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Evaluation of continuous consensus algorithm in border surveillance missions

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***Abstract*— Large scale wireless sensor networks require intelligent and reliable distributed information processing mechanisms which can effectively delegate decision at the field level. Consensus algorithms have been extensively studied and deployed in many generic multi-agent systems framework and are able to provide localized agreement among sensing entities. The paper discusses the evaluation of a local consensus algorithm for a border surveillance system, focused on detection of military terrain vehicles, starting from a system architecture for large scale monitoring systems previously proposed. Simulation scenario of a ground local WSN was developed using real data as reference for initial states of the sensor nodes. Performance indicators such as speed of convergence and accuracy of consensus were discussed.**

Keywords-wireless sensor networks; consensus algorithm; convergence; border surveillance; area monitoring

I. INTRODUCTION

Nowadays, wireless sensor networks have become a robust technology which enables reliable deployments with numerous applications including environmental conditions observation, modern agriculture solutions, critical infrastructure monitoring, healthcare and even military surveillance missions. Recent studies focused on in-network data processing have leaded to the emergence of efficient decentralized sensor fusion algorithms designed for wireless sensor networks. In stressful environments the use of a centralized sensor fusion scheme is a vulnerable architecture. Instead, distributed sensor fusion schemes provide solutions for consensus decision making in a way that leverage the on-board computing resources and reduces the burden on communication channel. In a consensus mechanism each sensor node performs a local estimate of the global average, and keeps improving it by an updating rule and the estimates of all its neighbors. More precisely, each sensor node seeks to reach consensus over the mean of the initial values. The advantage of consensus algorithms is that they can calculate iteratively the average value in a completely distributed way through local information exchange among neighbors. This means, in a large WSN, even if some sensor nodes fail because of particular reasons, the consensus is still performed by the rest of the sensor nodes. Consensus algorithms have been extensively studied and promise efficient information extraction and data reduction by means of reducing the energy and the communication constraints of the embedded sensing nodes. The speed of convergence of consensus algorithms is a critical performance metric for energetic reasons. Reducing the convergence time leads to a smaller number of transmissions among the sensor nodes which of course leads to lower energetic costs for each sensor node.

In this paper, we evaluate a local consensus algorithm for border surveillance system, focused on detection of military terrain vehicles. Previous, we proposed a system architecture for achieving data aggregation in hierarchical networks of cooperative entities based on wireless sensor network for large scale monitoring. We take advantage of MTIDS (Matlab Toolbox for Interconnected Dynamical Systems) simulation tool in order to test the performance of the consensus algorithm on a simulated border surveillance scenario.

The outline of the paper is as follows. Section II provides the role of WSNs in border surveillance applications. We describe our system architecture for border surveillance in section III focussing on military terrain vehicles detection. In Section IV simulation results are presented with focus both on convergence time and consensus accuracy. Finally section V summarizes the paper and discusses future work.

II. WSN IN BORDER SURVEILLANCE

The purpose of border surveillance is to maintain order and security at borders and prevent unauthorized border crossings. Nowadays implementation of real-time border intrusion detection and control has become a strong demand, due to large costs of conventional surveillance systems, which basically involves a lot of resources.

Using WSN for data aggregation in border surveillance missions is a suitable approach which comes with numerous advantages.

Several recent works have discussed the design of country border surveillance systems based on WSNs.

In a border surveillance system based on WSN, two major objectives have to be achieved: first, it should build on a deployment scheme capable of offering total coverage of the surveilled area so that any target passing the area is detected. Second, it should be able to track moving objects of interest in the area. Both goals have received an extensive attention during the last decade [1]. In an efficient in-network data processing system, energy conservation is vital. The sensors should be able to dynamically move between a sleeping status and an active status.

There are plenty of studies focused on the design of country border surveillance. Starting from area of coverage, and sensor nodes deploy, proposed solutions provide either linear WSN [2], which is basically a barrier, or WSNs comprising on multiple layers such as 3-layered hybrid network architecture for border patrol discussed in [3]. The case of border surveillance when sensor are randomly but non-uniformly deployed has been investigated in [4,5].

To enhance the performances of border surveillance WSN, it is recommended to deal with connected-coverage [6].

III. System Architecture

In [7] we discussed a general system architecture of a large scale heterogeneous monitoring system and information processing by means of a decentralized fusion approach. The monitoring system consists of surveillance UAV (unmanned aerial vehicle), ground sensor network subsystems and a ground control center. Information extraction from ground sensor networks can be achieved by means of a consensus approach. In [8] we proposed a binary consensus-based decentralized algorithm for event detection in WSN. Experimental results such as convergence time and energy consumption estimation were provided stemming from a flexible test-bed based on Contiki-Cooja WSN simulator.

The multi-level structure is illustrated in Fig. 1.

