Remote Online Machine Condition Monitoring Using Advanced Internet, Wireless and Mobile Communication Technologies

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Abstract

A conceptual model with wireless and mobile techniques is developed in this thesis for remote real-time condition monitoring, which is applied for monitoring, diagnosing, and controlling the working conditions of machines. The model has the following major functions: data acquisition, data processing, decision making, and remote communication. The data acquisition module is built up within this model using the sensory technique and data I/O interfaces to acquire the working conditions data of a machine and extract the physical information about the machine (e.g. failure, wear, etc.) for data processing and decision making. The data processing is conducted using digital conversion and feature extraction to process the received analogue condition data and convert the data into the physical quantities of working condition of the machine for sequent fault diagnosis. A real-time fault diagnostic scheme for decision-making is applied based on digital filtering and pattern classification to real-time identify the fault symptom of the machine and provide advice for decision making for maintenance. Process control is implemented to control the operation status of the machine automatically, inform the maintenance personnel diagnostic results and alert the working conditions of the machine. Remote communication with wireless and mobile features greatly advance the machine's condition monitoring technology with real-time fault diagnostic capacity, by providing a wireless-based platform to enable the implementation of data acquisition, real-time fault diagnosis, and decision making through the Internet, wireless, and mobile phone network.

The model integrating above techniques and methods has been applied into the following three areas: (1) Development of a Remote Real-time Condition Monitoring System of Industrial Gearbox, supported by the Stimulation Innovation Success programme (2007-2008); (2) Development of a Remote Control System of Solid Desiccant Dehumidifier for Air Conditioning in Low Carbon Emission Buildings, supported by the Sustainable Construction iNET programme (2009-2010); (3) Development of an Innovative Remote Monitoring System of Thermo-Electric-Generations, supported by the Sustainable Construction iNET programme (2010-2011).

The combination of wireless and mobile techniques with data acquisition, real-time fault diagnosis, and decision-making, into a model for remote real-time condition monitoring is a novel contribution to this area.

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List of Publications

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Nomenclature

A/D   Analogue-to-Digital

AI   Artificial Intelligence

ARMA   Autoregressive Moving Average

BP   Back Propagation

CBM   Condition-based Maintenance

CDMA   Code Division Multiple Access

CPC   Ceramic-Polymer-Composite

D/A   Digital-to-Analogue

PAC   Distributed Programmable Automation Controller

FFNN   Feed-forward Neural Network

GA   Genetic Algorithm

GSM   Global System for Mobile

GPRS   General Packet Radio Services

HTML   Hyper Text Mark Language

HTTP   Hyper Text Transfer Protocol

I/O   Input/output

J2EE   Java2 Enterprise Edition

MCM   Machine Condition Monitoring

MXML   XML-based User Interface Markup Language

ODBC   Open Database Connectivity

POF   Poly-based Optical Fibre

PDA   Personal Digital Assistant

RCM   Remote Condition Monitoring

RCBM   Remote Condition-based Maintenance

RDP   Remote Desktop Protocol

RMI   Remote Method Invocation

SDE   Software Development Environments

SME   Small and Medium Sized Enterprises

SOAP	Simple Object Access Protocol
SPA	Statistics-related Parameter Analysis
TCP/IP	Transmission Control Protocol/Internet Protocol
TSA	Time Synchronous Average
URL	Uniform Resource Locator
WAP	Wireless Application Protocol
Wi-Fi	Wireless Fidelity
WWW	World Wide Web
XML	Extensible Markup Language

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Chapter 1   Introduction

This chapter gives a thorough introduction to the research undertaken by the project. The background of the research is presented first, followed by the project's aim and objectives, and then the outline of the thesis is given.

1.1   Background of the Project

With the development of modern technologies, the idea of a machine has been extended. Generally, *a device having moving parts that perform or assist in performing any type of work is defined as a machine* [1], such as a motor and gearbox. However, the advent of electronics and information technologies has led to the development of devices without moving parts; and these *devices without moving parts may also refer to as machines* [1], such as a computer, television, semiconductor and air-conditioning.

The machines concerned in this research involve an industrial gearbox, a solid desiccant dehumidifier for air-conditioning, and Thermo-Electric-Generations (TEGs) for power electrical generation. The condition monitoring techniques required for the above machines are usually focused on conditions signal/data analysis, such as vibration, torque, rotational speed, flow-rate, voltage, current, temperature, and/or humidity, for diagnostics of the health of the machines. On-line diagnosis and prognosis of machines' working condition and the prediction of their failure are important to keep the competitiveness of the manufacturing and service industries.

For the past few decades, there has been a constant endeavour to improve the monitoring techniques for faults detection of machines. Such monitoring techniques are usually focused on the spectrum analysis of signals for diagnostics of the health of the machine. The vibration signal is one of significant parameters that reflect the

machine working conditions. When a machine operates properly, vibration signals that it generates are weak but constant; however, when machine faults occur and some dynamic processes (e.g. workload or rotating speed) in the machine would change, the vibration signals and their spectrum/waveform may change as well. Based on this principle, a deterioration condition may be immediately reflected by the spectrum of machine vibration signals. Because data acquisition and analysis are complicated and computer techniques were inefficient in the past, the diagnosis is usually a time consuming and laboratory-based exercise.

Traditional condition monitoring technique has been used in laboratories or plants for machine's fault diagnosis for many years. This technique can detect and recognise the machine faults by analysing the sampled vibration signals of the machine. However, it is unable to keep a continuous track on machine's working conditions for a relatively long period of time, and the monitoring process cannot be remotely maintained through the online network, such as Internet and mobile phone network. The traditional monitoring procedures can be briefly described as follows: (1) the maintenance personnel collects working condition data from machines at the planned time using the computer or specialised device, such as handheld detector or handy sensor; (2) the sampled data are passed to the monitoring centre for further processing; (3) fault diagnosis is subsequently conducted and the potential machine problem is discovered or predicted; (4) then the necessary maintenance work will be scheduled or performed. The above-stated process is called "schedule-based diagnosis". Because the monitoring process is discontinuous and the decision making for fault diagnosis and preventive maintenance depends heavily on engineers' experience and the out-of-date sampled data/graphs, such monitoring techniques are unreliable in generating meaningful diagnostic results.

With the global competition and the technology development, there have been increasing demands from industry for more efficient approaches to remotely real-time

monitor machines' working condition. Recent advances in computer technologies and the Internet provide the support to develop the advanced remote condition monitoring system. For example, Kwon et al. [2] proposed a framework of the web-enabled maintenance system, which focuses on the remote maintenance schemes with an emphasis on condition-based maintenance strategies. A case study of monitoring the robot harmonic drive system was conducted; the operational status of the system was obtained over the Internet. Compared with the conventional schedule-based maintenance strategies, the proposed approach shows the great potential for improving overall production efficiency and reducing the cost of maintenance.

Based on the introduction and background previously mentioned, this research is seeking for answers to the following questions:

1. Identify the gaps in the current solutions in machine's condition monitoring? How can a new conceptual model developed to address the identified gaps?

2. How can the advanced wireless and mobile techniques be combined with data acquisition, fault diagnosis and decision making to provide an effective means for real-time remote condition monitoring and maintenance?

3. How to validate the system which integrates the advanced techniques mentioned above?

1.2   Aim and Objectives of the Research

The aim of this research is to develop the innovative approaches to remotely online monitor, diagnose, and control the machine's working conditions utilising the digital/information technologies, such as data I/O communication, sensor technology, Internet, wireless Wi-Fi, and mobile communication. The main objectives in support of this aim are listed below:

- To review current relevant work on condition monitoring and fault diagnostic techniques and tools in order to understand the latest developments in this

research area, identify the research gaps in condition monitoring, , and to recognise the techniques suitable for this proposed research.

- To extract the physical information of machines (e.g. failure, wear and overload) and transfer quantities of machine's working conditions, such as vibration, torque, rotational speed, temperature, humidity and flow-rate, to the computer for data processing and condition monitoring.

- To diagnose in real-time the working conditions of machines using on-line fault diagnosis techniques to identify the nature of machine faults and prevent potential failures, and to schedule necessary maintenance work according to the diagnostic results;

- To control the working conditions of machines by transmitting the commands/parameters to the machine controllers via data I/O interfaces, to operate machines in order to maintain the normal operation of the system.

- To develop a web-based platform utilising the Internet, and wireless/mobile communication technologies, in order to enable users to communicate with the server by using multiple mobile devices, such as PDAs and mobile phones, and access the data and information required to regulate the operational status of machines.

- To develop a conceptual model to integrate the above-mentioned techniques and technologies, and to validate the model with three case studies:

  - the development of a remote on-line condition monitoring system of an industrial gearbox, in order to monitor its performance in real-time, diagnose the gearbox's working condition and provide advice to ease the decision making process for maintenance.

  - the development of system to monitor and control a solid desiccant dehumidifier for air-conditioning in low carbon emission buildings.

  - the development of system to monitor the working condition of Thermo-Electric- Generation (TEGs) system in real time.

1.3   Research Methodology

This research includes the development of a model and its application in three areas including industrial gearboxes, solid desiccant dehumidifier for air conditioning and thermo electric generation. The author intends to solve the problem theoretically, and prove the theory by laboratory experiments and case studies. This is the main approach for the author to carry out the research process. In this case, the following methods are applied in the research.

Set up the aim and objectives of the research. This is to be conducted by carefully investigating the background of the research and the research questions. The objectives may be further refined after the literature review with the new findings of the research trend, technical development and demands in the research area.

Literature review will be conducted because the technology is developing so quickly, it is necessary to know the progress made by other researchers. The purpose of the review is to understand the development in this research area, to identify the techniques suitable for this proposed research, and to find the gap in research area.

Development of the research project concept. At this stage, the author will get as much information as possible related to this research project. After a whole picture of the research area is developed, the next step will identify the problems and the gaps of the currently existing research. The advantages of existing research will be incorporated into this project and the author's own to solve the research problems will be formulated. Finally, the author will need to theoretically prove his potential solution. This is so called 'Theorem Proof'.

Theoretical study, software development and experimental investigation will be conducted to implement the proposed research project. The theories related to the

condition monitoring will be studied such as adaptive algorithm, fault diagnostic and sensory theory, which will form the theoretical basis of the investigation. The software development methods will be utilised in the development of the wireless software and data acquisition programs. The experimental investigation will include the design of the experimental system, selection of sensors, construction of the test rig, and analysis of the experimental results.

Validation of the research results and optimisation. The outcomes of the research must be validated to prove their correctness and to identify the areas for further development and optimisation. The validation will be conducted by experimental tests and case studies. The case studies must be convincing and the applications must be carefully selected.

1.4   Outline of the Thesis

The thesis consists of 7 chapters. A brief description from Chapter 2 to Chapter 7 is given below.

Chapter 2 – Literature Review

This chapter reviews the research on the remote monitoring, diagnosis and control of machines' working conditions with the emphasis on the technologies and algorithms.

Chapter 3 - Development of the Remote Condition Monitoring System

This chapter takes gearbox's condition monitoring as an example to illustrate the development of remote condition monitoring and fault diagnostic approaches. The condition monitoring approaches for gearbox are also suitable to the remote

monitoring and diagnosis of the solid desiccant dehumidifier and Thermo-Electric-Generations.

In the following three chapters, i.e. Chapters 4-6, the developed remote condition monitoring and diagnostic methods have been applied to monitor, diagnose, and control the working conditions of an industrial gearbox, the solid desiccant dehumidifier used in an air-conditioning unit, and Thermo-Electric-Generations, respectively.

Chapter 4 - Remote Condition Monitoring and Fault Diagnosis of Industrial Gearboxes using Internet and Wireless Technologies

In this chapter, a remote online machine condition monitoring system has been developed, which is applied for diagnosis and prognosis of gearboxes' working condition. Within the system, the diagnostic classification is performed by pattern recognition using gear feature parameters; and remote diagnostic capability is enhanced by applying Internet and wireless technology. An online signal-processing scheme is adopted based on digital noise filtering and statistics-related gear feature algorithm to detect early fault signals of the gearbox and to provide advice for decision-making for maintenance. Remote communication is developed to transmit the working condition data and analysis results of the gearbox to the mobile users via the Internet, wireless network in real time. An experimental investigation for monitoring an industrial gearbox was conducted using the developed remote condition monitoring system. The experimental result shows that the developed monitoring system is effective; the proposed approach of fault diagnostics can be utilised to monitor the gear conditions and detect the potential faults.

Chapter 5 - Remote Control of Solid Desiccant Dehumidifier for Air Conditioning in Low Carbon Emission Buildings using PDA, Wireless and My-SQL based

Database Technologies

In this chapter, remote condition monitoring technologies have been applied to develop a remote control system of solid desiccant dehumidifier for air-conditioning unit. The system works to remotely monitor and control the internal conditions of air-conditioned buildings with a view to reducing carbon emissions. The system provides the functions of data acquisition, data processing and decision-making. Data acquisition is conducted within this system based on the data I/O interfaces and sensor technology to acquire the working conditions data of solid desiccant dehumidifier to detect the operating status of the conditioned air; the real-time data processing is implemented via A/D conversion to process the received data and to transmit control commands to a controller interface. Remote communication allows the users to utilise mobile devices such as PDA and mobile phone to remotely access the working condition data and analysis results via the Internet and wireless network. The experimental test was carried out by monitoring and controlling the working conditions of the dehumidifier used in an air-conditioning unit. Process control for solid desiccant dehumidification was performed by tuning the DAQ controller's parameters to regulate humidity, temperature, flow-rate, and other conditions of the air-conditioning unit. The experimental result proves that the system has been successfully developed.

Chapter 6 - Remote Condition Monitoring of Thermo-Electric-Generation using Mobile Phones, GPRS Mobile Network and Cross-platform Communication

A remote online condition monitoring system of Thermo-Electric-Generations (TEGs) is developed in this chapter. The system online monitors electrical power and heat energy generated by TEGs and also is applied to regulate the temperature of cold side of thermoelectric units used in TEGs. The system provides the following functions: data acquisition, data processing, system control and remote communication. Within

this system the data acquisition module is built to acquire the data of working conditions of TEGs. The data processing is conducted using data calibration and pattern classification to real-time process the received condition data, and, meanwhile, to display the data/results on a monitor panel. System control is implemented by sending the commands/parameters to the control unit of the water valve for adjusting the temperature of cold side of TEGs. Remote communication further enhances the capability of monitoring and controlling TE modules' working conditions. Remote communication module is developed, which allows the users to utilise the mobile devices, such as mobile phone, PDA and laptops, to access the data of working conditions via Internet and mobile phone network. The remote monitoring system using the above technologies has been validated by carrying out a case study of monitoring the working condition of TEGs. The working conditions data were wirelessly accessed and controlled using Nokia mobile phone via GPRS cellular network and Internet. The real-time video for monitoring the work of the TE modules was displayed on the user interface of mobile phone. Temperature control of the cold side of TE modules was conducted by regulating the switch of a water valve. The experimental result proves that the system has been successfully developed and applied to remotely monitor and control the actual working conditions of TEGs.

Chapter 7   Conclusion and Future Work

The last chapter gives the conclusions from the research work with the description of contribution to knowledge and future work.

Chapter 2   Literature Review

Machine condition monitoring has attracted increasing interests in recent years, due to the need to reduce the amount of down time in the production lines and to reduce the chances of serious damages and losses caused by failures. An effective condition monitoring system should be capable of monitoring the operating conditions of machines, issuing advanced warnings of possible faults, predicting the life span of a defective machine component prior to a fatal breakdown, and thus reducing unscheduled production shutdowns [3]. This chapter reviews the development trend and technologies in machine condition monitoring related to this research in the subject areas of remote condition monitoring; condition monitoring of industrial gearboxes, solid desiccant dehumidifier for Air-conditioning, and thermo electric generations; as well as software development environments.

2.1   Remote Condition Monitoring

Mobile devices, such as personal digital assistants (PDAs) and cellular phones, can be combined with different remote communication technologies to closely monitor the machine's working conditions and check the machine's operation status. Machine data/information such as status and alarms can be quickly transmitted and analysed by remote service personnel.

A typical remote condition monitoring (RCM) program consists of following four steps:

1. Data acquisition (information collecting), to collect the analogue data of the working conditions from machines and convert the data to the digital data.

2. Data Processing (information handling), to convert the digital data to real quantities of working conditions of machines.

3. Decision-making (fault diagnosis and/or system control), to determine the

nature of the machine fault when it is detected, recommend efficient maintenance policies, and take appropriate measure such as a control.

4. Remote communication, to transmit data/information, such as machine's operation status and alarm conditions, through the network.

In some literature [3][4][11], the first step 'Data acquisition' and the second step 'Data processing' were combined into one step. Therefore, a remote condition monitoring system can also be considered as three parts, i.e. data acquisition/processing, decision-making, and remote communication.

This section reviews the research on the remote machine condition monitoring with an emphasis on algorithms and techniques for data acquisition, data processing, decision-making, and remote communication.

2.1.1 Data Acquisition

Data acquisition is a process of acquiring useful data/information from machines and converting the acquired analogue data into the digital data. Condition monitoring data are very versatile. It can be vibration data, acoustic data, oil analysis data, temperature, pressure, moisture, humidity, weather or environment data, etc. Various sensors, such as micro-sensors, ultrasonic sensors, acoustic-emission sensors, etc., have been designed to collect different types of data.

The condition monitoring data used in this research include vibration data, torque data, rotational speed, temperature, humidity, voltage and current; the sensors used to collect the above types of data include accelerometer, torque/speed transducers, thermocouple, humidity sensor, voltage sensor, and current sensor. Because the collected data are often existed in form of analogue voltage/current signals (data), these data need to be converted to the digital data, which can then be read by a computer for further

processing. The above digital conversion is performed using a data acquisition instrument, which is called data acquisition (DAQ) card.

The accelerometer, also called vibration sensor, is a vibration sensing instrument/device, which is used to measure vibration signals of motion of machines. The vibration analysers usually acquire the vibration signals of accelerometers and process the signals to display the acceleration amplitude of vibration signals [6]. The most commonly used accelerometer is the Kistler accelerometer, which has been used in this research to monitor the vibration signals of a machine such as a gearbox. KSC et al. [9] utilised Kistler accelerometers to monitor the structural health of machine. The different time-dependent responses of the accelerometers were applied using Fourier Transform technique to determine the modal-frequencies of gearbox. Other accelerometers, known as G-mac signal-conditioning accelerometers [4], are also used in machine condition monitoring. G-mac accelerometer is an alternative to traditional vibration monitoring instrumentation. The G-mac accelerometer features signal conditioning and filtering circuitry. It can indicate the early symptom of machine's faults by identifying the small amplitude and high-frequency elements of vibration signals. It can also be integrated into wired and wireless networks to facilitate the remote condition monitoring applications of machine [4].

Torque and rotational speed are usually collected using torque/rotation speed transducers. Torque and rotational speed transducers are critical in remote condition monitoring. In remote condition monitoring, their use is in detecting changes in machines, such as a high starting torque and increased/decreased resistance to rotation, which is likely to indicate a fault. Two widely used torque/speed sensors are: Magtrol-213, an in-line torque rotary transducer with the range of 50-500Nm; and Kistler-9039, a clamp-able torque rotary transducer with the range of 50-200Nm [13]. In addition, Datum Electronics has developed RS420 non-contact rotary torque transducer [23], which has been used in this research. RS420 torque/speed transducers

utilise a strain gauged shaft for accurate and reliable torque measurement, and can operate with no direct contact from the rotor to the stator.

Thermocouple is applied by converting a heat gradient into electricity to measure the temperature. K-type thermocouple used in this research consists of two different conductors (usually metal alloys) that produce a voltage proportional to a temperature difference between either ends of the pair of conductors [5]. The main limitation with the thermocouple is accuracy and system errors of less than one degree Celsius can be difficult to achieve [6].

The device used to measure humidity is called a psychrometer or hygrometer. The humidity sensor SHT15 [7] used in this research can measure the humidity of a building or system with a dehumidifier. These can be analogous to a thermometer and thermostat for temperature control.

2.1.2 Data Processing

Data processing is a process of converting the digital data to the real quantities of working conditions of machines. This process is essential in remote condition monitoring for diagnosis of machines.

Data acquisition and data processing are called A/D (analogue-to-digital) conversion [23]. A/D conversion includes following two steps:
(1) the conversion from analogue signals (data) to digital signals (data);
(2) the conversion from digital signal (data) to real quantities of working conditions of machines.

Usually, A/D conversion is performed using data acquisition (DAQ) card via linear/non-linear calculations. NI-DAQ6259 card is utilised in this research as the

interface between captured signals and a computer [8, 9]. NI-DAQ card is connected to the computer using the ports, such as parallel, serial, USB, etc. NI-DAQ cards contain multiple components (multiplexer, ADC, DAC, TTL-IO, high speed timers, RAM). These are accessible via a bus by a microcontroller, which can run small programs. A controller is more flexible than a hard wired logic, yet cheaper than a CPU so that it is permissible to block it with simple polling loops. For example [7][9]: Waiting for a trigger, starting the ADC, looking up the time, waiting for the ADC to finish, move value to RAM, switch multiplexer, get TTL input, let DAC proceed with voltage ramp. Many times reconfigurable logic is used to achieve high speed for specific tasks and digital signal processors are used after the data has been acquired to obtain results. The fixed connection with the PC allows for comfortable compilation and debugging. Using an external housing a modular design with slots in a bus can grow with the needs of the user [8].

2.1.3 Decision-Making

The third step of a remote condition monitoring program is decision-making. Sufficient and efficient decision support is crucial to maintenance personnel's decisions on taking maintenance actions. Technique for decision support in remote condition monitoring is called fault diagnosis, which focuses on detection and identification of machine fault. When the fault occurs, the appropriate actions can be taken automatically to control the operation status of machines [9-12].

Most commonly used fault diagnostic technology is time-domain analysis that is based on the time-waveform of vibration signals. With time-domain analysis, machine's characteristic features can be obtained from time-waveform signals. Machine characteristic feature, also called statistics-based machine feature, includes the following two types of parameters [13, 14]:

(1) Descriptive parameters: mean, peak, peak-to-peak interval, standard deviation;

(2) High-order parameters: kurtosis factor, crest factor, impulse factor, shape factor, clearance factor, root-mean-square, skew-ness, etc.

These parameters are also called statistics-based machine feature parameters [15-18], some of which have been used in this research to monitor vibration condition of machines. There are many literatures about the research on the time-domain analysis techniques. Some of them are briefly mentioned as follows. Wang et al. [27] discussed three non-linear diagnostic methods, known as pseudo-phase portrait, singular spectrum analysis and correlation dimension, based on the signal time-domain theory. Zhuge and Lu [31] proposed a modified least-mean-square algorithm to model the non-stationary time-domain signals. Baydar et al. [32] investigated the use of a multivariate statistical feature technique known as principal component analysis (PCA) for analysis of the time-waveform signals in machine fault diagnostics.

Other popular fault diagnostic approaches, such as wavelet transform [25] and artificial intelligence (AI) [33], are not used in this research due to the restriction of time, but could be applied in the future work.

Wavelet analysis of a waveform signal expresses the signal in a series of oscillatory functions with different frequencies at different time by dilations via the scale parameter a and translations via the time parameter b. Similar to power spectrum and phase spectrum in Fourier analysis, a scaling-gram defined as $|W (a, b)|^2$ and a wavelet phase spectrum defined as the phase angle of the complex variable $W |a, b|$ are used to interpret the signal. One main advantage of wavelet transform is its ability to produce a high frequency resolution at low frequencies and a high time resolution at high frequencies for signals with long duration low frequencies and short duration high frequencies. Another advantage of wavelet transform is its ability to reduce noise in raw signals [25-27].

Artificial intelligence (AI) techniques have been increasingly applied to machine fault

diagnosis and have shown improved performance over conventional approaches. In practice, however, it is not easy to apply AI techniques due to the lack of efficient procedures to obtain training data and specific knowledge, which are required to train the models. So far, most of the applications in the literature just used experimental data for model training [33]. In the literature, two popular AI techniques for machine diagnosis are artificial neural networks (ANNs) and ESs. Other AI techniques include fuzzy logic systems, fuzzy-neural networks (FNNs), neural-fuzzy systems and evolutionary algorithms (EAs). A review of recent developments in applications of AI techniques for machine fault diagnostics was given by Siddique et al. [33].

- System Control Methods

Linear system control is applied in this research using linear negative feedback to produce a control signal mathematically based on other variables, with a view to maintaining the controlled process within an acceptable operating range [81, 82].

The output from a linear control system into the controlled process may be in the form of a directly variable signal, such as a valve that may be 0 or 100% open or anywhere in between [83]. Sometimes this is not feasible and so, after calculating the current required corrective signal, a linear control system may repeatedly switch an actuator, such as a pump, motor or heater, fully on and then fully off again, regulating the duty cycle using pulse-width modulation [84-86]. When controlling the temperature of an industrial furnace, it is usually better to control the opening of the fuel valve in proportion to the current needs of the furnace. This helps avoid thermal shocks and applies heat more effectively [87].

Xue et al. [88] developed a proportional negative-feedback system based on the difference between the required set point (SP) and process value (PV). Power was applied in direct proportion to the current measured error, in the correct sense so as to

tend to reduce the error (and so avoid positive feedback) [88]. The amount of corrective action that was applied for a given error is set by the gain or sensitivity of the control system.

Kezu el al. [91, 93, 94] built up a furnace model supposing the temperature is increasing towards a set point at which, say, 50% of the available power will be required for steady-state. At low temperatures, 100% of available power is applied. When the PV is within, say 10° of the SP the heat input begins to be reduced by the proportional controller. (Note that this implies a 20° "proportional band" (PB) from full to no power input, evenly spread around the set point value). At the set point the controller will be applying 50% power as required, but stray stored heat within the heater sub-system and in the walls of the furnace will keep the measured temperature rising beyond what is required. At 10° above SP, we reach the top of the proportional band (PB) and no power is applied, but the temperature may continue to rise even further before beginning to fall back. Eventually as the PV falls back into the PB, heat is applied again, but now the heater and the furnace walls are too cool and the temperature falls too low before its fall is arrested, so that the oscillations continue [93].

2.1.4 Remote Communication

The fourth step of a remote condition monitoring program is remote communication. Remote communication technologies, such as wireless networking and mobile communication, are joining with mobile devices to make possible the remote monitoring/diagnosis of working conditions of machine. In the following sections, remote communication technology is discussed with the emphasis on wireless networking and mobile communication approaches [102-104].

2.1.4.1 Wireless Technology Integrated with Mobile Devices

Wireless networking technology has helped enable remote machine condition monitoring, allowing machines located hundreds of miles away to be tied in to a central monitoring station. This technology greatly reduces the frequency of required visits by field service personnel to the remote monitoring site, for data collection or preventive maintenance [118].

The use of mobile devices provides further flexibility when remotely monitoring machine conditions. Instead of being tied to a PC-based monitoring centre, mobile devices such as PDA, mobile phone, and laptop, give operators and managers the ability to monitor machine conditions from any location with the wireless network, such as in the user's lab or home[110-114].

Nowadays, the majority of commercially available mobile devices offer sufficient memory and processing power to handle many industrial applications. In addition, mobile devices often include built-in wireless connectivity for sharing data with remote computer systems, giving developers and integrators the ability to easily build portable applications for remote system monitoring or wireless instrument control [129, 130].

Although some mobile devices offer a small, lightweight and portable measurement and alarming system, most of applications require extended temperature, humidity, moisture and shock specifications not found in consumer-grade mobile devices.

In creating a custom remote condition monitoring system, portable hardware is not the only consideration. Another key factor is a flexible software development platform that can easily take advantage of the abundance of available technology. Developers need to quickly create their own fully customizable monitoring applications for use on these

mobile devices. With software development packages such as National Instruments' LabVIEW graphical development environment [132], powerful and flexible monitoring applications can be built to run on these mobile devices. These software packages also include built-in functionality that takes advantage of the variety of communication options available, such as wireless Wi-Fi 802.11 [131]

2.1.4.2 Mobile Communication Technologies

Nowadays, mobile communication is very popular. Messages, voices, even video clips can be sent remotely via mobile communication and received by mobile devices such as mobile phone or PDA. The GSM (Global System for Mobile Communication), GPRS (General Packet Radio Services), and CDMA (Code Division Multiple Access) have been widely utilised in wireless/mobile communication. Wireless Application Protocol (WAP) has also been developed for the mobile devices, such as mobile phones and PDAs, to access the Internet [120-124].

On the other hand, the developments of Smartphone and PDA technologies allow the transformation of a mobile terminal into a mini computer, and make it possible to process data within a mobile phone or PDA. Sun Microsystems provide free binary implementations to their Java ME runtime environment which is supported by all types of PDAs and Smartphones (iPhone is not included). Hence, the mobile phone grows from a voice communications device into a multipurpose information terminal. The development of these technologies makes it possible to maintain machines at anywhere and anytime [116-118].

2.1.4.3 Design Considerations for Remote Condition Monitoring

A number of wireless industry standards are suitable for use in the industrial environment. The most widely accepted and widely available wireless standards to

date are IEEE 802.11a/b/g/n for wireless LANs, Wi-Fi and wireless Ethernet [123]. Bluetooth is a wireless standard for short-distance communication between computers and peripheral devices. Zigbee is the first wireless standard to be designed for sensors, monitoring and control devices. It offers a greater range than Bluetooth devices at a limited bandwidth [124].

The next generation 4G cellular standard will offer an increased range from one base station to the next over previous cellular standards. Its data transmission speed is faster than that of Wi-Fi 802.11g [126].

The proliferation of wireless industry standards can make it difficult to determine which technology is best suited for a particular application. In addition, there are proprietary wireless technologies such as e2e for hearing aids, and the 900 MHz Max technology considered by some to be a potential Bluetooth competitor. Some of the most critical factors that developers must keep in mind include range, performance and RF interference [127].

Additionally, not all of these wireless technologies are available for use with mobile devices, and thus, only some can be used when integrating handhelds with a monitoring system [128].

One industrial application for wireless technologies is wireless machine condition monitoring (MCM). MCM is an approach used for the maintenance and process control of industrial machinery. It assists with machine repair decisions, as well as process control and optimization. When deployed in wireless applications with standards such as 802.11, MCM can be used for large rotating machinery [116].

