Coordinated Distributed Mobile Sensors and How to Measure Their Performance

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Abstract: At present dramatic advances are seen in sensor and multi-sensor fusion techniques, in networking and multi-agent system design, and in capabilities of robotic platforms in terms of robustness and endurance. Applications for autonomous surveillance appear on the horizon, especially wanted for hazardous or dangerous environments. However, whilst for each subsystem measurements of performance exist (e.g. Receiver Operating Characteristics for sensors, data rate for networks, energy efficiency for a robotic platform), we have to find also a systematic approach on how to construct measures of performance for an entire system of distributed sensing robots. Having such a methodology available would allow the comparison of complete systems which are designed with different emphasis on sensor quality, collaboration tactics and platform capabilities, finally resulting in profound investment decisions. In this paper, we discuss two example applications, in underwater surveillance and in logistics, respectively. Furthermore, we describe the recent effort of the “Distributed Mobile Sensors Interest Group” (DMSIG) for which a roadmap towards collaborative work has been proposed. A first aim of this collaboration is to comprehensively understand how better coordination between platforms can compensate lower sensor quality.

1 Introduction

The output of Sensor Data Fusion algorithms depends on how well the redundant and complementary information from multiple sensors can be exploited. When the algorithms reach their performance limit given by the quality of the input data, the output of the entire system of multiple sensing platforms can be further improved by moving the sensors in better measurement conditions. This requires a coordination between the sensing platforms taking into account both, the spatio-temporal data integration and the changing context information regarding the environment and the target, respectively.

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A single inexpensive, small and autonomous sensing platform is suffering from a rather poor performance, but as a coordinated sensor team the system-performance can be quite high.

Recently, an interdisciplinary initiative has been started, called the Distributed Mobile Sensors Interest Group (DMSIG), which has brought together a team of international researchers, with the objective to promote collaboration among them in the area of Distributed Mobile Sensor Networks for Surveillance Applications, with a current focus on active surveillance systems, e.g. multistatic sonar, radar, or laser scanners, whereby application fields can be indoor, outdoor and underwater. This collaboration is achieved through regular meetings, participation in special sessions at conferences (e.g. [DMS2012]), publications in journals (e.g. [SHA2011]) and, currently planned, the analysis of common test-beds. To generate common test-beds, as a first step, a questionnaire has been sent to the participants and determined the focus of the group to be on the *coordinated* distributed mobile sensors. As a second step a roadmap has been generated to allow the participants to work towards common results while analysing the test-beds. This roadmap is outlined in Section 5 of this paper.

While generating the roadmap, it became obvious that, without having a method to construct performance measures, the generation of common results is impossible [DMS2012]. A discussion of ideas towards generating performance measures in the DMSIG is given in Section 2.

Performance measure for multi-robot teams with the focus on the coordination of the platforms is also the topic of the IROS 2011 Workshop on Metrics and Methodologies for Autonomous Robot Teams in Logistics (MMART-LOG) [IRO2011]. Roughly speaking, by changing 'transportation tasks' into 'information gathering tasks' commonalities between the two initiatives, DMSIG and MMART-LOG, can be further examined on a theoretical level.

Even more, also from the practical or operational point of view, there are similarities between the equipment used in both fields, the Automated Guided Vehicles (AGVs) in MMART-LOG and, for example, the Autonomous Underwater Vehicles (AUVs) as a potential part of test-beds in DMSIG.

In Section 3, we describe the potential usage of AUVs in underwater surveillance applications in more details. We show that a team of AUVs is necessary to perform the surveillance task. Then, in Section 4, we show that in an operational environment, it might be necessary to program the AUVs to follow specific paths, i.e. to take away degrees of freedom from their autonomous behaviours, which, at the end, makes them more similar to AGVs that act in a structured environment.

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The reason for not allowing the AUVs to perform autonomously multi-objective optimization within the objective function calculated by a large number of practical constraints (as further discussed in Section 4) is the necessary linkage to human decision makers in military operations who have to know at any point in time with sufficient precision where the AUVs are and what their next actions are. For example, in the framework of Underwater Communication this necessary information cannot be transmitted always, hence only pre-planning can generate a feasible Concept of Use for the surveillance applications. A more general application with communication constraints exists when covert receivers are used which should only very rarely give the target a chance to estimate their positions by intercepting communication signals. In this case of covert receivers, the necessity for pre-planning seems to be especially interesting from the point of view of how to enable coordinated team work. An example from sports is the ‘no-look pass’ which members of a soccer or basketball team practise in training before they use it in the actual competition [SDF2010].