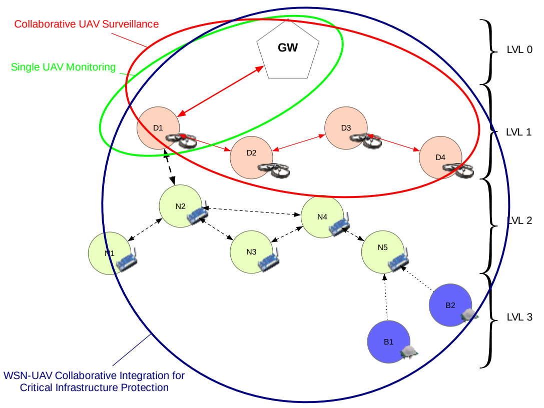

Fig. 1: General colaborative large scale monitoring system based on WSN-UAV integration

Ground level comprising levels 2 and 3 in the multi-level structure proposed is dedicated for data collection and in-network processing. WSNs are geographical distributed in local sensor node clusters that collect data from specific areas of interest. In the aerial level (level 1), UAVs collect information from the ground sensor node clusters and relay it to the upper level (Center Gateway – level 0).

This overall system architecture perfectly suits the particular application of border surveillance. Multiple sensors can be deployed to simultaneously monitor given points within the border, guaranteeing that the failure of one node would not necessarily compromise the network's integrity. Figure 2 illustrates a border surveillance scenario using the multi-level structure proposed.

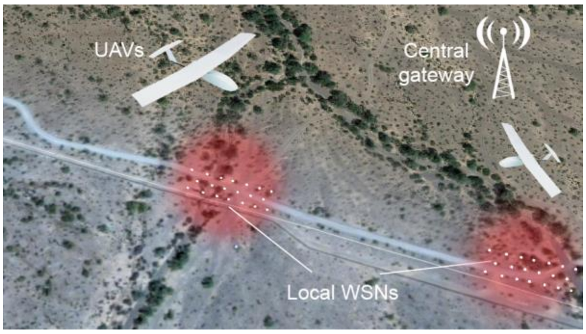

Fig. 2: Border surveillance scenario

Local sensor node cluster

Ground level comprising sensor node clusters, require advanced local in-network data processing mechanisms to ensure efficient information extraction. In this paper we propose a sensor node cluster with static topology, modeled as an undirected graph. One must consider a critical issue of the WSN topology, when it comes to object detection or tracking. Area coverage and connectivity are vital for the quality of in-network data processing. The sensor nodes are deployed in order to cover a wider area, but the dimensioning of the area coverage must consider the quality of service provided by the sensing nodes. Each sensing node in the WSN cluster should have a direct route through which it can reach the data source. The topology and the positioning of the sensor nodes must be analyzed in order to minimize the number of sensor nodes that are deployed outside the coverage area. Regarding border surveillance, sensor nodes deploy should be set considering the measuring range, and communication radius of the sensor nodes used, so that the number of sensor nodes deployed outside the area coverage to be minimal, and to ensure that in the same time all the inspected area is optimally covered. Furthermore it is also important to analyze environmental conditions that should be monitored.

IV. Simulation and Results

We built the topology of the evaluated WSN starting from the environmental conditions and the features of the simulated sensor nodes. Military terrain vehicles include large metal parts that can be observed using dedicated sensing devices such as magnetometers. Because of the large ferrous mass, earth magnetic field is distorted, and distortion level is measured by the magnetometer. For this simulation, 3-axis anisotropic AMR magnetometers are used. Initial data for simulation was generated according to real measurements mentioned in [9]. Reference values are listed in table 1. A number of 20 sensor nodes were deployed to monitor a given interest point on the border, with an area less than 1000 m^2. The proposed sensor nodes deploy is illustrated in figure 3.

Army vehicles	Light wheeled vehicle	Tank	Truck
Total magnetic field at 32 ft	200 [nT]	680 [nT]	310 [nT]
Total magnetic field at 12 ft	5000 [nT]	23000 [nT]	7500 [nT]

Fig. 3: Sensor nodes deploy

For simulation of our approach we take advantage of MTIDS (Matlab Toolbox for Interconnected Dynamical Systems) simulation tool. We built an undirected graph following the sensor nodes deploy and apply the dynamics for the local consensus algorithm. The dynamics model follows the generic continuous consensus algorithm for updating the information state $x_i(t)$ of node *i*, formulated as [10]:

$$\dot{x}_i = -\gamma \sum_{j\in \mathbb{N}_i}(x_i - x_j)$$

where N_i is the set of nodes connected to node i.

The reference topology for the undirected sensor network communication graph is shown in Figure 4. The quantitative graph parameters that are automatically computed show that the graph is well connected and offers good performance in a time invariant communication channel model.

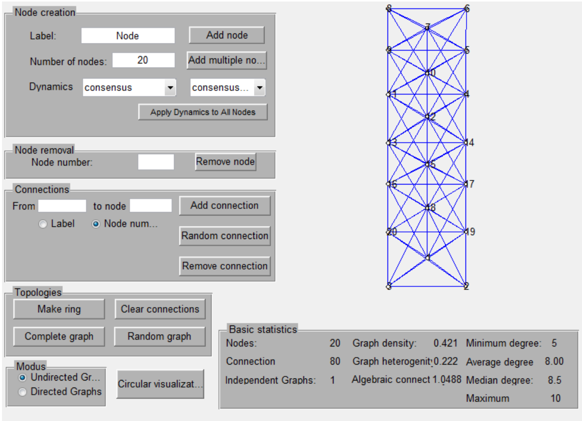

Fig. 4: Reference topology used for simulation

Initial measurement values were generated for a specific scenario that captures an armored fighting vehicle, more precise a tank, inside the surveillance area. This simulation scenario is illustrated in figure 5. The measured values for total magnetic field range between 0 nT ... 35800 nT, with an average of 16810 nT. Figure 6 illustrates a chart with the initial measured values.

