Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Measurement

DOCTORAL THESIS STATEMENT

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Wireless diagnostic methods in an aerospace application

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Those interested may get acquainted with the doctoral thesis concerned at the Dean Office of the Faculty of Electrical Engineering of the CTU in Prague, at the Department for Science and Research, Technická 2, Prague 6.

....

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Contents

Chapter 1

Introduction

The early alert monitoring system for an effective scheduled maintenance strategy based on a wireless technology requires reliable transfer of diagnostic information between the sensor and the gateway. The thesis presents WSN-based machine condition monitoring (MCM) system capable of overcoming a false indication caused by temporary loss of data, signal interference or invalid data.

We establish multi-sensor fusion driven by a quality parameter, produced by each sensor node according to the data history outliers and the actual state of the node. The fusion node also provides a quality evaluation on its output.

This novel approach enables the propagation of information about the uncertainty of a measured value from the source node to the sink node. Thus potential degradation of acquired or transferred diagnostic information is minimized. Instead of raw data the signal features are transferred, so that bandwidth savings are improved considerably.

The proposed concept was experimentally verified on real WSN hardware. The performance evaluated using the Signal-to-Noise ratio and false alarm rate detection demonstrates the effectiveness of the proposed approach. The results confirm that the proposed system has similar reliability to a sensor connected by wire to a central unit.

The machine condition monitoring system based on WSN with multi-sensor fusion is able to monitor a critical application, and even to monitor light aircraft powerplants.

Chapter 2

State of the art

Commercial air transport is one of the safest forms of travel. This has been proved by data collected and published by national, union and international aviation safety authorities like ICAO (International Civil Aviation Organization) and EASA (European Aviation Safety Agency) [1–3]. However, light aircraft (Maximum Take Off Mass below 2250 kg) with the very rapidly growing subcategory of microlights (also called ultralights) used for recreational, personal and sports flying do not show such positive safety records as for larger aircraft. For example, EASA data records 129 fatal accidents in 2010 and 169 fatal accidents in 2011 in the EU countries.

One of the factors affecting the progress in commercial aircraft safety, alongside improved aircraft design, engineering, the evolution of navigation aids and avionics, has been the development of maintenance schemes [4]. In contrast to the highly-developed maintenance scheme and the strict inspection processes for CAT operation aircraft, light aircraft do not use any condition-based approach to maintenance.

2.1 Machine condition monitoring (MCM)

Present-day machine condition monitoring (MCM) techniques are able to detect many types of mechanical faults in the industrial field. Early fault detection of a rotating device, e.g. imbalance, misalignment, bearing faults, and mechanical looseness protects the device against a fatal accident.

The increasing number of light and very light aircraft for personal use (i.e. sightseeing, sports activities, or private flights) has led to an increased number of accidents. Hence the general idea of this thesis is to introduce a low-cost early warning system into newly-produced and also currently operating light aircraft.

The adoption of network communication technologies in factory monitoring and automation systems also establishes new technologies for MCM systems. Recent research papers refer to wireless MCM techniques [5]. Wireless sensors and their networks can offer very attractive progress not merely in factory monitoring but also in the aerospace area.

2.2 Wireless MCM

The main benefit of a wireless approach, as opposed to a wired system, is that there is unrestrained sensor placement, installation and maintenance. A wireless sensor can be freely mounted on moving, rotating parts and in many types of environments, including hazardous areas. In addition, a wireless sensor is easier to install in new or already-functioning machinery equipment.

Technology with sensing, data processing and communication capabilities is referred to as a Wireless Sensor Network (WSN) [6]. WSNs are characterized by flexibility, self-organization, self-configuration, inherent intelligent-processing capability, and the ability to be deployed rapidly [7]. The sensor nodes employ miniaturized hardware design, miscellaneous sets of energy-efficient communication protocols [8,9], various communication technologies [10], suitable power sources and energy management [11]. However, sensor nodes have constrained hardware resources due to power supply from batteries or from energy harvesting systems. This has a significant effect on transfer rate and computing complexity.

Some producers of MCM systems already offer a wireless monitoring solution where the wire connection is replaced by wireless technology. Two basic approaches are used:

- **A broadband wireless technology (e.g. Wi-Fi)**: This replaces signal cables from sensors to a central processing unit. The power supply remains wired due to the high energy consumption of broadband wireless sensors (Wi-Fi uses up to 100 mW transmitting power). This enables high-speed data transfer from sensors to a freely mounted central unit. The benefit is a constantly uncluttered workspace even if many sensors are engaged.

- **A self-powered wireless sensor**: This type of system has to be composed from low-energy consumption hardware, an optimized software code and adapted signal processing methods. For example, the sensors acquire signals in time slots or react to specific excitation (some event occurs or the threshold of a measured value is exceeded), otherwise they are in sleep mode to save energy. The sensors are then wire-free stand-alone units.

Recent research papers refer to wireless sensors and their networks for industrial deployment as Industrial Wireless Sensor Networks (IWSNs) [12, 13]. IWSN ideas result from an effort to introduce and adapt already known wireless sensor network (WSN) technology into industrial applications. The centralised star topology that many systems currently use does not utilize the sophisticated networking available under a WSN system. The WSN concept is based on a large mesh network between nodes equipped with a sensor to ensure a reliable measurement task over a wide area. The sensor nodes employ a miniaturized hardware design, miscellaneous sets of energy-efficient communication protocols [8, 9] and communication technologies [10], suitable power sources and energy management [14]. The sensor node is able to carry out only simple computing tasks due to restrained resources, but if signal and data processing distribution among nodes is engaged, the network achieves robustness and sophisticated functionality.

