Wireless instrumentation for aerospace applications—thermal monitoring for a gas turbine engine

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Wireless Instrumentation for Aerospace Applications – Thermal Monitoring for a Gas Turbine Engine

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***Abstract* – Rolls-Royce are pioneers in the concept of "power-by-the-hour", whereby they no longer sell gas-turbine engines and leave maintenance and spare parts costs to the customer but rather sell a service agreement to provide thrust on an hours of use basis. This approach has reoriented engine manufacturers from selling spare parts to trying to maximise each engine's longevity. This reorientation has introduced a new emphasis on sensing and monitoring. An example is the temperature sensors harness developed by Vibro Meter UK, a wholly owned subsidiary of Meggitt Plc. Their thermocouple probes are able to withstand the high temperatures found within the gas stream. In principle, the large number of thermocouple sensors mounted within the engine could provide detailed thermal maps and thus provide for accurate diagnosis of potential problems before they occur. A difficulty, however, is that sending all the individual sensor data back to the control unit would require a large amount of heavy duty cabling, thus significantly increasing the weight of the engine. To avoid this, sensor values are averaged, and only a single cable is used.**

Even a single cable may be more than is necessary, however. By making use of wireless technology, low-power electronics, and advanced visualisation techniques researchers at Coventry University's Cogent Computing Applied Research Centre (CCARC), are developing a system to wirelessly connect the high temperature thermocouples and perhaps other sensors on the gas turbine engine. Furthermore, they are looking at developing visualisation tools to ensure that the much more detailed gathered data can be easily interpreted. It is hoped that the development of such a wireless sensing system will lead to several important benefits: it will reduce the weight of the engine; it will allow a detailed map of temperatures within the gas flow of the engine to be obtained; it will allow sensor faults to be detected more readily.

I. Problem Statement and Project Goals

Measurement of temperature in a gas turbine engine is critical to its control and the assessment of its health and performance. Currently, gas temperature is measured predominantly by thermocouples installed at a number of sites within the engine. For example, in the exhaust region of the engine, the temperature is measured at different circumferential (and often radial) positions via an array of thermocouples connected through harness cabling. Transmission of individual thermocouple data to the central control unit would require many individual cables and so, due to weight restrictions, measurements are averaged before transmission over a single heavy duty cable to the central control unit. Not only does this preclude the determination of a detailed picture of the engine gas temperature, which could indicate potential engine problems, but also prevents the diagnosis of individual sensor faults, de-calibration, and drift detection.

The use of wireless technology to create a wireless instrumentation system could substantially increase the complexity of the data that could be sent to the engine control unit and hence enable more sophisticated engine health monitoring. Further, replacing cables with wireless transmissions will reduce the monitoring system weight and lead to improved fuel efficiency and reduced carbon emissions. On-line statistical analysis of data from such a wireless system could also permit a clearer understanding of engine/aircraft health. The system proposed here will allow condition-based maintenance, whereby maintenance can be scheduled according to actual wear and usage rather than at fixed intervals, thereby reducing through-life costs.

In addition, a wireless system could allow for the sensors in the network to communicate their "health metrics" with each other, in turn allowing fault and drift detection to be identified and possibly corrected for in the control systems. This would give much greater confidence in the accuracy of the measured temperature and could, potentially, allow the engine to run with less safety margin and, therefore, more efficiently (with similar benefits on fuel consumption and emissions).

However, embedding wireless technology into an aerospace or industrial gas turbine will have some very significant challenges to overcome, particularly for aero-engines, which require a very high degree of safety assurance and certification. With regard to temperature measurement, for example, the temperatures outside the casing of the engine can reach in excess of 250°C, precluding the use of most conventional silicon-based electronic systems. Moreover, maintaining the integrity of an RF signal transmission in an environment that is largely composed of metal whilst not interfering with (or being interfered by) other electronic equipment will present major hurdles. Powering the sensors also presents a significant challenge as battery power is not appropriate, hence some means of energy harvesting will be required. However, if these hurdles can be overcome, the benefits to engine management will be significant and could also pave the way for use with other types of engine sensors such as tip clearance and speed sensors.