Distributed Programmable Automation Controller (PAC)-based MCM systems are deployed throughout a factory floor. Each PAC collects vibration data and performs

analysis. Alarms and reporting data are then transferred wirelessly to a control system using a standard 802.11 network [118]. This type of wireless MCM system offers several benefits. First, it reduces costs by eliminating physical wiring. Existing machinery can be retrofitted easily, without adding infrastructure. Machinery and the MCM system itself can be easily relocated without the need to also relocate infrastructure. Finally, PAC-based MCM system makes the use of MCM possible for rotating or mobile machinery where wires are not feasible [129].

For wireless monitoring applications that deploy mobile device, such as MCM, several different wireless communication protocols may be considered. The most common form of Wi-Fi available for mobile device is 802.11g. Recently, 802.11n was introduced for mobile device, which provides faster connection speeds [102].

Alternatively, if a mobile device is being used to selectively retrieve information wirelessly from a distributed monitoring system, Bluetooth connectivity might be a better choice for the wireless communications protocol. Bluetooth's biggest benefit is the fact that it supports automatic connection between devices. This means that users can roam the plant facilities, establishing communication only with those machines they want to monitor. Bluetooth uses an RF frequency of 2.4 GHz. Its short range, which is only 30 to 40 feet, limits the interference of competing wireless signals and makes it difficult for other, nearby companies or organizations to access machine data. Creating custom Bluetooth communications applications is similar to creating custom TCP applications, in that both server and client programs must be considered [124].

Cellular technology, specifically 3G, is often the only method that can be used for communicating with long-distance distributed systems, via wireless data modems. Using cellular modems, remote PACs can connect to central monitoring systems and notify operators on cellular phones many miles away. For example, cellular modems can quickly and easily provide alarms to operators and engineers in an alarming system

for oil field equipment, such as pumps and compressors that are spread across large distances [130].

2.2   Condition Monitoring of Industrial Gearbox

A research project has been conducted with the support of the Stimulation Innovation Success programme [23] to develop an online condition monitoring system for fault diagnosis of an industrial gearbox. The system utilises condition monitoring and remote communication technologies to remote on-line monitor and diagnose the working conditions of the gearbox.

Because of its importance in power transmission in any industry, gearbox's condition monitoring has been widely applied in the past decades. There has always been a constant endeavour to improve upon the monitoring techniques and analysis tools for the early detection of faults in the gearbox [3]. Techniques such as vibration monitoring and acoustic emissions have found application in gearbox's fault diagnosis through vibration and acoustics monitoring. Vibration-based monitoring, however, is the most commonly used approach in industries because of its ease of measurement, which is also used in this research.

Fault diagnosis, also called fault recognition, is a sequential process involving the following two steps: feature extraction and pattern classification. Feature extraction is a mapping process from the measured signal space to the feature space. Characteristic features associated with the working conditions of gearbox components, such as bearing, gear and shaft, are extracted by using signal processing techniques [3]. Pattern classification is the process of classifying the characteristic features into different categories.

The classical approach, which is also widely used in industry, relies on human

expertise to relate the vibration features to the faults. This method, however, is tedious and not always reliable when the extracted features are contaminated by noise. Furthermore, it is difficult for a diagnostician to deal with the contradicting symptoms if multiple features are used [4].

The alternative is to use analytical tools [5, 6] and statistics-based feature analysis with a digital filter [7]. The latter has been used in this research because the representative feature of gears can be effectively extracted using the digital noise filter from noisy environments and then be diagnosed utilising the statistical gear-feature algorithm.

Shao et al. [7] developed a mixture de-noising technique to detect early faults of bearings under actual plant conditions. The mixture de-noising technique consists of an adaptive noising-cancelling filter and a statistic-based de-noise estimator. The mixture de-noising technique can improve the signal-to-noise ratio when the signal is contaminated by noise. The performance of mixture de-noising was investigated under different noise ratios, bearing failure sizes and shaft speeds.

There are many categories of digital filters. One of the widely used digital filters is the adaptive filter with the least-mean-square (LMS) algorithm, which requires few computational resources and features the fast convergence. In this research, the adaptive filter with LMS algorithm is combined with statistical gear-feature analysis to fast detect and identify the fault symptom of the gearbox.

Kezu et al. [13] proposed an approach using the adaptive filter to improve the signal-to-noise ratio of vibration signals of the gearbox. The comparison of fault detection capabilities between a linear adaptive filter using the least-mean-square algorithm and a non-linear adaptive filter using the ANF algorithm was made in conditions of large amounts of environmental noise. Experimental results showed that the adaptive filter using a LMS filtering algorithm can effectively detect the symptoms

of faulty bearings under different conditions.

Xi et al. [14] investigated a filtering process in fault diagnosis of rolling bearings. An experiment for monitoring and diagnosing the working conditions of rolling bearings was carried out using the adaptive filtering algorithm and the wavelet filtering algorithm at different load conditions. Experiment result showed that the adaptive filtering algorithm is more efficient than the wavelet filtering algorithm when extracting fault signals of rolling bearings from noise environments.

The performance of the adaptive digital filter can be further improved using reasoning tools such as artificial neural networks [8], fuzzy logic [9, 10], and neural fuzzy synergetic schemes [11, 12]. Due to the restriction of time, the research on the adaptive filter with reasoning tools has not been made in this research, but it should be carried out in the future work. The development of the adaptive filter with reasoning tools is reviewed as follows:

Wang [15] developed an approach using the adaptive filtering and fuzzy-neural network techniques to detect the fault symptoms of the gearbox used in a reciprocating machine. The adaptive filtering is used for noise cancelling and feature extraction of vibration signal of the gearbox. Using the adaptive filtering, the fuzzy-neural network can identify the fault types of the gearbox using a quick converging method.

Xue el al. [16] developed an adaptive matched filtering algorithm based upon an artificial neural network to detect the lower frequency signals of the electrocardiogram (ECG). The adaptive ANN filtering algorithm was utilised to remove the time-varying, nonlinear noise characteristic from ECG signals.

Even though several techniques have been proposed in the literature for gearbox's condition monitoring, it still remains a challenge in utilising diagnostic tools or

methods for actual condition monitoring applications because of the complexity of gearbox structures and operating conditions. To tackle these challenges, a remote online condition monitoring system has been developed to monitor and diagnose the working conditions of the gearbox. Within this system, the capability of gearbox's condition monitoring is enhanced in the following ways:

(1) To online (real-time) monitor and diagnose the working conditions of the gearbox. An online fault diagnostic scheme has been implemented using the adaptive filter with LMS algorithm and statistics-based feature analysis to fast extract the representative feature, i.e. gear feature, from the contaminated vibration signals, and real-time identify possible faults of the gearbox. Online diagnostic results are then used to schedule necessary maintenance activities.

(2) To integrate remote technologies, such as the Internet, wireless and mobile communication, into the condition monitoring process. Remote condition monitoring allows the user, such as a diagnostician, to utilise mobile devices, such as mobile phone and PDA, to remotely access the working conditions data and diagnostic results of the gearbox, and to be informed the gearbox's working conditions when a fault occurs.

2.3 Condition Monitoring of Solid Desiccant Dehumidifier for Air-conditioning

Air conditioning is essential nowadays for most commercial buildings, and it is going to be more popular for domestic buildings as well in the next 5 to 10 years due to the climate change and global warming. Currently, the air conditioning devices are still operated based on conventional refrigerants such as CFCs (Chlorofluorocarbons) [18-20], which generate considerable emission of carbon, green gas and harming materials. The devices also consume substantial amount of electrical energy. Thus, the current systems/devices have obvious negative impact on the sustainability of the built

environment, climate change and energy consumption.

A research project has been conducted with the support of Sustainable Construction iNET High Education Collaboration Fund [17] to develop a novel system of solid desiccant dehumidification with the electro-osmosis regeneration suitable for domestic use or small THICAC (Temperature and humidity independent control air-conditioning) units [19] and renewable energy applications, and typically for developing low/zero emission buildings.

The system uses water, which is environment-friendly, to replace conventional refrigerants to operate air-conditioning systems in buildings and will overcome the major problems of current system of evaporative cooling to satisfy the requirement of thermal comfort. The application of water evaporative cooling is often restricted in the UK and some areas of Europe typically due to relative higher humidity there. To overcome this problem, an effective solid desiccant dehumidification method is developed by this project.

Mobile communication is utilised as an important feature in this project research. The use of mobile devices, such as PDA (personal digital assistant) and mobile phone, provides the flexibility for remotely monitoring the working conditions of the system/devices, such as solid desiccant dehumidifier and air-conditioning. Instead of manipulating the central system in the PC-based monitoring centre, mobile devices give engineers and operators the ability to monitor system's working conditions via Internet and wireless network from any location, such as in the user's home or laboratory.

This research is part of the research project conducted by the Nottingham Trent University (NTU) team in collaboration with the project consortium members, University of Nottingham, and CE Technology Ltd, an SME in the East Midlands area.

Within the iNET supported collaborative project, the NTU team is responsible for the development of data collection, wireless control method, controller and control software used in the solid desiccant dehumidification, which is part of this PhD research.

2.4   Condition Monitoring of Thermo-Electric-Generations (TEGs)

A research project has been conducted with the support of Sustainable Construction iNET High Education Collaboration Fund [17] to develop a novel building block of thermoelectric co-generation for electricity and hot water. The block uses heat energies from the exhaust gas of domestic boiler and solar radiation to generate electricity and also supply the heat energy in hot water for domestic use.

The purpose of this project is to utilise solar thermal energy and integrate this into a building management system which uses a co-generation method. The total concept must be extremely reliable with no moving parts and be protected against the environment, with a 15 to 20 year life. The main purpose is to reduce the carbon emission of buildings.

Thermo-Electric-Generations (TEGs) are made from thermoelectric modules which are solid-state integrated circuits that employ three established thermoelectric effects known as the Peltier, Seebeck and Thomson effects [22, 23]. It is the Seebeck effect that is responsible for electrical power generation. Their construction consists of pairs of p-type and n-type semiconductor materials forming a thermocouple. These thermocouples are connected electrically forming an array of multiple thermocouples (thermopile), and then sandwiched between two thin ceramic wafers. The energy from heat sources can be converted into electricity by such thermoelectric module in the presence of temperature difference.

At present, there is nothing generally available in the market involving solar TEGs. Although currently photovoltaic (PV) systems are becoming dominated in the market [21], the costs are generally high and much dependant on silicon cells which result much CO_2 emission during the production. The purpose of TEGs is to make the device as simple and cost effective as possible to augment existing systems and be integral to an eco-structure, providing another area to make small efficiency improvements and to be deployable on mass scale.

This research is part of the Sustainable Construction iNET project conducted by Nottingham Trent University (NTU) team, in collaboration with the project consortium members, University of Nottingham, and European Thermodynamics Ltd, a SME. In this project, the author has developed a remote condition monitoring system for monitoring, controlling and recording the working conditions of Thermo-Electric-Generations.

2.5   Software Development Environments

Remote communication technologies are affecting how remote condition monitoring is performed. As remote communication technologies develop, a brilliant remote condition monitoring software will support multiple targets (terminals), integrate a broad range of commercial technology and deliver distributed software control [24]. In order to develop such software, the software development environments (SDEs) must be interoperable with a wide range of third-party hardware, such as data acquisition cards and reconfigurable I/O boards [24]. Multiple SDEs need to be used to program both a central computer and different types of targets (terminals), such as PDAs and smartphones [25].

In this research, LabVIEW professional, Adobe Flex, and Open-plug studio programming environments are integrated to develop a remote machine condition

monitoring system with server-client networking structure.

LabVIEW professional, shown in Figure 2.1, is a development platform for G programming language. LabVIEW is commonly used to develop applications for data acquisition, instrument control, and industrial automation on Microsoft Windows operation system. Due to the capability of LabVIEW's multi-threading/parallel execution, the applications are able to implement distributed applications with the server-client architecture. In this research, LabVIEW is utilised to develop the server-end remote conditions monitoring software [27, 28].

However, LabVIEW cannot be used to develop applications/codes of the client and does not provide the support for the application programming interface (API) of mobile operation system, either. To overcome the above problems, Adobe Flex Builder and Open-plug studio are applied to develop the client-end remote condition monitoring software, which can effectively communicate with API of mobile operation system.

Figure 2.1 LabVIEW graphical programming environment

Adobe Flex, similar to Microsoft Silverlight and Java applets, is one of the most common development platforms for developing web-based applications. Open-plug

studio is utilised as a plug-in of Adobe Flex to compile Flex code/script and make it effectively function in the mobile operation systems [30].
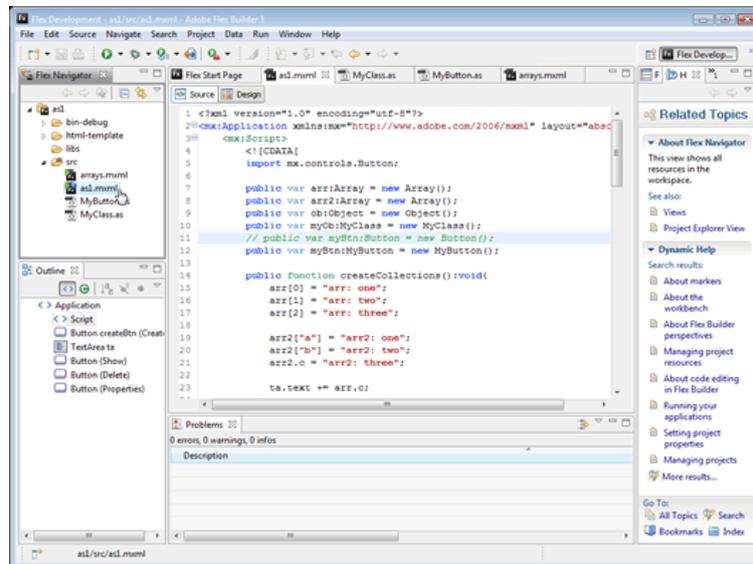
Figure 2.2 Adobe Flex Builder programing environment with Open-Plug

The combination of Adobe Flex and Open-plug greatly improve the interactive capability of web-based user interfaces and scripts. Furthermore, due to its efficient cross-platform feature, the developed application software has outstanding compatibility with different mobile devices such as PDA, mobile phone and laptop. Figure 2.2 presents the programming interface of Adobe Flex Builder.

2.6   Concluding Remarks

The above sections have reviewed the development trend and technologies in machine condition monitoring, including data acquisition, data processing, decision making, remote communication; their three application areas, including industrial gearboxes, solid desiccant dehumidifier for air-conditioning and thermo-electric generation; and the software development environment related to this research.

Traditional condition monitoring systems do not apply a network technique to monitor

the operation of machines, while modern condition monitoring systems employ the Internet technique to enhance condition monitoring and fault diagnostic capacities, and enable the implementation of data-acquisition, real-time diagnostic and decision-making processes through the Internet. However, as revealed in the review results, modern wireless/mobile techniques, such as wireless Wi-Fi, GSM, and GPRS mobile phone network, have not been effectively combined into the existing systems for remote condition monitoring of machines.

As indicated in this literature review, today's advance of wireless and mobile techniques leads to significant improvement of the processing power of mobile devices and the transmission capability of wireless and mobile phone networks, which provides the base for their effective application into remote real-time condition monitoring machines. However, *Integration of wireless and mobile techniques with signal processing, real-time fault diagnosis, and decision-making, into a model for remote real-time condition monitoring* is still a challenge.

To meet this challenge, a conceptual model is developed in this research with wireless and mobile techniques for remote real-time condition monitoring, which makes data acquisition, real-time fault diagnosis and decision-making available through the wireless and mobile phone network. The model makes the use of wireless and mobile features to implement remote real-time condition monitoring via mobile devices, such as mobile phones and PDAs. Because real-time working condition data are usually large and heterogeneous and wireless-based real-time applications are complicated, the conceptual model and related techniques with mobile cross-platform features developed by this research are novel contributions to this area.

Chapter 3   Development of the Novel Remote Real-time Condition Monitoring Model with Wireless and Mobile Technologies

3.1   Introduction

Machines are widely used in most manufacturing and service industries. Failure of machines may result in serious damage to equipment and/or people, lead to a decrease in productivity and bring financial loss. Real-time diagnosis and prognosis of machine condition and correct prediction of machine failure are obviously important.

As indicated in Chapter 2, although current condition monitoring systems employ the Internet communication to enhance condition monitoring and fault diagnostic capacities, it is still a challenge to combine the wireless and mobile techniques with signal processing, real-time fault diagnosis, and decision making, to provide a means for remote real-time condition monitoring. To meet such a challenge, a conceptual model of novel remote real-time condition monitoring is developed by the author, which is further detailed in this chapter.

3.2   Overview

The novel remote real-time condition monitoring model developed by this research enables the implementation of data-acquisition, real-time fault diagnosis and decision-making processes through the Internet, wireless and mobile phone network. In this chapter, gearbox condition monitoring is utilised as an example to illustrate the development of the remote real-time condition monitoring model. The condition monitoring method is also suitable for application in other areas such as the remote condition monitoring and fault diagnosis of solid desiccant dehumidifier and

Thermo-Electric-Generations, which are further illustrated in Chapters 5 and 6.

3.2.1   Structure of the Novel Remote Condition Monitoring Model

Figure 3.1 presents the overall structure of the novel remote real-time condition monitoring model. This model consists of the following modules (components): data acquisition, data processing, decision making, condition based maintenance, and remote communication.

The associated application software for building the model has been developed using sensory technique, data input/output (I/O) communication, digital noise filtering, pattern classification for fault diagnosis, the Internet, and wireless/mobile techniques.
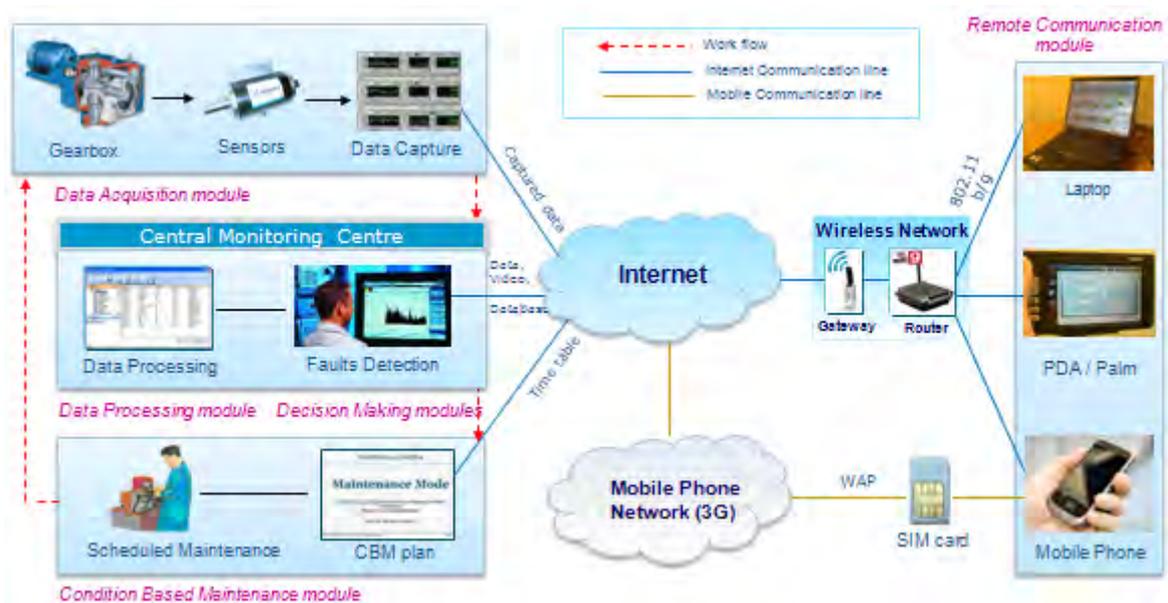
Figure 3.1 Concept model of remote real-time condition monitoring with wireless and mobile techniques

Each module of the conceptual model is detailed below, which provides the justification of the selection of technologies and explains why the model is developed in this way.

(1) <u>Data Acquisition Module</u>

Within this model, the data acquisition module is built up using the sensory technique and data I/O interfaces to collect the working conditions data from a machine, i.e. an industrial gearbox, which is located in a mechanical test rig. The sensory technique utilises sensors as data-acquisition devices to extract the physical information of the gearbox (e.g. failure, wear, etc.) and transfer the gearbox's physical quantities, such as vibration, torque, and rotational speed, to the computer via data I/O interfaces for data processing and decision-making.

The sensors used in gearbox condition monitoring includes: (1) vibration sensors, also called accelerometers, to acquire vibration data of motion of the gearbox to extract feature information of gearbox vibration, such as acceleration amplitude, for data processing and sequent fault diagnosis; and (2) torque and rotational speed sensors/transducers, to collect torque and rotational speed data to detect changes in motion of the gearbox, such as a high starting torque or an increased resistance to rotation, which are likely to result in a fault.

The physical quantities of working conditions of the gearbox include vibration, torque, and rotational speed. The vibration data are able to interpret internal operation status of the gearbox through the characteristic features of vibration signals, such as the acceleration's amplitude, frequency, and shape (waveform). These characteristic features are used to form the fault diagnostic criteria to identify fault symptoms of the gearbox, e.g. breakage/wear/pitting of gear teeth. The torque and rotational speed are applied to detect the changes of the gearbox motion when a fault occurs to identify the influence of workload and rotational speed on vibration of the faulty gearbox.

(2) <u>Data Processing Module</u>

The data processing is conducted in this module using the A/D (analogue-to-digital) conversion to convert the analogue data received from the data acquisition module to physical quantities of working condition of the gearbox (i.e. vibration, torque, and rotational speed), and then display the quantities of working condition and their waveforms over time on a monitor panel. In order to ensure the accuracy of the received data, the data are pre-processed by the means of a grouping method to get rid of odd/invalid data to reduce the calculation error and improve the accuracy of data processing. The A/D conversion is then utilised to transfer the analogue data in the form of voltage, current or impulse, to the digital data representing physical quantities applying conversion coefficients and linear/non-linear equations, which are obtained by calibrating the sensors.

(3) <u>Decision Making Module</u>

A real-time fault diagnostic scheme for decision making is applied based on digital noise filtering and pattern classification for fault diagnosis to real-time detect the fault symptom of the gearbox (e.g. breakage and wear of gear teeth). The digital noise filtering is utilised to remove unwanted noise signals from the signal source of the gearbox to extract gearbox signals required for further fault diagnosis. Because the acquired signals are contaminated by noise in the signal source, the signal-to-noise ratio is low and hence noise signals need to be removed to ensure that the acquired signals are about vibration information of the gearbox. Within this module, the adaptive filtering with least-mean-square (LMS) algorithm, as a fast and effective digital filtering method, is applied to extract gearbox signals from the noisy environment for the subsequent fault identification of signals.

The pattern classification for fault diagnosis employs the statistics-related gearbox feature analysis technique (SFA) to identify the symptom of the gearbox and to predict the potential failure of the gearbox. The statistics-related gearbox feature analysis

interprets the impulse energy and impulse strength of the gearbox using the following feature parameters: crest factor, impulse factor, kurtosis factor, clearance factor, and root-mean-square. The above feature parameters can be used to effectively identify the symptom of the gearbox by detecting the change in impulse features of the gearbox, and provide the basis for scheduling necessary maintenance work.

The combination of the statistics-related gearbox feature analysis and adaptive filtering has the following three characteristics: fast feature extraction, real-time fault identification, and few computational resources.

(4) Condition based Maintenance Module

In the condition-based maintenance module, the required maintenance is then scheduled according to the fault analysis results obtained to replace/repair any component and/or conduct the necessary maintenance.

(5) Remote Communication Module

Remote communication with wireless and mobile techniques greatly advance the gearbox's condition monitoring technique with real-time fault diagnostic capacity, by providing a wireless-based web platform to make data acquisition, data processing, and decision making available through the Internet, wireless, and mobile phone network, which is a novel contribution to this area. Based on wireless/mobile and the Internet technologies, the remote communication module is built up, which enables geographically dispersed users to utilise mobile devices with multiple mobile architecture/platforms to access the working condition data and diagnostic results of the gearbox from the server (central) computer located in the monitoring centre. The module is able to transmit the working condition data of the gearbox from a data-acquisition computer associated with the gearbox to the server computer through

the wireless and mobile phone network. The remote communication with mobile cross-platform features is applied to improve the gearbox's real-time condition monitoring capacity, which has not been reported in the literature.

The server-client network structure with mobile cross-platform feature is constructed in this module using the Web Service and the Data-Socket techniques for remote real-time condition monitoring. The Web Service is used as the HTTP-based application programming interface (API) to transmit the working condition data and analysis results from the server computer to the mobile devices in the client; and the TCP/IP based Data-Socket technique is able to transmit the working condition data from the data-acquisition computer to the server computer. The client including multiple mobile devices can be located in any location where the Internet or the wireless/mobile phone network is available. The communication standards for communicating with the client include the Transmission Control Protocol (TCP/IP), the Wireless Application Protocol (WAP) for small mobile devices such as mobile phones and PDAs, and the Hypertext Transfer Protocol (HTTP).

3.2.2   Software Functions

The remote real-time machine condition monitoring software has been developed using the Labview professional, Adobe Flex and Open-Plugin (C-plug) programming environments. Within this software, wireless, mobile, and the Internet techniques are combined with data acquisition, real-time fault diagnosis, and decision making, to provide a tool for remote real-time condition monitoring of a machine, which is a novel contribution to the existing remote monitoring systems. The software is applied to monitor and diagnose the working condition of an industrial gearbox to identify the symptom of the gearbox (see Figure 3.2), such as breakage and wear of gear teeth. The software is able to transmit the working condition data to the users in real time, such as

diagnosticians, via the Internet, wireless, and mobile phone network, and actively inform the users the diagnostic results to alert the users the working conditions of the gearbox. The real-time diagnostic results can be recorded to the hard drive located in the server automatically, and be used as the base of decision making for maintenance (see Figure 3.3).

The remote communication with mobile cross-platform capacity, as a significant feature of the software, is applied in the development of remote real-time condition monitoring system, which makes data-acquisition, real-time fault diagnostic and decision-making processes available via the mobile phones with multiple mobile architecture/platforms, which extends the multiple-platform feature of mobile devices to the condition monitoring area and is a novel contribution to this area. With this feature, the software enables various mobile users to access the working condition data and analysis results from the server in real time regardless of the architecture/platforms of mobile phones, e.g. Nokia mobile phone, HTC mobile phone, iPhone, and PDA, and even, to communicate with the server by joining a multiple-people conversation, which is similar to an online chat with multiple terminals, as shown in Figure 3.4.

The software developed by this research contains (1) Server of the Remote Real-time Machine Condition Monitoring System, (2) Client, including PDA and mobile phone, of the Web-based Remote Machine Condition Monitoring System, and (3) Remote Data Acquisition.

The Server software is the core of the remote real-time condition monitoring system software, which is deployed in the server computer and responsible to manipulate and manage the operation of the system. The Server software undertakes the work of signal processing and complex calculations, including data acquisition, digital filtering, pattern classification, real-time fault diagnosis, and data transmission with the client. It mainly has the following functions: data acquisition, data processing, decision making,

and remote communication.

The Client software for mobile phones and PDAs is able to access the working
condition data and diagnostic information, such as analytic results and warning
messages, from the server, and to display the data/information in the user interfaces of
the mobile devices (see Figure 3.5).

