A Multi-agent Concept for Multistatic Sonar

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Abstract. In this paper we present a novel and relevant application for multi-agent systems which is to implement autonomy for Multistatic Sonar. Multistatic Sonar is used in Antisubmarine Warfare and exploits multiple aspects on the target generated by multiple acoustic sources and receivers. We propose to use a team of unmanned underwater vehicles starting with search operations as covert receivers and then switching to pursuit operations as actively communicating multistatic receivers. This results in a safe, persistent and efficient surveillance system. With the help of a simulation setup, we explain what are the specific challenges related to the Multistatic Sonar setup. These challenges are mainly related to the highly nonlinear measurement model and to communication constraints. We then briefly outline a potential "baseline" solution for the overall system architecture capable to face these challenges.

Keywords: data fusion, multistatic sonar, multi-agent control

1 Introduction

As an example for a multi-agent surveillance application, the problem tackled in this paper is that of decentralized sonar detection and tracking with a team of autonomous agents (typically AUVs, Autonomous Underwater Vehicles) [1]. The problem is further made more complex by communication constraints: Underwater acoustic communication is notoriously affected by bandwidth and range limitations; in addition, the tracking team members wish to remain covert, and hence they do not want to communicate to each other, unless to hand over to the other team members not only the information but also the tracking task. They have to do so for two reasons: (i) because only the diversity generated by multiple aspects on the target allows a sufficiently high probability of detection [2] and (ii) because the target can be much faster than a single AUV.

However, adding 'autonomy' to multistatic sonar has to face especially the challenge that 'teamwork' is required between team members including the coordination of work schedules on potential targets (including a lot of clutter targets) while communication between team members can only happen on a very limited basis. In other words, the autonomous multistatic sonar will fail if the AUVs show pathological behavior, e.g. they all stick to the same target (which might not even be the real

target, but a false alarm) and it will fail if they all communicate (indicating where they are and allowing the target to make a plan to evade).
The contribution of this paper is a complete concept for the implementation of autonomy in multistatic sensor networks. Although the specific algorithms for this implementation are not given in detail, the high-level description of the concept is useful to explain special demands on sensor data fusion algorithms for autonomous applications.

2 Description of a Multistatic Sonar System

In this section, we introduce the multistatic measurement system. The description summarizes state-of-the-art technology for manned systems. Furthermore, it serves as the basis for the plans (which are then further outlined in section 3) on how to add autonomy to this surveillance system.

2.1 Teamwork in Multistatic Sonar

Multistatic sonar is by default a coordinated effort aimed at gaining a more accurate view of the target and discriminating it from the background. This is true already for manned systems. The plan for the autonomous system is to use the degrees of freedom added by the autonomy of its assets in order to improve the quality of the measurement. Autonomy provides additional degrees of freedom because the assets are designed for the specific surveillance task only and do not have to be as much under constraints as manned platforms are which have normally multiple objectives and parallel missions.

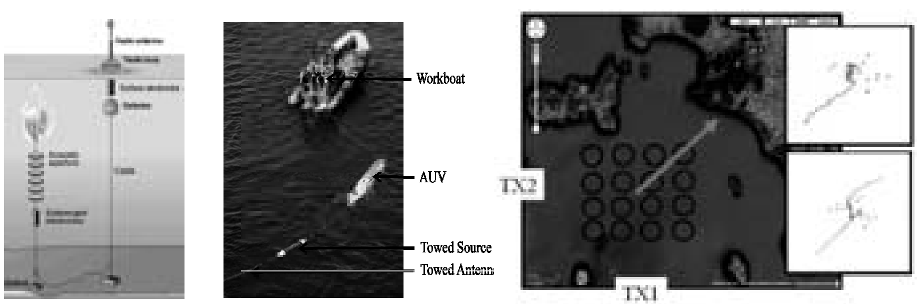

Fig. 1. (Left) Stationary acoustic source, (Middle) Deployment of the OEX Explorer AUV and its towed source, together with a slim towed array. (The workboat is only necessary for deployment and recovery. During the operation the AUV is operating at about 80m depth.) (Right) Test bed: Geometry in an example environment (right/main picture). Simulation results of teamed AUVs trapping a target: For a slow target (right/top right) and a faster target (right/bottom right).