Various already published subsystems can be well utilized in MCM. However, propagation of maximum information content picked up from a device by sensors to a sink node, while the system complexity and the energy consumption of each node remain reasonable, remains a major challenge for WSN application in the CM area. To the best of the author's knowledge, several studies for high-sampling IWSN systems have been presented in the literature, but no complex solution is available, not even in another application than MCM.

Chapter 3

Aims of the doctoral thesis

Sudden loss of aircraft power plant power is a very stressful situation in which pilots have a tendency to make an incorrect judgment leading to an accident. A warning signal or a message from an aircraft condition monitoring system can alert the pilot to oncoming failure in advance. A well-informed pilot can make a more confident decision [15]. The system has to detect a fault before it develops into a serious failure. In addition, comfortable installation and maintenance are required, without increasing the overall weight and complexity of the avionics. This type of situation is a major challenge for wireless sensor networks, where it is attractive to have a simple mounted sensor node capable of monitoring abnormal device behavior, communicating with neighboring sensors in order to process data, and transferring the results to an indicator on the instrument panel of an aircraft.

3.1 Specific aims of the doctoral thesis

The early alert monitoring system for an effective scheduled maintenance strategy based on wireless technology requires reliable transfer of diagnostic information between the sensor and the gateway. This thesis aims to improve WSN reliability to the level achieved with a wired connection, by means of:

- **WSN-based MCM system design**: The present-day WSN scheme used for monitoring purposes (presence of enemies, forest fires, etc.) is not feasible for signal monitoring using high sample rates. The aim is to propose a new scheme based on distributed signal processing methods, taking into account the nature of diagnostic signals.
- **WSN reliability improvement**: A redundancy-based fusion concept is capable of overcoming a false indication caused by temporary loss of data, signal interference or invalid data. This is especially true if multi-sensor fusion is driven by a quality parameter corresponding with sensor node imperfections (signal jamming, health of a sensor node - battery discharging).

- **WSN bandwidth savings**: A raw diagnostic signal represents a huge number of samples in addition to the redundancy concept, which increases the amount of data in the input section of the network. Instead of raw data, the signal features will be transferred and a compression method will be engaged.

- **Verification**: The proposed methods will be simulated in a high-level interpreter language (e.g. Matlab) to optimize the efficiency.

- **Performance evaluation**: The proposed multi-sensor fusion system will be implemented in real WSN hardware and performance tests will be carried out.

This novel approach will enable information about the uncertainty of a measured value to be propagated from the source node to the sink node. In this way, potential degradation of acquired or transferred diagnostic information will be minimized.

Chapter 4

Proposed methods

A wide-ranging wireless diagnostic system monitoring fast-changing signals (e.g. mechanical vibrations) based on the advantages of WSN technology is not feasible without engaging distributed signal processing methods.

The key idea for introducing these systems is based on distributed signal processing methods, mainly information fusion, see Fig. 4.1.

- The entry level consists of sensor nodes equipped with a built-in sensor or ADC with an externally connected sensor. If more sensors of the same type are connected to a sensor node, raw data fusion can be performed to reduce the information produced by the sensor node.
- To reduce drawbacks caused by wireless data transfer or restricted power capabilities (battery discharging), the sensor nodes can be placed in redundant fashion. Several sensors sense the same phenomenon. Due to the feature fusion node, correct information is transferred, even if one or more sensors are corrupted.
- Various phenomena can be classified, and partial results can be combined into a final condition evaluation of the monitored device.

This concept ensures efficient information transfer through a wireless sensor network, suppressing node resources overload and/or communication channel overload.

We focus especially on the segment between the sensor nodes and the feature fusion node. Established redundancy in a number of sensors suppresses the disadvantages of WSN systems (susceptibility to sensor degradation, unreliable RF links, etc.), see Fig. 4.2.

4.1 Sensor Node

The proposed sensor node software design is depicted in detail in a block diagram in Fig. 4.3. The initial node settings (referred to as "preset" in the figure) are executed by a dissemination message in connection with the node identification number (ID). The feature extraction method