Work is only beginning on this project, however a demonstrator with five wireless nodes and 24 temperature and sound sensors has been created and a back-end system for receiving, storing, analysing, and visualising this data has been implemented. The end-to-end system has been successfully deployed and detailed testing carried out.

This project is funded as a three and a half years EPSRC CASE Studentship through the Integrated products Manufacturing KTN and it is officially due to start in September 2008.

II. System Design and Architecture

The instrumentation system presented here is designed to sit within a larger conceptual flow as represented in Figure 1. Temperature is sensed at a number of circumferential and radial locations ("sense") within the gas turbine engine. Raw sensor data is noisy and in some cases, sensors may be faulty. Modelling using a Kalman filter ("model") smoothes the data, making use of assumptions about the rate of change of temperature.

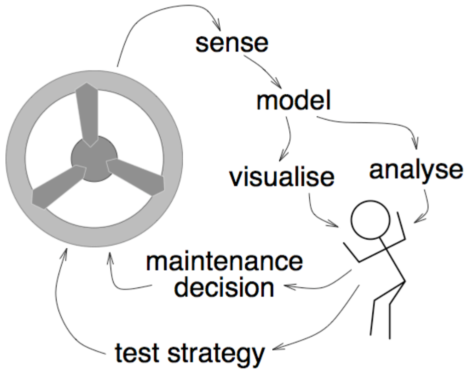

Figure 1: Conceptual flow for prototype gas turbine engine monitoring system

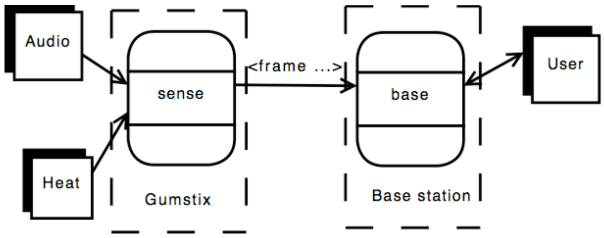

Figure 2: System overview

An interpolation model is also used here to derive a field function that fits the sensed data. From the model, real-time visualisation ("visualize") is performed, allowing temperature events to be identified as they occur. Furthermore, analysis of data over a time period ("analyse") can also be performed off-line, post event.

These two information flows allow the human expert to either derive a "maintenance decision" (such as a component or sensor is faulty and must be replaced), or to devise a "test strategy" (such as modifying the engine actuation in some way to try to even out the heat distribution). The set of steps and actions can be seen as part of a control loop, feeding back changes to improve or maintain the engine.

Several end-to-end system requirements have been established for the prototype described here. The instrument should enable:

- *multi-point and multi-modal sensing*

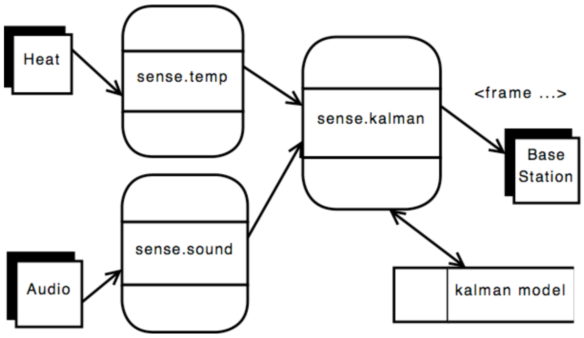

Figure 3: Breakdown of the “sense” component

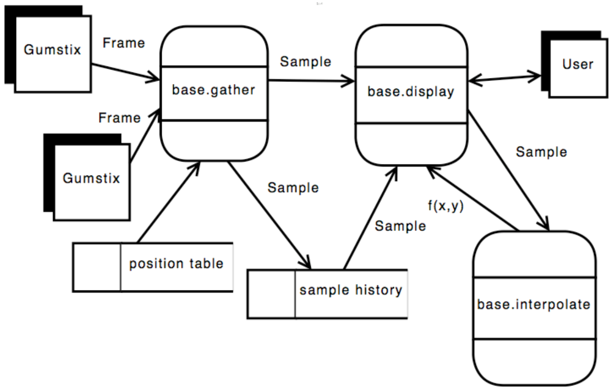

Figure 4: Breakdown of the “base” component

The system makes coherent use of 20 temperature sensors at different points circumferentially and at differing radial depths. It also supports 4 sound sensors thus demonstrating multi-modal sensing.

