A down-to-earth case for autonomy in massively plural sensor systems

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ABSTRACT

The role of autonomy in wireless sensor networks remains something of a controversial issue. Although most of the early work in the field, and the subsequent research agenda, has implicitly assumed the use of autonomous sensor nodes, few if any of the practical implementations that have followed have featured autonomy at node level. Systems deployed so far have been relatively small, and their operation posed few problems which require autonomy. At this scale, "planned", non-autonomous systems are seen to be highly successful, so much so that the largest operation WSN so far achieved was designed using similar principles. In this paper, the authors look forward to larger networks, with 100,000 or more nodes, and it is argued that for these networks it is unlikely that "planned" architectures will be feasible. Rather, a return to node-level autonomy as the basis for self-configuring, self-maintaining and self-optimising systems is proposed. The paper concludes with a review of some of the work being undertaken towards this end.

Keywords: wireless sensor networks, autonomy, intelligent sensors

1 A BRIEF HISTORY OF WIRELESS SENSOR NETWORKS

Wireless sensor networks (WSN), in the broadest sense, have been around for a long time. Autonomous sensing devices that incorporate embedded intelligence and are networked together using digital radio have existed at least since the 1980s and probably earlier. An example is the network of automatic weather stations installed in Antarctica [1], which currently connects 84 stations. Many similar networks have been installed worldwide, and weather forecasting and climate research has depended heavily on what must now be considered to be a mature technology. Despite this long history, WSN are still seen by many to be an emerging technology. Their re-emergence as something "new" came with Kris Pister's "Smart Dust" vision in the late 90s [3], which has even caught the imagination of those peripherally associated with the field and has shaped the research agenda of the whole domain.

Nonetheless, the key difference between the smart dust idea and previous practice is usually misidentified to be that of the physical size of the sensor node. Pister himself wrote:

> "The science/engineering goal of Smart Dust and its follow-up projects is to demonstrate that a complete sensor/communication system can be integrated into a cubic millimeter package. This involves both evolutionary and revolutionary advances in miniaturization, integration, and energy management. [4]"

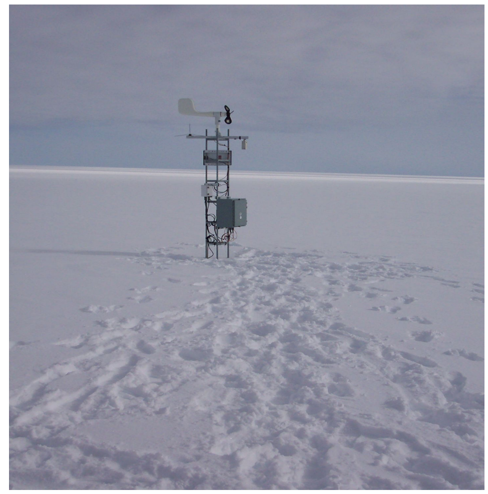

Figure 1: The Byrd Automatic Weather Station in Antarctica [2]

The enabler for the new vision was the association of wireless sensing with MEMS, which offer the promise of tiny sensing and actuating devices, and, more importantly, allow construction of the sensing devices at a cost low enough to give economies of scale. In the author's opinion, it is the possibility of building massively plural sensing systems that is the major attribute which makes "smart dust" a qualitative advance on what went before. The availability of tiny devices is unlikely to enable many practical applications – indeed often there is a practical minimum size that is much larger than microscopic. By contrast, the use of a plurality of sensing devices will allow the building of sensing systems which will make available information of a quality and quantity that will revolutionise many scientific research and monitoring applications.

2 FIELD SENSING AND MASSIVELY PLURAL SYSTEMS

Many promising WSN applications fall into the category of *field sensing.* That is, they employ an array of sensing devices to determine the value of some measurand over a volume, or, more usually, a surface. For example, in the Microclimate Sensor and Image Acquisition Networks system reported by the Center for Embedded Network Sensors (CENS) at UCLA [5], modern day, miniaturised versions of the automatic weather station have been deployed, to allow, amongst other functions, maps to be made of climate data.

A complete map, in terms of an air pressure chart or temperature map, is derived from relatively few data points by *modeling*. The promise of field sensing, with many data points, using a massive plurality of sensors, is to produce the map *directly* from the sensed data. A major attempt to demonstrate such a system is the ExScal (short for Extreme Scale Networking) project [6]. This project started with the goal of the deployment of a 10,000 node sensor network and built the world's largest deployed WSN, some 1,200 nodes, installed over an area of 1.3km by 300m. The network was designed to detect and track intruders using acoustic methods. ExScal remains the most thoroughly researched and documented massively plural network, and thus is a reference point for future applications.

2.1 A down-to-earth application

One problem with the design of massively plural WSN applications is the current "credibility gap". Integrators are not sufficiently convinced of the ability of WSN to fulfill requirements, and thus do not employ them. Furthermore, WSN experts have little knowledge of application needs and thus may not be evolving the technology so that it can fulfill these requirements. The most successful WSN research has been conducted in environments in which there is close collaboration between WSN and domain experts. This is facilitated by large multidisciplinary centres such as CENS.