To implement real-time fault diagnosis for a remote machine, Remote Data-acquisition
software is developed to acquire the working conditions data from a machine which is
installed at a place far from the server, and transmit the data to the server computer for
data processing and real-time fault diagnosis via the Internet and wireless/mobile
phone network. Figure 3.6 presents the real-time data transmission from the
data-acquisition computer located besides the gearbox monitored to the server
computer.
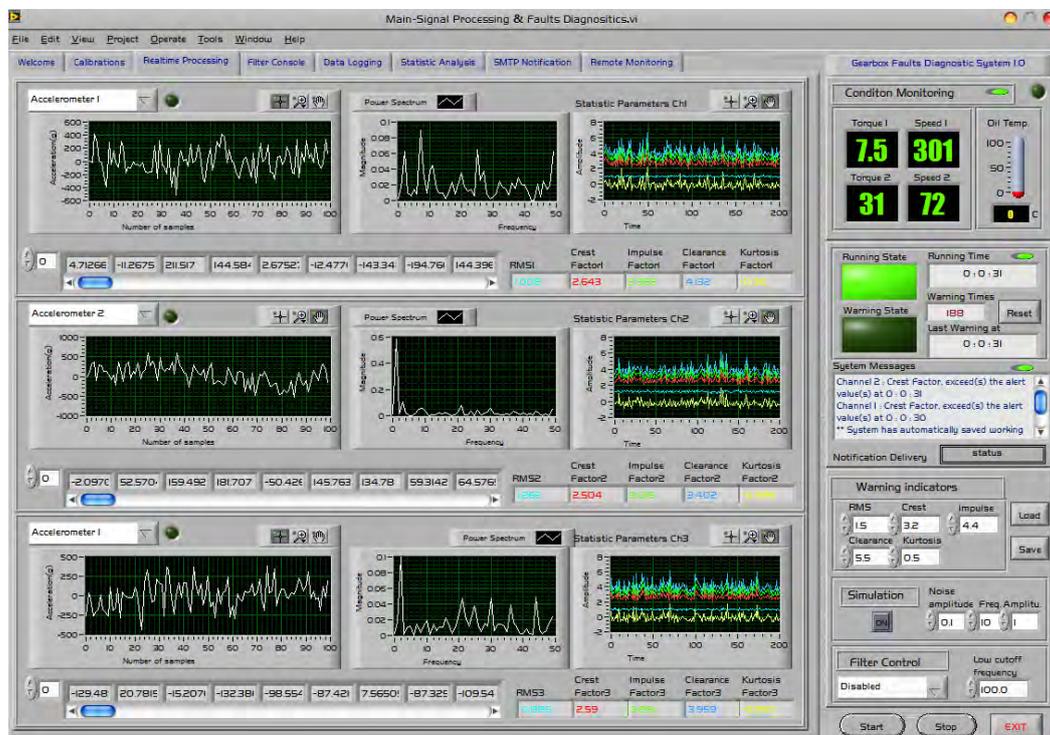
Figure 3.2 Data acquisition and real-time fault diagnosis using the developed Server
software of the remote condition monitoring system developed by this research
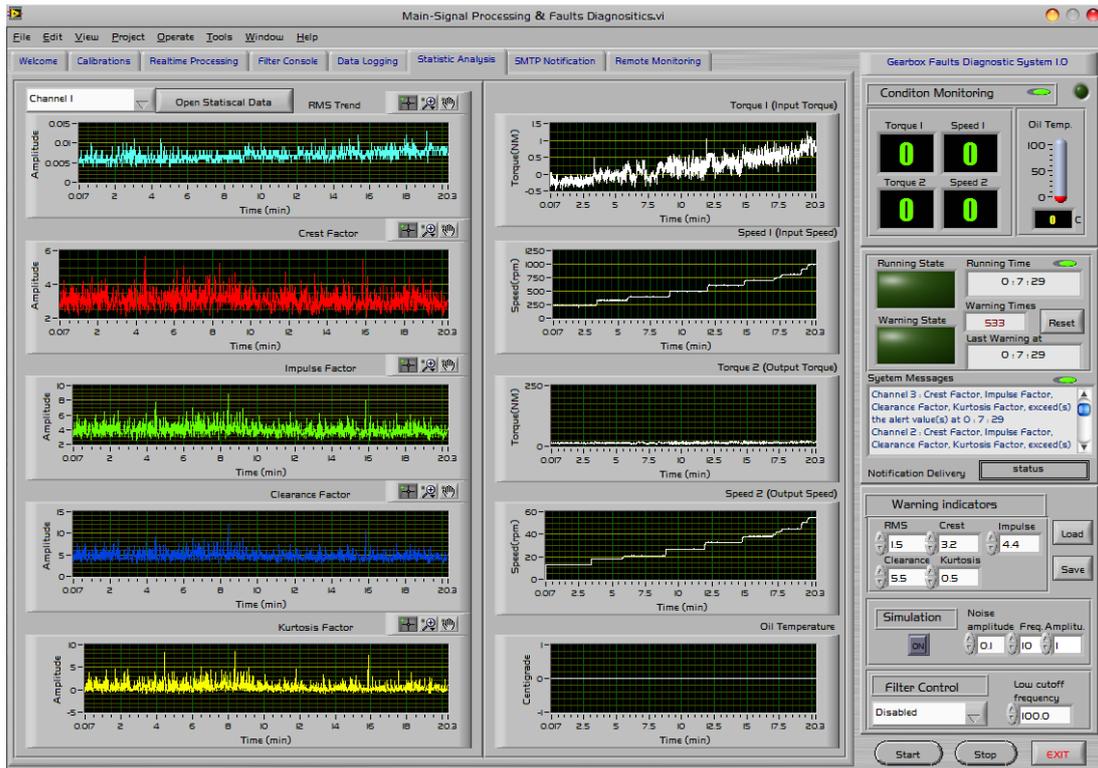
Figure 3.3 Data-logging using the server of the remote conditon monitoring system
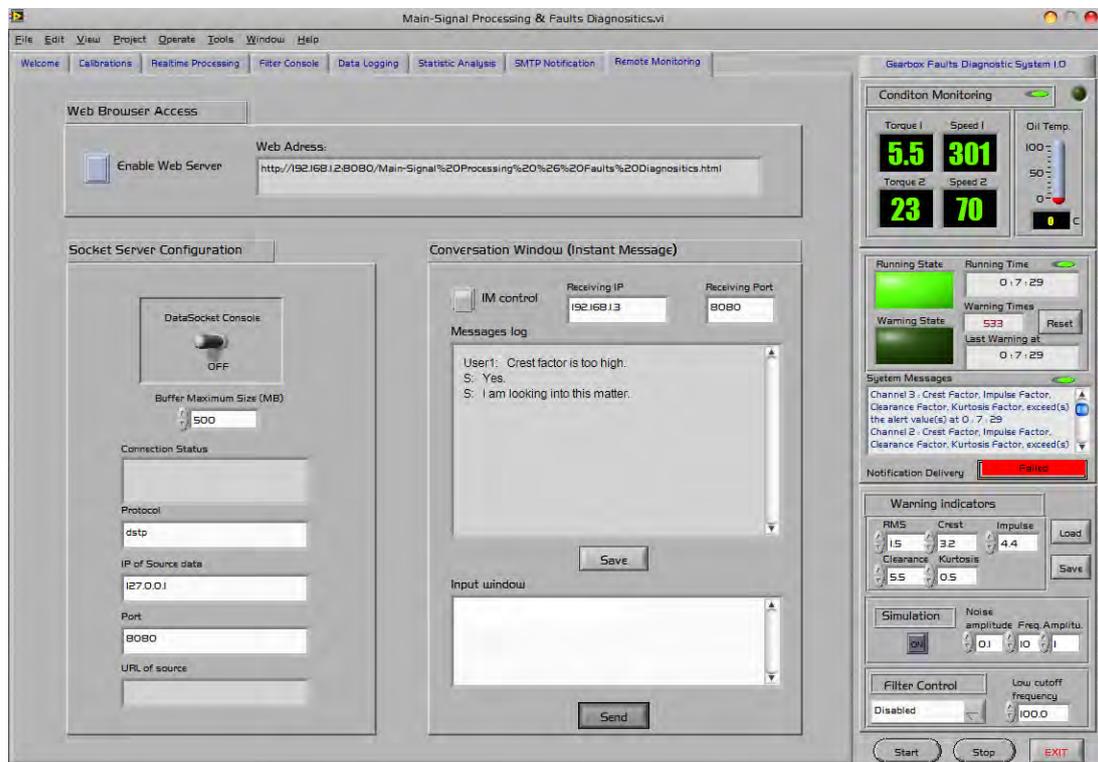
Figure 3.4 Remote communication with the client via Internet and wireless network
using the Server software developed by this resaerch
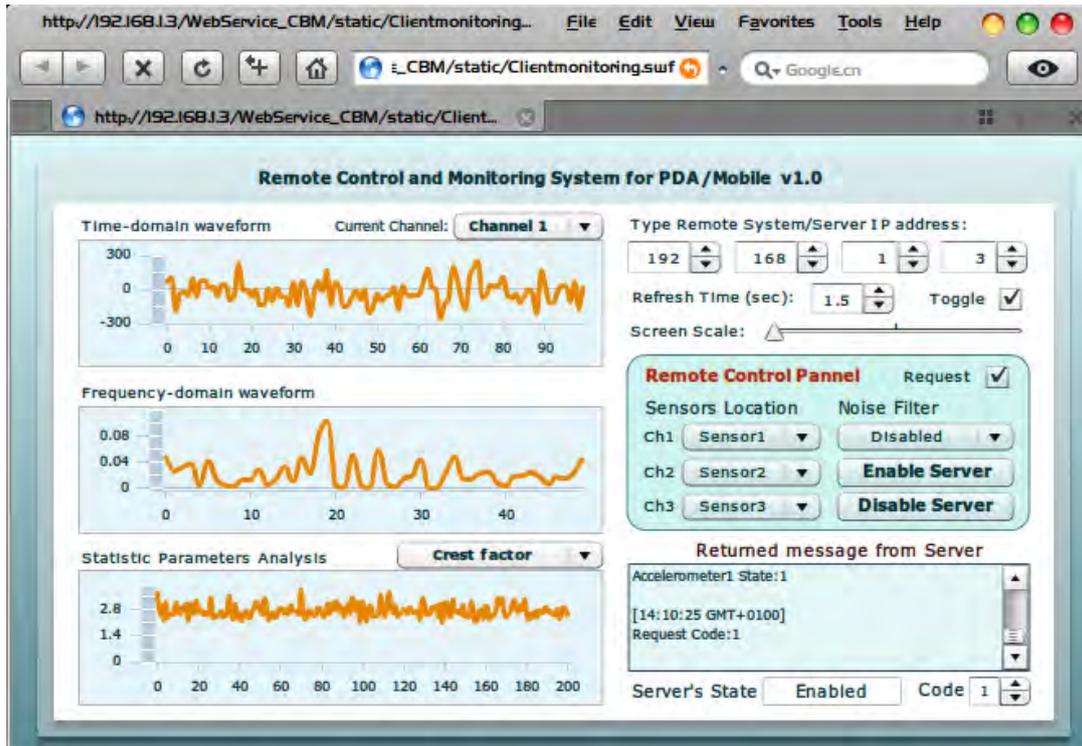
Figure 3.5 Real-time monitoring of working condition data and analysis results using
the Client software developed by this research
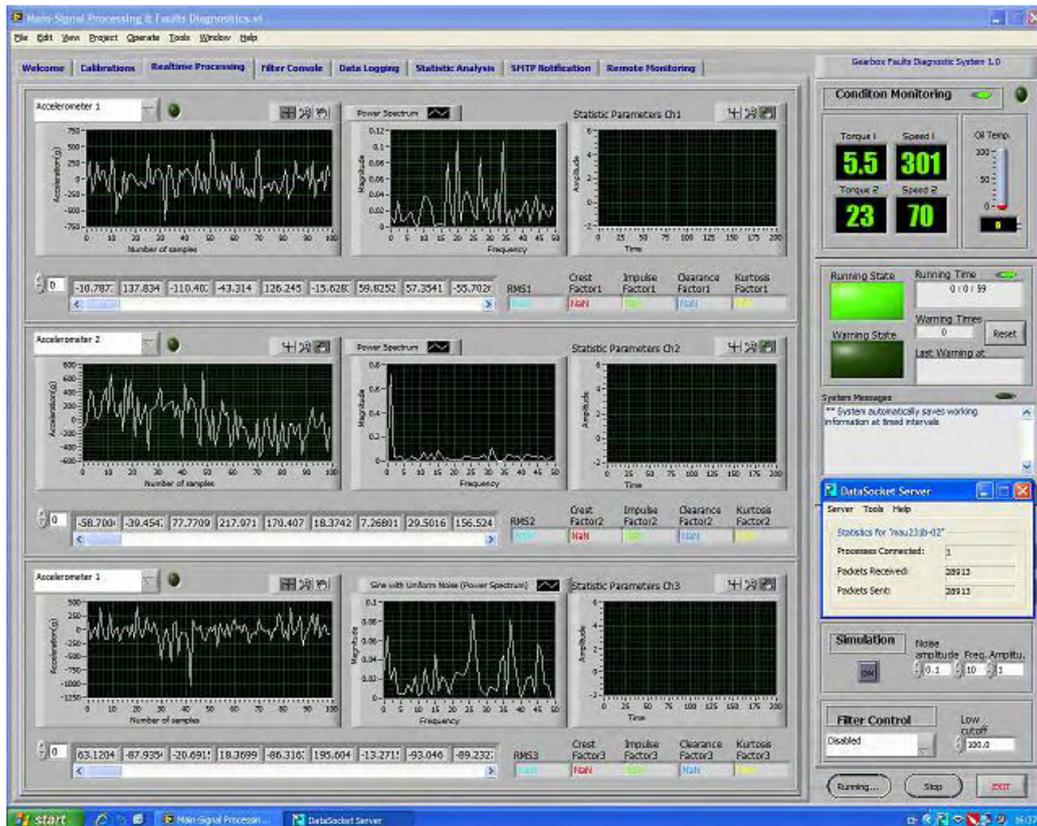
Figure 3.6 Real-time data communication from the data-acquisition computer to
the sever computer using the Remote Data-acquisition software developed by this
research

3.3   Development of Innovative Modules

Remote real-time condition monitoring model consists of five modules: data acquisition, data processing, decision making, condition based maintenance, and remote communication. The functionality of each module is detailed in the following sections.

3.3.1   Data Acquisition

The data acquisition module is built up with this model using sensory technique and data I/O interfaces to extract the physical information of an industrial gearbox located in a mechanical test rig, and to transfer the physical quantities of gearbox's working condition, such as vibration, torque, and rotational speed, to the computer for data processing and decision-making. The data acquisition module contains a mechanical test rig, accelerometers, torque/speed transducers, a computer for data acquisition, a server computer, acquisition hardware, and relevant software.

The mechanical test rig comprising of an input drive and an output drive is developed to test an industrial gearbox for a Chemineer agitator. The input drive consists of a 3kW variable speed AC motor to drive the gearbox via an input shaft, and a torque limiter set to stop applying the load at 18Nm for preventing the overload of the gearbox. The drive motor is fitted with the gearbox by delivering the rotational speed between 100 rpm and 1440 rpm.

The output drive includes a DC motor (generator) for applying a load to the gearbox to change gear engagement, and a control station in conjunction with the DC motor to control the output of the load. The DC motor can supply a load of 18Nm to the gearbox by tuning the voltage/current of the control station, and transmit the load to

the gearbox via an output shaft and a 2-level transmission belt.

The gearbox mounted in the mechanical test rig is part of driving system for Chemineer HT agitator [136], which includes a helical gear drive, a bevel gear drive, bearings, and shafts for transferring loads. Gearbox fault such as wear or failure of gear teeth can be discovered by monitoring vibration of the gear. While the gear is running, the gear transmits vibration that it generates to the bearing; the vibration data are then acquired by the sensor and transmitted to the computer via the data acquisition hardware for data processing and fault diagnosis. Figure 3.13 presents the mechanical test rig developed by this research and associated data acquisition unit including sensors and data acquisition card.
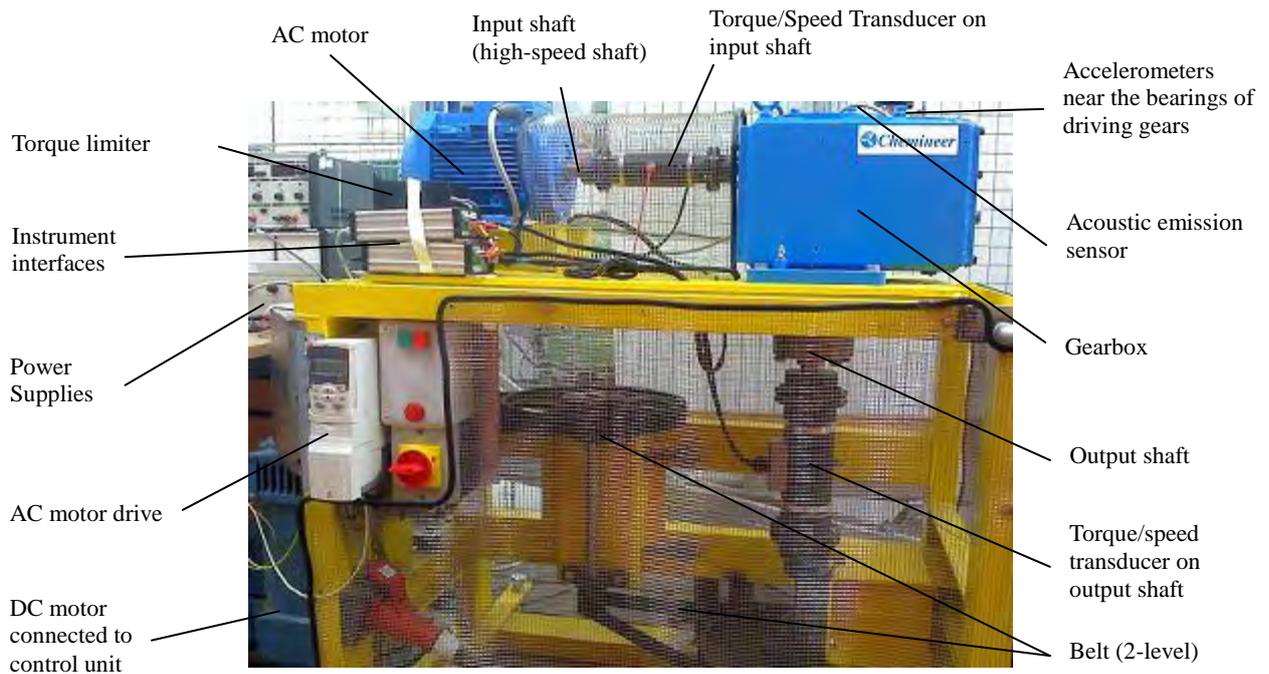
Figure 3.13 Mechanical test rig for testing an industrial gearbox and the associated data acquisition unit

The acquisition hardware includes a data acquisition card (DAQ) associated with distributed sensors for capturing physical phenomena such as vibration, torque, and rotational speed.

The DAQ card is not only a data acquisition instrument but a control unit of machine. The DAQ card has the data-transmission capability of double-way channels for data input (acquisition) and data output (control). On one hand, the DAQ card acquires data from input channels through the sensors and converts the analogue data to digital data, which can be read by the computer; on the other hand, the DAQ card converts digital data for output control into analogue data, which are then transmitted to the control units via output channels. The DAQ card simultaneously monitors two test gears on two shafts (driving shaft and driven shaft) respectively. The data sampling rate is 10 kHz and data length is 10k. Data is collected at the rate of 1 second per group. Figure 3.14 shows the installation sketch map of the data acquisition system.

Sensors/Transducers extract the information about the gearbox' operation process (e.g. gear teeth breakage, gear teeth wear, etc.) and transfer the physical quantity such as vibration, torque and rotational speed to the data-acquisition computer in form of analogue voltage via the data acquisition card. The functionality of the sensors is described as follows:

- Accelerometers are used to collect the information regarding the gearbox's vibration, and transmit the vibration data to the computer for further processing. Accelerometers are located at the positions near the bearings of the driving helical gear, driving bevel gear and driven bevel gear respectively. Two accelerometers near the driving gears are used as primary sensors to acquire the signals including gear signal and noise signal, while one accelerometer is utilised as the reference sensor to particularly collect the noise signal (For the details about the primary/reference sensors, please see the section '*Noise Filtering*'). Three accelerometers are connected to the amplifier, which provides the excitation to all accelerometers and amplifies the signals received from accelerometers.

- The non-contact torque/speed transducers are utilised to measure the torque and

speed, which are generated from the driving/driven shaft. The measured data are transmitted to the central computer in two forms: (1) digital form via a USB instrument interface (The method of data transfer with the digital mode is detailed in Appendix [3]); (2) analogue format via the data acquisition card.

- The fail-safe unit, which is indicated as 'Torque limiter' in figure 3.14, is set up in the mechanical test rig to prevent the gearbox from overloading. Once the rotation speed of driving shaft reduces below a given value or the workload exceeds a given value, the machine will be shutdown with the effect of the fail-safe unit automatically. The maximum workload of the preventive unit is adjustable from 0 to 18Nm.
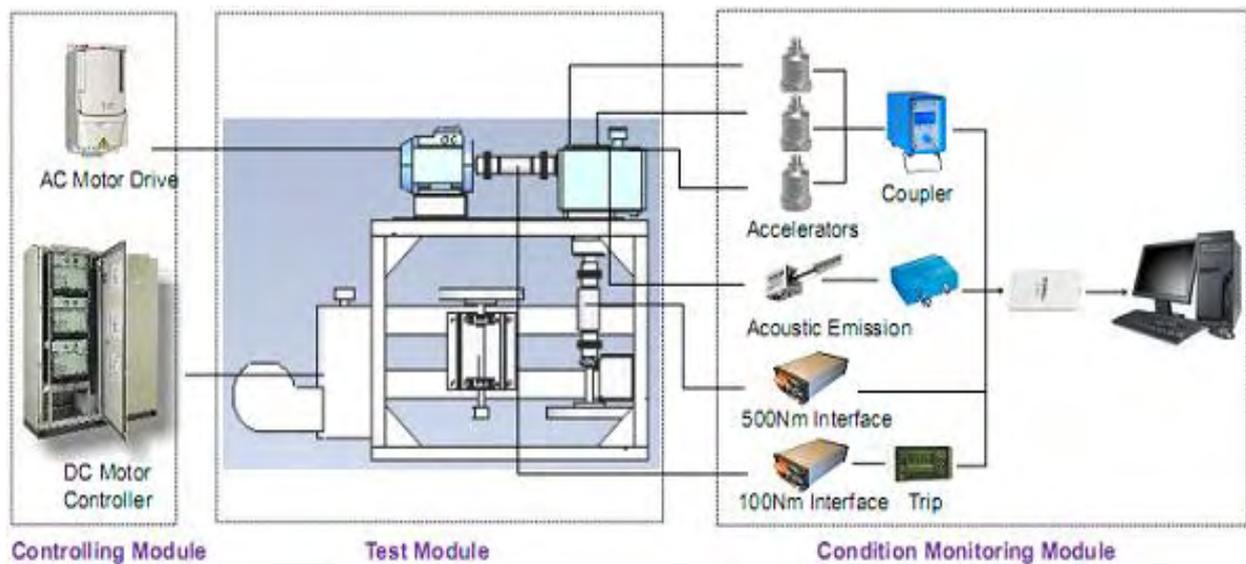
Figure 3.14 The structure of data acquisition module

3.3.2 Data Processing

The working condition data, which are acquired from the gearbox via the sensors, are transmitted to the data-acquisition computer, and then are transmitted via Internet and/or wireless network to the central (server) computer in the monitoring centre for further data processing. For the details about the data communication, please refer to

the section *Remote Communication*.

Data processing is implemented based on the coefficients and formulas of A/D (analogue-to-digital) conversion to convert the received data into real physical quantities, such as newton-meter (Nm) and rounds per minute (rpm). The A/D conversion coefficients/formulas are acquired by calibrating the sensors, i.e. three accelerometers and two torque/speed transducers. The process of calibration of the sensors is detailed in the following sub-sections:

3.3.2.1 Calibration of Accelerometers
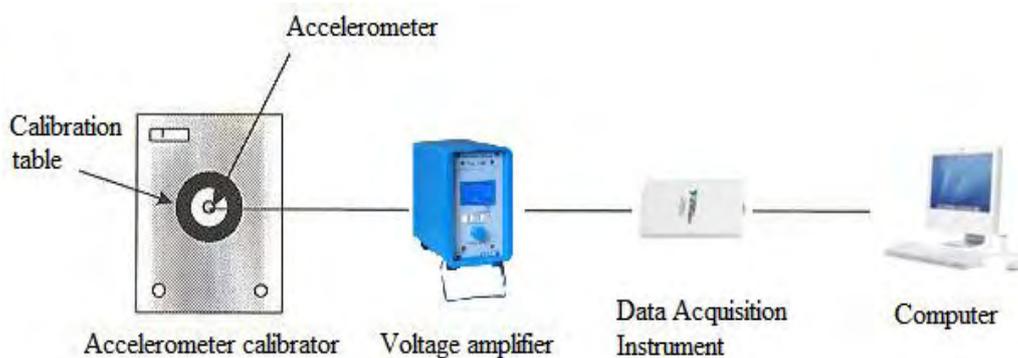
Figure 3.15 Calibration setup for the accelerometer

The calibration process of the accelerometer is conducted using the accelerometer calibrator B&K 4291. The accelerometer calibrator consists of a built-in 79.6Hz sinusoidal generator. The accelerometer is fixed on the calibration table of the calibrator and subjected to a standard vibration acceleration level of 10 m/s^2 peak at displacement of 40 um peak. The calibration system is shown in Figure 3.15.

The calibration process starts by adjusting the Acceleration Level of the accelerometer calibrator to the accelerometer used. The accelerometer used has a weight of 8.2 grams including the screw, which connects the accelerometer to the calibration table. The sensitivity of the voltage amplifier is then adjusted to the sensitivity of the

accelerometer.

Figure 3.16 shows the calibration results of the three accelerometers. The sensitivity of the accelerometers is measured 10.31mv/g (g=9.80665m/s^2), 10.38mv/g, and 10.34mv/g, respectively, while the gain of the amplifier is set by default. According to these sensitivities, the A/D conversion coefficients of three accelerometers are obtained, which are listed as follows:

Sensors	A/D conversion coefficients
Accelerometer 1:	amplitude per volt = 96.993g
Accelerometer 2:	amplitude per volt = 96.339g
Accelerometer 3:	amplitude per volt = 96.712g

Table 3.1 A/D conversion coefficients of three accelerometers
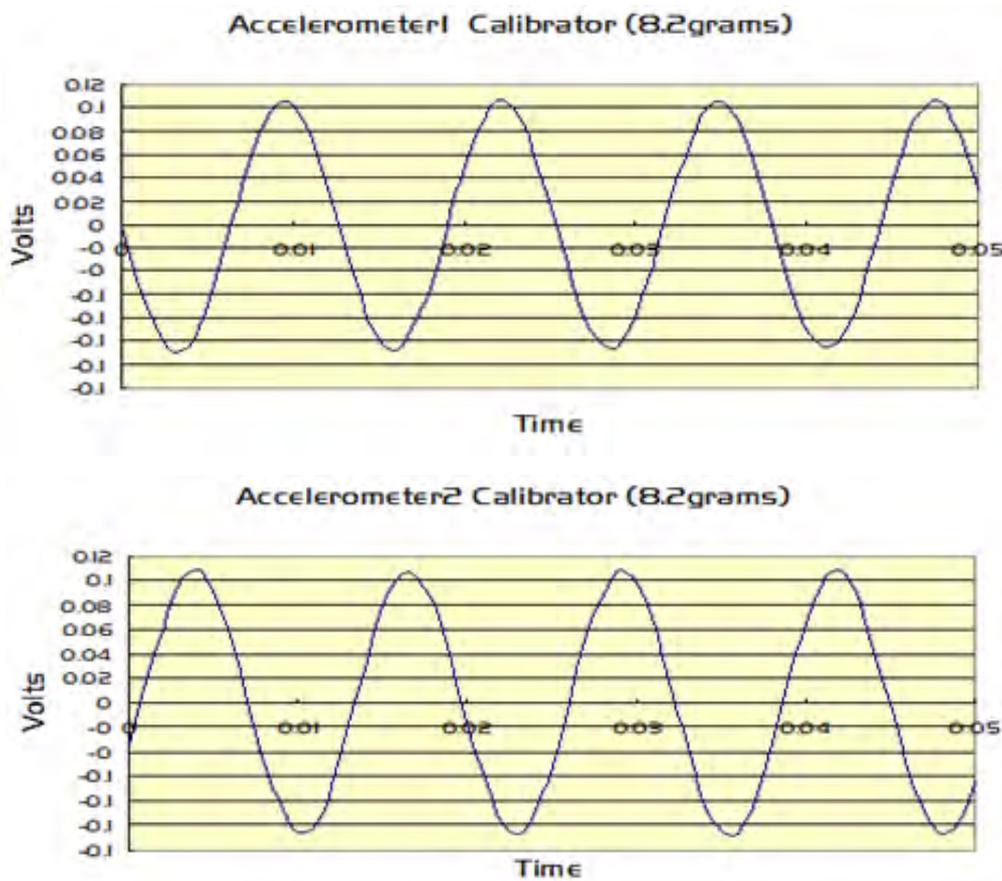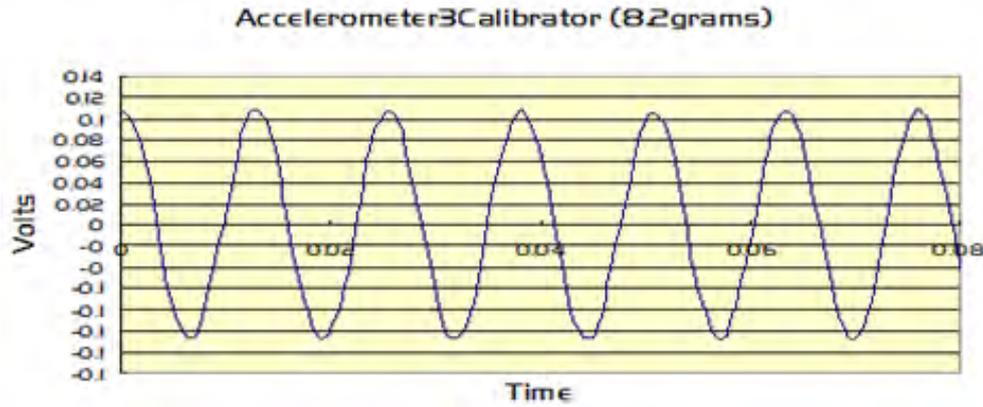
Figure 3.16 Calibrations of accelerometers with the use of the calibrator

3.3.2.2 Calibration of the Torque/Speed Transducers

The calibration of the torque/speed transducers are implemented by calculating the linear factors, which reflects the linear relationship between the voltage data of the transducers and real working condition values, which are acquired by the digital tachometer. Figure 3.17 shows the linear relationship of the torque/speed transducers under different working conditions.