Fig. 5: Simulation scenario

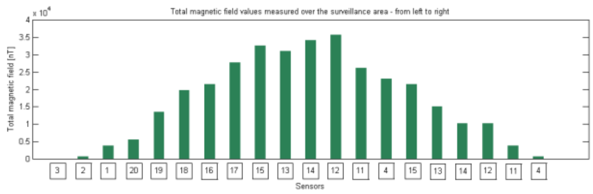

Fig. 6: Total magnetic field values

For the proposed scenario we evaluated the convergence time and the accuracy of the consensus algorithm. The main result is illustrated in figure 7.

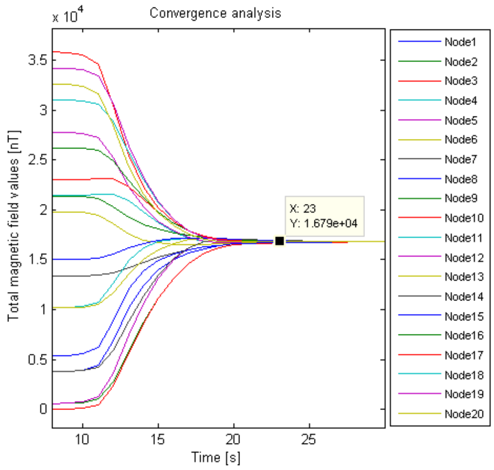

Fig. 7: Convergence analysis

As one can see the initial values update in an iterative way and slowly converge to the average value, through the information exchange with local neighbors. Convergence time in this scenario is around 20 seconds. It can be seen how the convergence rate decreases as the consensus value is reached. As expected, the consensus value, which is about 16800 [nT] is very close to the average of initial measurements. Figure 8 illustrates some frames captured at different steps of the local consensus algorithm, in a "color map" representation. One can easily see this behavior, as from initial values distributed across the local WSN, the sensor nodes iteratively update values step by step up to consensus value.

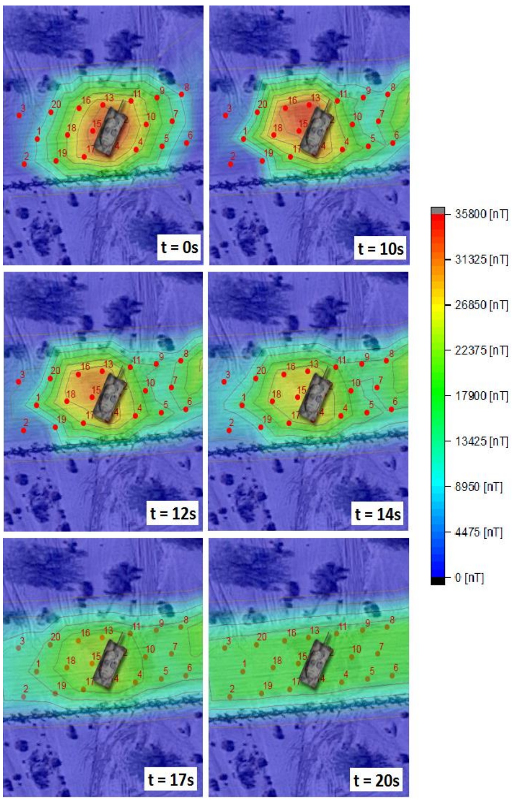

Fig. 8: Convergence analysis – "heat map"

In the proposed multi-level system architecture, discern between the military terrain vehicles is carried out at the top level, were decision making is based on data fusion from all the surveillance levels and the help of a decision support framework. However this can be reached also at ground level using simple classification algorithm, based on threshold values e.g. an average value over 10000 [nT] corresponds to the detection of a tank vehicle inside the surveillance area.

V. Conclusions

The paper discussed the evaluation of a consensus algorithm used for local ground data aggregation in a multi-level heterogeneous monitoring system proposed for border surveillance missions.

The simulated scenario was developed considering real data values as reference, and the main constraints of WSN topologies, such as coverage area and connectivity, which are considered critical issues of the WSN, when it comes to object detection or tracking.

The simulation results clearly show how initial vales update in an iterative way spreading across the entire network. Performance indicators such as speed of convergence and accuracy of consensus were discussed.

In-network data processing can be successfully achieved using consensus algorithms, but special attention must be given to the sensor nodes deploy, in order to keep the quality of data aggregation and to ensure that all the inspected area is optimally covered.

Current and future work includes the evaluation of the consensus-mechanisms using weight selection for information state update with time-variant communication.

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