• *field mapping of sound and temperature and rate of change of temperature in real-time*

A central aspect of the prototype is the development of a visualisation tool that allows not simply the viewing of individual point data but viewing and interpretation of whole planar area profiles. For points where there are no sensors, an estimate is made via interpolation. Three forms of interpolation have been implemented (Radial basis function, Quadratic Shephard 2D, and Nearest neighbour) and their performance evaluated in terms of accuracy.

The in-network Kalman filter provides smoothed rate of change of temperature as well as smoothed temperature and this can optionally be used as the basis for generating the field map.

• *selection of sensors for history/time-series type display,*

Historical time-series display are displayed for selected sensors. This allows assessment of trends and focusing in on a single sensor point.

• *data storage*,

As well as real-time display, data received at the base station is also logged in a central MySQL database, with the user option of setting individual records as tests proceed and hence allowing easy data retrieval for post-test analysis.

• *post event data retrieval*,

Based on the logged data, it is possible to perform post-event data retrieval and analysis.

• *cross-validation of the mapping produced at point and over specified intervals of time*,

One form of post-event analysis that has been developed is a cross-validation tool, allowing different interpolation schemes to be compared.

• *system extendibility (ease of addition of sensors),*

The design of the system makes it easy to add or replace sensors or nodes. New nodes can be added in by simply configuring their location.

• *integration of calibration tools*

To allow for varying response from different sensors, calibration coefficients are built in to the system. Post event analysis tools have been developed to help with tuning the calibration coefficients.

• *network debugging and testing*

A number of tools have been developed to assist with automating the process of updating software on nodes, stopping and starting sensing software on all nodes, and to ensure time synchronisation (making use of NTP- Network Time Protocol). Network latency analysis tools have also been built into the system as well as tools for nodes connectivity continuous assessment. Visual output to the user is generated when nodes fall out of the network or rejoin the network after periods of communications loss.

Figure 2 shows a high-level abstract view of the system. External phenomena are sensed in two modes: Audio and Heat. (The Audio component is presently a place-holder for the investigation of vibration monitoring. The decision to use microphones at this stage comes from the similarity of vibration and audio data in terms of format, frequency profiles and data rate.) The sensors are attached to wireless processing nodes that communicate with the base-station. Mode dependent sub-components deal with temperature and sound, while a generic filtering system applies either no filter, a simple Kalman filter and a more sophisticated Kalman filter that provides an estimate of the rate of change of the sensed value. The base-station, which is running on an ordinary desktop/laptop computer, is responsible for storing data, displaying the visualisation and interacting with the user. The “sense” and “base” components are shown in detail in Figures 3 and 4.

The `sense.temp` module makes use of an in-house written I^2C library to query each temperature sensor in turn. Timestamps are also gathered at this point. The use of NTP is important here in ensuring that the timestamps correspond to the actual time. Through trial and error, we found that a cycle time of about 0.25 seconds maximised the data rate without causing congestion or loading the processor too heavily.

The sense.sound module uses the on-board AC'97 processor and periodically extracts signal peak levels over short periods of time.

The sense.kalman module performs filtering on the data. The initial approach for filtering was to use a simple Kalman filter that took no account of the proximity of nearby sensors or their current reading but rather assumed that the ground truth sensor value was constant. The Kalman ``model'' is on a per sensor basis and consists of the current estimate and the covariance matrix. It was found that the assumption of constant value was not valid for sound, which tends to vary rapidly and a pass-through filter was used instead.

A later requirement added to the system specification was to allow the user to visualise the rate of change of temperature. To support this, a new Kalman filter was developed based on the assumption of a constant rate of change of temperatures. The advantage of this approach is that both the value and the rate of change are smoothed.