2.2 Advantages of Multistatic Sonar

Multistatic active sonar has the obvious benefit of combining data from multiple pairs of sonar transmitters and receivers. When using multiple sources, a single receiver can already exploit these "data fusion benefits" of different bistatic aspects, without communicating, i.e. it can operate completely covert. This covertness does not allow the target acting cleverly, thus its stealth capability diminishes. The cost of losing covertness can be quantified by comparing the detection performance for two different Target Strength values: assigning to the clever target the lowest value and for the innocent target a substantially higher value.

However, to finally discriminate the target from background noise or clutter targets, the cross-fixing of tracks from multiple receivers is necessary. This has been demonstrated by several sea trials. I.e. in the final stage of target tracking (or target classification) the receivers have to give up their covertness for the benefit of a low false track rate (or 'low false alarm rate' when speaking about the entire autonomous surveillance system).

2.3 Physical agents carrying sonar receivers

Fixed and moving assets can be mixed. At NURC, a transmitter buoy is available and as receivers AUVs (Fig. 1) are used towing a receiving array and a quite powerful transmitter (given limited battery capacity) that is proposed in our context to be used for reliable long-range communication purposes. The source buoys can also be used for underwater communication (given an adequate receiving unit), and they can receive/exchange commands & data via radio (allowing the utilization of communication gateway buoys). The AUVs have low speed compared to the speed of the target.

2.4 Multistatic data fusion architecture

Data fusion merges the data taken from the different receivers in the multistatic system into a coherent picture. This picture reveals a series of contact points, which create a track showing the target's progress through the water [4].

2.5 Example Concept of Use

As an example, the idea is to implement the scenario of a multistatic survey and pursuit in clutter as a test bed (or simulation/experimentation environment). The geometry of the test bed is depicted in Fig. 1 (right). (Note: The region depicted has just been chosen as an example.) Two stand-off sources ensonify ("illuminate") a shallow water area. Since sound is reflected from a complex sea bottom structure, false alarms are generated by these clutter returns. The best way to overcome this is to send AUVs, equipped with towed arrays into the area, using their good angular resolution and, hence, their ability to discriminate target echoes from background echoes when they are close enough. As a target, a submarine is hiding in this area. Its evasive action is to move to North East. The task of N (in Fig. 1 (right): N=16) AUVs is to organize themselves in a way that they keep the most accurate track of the target under the constraints of both: a minimal usage of communication and a minimal number of AUVs involved in the tracking task. Minimal communication is important, because covertness is a big advantage. Involving a minimal number of AUVs is important to prevent being exhausted by false alarms/false tracks (which cannot be avoided in difficult measurement environments).

3 System concept

In this section we describe the system concept for the autonomous multistatic surveillance system. We divide the entire problem into subtopics by making appropriate approximations and simplifications. This leads to a chain (or sequence) of tasks for which a solution is much easier to find than for the original entire problem.

3.1 Decision making necessary for a computationally feasible solution

For the heterogeneous multi-agent concept described in section 2, we can formally write the solution of the corresponding control problem for the system following the description as a stochastic nonlinear minimax dynamic game with noisy measurements [6]. However, we will not be able to solve it with standard methods (even numerically) because of its complexity. Thinking about a particle stream like simulation, it is shown in [7] that taking out particles associated with low probability greatly minimizes the demand on processing power in the numerical simulation. We interpret "taking out particles" in our context as "making decisions", and by introducing a reasonable structure for the decision making process, we generate a computationally feasible solution of the formally written control problem.

3.2 Evasive target behavior

As far as target behavior is concerned, the general formulation in 3.1 covers the observer design for a maximally 'clever' target. However, while implementing the concept 3.1, simplifications are made and this optimal behavior of the surveillance team is not guaranteed anymore. Therefore, we put the developments described next under an 'outer training loop', meaning that once these developments are implemented, a simulation based learning phase starts where iteratively clever target behaviors and adaptive surveillance team parameters are found. This iteration should converge to a stable surveillance system because of its in general 'worst case design' implemented by the minimax formulation in subsection 3.1.

3.3 Multi-agent decision making

The decision making process envisioned for the multistatic surveillance task should be data driven, because we know from previous experiments (as described in section 2), that the quality of the achievable data fusion depends on the quality of the contributing sensors which then depend on the hypothetical target track itself. In order to keep the overall complexity of the decision making process low, we separate the individual planning (data driven because it depends on the specific target track) from the team behavior. This separation idea is further explained in subsection 3.5. Before that, we have to introduce a grid-based processing and control scheme in subsection 3.4.

