Measurement requirements and performance criteria for data acquisition in gas turbine engine testing

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Abstract:
As the first technical report of WP3, this document summarises our investigation of the application requirements, including the data acquisition process and quality as well as the performance criteria. It is concerned with understanding the current data measurement process, requirements and limitations of Rolls Royce with wired sensor devices, and identifying the key performance criteria, such as testing time, data quality and data gathering latency, for data acquisition in gas turbine engine testing.

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1 Introduction

Wireless and mobile communications, mobile ad hoc networks and wireless sensor networks (WSN) in particular, are enabling technologies for ambient intelligence. Examples of these technologies can already be observed in personal and body area networks, environmental and military applications, structural health monitoring, and home networks. Especially, WSN play an important role for pervasive and ubiquitous computing with their ability to be optimised for data acquisition and ad hoc communication.

Essential to a typical wireless sensor networkapplication are the advanced wireless networking technologies used to provide real-time/on-demand connectivity between the various components of the system. In this regard, the basic functions of the wireless network are:

(1) To distribute in a reliable and timely manner among neighbouring sensors the raw or partially processed data being sensed, comprising the WSN system through single-hop or multi-hop wireless paths;

(2) To communicate through single-hop or multi-hop wireless paths to the data collectors of the WSN system;

(3) To share information between the sensors and a central knowledge base; and

(4) To interface with legacy networks to enable remote monitoring and configuration of the system.

On the other hand, gas turbine engine testing, the WSN application in our project, introduces heavy environmental conditions, such as high metal content, high levels of vibration and extreme temperatures, to the wireless sensor network, which need to be taken into consideration when designing an architecture to realise these basic functions. Thus, the aim of WP3 is to develop an integrated wired-wireless data gathering architecture meeting the requirements of data measurement for gas turbine engine testing, with the following tasks:

(1) The investigation of the application requirements, including the data acquisition process and quality as well as the performance criteria (such as testing time and data gathering latency);

(2) The evaluation of the candidate network architectures (such as cluster, tree and grid topologies) and, using the best candidate, the integration of the high-density wired and wireless sensor devices;

(3) The development of the self configuration and self organisation algorithms for dynamic network topology management.

The outcome of WP3 will enable the subsequent work packages (WP4 and WP5) to be based on the dynamic network architecture needed by the gas turbine testing application to be able to run even under extreme environmental conditions. The need for cooperative and multi-hop communication results in a strict interdependence among functions handled at all layers of the communication stack. The physical, MAC, and routing layers together impact the contention for network resources, as well as the QoS offered to higher layers. The physical layer has a direct impact on the MAC in wireless channels by affecting the signal-to-interference ratio or reliability of a communication link. The MAC layer determines the bandwidth allocated to each node, which naturally affects the performance of the physical layer in terms of throughput. On the other hand, as a result of low throughput and/or high packet delays the routing layer is forced to change its route decisions. Different routing decisions alter the set of links to be scheduled, and thereby influence the performance of the MAC layer. Furthermore, congestion control and power control are also inherently coupled, as the capacity available on each link depends on the transmission power. Thus, a well-designed, efficient and dynamic network architecture, which is the ultimate goal of WP3, needs to support cross-layer approaches.

This report fulfils the first of the tasks listed above and is concerned with understanding the current data measurement process, requirements and limitations of Rolls Royce with wired sensor devices, and identifying the key performance criteria, such as testing time, data quality and data gathering latency, for data acquisition in gas turbine engine testing. In the next sections, first, the application requirements are introduced, and then, the design considerations for the subsequent tasks in WP3 are presented. The report concludes with final remarks for the next phases of the project.

2 Application Requirements

In order to shape our design, we need information on the types of data being sensed, such as air pressure, wind speed, temperature, and used in gas turbine engine testing. We are also interested in the traffic patterns generated as a result of the sensing activity. In other words, we'd like to know the size, frequency and priority of the generated data. We will use this information to optimise our architecture, communication algorithms and data aggregation methods according to the requirements of the application. We will also define the design parameters and capabilities of the sensors accordingly. Examples of these parameters are signal processing, storage, communication range, energy consumption, and reliability.