The base.gather module is responsible for receiving frames and breaking them up into individual samples. Each frame is a recording of the environment at a given instant and can contain multiple samples – two volume measurements, for example, for the audio sensing mode. The base.gather module tracks the current state of the sensor value and reports this, on request, to base.display. The timestamps of original transmission is used to determine if the value is ``stale''. The base.gather module also logs all received sensor samples to a remote MySQL database. This module deals with both calibration of sensor values (by applying a linear transform) and identifying the position of the nodes physically and on-screen.

In base.interpolate, three interpolation methods have been developed, the first two of which have been fully integrated into the end-to-end system:

- cinterpol - based on a radial basis function (RBF) applied to provided sensor points
- QSHEP2D - based on a series of quadratic curve fits
- Nearest neighbour – estimating the value for any point as being the same as its nearest neighbour.

The user-interface allows the user to select which interpolation algorithm is to be used. Furthermore, a number of false-colour schemes have been developed: red-scale (values between black and red); jet-map (provided by TRW); thermograph. The thermograph false-colour scheme has been selected for the current prototype.

The maximum and minimum values of the interpolated result are used to scale values before being mapped through the false-colour lookup table.

The interpolated region shape is a ring (doughnut). Specifically, it is a large circle with a smaller circle cut out from the centre, representing the hollow region of the engine exhaust (lumen). A number of options for region topology exist. The method used here is to consider the distance between two points to be the Euclidean distance.

The base.display module displays interpolation results and history of a selected point. The base.display module has the following main functions to perform:

- periodically (or as often as possible) requests gathering of new samples
- initiating the logging of data to a database
- interpolation of current data
- displays interpolation results and history of one node
- allows configuration, including: whether to display sound or temperature; selection of which sensor to provide history for; block size (to improve or reduce resolution); desired frame rate (adjusting block size automatically to meet set frame rate)

III. Integrated Prototype Description

The deployment environment for the prototype instrumentation consists of a jet pipe, with the sensors mounted in a radial pattern within the pipe. Sensors are wired in sets to five microprocessing and communication units (Gumstix boards with Bluetooth communications) mounted on the outside of the jet pipe (Figure 5). Sensor values are wirelessly transmitted to a base station (a laptop), which provides a visualisation of the temperature map over the monitored surface area, field profiles of the temperature rate of change and, on demand, a history of individual sensor values. As well as thermal sensors, a smaller number of microphones

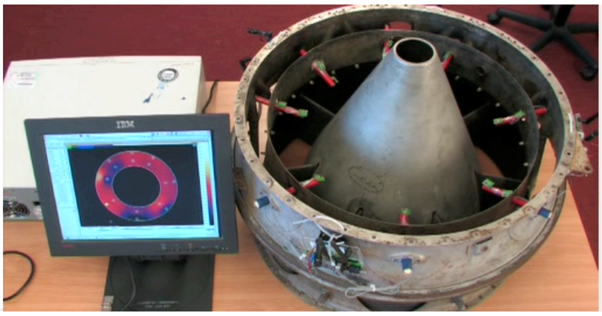

Figure 5: Base station and instrumented gas turbine engine

are connected to demonstrate the possibility of adding in a variety of types of sensors and the ability of the prototype to function with high bandwidth sensors.

All-in-all, the wireless gas turbine engine monitoring system consists of 20 temperature sensors (IC-type with an I^2C interface); 4 microphones; 5 processing nodes based on Gumstix Connex 400xm-bt, with custom-built expansion board to provide audio and I^2C connectivity and a base station with visualisation software and a non-volatile database for storage.

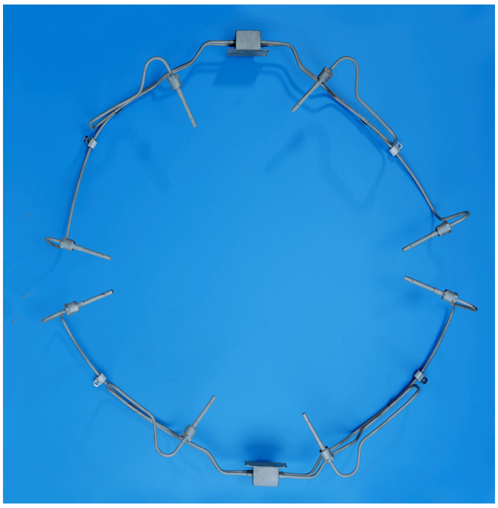

Figure 6: Vibro Meter's existing thermocouple harness

Temperature sensors are arranged in a similar manner to Vibro-Meter's existing thermocouple harness shown in Figure 6.

