MULTISTATIC PROCESSING AND TRACKING OF UNDERWATER TARGET USING AUTONOMOUS UNDERWATER VEHICLES

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Abstract: This paper discusses the use of distributed autonomous underwater vehicles (AUVs) for multistatic processing and tracking of underwater target. A localized processing chain is implemented on each AUV to generate the contact report of an underwater target that is transmitted to a command center via underwater acoustic communications (UWA). The contact reports from several AUVs are combined together using data fusion to create the fused report for formulating the target track solution. The experimental results obtained from the recent Generic Littoral Interoperable Network Technology (GLINT) 2008 experiment illustrates this concept and provides the discussion for further experimentation.

Keywords: Multistatic processing, multistatic tracking, autonomous underwater vehicle (AUV), data fusion
1. INTRODUCTION

The detection and localization of underwater target using active monostatic system can be difficult in situations where you have very low acoustical backscattering. To mitigate this problem, the active multistatic system is commonly employed as it offers multiple angle observations that enhance the performance. However, operating the multistatic platforms on conventional ships can be costly. More importantly, the exposure of these platforms to possible threats should always be minimized. For these reasons, there is a need to explore unmanned platforms for multistatics, particularly those capable of a certain level of autonomous maneuverability, provide ease of rapid insertion and offer effective sensing. The use of distributed autonomous underwater vehicles (AUVs) for active multistatic system is particularly attractive. However, with a much smaller payload, there is a general restriction on the processing power in each platform. There is also a need to link up these distributed AUVs together with a command centre via underwater acoustic communications (UWA) to provide a multistatic solution. In this paper, we will first start by exploring the feasibility of processing the multistatic data off-line and determine the information exchange between the AUV and the command center. In future work, we will explore the possibility of real-time processing onboard each platform and the usage of UWA to exchange information between the platforms.

2. PROBLEM FORMULATION

We consider the case where there are two underwater sensors, active sonar denoted by \( S_1 \) and passive receiver denoted by \( S_2 \), and one underwater target denoted by \( T_1 \). The objective here is to estimate the target state of \( T_1 \) at any time measurement number \( k \) given the acoustic measurements obtained by \( S_1 \) and \( S_2 \),

\[
X_{\text{ti}}[k] = \begin{bmatrix} x_{\text{ti}}[k] & y_{\text{ti}}[k] & v_{x_{\text{ti}}}[k] & v_{y_{\text{ti}}}[k] \end{bmatrix}^T.
\]

(1)

Here, \( x_{\text{ti}}[k] \) and \( y_{\text{ti}}[k] \) are the x and y positions of \( T_1 \), and \( v_{x_{\text{ti}}}[k] \) and \( v_{y_{\text{ti}}}[k] \) are the corresponding speeds.

The target state of \( T_1 \) can be inferred from the monostatic ranging carried by the active sonar \( S_1 \) as shown in Fig. 1. Here, the active acoustic source is co-located with the sensor array, which listens to the target echo. The monostatic range \( r_{s1,t1}[k] \) measured will determine a circular locus of probable \( T_1 \) positions, called the ambiguity circle. The direction-of-arrival (DOA) \( \theta_{s1,t1}[k] \) measured will then specify two probable \( T_1 \) positions on the circle. The velocity of \( T_1 \) can be deduced from the target Doppler, which is readily available by measuring the target echo frequency \( F_{s1,t1}[k] \). The details of how these measurements are obtained are provided in [1]. These measurements can be readily compared with the true values computed from the expressions in [2].

The target state of \( T_1 \) can also be inferred from the bistatic ranging of passive receiver \( S_2 \) as illustrated in Fig. 1. Here, the sensor array is passively listening to the active acoustic source transmissions either directly from \( S_1 \), or indirectly reflected from \( T_1 \). The bistatic range \( r_{s2,t1}[k] \) measured will determine an elliptical locus of probable \( T_1 \) positions, called the ambiguity ellipse. The DOA \( \theta_{s2,t1}[k] \) will then specify two probable \( T_1 \) positions on the
ellipse. Similarly, the velocity of $T_1$ can be deduced from the target Doppler, which is readily available by measuring the frequency of the indirect active acoustic source transmission $F_{s1t1s2}[k]$. Both [1] and [2] also provide detailed information on the measurements and their true values.