3.4 Grid-based processing and control scheme

In this subsection we introduce the term ‘virtual Sonobuoy’ (virtSB). A virtSB is meant to be a sensor located in a grid cell, whereby a grid is covering the complete surveillance area. Each grid cell contains several virtSBs, belonging to each multi-bistatic receiving unit and to each multistatic combination of receiving units. Each virtSB is used to describe a partially observable Markov decision process (POMDP).
We assume that the virtSB has (virtually) the capability to (i) pursue a target occupying the same (or neighboring cells), (ii) ignore the contact data from this cell (or neighboring cells), or (iii) wait for more data before making a decision between (i) and (ii). How the virtSBs will be used to lead to AUV actions will be shown in subsections 3.7 and 3.8. Before that, we especially deal with the multistatic virtSBs in subsections 3.5 and 3.6.

3.5 Multistatic virtSBs

The virtSBs for multistatic actions would require communication between their mother-AUVs (from which they are stemming) to perform the joint pursuit action. But this communication should occur as rarely as possible. Furthermore, the overall concept has to prevent also a pathological behavior where all AUVs pursue the same target track.
We propose to overcome this challenge by introducing a learning phase especially for teamwork. In team sports, team members are exploring the value of collaboration during training sessions. For example in basketball, they exercise on the so-called ‘no-look pass’ between them. We make the analogy between ‘no-look’ and no-communication and propose a training (or learning) phase for the specific autonomous teamwork features. We explain in the next subsection how this analogy influences the overall design architecture of the multistatic surveillance team.

3.6 Efficient team behavior

We assume that a sufficient number of receivers for tracking a target is only the minority of all available receivers. A solution of this (now simplified) problem can be found if we recall the ‘minority problem’, well studied in game theory [5]. The ‘minority problem’ can be solved by learning. There exists also an analogy between the proposed learning scheme and the Potts model known in statistical physics.

3.7 virtSBs with weights

The virtSBs stemming from different mother-AUVs have different sensor quality, as bistatic (or multi-bistatic) sonar geometries are range and aspect dependent. The multistatic virtSBs found in the multistatic activation map have a potentially better quality than the single receiver virtSBs. The quality of each virtSB can be calculated in the same manner as for the sensor model in a multistatic tracker [4]. In [4], measurement uncertainties and the detection performance are appropriately modeled.

3.8 virtSBs generate plans

The virtSBs inherit from their mother-AUVs or mother-‘team of AUVs’ constraints on their motion. Whereas previously we were assuming a virtSB could pursue a target with no constraints on its own motion, we now have to introduce that own motions in-line with the motion of the mother-AUV/team are more likely.
Given a sensor model in subsection 3.7 and a motion model here, the virtSBs are now able to perform path planning with the goal to follow their targets.

3.9 Movement equations AUVs

Onboard each AUV, it is then possible to collect all plans generated from the virtSBs so far. Each plan comes with a length in time and a quality. Clustering algorithms are able to shrink the collection of plans to a few options. The AUV is then choosing the option that helps most to reach the operation goal defined by the system’s operator.

3.10 Waypoint for AUVs and Decisions on Communication

Given a decision on a plan inside the AUV in subsection 3.9, this plan also includes waypoints that the physical AUV has to reach next and in the near future. Also, in the case that the plan includes active communication to exchange target track information, this communication has to be executed. Speaking in terms of a behavioral design of the AUV control, this simply means that input to waypoint and communication behaviors has to be provided.

3.11 Real-time measurement/simulation

Simulations play a crucial role in the concept. They are used in subsection 3.6 and 3.2 in order to learn the multistatic behavior (or activation map) and to learn adaptability to clever target behavior. The usage of simulations, like here in the sense of a reinforcement learning structure, is a common procedure and part of a numerical solution of the problem described in 3.1. The demonstration of the concept at sea needs real physical assets and real-time measurement facilities, which are developed and tested now in the framework of NURC's collaborative ASW project [3].

4 Summary

Multistatic operations with autonomous underwater vehicles enable new anti-submarine warfare missions. Under the umbrella of game and control theory with a probabilistic multi-sensor setup for data fusion and tracking, a complete concept for the implementation of autonomy in multistatic sensor networks has been developed. The concept identifies special demands for sensor data fusion algorithms and the interfaces to the overarching control, decision and communication processes. A realization of this concept is aiming to produce teamed (or swarming) multiple AUVs which autonomously perform data based (and target adaptive) multistatic surveillance.

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