2 Performance measures

The major difficulty in creating performance measures for the team of surveillance units is that the performance of the team depends on the cleverness of the target. It is a non-cooperative game which the surveillance units and the targets play. Trying to solve this in a straight forward manner by sequential simulation of all aspects (already many parameters for the team, and many degrees of freedom for the targets) is infeasible. Help is coming from two standard procedures: (i) Parallelization and (ii) simulation only on the important aspects (like importance sampling). These paradigms have been incorporated in the development of the roadmap described in Section 5. In the following subsections of this section we explain why performance measures are a mandatory element of future research on Coordinated Distributed Mobile Sensors and a methodology how to implement performance measures.

2.1 The need for performance measures

For surveillance systems, from a procurement strategy point of view, a quantitative statement on potential improvement is necessary to justify investments for the introduction of unmanned systems. Three major thrusts to work on distributed sensor network based robotic teams are easily listed: data fusion from distributed multi-sensor measurements clearly improves the overall Receiver Operating Characteristic, design and maintenance tools of multi-agent teams are available and guarantying disruption tolerant services, the robustness and persistence of robotics platforms is dramatically increasing [DMS2012].

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An open question is how Distributed Mobile Sensor Networks can be compared, i.e. how to generate procurement decisions for the system with “better” quality (or capability). One systematic way of defining the statement “better” could be to place this research in the framework of game theory for non-cooperatively acting teams. A team of targets is challenging different surveillance teams and their success rate is compared. The expertise needed in this case is on how to organize, evaluate and predict outcomes of such competitions. The role of learning mechanisms for distributed robot systems is then to ensure that optimal parameter settings for the challenged systems are used.

The DMSIG could be a forum capable to initiate collaborations in form of potential future competitions and joint definitions of quality measures for 'smart sensors on cleverly teamed smart platforms'.

2.2 Methodology how to implement performance measures

For Distributed Mobile Sensors, another important aspect to mention concerns the communication constraints. Data fusion needs data exchange. Thus, performance measures for distributed surveillance systems have to account for this and also for networking requirements (topology control) and energy efficiency requirements, all together with the already mentioned detection and tracking performance depending on the sensor quality. An example for an overarching concept handling the aspects of a multi-agent surveillance network can be found in [WSS2010] and [SDF2010]. Here, in this paper and as a focus of a first step inside the intended DMSIG collaboration, we concentrate on the aspects of sensor quality on the team coordination.

3 Application in Underwater Surveillance

In this section, we first introduce the ‘sonar equation’ which describes sensing performance of active sonar systems. Then, we discuss with the help of the sonar equation why coordinated teams of platforms produce a much higher overall system performance than non-cooperating single platforms. We shortly mention that, for the underwater surveillance, hardware exists to perform autonomous sensing, and conclude this section with the statement that the implementation of the coordination in an efficient manner is needed to fully exploit the high overall performance with a limited amount of participating platforms.

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3.1 Sonar equation

The sonar equation combines in logarithmic units (i.e., units of decibels relative to the standard reference of energy flux density of rms pressure of 1 μPa integrated over a period of one second) the following terms:

$$SE = (S - TL1 - TL2) - (NL - AG) + TS$$

which defines signal excess (SE) where: S: source energy flux density at a range of 1m from the source; TL: propagation loss for the range separating the source and the target (TL1) and the target and the receiver (TL2); NL: noise energy flux density at the receiving array; AG: array gain that provides a quantitative measure of the coherence of the signal of interest with respect to the coherence of the noise across the receiving array; TS: target strength whose value strongly depends on the aspect of the target to the source receiver pair, if the target is a long thin cylinder [DAU2010].

Note: In this paper, we only refer to the sonar equation in the noise limited case. A similar formulation is proposed for the reverberation limited case.

For the description of active sonar, the sonar equation has to be applied for the sound path from the source to the target where the received level plus the target strength (TS) is reflected to the receiver. Especially interesting with respect to the control of receiver platforms are the parts of the sonar equation, which depend on the target position (TL, TS) and on target position and velocity (TS), as explained in the next subsection.

