Dynamic Task Planning of Aerial Robotic Platforms for Ground Sensor Data Collection and Processing

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Abstract. The adoption of wireless sensor network systems is becoming wide-spread in critical large-scale monitoring applications. These include but are not limited to pipeline infrastructures for oil and water, border areas, roads and railway systems. In such scenarios, airborne robotic platforms like unmanned aerial vehicles (UAVs) can provide valuable services for data collection, communication relaying and higher level supervision. This the case for both single UAV deployment as well as for swarms of UAVs collaboratively integrated into the monitoring system. The paper discusses the opportunity for in-network pre-processing of sensor data for local UAV task planning in order to increase the efficiency of the data collection process. A gradient scheme is introduced for decision support of the UAV task planning. The results are validated by simulation.

Keywords. wireless sensor networks, unmanned aerial vehicles, information processing, data collection, large scale monitoring

1 Introduction

As dense monitoring and control applications become wide-spread through networks of embedded computing communication devices, significant challenges arise for effective data management at the node and network levels. The integration of tens to thousands of wireless sensor nodes, which have the task of periodically sampling a process or set of process variables, and to communicate the data via low-power links towards a central control gateway, demands data reduction mechanisms which are usually implemented by means of aggregation and sensor fusion [1]. The goal afterwards is to reliably relay the high level resulting pieces of information back to a central server for automatic or assisted decision support. The long distance links and storage buffers required for redundancy lead to an increase in the complexity and cost of the individual nodes which suggests the use of layered monitoring architectures.

These are strongly dependent on the application specific requirements for data collection and control and must offer the possibility of dynamic parameter adjustment [2].

We focus on the essential support role that can be played by unmanned aerial vehicles (UAV) in effectively supervising large scale distributed sensor systems. The WSN-UAV symbiosis for security perimeter and critical infrastructure systems monitoring has become an interesting new research direction over the last few years. Several global frameworks have been proposed and classified, among which:

- *hierarchical structure* where the fixed wireless sensor network operates in the designated target area, collects ground data according to predefined or dynamic behaviour. UAVs act upon several alerting and alarm levels generated by embedded algorithms running on a network control center for data collection, processing and decision. This can be showcased by event detection such as an intruder entering a protected area which leads to on-demand dispatching of an UAV capable of video surveillance of the target area signaled by the WSN;
- *collaborative heterogeneous structure* in which UAVs are able to support the sensor network by acting as mobile communication relays in order to restore WSN connectivity in case of a fault, like is the case of reduced network throughput or even network partitioning if a critical node fails. This can also be extended to soft constraints such as effective load balancing of the communication channel by offering alternative routes through the mobile relays. Evaluating the issue from an opposite perspective, the sensor network can operate as a fixed reference infrastructure for localization and UAV communication;
- *mobile wireless sensor network* where the nodes are implemented as mini- and micro- UAVs, equipped with scalar and multidimensional/multimedia sensors, enhanced local processing and storage capacity, collaborative swarm type algorithms for multi-UAV coordination and planning and various communications interfaces;
- *hybrid application-specific systems* which include elements from all of the above.

Current research issues in this field lay at the convergence of several areas: low-power radio communication including medium access control and routing, data aggregation and sensor fusion for in-network or centralized processing, energy efficient localization methods and navigation/task planning and collaboration for mobile robots, in the particular situation of airborne robotic platforms. Modern approaches leverage intensively multi-agent system theory for task assignment and efficient operation of individual entities or groups of entities: sensor nodes, UAVs and mixed clusters.

The rest of the paper is structured as follows. Section 2 highlights related work concerning effective task planning for data collection and communication in hybrid large scale monitoring systems and underlines the contribution of our work. Section 3 describes the reference system architecture, objectives and relevant algorithms. We present simulation results based on reference temperature/humidity data sets for ground data and UAV decision support in Section 4. The paper is concluded in Section 5, including an outlook on future work.

2 Related Work

The main context of our work is defined by the application-specific nature of large scale pipeline and road infrastructures which can be best described by a linear wireless sensor network (LWSN) deterministic deployment [3]. This assumes that generic communication and processing protocols can be adapted to exploit this linear deployment, or new ones can be developed altogether. It concerns the directed optimization of the communication and data collection protocols according to a linear or quasi-linear topology following one of the above mentioned infrastructure systems. The authors of [4] propose localized power-aware routing for LWSN which exploits the directed nature of the sensor node links. A multi-level system architecture specifically designed for oil pipeline monitoring is introduced in [5]. Key issues that are covered include the selection of the channel sharing method: TDMA versus CSMA/CA, source data fusion and compression for lowering the burden on the communication channel and increased reliability and energy supply of the nodes through energy harvesting from the monitored process.