Alternatively, speculative scenarios that do not rely on detailed application domain knowledge are often used as a vehicle to excite application specialists about the potential of WSN technology. Such scenarios are only useful if they lead to a calibration of the use of the technology with both the system design and application requirements.

A WSN application in this vein is their use for detection of forest fires [7]. This application is attractive because forestry is a major industry, and forest fires are a major cause of economic and social loss. In the USA, 17,000 km^2 of forest are lost annually to fire. WSN might potentially provide warning and predictive information about forest fire behaviour. Recently, MEMS chemical sensors have become available that can detect the volatiles produced in the early stages of a fire, which typically results in days of smouldering, before a full-scale conflagration starts. Other useful information to firefighters will be air temperature and wind direction, for which sensors are easily available. These sensors may be readily interfaced to an existing wireless sensor node (generally known as a "mote" following the smart dust terminology), indicating that such a system is easily feasible.

Nonetheless any practical forest fire detection system is likely to exceed the scale of present WSN by a considerable margin. To plan this network properly, accurate figures would be required, both for the sensitivity of the detectors to the pre-conflagration gases and for the likely concentration of these gases in a critical situation. In the absence of these figures, a rough guess is that 10m from the source of the fire may be adequate, which equates to a coverage of 100 nodes/hectare. In this case, an installation for even a small forest would far exceed the scale of the ExScal network. For instance the Wyre Forest, Worcestershire, UK covers 2634 hectares and would therefore require in excess of 200,000 nodes (US forests dwarf this). Even assuming that node cost could be reduced sufficiently to make such an installation economic (which is not out of the question, given the volumes required), it is quite clear that some advances in the science of WSN are required in order to build this system. Given that ExScal fell short of the "extreme" scale required by some 200 times, a worthwhile starting point would be to study the difficulties which were encountered in building this 1200 node network.

2.2 Problems of large networks and the need for autonomous services

Bapat et.al., [6] in their summary of the results of the ExScal project cite the problems expected to be encountered in the design of a very large network. They are:

- Failure of sensor network protocols to scale. Protocols designed to work with small numbers of nodes may become unusable as the network size grows.
- Complexity of integration. The dynamics of the interaction of multiple protocols that deal with issues such as medium access, reliable communication, sensing, and time synchronization is not completely understood.
- Lack of sufficient fault data. Given the susceptibility of networks to faults, it was argued that there was a need for more real fault data in a working context.
- Unpredictability of network behavior. A consequence of the previous points is that little is known about the behaviour of large scale networks and scalable solutions have not been validated for real-life use.

The design approach used to address these concerns was one of use of a "planned architecture"; the imposition of various design constraints to simplify the operational complexity of the system. Nonetheless, it would seem when the results are studied, that ExScal was at the limit of network size feasible with such an approach.

To simplify the localisation of nodes and the interpretation of the data from them, the system was laid out on a rectangular grid, with nodes being located on installation using a hand held GPS device. Nonetheless, 11.4% of the nodes were incorrectly located.

To ensure reliable data transmission, a three-level hierarchical architecture was adopted, with different specialised hardware at each level. The end to end reliability achieved using this architecture was 85.61% for the best traffic type (low bandwidth) and 55.14% for the worst type of traffic (high bandwidth).

A conservative attitude to hardware specification was adopted. Despite this 6% of the nodes were non-functional after the 15 day trial. Loss of a second tier node caused loss of a complete section of the network. A significant amount of node malfunction (7%) was associated with their reprogramming.

Without doubt, completion of the ExScal network was a considerable achievement, but it has not established "planned architecture" as a suitable basis for networks an order of magnitude larger that was achieved there. A brief consideration of the forest fire application suggests some of the shortcomings this approach may have when it comes to the building of much larger networks.

In a real forest, it is unlikely that it will be possible for nodes to be laid out on a rectangular grid, and certainly not on a flat surface. In fact, the precise geographical topology of the forest floor (in three dimensions) is a likely information output of the system. The prospect of deployment of 200,000 nodes brings with it at least two practical considerations. Firstly, installation time will need to be minimised. Ideally, it will be an automated process similar to the sowing of seeds. Certainly, there will be no scope for manual, node-by-node localisation. Secondly, the cost of deploying such a network will most likely mean that installation will be staged, as and when funding becomes available, and after early, partial networks have been validated.

Ultimate communications reliability will need to be much better than was achieved in ExScal. The precise reliability level depends heavily on the application, and is impossible to assess accurately at this point.

In the context of a long term deployment, failures will have to be much less frequent than the rate experienced in ExScal, and those that do occur will need to be detected and managed, with the network being reconfigured to ameliorate the failures.

Finally, the network will need to be retargetable by means other than reprogramming. Not only is the level of reprogramming error found in ExScal unacceptable, but the development of what are massively parallel programs, and their installation on hundreds of thousands of nodes is unlikely to be practicable.