The linear factors, also known as the A/D conversion coefficients of torque/speed transducers, are obtained as follows: (1) torque per volt (driving shaft) is 10 Nm; (2) speed per volt (driving shaft) is 500rpm; (3) torque per volt (driven shaft) is 50.76Nm; and (4) speed per volt (driven shaft) is 10rpm.
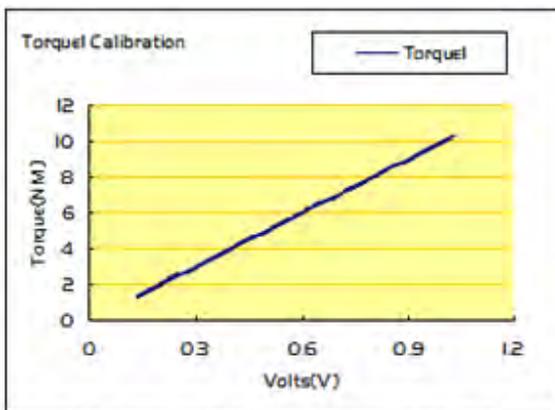
(a) Torque calibration for transducer 1

(b) Speed calibration for transducer 1

(c) Torque calibration for transducer 2   (d) Speed calibration for transducer 2
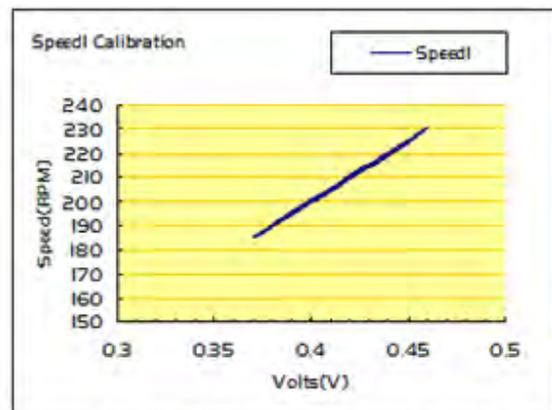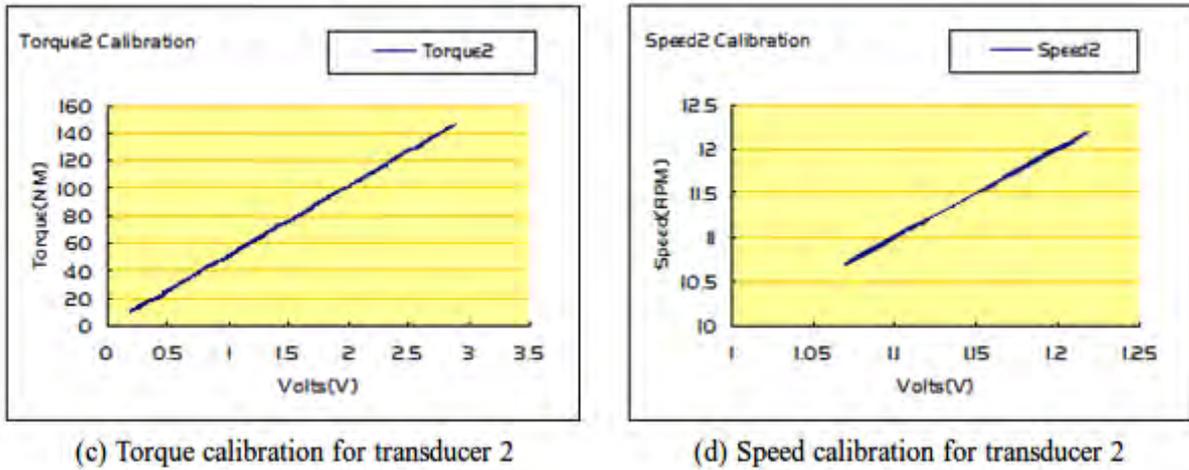
Figure 3.17 Calibrations of Torque and Speed Transducers

3.3.2.3 A/D Conversion

The acquired A/D conversion coefficients are configured in the system as shown in Figure 3.18. According to these coefficients, the A/D conversion formulas are then obtained, as listed in the table 3.1, which are used to convert the voltage data of the sensors into real physical qualities of the working conditions.
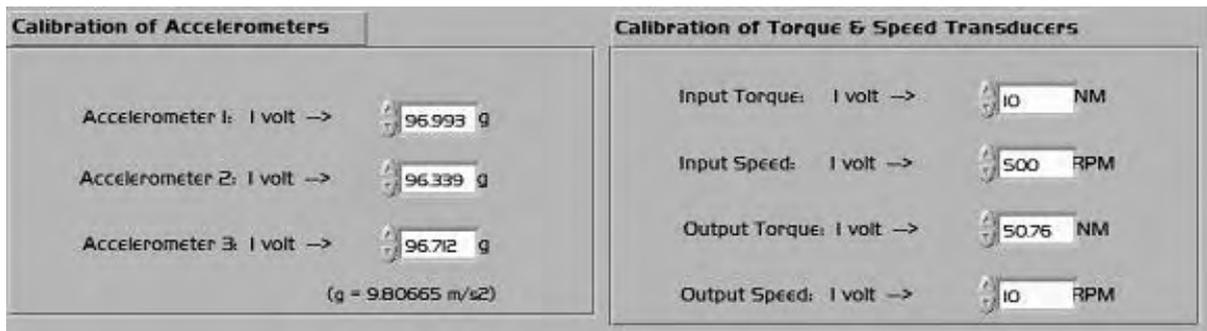
Figure 3.18 A/D panels of torque/speed transducers

Sensors	A/D Conversion
Accelerometers	Amplitude value of Acce. 1 = 96.993 * SensorValue
	Amplitude value of Acce. 2 = 96.339 * SensorValue

	Amplitude value of Acce. 3 = 96.712 * SensorValue
Transducer on driving shaft	Torque of Driving shaft (NM) = 10 * SensorValue
	Rotation Speed of Driving shaft (RPM) = 500 * SensorValue
Transducer on driven shaft	Torque of Driven shaft (NM) = 50.76 * SensorValue
	Rotation Speed of Driven shaft (RPM) = 10 * SensorValue

(SensorValue refers to the voltage data, which are acquired from the sensors)

Table 3.1 A/D conversion for calculating real working conditions

3.3.3 Decision Making

Decision making is utilised based on digital noise filtering and fault diagnosis to identify the fault of the gearbox. The digital noise filtering removes noise data from the acquired vibration signal data to extract vibration information of the gear. The filtered gear signals (data) are then analysed using fault recognition with statistics-related feature parameter algorithm (SFA).

SFA is a type of statistics-based mathematical method, which uses the amplitude of time-domain signal to calculate gear's impulse features and impulse energy. Typical SFA feature parameters include crest factor, impulse factor, kurtosis factor, clearance factor and root-mean-square.

The feature parameters are online calculated and displayed in the central computer in real time. When any of the parameters exceeds the upper limit set by the system, a warning message will appear on the software interface of the central computer; in the meantime, the technician and user will be informed the analysis results and alerted the working conditions of the gearbox by email.
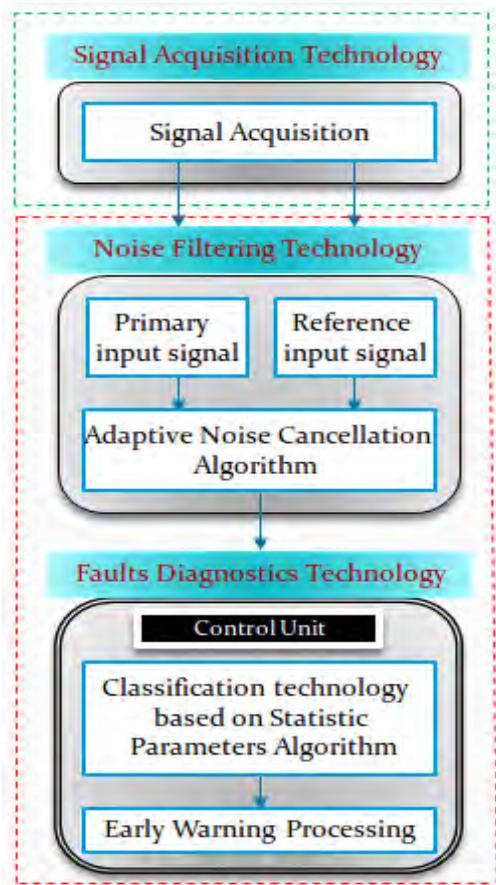
Figure 3.19 Digital filtering and faults recognition of gearbox

On the basis of the above methods, the gear's fault can be discovered in time. The required maintenance is subsequently scheduled according to the fault results to replace/repair components or conduct the necessary maintenance activity. Figure 3.19 presents the process of digital noising filtering and fault recognition of gearbox.

In the following sections, fault diagnosis using digital noising filtering and statistics-related parameter calculation is illustrated.

3.3.3.1 Digital Noise Filtering

For the recognition of fault signal, the application of digital noise filtering technology is a key step, which can get rid of noise signal from the received vibration signals to extract the gear signals for the analysis of gear symptom. To remove the noise, the

noise filtering with the adaptive filter and traditional digital filter is utilised by improving signal-to-noise ratio of signal.

3.3.3.1.1 Noise Filtering with Adaptive Filter

Figure 3.20 presents the schematic diagram of the noise filtering with adaptive filter. Within this diagram, S is the gear signal and N_0 is the noise signal to be removed. Because the gear's signal S is corrupted by the noise N_0 when the gear is running under abnormal conditions, neither the signal S nor N_0 can be acquired directly. That is, only the signal d(n) formed by S and N_0 can be acquired.
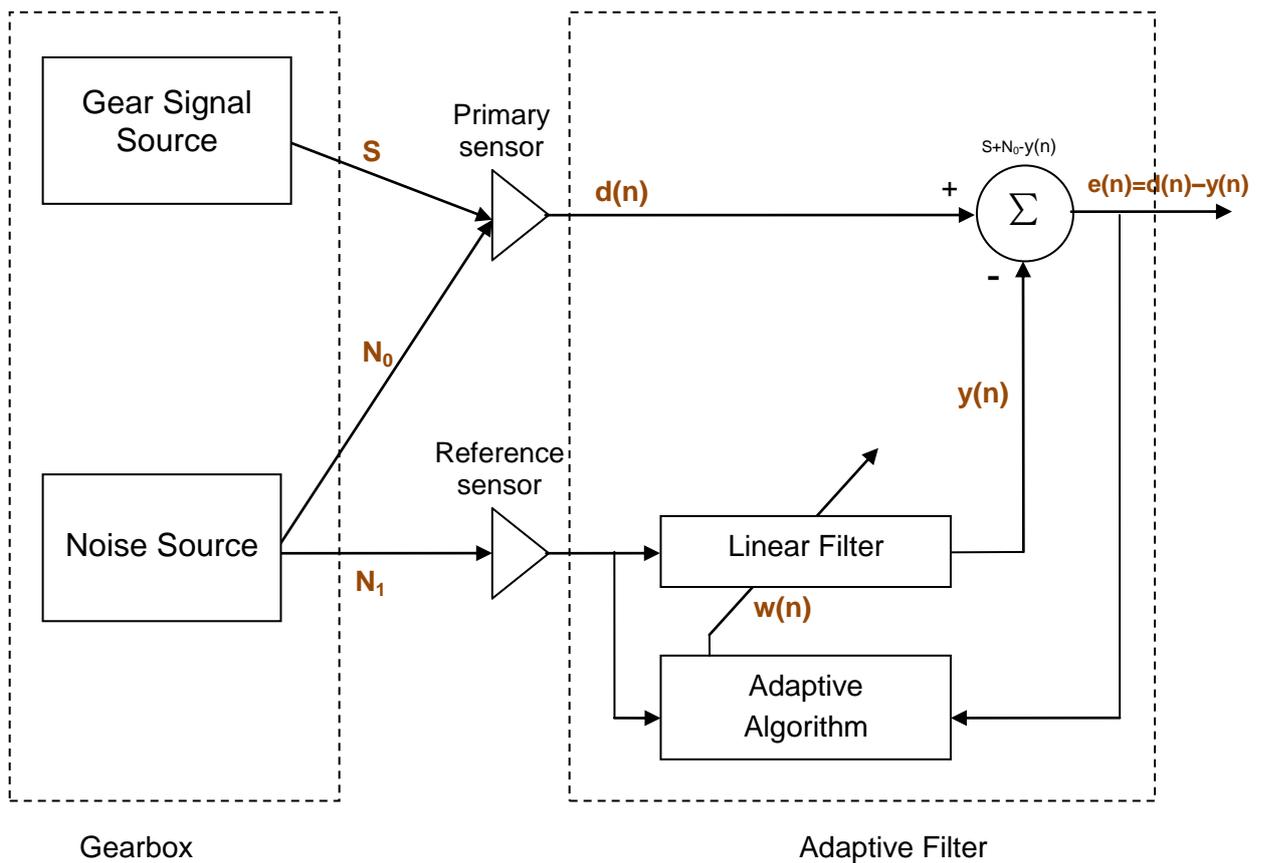
Figure 3.20 Machine noise filtering using adaptive filter

Adaptive filter requires two sensors, i.e. primary sensor and reference sensor, to

acquire signals from the signal source and noise source, respectively. The primary sensor is installed at the position that is very close to signal source, such as helical driving gear, to collect the signal d(n), while the reference sensor is placed at the position which is near noise source to acquire the noise signal N_1. The noise signal N_1 is used as a reference signal to be sent into the adaptive filter. It is highly related to noise N_0 but uncorrelated with gear signal S.

The adaptive filter utilises the adaptive algorithm to extract the gear signal S from the signal d(n). The adaptive filtering process starts by computing the machine noise y(n). The adaptive filter uses the reference noise N_1 and the filter coefficient w(n) to acquire the machine noise y(n), which is related to noise signal N_0. Then the error signal e(n) is calculated as e(n)=d(n)-y(n), which measures the difference between the input and the output of adaptive filter. On the basis of this measure, the adaptive filter adjusts the filter coefficients w(n) to reduce the error e(n). When the mean-square of the error converges at minima, the machine noise y(n) becomes close to the noise N_0 and the error e(n) converge at gear signal S. Thus, the noise N_0 is eliminated in the subtraction unit, and the gear signal S is detached from the signal d(n).

3.3.3.1.2 Adaptive Algorithm

For the choice of adaptive algorithm, both the convergence speed and the requirements of computational resource must be considered first. For example, The QR decomposition-based recursive least squares (QR-RLS) algorithm requires the most computational resources; however, the corresponding convergence speed is fast. The least mean-squares algorithm (LMS) requires the fewest computational resources; however, the corresponding convergence speed is slow. In particular, when the input signal of filter is corrupted by time-varying noise, the convergence rate of least mean square becomes very slow.

However, adaptive filtering can overcome the shortcomings of LMS algorithm in calculating convergence rate. The adaptive filter using LMS algorithm is able to eliminate the overlapping noise components which are uncorrelated with gears fault symptom signal in the same frequency range.

3.3.3.1.3 Adaptive Filter

Labview provides mathematical functions for creating the adaptive filter. Using these functions, the adaptive filter with least mean-square (LMS) algorithm is established. Figure 3.21 presents the block diagram of the Labview adaptive filter with LMS algorithm.
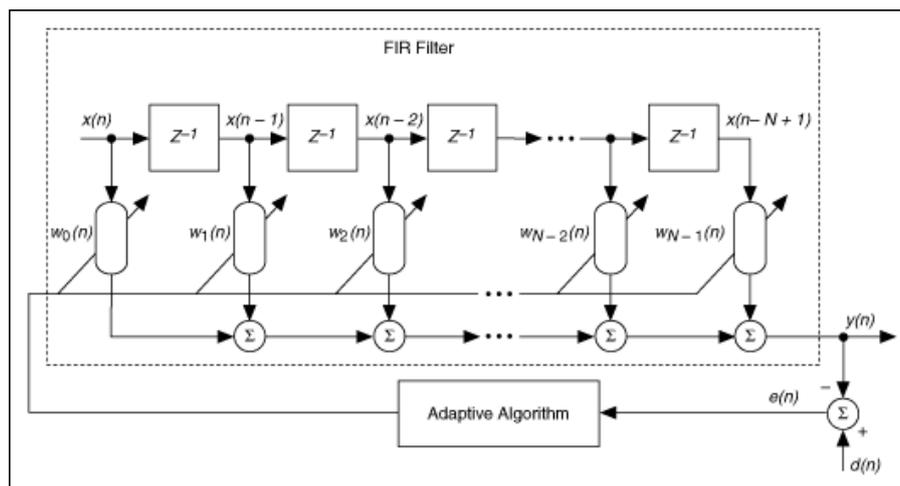
Figure 3.21 Diagram of the adaptive filter with LMS algorithm

Within this diagram,

    x(n) is the input signal to the linear FIR filter at time n, which is equal to noise signal N_1;

    y(n), known as machine noise function, is the output signal of the FIR filter;

    d(n) is another input signal to the adaptive filter, which is equal to $S+N_0$;

    e(n) is the error signal that denotes the difference between d(n) and y(n);

    $w_i(n)$ is the filter coefficient, and is also known as the multiplicative gain;

i is an integer with a value range of [0, n–1];

Z–1 is a unit delay.

3.3.3.1.4 Filter Coefficients

The following procedures detail how the filter coefficients $w_i(n)$ is computed using LMS algorithms.

(1) The adaptive filter adjusts the filter coefficients $w_i(n)$ to minimize J(n), which is the expectation of the square of the error signal e(n) at time n. J(n) is given by:

$$J(n) = E[e^2(n)] = e^2(n) \tag{1}$$

where $E[e^2(n)]$ is the expectation of $e^2(n)$, and the instantaneous value of $e^2(n)$ at time n is taken as the estimation of $E[e^2(n)]$.

(2) The error e(n) is calculated with the following equation:

$$e(n) = d(n)–y(n) \tag{2}$$

(3) The machine noise y(n) is computed with the equation[3]:

$$y(n) = \vec{a}^T(n) \cdot \vec{w}(n) \tag{3}$$

where $\vec{a}(n)$ is the filter input vector, and $\vec{w}(n)$ is the filter coefficients vector

$$\vec{a}(n) = [x(n)x(n-1)...x(n-N+1)]^T \tag{4}$$

$$\vec{w}(n) = [w_0(n)\, w_1(n)...w_{N-1}(n)]^T \tag{5}$$

(4) Next, the adaptive filter updates the filter coefficients $w_i(n)$ iteratively using the equation [6]:

$$\vec{w}(n+1) = \vec{w}(n) + \mu \cdot e(n) \cdot \vec{a}(n) \tag{6}$$

where μ is the step size of the adaptive filter. Thus LMS complete a cycle of computation of the filter coefficient.

3.3.3.1.5 Length of Adaptive Filter

The filter length is a significant filter factor, which affects the mean square error, convergence speed, and computational resource required. The filter length must be long enough to satisfy the requirement of noise filtering. The longer the filter length is, the smaller the mean square error becomes.

However, if the filter length is too long, the mean square error cannot converge at the minimal and the convergence speed becomes slow. Also, a long filter length requires more computational resources. Therefore, the minimum filter length that can satisfy noise-filtering requirement is appropriate.

Decision of a filter length is a trial-and-error process. The simulation of adaptive filter is used to determine an appropriate filter length.
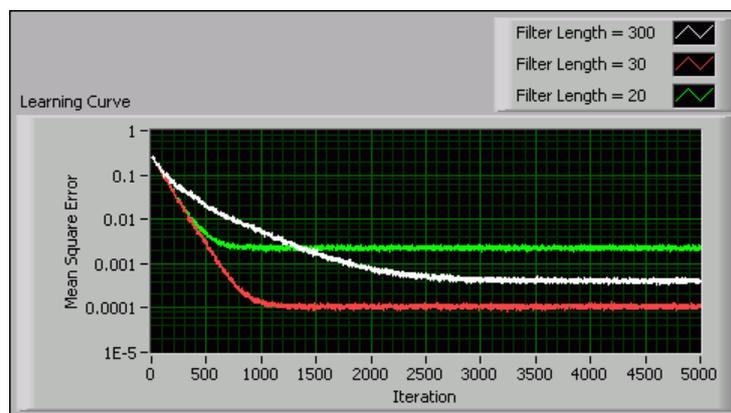
Figure 3.22 Adaptive filter simulation with three different
filter lengths and the same step size

Figure 3.22 shows the simulation results of adaptive filter. Within this simulation, three different filter lengths and the same step size are used to filter a noise signal. The following results are obtained:

(1) When the filter length is 20, the adaptive filter becomes steady and the mean square error converges at 0.002 after approximately 800 iterations.

(2) When the filter length increases to 30, the adaptive filter spends more time to

converge, but the least mean square error decreases. As seen in the figure 3.10, the least mean square error drops down to 0.0001 after 1100 iteration.

(3) When the filter length arrives at 300, the least mean square error increases instead. This shows that the filter length is much too long. Based on the above results, the filter length is determined as 30.

3.3.3.1.6 Step Size of Adaptive Filter

Similar to the filter length, the step size is also an important factor, which affects the mean square error and convergence speed.

A small step size can acquire a small mean square error. However, if the step size is too small, the convergence speed will become slow.
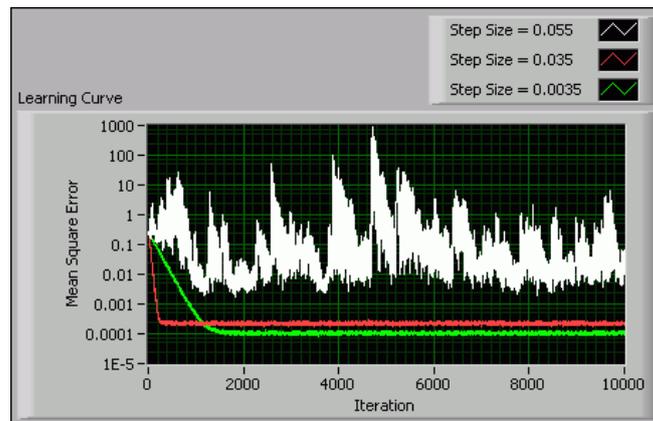
Fig 3.23 Adaptive filter performance with different step size

Figure 3.23 presents the simulation results of the adaptive filter with different step size. It can be found that:

(1) When the step size is set 0.0035, the adaptive filter has a least mean-square error of 0.0001. The convergence curve becomes steady after approximately 700 iterations.

(2) When the step size increases to 0.035, the convergence speed become fast, but the mean-square error increases to 0.0004. (3) When the step size arrives at 0.055, the adaptive filter becomes unstable. According to the above results, the step size is set as

0.0035.

3.3.3.1.7 Traditional Digital Filter

In addition to the adaptive filter, Infinite impulse response (IIR) filter is utilised as a traditional digital filter to eliminate noise signal from the work environment. IIR filter contains five standard filter topologies: Butterworth, Chebyshev, Inverse-Chebyshev, Elliptic and Bessel. The feature of the each filter topology is listed in the following points:

(1) Butterworth filter has a smooth and monotonically decreasing frequency response. Figure 3.24 shows a typical filter with Butterworth.

(2) Chebyshev filter can achieve a sharper transition between the passband and the stopband with a lower order filter than Butterworth filter.

(3) Elliptic filter minimize the peak error by distributing it over the passband and the stopband, and therefore provide the sharpest transition between the passband and the stopband.

(4) Bessel filters have maximally flat response in both magnitude and phase. It can be used to reduce nonlinear phase distortion inherent in all IIR filters.
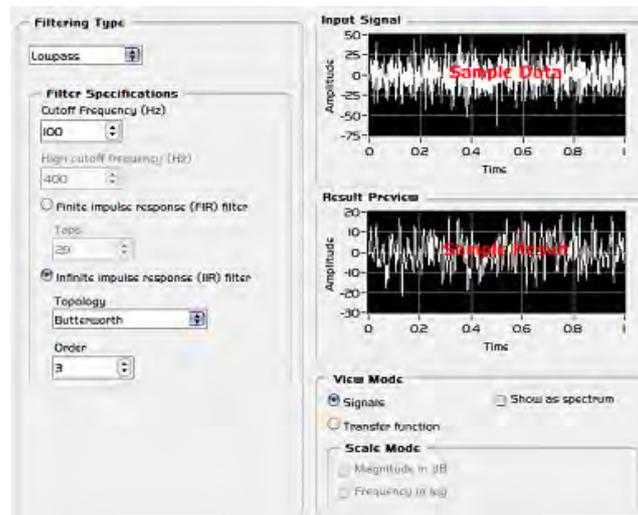
Figure 3.24 A typical digital filter - Butterworth filter

3.3.3.1.8 Comparison of Adaptive Filter with Traditional Digital Filters

The adaptive filter differs from a traditional digital filter in the following ways:

1. A traditional digital filter has only one input signal $x(n)$ and one output signal $y(n)$. An adaptive filter requires an additional input signal $d(n)$ and returns an additional output signal $e(n)$.

2. The filter coefficients of a traditional digital filter do not change over time. The coefficients of an adaptive filter change over time. Therefore, adaptive filters have a self-learning ability that traditional digital filters do not have.

3. Adaptive filters can complete some signal processing tasks that traditional digital filters cannot. For example, adaptive filters can be used to remove noise signal that traditional digital filters cannot remove, such as noise whose power spectrum changes over time.

4. Adaptive filters can complete real-time modelling tasks that traditional digital filters cannot. For example, adaptive filters can be applied to identify an unknown system in online mode. Typically, adaptive filters are useful when performing online signal processing applications.

3.3.3.2 Fault Recognition based on Gear Feature Parameters

Fault recognition is a pattern classification technology, which typically uses time/frequency domain and statistics-related methods to identify whether the gearbox is good/defective. Time/frequency domain utilises the time/frequency-based waveform, such as amplitude-time chart, to determine the gear's symptom.

The statistics-based feature parameter analysis is conducted using gear's feature parameters to calculate the impulse energy/feature of gear. The feature parameters

used include crest factor, impulse factor, kurtosis factor, clearance factor and root-mean-square. These parameters are well adapted to detecting the gear's impulse feature in a time-domain serial and to discover the gear's abnormality. When the gear fault such as wear or failure occurs, the parameters may change. The calculation with regard to the feature parameters is detailed as follows:

(1) Root mean square (RMS), also known as the efficient value, is a statistical measure of the magnitude of a varying time. The RMS of a collection of N number of samples $\{x_1, x_2\ldots, x_n\}$ is:

$$x_{rms} = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} x_i^2} \qquad (i=1, 2\ldots, N) \qquad (7)$$

with N the number of samples taken within the signal, i the index of samples, and x(i) the time domain signal, which is also used in the following equations.

(2) The crest factor corresponds to the ratio between the crest value X_{max} (maximum absolute value reached by the function representative of the signal during the considered period of time) and the r.m.s value X_{rms} (efficient value) of the signal:

$$Crest\ factor = \frac{x_{max}}{x_{rms}} = \frac{\max|x_i|}{\sqrt{\frac{1}{N}\sum_{i=0}^{N-1} x_i^2}} \qquad (i=1, 2\ldots, N) \qquad (8)$$

As the value of the crest factor of a signal whose amplitude distribution is Gaussian is between 3 and 6, this indicator can detect that kind of defects only if its value is at least equal to 6.

(3) The impulse factor corresponds to the ratio between the crest value X_{max} and the average amplitude value $|\bar{x}|$ (mean value of the amplitudes for N samples of the signal) :

$$impulse\ factor = \frac{x_{max}}{\left|\overline{x}\right|} = \frac{\max\left|x_i\right|}{\dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1}\left|x_i\right|} \qquad (i=1,\ 2\ldots.,\ N) \qquad (9)$$

(4)   The clearance factor corresponds to the ratio between the crest value X_{max} and the amplitude root value X_r:

$$Clearance\ factor = \frac{x_{max}}{x_r} = \frac{\max\left|x_i\right|}{\left(\dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1}\sqrt{\left|x_i\right|}\right)^2} \qquad (i=1,\ 2\ldots.,\ N) \qquad (10)$$

(5) The shape factor corresponds to the ratio between r.m.s value X_{rms} and the average amplitude value $\left|\overline{x}\right|$ (mean value of the amplitudes for N samples):

$$Shape\ factor = \frac{x_{rms}}{\left|\overline{x}\right|} = \frac{\sqrt{\dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1}x_i^2}}{\dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1}\left|x_i\right|} \qquad (i=1,\ 2\ldots.,\ N) \qquad (11)$$

(6) The kurtosis factor is an important statistical parameter allowing to analyse the distribution of the vibratory amplitudes contained in a time domain signal. It corresponds to the moment of fourth order norm and it has been shown that for a Gaussian distribution, its value is of 3:

$$Kurtosis\ factor = \frac{\beta}{x_{rms}^4} = \frac{\dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1}x_i^4}{\left(\dfrac{1}{N}\displaystyle\sum_{i=0}^{N-1}x_i^2\right)^2} \qquad (i=1,\ 2\ldots.,\ N) \qquad (12)$$

with β the fourth order statistic moment, X(i) the amplitude of the signal for the i sample and N number of samples taken in the signal.

3.3.4 Condition Based Maintenance

In the condition-based maintenance module, the required maintenance is then scheduled according to the fault analysis results obtained to replace/repair any

component and/or conduct the necessary maintenance.

3.3.5 Remote Communication

A web platform is developed for the modules to communicate each other via Internet, wireless, and mobile phone network. The web platform provides two functions:

(1) To allow the users to utilise mobile devices, such as mobile phone, PDA and laptops, to remotely access the data and analysis results from the central (server) computer, and also, allowing the users to send the control commands to the server to perform the required control operations.

(2) To transmit the data from the data-acquisition computer to the server computer for data processing.

On the basis of the above-stated functions, the development of web platform contains the following two aspects:

(1) The communication between the central computer and mobile devices;

(2) The communication between the central computer and the data-acquisition computer;

3.3.5.1 Remote Communication between the Central Computer and Mobile Devices

3.3.5.1.1   Server/Client Networking Structure

The server-client networking structure is adopted to realise the remote communication between the server and the client. The server-client network is constructed with the following arrangement:

(1) The server is deployed in the central computer in the monitoring centre. It

combines Web server and Flex Media server. Web server works to transmit the data/results to the mobile devices in the client, and meanwhile, allows the users to send the commands/parameters to the server to regulate the working conditions of gearbox. Flex Media server is used to encode the video stream captured by web camera into flash format and broadcast the stream to the mobile devices in the client end. The central computer is located in the server to conduct required calculation and data communication, such as data acquisition/processing, fault diagnosis, etc.

(2) The client is allowed to be set up in any location, such as user's home, lab, or somewhere far away from the server as long as Internet, wireless, and/or mobile phone network is available. The client is composed of a mobile phone or a handheld PDA and a wireless Wi-Fi router for wireless connectivity.
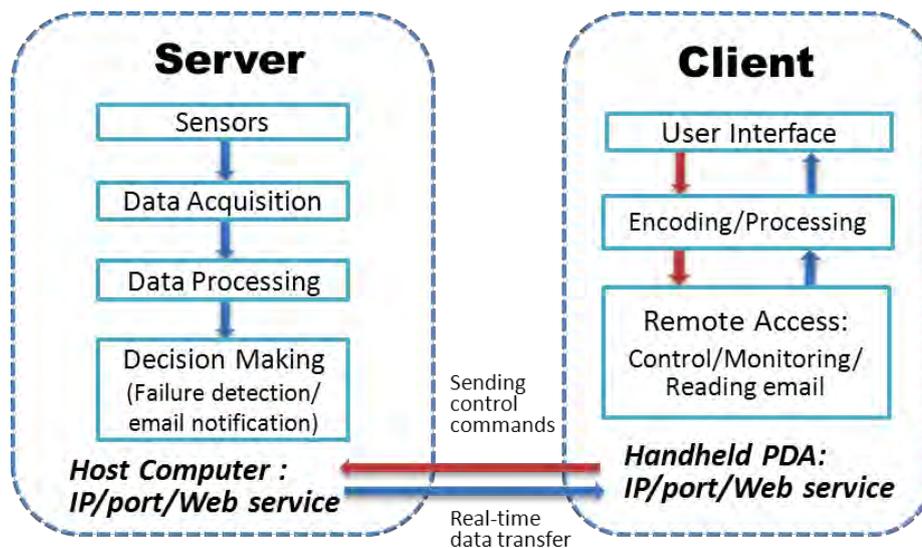
Figure 3.25 Server-Client networking structure

Within such the networking structure, remote communication between the central computer and the mobile devices is implemented by applying Web Service application program interface and MXML-based cross-platform programming standard. Web Service allows mobile users to access the central computer located in the server via Internet, wireless Wi-Fi and mobile phone network. Figure 3.25 illustrates the

server-client networking structure and functions developed, which completes real-time
data acquisition, data processing, and remote communication.