UAV-support for heterogeneous sensor network monitoring is discussed in [6]. Here the UAV is mainly used as passive relay towards the main communication backbone for remote sensing purposes. The main objective is to design effective clustering strategies for resource balancing given the constraints of the embedded sensing devices. The challenges stemming from self-organization of such a large scale monitoring system in the military domain are presented in [7]. Through simulation results, the authors highlight the impact of parameter tuning on network connectivity and global coverage for such hybrid systems. A Markov random mobility model for the UAVs offers the best results for the relay network as compared to a pure random model.

With regard to UAV trajectory control and target tracking, a large body of knowledge has been produced over the last years. Some examples include single UAV scenarios [8] for constrained trajectory planning. It involves both an aerial robotic platform motion model and target model. This is illustrated for road network following and obstacle avoidance by using intelligent optimization methods based on genetic algorithms (GA) and particle swarm optimization (PSO). The problem is usually extended and evaluated also at the collaborative or competitive UAV-swarm level [9]. In this case, the optimization problem is defined by the number of targets and UAVs and by defining an appropriate cost function e.g. having as objective the minimization of the time to detection, which can be solved with gradient-based approaches.

While acknowledging the current state-of-the-art, our contribution lays in advancing WSN-UAV integration at a system level through in-network processing of the collected data for UAV task planning. Basic aggregation of data is carried out at the cluster head level and provided to the UAV which then autonomously decides the following waypoints based on a classification of the aggregated collected data.

3 Large scale deterministic system deployment and algorithms

The system design for large scale monitoring based on ground sensor networks with UAV support is illustrated in Figure 1. Main components of the sensor network are the cluster head nodes N1…n which collect and aggregate data from local sensor nodes and interact with the UAVs D1…n. Apart from data collection, the drone operates as a long-range network relay towards the network control center (NCC) and has the ability to bridge the low power wireless links in the sensor network. The main challenge consists of on-demand dispatching of the UAV towards the cluster head nodes which, based on a local processing algorithm, exhibit significant and persistent variations of the monitored parameters: environmental data, process variables, binary event detectors. For large scale monitoring applications with distributed parameters like is the case of oil pipeline monitoring, this helps reducing the number of UAVs and operating costs [10]. The UAV is supposed however to have sufficient on-board storage and computing resources to keep a history of aggregated data from the nodes and update this periodically in order to run the task planning algorithm.