From Fig. 1, each of the sensors is able to estimate the target state of $T_1$, but with an undesirable ghost. The estimated state will form the contact report transmitted to a command centre. The combined reports can be used to remove the ghosts by simple cross-fixing [2]. More importantly, the likelihood of the estimated target state can be ascertained taking into account the detection statistics of both sensors [2][3]. This will help in creating the fused report that will be subsequently used to formulate the target track solution.

The definition of multistatics simply extends the above problem to more complex cases. Examples include cases with (i) one active acoustic source and several passive receivers, (ii) few active acoustic sources with several passive receivers, and (iii) many other variants. In this paper, we are particularly interested in multistatics using distributed AUVs with passive receivers that are linked together via UWA.

\[
\begin{align*}
    r_{s1t1}[k] & : \text{monostatic range, } S_1 \text{ to } T_1 \\
    r_{t1s2}[k] & : \text{range, } T_1 \text{ to } S_2 \\
    r_{s1s2}[k] & : \text{range, } S_1 \text{ to } S_2 \\
    r_{s1t1s2}[k] & : \text{bistatic range, } r_{s1t1}[k] + r_{t1s2}[k] \\
    \theta_{s1t1}[k] & : \text{DOA of } T_1 \text{ at } S_1 \\
    \theta_{t1s2}[k] & : \text{DOA of } T_1 \text{ at } S_2 \\
    \theta_{s2s1}[k] & : \text{DOA of } S_1 \text{ at } S_2 \\
    \gamma[k] & : \text{separation angle, } \angle S_1S_2T_1 \\
    F_{s1t1s1}[k] & : \text{echo frequency over path } S_1T_1S_1 \\
    F_{s1t1s2}[k] & : \text{echo frequency over path } S_1T_1S_2
\end{align*}
\]

*Fig. 1: Illustration of monostatic and bistatic ranging by $S_1$ and $S_2$ respectively*

### 3. EXPERIMENTAL SETUP

To evaluate the feasibility of multistatic processing and tracking using distributed AUVs, the Generic Littoral Interoperable Network Technology (GLINT) 2008 experiment was conducted at Pianosa, Italy from Jul to Aug 2008. The experimental assets involved the (i) NRV Alliance that functioned as a command centre and deployed with an active acoustic source (active source ($S_1$)), (ii) Unicorn AUV that towed the DURIP sensor array (passive receiver 1 ($S_2$)), (iii) OEX AUV that towed the SLITA sensor array (passive receiver 2 ($S_3$)), and (iv) CRV Leonardo that deployed an echo-repeater to simulate active insonification of a target (target ($T_1$)). Data acquisitions were carried out on the AUVs, but the processing was done off-line.

Hyperbolic frequency modulated (HFM) pulse and continuous wave (CW) active sonar pulse signals were transmitted from $S_1$. The HFM pulse signal was selected because of the pulse compression property that provides good range resolution, and the lower coupling effect of the errors in the range and Doppler estimations compared with the standard linear frequency modulated (LFM) pulse signal [4]. Although the CW pulse signal offers poor range resolution, the absence of the abovementioned coupling effect makes it preferable for Doppler estimation [4].
4. PROCESSING CHAINS

Two processing chains, namely the localized chain at each AUV (S₂ and S₃) and the centralized chain at command center (S₁), were set up off-line. The beamformers and the matched filters in the localized chain, as shown in Fig. 2, were implemented as described in [5] and [4] respectively.

The contact reports from both sensors (S₂ and S₃) were generated in a format suitable for UWA. These reports were combined at the centralized chain and assigned on a discretized four-dimensional contact grid of x and y cells, and vx and vy cells [2]. Cells with contacts from both sensors were flagged out, while those with contact from one sensor were assumed ghosts [2]. Thereafter, the fusion grid was created in the process of spatial fusion where cells with two contacts were assigned with higher likelihood, taking into account the detection statistics of both sensors [2][3]. The fusion grid assumed the same dimensional structure as the contact grid but with calculated likelihood values [2]. Target track solution can then be formulated using the fusion grid. However, the target tracking algorithm is still undergoing development at the time of submitting this paper and the corresponding results will not be discussed here. The reference in [3] provides an extensive selection of possible tracking algorithms.