3.3.5.1.2   Development of the Server

3.3.5.1.2.1 Deployment of Web Service

The data collected from the gearbox is often large and heterogeneous. Generally, a
single data point may include thousands of data values corresponding to different
measured times, positions and variables. Considering that the mobile device, such as
mobile phone and PDA, has the lower computational capability and resource than a
computer, to transfer such large number of data would probably block the
communication between the server and client-end mobile devices.

In addition, the programming languages and data formats of different ends are also
required to be considered. Because the applications of server-end and client-end are
coded using different computer languages, the server and the client must communicate
with each other across different language and data formats.

To overcome the above problems, Web Service is utilised as application programing
interface to improve the data transfer capability and ensure the reliability of the remote
communication. Web Service enables the server-to-client interaction over the Web
regardless of platform, language, or data formats. As usual, Web Service refers to the
services implemented and deployed in middle-tier application servers.

Web services enable the remote invocation/calling of a method on the client using
standard Web-based protocols. The client sends a request to the server, which
processes the request and replies with a response; the response is then interpreted and
displayed by the client application. Such communication method is used for web

activities such as real-time monitoring data, browsing the Web pages, checking e-mails, and reading online datasheet of diagnostic results.

Labview provides the Web Service module/function, which is shown in Figure 3.26, to develop the services used in the server. Web Service in Labview uses RESTful method, which is implemented using HTTP and the principles of REST. RESTful is a collection of resources with the following aspects:

- The URI for the web service, such as http://example.com/resources/
- Data media type, such as XML and YAML.
- The operations using HTTP methods. e.g., POST, GET, PUT or DELETE.
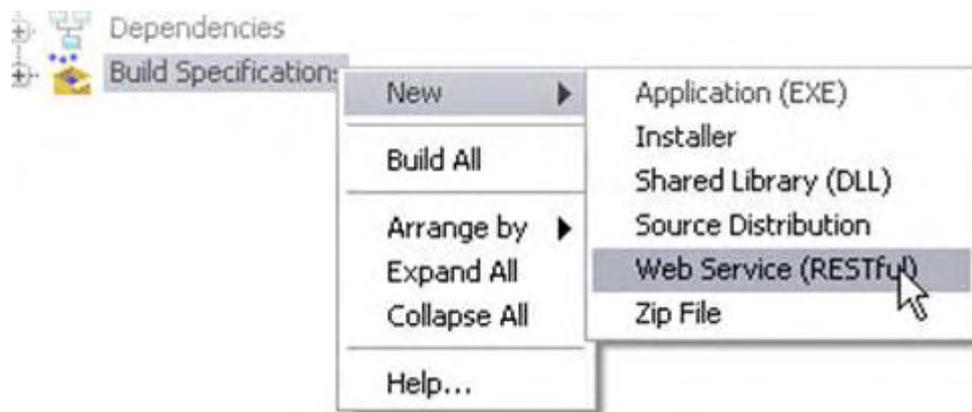
Figure 3.26 Configure, build, and deploy Web service from the Build Specifications menu

RESTful method is implemented in the following ways: The client initiates requests to web server; web server process requests and return appropriate responses. Requests and responses are built around the transfer of *representations of resources*. Because RESTful involves minimal additional mark-up, it is particularly useful for developing the applications that requires lightweight solutions.

3.3.5.1.2.2 Set up the Web Server

A built-in Web Server is utilised to provide the services in the server. Web Server can be switched on using the option *Server Active Property* in Laview. This option offers the following parameters to configure Web Service:

- HTTP methods: In order to send data such as a terminal input to a Labview application, Web server needs to determine how to transmit the data. GET and POST are the most commonly used HTTP methods. POST allows data to be passed in via variables that extend the URL (uniform resource locator) by adding commands of requests. GET is most commonly used for retrieving data from an HTML form that contains a large amount of user input, which is also used in this research.

- Static content: Static content used in Web server refers to any document other than a Labview programme that we want to make available to a client communicating with the Web server. In most case, static content includes a user interface designed to invoke the methods of Labview programme and interpret the response. Static content has been placed in a destination directory, which is linked by the name in the URL mapping dialog.

- HTTP Port: TCP/IP port is set 80 by default.

3.3.5.1.2.3 Data transmission using XML

XML (Extensible Markup Language) is a data media type used in Web Service. At present, XML is quickly gaining popularity for data exchange and representation on the Web, and hence, it is fast becoming an industry-standard for a system-independent way of representing data. XML is suitable for data binding and description, which provides an automated translation between an XML document and programming-language objects. Figure 3.27 depicts the XML-based data transfer mechanism, which is built in Labview programing environment.
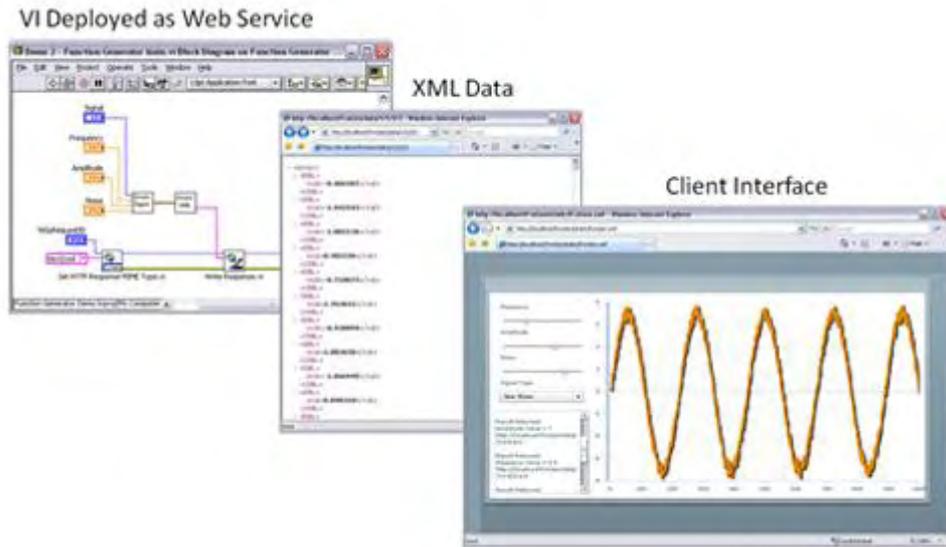
Figure 3.27 The client-end interface calls a URL to run the deployed Labview VI,
which programmatically generates and streams XML data in response

In the actual remote monitoring process, the real-time data and analysed results are processed as *return objects* and are wrapped in XML form. In detail, the server uses the developed codes to create return objects including analytical results in advance and places them in a 'data buffer' that could be formed by shared variables or data sheets. When a user sends a request by invoking the Web Service application programming interface, it first looks up the existing objects in data buffer with the object name. If the object exists, the server will transmit the return objects to the user in the XML format. Therefore, as long as there are return objects in data buffer, the user can keep receiving the data from the server.

3.3.5.1.3   Development of the Client

The client contains mobile devices, such as mobile phone, PDA and laptops, and a wireless access point like router. The software of the client is developed to perform the following functions: (1) passing control commands/parameters to the server, and (2) retrieving the returned data from the server in real time. Cross-platform communication is applied as the significant feature of the client to achieve the above

functions.

3.3.5.1.3.1   Cross-platform Communication

Cross-platform communication between the server and the client is developed using Adobe Flex Builder and C-plug (Open-Plugin) programming environments.

With the cross-platform communication, the client can efficiently interact with the server, across the desktop PC and various mobile devices. As a significant advantage of cross-platform communication, the developed modules/software can work on the different operating systems with different computer architectures, whether desktop PC, mobile phone or PDA, without re-writing or modifying the source code.

Such an advantage arises from the combination of MXML mobile programming language in Adobe Flex and C-plug cross-platform communication standard. Cross-platform communication enables mobile users to communicate with the server regardless of operating systems/platforms. Engineers or managers may take advantage of the flexibility and portability of mobile devices to obtain required information by accessing the central computer located in the server, and to conduct specific remote monitoring applications.

The application/software developed using Adobe Flex and C-plug can work on the most mobile operation systems/platforms, which are shown in the Figure 3.28.
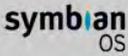
PLATFORMS	iOS	android	symbian OS	Windows Mobile
OS versions	iOS 3.0 to iOS 4.3	Android 1.6 (donut) to 3.1 (honeycomb)	S60 3rd & 5th ed. Symbian^1 Symbian^3	Windows Mobile 6.x
User inputs touch, keys, screen orientation	✓	✓	✓	✓
Call open dialer	✓	✓	✓	✓
Messages compose email, SMS	✓	✓	✓	✓
Open URL links in browser / native app	✓	✓	✓	✓
Contacts read / write	✓	✓	✓	✓
Geolocation via GPS	✓	✓	✓	✓
Audio play local / remote file	✓	✓	✓	✓
Video open in media player	✓	✓	✓	✓
Photo from camera / photo gallery	✓	✓		
Web view in-app HTML view	✓	✓		

Figure 3.28 the list of mobile operation systems/platforms supported
by Adobe Flex and C-Plug

3.3.5.1.3.2   Data Transfer Method

Web Service is also applied in the client as an application programming interface to allow the user to access the working condition data from the server and to send the control commands to the server.

In the Web Service running environment, the control commands are processed as 'user requests', which are encoded with XML rule for the communication with the server. When the user requests with control commands are sent to the server by calling Web Service via wireless Wi-Fi connectivity, the server immediately passes the received user requests to the data processing module (the second module) for D/A (digital-to-analogue) conversion, and subsequently transfers control parameters to the

DAQ controller to adjust working conditions of the machine. In the meantime, the server transmits required measurement data and analytical results as 'response to client' to the client.

The client-end users can parallel access the server at the same time using Web Service (the number of users is subject to the processing capability of the central computer), so that geographically dispersed users are able to simultaneously access the same central computer to retrieve data using the specified IP address of the server. (However, users are not advised to stay online to acquire data all the time. They can connect to the server when notified the machine's failure warning, rather than receiving the data day and night to watch out machine's operation.)

3.3.5.1.3.3   Designing Web Service in Adobe Flex

Web Service is created using MXML programming language in the client. MXML provides several syntax and commands for developing the applications.

An example of Web Service is created below using the class 'HTTP Service' in MXML syntax:

Example 1:

```
<mx:HTTPService id="photoService"
        url="http://api.flickr.com/services/feeds/photos_public.gne"
        esultFormat="xml"
        result="photoHandler(event)" />
…..
    photoService.send(params);
…..
```

In the above MXML code, the tag <mx:HTTPService> is used to represent an Web Service object. According to MXML syntax, when the HTTPService object's send() method is called, it makes an HTTP request to the specified URL, and then an HTTP response is returned. Optionally, parameters used in this method can be passed to the specified URL.

3.3.5.1.4   Real-time Video Display

The real-time video for displaying the operation of the machine is broadcasted to the mobile devices using the code/script developed by Adobe Flex and Flex Media Server (FMS) (For the details of FMS, please see Appendix).

The video is captured by the web camera connected to the server computer, and is processed by Flex Media server (FMS). Flex Media server, similar to Web server, works to publish the video stream over the Internet. It encodes the captured video stream to the Flash format and transfers it to the client in form of stream-data.

3.3.5.1.4.1   Publishing a Video Stream using FMS

To publish a video stream, web camera and/or microphone hardware are required. The following code illustrates how to publish and broadcast a video stream using Adobe Flex and FMS.

Example 2:

```
private function Connection():void {
…..
netconnection.connect("rtmp://IP_address/test") ;
netconnection.objectEncoding = ObjectEncoding.AMF0 ;
```

//FMS is built on AMF0

…..

}

In the above example, the following steps are followed:

- A NetConnection Object is used to connect to the FMS Server, which is done in the Connection() method in the code.

- The client propery of the NetConnection Object is set to a particular class. This indicates that callback method on the object needs to be invoked.

- objectEncoding is set to AMF0 (Action Message Format) because FMS is built on AS2 which uses AMF0 while Flex is built on AS3 which streams using AMF3 by default.

Once the connection is established using the NetConnection Object, it generates a netStatus Event. This event is used to check if the connection is established. When the connection is validated the stream can be published using the NetStream Object.

3.3.5.1.4.2   Viewing the Video Stream using FMS

After the stream is published, another code needs to be developed to view the stream video. Here's an example that illustrates how to display a video using Adobe Flex and FMS.

Example 3:

```
private function Processing(e:NetStatusEvent):void {
            var result:String = e.info.code ;
            stream = new NetStream(netconnection) ;
            var video:Video = new Video() ;
```

….

```
            videodisplay.addChild(video) ;

            stream.play("videostream") ;

        }

private function Pause():void {

            netconnection.close() ;

        }
```

..….

```
<mx:Button  label="Play"  click="Connection()"  x="60"  y="228"  width="82"

        height="31">

        </mx:Button>

<mx:Button  label="Pause"  click="Pause()"  x="166"  y="228"  width="82"

        height="31" >

        </mx:Button>
```

…...

Figure 3.29 Executing result of the example 3

In this example, the VideoDisplay object is used to control the display of the video. It uses the methods of pause() and play() in the event-listener for two Button controls to pause or play an FLV file. The executing result of the above example is shown in Figure 3.29.

3.3.5.1.4.3   Video Decomposition

Considering the quality of displaying video in different mobile devices, a video decomposition based method is developed as an alternative solution of video display, to allow the users who are using the low-level mobile devices to view the video smoothly.

This method is based on video-decomposition, which separates the video into several single images before publishing video to network. Because a video with the length of a second is made up of 24 static images, a video may be split into up to 24 images. Thus, maximum 24 images will be sent to the mobile device for display. The number of the images to display is adjustable from 1 to 24, which is determined by the user.

Such the method is good for those who are using mobile devices with low performance to view the video. Using Labview's ActiveX Contol technique, the decomposed video is sent to the mobile devices; and the users can find out an optimal choice/parameter to view the video by adjusting the number of displaying image per second. Figure 3.30 illustrates how to use Nokia 770 to retrieve the video/images from the server (In Chapter 5, this technique has been applied utilising mobile phone to view a live video captured by a web camera).

Figure 3.30 Remote video display using decomposing method

3.3.5.2 Remote Communication between the Central Computer and Data Acquisition Computer

The communication between the central computer and data-acquisition computer must meet the demand of data transmission of high speed to ensure that the server acquires up-to-date data from the monitored gearbox.

Web service is suitable for the communication of mobile devices such as mobile phone, because it can meet the demand of data transfer of standard speed. However, it cannot be used for high-speed transmission with a great number of data.

To resolve the above problem, Data-Socket is utilised as a method, which realises the remote communication between the central computer and acquisition computer.

3.3.5.2.1 Introduction of Data-Socket

Data-Socket is a programming technology based on industry-standard TCP/IP, which simplifies live data exchange between computers and applications connected via a network. Although a variety of different technologies exist today to share data between applications, such as TCP/IP and DDE, most of these tools are not targeted for live data transfer. Data-Socket implements an easy-to-use, high-performance programming interface designed for sharing and publishing live data in measurement and automation applications.
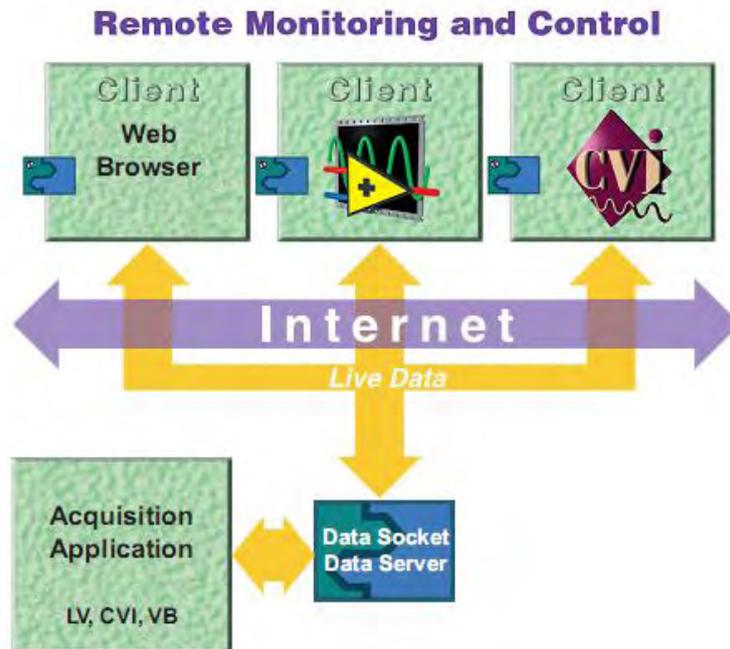
Figure 3.31 Remote conditions monitoring using Data Socket in Labview

Without Data-Socket, TCP/IP server and client applications require to be written to transfer the data from the monitored machine to the central computer. The server application would acquire the process data, flatten the data into a bit stream, and transfer the data to the server. The server reads the data, unflattens the data, and displays the data. In addition to the code required to read information from the server, the client application must also contain the code required to manage multiple connections, one connection for each process line. Writing all the low-level TCP/IP

code to handle such data transfers would add a significant amount of overhead to the
development process.

3.3.5.2.2 Data-Socket API and Data-Socket Server

Labview provides the interfaces and functions to create Data-Socket connectivity.
Data-Socket consists of two pieces – the Data-Socket API and the Data-Socket Server.
The Data-Socket API presents a single interface for communicating with multiple data
types. Data-Socket Server simplifies Internet communication by managing TCP/IP
programming.

The Data-Socket Server is a standalone component with which the programs using the
Data-Socket API can transmit live measurement data at high rates across the Internet
to several remote clients concurrently. Data-Socket Server simplifies network TCP
programming by automatically managing connections to clients.
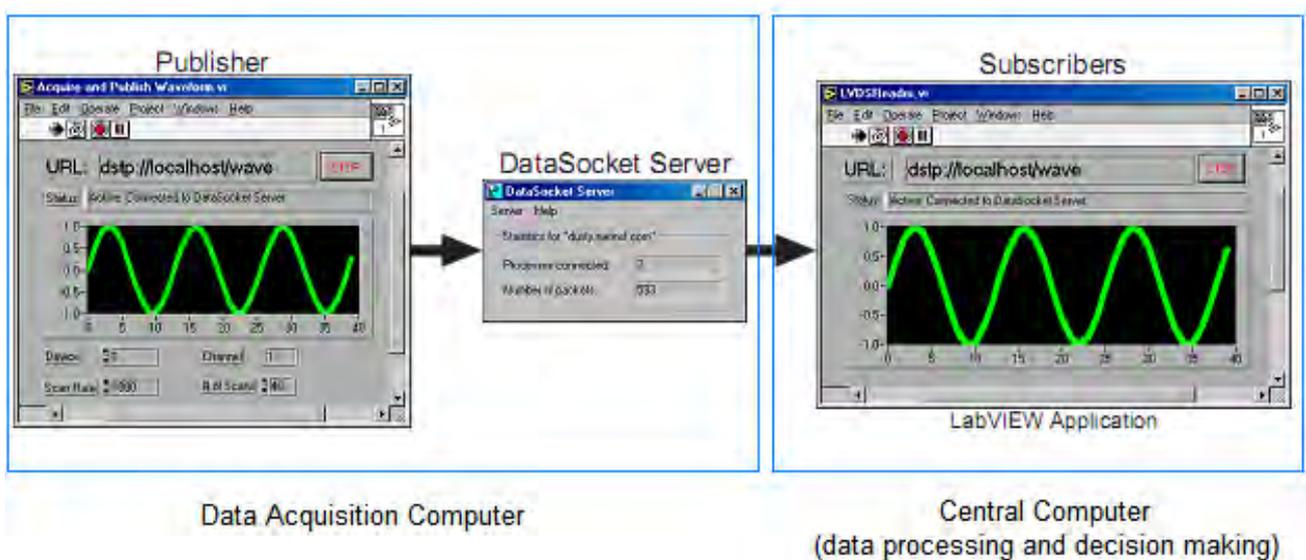
Figure 3.31 Transmission of the live data using Data-Socket server

Transmitting data with the Data-Socket Server requires a publisher, the Data-Socket
Server, and a subscriber. The publishing application and the Data-Socket server are

both deployed in the acquisition computer. The publishing application uses the Data-Socket API to write data to the Data-Socket server. The subscribing application is installed in the central computer to read data from the server via the Data-Socket API. Both the publishing and the subscribing applications are "clients" of the Data-Socket Server. Figure 3.31 presents the data-transfer process with the Data-Socket server.

3.3.5.2.3   Security and Permissions of the Data-Socket Server

The Data-Socket Server restricts access to data by administering security and permissions. With Data-Socket, confidential measurement data can be shared over the Internet while preventing access by unauthorized users.

The users are categorised according to how they interact with the socket server and what permission they need for connecting to the socket server. Different permission groups include read access, write access, data item creators, and administrators. The Data-Socket server provides the following permission groups:

- The Administrators permission group is mainly intended for retrieving management information from the socket server;

- The DefaultReaders permission group can read all dynamically created data items from the socket server;

- The DefaultWriters permission group can write all dynamically created data items on the socket server;

- The Creators permission group can dynamically create new data items on the socket server;

3.3.5.2.4   Designing Data-Socket applications

With Data-Socket, we can easily handle the network communication required to

transfer data from the data-acquisition computer to the central computer. The sample

LabVIEW block diagram below illustrates how to write and read process variable data

using the Data-Socket API. Because data is being written to a Data-Socket server, the

central computer application does not need to implement extra code to handle the extra

connections of multiple monitoring lines/channels. It simply reads the data item for

each line.

Figure 3.32 Block diagram illustrating how to write and read process variable
data using the Data-Socket API

Chapter 4   Remote Real-time Condition Monitoring and Fault Diagnosis of Industrial Gearbox Using Internet and Wireless Technologies

4.1 Introduction

A reliable monitoring system is critical for the detection of faults in order to prevent failure, wear, and pitting of gearbox, which is used in the mechanical system. Further, the condition monitoring information can enable the establishment of a maintenance program based on an early warning of gearbox defects.

The advances in Internet and computer technologies greatly enhance the capability of gearbox's condition monitoring. The transmission control protocol/Internet protocol (TCP/IP) and Internet software have become the standard modules in computer systems. Wireless and mobile techniques enable the end-users to utilise wireless devices, such as cellular telephone and personal digital assistant (PDA), to access the working condition data from the monitoring centre.

Although several techniques have been proposed in the literature, as reviewed in Chapter 2, for gearbox condition monitoring, it still remains a challenge to combine wireless and mobile techniques with data acquisition and real-time fault diagnosis into a system for remote real-time condition monitoring of industrial gearbox. The objective of the research reported in this chapter is to develop a wireless-based remote real-time condition monitoring system to monitor and diagnose the working conditions of gearbox and detect potential faults of gearbox in real time.

4.2 Overview of the Remote Real-time Gearbox Condition Monitoring System

A remote real-time condition monitoring system has been developed, which is applied to monitor and diagnose the working conditions of the gearbox, and to provide advice for decision making for maintenance.

The overall structure of the remote real-time condition monitoring system is shown in Figure 3.1 (see Chapter 3). Within this system, the data acquisition is conducted based on sensory technology and data I/O communication to acquire the working condition data of the gearbox; the data processing is implemented using A/D (analogue-to-digital) conversion to process the received analogue data and convert the data into the physical quantities, such as vibration, torque, and rotational speed for sequent fault diagnosis.

Real-time fault diagnosis is implemented based on digital filtering and the gear feature parameters for pattern classification to detect the fault signals of the gears. The digital filtering is utilised to extract vibration signals of gears from noisy environment. Pattern recognition is used to identify the fault of the gear and to provide the support to necessary schedule maintenance work.

Remote communication with wireless and mobile features enhances the capability of machine's condition monitoring, by providing wireless-based network connection to the server computer located in the monitoring centre. Based on wireless and Internet technologies, the server-client networking structure is built up, which realises the data communication between the server and the client, and allows geographically dispersed users to access the working condition data from the server utilising the mobile devices, such as PDAs and mobile phones.

Web Service is implemented as a web-based application programing interface of the server to build the Web communication between the server and the client. The software deployed in the server end is coded with the use of the LabVIEW software-development environment, while the client-end interfaces are programmed by

utilising the Adobe Flex and C-plug mobile programming environments. Wireless communication technique using Flex and C-plug greatly improves the interactive capability of HTML-based user interfaces.

4.3 Techniques Utilised for the Remote Condition Monitoring System

The remote real-time gearbox condition monitoring system consists of following modules: data acquisition, data processing and fault diagnosis, condition-based maintenance, and remote communication. The associated software has been developed and applied in the system using sensory technique, digital filtering, pattern classification for fault diagnosis, and wireless communication.

4.3.1 Data Acquisition

The experimental system (Figure 4.1) contains a mechanical test rig, accelerometers, torque/speed transducers, data acquisition hardware and relevant software. The acquisition hardware contains a DAQ6259 data acquisition card associated with distributed sensors for acquiring working conditions such as gearbox vibration, torque, speed, etc. It simultaneously monitors two test gears on two shafts (driving shaft and driven shaft) respectively. The data sampling rate is 100 kHz and data length is 100k. Data group is collected at the rate of one second per data group.

The mechanical test rig with an AC motor and a DC generator is constructed to test an industrial gearbox. Within the test rig, the AC motor supplies 3kW variable speed to drive the gearbox via an input shaft; and the DC motor (generator) applies a variable load of 0-18Nm to the gearbox by tuning the voltage/current of a control station, and transfer the load to the gearbox via a 2-level transmission belt.

Accelerometers

Gearbox

Torque/speed
Sensors

AC motor

2-level belt

DC motor

Figure 4.1 Experimental System

4.3.2　Data Processing and Fault Diagnosis

The acquired working condition data are then transferred to the server computer for further data processing. Data processing is conducted using the A/D (analogue-to-digital) conversion to convert the received analogue data to physical quantities of working condition (For the method of A/D conversion, see *3.3.2 Data Processing* in Chapter 3). On the basis of the results of A/D conversion, digital filtering are then utilised to remove noise signal from acquired working condition data to extract vibration information of gearbox for sequent fault diagnosis.

For the analysis of a fault signal, the digital filtering technique plays an important role in identifying whether the gearbox is defective. Two types of digital filtering techniques, i.e. adaptive digital filtering and traditional digital filtering, are applied by removing contaminated signals to improve signal-to-noise ratio of signals. Traditional digital filtering uses the infinite impulse response (IIR) filter to remove or attenuate unwanted frequencies. In comparison with the traditional filtering, adaptive digital filtering using adaptive filter has a self-learning ability that traditional digital filtering

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does not have. This ability can effectively extract gearbox vibration signal from the
noisy source using its specific filter types and topologies. Therefore, adaptive filtering
is suitable to complete the signal processing tasks that traditional digital filters cannot.

The diagram of a typical adaptive filter, which has an additional input signal, is shown
in Figure 4.2, where x(n) is the input signal to a linear filter at time n,   y(n) is the
corresponding output signal, d(n) is an additional input signal to the adaptive filter,
and e(n) is the error signal that denotes the difference between d(n) and y(n).
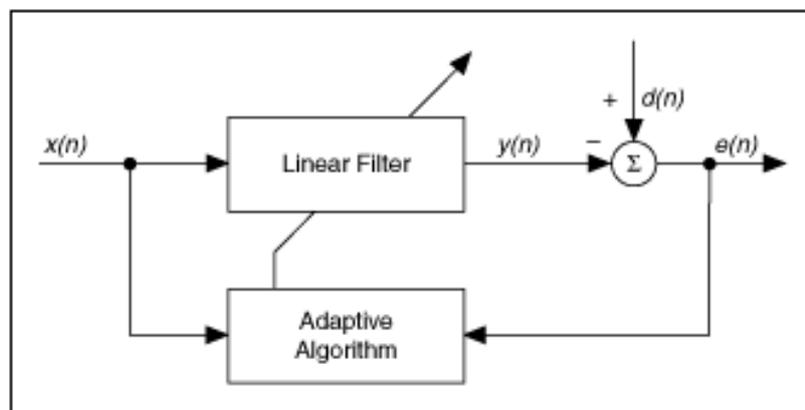
Figure 4.2 A typical adaptive filter
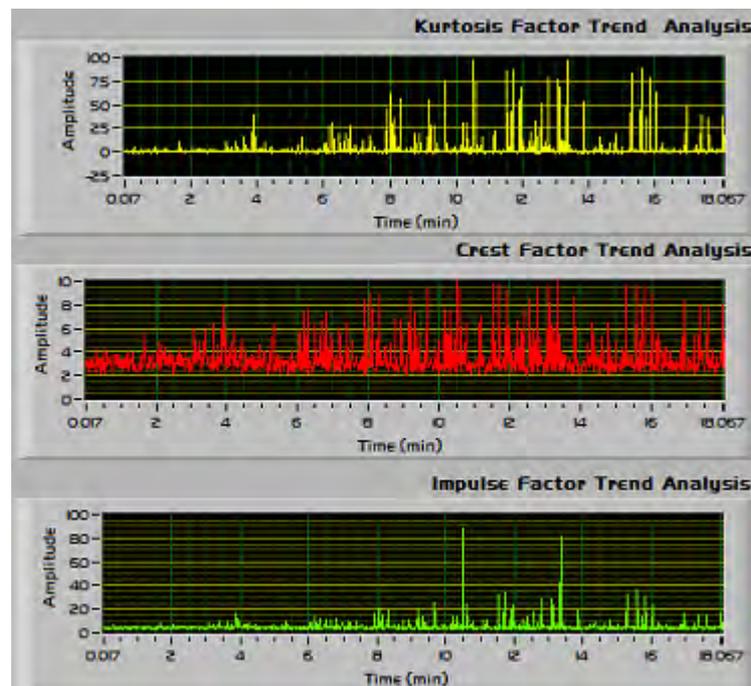
Figure 4.3 Statistic factors used for detecting the abnormality of gearbox

The filtered gear signals are then computed using statistic-related feature parameter analysis (SFA) algorithm. SFA utilises the amplitude value of time-domain signal to interpret impulse feature and impulse energy of the gearbox. The feature parameters used in this research include crest factor, impulse factor, kurtosis factor, clearance factor and root-mean-square of the vibration signal. The gearbox fault such as failure and wear can be identified using the above feature parameters, as shown in Figure 4.3.