The Connex Gumstix board includes an Intel XScale PXA255 400MHz processor, 16MB of flash memory, 64MB of RAM, a Bluetooth controller and antenna, and 60-pin and 92-pin connectors for expansion boards. The custom expansion board provides Zigbee communications via a MaxBee chip, I^2C bus support, and audio processing. Temperature sensing is provided via the Analog Digital ADT75A chip, which performs sampling and conversion internally, before delivering the sensed temperature values via an I^2C bus. The ADT75A provides temperature resolution of 0.0625 degrees Celsius via a 12 bit ADC, and is rated for operation between -55°C and +125°C.

Software running on the board performs Kalman filtering and forwards temperature and audio sensor data via Bluetooth to the base station. Base station software receives temperature and sound samples and interpolates one or the other in real time to obtain an estimated map of temperatures. Stale sensor values (possibly due to sensor faults or power loss) are also identified and excluded from the real-time map. Historical data is maintained and can be queried by selecting any sensor from the display.

IV. Evaluation

Preliminary evaluation of the system as a whole and in parts has been performed. Over a period of 10 days, in excess of 1 million samples have been logged in the database and made available for post-analysis. Results and observations are detailed below.

Networks and end-to-end system performance

The wireless network performance has been analysed in terms of latency, data throughput, bandwidth and communications range. It was found that the average time taken for data to travel through the system was 0.15 seconds with a minimum of 0.12 seconds and maximum of 0.19 seconds for each data sample.

The maximum transmission range has been found to be 11 meters indoors after which the transmission signal was lost, This is consistent with the quoted range for class 2 Bluetooth devices.

The system overall appears to be sufficiently robust for this stage of development and has run for up to 10 days without incurring any data loss or, indeed any problems.

Sensing devices

As with any measurement system, sensor calibration is an important issue. The system reported here has been built with low cost integrated temperature sensors that would not be suitable for industrial deployment where reliably accurate temperature measurement was required. Repeated experimentation with the ADT75A showed that in near uniform environments their response varied greatly. Both offset and slope errors in factory calibration are significant. Whilst the effects can be alleviated through additional calibration (using the integrated calibration facility) experimentation has shown that the temperature response tends to drift over time and an adjustment to the calibration is needed after a day or so. The error in sensor values prevents a clear evaluation of the absolute temperatures visualization and interpolation procedures. However, the "rate-of-change" ("delta mode") visualisation method removes some of the problems to do with lack of calibration as it inherently ignores offsets between sensors and is hence explored below.

Given that the project aims to use high quality thermocouples with well specified properties and well understood behaviour in the next prototype, it is expected that all parts of the system will then be more precisely evaluated.

Interpolation and visualization

While the data generated by the sensors provides known points in the interpolation, it is important to be able to assess the effect sensor failures on the field representation of the phenomena (i) and to have a means to measure the quality of values predicted between these points leading to the field representation of the sensed phenomena (ii).

(i) In order to assess the effect of sensor faults and their respective replacement in the field by interpolated values, the aforementioned "leave-one-out" cross-validation tool has been developed. The tool allows the user to retrieve historical data from the database for off-line processing and evaluation. Upon user selection of a logged test and selection a point in time within the test, the cross-validation tool excludes the data for each sensor in turn and attempts to predict it from the remaining points. The difference between the actual and predicted values provides an error value and hence an indication of the interpolation quality. The root-mean-square (RMS) of the errors above over the duration of the test also provides a good indication of the level of error expected to be encountered if a sensor has failed. An example of interpolated versus actual sensor values for a cross validation run is given in Figure 7, for one selected sensor.