We argue that these considerations call for a design philosophy almost the reverse of that used in ExScal, rather than a "planned architecture", an approach of autonomous configuration and self management on the part of the network nodes is called for, for the following reasons:

1. Planned or manual localisation seems infeasible for systems of this scale, necessitating some system of autonomous localisation. Such a system inevitably includes a phase of geographical network discovery, which will make many of the other steps involved in network planning redundant.
2. Without a prior view on the geographical topology of the network, is impossible to plan the type of heterogeneous, multi level communications architecture used in ExScal. Rather, the network topology will need to be self configuring, once geographical discovery is achieved. This suggests a homogeneous network (in computational and communications terms) onto which can be mapped an appropriate logical topology.
3. Continuous fault management implies a changing logical and data gathering topology for the network.

Thus, nodes in this type of network need to act autonomously in at least three regards: localisation, dynamic network discovery and fault management. Once node-level autonomy is accepted as a design principle, other possible advantages may be seen.

1. System operation may be optimised at a high level. For instance, decisions may be made on the management of information within the network (with respect to when to cache and when to transmit data) based on the usage and nature of the information.
2. This in turn necessitates an information retrieval mechanism that works at a higher level of abstraction than the usual, imperative programs. An applicative query system offers a double advantage. It provides semantic information upon which intelligent decisions may be made with regard to information distribution. Also, it provides for the collaborative optimisation of query servicing within the network, in a decentralised, and therefore robust, way.

The projects pursued by Cogent Computing Applied Research Centre are aimed at addressing some of these issues. Whilst the sum of the output of these projects will not provide a complete solution to the building of massively plural sensing systems, some of the major needs will have been provided for, in the form of a service centred architecture, based on autonomous nodes collaborating dynamically as required to support the various services. The services, around which the projects are based, are summarised below.

3 SERVICES

3.1 Localisation

Practical experience with the evaluation of localisation techniques suggests that it is unlikely that a single method will work and be foolproof in every instance [8]. Instead, different methods are appropriate for different applications, and in many cases a multimodal system will be the best choice. At a network service level, what is required is simply that each node be informed of its location, and be able to pass that information to others. Below that level there must be a flexible and comprehensive service, making use of the facilities available locally (special node hardware, local events) to provide good estimates of location. We call such a service "Geographical Network Discovery". Current work is aimed at defining the service and qualifying some location methods to provide it.

3.2 Information management

WSN operate under the general constraints of limited power and computational resources. The major power user is generally RF communication, and this leads to a need to minimise communication achievable possibly through transmitting information. Thus it is generally better for nodes to cache frequently used information rather than to repeatedly communicate it. On the other hand, WSN nodes have limited memory resources, so caching must be used judiciously. For any given application and installation context, there will be an optimum tradeoff between caching and transmission. The ultimate aim of this project is to provide a self adaptive information management service.

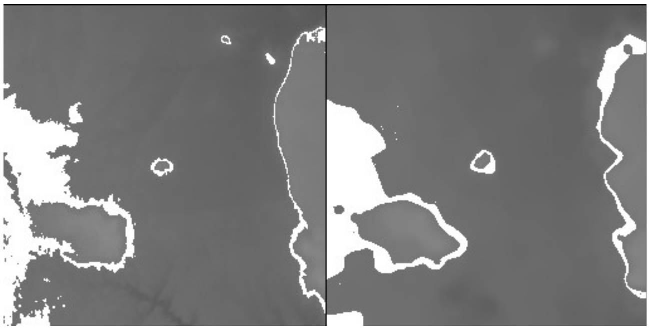

Figure 2: Isopleths generated using original and interpolated data from 600 nodes.

The issues involved are quite subtle, since the quality of information, and therefore the amount of data needed to support it can depend on techniques such as interpolation and data fitting, as well as the use that the information will be put to. Our current research in this area studies the issues of data interpolation and presentation in mapping applications. Figure 2 shows isopleths derived directly from a dataset (left), and those using an interpolation using data gathered from 600 nodes (right) [9].

3.3 Information retrieval

For the reasons given in section 2.2, we favour an applicative query mechanism, using complex queries (which allow sub queries) to provide much of the functionality usually associated with programmatic ways of retrieving information from a network. This service requires both the definition of a query language, its formal specification [10], and the distributed resolution of queries. The outcome will be a technology that will allow the extraction of a full range information from massively plural WSN without the need for writing imperative programs to suit each specific application.

3.4 Fault management

As observed previously, fault detection and management it essential to the continued operation of a massively plural WSN. This work differentiates three separate, but interlinked services: fault detection, fault management, and information integrity management. We believe that the figures of merit for a fault management mechanism include false alarm rate, fault detection time and false fault correction time [13], and a fault detection mechanism evaluated which performs well against this criterion [14]. Future work will develop autonomous services to cover the three interlinked services.

4 CONCLUSION

Massively plural WSN offer the promise of field sensing systems that will open up new sensing applications, such as the forest fire detection system discussed in this paper. The existing system design techniques, as used for the 1200 node ExScal project, are unlikely to scale to systems of 100s of thousands of nodes. Instead, design methods based on collaborating autonomous nodes have been proposed, with that collaboration being used to provide network wide services. The development of these services is an ongoing research task, and forms the current agenda for the Cogent Computing Applied Research Centre at Coventry University.

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