4.3.3 Condition-based Maintenance

According to the fault analysis results obtained, the required maintenance is scheduled to replace/repair any components and/or conduct the necessary maintenance.

4.3.4 Remote Communication

Remote communication with wireless and mobile techniques allows mobile devices, such as mobile phone, PDA and laptop, to remotely access the server computer to retrieve the working condition data and analysis results via the Internet and wireless Wi-Fi network. It is highly helpful for those who roam between multiple locations and often concern about the first-hand experiment information.

Data transmission over the network has a great effect on the remote real-time monitoring process. Extensible Mark-up Language (XML) has been developed in the system as the transmission carrier to ensure the reliability of the data communication between the ends during the monitoring process. XML is a textual language that is quickly gaining popularity for data exchange and representation on the Web, and hence it is fast becoming an industry-standard for a system-independent way of representing data. XML is particularly suitable for data binding and description.

Web Service is applied as the application programming interface (API) of the server to implement the communication between the server and the client. In the server-client architecture, the server computer is applied to acquire the working condition data, diagnose the received data for decision making, and transmit the data and analytical results to the client; the mobile device located at the client end is used to retrieve the response, such as data and analysis result, from the server, and meanwhile, and send the requests with control commands to the server.

4.3.4.1 Server-end Software Interfaces

This section presents the interfaces and functions of the server-end software. For the details of development of the software, please refer to Appendix (A).

The data acquisition/processing, fault diagnosis and remote communication at the server end are coded with the use of G language in LabVIEW programming environment. Figure 4.4 presents the software interface of the remote real-time condition monitoring system. Figure 4.5 shows the real-time signal processing and fault diagnosis using the server-end software developed by this research.

Figure 4.4 Remote online gearbox condition monitoring system in the server end
developed by LabVIEW software-developing environment
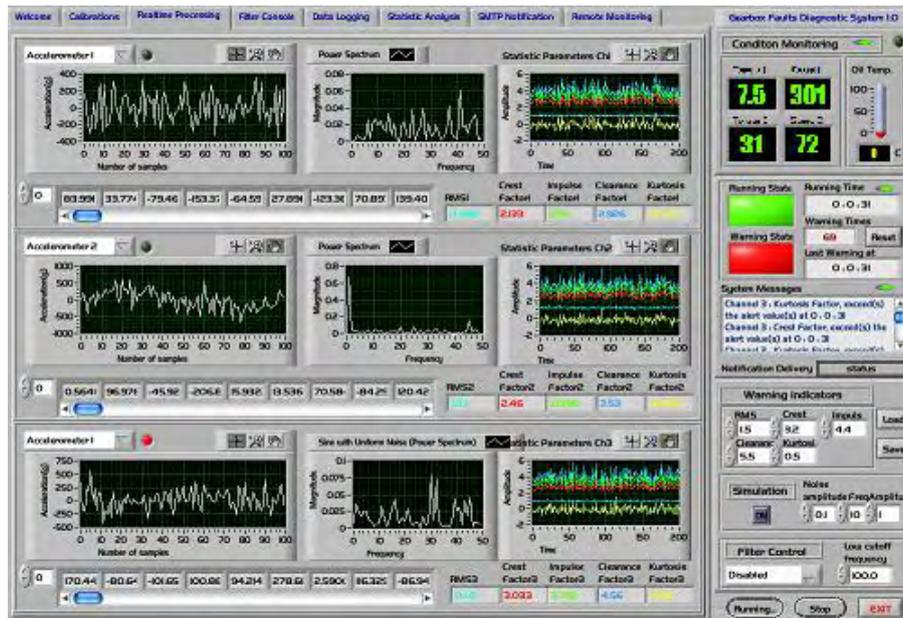
Figure 4.5 Real-time data acquisition, online fault diagnosis, and automated
warning notification using the developed server-end software
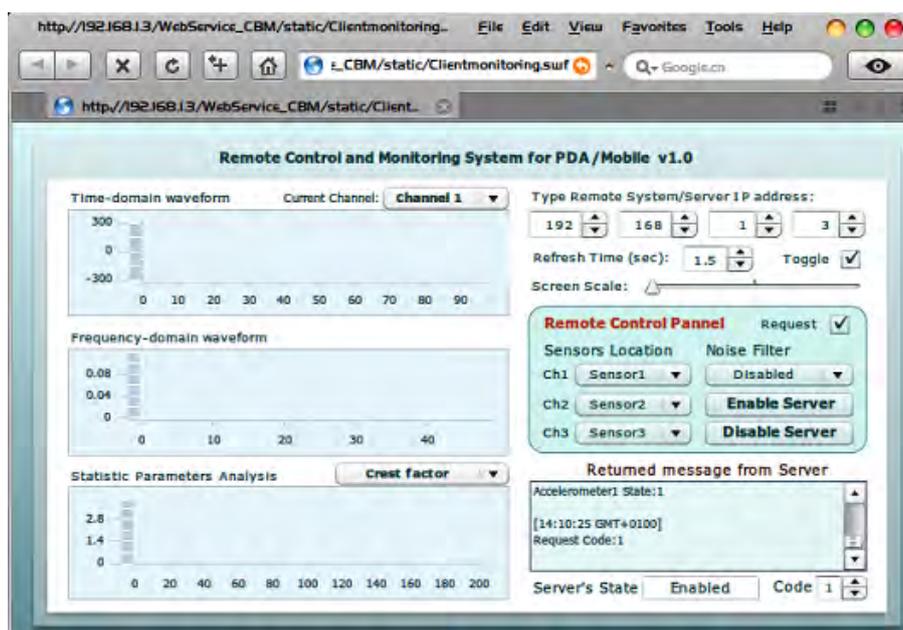
Figure 4.6 User interface developed by Adobe Flex programming environment

The developed application software has the following functions: multi-channels signal processing, real-time display of the working condition data and the waveforms of time/frequency-domain and feature parameters for pattern classification, automated warning notification for preventive maintenance, data logging facility, and remote communication with the client over Internet and wireless network.

4.3.4.2 Client-end Software Interfaces for Mobile Devices

The client-end application software is programmed utilising Adobe Flex and C-plug mobile programming environments. The user interfaces, such as those shown in Figure 4.6, are developed to provide mobile users with dynamic graphics within web pages and also offer solutions to minimize the amount of data sent from the server.

The user interface provides the functions of server-to-client communication and remote monitoring/control. It allows the mobile users to remotely access the server computer to retrieve the working condition data and analysis results, and to control the operation of the system using PDA via the Internet and wireless network.

4.4　Remote Real-time Condition Monitoring of the Industrial Gearbox

The developed system has been applied in the experimental environment, which mainly includes the mechanical test rig, three acceleration sensors, two torque and speed transducers, three signal switch instruments, a data acquisition card, a Nokia PDA, a central computer as the server, and the associated diagnostic software. The server-client networking structure is applied in the system to realise the communication between a server computer and a mobile device.

4.4.1　System Setup

The accelerometers were installed in the gearbox as primary sensor and reference sensor to acquire the vibration signals from the gearbox; the torque/speed transducers were installed on the driving shaft and the driven shaft to monitor two test gears respectively. According to the sampling theory of signal processing, the data sampling rate was set 100 kHz and data length was 100k.

Figure 4.7 presents the technical parameters of the sensors used and the information for A/D (analogue-to-digital) conversion, which are configured in the system. The coefficients of A/D conversion were adjusted to match the physical properties of the sensors. The A/D conversion of working condition data was conducted in real time and the conversion results were plot as a waveform that varies with voltage signals.
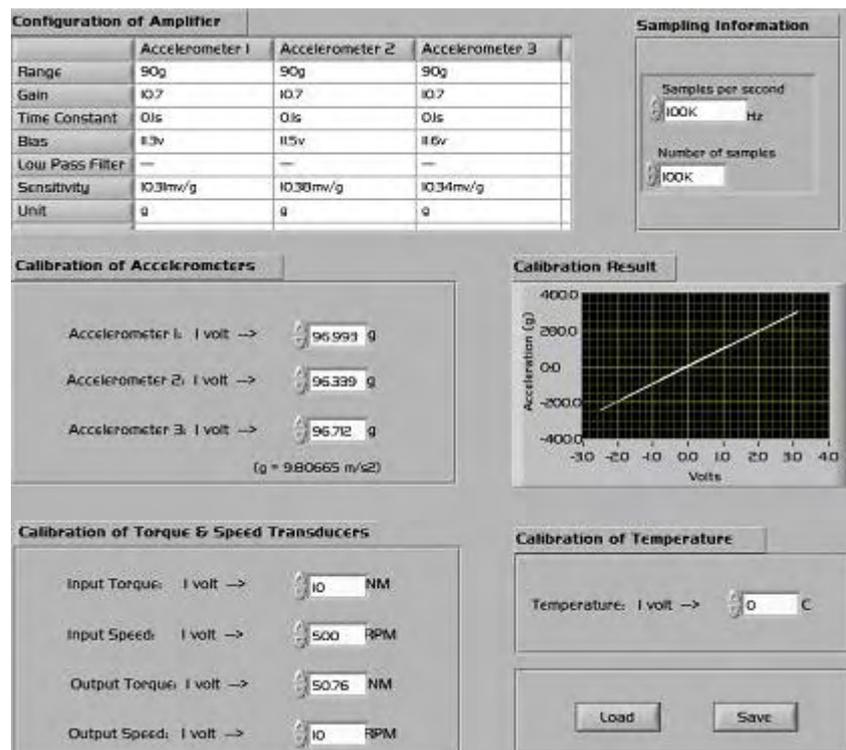
Figure 4.7 A/D (analogue-to-digital) conversions

4.4.2 Real-time Data Acquisition and Real-time Fault Diagnosis

While the system was in operation, the working condition data of gearbox were collected at the rate of one second. The three measurement channels that measured three accelerometers were acquired concurrently, and vibration signal data of gearbox were transmitted to the server computer and then to the client. For each measurement channel, the signal processing, such as time-domain, frequency-domain, and feature parameters analysis, was online implemented using the digital filtering and pattern

classification; and the vibration signal data and waveform that it generates were displayed on the monitoring interface of the server. Figure 4.8 presents the real-time monitoring interface of the server-end.

When a fault such as failure or wear of the gearbox occurs, a warning message was immediately sent to the user by email, and meanwhile, was displayed in the monitoring interface of the server to alert the operator working conditions of the gearbox.
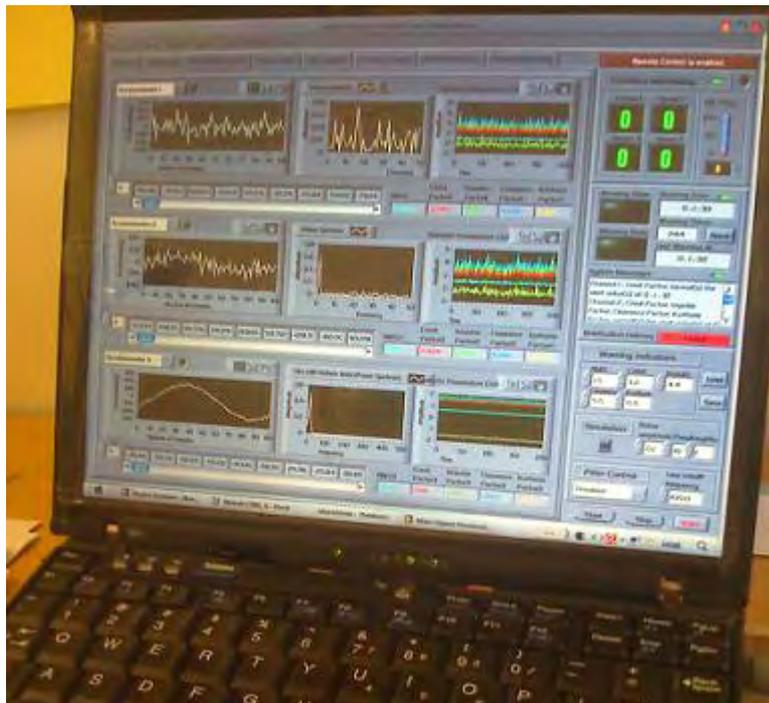
Figure 4.8 Real-time data acquisition and online fault diagnosis in the server end

4.4.3 Remote Communication using Nokia PDA, Internet and Wireless Network

In the client, the end-user utilised Nokia PDA to remotely access the working condition data from the server by sending the requests to the server via Internet and wireless Wi-Fi network. The requests consist of the following four types of commands: connect (log-in), read data (access), write data (control), and disconnect (log-off). While the server receives the requests including the above commands, Web service

resolves the requests and executes the corresponding commands; in the meantime, Web service invoke a HTTP method to transmit the working condition data and analytical results as responses to the client. The client retrieves the responses via a listener event, interprets the responses, and then displays the data and results as web pages form in the client-end interface.
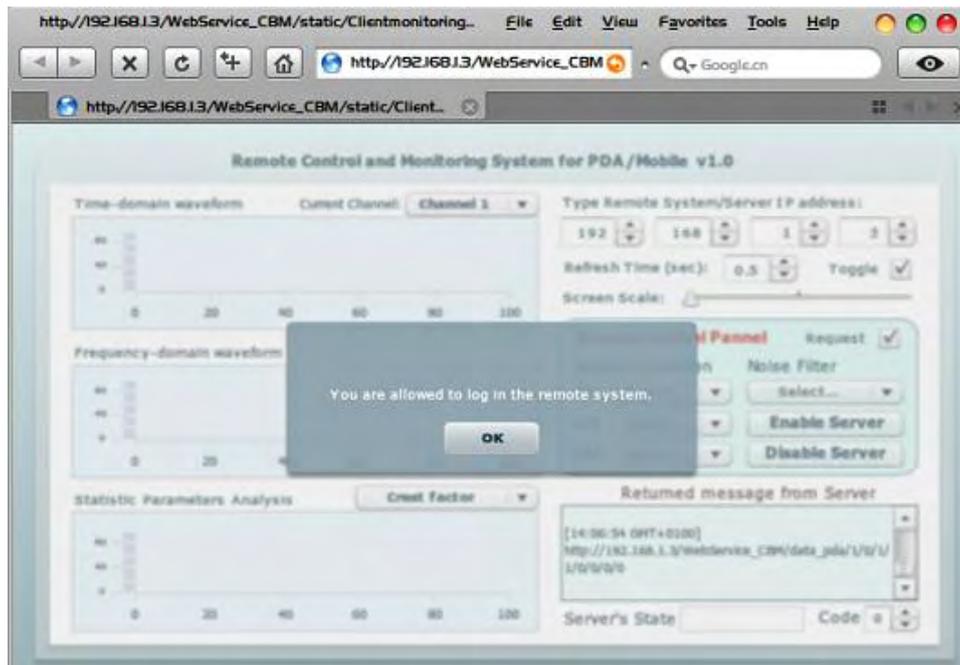
Figure 4.9 log-in interface that allows users to access the server computer

The log-in interface, shown in Figure 4.9, indicates that the user was authorised to access the server to access the working condition data, and to regulate the control parameters of the system. Subsequently, the data acquisition (DAQ) card was triggered by the user remotely and the measurement channels of sensors/accelerometers were accessed.

Figure 4.10 presents the remote real-time monitoring process using Nokia PDA. Using the client-end online monitoring interface, the user continuously retrieved the working condition data and analysis results from the server via Internet and wireless network. The user is able to adjust or set the system parameters/methods, such as the type of digital filter, gear feature parameters, and time/frequency domain waveforms. Also, the

user is allowed to configure the network parameters with regard to remote connection, such as server's IP address, the number of network port, and update frequency of the data received.

Once gear fault such as failure or wear is detected, the user is able to receive an email, which contains the working condition data and diagnostic result of the gearbox, from the server. The user can view this email utilising the email application embedded in mobile device.

Figure 4.11 shows the log-off interface, which indicates that the user was disconnected from the connection with the server. When the users end up the remote monitoring process in the client, the server-end monitoring system still works. Therefore, the user can use the log-in interface, shown in Figure 4.9, to access the server again to carry out remote monitoring at any time.

Figure 4.10 Remote access the working condition data of the server and regulate the parameters of the system using Nokia PDA via Internet and wireless Wi-Fi

Figure 4.11 the log-off interface that indicates the user is disconnected with the server

4.5 Experimental Investigation of the Gearbox Performance

4.5.1 Experimental Procedure

The experimental investigation of the gearbox performance was conducted by acquiring gearbox's vibration data under different conditions of workload and rotational speed.

In this experiment a bearing in the gearbox was loosened, as shown in the Figure 4.12. The bearing is located at the position between the driving helical gear and the torque transducer on the driving shaft. The data acquired in this experiment is used to adjust the position of gearbox when installing the gearbox in the mechanical rig.
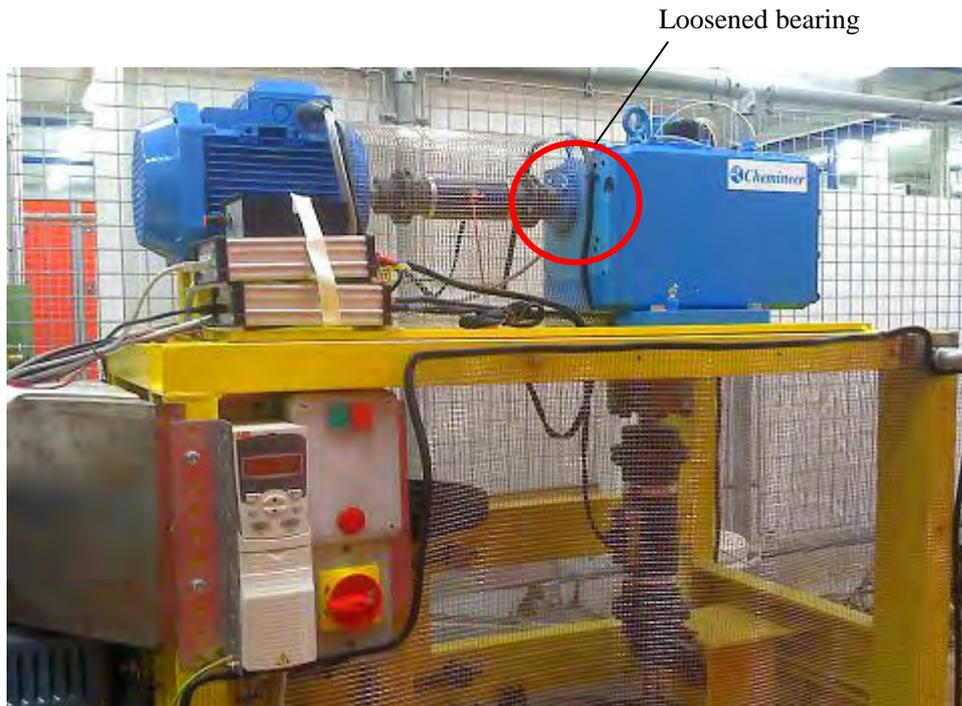
Figure 4.12 Experiment system with the industrial gearbox

The experiment was conducted in the following two ways:

(1) To investigate the influence of variance of workload on gearbox's vibration signal
     by acquiring the vibration signal data under five different load-conditions,
     including 0, 5, 8.5, 12 and 15 Nm, with the shaft rotation-speed of 300rpm. The
     cases of such the load variance are listed in the following table:

Case No.	Duration	Rotational speed of driving shaft	Workload
Case I:	3min		0Nm
Case II:	3min		5Nm
Case III:	3min	300rpm	8.5Nm
Case IV:	6min		12Nm
Case V:	3min		15Nm

Table 4.1 List of the working conditions in gearbox performance experiment (1)

(2) To investigate the influence of variance of shaft rotation-speed on gearbox's

vibration signal by acquiring the vibration data under nine different rotation-speed conditions. The rotation speed of the driving shaft is gradually increased from 200 to 1000 rpm with the workload condition of 4 Nm. The cases of such speed variance are listed in the following table 4.2:

Case No.	Duration	Rotation speed of driving shaft	Workload
Case I:	3min	200rpm	
Case II:	3min	300rpm	
Case III:	3min	400rpm	
Case IV:	3min	500rpm	
Case V:	3min	600rpm	4 Nm
Case VI:	2min	700rpm	
Case VII:	2min	800rpm	
Case VIII:	1min	900rpm	
Case IX:	1min	1000rpm	

Table 4.2 list of the working conditions in gearbox performance experiment

The working condition data were acquired with the sampling frequency of 100 kHz for a total time length of 18 minutes duration. The analysis bandwidth was set from 0-100kHz. Five statistics-related feature parameters, i.e. crest factor, impulse factor, clearance factor, kurtosis factor and RMS (root-mean-square) were calculated. In order to avoid the disturbance of instantaneous (abnormal) signal, each group of data was separated into 10 segments. Because the system collected 100k signals at a time, each segment length is 10k. Each parameter based on each segment was computed, and then the average of 10 segments of parameters was taken as the feature parameter at this time. In addition to the calculation of feature parameters, time-domain waveforms of three acceleration channels were acquired and analysed.

Because the gear vibration signals are vulnerable to the environmental noise, which could come from the motor, the rig, and somewhere outside the gearbox, the digital

filtering is required to eliminate the noise signals from the work environment. In the actual test, the noise signal is taken as oddity/abnormality to be filtered.

4.5.2 Gearbox Experiment under Different Workload Conditions

Figures 4.13–4.17 present the experimental results of five feature parameters under all load conditions over vibration signals when the bearing is loosened. Figure (b) is the local enlargement of Figure (a) to more distinctively describe each parameter's variance of gears over the process of vibration. From Figure 4.13, it can be found that the crest factor substantially increases by 50 per-cent of the initial value when the workload increases from 0 to 5 Nm; then the crest factor keeps upwards with the change of load-conditions. When the workload is 12Nm the crest factor arrives at the maximum of amplitude 10.

Similarly, the kurtosis factor has the upward trend with the variance of the workload, as shown in Figure 4.16. While the workload is 5Nm, kurtosis factor has a visibly increase at 3 minutes; then it arrives at the maximum value when the workload increases to 12Nm. Also, the impulse factor increases with the variance of load conditions. However, there is little change in the other parameters, such as clearance factor and root-mean-square. When the workload varies with time, their amplitudes do not have obvious change. Figure 4.18 presents the experimental data of time-domain of vibration signals of the gearbox. It can be found that the amplitude of acceleration of vibration signals fluctuates between the -8 and +8. Due to the effect of loosening bearing, the transient change of the amplitude is prominent when the workload changes.
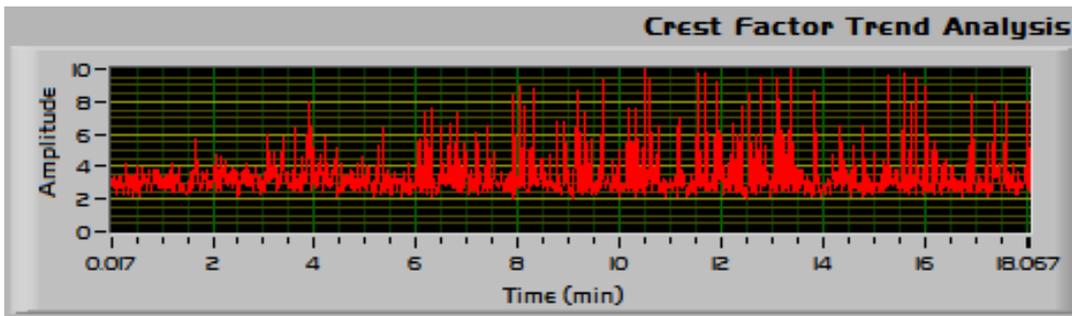
(a)
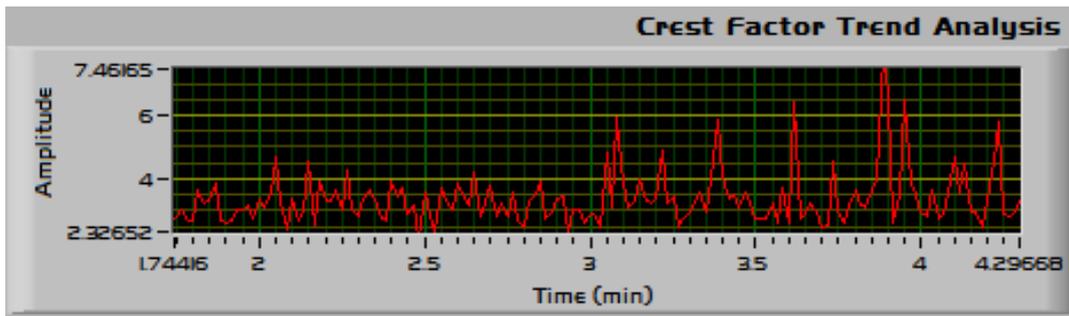
(b)

Figure 4.13 Crest factor with all the load conditions (the bearing is loosened):
(a) the crest factor analysis (b) local enlargement of (a)
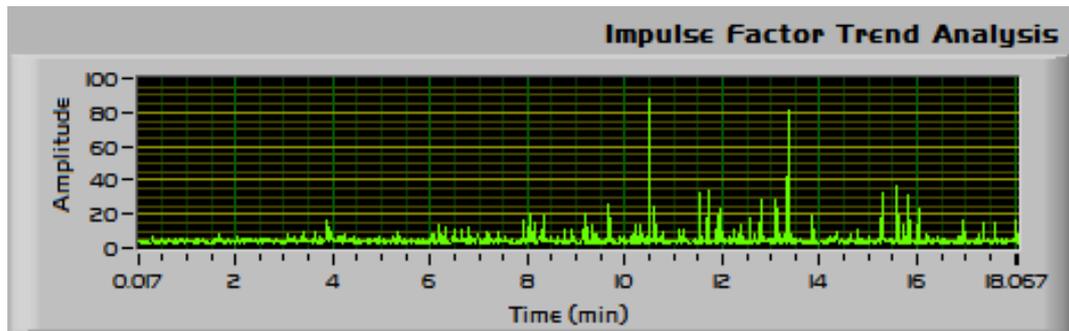
(a)
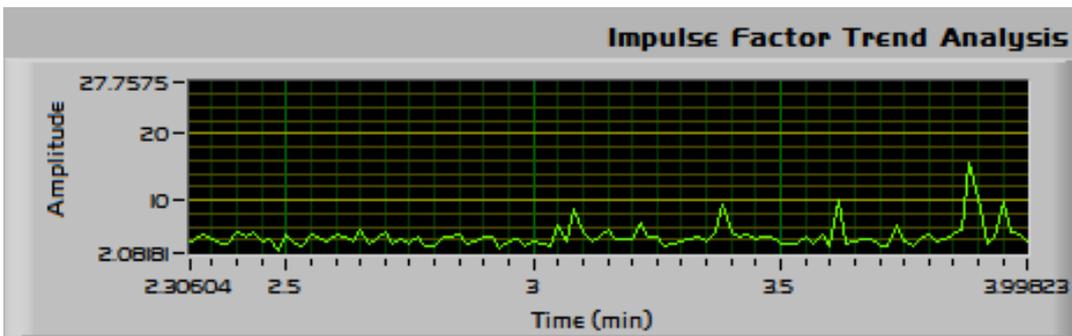
(b)

Figure 4.14 Impulse factor with all the load conditions (the bearing is loosened):
(a) the impulse factor analysis (b) local enlargement of (a)
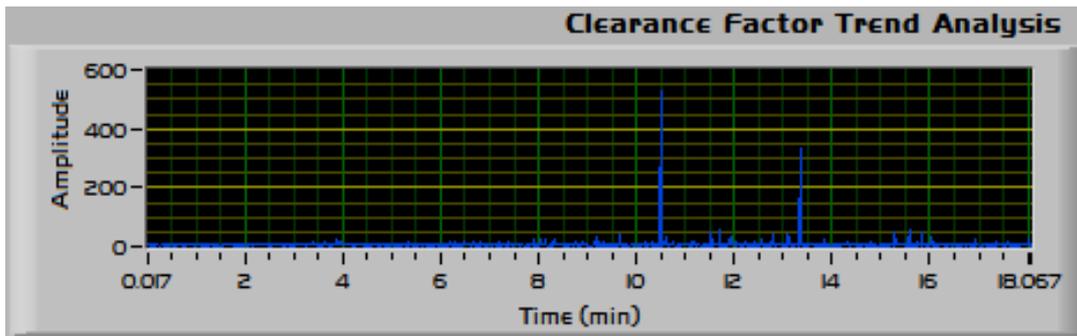
(a)
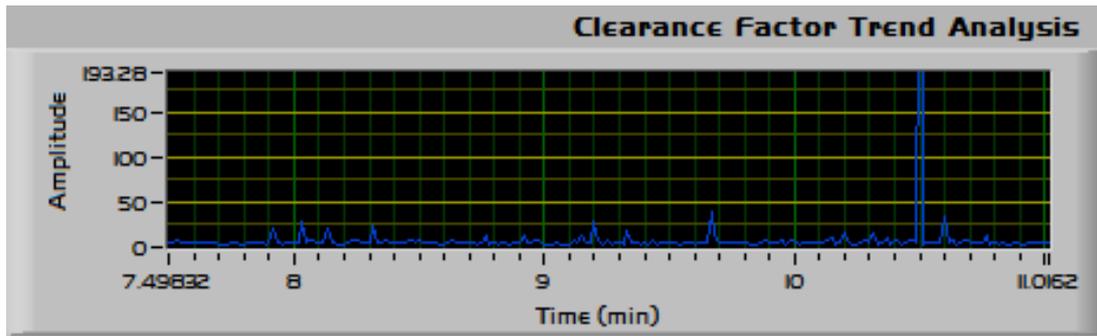
(b)