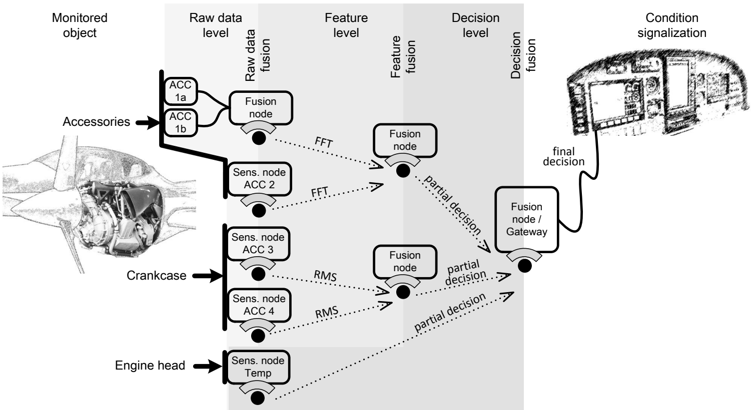

Figure 4.1: WSN monitoring system based on information fusion

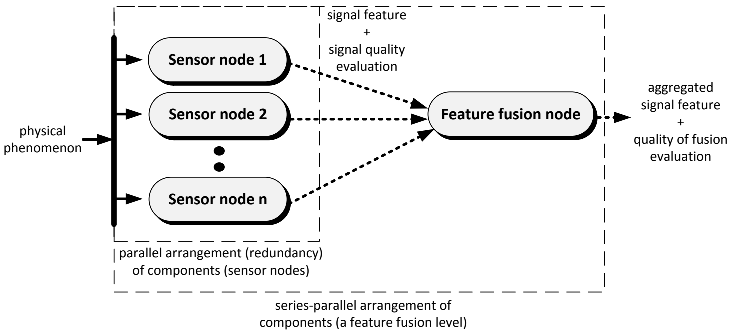

Figure 4.2: Feature fusion level arrangements

and the invariables are determined. Raw signal data picked up by an integrated sensor or (in this case) by an ADC connected sensor enter the node. The first processing method uses feature extraction. The output of the feature extraction method is an output of the sensor node if the data compression method is not engaged. The same data are saved into the memory buffer as part of overall quality computation based on trend monitoring. Further quality computation sources are the sensor node inner status and checks on whether a feature is within a physical limit or within a predefined pattern.

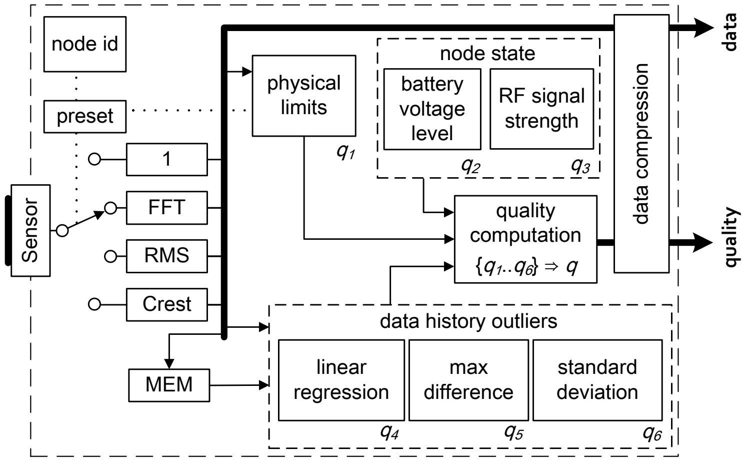

Figure 4.3: Sensor node scheme

4.1.1 Feature Extraction Methods

On the basis of signal features used in MCM, we adopt RMS, the crest factor and the discrete Fourier transform (DFT) of vector x, computed with a fast Fourier transform (FFT) algorithm. The block labeled as “1” does not perform any extraction method. This option transfers raw time signal data into the node mainly for testing and verification purposes.

4.1.2 Data compression methods

Data compression methods lead to radical bandwidth saving when only the main spectral components are transferred via the network, instead of the original full spectrum. The data compression block provides a list of frequencies and amplitudes of spectral components with amplitudes higher than threshold value T:

$$T = k \cdot RMS \tag{4.1}$$

where the k is a constant depending on the amplitude distribution of the noise, and RMS is a root mean square value. We propose the RMS function because of its presence in the sensor node (see the RMS block in Fig 4.3). Another method for setting the threshold could be a level (e.g. a minimal bin) at the position of the first n harmonics, i.e. multiples of the rotating frequency. However, the definition of n requires expert knowledge about the monitored device.

4.1.3 Quality evaluation

The *state of the node* is represented mainly by the *supply voltage* (primarily from a battery) and the strength of the *RF signal* to a neighbor node/s. Both of these quantities have a significant impact on the transferred signal. Although each node is equipped with a voltage regulator, fluctuation in the input voltage and discharging near to low level has a negative influence on the voltage reference of ADC, RF power and all other circuits of the node. RF signal strength could not be used to compute directly in the sensor node because of its absence. The RF received signal strength indication (RSSI) is read directly from the CC2420 Radio and sent with every radio packet. It is possible to use a previous RSSI datum or additionally the current RSSI at the fusion node input.

Data history outliers compare a few previous records with a current value by the trapezoidal membership function (4.2).

$$f(s; a; b; c; d) = \begin{cases} 0, & \mathrm{s}(i) \leq a \\ \frac{s(i)-a}{b-a}, & \mathrm{a} \leq s(i) \leq b \\ 1, & \mathrm{b} \leq s(i) \leq c \\ \frac{d-s(i)}{d-c}, & \mathrm{c} \leq s(i) \leq d \\ 0, & \mathrm{d} \leq s(i) \end{cases} \tag{4.2}$$

The current sample is described as $s(i)$. The parameters a, d locating the ‘feet’ and b, c locating the ‘shoulders’ of the trapezoid are computed by a proposed method introduced in the thesis. Previous data records are collected in the memory block described as *MEM*. If time-domain features are used, the current RMS value or crest factor value is compared with the previous feature record. If frequency domain features are applied, the current sample is compared with the sample at the same position in the previous spectrum record.

The *Physical limits* block contains a simple comparison between the current data and pre-set physical limits. In specific applications where the frequency domain is engaged, simple threshold checking can be substituted for a comparison with an amplitude spectrum pattern.

Quality computation here involves all partial qualities combined into a single overall quality. We model the quality of the physical limit using a two-state logic. If the sample is outside the physical limit, quality q1 is strictly zero. For other qualities we use the geometric mean that one quality term which is equal to zero does not drop overall quality q to zero:

$$q = q_1 \cdot \sqrt{mean\left(q_2 \ldots q_n\right) \cdot 2ndpercentile\left(q_2 \ldots q_n\right)} \tag{4.3}$$

Overall quality q is computed from partial qualities q1 to q5. With the exception of quality q1, strictly assigned to zero if the value is outside defined physical limits, other partial qualities are computed by a membership function. Quality q2 representing battery discharging uses a sigmoidal membership function. Other qualities use trapezoidal membership functions. The membership curve depends on scalar parameters.