(ii) The "leave-one-out" cross-validation procedure, however, does not provide a clear measure of the difference between real and predicted values *between* the sensed data points. In order to assess the quality of the interpolation between points, the fifth node in the networks, geared with 4 temperature sensors is used as a "probe" node. This node and its sensors have no fixed location. Instead, the sensors are used to take measurements at arbitrary points in various test runs. Combined with the cross-validation tool, the probe provides a method to determine the accuracy of predicted (interpolated) temperature values between nodes.

V. Concluding Remarks

The system proposed has a high innovative value, potentially allowing detailed in-flight monitoring of temperatures within a gas turbine engine, with extension to a wide range of potential aircraft monitoring applications. A key potential benefit of the approach is weight reduction through replacing cabling with wireless transmission. Additional benefits are in the area of providing better exploitation of available sensor data through computer visualisation of the data and autonomous identification of sensor faults.

The work described here is building on existing test-bed demonstrators and visualisation systems at the Cogent Computing Applied Research Centre. The application domain specialism is covered by Vibro Meter UK through Dr. Mark Langley whilst the electronics for harsh environments issues are brought forth with proposed solutions by TRW Conekt through Roger Hazelden.

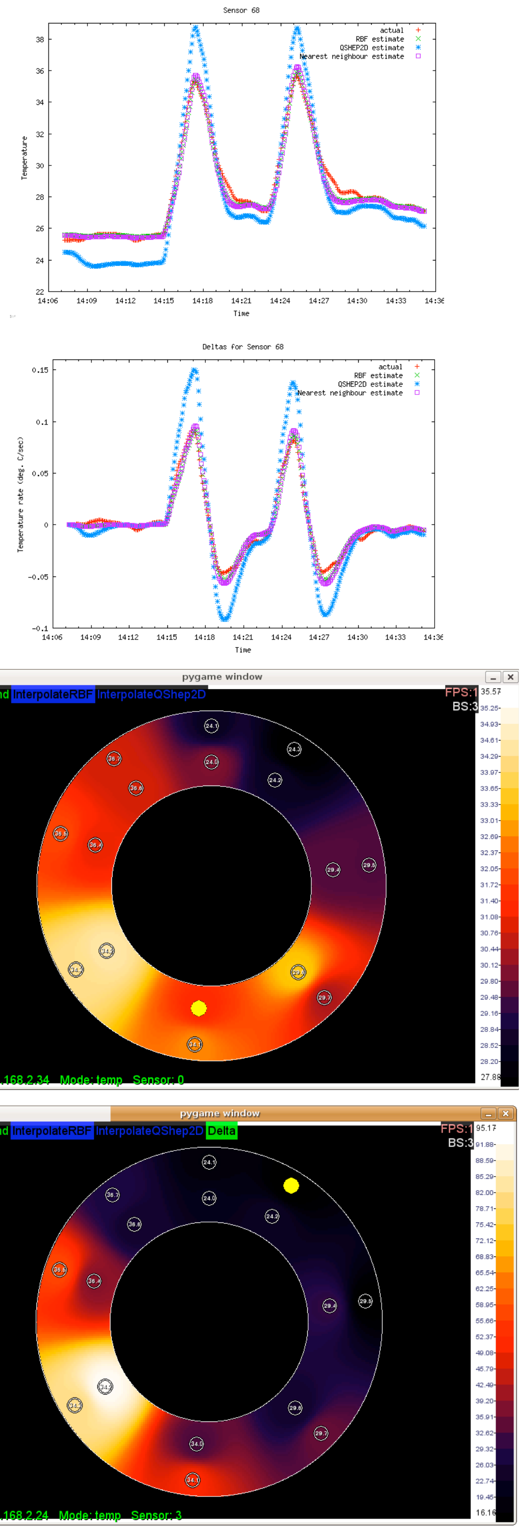

Figure 7: Cross-validation results for two heating and cooling cycles. Top first: Actual temperature values from one sensor and estimated temperature through RBF and QShep2D interpolations based on all other sensors; Second: Same as the first graph but with temperature rate of change ("Delta-mode"); Third: Field view of temperatures using RBF interpolation; Forth: Field view in "Delta-mode" using RBF interpolation