In summary, we are interested in the answers to the following questions:

(1) What are the phenomena to be measured?

(2) What types of measurements should be expected?

  a. Event-driven vs. periodic;

  b. Real-time vs. store-and-forward.

(3) What is the frequency of measurement?

(4) What is the average and maximum size of data to be communicated?

(5) What are the system requirements, upper and lower bounds on the following?

  a. Measurement accuracy;

  b. Data reliability;

  c. End-to-end data delivery delay;

  d. Packet loss rate; and

  e. Bandwidth.

(6) What are the expected environmental conditions?

(7) What are the system installation requirements and constraints?

Two key applications are identified for using wireless sensor networks in gas turbine engine testing. These are discussed in the following sections with regard to the questions above.

2.1 Development and Production Testing Measurements

Development and production testing takes place under the extreme environmental conditions summarised in Table 1.

Table 1. Environmental conditions during development and production testing

Oil system temperature	250˚C
Air temperature	350˚C
Metal temperature	1100 - 1300˚C
Pressure	40 – 42 bar
Vibration	40 g

1000 thermocouples, 1500 pneumatic lines, and 500 accelerometers are used during the tests to measure and record the temperature, pressure, and vibration, respectively. The instrumentation lead-out for this test configuration is very costly, exceeding 12 km in cabling. Although the engine has a modular structure, the modules cannot be swapped due to cabling. A solution to this problem, currently under development in the "Distributed Engine Mounted Instrumentation Conditioning" (DEMIC) project, is to let each module have its own measurement instrumentation. However, this solution would still be wired, which makes a fully wireless measurement alternative more attractive to address the lack of modularity problem.

Typically, two test sessions with a total testing time of 500 h per year is estimated for each set of measurement instrumentation, with the chance to recharge the batteries of the sensors between these two sessions. However, there are still concerns over powering for the wireless solution, mainly due to cooling needed for the sensor devices. Cooling at this temperature (350˚C) typically requires 15 W. Unfortunately, current energy harvesting techniques cannot reach this power level.

The characteristics of the measurements by the thermocouples are given in Table 2. From this table, it can be concluded that 2 bytes are sufficient to store the actual data, whereas another 4 bytes are needed to store the time of the data and to identify the sensor measuring it. Thus, a total of 6 bytes, i.e. 48 bits, are used for each sample, which results in a bandwidth requirement of 1.5 kbps per sensor. Given the current wireless communication capabilities of wireless sensor networks, this data rate can be achieved and maintained easily. These values can change later due to the fact that all data is actually stored in bulks and interpreted later, and only a subset of the data is monitored in real time for emergencies during the tests. Nevertheless, the values are still realistic, i.e. they are close estimates to the real world operation of the system.

Table 2. Measurement characteristics

Dynamic measurement range	From -50˚C to 1600˚C
Data resolution	0.1˚C
Sampling rate	33 Hz
Timing accuracy	1.5 μs
Estimated packet size per sample	48 bits
Estimated bandwidth per sensor	1.5 kbps

The measurements we are interested in are basically the external vibration and the internal temperature, both of which are quite homogeneous. In other words, the requirements concerning these measurements are the same regardless of the position of the measurement. On the other hand, the sensors are placed at fixed, known positions on the engine and each of them needs to be uniquely identifiable. There will also be a small number of sensors added at a later stage of testing. Their locations will be deterministic from the viewpoint of the user, but the sensor network in operation needs to include them in its topology as soon as they become alive.

There is a three-level hierarchy in the current, wired test and measurement instrumentation. The first level consists of the sensors on the engine. The concentrators collecting data from the sensors comprise the second level. Finally, the third level is made of a data centre collecting data from the concentrators. The connections between the entities in this three-level hierarchy are all wired. Thus, it is a significant improvement in the test system to replace the wires with wireless communication even in one of these connections.