If RSSI is computed in the fusion node the final quality equation (4.3) takes on the form:

$$q = \sqrt{q_{received} \cdot q_{RSSI}} \tag{4.4}$$

where $q_{received}$ is (4.3) without a readout on RF signal strength.

4.2 Data Fusion Node

The data fusion node consists of a data fusion block with the implementation of a data fusion algorithm. We verified DST-based fusion and fuzzy-based fusion. The idea of a fusion node requires an algorithm that produces a quality estimate of the fusion process in addition to the fusion result. The other blocks correspond to the sensor node structure.

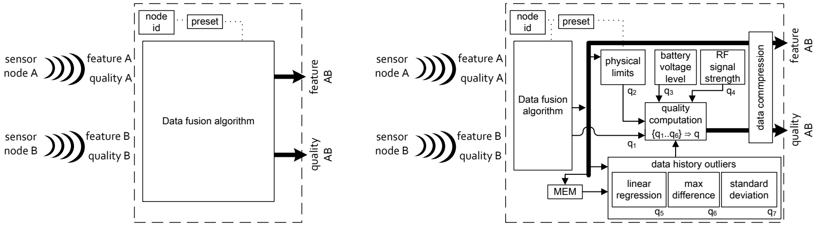

Figure 4.4: Fusion node scheme; left - simple fusion node; right - fusion node enhanced to next fusion process

4.2.1 Dempster-Shafer theory based fusion method

Our interpretation deals with Barnett's algorithm [16], which is a special case of belief functions focused on singletons (one-element subsets), so the computation requires only linear time.

$$\mu_{ij}(\{i\}) = q_i \times \int_{segment\ i} g(x)dx \tag{4.5}$$

$$\mu_i(\{i\}) = 1 - \prod_S (1 - \mu_{ij}(\{i\}) \tag{4.6}$$

$$K^{-1} = \prod_{i=1}^{|A|} (1 - \mu_i(\{i\})) \left(1 + \sum_{i=1}^{|A|} \frac{\mu_i(\{i\})}{1 - \mu_i(\{i\})} \right) \tag{4.7}$$

$$m(\{q\}) = K \cdot p_q \prod_{i \neq q} d_i \Rightarrow m(\{i\} = K \cdot p_i \frac{\prod_{i=1}^{|A|} d_i}{d_i}) \tag{4.8}$$

The fusion algorithm can be divided into four blocks, according to the main computation tasks, see Fig. 4.5:

1. The input data range is delimited (min, max value) and is fractioned into segments of constant width. Optionally, we establish a dynamic range correction so that the median of all valid values lies in the middle of a segment. Finally, the Gaussian function $g(x)$ is constructed over the value from a node (the Gaussian interprets the distribution of the measurement uncertainty in addition to the fact that the area of the bell curve is always equal to 1).

2. Each item of evidence is represented as a mass function $\mu_{ij}(A)$, the value of which on segment i is the area under the Gaussian bell curve multiplied by the evaluation quality (4.5). Then the basic probability assignment μ_i is computed as the orthogonal sum of μ_{ij} by using (4.6).

3. The combination of evidence is processed by Dempster's rule, so that it produces the final mass function $m(A)$, using (4.8). The quantity $m(A)$, is called A's basic probability number. It represents our exact belief in the proposition represented by A (the most credible segment). In other words, this quantity represents the fusion quality in our scheme.

4. As a result of fusion the most credible segment loses precision, since it is wider than a single input value. We therefore adopt a weighted average to regain precision for the fusion result f according to (4.9).

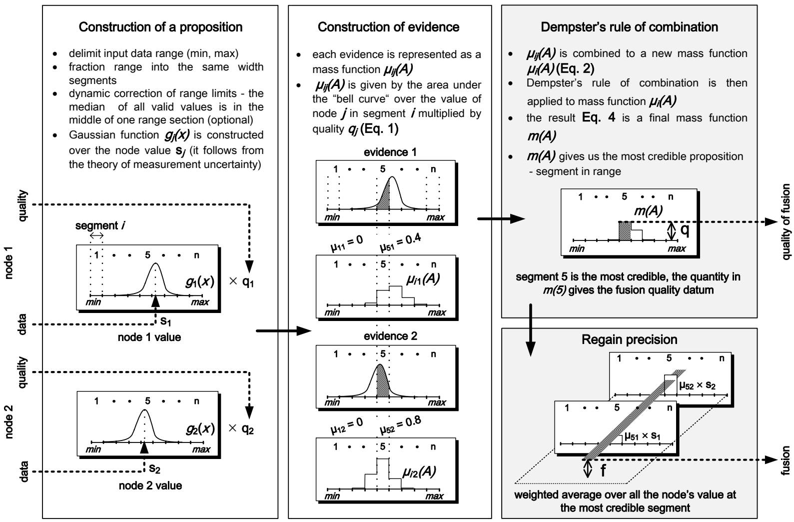

Figure 4.5: The Dempster-Shafer-based data fusion process

$$f = \frac{\sum_S \mu_{ij}(\{i_{\max(m(A))}\}) \times s_j}{\sum_S \mu_{ij}(\{i_{\max(m(A))}\})} \quad S = \{j|1 \leq j \leq \mathrm{k}\} \tag{4.9}$$

4.2.2 Fuzzy logic-based fusion method

Fuzzy logic-based data fusion is an effective paradigm for mapping an imprecise input space to an output space. The general fuzzy system is defined by inputs, outputs, membership functions associated with a given fuzzy set and a list of IF-THEN statements, called rules.