3.2 Coordinated platforms

Looking at the terms of the sonar equation and taking into account that potential targets often have a cylindrical shape, the added-value by using coordinated platforms can be seen at the TS term: If the coordinated platforms can achieve to see the target (independently on its manoeuvres) often in high TS regions, the stealth capability of the target has been taken away. In other words, the aim of the coordination is to generate and hold tracks of a target which cannot be detected by a single platform on its own. Data fusion and tracking algorithms for this scenario are described in [DAU2010].

3.3 Equipment for Autonomous Underwater Surveillance

A survey in the Internet shows that there are plenty of AUV platforms available to provide essential capabilities for an autonomous underwater surveillance. For example, in [AUV2010], 112 AUV types from 53 suppliers are listed. This information is from October 2010. The number of AUVs in the field is constantly increasing. In [SDF2010], a system concept for the autonomous multistatic surveillance system is described. Figure 1 is sketching the application of this concept.

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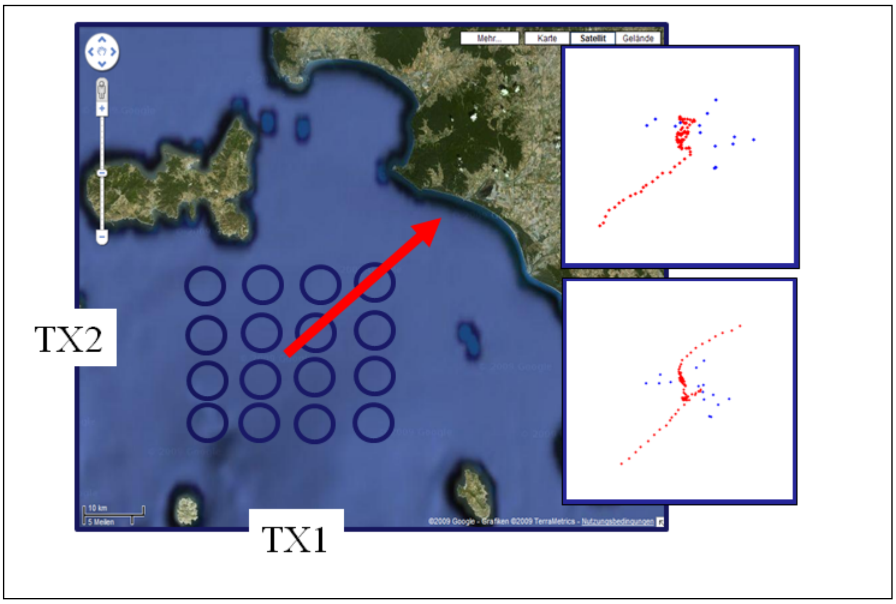

Figure 1: Geometry in an example environment (left).
Simulation results of teamed AUVs trapping a target: For a slow target (top right) and a faster target (bottom right) [SDF2010].

3.4 Requirements

However, underwater surveillance areas are very large, whilst sensor ranges are rather small. Hence, to cover an entire area with a complete network of uncoordinated AUVs would be too expensive. Therefore, we have to learn how to use the Distributed Sensor System efficiently. In the case of underwater surveillance, we have to learn how to exploit the added-value, as explained above in terms of the TS value. I.e, we need to implement the capability to autonomously generate teams with the available platforms. And we have to be able to compare the performance of different implementations of team behaviours.

4 Link to Logistic Problem

In this section, we further describe the potential similarities between the aforementioned task of organizing teams of sensing robots in a surveillance task and a team of transport robots in the logistic task. The common focus is on the construction of performance measures for the autonomously self-organized team of (transporting or sensing) robots.

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4.1 Constraints in the underwater surveillance planning

Looking in more details at the capabilities of the AUVs and at the operational constraints, it turns out that the AUVs have to stay within geographical limits, keeping also specific distance limits to each other. They have to be maintained, also in terms of battery capacities in order to achieve a persistent surveillance. Furthermore, minimal distances to communication devices have to be ensured. Other constraints are generated by the sensors themselves which limit the manoeuverability of the AUVs. This list of constraints can be easily extended. Of particular importance in this paper are the constraints generated by the need to perform a coordinated surveillance without constantly sending coordinating messages between team members.

4.2 Information gathering instead of transportation

As discussed before, we might think about a team of sensing robots as if they were a team of AGVs which have the task to 'gather information', instead of transporting goods.