2.2 In-Service Engine Health Monitoring Measurements

The measurements concerning the in-service health monitoring application are inherently different than the development and production testing measurements. For instance, ad hoc communication capabilities, such as self configuration, self organisation, and self management, are required to support unplanned, dynamic measurements conducted with a small number of sensors, placed on the engine and communicating, directly or in a multi-hop fashion, with a control unit. Wireless sensor network technology is suitable for this type of operation and, thus, can provide the features required for rapid diagnostics.

3 Design Considerations

In addition to the application specific requirements explained above, we also have general design considerations related to energy efficiency, network architecture, wireless medium access control (MAC), and routing. This is a necessary step towards meeting the objectives of the subsequent work packages, WP4 in particular, defined as follows:

(1) Evaluation of different MAC and routing protocols to satisfy performance and quality requirements of data acquisition in gas turbine engine testing.

(2) Selection and further development of communication protocols considering realistic radio channel characteristics and integrated wired/wireless network architecture.

(3) Cross-layer design and optimisation of communication protocols, in order to reduce signalling overhead, improve performance, energy efficiency and reliability.

The constraints related to the physical world are common to all types of sensor applications, so that research on physical and link layers usually focus on system-level energy awareness. When designing at the network layer, on the other hand, application requirements need to be considered in the design process to ensure efficient resource management. With respect to MAC, it is essential to utilise the wireless medium as efficiently as possible, while maintaining a long network lifetime. With respect to routing, the main aim is to set up and maintain energy-efficient routes to deliver sensor data to sinks (and, eventually, to a central controller) in a reliable manner while keeping the network up and running as long as possible. In this regard, energy efficiency can be considered as the primary design objective, the common denominator of all WSN routing approaches, which relates to both the selection of the routes as well as the overhead of routing.

3.1 Design Considerations for Medium Access Control

These requirements fall loosely into three groups, namely system constraints imposed by data patterns and network topology, performance requirements and essential design features.

3.1.1 Periodic Data Flow

The periodic sensor measurements will tend to generate a periodic data flow of data from the sensors to the collectors. This implies a schedule-based MAC approach, in order to effectively exploit this pattern to maximise performance. Some spatial correlation between the sensor measurements is expected. The MAC protocol must have the ability to manage the local data communication in a manner that enables this available data redundancy to be exploited.

3.1.2 High System Spectral Efficiency

The periodically generated sensor data requires real-time processing and fast delivery to the collectors. Maximising the system spectral efficiency (throughput per unit bandwidth per unit area) in the multi-hop sensor network is essential to minimising latency and maximising energy efficiency. Therefore, a high system spectral efficiency MAC protocol is required that minimises data forwarding delay between the tiers of the network hierarchy and maximise the number of sensors communicating simultaneously.

3.1.3 Receiver Channel Sensing

Interference management between groups of sensors is a major challenge for the MAC protocol. Interference can be managed by centralised scheduling coordinated by the parent node of the highest tier. However, without receiver channel sensing, this results in either over-provisioning at best or poor interference management at worst, both of which deliver poor system spectral efficiency. Receiver channel sensing requires that scheduled transmitters listen for feedback signals from receivers in other parts of the gas turbine engine in their vicinity to determine (based on channel reciprocity assumptions) whether they can transmit without causing unacceptable interference to these vulnerable receivers. This information can be used by the parent nodes to optimise the schedule to maximise system spectral efficiency.

3.1.4 Minimum Handshaking Overhead, Idle Listening and Overhearing

Sender-receiver handshaking via request-to-send (RTS) and clear-to-send (CTS) messaging prior to data transfer (DATA) is unnecessary for deterministic periodic data, and yields potentially significant overhead given that sensor data typically comprises of short bursts of data. However, receiver acknowledgements (ACK) provide a powerful means of enabling interference awareness. Therefore, MAC approaches with DATA/ACK are preferable to RTS/CTS/DATA access. Furthermore, idle-listening to channel activity and overhearing data of other links must be minimised to enhance energy efficiency since, while enhancing the interference management capabilities, they consume a lot of energy.