Our problem has $2j$ input variables (j feature data, j quality data) and two output variables (fusion, quality of fusion). Input feature samples are normalized, i.e. the highest sample value is equal to 1. We use the Mamdani scheme for the fuzzy system in Fig. 4.6. We have proposed two sets of rules. The first set is for the fusion output, and the second set is for the quality output. To create a general set of rules we proceed from a generic truth table (established according to Boolean logic) and simple expert knowledge.

Let us assume two sensor nodes. The value of the first node is high (1), and the second also has a high value (1). The quality indicator of the first sensor node is high (1) and the quality of the second is also high (1). The fusion result and the quality of the fusion have to be high, or both have to be low in the opposite situation. It is evident that a few contradictory statements occur. For example value 1 – high, quality 1 – high and value 2 - low, quality 2 – high. If we repeat this approach for all alternatives we get the complete truth table. To simplify the logic expressions - i.e. to write a minimal Boolean expression representing the required logic - we use the well-known Karnaugh map.

We therefore prepare a "moderate" version and a more "radical" version of the rules. The moderate approach, unlike the radical approach, means that in the event of a contradictory statement the result is high. These rules can be verbalized as follows:

***Moderate fusion output* – is high**

- If at least one half of the sensors declare both feature and quality high.

- If a minority of the sensors declare both feature and quality high and at least one half of the other sensors have quality low.

- If a minority of the sensors declare both feature and quality high and the same number of sensors have quality high and feature low.

***Radical fusion output* – is high**

- If more than one half of the sensors declare both feature and quality high.
- If a minority or one half of the sensors declare both feature and quality high, and more than one half of the other sensors have quality low.
- If exactly one half of the sensors declare both feature and quality high and one half of the other sensors have quality low and feature high.

***Moderate quality of fusion output* – is high**

- If at least one half of the sensors declare the quality high and their features have the same value (0 or 1), and if the other exact half of the sensors are not in direct contradiction (f1 – high, q1 – high; f2 – low, q2 – high).

***Radical quality of fusion output* – is high**

- If more than one half of the sensors declare the quality high and their features have the same value (0 or 1).

The next step is to combine these rules into a rule-based system (e.g. nine rules for the moderate fusion output). We define the membership functions for fuzzification as trapezoidal-shaped for feature input and quality input, and also for both defuzzification outputs.

Finally, both outputs of fuzzy fusion lie in the interval $\langle 0, 1 \rangle$. This range is adequate for quality evaluation of the fusion, but the amplitude of the fusion output has to lie within the same range as the feature input. This is arranged by multiplying the highest input feature sample by the resultant sample of fuzzy fusion (see Fig. 4.6).

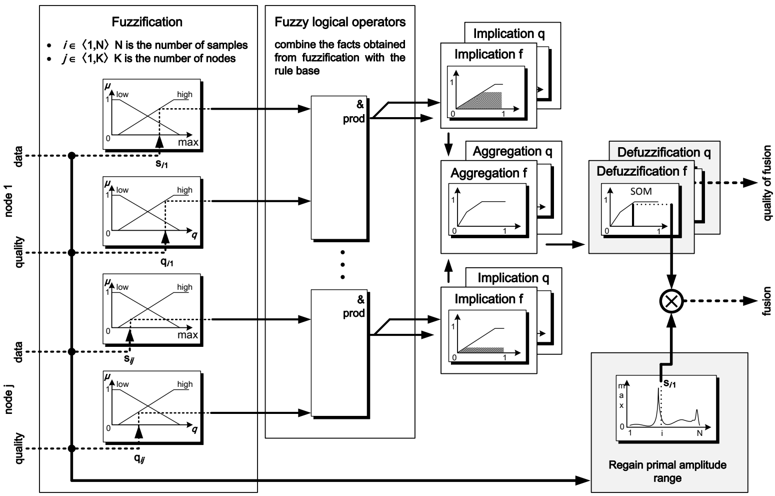

Figure 4.6: The fuzzy logic based data fusion process

Chapter 5

Results

The achievements of this doctoral project are well summarized in Fig. 5.1. The ball bearing housing is measured by three WSN sensor nodes (accelerometers). All sensors are mounted at one place in redundancy fashion. All sensors make improper measurements of physical phenomena (i.e. vibration) to simulate imperfections in the wireless measurement chain. This means that the redundant sensors are improperly mounted, temporarily terminated, overloaded, etc. Raw signals, in the top row in the figure, demonstrate invalid measurements in the time-domain. WSN technology is limited in bandwidth (250 kbps), which means that it is not feasible to acquire raw data samples and transfer them to a central unit to analyse all of them. Therefore each sensor node extracts a signal feature (the middle row of the figure). In this case, it is an amplitude spectrum, where the data are reduced whereas MCM useful information is maintained. However, the imperfection of individual measurements persists. This is solved by the next level of the nodes, where the sensor nodes transfer their data. We have called this level the feature fusion level, where the data are aggregated. The output of the feature fusion level node is demonstrated in the bottom row of the figure. We have proposed two independent aggregation methods based on information fusion. The first is based on Dempster-Shafer theory (we refer to it as DST fusion), while the second is based on fuzzy-logic (we refer to it as fuzzy-logic fusion).