Fig. 2: Localized processing chain at each AUV [processing chain at S₂ illustrated here]

5. DATA ANALYSIS

For purpose of illustration, a particular experimental run on 07 Aug 2008 is used. The ground truth for this run is given in Fig. 3. Using the localized processing chain in Fig. 2, the contact reports from the DURIP (S₂) and SLITA (S₃) sensor arrays were obtained. The results for the DURIP array are depicted in Fig. 4 where the measurements and calculated values are plotted. The calculated values are computed using the ground truth in Fig. 3.
Clearly, we see close matches between the measurements and calculated values for the bistatic ranges, DOAs and echo frequencies. The only exception is the bistatic range for time before 1300 seconds. This actually corresponds to the case when Leonardo ($T_i$) was stationary, where the GPS log was unfortunately corrupted.

The contact grid generated by the centralized processing chain is shown in Fig. 5 for a selected time measurement number $k$. Here, $k$ increments in a time block of pulse repetition interval (PRI). Cells with contacts from both DURIP and SLITA arrays are flagged out as “o” on the contact grid of $x$ and $y$ cells, and $vx$ and $vy$ cells. These cells are then assigned with higher likelihood values shown in the corresponding fusion grid in Fig. 6. From the fusion grid, we also see that the ghost contacts are assigned with much lower likelihood values. The ground truth of Leonardo ($T_i$) is plotted blue in both Fig. 5 and Fig. 6. Clearly, we see that the $x$ and $y$ positions and the $vx$ and $vy$ velocities of $T_i$ are rather accurately estimated. Ghost and/or false contacts in both the $x$ and $y$ positions and the $vx$ and $vy$ velocities can be easily removed using target tracking algorithm that associates the fusion grids across time measurement number $k$ [3]. By combining the estimated $x$ and $y$ positions and $vx$ and $vy$ velocities of $T_i$, the target state of $T_i$ in (1) is approximated.

6. RECOMMENDATIONS

Following the successful implementation and experimental testing of the off-line processing chains, the next task is to develop the localized processing chain in Fig. 2 to real-time. Work has already embarked to develop each AUV for the GLINT 2009 experiment, planned at Pianosa, Italy from Jun to Jul 2009. More multistatic runs, particularly those with moving target, will be planned to ascertain the Doppler performance and establish better detection statistics for each sensor array. We also hope to demonstrate the generation of bistatic contact reports to activate simple AUV maneuvering behaviours that adaptively optimize the multistatic performance, including synchronized swimming of two or more AUVs. The communication requirements for the contact reports between the AUVs and the command center will be examined as well.

At the same time, the target tracking algorithm of the fusion grids across time measurement number $k$ will be studied and implemented. With more data, rigorous experimental testing will be carried out to evaluate the multistatic processing and tracking performance quantitatively.

7. CONCLUSION

In this paper, we have explored the feasibility of distributed AUVs for multistatic processing and tracking of underwater target. Specifically, the GLINT 2008 experimental setup was used for illustration. Both the off-line localized and centralized processing chains on each AUV and command centre, respectively, were presented. A particular experimental run here clearly illustrated close matches between the measurements and calculated values for the contact reports in terms of bistatic ranges, DOAs and echo frequencies. By combining these reports from both AUVs, the ghost contacts were removed and the target state was estimated. Following this paper, the GLINT 2009 experiment has been planned to explore real-time localized processing chain and to provide an opportunity to collect more data, particularly those with moving target, to ascertain the Doppler performance and establish better detection statistics for each sensor array.
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Fig. 3: Ground truth (x and y grid) of assets for experimental run on 07 Aug 2008
Fig. 4: Measurements (plotted in magenta markers) from DURIP sensor array (S₂) compared with calculated values (plotted in orange lines)

Fig. 5: Contact grid obtained at k = 78 by combining contact reports from S₂ and S₃

Fig. 6: Fusion grid obtained at k = 78 by fusing contact grid