Figure 4.15 Clearance factor with all the load conditions (the bearing is loosened):
(a) the clearance factor analysis (b) local enlargement of (a)
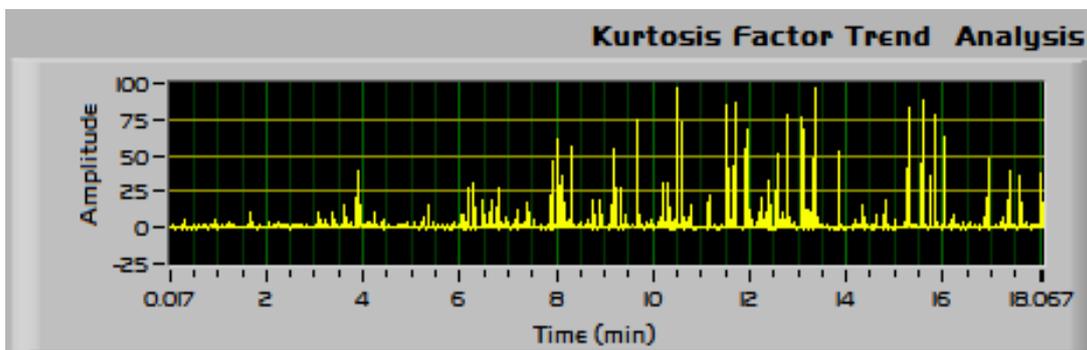
(a)
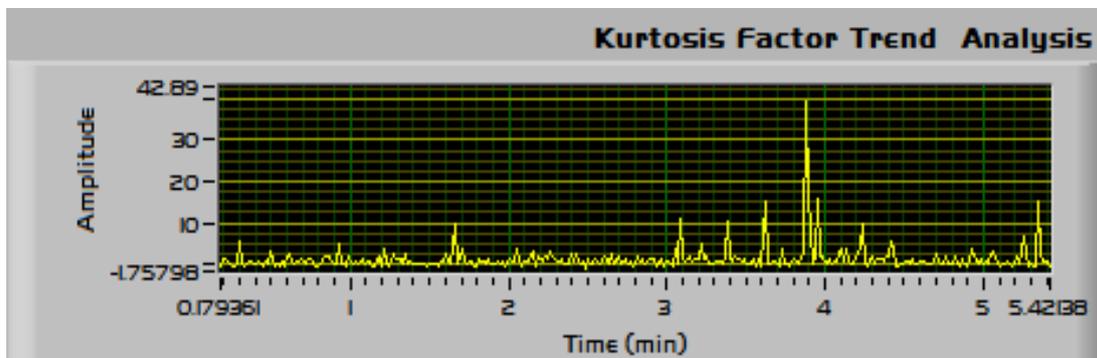
(b)

Figure 4.16 Kurtosis factor with all the load conditions (the bearing is loosened):
(a) the kurtosis factor analysis (b) local enlargement of (a)
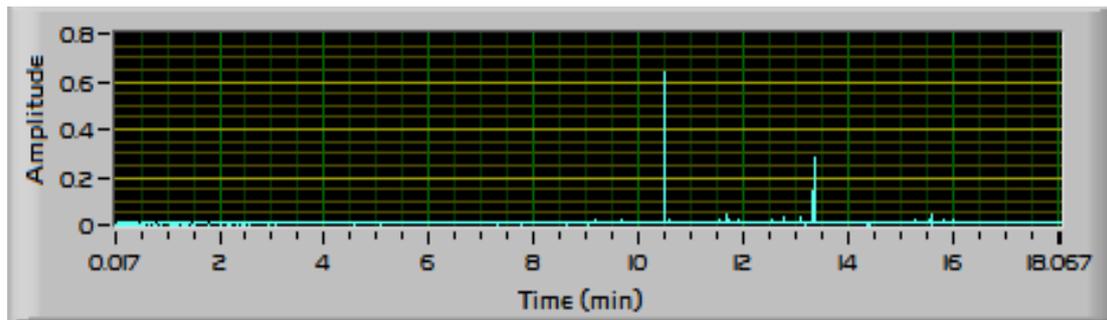
Figure 4.17 Root-mean-square with all the load conditions (the bearing is loosened)
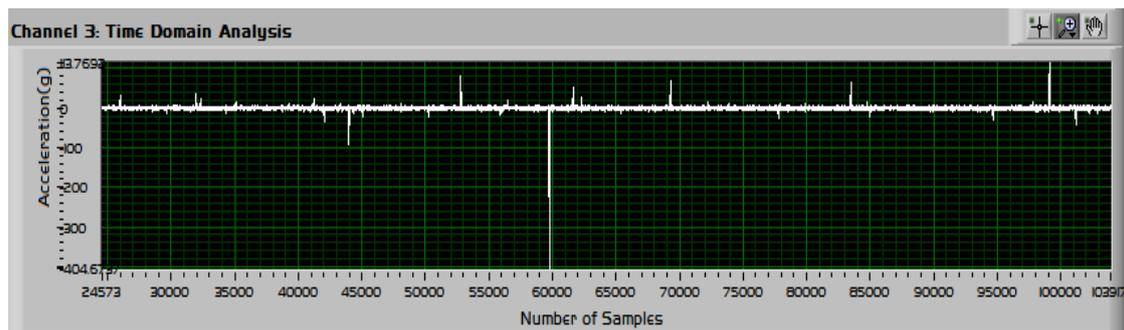
(a)
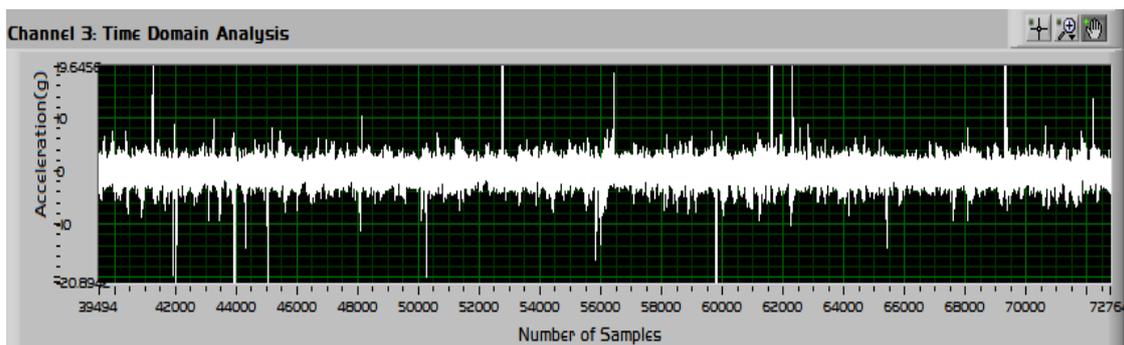
(b)

Figure 4.18 Time-domain waveform with all the load conditions (the bearing is
loosened): (a) time-domain wave form (b) the local enlargement of (a)

4.5.3   Gearbox Experiment under Different Rotation-Speed Conditions

Figures 4.19-4.21 shows the experimental results of the feature parameters with
different shaft rotation-speeds over gearbox's vibration signal. It can be found that
neither the feature parameters nor amplitude of acceleration of the time-domain signal
has the significant change when the shaft rotation speed varies from 200 to 1000 rpm
(workload is 4Nm).
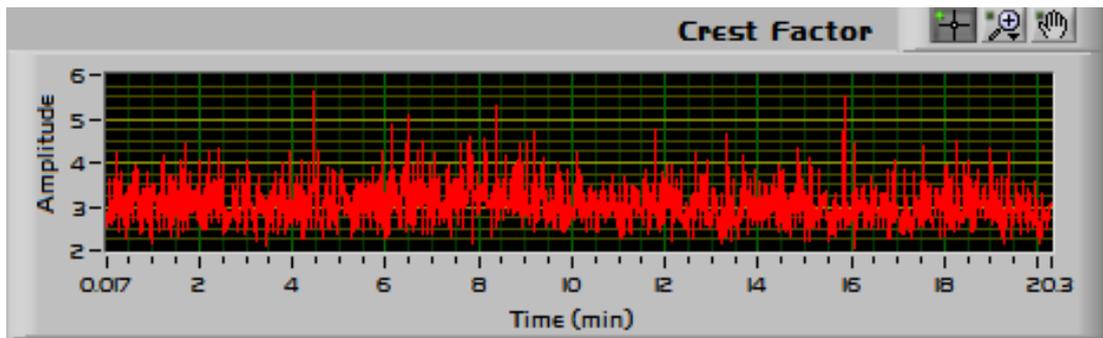
Figure 4.19 Crest factor with variance of shaft speed (the bearing is loosened)
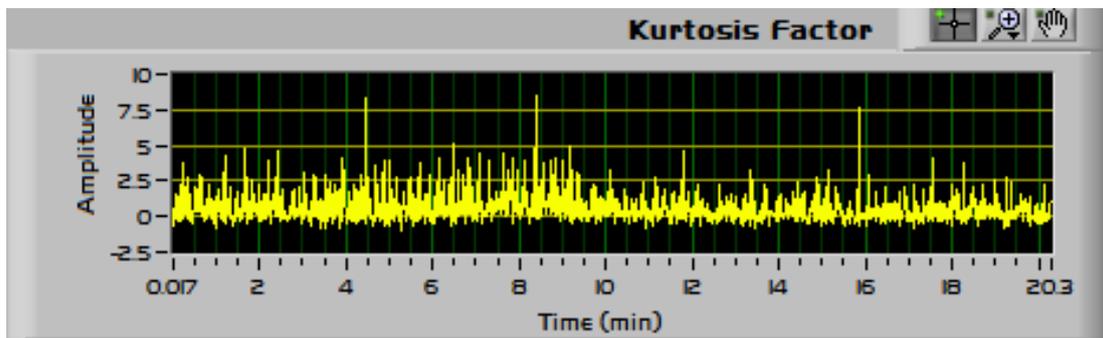
Figure 4.20 Kurtosis factor with variance of shaft speed (the bearing is loosened)
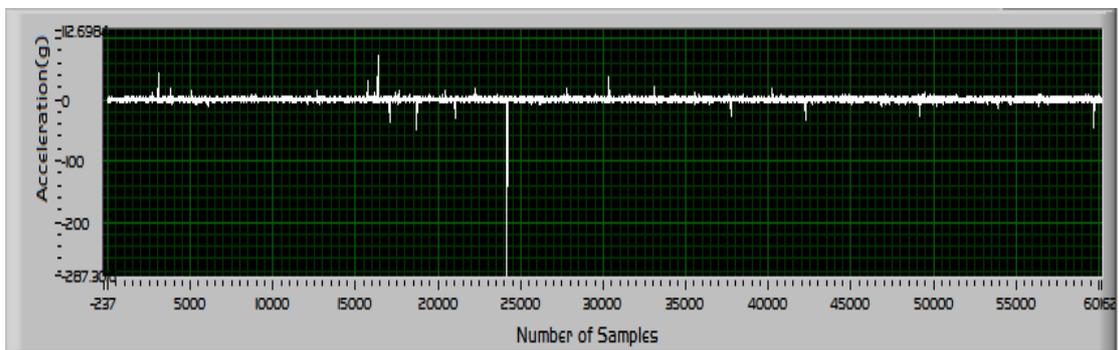
(a)
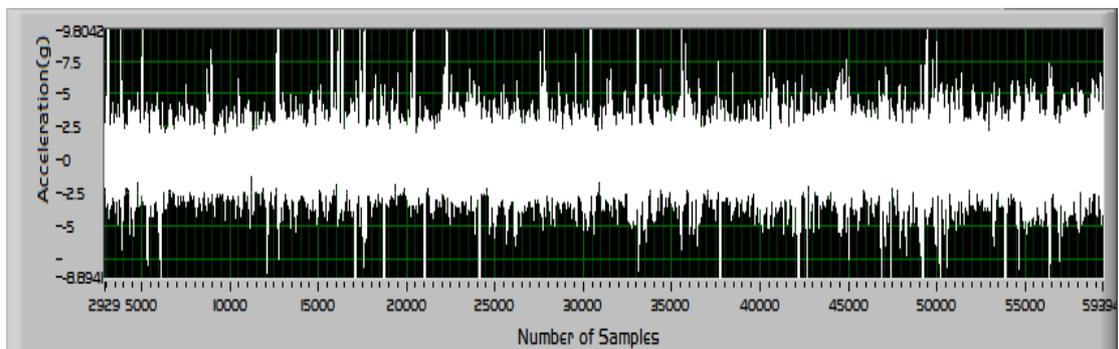
(b)

Figure 4.21 Time-domain waveform with variance of shaft speed (the bearing is
loosened)

4.5.4   Results and Discussion

Figures 4.22–4.27 show the experimental results of the feature parameters and time-domain signal with all load conditions when the bearing of the gearbox is tight.

In comparison of the experimental data before and after loosening the bearing, it can be found that:

(1) After the bearing in the gearbox is loosened, the values of most feature parameters are significantly improved. In detail, when the bearing is tight and the workload is 12Nm (or above), the absolute value of the kurtosis factor fluctuates at between 5 and 12, as shown in Figure 4.25; after the bearing is loosened, the absolute value of kurtosis factor increases to between $50 - 75$ as shown in Figure 4.16. The other feature parameters have the similar variance after the bearing of the gearbox is loosened.

(2) The amplitude of acceleration of time-domain signal has an obvious upward after the bearing is loosened as shown in Figure 4.27 and Figure 4.18. The amplitude of acceleration fluctuates at between 1 and 4 when the bearing is tight, while it fluctuates at between 5 and 9 after the bearing is loosened.

(3) Transient variance occurs at the waveform of the vibration signals. While the workload changes, there is a dramatic increase of feature parameters and the amplitude of the time-domain signal.
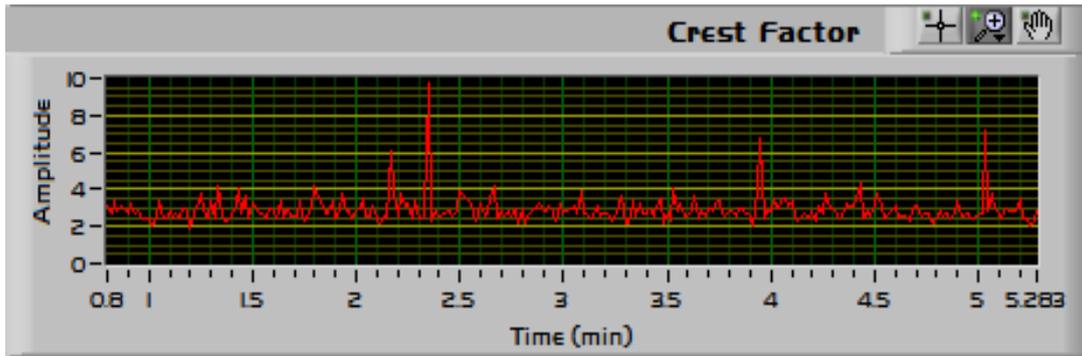
Figure 4.22 Crest factor trend (the bearing is tight)
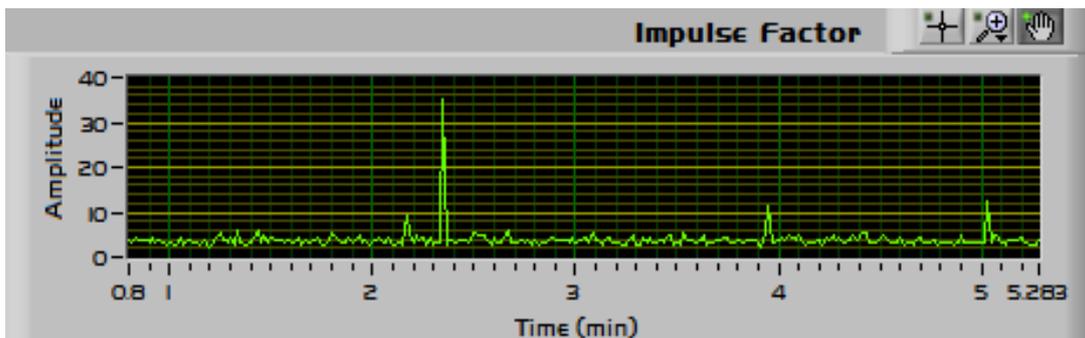
Figure 4.23 Impulse factor trend (the bearing is tight)
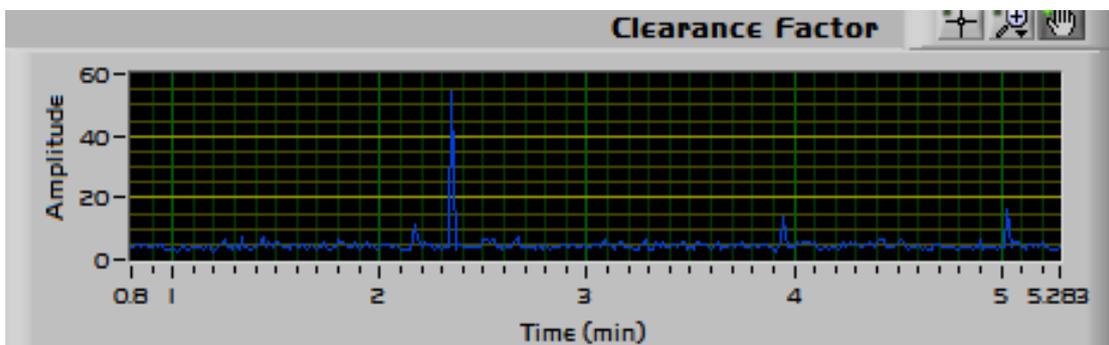
Figure 4.24 Clearance factor (the bearing is tight)
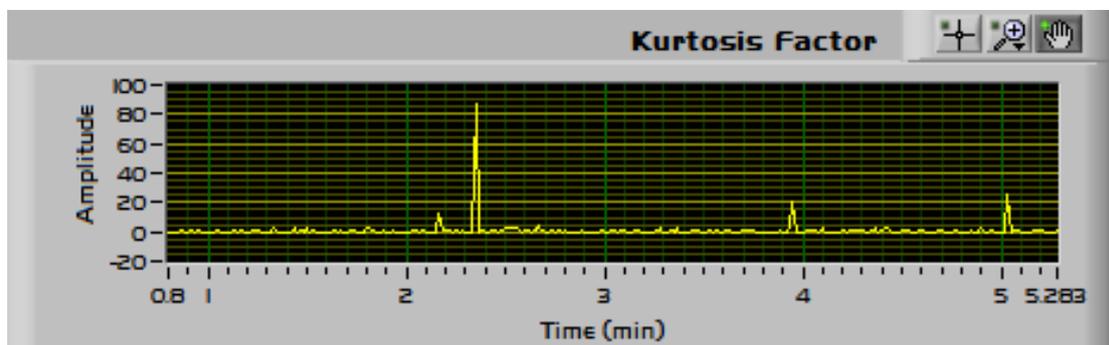
Figure 4.25 Kurtosis factor (the bearing is tight)
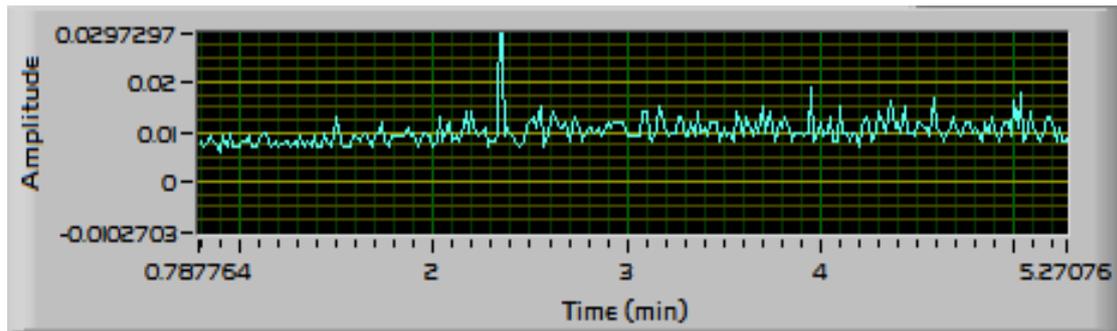
Figure 4.26 Root-mean-square (the bearing is tight)
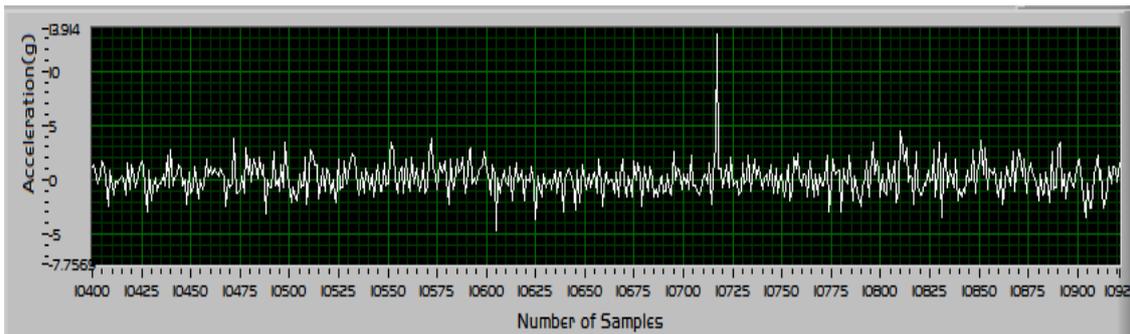
Figure 4.27 Time-domain waveform (the bearing is tight)

With introducing the external vibration such as loosening the bearing in the gearbox, the amplitude and its distribution of the vibration signal varies with the type of working conditions, which can be measured by the amplitude of time-domain signal and feature parameters such as crest factor, impulse factor, clearance factor, kurtosis factor and RMS. The vibration signal with all load conditions can be detected and the difference is prominent at higher load conditions. The following can be concluded according to the above experiment:

(1) After a bearing of the gearbox is loosened, the change of workload is always accompanied by the increase of the feature parameters and the amplitudes of time-domain signal. For example, when the workload increases to 5Nm there is an obvious upward process of the feature parameter (see Figures 4.13, 4.14 and 4.16). This upward process changes with the variance of workload. When the workload jumps to 15Nm or above, most feature parameters arrive at their maximum values. It proves that loosening bearing leads to a significant change of the amplitude distribution of vibration signal of gearbox.

(2) The varying processes of five feature parameters with load conditions are close

to each other. In particular, the change of crest factor and kurtosis factor are more distinctive than that of the other parameters.

(3) The feature parameters have an instantaneous fluctuation every when the workload increases. For example, there is an outstanding upward of impulse factor after 10.5 minute while the workload increases to 12Nm.

(4) The feature parameters do not change with the variance of the rotation speed of the gearbox (the workload is applied).

For more details about the experiment data and calculation results, please see the Appendix.

4.6   Concluding Remarks

A remote real-time condition monitoring system has been developed to monitor the working conditions of an industrial gearbox and to detect the faults of gearbox. The remote system is coded using the Web Service for the Internet communication, and coded in combination with G programming language and MXML Web-based developing language. The HTML-based user interface, as an important feature of the developed system, offers the remote monitoring/control functions for mobile devices such as PDA.

The real-time fault diagnostic scheme has been applied for identifying the fault of the gearbox. Within this scheme, time-frequency analysis and pattern recognition are used to real-time detect gear fault. The pattern recognition is performed using digital noise filtering and statistics-related methods. An experimental investigation for monitoring the industrial gearbox was carried out in this research using the developed remote condition monitoring system under different gear conditions. The experimental results show that the system is effective and the applied techniques can be utilised to online monitor gearbox's working conditions.

Chapter 5   Remote Control of Solid Desiccant Dehumidifier for Air Conditioning in Low Carbon Emission Buildings using PDA, Wireless Wi-Fi, and Database Technologies

5.1   Introduction

A research project has been conducted with the support of Sustainable Construction iNET High Education Collaboration Fund [17] to develop a novel system of solid desiccant dehumidification with the electro-osmosis regeneration suitable for domestic use or small THICAC (Temperature and humidity independent control air-conditioning) units and renewable energy applications, and typically for developing low /zero emission buildings.

The system uses water, which is environment-friendly, to replace conventional refrigerants to operate air-conditioning systems in buildings and will overcome the major problems of current system of evaporative cooling to satisfy the requirement of thermal comfort. The application of water evaporative cooling is often restricted in the UK and some areas of Europe typically due to relative higher humidity there. To overcome this problem, an effective solid desiccant dehumidification method is developed by this project.

This research is part of the work conducted by the Nottingham Trent University (NTU) team in collaboration with the project consortium members, University of Nottingham, and CE Technology Ltd, an SME in the East Midlands area. Within the iNET supported collaborative project, the author carried out the development of data collection, wireless control method, controller and control software used in solid desiccant dehumidification.

5.2   Overview of the Remote Control System of Solid Desiccant Dehumidifier

A remote control system for solid desiccant dehumidifier used in air conditioning has been developed. The system is applied to remotely monitor and control the working conditions of the solid desiccant dehumidifier using mobile devices, such as PDA and laptop, via the wireless Wi-Fi network. The system is able to regulate the dehumidifier's humidity, temperature and air's flow-rate, and to maintain the dehumidifier's normal operating status to satisfy the requirement of water evaporating cooling of air conditioning.

Figure 5.1 shows the overall structure of the remote control system for solid desiccant dehumidifier. The system contains a solid desiccant dehumidifier, an air conditioning unit, a fan, a data acquisition (DAQ) card associated with a voltage/current amplifier, two humidity/temperature sensors, a computer, a PDA, a wireless access point (router), and relevant software.
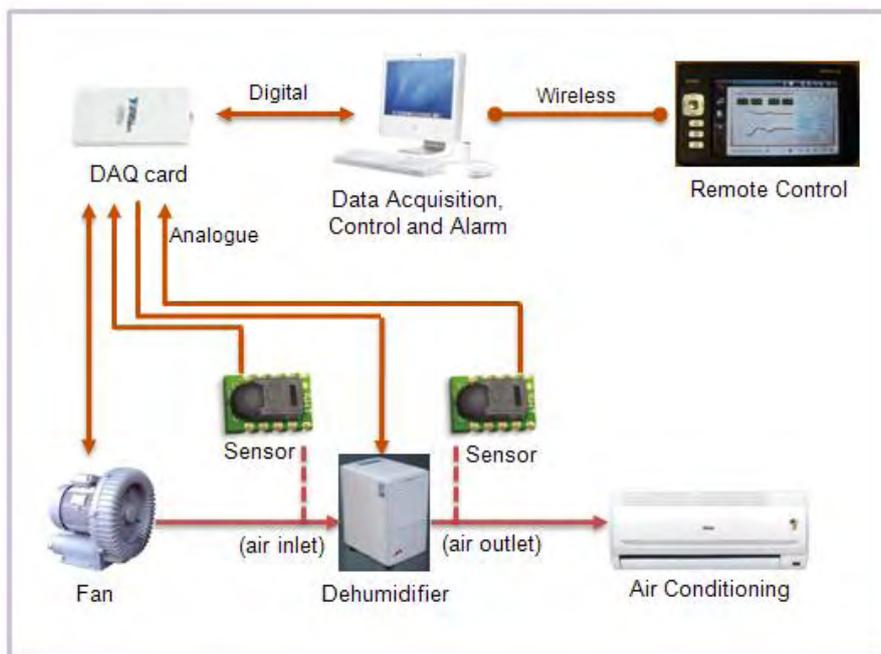
Figure 5.1 Remote control system of solid desiccant dehumidifier for air-conditioning using PDA and wireless communication

The solid desiccant dehumidifier plays a significant role in tuning the air's humidity. The air's dehumidification process is performed within the dehumidifier by removing moisture of the air. The dehumidifier provides an air-inlet and an air-outlet for air-flow's input and output respectively. The humid air enters the dehumidifier from the air-inlet at a certain flowing rate; with the effect of solid desiccant dehumidifier, the conditioned low-humidity air is outputted from the air-outlet, and is subsequently conveyed to air-conditioning unit for water evaporative cooling. The dehumidifier's operation is controlled by a DAQ card (analogue output controller) and a voltage/current amplifier.

The fan is applied to supply the source of air-flow to the dehumidifier. The fan's rotating speed determines the air's flow-rate in the dehumidifier. The faster the fan's rotating speed is, the larger the amount of air-flow passes through the dehumidifier within a time unit. When the amount of air-flow through the dehumidifier per second is more than that the dehumidifier can afford to, the control system automatically slows down the air's flow-rate by decreasing the fan rotating speed. The adjustment of fan rotating speed is performed by tuning control parameters of the DAQ card.

The control system adopts the DAQ card as the controller to regulate the operations of the dehumidifier and the fan, such as the dehumidifier's start/stop and fan's acceleration/deceleration. For further detailed control method using DAQ card, see section '*5.3.3 Decision Making*' in this chapter.

In order to monitor the operation status of the dehumidifier, the sensors are placed at both the inlet and outlet of the dehumidifier to acquire air-flow's working conditions data, which includes the humidity, temperature and flow-rate. The data acquisition, feature extraction and A/D conversion of the working conditions are detailed in section

'*5.3.1 Data Acquisition/Control*' and '*5.3.2 Data Processing*' respectively in this chapter.

The computer is used as the console to manage the above control and monitoring process. All the control commands and acquired working condition data are processed and executed within the computer, and then transmitted to the controlled devices, display panel, and/or the PDA.

Remote communication allows the users to utilise the PDA to wirelessly access the working condition data from the computer via wireless Wi-Fi connectivity, and to regulate the working conditions of the system/devices by tuning the control commands of the DAQ controller. The server-client networking structure is built based on the Web Service application program interface to realise the communication between the computer and the PDA. The application software for the server and the client are coded with the use of G programing language and MXML-based mobile programming standard.

5.3   Technologies Applied for the Control System of Solid Desiccant Dehumidifier

The system consists of four modules: (1) data acquisition and control, (2) data processing including feature extraction and A/D conversion, (3) decision making, and (4) remote communication.