Both algorithms making information fusion are driven by a quality indicator produced by the sensor nodes according to the validity of the acquired data and the health of the sensor node. This concept was first published by Hermans et al. [17] to improve temperature monitoring. We adopted this idea for signals using high sampling rates, and we improve it for signal feature extraction and quality indicator heuristics. We have introduced a new fuzzy-logic based fusion algorithm. All proposed methods have been verified via simulation and via real WSN experiments numerically summarized in table 5.1.

All experiments summarized in table 5.1 demonstrated rapid signal improvement when multi-sensor fusion was applied. In the case of the first two experiments, where an artificial signal with artificial imperfec-

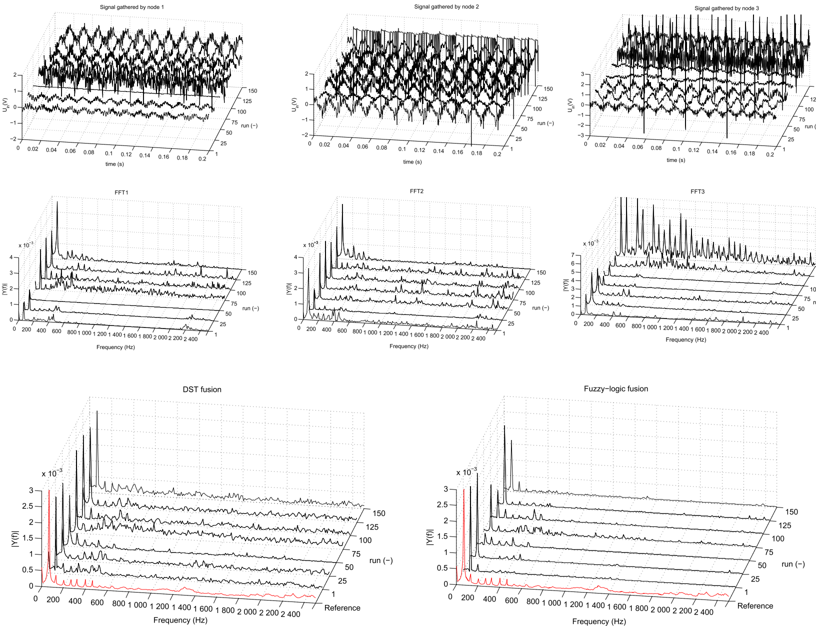

Figure 5.1: Data fusion from three sensor nodes (top row – degraded time-domain signals on the input of the nodes, middle row – amplitude spectrum produced by the nodes, bottom – fused spectrum produced by the fusion node. The red line is the reference from a sensor connected by wire).

Table 5.1: Summary of results

	SNR(-), FAR(-), std		
	Simulation	**Simulation HW**	**Real test**
Raw feature data (average)	28.16, 12.16, -	33.71, 13.31, -	- , - , 2.57×10^{-4}
Fuzzy-logic fusion (moderate)	60.4, 1.91, -	47.15, 3.48, -	- , - , 5.84×10^{-5}
Fuzzy-logic fusion (radical)	61.2, 1.64, -	49.54, 3.34, -	- , - , 5.17×10^{-5}
DST fusion	56.6, 0.86, -	42.29, 2.12, -	- , - , 6.12×10^{-5}

tions (cut off, steps, jumps, overloading etc.) was used, the best result was for the DST fusion method when FAR evaluation was engaged. In the case of the SNR evaluation, however, both fuzzy-logic approaches had better results. The better fuzzy-logic SNR results were due to the extremely low level of amplitude outside the effective frequency bins because of signal normalizing between 0 and 1, followed by mapping logic where the low amplitude levels are near to zero. The FAR results are of greater importance for further feature analysis. They indicate whether correct information is present or not. By optimizing the DST fusion parameters (i.e. sigma and length of segment) we achieve a very low value of error occurrences in the features that are produced.

Real signals / features were compared by the average standard deviation of each sample position over 150 waveforms. The improvement ratio (approximately five times) is very similar to the results from the simulations.

Algorithmic implementation of the proposed fusion approaches is simple and computationally inexpensive for use in wireless sensor network nodes. Both algorithms take a similar amount of memory - approximately 30 KiB of ROM without optimization (the sensor node code takes 50 KiB of ROM). DST fusion parameters should be adapted to the measured signal / features. Fuzzy-logic based fusion is more general-purpose, and mainly requires a definition of the logic rule strictness to define what type of input is acceptable to transfer as output. However, an improper setting of the rules or another part of the fuzzy-logic algorithm leads to false results. DST fusion is more robust to an improper setting of the input parameters.

Both proposed algorithms evaluate their own results. Information about the quality of the signal and the condition of the network can be transferred to a further network level. The presence of a quality indicator in the data fusion node output also enables redundancy at this level. Thus very reliable wireless systems are feasible, although high sampled signals are monitored.

Finally, we attempted to increase the number of sensor nodes to obtain a DST fused spectrum without any error (within both thresholds). This situation for artificial signal sequence occurred when 8 sensor nodes were engaged. Obviously, the more redundant the sensors were, the higher the resistance to disturbances and imperfections in the transferred signal. The experiments carried out in this thesis engaged three sensor nodes in redundant fashion. Both proposed fusion algorithms produce valuable results, while the complexity of the system remains reasonable.

The number of redundant sensor nodes that is used should be a compromise between robustness and network size, based the demands for particular applications. The main limitation of WSN multi-sensor fusion system proposals, which has to be taking into account, is the bandwidth of the IEEE 802.15.4 systems.