We can further interpret the task of 'information gathering' as maximizing the likelihood of receiving high Signal-to-Noise-Ratios at the receivers. In a recent work [ORL2011], this has been formulated as an “optimisation and search” problem:

It has been shown that the likelihood function of the Signal to Noise Ration (SNR) of the target contact for the i^{th} receiver at the m^{th} sonar ping can be calculated as a function of the terms of the sonar equation (see Section III A). Hence it is possible to choose the best receivers from a given set of receivers [ORL2011]. In [OCE2007], it has been shown that the setup of the acoustic sources in the active sonar scenario can be found by optimizing the information predicted to be gathered from a tracked target.

Since these formulations are linked to the actual tracking and data fusion algorithm, which is constantly fed with measurements, and also explicitly contain the target strength term (TS) of the sonar equation, we can be sure that these formulations are able to exploit the 'added-value' of the team work automatically.

Instead of just selecting setups from a small set of possible setups as in [OCE2007] and [ORL2010], these formulations have to be extended to determine the best sensor positions and movements at future time steps whereby current positions and movements of sensors are given as input into these new algorithms.

5 The DMSIG roadmap

For the DMSIG, we aim to generate a framework to allow collaboration between researchers in the field of Distributed Mobile Sensors. Therefore, we have written a roadmap (as part of a recipe, which is outlined in this section).

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5.1 Ingredients to generate a team of coordinated distributed sensing robots

- Sensors whose quality is geometry dependent
- Platforms which are spatially distributed and unmanned
- Communication which is limited for both control & data exchange
- Targets which have a stealth design and are faster than sensing platforms
- Surveillance area which is a 2D grid whereby sensor quality measures are mapped into cells of this grid
- Constraints which can be started to be listed as
  - not enough sensors being available to cover the surveillance area entirely
  - only a limited period of time given to find targets
  - etc.

5.2 Tools to enable collaborative research

- software ‚test-bed‘ which simulates a surveillance scenario
- performance measure in order to compare different team behaviours (including the way they are implemented, see [WSS2010] for one example of an implementation) by ‘competition‘ (like a Champions League season in the soccer)
- systematic approach: There are many free parameters in the ‘test-bed‘. As a first step, leading to the roadmap below, we keep the communication settings and the parameters describing the platform capabilities fixed, and we elaborate only on the effect of a changing sensor performance for the overall team performance.

5.3 Instructions (roadmap)

1. Build software ‘test-bed‘ with common interfaces
2. Select a reasonable number of sensors, reasonable parameters for the bandwidth of communication networks, for the manoeuverability of platforms, etc.
3. Within DMSIG give a specific setup to each participant (where the quality of sensors differs).

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4. Each participant calculates the performance of a non-coordinated behaviour.

5. Each participant uses "internal competition" to generate the best performing team behaviour.

6. Collect performance limits from each participant.

5.4 Aim of the roadmap

By following the roadmap, the participants of the collaborating researchers can jointly work on finding answers for the following questions:

- Can 'coordination' compensate for having lower sensor performance?
- When and how to implement 'coordination?
- How much 'money' can be saved by using cheaper sensors and boosting the performance by the efficient usage of a 'coordinated' sensor team?

6 Conclusion and Summary

In this paper, we have discussed the interface between the workshop topic "Sensor Data Fusion" (SDF) and the field of research discussed in the Distributed Mobile Sensors Interest Group (DMSIG). When a surveillance task even with the best possible Data Fusion Algorithm cannot be achieved, a potential solution for better surveillance performance is to change the sensor location, speed and orientation, making the sensors to become a coordinated team of mobile sensors.

As an example for a potential field of collaboration within the DMSIG, we outlined the task of underwater surveillance performed by Autonomous Underwater Vehicles (AUVs). There, we noted that many practical and operational constraints have to be maintained, which, at the end, results in the statement that, in order to avoid problems while handling a multi-AUV team for underwater surveillance, it is recommended to take away many degrees of freedom from a single AUV behaviour, letting the manoeuverability of the AUVs become similar to the manoeuverability of Automated Guided Vehicles (AGVs), used in logistics.

As in logistics, where e.g. many small robots are used to move heavy goods, also in the underwater surveillance only the team behaviour is enabling the capability to track and pursuit of stealthy and fast targets under the given environmental conditions.

For the DMSIG, a roadmap has been developed to enable collaboration between researchers and, in the future, to build upon joint results. Since the sensor data fusion is a fundamental element when implementing/realizing the roadmap, the SDF workshop gives the opportunity to discuss potential future joint steps ahead.

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