3.1.5 Minimum Storage of Neighbourhood States

Neighbourhood data is required to identify communicating nodes, their bandwidth requirements and channel allocations, as well as what nodes are available to relay data to the next hop neighbour and the quality of communication on each one. However, given the high density of nodes and the need to maximise the use of the limited storage resources, it is essential to minimise the amount of neighbourhood data stored at each node.

3.1.6 Scalability, Self Healing and Adaptability

The MAC protocol must be capable of supporting a high density WSN with multi-hop communication. It must able to quickly recover and reconfigure the network connectivity and update the transmission schedule in the event of unpredictable changes such as, sudden node unavailability or recovery of a previously unavailable node, which impact on the traffic and interference patterns.

3.2 Design Considerations for Routing

Considering the gas turbine engine testing application scenario, several assumptions need to be made on the topology of the network, flow of information, amount of data, energy and QoS requirements of the nodes. Once these assumptions are made, a requirement specification can be given and compared to the characteristics of the existing routing protocols.

3.2.1 Network Dynamics

The sensor nodes will be stationary. Most probably they will have a grid-like topology along the surface of the engine. This will make it relatively easy to define routing paths and, if necessary, map geographical regions (relative to the engine surface) to network addresses in a deterministic way.

3.2.2 Node Deployment

Manual node placement will be possible. However, the sensor nodes will be wireless, which means that they will be battery-powered. Since many sensors will experience temporary as well as permanent communication problems due to the extreme environmental conditions, self-organisation will also be needed in the network.

3.2.3 Data Delivery Model

Most of the flow of information will be periodic. To a relatively small extent, event-driven information gathering can be required to enable the test system to record unexpected and rare events.

3.2.4 Node Capabilities

It will be possible to install a relatively small number of sinks with unlimited energy and high computational power to the WSN. Being considerably more powerful, the sinks can be configured as gateways to the wired or wireless infrastructure backbone network. They can take over heavy duties such as collecting, processing and interpreting data. However, energy considerations will be in charge for the rest of the WSN.

4 Conclusion

In this report, we investigated the current data measurement process, requirements and limitations of Rolls Royce with wired sensor devices for data acquisition in gas turbine engine testing, and presented our design considerations regarding the development of efficient MAC and routing protocols in the next phases of our project.

Further general design objectives have to be taken into account for an effective network. For instance, similar to the case of conventional networking, scalability is one of the major attributes for WSN. A flat network topology can cause the gateway node to become overloaded with the increase in sensor density, which causes delay in communication and data loss. To allow the system to cope with additional load and to be able to cover a large area of interest without degrading the service, hierarchical routing protocols form clusters to organise sensor nodes into. Nodes are encouraged to take part in multihop communication within clusters, which allows them to transmit messages using less power. The cluster heads aggregate and relay data to the sink. This approach decreases the energy consumption of single sensor nodes as well as the number of transmitted messages to the sink.

The lifetime of a sensor network typically consists of long periods of idle state, interrupted by short periods of high traffic volume. It is not viable to make all battery-powered nodes active all the time in sensor networks, because it reduces the network lifetime. Keeping only a minimum number of nodes active to save energy, however, introduces a potential problem—as soon as the network enters its high activity state, congestion is likely to occur because the data rates may exceed the capacity available from the currently active nodes. Once congestion occurs, many packets that contain valuable data may be dropped, the loss of which can defeat the very purpose of the application. Thus, resource management and adaptation, i.e. increasing capacity by turning on more resources to accommodate high incoming traffic during the active state, becomes essential for WSN. The goal of resource management and adaptation is to increase the fidelity level observed by the deployed application while minimizing the scarce energy in the network. To meet these requirements, an efficient resource management scheme should consider traffic rate, congestion level and, most importantly, network topologies.

There are several solutions proposed to tackle these challenging research problems. We will investigate some of these solutions and include them as necessary to our algorithms as we continue our work by evaluating candidate network architectures and developing self organisation algorithms for dynamic network management.