Chapter 6

Conclusion

This thesis has worked on feature level fusion in the WSN-based early warning monitoring MCM system to improve reliability. Feature level fusion deals with multi-sensor fusion, where a group of sensor nodes measure the same physical phenomena at the same place in redundant fashion. Instead of raw data, the sensor nodes transfer extracted features such as diagnostic information contained in the measured signal. Together with the features, each sensor node produces an uncertainty evaluation of the transmitted information (referred to as quality). The sensor node data are received by a fusion node, where the data are aggregated to the most appropriate result with respect to the quality of the received feature. The fusion node also evaluates its output by the quality indicator.

The design described here has been verified by means of simulation and real WSN experiments. For three independent nodes sensing the same randomly degraded signal, the improvement in SNR is higher when fuzzy fusion is applied. The radical approach produces slightly better results than the moderate approach. The improvement is almost 1.5 ×, due to the extremely low level of amplitude outside the effective frequency bins. Fuzzy fusion consumes less than 50% of the computing time for DST fusion. However, DST fusion is more efficient for preventing false alarms (in our experiment 6 × fewer errors on an average). Moreover, DST fusion does not contain inner variables (rules, membership function settings, etc.) that strongly influence the results, as in fuzzy-logic based fusion. DST fusion is influenced by the length of the segment and by the sigma value, but this method produces appropriate results in a relatively broad range of value settings between the apparent limits.

6.1 Accomplishment of the aims of the thesis

The aim of our project was to propose a quality-based data fusion approach to propagate maximal information content picked up from a device by a wireless sensor network to a sink node, while retaining reasonable system complexity. This objective was addressed in the following way:

WSN-based MCM system design

- making a review of the literature on aircraft MCM techniques and WSN technology, summarising key issues for the establishment of a WSN-based early warning monitoring system,
- establishing an essential system design, taking into account the character of the diagnostic signals, mainly vibrations, acquired from various mechanical devices by conventional wire systems,
- applying distributed signal processing methods, mainly information fusion, see Fig. 4.1,
- focusing on the feature fusion section of the scheme,
- designing the structure of a sensor node and a fusion node,

Improving WSN reliability

- utilizing redundancy - an information fusion scheme referred to as multi-sensor fusion, as developed in the thesis,
- proposing a quality indicator to drive the fusion based on signal imperfections and the health of the acting WSN node,
- composing a suitable heuristics for finding signal imperfections, i.e. for identifying samples varying in comparison with previous records,
- establishing a fusion algorithm based on Dempster-Shafer theory able to produce data aggregation and quality evaluation of fusion,
- proposing a new fusion algorithm based on fuzzy logic in addition to the DST fusion algorithm,

WSN bandwidth savings

- proposing an asynchronous monitoring method that applies defined time delay or event-based wake-up,
- dealing with an enormous amount of raw data in the case of signal monitoring with a high sample rate, using:
    - extraction of features from the signal,

    - an FFT spectrum compression method executed by a threshold limit driven by the RMS value,

Verification

- simulating the feature fusion WSN level in Matlab,
- evaluating sensor node heuristics that achieve the required performance,
- establishing a False Alarm Rate (FAR) for evaluating the correctness of the data,
- examining DST and fuzzy-logic based fusion algorithms influencing the parameters,
- optimizing factors influencing feature fusion,

Performance evaluation

- arranging the proposed multi-sensor fusion system by implementation into real Crossbow Imote2 WSN hardware,
- conducting an experimental test showing the proper functionality and feasibility of the proposed multi-sensor fusion in the WSN system.

The results of this thesis have been published in two international journals *IEEE Transactions on Industrial Electronics*, *IEEE Transactions on Industrial Informatics*, and presented at three international refereed conferences. In addition, some partial results have been presented locally, see the list of publications.

6.2 Future work

The weakest point of this thesis is the absence of a large-scale validation campaign. The results of the proposed methods have been shown only in the form of case studies on artificial signals and on one real device. This problem is due to the difficulty in obtaining a large amount of real data.

To complete the whole monitoring system, it is necessary to work on the decision fusion part. This will involve proposing a suitable fault classifier working in a constrained embedded system, as is required for WSN nodes.

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List of Publications

Work and publications related to the thesis

International Journals

[A1] O. Kreibich, J. Neuzil, and R. Smid, "Quality-based multiple sensor fusion in an industrial wireless sensor network for mcm," *Industrial Electronics, IEEE Transactions on*, 2013. online access.

[A2] J. Neuzil, O. Kreibich, and R. Smid, "A distributed fault detection system based on iwsn for machine condition monitoring," *Industrial Informatics, IEEE Transactions on*, 2013. online access.

International Conference Proceedings

[B1] O. Kreibich, J. Neuzil, and R. Smid, "Application of wireless sensor networks in condition monitoring of rotating devices," *CM 2012 / MFPT 2012 - The 9th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies*, London, UK, 2012.

[B2] J. Neuzil, O. Kreibich, and R. Smid, "Advanced signal processing in wireless sensor networks for MCM," *CM 2012 / MFPT 2012 - The 9th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies*, London, UK, 2012.

[B3] J. Neuzil, R. Smid, and O. Kreibich, "Rotary machine condition monitoring using one-class classification in wireless sensor networks," *CM 2011 / MFPT 2011 - The 8th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies*, Cardiff, UK, 2011.

