receiver in order to record its trajectory as a ground truth. In the selected data set, a second motorboat—the support boat used for the experiment—that was drifting roughly 700 meters south-east of the wave glider was also measured by the hydrophone array. Unfortunately, for this second target, accurate ground truth information is not available.

For the presented results, we processed 100 seconds of data resulting in 100 time steps. Fig. 3 shows the resulting cross-correlogram and the extracted TDOA measurements $r_{t,kl}^{(m)}$. Here, for each time step the cross-correlation function was normalized to the maximum absolute value. In our tracking algorithm, we used a measurement noise standard deviation of $\sigma_z^2 = 10^{-5}$. Note that the measurement noise depends on the power and the bandwidth of the received signal. Furthermore, we set the expected number of clutter measurements to 1 and the probability of detection to 0.8. The clutter pdf at hydrophone pair is uniform on $[-\frac{1}{\nu}\|q_{t}^{(k)} - q_{t}^{(l)}\|, \frac{1}{\nu}\|q_{t}^{(k)} - q_{t}^{(l)}\|]$. The speed of sound is set to $\nu = 1508$. We used $L = 10^4$ particles for each potential target (see [7] for details). Furthermore, we used a constant velocity motion model that allows for target birth and dead [11], where we set the variance of the driving noise to $4^2$, the birth probability to $p_b = 0.01$, and the survival probability to $p_{su} = 1 - 10^{-7}$. Note that this high survival probability is necessary to compensate for the bursts of missed detections in the measurement data (see Fig. 3). The reference frame for this processing of measurement data is chosen to be the initial position of the wave glider at time $t = 1$ and $p_{t,z} = 0$ corresponds to the water surface, i.e., zero depth. The depth of the hydrophone array is approximately 5 meters.

Fig. 4 shows the output tracks estimated by the Bayesian tracking algorithm and RMSE related to the track of the main target. The main target is close to the hydrophone array and can thus be reliably tracked. The second target can only be approximately localized, since due to its distance from the array, its uncertainty in range is very large.
Fig. 4. Tracking output and ground truth for the main target (left), for the whole scene (middle), and RMSE localization error vs. time $t$ (right) for a data set acquired in La Spezia area, 3-9 April 2015. The tracker output is indicated by a red line, ground truth information by dashed lines, respectively.

V. CONCLUSIONS AND FUTURE ACTIVITIES

Maritime surveillance is performed using a wave glider equipped with a passive underwater payload able to provide results for detection, localization and tracking of multiple surface vessels at the same time. Preliminary tests at sea showed very promising results in which accurate vessel tracks are estimated. Future activities include the real-time implementation of the Bayesian multitarget tracking algorithm on the processing unit of the wave glider.

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