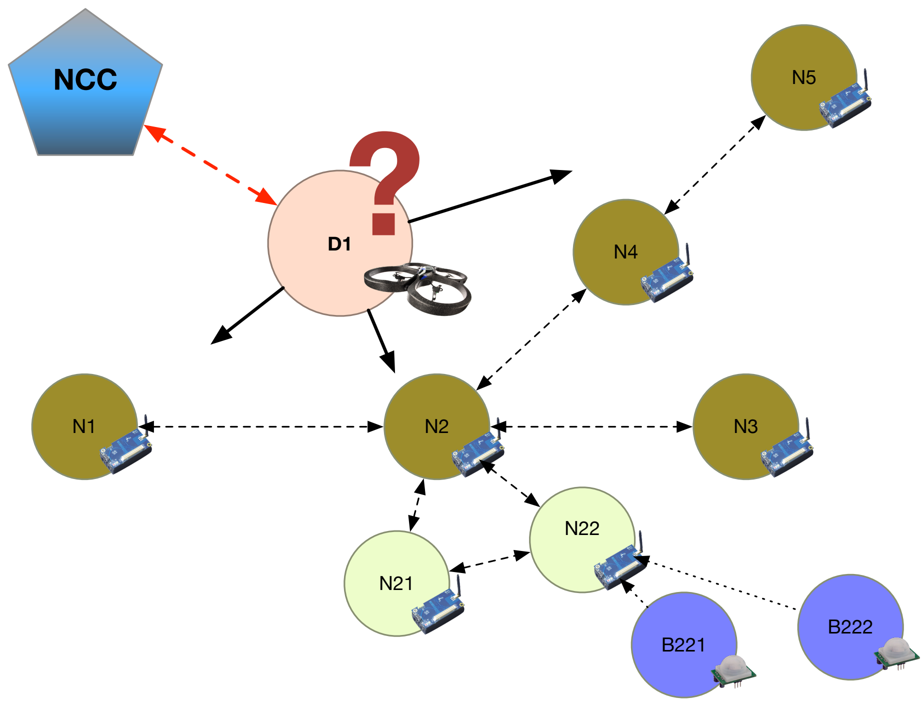


Fig. 1. System diagram for UAV-supported cluster head data collection

It is assumed that both the sensor network and the aerial robotic platform support over-the-air reprogramming in order to dynamically adjust the algorithms parameters and mission objectives. In the case of network congestion or faults, the task planning can revert to a static, pre-defined, operation mode in which the cluster heads are periodically queried for the available data in a deterministic fashion. Introducing in-network processing of data leads to a reduction in the quantity of data transmitted over the wireless links and positively impacts battery life for both static and mobile nodes. Another benefit of this type of multi-level monitoring system is that more complex sensors like high resolution cameras, thermal imagers and radar devices, can be fitted to the UAV in order to validate information extracted from the low-cost, high density, sensor network. The human operator at the NCC is also able to adjust the WSN sampling rate and monitor network parameters relayed through the long-range wireless link.

The main contribution of the work consists of a proposed method for dynamic task planning of a UAV whose mission is to collect data from the cluster head in an opportunistic fashion. Basically the UAV has the capacity to decide by its own which cluster-head to query next depending on history, current conditions and a priori knowledge of network topology and parameter distribution.

The steps of the proposed algorithm are as follows:

Step 1 System initialization: The UAV receives information regarding the WSN cluster head localization, sensors, data format and the long range wireless communication channel is set-up;

Step 2 First pass: According to an optimal path planning based on the geographical placement of the nodes, the UAV collects initial data from each one. Aggregated information is stored locally while raw values can be streamed towards the NCC operator in real-time;

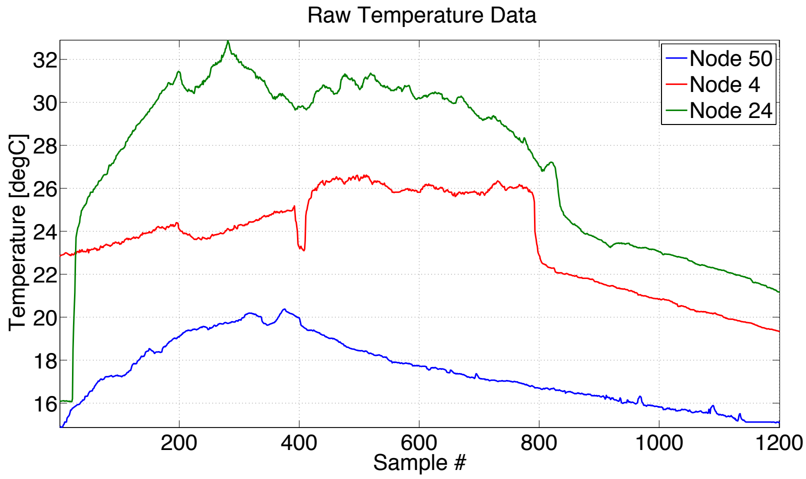
Step 3 Cluster head ranking: The cluster head nodes are ranked based on variations and preset thresholds for the process variables, a forgetting factor is used to prioritize recent events;

Step 4 Decision: The UAV autonomously decides which cluster head to visit next by weighting the above-mentioned ranking with both the travel distance to the next node and based on the time elapsed since the last visit for each of the nodes.