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[C1] O. Kreibich, "Imote2 installation procedures within WSN based MCM project," tech. rep., CTU in Prague, 2013.

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[C6] O. Kreibich, "Vibration simulator for experiments in vibro-diagnostic," *POSTER 2007 - Proceedings of the 12th International Conference on Electrical Engineering*, Prague, CZ, 2007.

Other Work

[D1] "Safe and safety elements in aerospace and space technology," Member of the research team of a project no. SGS12/193/OHK3/3T/13, funded by the Student Grant Agency of CTU in Prague. 2013 - 2014.

[D2] "Advanced methods of data and signal processing for diagnostics," Member of the research team of a project no. SGS12/155/OHK3/2T/13, funded by the Student Grant Agency of CTU in Prague. 2012 - 2013.

[D3] "Digitization, synchronisation and signal processing in sensors and sensor networks," Member of the research team of a project no. SGS10/207/OHK3/2T/13, funded by the Student Grant Agency of CTU in Prague. 2010 - 2011.

[D4] "Sensors and intelligent sensor systems," Member of the research team of a project no. 102/09/H082, funded by the Czech Grant Agency. 2009 - 2011

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[D6] O. Kreibich and R. Smid, "Control module for a vibrodiagnostic simulator device," prototype. 2010.

[D7] O. Kreibich and R. Smid, "Power control unit for a DC motor," prototype. 2008.

[D8] O. Kreibich and R. Smid, "Vibration simulator for experiments in vibrodiagnostics," prototype. 2008.

Work and publications not directly related to the thesis

International Journals

[E1] M. Kubinyi, O. Kreibich, J. Neuzil, and R. Smid, "EMAT noise suppression using information fusion in stationary wavelet packets," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, vol. 58, no. 5, pp. 1027–1036, 2011.

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International Conference Proceedings

[F1] O. Kreibich and R. Smid, "E-learning tools for education and training in diagnostics and machine condition monitoring," in *Proceedings of the 2nd International Conference on Computer Supported Education - CSEDU 2010*, Valencia, Spain, 2010.

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Other Work

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The participation in the authorship:

Table 6.1: The participation in the authorship in %

A1	O. Kreibich	40	J. Neužil	30	R. Šmíd	30		
A2	J. Neužil	40	O. Kreibich	30	R. Šmíd	30		
B1	O. Kreibich	80	J. Neužil	15	R. Šmíd	5		
B2	J. Neužil	80	O. Kreibich	15	R. Šmíd	5		
B3	J. Neužil	65	R. Šmíd	20	O. Kreibich	15		
B4	R. Šmíd	90	O. Kreibich	10				
B5	J. Neužil	65	R. Šmíd	20	O. Kreibich	15		
C3	O. Kreibich	65	J. Neužil	35				
C4	J. Neužil	95	O. Kreibich	5				
D6	O. Kreibich	90	R. Šmíd	10				
E1	M. Kubínyi	55	O. Kreibich	15	J. Neužil	15	R. Šmíd	15
E2	M. Kubínyi	55	O. Kreibich	20	J. Neužil	20	R. Šmíd	5
F1	O. Kreibich	90	R. Šmíd	10				
F2	M. Kubínyi	50	M. Reinštein	30	O. Kreibich	20		

All other publications in the list have equal participation in the authorship.

Annotation

Strategie plánované údržby je založena na průběžném sledování stavu zařízení se systémem včasného varování před nestandardními stavy v chování sledovaného zařízení. Využití bezdrátové technologie WSN v této oblasti by přineslo řadu výhod vycházejících z konstrukce senzorového uzlu sítě, ke kterému nevede žádný přívod. Takové řešení usnadní montáž senzorů na těžko dostupná místa, ale zároveň otevírá možnosti pro zcela nové aplikace, například měření na pohyblivých částech zařízení.

Aby takový systém mohl být nasazen do průmyslové praxe, je potřeba zaručit spolehlivý přenos informace mezi senzorovými uzly a bránou napojenou na nadřazený kontrolér, či počítač. Tato práce navrhuje systém pro sledování stavu strojů založený na technologii WSN schopný překonat falešné indikace způsobené dočasnou ztrátou dat, rušením signálu nebo přenosem neplatných dat a to za použití multi – senzorové datové fúze rozhodující se dle parametru kvality, zasílaném senzorovým uzlem spolu s daty. Tento ukazatel je založen na stavu senzorového uzlu (napájení, síla signálu) a porovnání aktuální hodnoty s hodnotami v předchozích datových záznamech. Algoritmus datové fuze rovněž tento indikátor poskytuje. Tento nový přístup umožňuje šíření informace o nejistotě měřené hodnoty ze zdrojového uzlu až k bráně a zároveň vyřazuje neplatná data na uzlech datové fuze. Tím možnost degradace posílané diagnostické informace značně klesá. Přenos rychlých signálů je zajištěn extrakcí a přenosem příznaků ze surových dat, tím dochází k úspoře přenosové šířky pásma sítě. Koncept byl experimentálně ověřen nejen matematickou simulací, ale i na reálném WSN hardware (Imote2). Předpokládaná efektivita systému byla vyhodnocena pomocí poměru signál / šum (SNR) a vlastním detektorem četnosti výskytu chyb (FAR).

Výsledky potvrzují, že se navrhovaný přístup vyrovná drátovému propojení senzoru s měřicí ústřednou. A proto lze takový systém aplikovat i na kritická zařízení, jako jsou pohonné jednotky ultralehkých letadel, kde se systém včasné kontroly závad doposud nevyužívá.