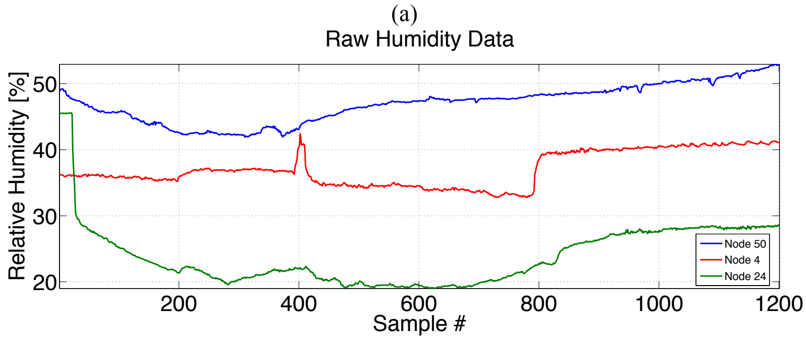
Depending on mission objectives and available resources, Step 4 loops continuously until a stop command is triggered. The scenario can be extended to multiple-UAVs by partitioning the ground sensor network into several areas which are each assigned to a single aerial robotic platform. The approach combines good response for event detection with fairness in periodically visiting each of the cluster heads. Several criteria can be added to the ranking mechanism for system tuning, e.g. for energy efficiency [11].

4 Evaluation by means of simulation

In order to showcase our approach we carry out simulations based on real-world sensor data, stemming from the Intel Lab database [12]. This is provided by three deployed wireless sensor nodes and we focus on temperature and humidity at this point. We have chosen nodes 50, 4 and 24 respectively, with a time window of around one day. Given the sampling period of around 31 seconds, each data set has 1200 points. Figure 2 illustrates the raw data stream: temperature and humidity, for the three nodes.



(a)



(b)

Fig. 2. Raw data collected from the sensor nodes (a) temperature and (b) humidity

We assume that data supplied by the cluster heads has been aggregated in some form for efficient communication and storage. This includes the average value, minimum and maximum, the standard deviation and the variance of the data set. Additionally for event detection and thresholding a count field can be included in the metadata. Cross-correlation of the data series is useful to identify phenomena that produce evolutions over a large number of nodes. The indicators for the analyzed data are listed in Table 1.

Table 1. Aggregation indicators for the raw data

Node	Parameter	AVG	MIN	MAX	σ	$σ^2$
50	Temperature	17.4279	14.863	20.3804	1.5311	2.3442
	Humidity	46.9908	41.9147	52.9368	2.8734	8.2563
4	Temperature	23.5489	19.3318	26.6132	2.2101	4.8844
	Humidity	37.0487	32.7907	42.4174	2.6548	7.0479
24	Temperature	27.3355	16.0684	32.895	3.8366	14.7192
	Humidity	23.8254	18.9947	45.5720	4.5888	21.0574

Based on this we go on to compute the unidirectional gradient of the data. The values are smoothed using a moving average filter and squared to emphasize variations in the positive domain. Accounting for the variation of both parameters, Figure 2 shows the final indicator as average of the squared gradients of temperature and humidity for each of the considered sensor nodes. This points out the fact that node 24 in the beginning of the observation period should be periodically queried by the UAV, while later the focus should shift towards node 4. As could also be seen on the raw data, node 50 exhibits a predictable behaviour which indicates that only sporadic attention should be given to it.

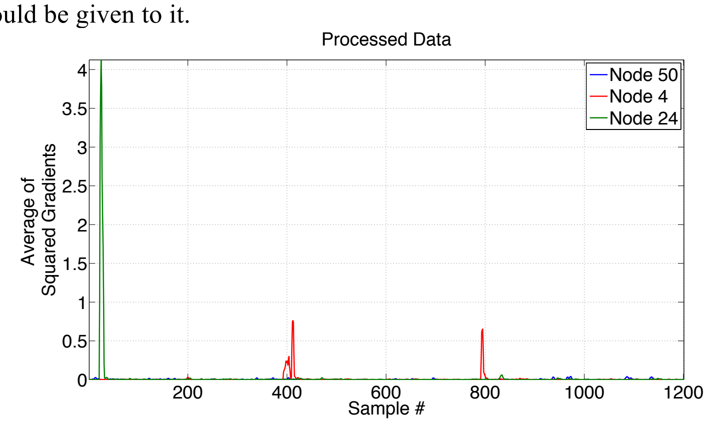


Fig. 3. Processing results for UAV task planning decision support

5 Conclusion

We have carried out initial work on multi-level large scale monitoring systems based on wireless sensor networks with aerial robotic platform support for in-network data aggregation and communication relaying. A system architecture and an algorithm were introduced to allow for effective task planning in data collection between the UAV and the WSN cluster-heads. Experimental results were provided in order to justify our approach. As future work, we aim at implementing the system based on the Ar.Drone2 platform [13] and using TelosB nodes as ground sensor network through appropriate low-power multi-hop communication protocols and data processing, which are aware of the UAV system integration.

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