Figure 5.2 presents the work flow of the remote control system and the functionality of each module. The data acquisition/control module provides dual functions of data collection (sensor-to-PC) and data control (PC-to-device). The data acquisition/control module first collects working condition data from the dehumidifier via the sensors; the captured data are subsequently converted to real physical quantities using feature

extraction and A/D (analogue-to-digital) conversion within the data processing module. The decision making module is applied for judging the dehumidifier's fault such as overload and generating control commands. When a fault is detected, the control commands are then automatically passed to the controlled units for regulating the working conditions of the dehumidifier through the data processing module (second module) and the data control module (first module). Remote communication module is built to transmit the working condition data to the user interface of the PDA via wireless Wi-Fi network, and meanwhile, to allow the user to control the working conditions of the dehumidifier by sending the requests with the control information to the computer.
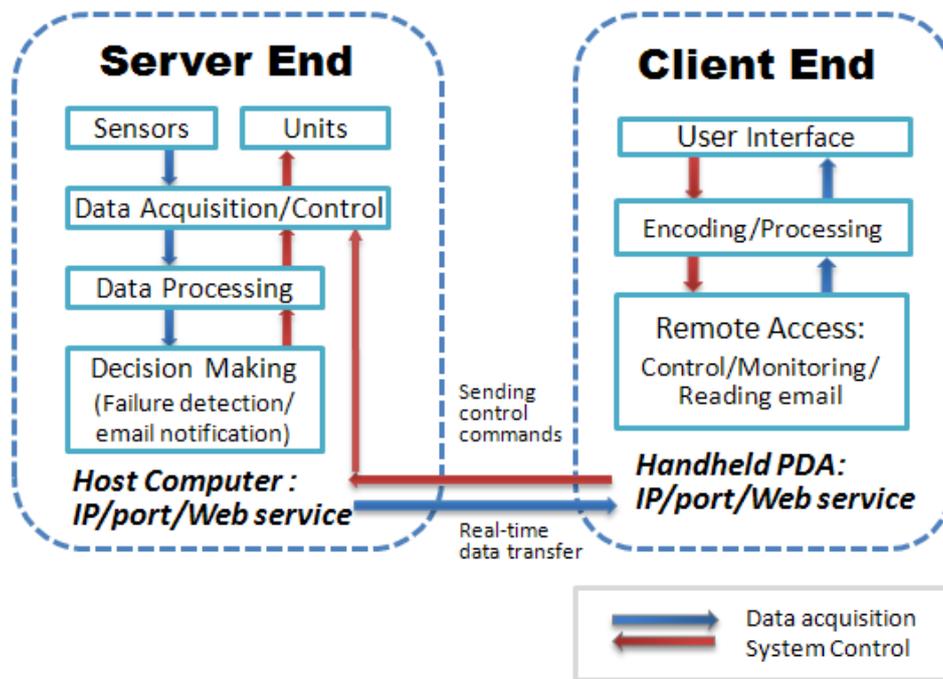
Figure 5.2 The monitoring and control flow of the remote control system

5.3.1 Data Acquisition and Control

Data acquisition/control is implemented using data I/O communication via the data acquisition/control (DAQ) card and associated sensors. The DAQ card is not just a data collection instrument but also a machine controller. It has the two-way

communication capability of data I/O, i.e. analogue data input (data acquisition) and analogue data output (data control).

On one hand, the DAQ card acquires data from the sensors and converts the analogue data to digital data, which can be read by the PC computer; on the other hand, the DAQ card converts the digital data for output control purpose into analogue data, which are then transferred to the controlled units/devices. The DAQ card's sampling rate is set 2 kHz and its data length is 2048. The analogue input/output voltage ranges from 0 to 10V.

The DAQ card utilised two analogue output channels, Channel-1 and Channel-2, to output the analogue voltage to control the operations of the dehumidifier and the fan. The analogue output channels have been developed with the following functions:

(1)   Channel-1 is used to supply the output voltage of 10V/0V to the dehumidifier to control its start/stop. When outputting 10V to the dehumidifier, the dehumidifier starts operating; when outputting 0V, it stops work.

(2)   Channel-2 supplies the output voltage of 0V-5V to the fan to adjust its rotating speed. The output voltage is proportional to the fan's rotating speed, which is adjustable in the range of 0 to 4500RPM. A voltage meter is utilised to measure the voltage applied in the fan.

The sensors are utilised to acquire the dehumidifier's working conditions data, such as temperature, humidity and flow-rate of the air. The working condition data are transferred to the data acquisition card in the form of analogue input voltage. All the sensors used have quick response to the humid atmosphere, as well as high accuracy with less than 2%.

Figure 5.3 presents the man-machine interactive interface of the remote control system deployed in the computer. Within the system interface, the analogue input data are captured at the rate of 2KHz per second from the sensors and are synchronically transmitted using the DAQ card to the Data Processing module for further data processing.
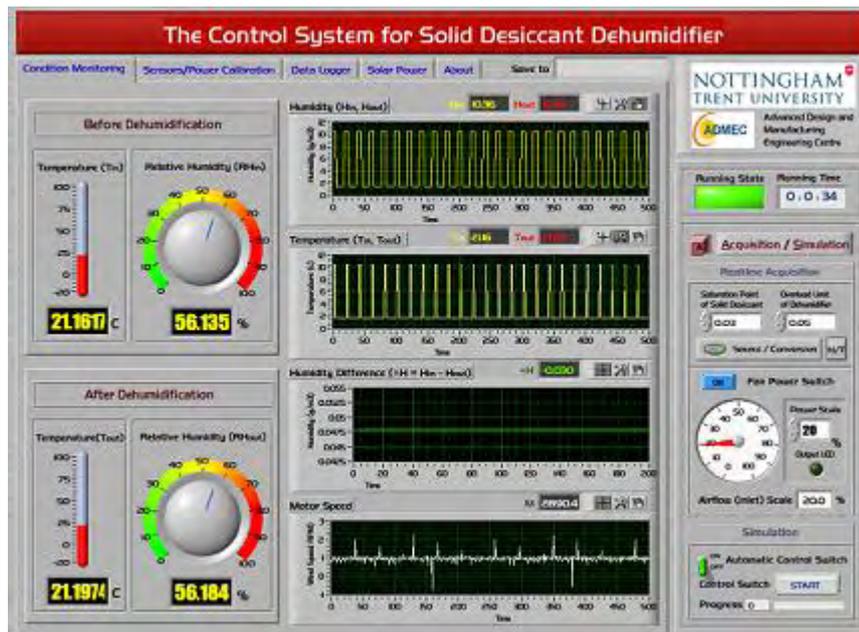
Figure 5.3 Real-time acquisitions of analogue signal data using the developed control system

5.3.2 Data Processing

The data processing module is built to convert the analogue data to the physical quantities representing actual working conditions (for instance, Celsius, RH%, rpm, etc), which can be understood by engineers. Data processing contains pre-processing, feature extraction and A/D (analogue-to-digital) conversion.

5.3.2.1 Pre-processing

In order to ensure the accuracy of the above conversion results, the acquired data are pre-processed using the following procedure:

(1) The data are divided into several groups and a group has 1024 data.

(2) Each group of data are calculated to generate a root-mean-square (RMS) result, and the average of the RMS results of all groups is taken as the working condition value at the time;

(3) The RMS's error is calculated using the mean square error (MSE). The above process ensures the calculation errors to be less than 1%.

5.3.2.2   Feature Extraction

The pre-processed data are transferred in the form of square-wave, which contains the information of real working conditions. The sub-modules for extracting the square-wave's feature parameters are developed, as shown in the Figure 5.4. Within the sub-module, the feature of square-wave is identified and its feature parameters are extracted from the data using the square-wave computing programmes. The feature parameters, also called A/D conversion coefficients, include root-mean-square, valley values, peak values, and periods. Figure 5.4 presents the feature extraction of square-wave for the temperature sensor and humidity sensor.
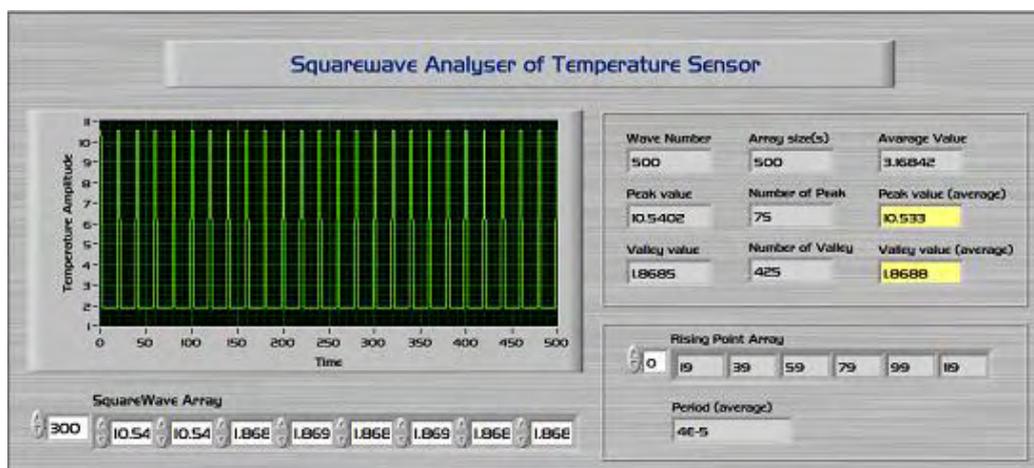
(a)
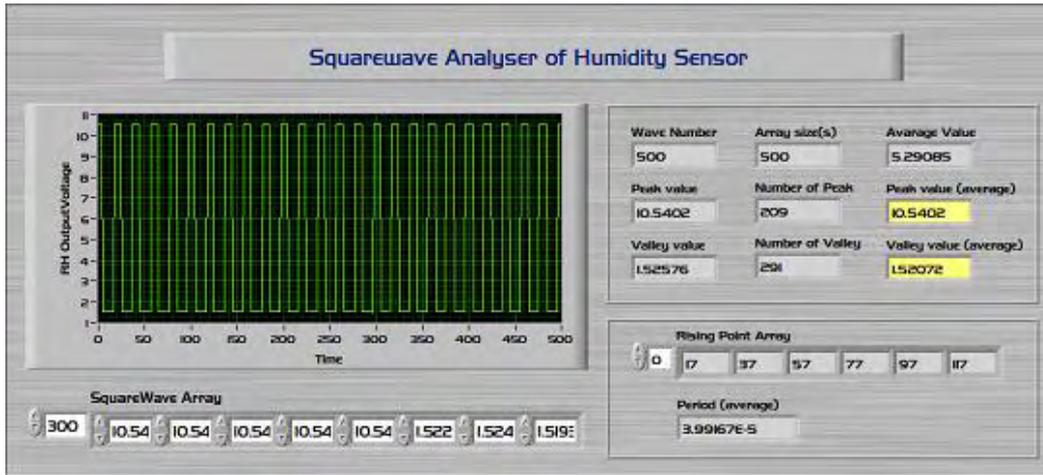
(b)

Figure 5.4 Feature extraction for the humidity sensor and temperature sensor

5.3.2.3   Digital Conversion

Utilising the above feature parameters and the non-linear/linear A/D conversion formulas, real working condition data, such as humidity (including both relative humidity and absolute humidity of the inlet/outlet), temperature and air's flow-rate, are calculated and presented in the interface of the control system in real time, as shown in the Figure 5.5.
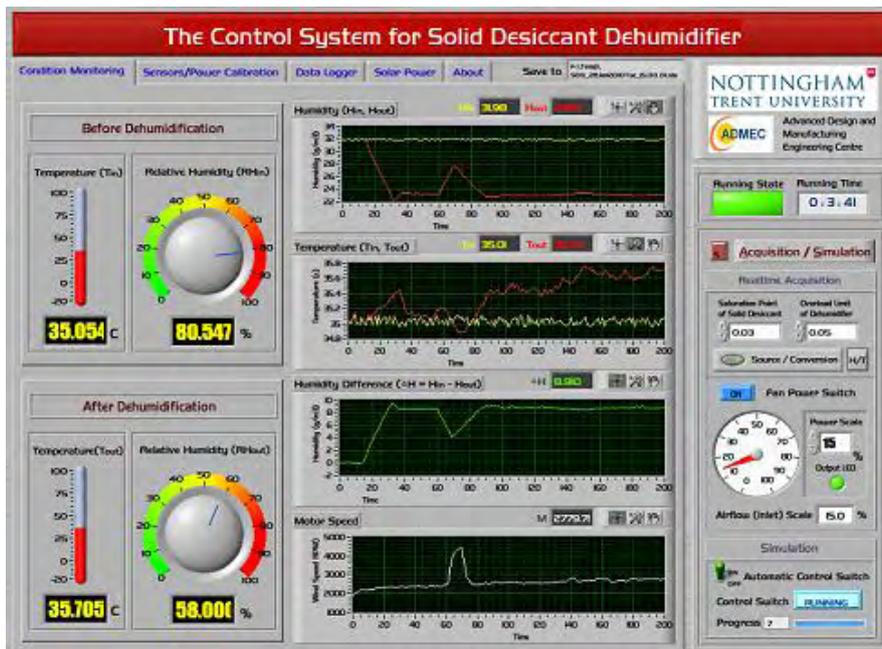
Figure 5.5 Acquisition of real physical quantities of working conditions of solid desiccant dehumidifier using feature extraction and A/D conversion

The formulas for A/D conversion are listed below as examples:

$$\text{Relative Humidity (\%)} = (\text{Value} * 0.1906) - 40.2 \tag{1}$$

$$\text{Temperature (°C)} = (\text{Value} * 0.22222) - 61.11 \tag{2}$$

$$\text{Absolute Humidity (g/m}^3) = 216.7*(RH/100.0*6.112*\exp(17.62*t/$$

$$(243.12+t))/(273.15+t)) \tag{3}$$

where the item 'Value' refer to the parameters for calculating the related working conditions, and 't' represents the temperature value.

5.3.3 Decision Making

Among the obtained working condition data, the humidity data as the most important indicators are used to judge the dehumidifier's overload. The overload of the dehumidifier is caused by the excess of air flow; excessive humid air is unable to be effectively conditioned in the dehumidifier and will be straight sent out of the dehumidifier. Thus, the overloading of the dehumidifier brings about the failure of air dehumidification.

5.3.3.1   Overload Factor ΔH

The judgement of overload of the dehumidifier is implemented by calculating the change quantity of the air humidity of the dehumidifier, which is indicated as ΔH. When the dehumidifier is in idle or not operational due to the failure, ΔH is zero; with the dehumidifier functioning, ΔH increases gradually. ΔH can be used to identify the operating status of the dehumidifier and judge if the dehumidifier is overloaded, and hence, ΔH is also known as overload factor.

It is supposed that the humidity of the air-inlet and air-outlet of the dehumidifier are indicated as H_{in} and H_{out} respectively. The change quantity of air humidity of the dehumidifier can be calculated by the following equation:

$$\Delta H = H_{in} - H_{out} \qquad (unit: g/m^3) \tag{4}$$

Here, ΔH is the change quantity of the air humidity of the dehumidifier, which is also called overload factor; H_{in} and H_{out} refer to the absolute humidity quantities of air-inlet and air-outlet, respectively. Correspondingly, RH_{in} and RH_{out} represent their relative humidity quantities of air-inlet and outlet respectively. The air humidity ratio of the dehumidifier is also an important indicator, which is calculated as follows:

$$\Delta H_c = (H_{in} - H_{out})/ H_{in} = \Delta H/ H_{in} \tag{5}$$

where ΔH_c is within the range of 0 to 1.

5.3.3.2   Influence of Air Flow-rate on Overload Factor ΔH

The overload factor ΔH is closely related to the air's flow-rate through the dehumidifier (The air's flow-rate represents the amount of air flow passing through the dehumidifier within a time unit). With the air flow-rate increasing, ΔH drops. When the air flow-rate is too fast, ΔH would become extremely low (probably approaching zero); it means that the amount of the air-flow accommodated in the dehumidifier is beyond that of the upper limit that the dehumidifier could afford to.

5.3.3.3   System Control

When ΔH is less than the specified values set by the system, the system claims that the dehumidifier is overloaded. The system is to rapidly make a response (decision) by the executing pre-set programme instructions, and to pass a control command/request of

decelerating fan's rotating speed to the DAQ card. The control commands are subsequently sent by the DAQ card to the switch of the fan in the form of analogue output voltage. Using DAQ card's digital-to-analogue (D/A) conversion, the system can automatically slow down the fan's rotating speed to decrease the air flow-rate through the dehumidifier until ΔH reaches the rated working range. Figure 5.6 presents the conversion process of digital-to-analogue (D/A), which utilises the data I/O interface to transfer the digital control command to the analogue control switch of the fan.

In case that ΔH cannot be adjusted to be in the safe-working range required by the dehumidifier using the above-mentioned deceleration method, the system is to stop the operations of the dehumidifier and the fan by sending the 'shutdown' command to the switches of the dehumidifier and the fan through the DAQ card. In the meantime, the system issues a warning message using the software interface to inform on-site operators and generates an online analytical report. As a result, the system has the capability of processing overloading problems to protect the dehumidifier from unexpected damage.
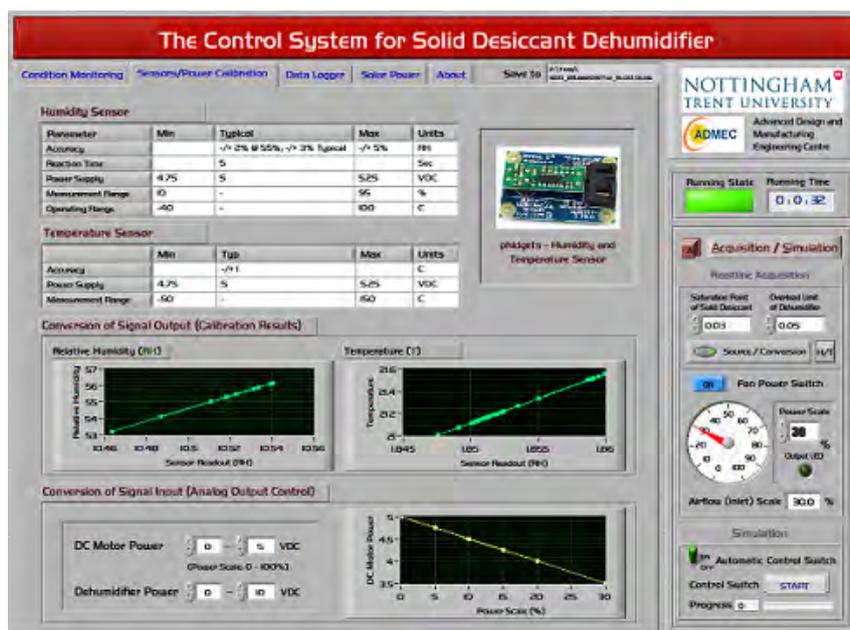
Figure 5.6 Digital-to-analogue (D/A) conversion that converts the digital
control command to analogue output signal

Temperature is also applied to aid the system with evaluating the operation of the dehumidifier. Generally, temperature increases with the drop of the air humidity.

Figure 5.7 presents the control flow of solid desiccant dehumidifier for air-conditioning. This flow is obtained by analysing the operation mechanism of solid desiccant dehumidifier and considering the related influencing factors, such as saturation point, overload point, balance point and control points. The experimental investigation of the control process of solid desiccant dehumidifier is illustrated in the section *5.4 Experimental Investigation of Solid Desiccant Dehumidifier*.
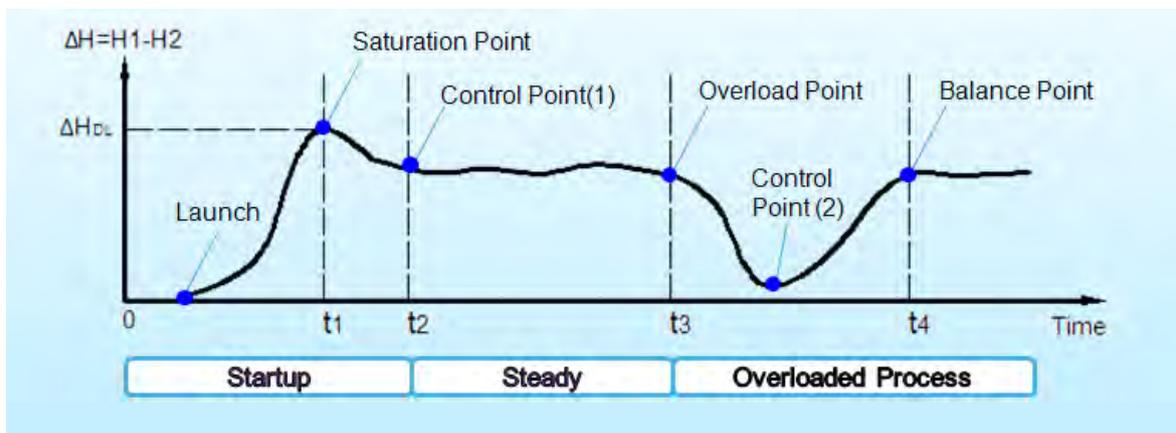
Figure 5.7 The work flow of solid desiccant dehumidifier for air-conditioning

5.3.4 Remote Communication

Remote communication module adopts the server-client networking structure, which is the same as the network structure used in the gearbox condition monitoring, to realise the remote communication between the server and the client.

The server-client network is constructed with the following arrangement:

(1) The server is located beside the machines to be monitored, i.e. solid desiccant dehumidifier; the computer is deployed at the server for conducting required

calculation and data transmission, such as data acquisition/processing, decision making, and system control.

(2) The client may be in any location where the wireless Wi-Fi network is available. The client is composed of a PDA (personal digital assistant) and a wireless access point, such as a router for wireless Wi-Fi connectivity.

Within such a networking structure, remote communication is implemented by applying Web Service application program interface and MXML-based cross-platform programming standard. Web Service allows mobile users to access the computer located in the server via the wireless Wi-Fi. Figure 5.2 illustrates the server-client networking structure and functions developed, which completes real-time data acquisition, data processing, system control and wireless communication.

5.4   Experimental Investigation of Solid Desiccant Dehumidifier used in the Air-conditioning System

The developed system has been applied to control and monitor the working conditions of solid desiccant dehumidifier used in the air-conditioning system in an experimental environment. The data acquisition hardware contains a NI-DAQ6259 card, two humidity/temperature sensors and a flow rate sensor. The sensors are set up at air-inlet and air-outlet of the dehumidifier to monitor the air's humidity, temperature and flow rate. Figure 5.8 presents the experimental environment of the air-conditioning system with the solid desiccant dehumidifier.

The control flow of the solid desiccant dehumidifier can be categorised into three stages: start-up, steady operation, and overloading (failure). The experiments conducted with the three stages are further detailed in the following sub-sections.

Figure 5.8 The experimental environment of the air-conditioning system with solid desiccant dehumidifier
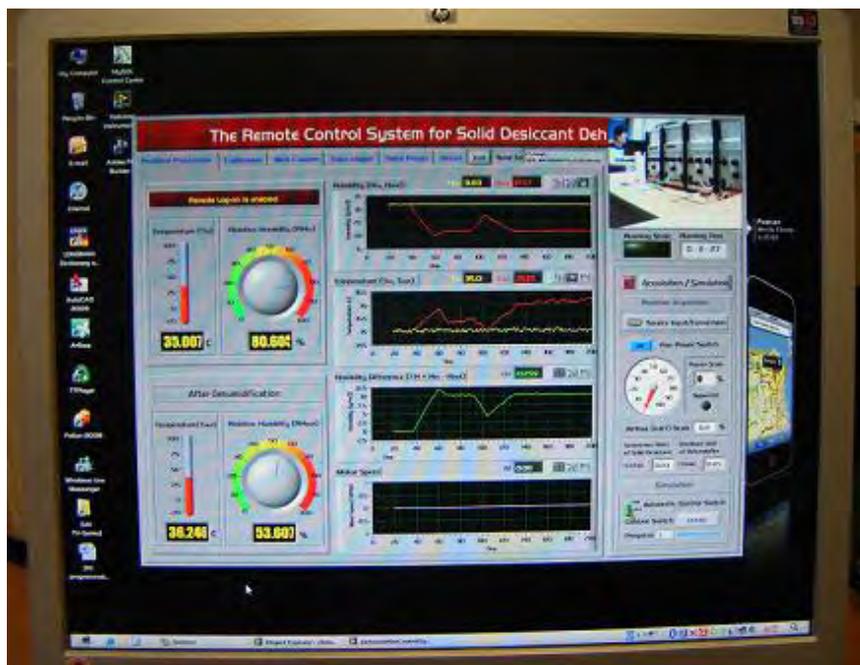
Figure 5.9 Real-time monitoring and control of solid desiccant dehumidifier

5.4.1   Start-up of Dehumidifier

Figure 5.9 presents the real-time monitoring and control interface of the solid desiccant dehumidifier. While operating the control system via the monitoring interface, the working condition data were acquired from the dehumidifier and real-time displayed in

the monitoring interfaces. Initially, the change quantity of air humidity of the dehumidifier ΔH was 0 g/m^3.

The control of the dehumidifier and fan were implemented by sending the control commands to the switches of the dehumidifier and the fan through the DAQ card. When switching on the dehumidifier and the fan via the monitoring interface of system, the DAQ card was first triggered, which was indicated by a flashing LED. Subsequently, the dehumidifier and the fan were launched, followed by a gradual increase in ΔH.

Figure 5.10 shows the variance of ΔH and the fan rotating-speed with time. It was clearly observed that ΔH increased to approximately 8.5 g/m^3 and fan's rotating speed was around 2400RPM after 20 seconds. The voltage, which is supplied to the dehumidifier and fan, was measured by the voltage meter to be 10V and 2.7V respectively.

During this stage, the dehumidifier worked normally and continuously outputted the low-humidity air, which can satisfy the requirement of water evaporating cooling of air conditioning.
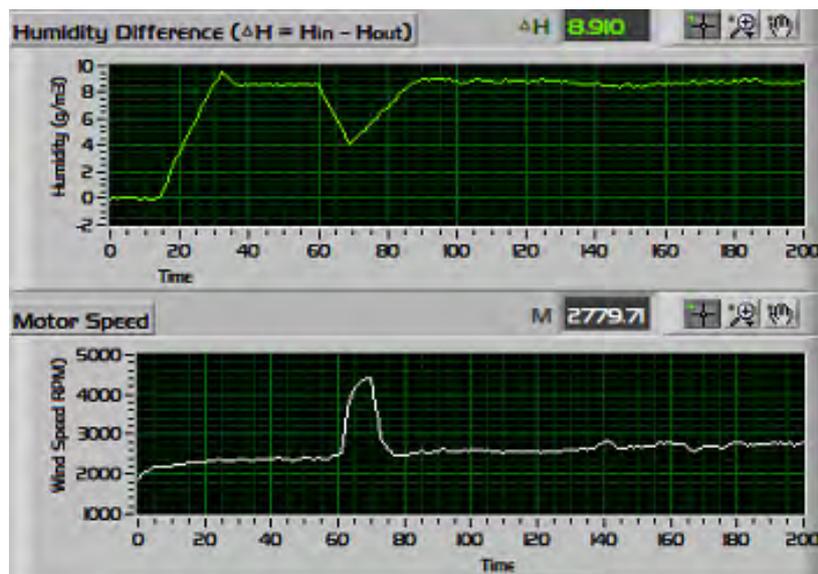
Figure 5.10 The experimental results of the change of ΔH and fan's
rotating speed with time

5.4.2   Steady operation of the dehumidifier

When increasing the fan's rotating speed by tuning the DAQ's control parameters via the monitoring interface of the control system, the measured air flow-rate through the dehumidifier turned fast. However, ΔH remained unaltered (at around 8.5 g/m^3) due to the normal operation of the dehumidifier.

5.4.3   Failure (Overload) of the dehumidifier

When air flow-rate was tuned over fast so that the dehumidifier was overloaded, ΔH dropped rapidly. As shown in the Figure 5.10, the fan rotating speed increased followed by the drop of ΔH after 60 seconds. When the fan rotating speed jumped to 4500rpm at 70 seconds, ΔH fell to 4 g/m^3. The control system quickly detected the overloading status of the dehumidifier by monitoring the change of ΔH.

With the effect of the automatic control of the system, the fan's deceleration commands were immediately passed to the DAQ card. The DAQ card regulated the fan's rotation speed by outputting the analogue output voltage to slow down air flow-rate in the dehumidifier. After 93 seconds, the fan's rotating speed fell back to 2500rpm and ΔH grew up to 8 g/m^3 again. Thus, the dehumidifier restored to the normal operation.

The experimental results are in accordance with the theoretical analysis results, which are shown in Figure 5.7. The experiment shows that the control system can effectively work to monitor and control working conditions of the solid desiccant dehumidifier; and the applied I/O control methods are able to regulate the operating status of the devices, such as dehumidifier and fan, by sending DAQ control commands, and to maintain the normal operation of the dehumidifier. Therefore, this study proved the

success of monitoring and controlling of the working conditions of the solid desiccant
dehumidifier.

5.5   Remote Monitoring and Control using PDA, Wireless Wi-Fi Network and Database Technologies

In this study, remote communication with the server-client networking structure is
applied to wirelessly monitor and control the working conditions of solid desiccant
dehumidifier used in the air-conditioning system.

In the server-client networking structure, the server is used to collect measurement
data and subsequently to process/analyse data for decision making. When
dehumidifier's overload/failure is detected, the server is able to automatically execute
the appropriate instructions to regulate the working conditions of the solid desiccant
dehumidifier to restore the operation of the air-conditioning system into the normal
situation. The server is not just a data acquisition/processing system but also a Web
platform, which enables the server computer and the client-end mobile device such as
PDA to communicate with each other.

Although the server is capable of regulating the working conditions of dehumidifier
automatically, the users, in a certain circumstance, need to adjust the working
condition, such as air humidity, according to their individual demands. To resolve this
problem, remote control system provides the function of tuning the working conditions
of the dehumidifier to satisfy the requirements of different users; in the meantime,
remote control allows the users to acquire the working condition data in real time using
PDA and wireless connectivity.

The remote monitoring/control process of solid desiccant dehumidifier for
air-conditioning system is detailed in the following sub-sections:

5.5.1   Remote Monitoring and Control of Working Conditions of Solid Desiccant Dehumidifier

While operating the system via the user interface of the PDA, the humidity and temperature data were acquired from the dehumidifier and displayed in the user interfaces of the PDA in real time, as shown in Figure 5.11. The user interface provides the following options/functions to view the data and results: analogue input (raw data), digital input (actual physical quantities), and waveform of different conditions. Figure 5.12 presents the real-time acquisition of waveform/diagram of different conditions using the option of the user interface.

Figure 5.11 Remote access to the working condition data of solid desiccant dehumidifier used in air-conditioning system using the PDA and wireless Wi-Fi

The control process of the working conditions of the solid desiccant dehumidifier was implemented by tuning the parameters of the DAQ controller/card. When switching on the system via the PDA, the DAQ controller connected with dehumidifier was first triggered, which was indicated by a flashing LED. Subsequently, the dehumidifier and

fan were launched, followed by outputting low-humidity air from the dehumidifier. With the effect of the solid desiccant dehumidifier, the humidity of output air gradually decreases.
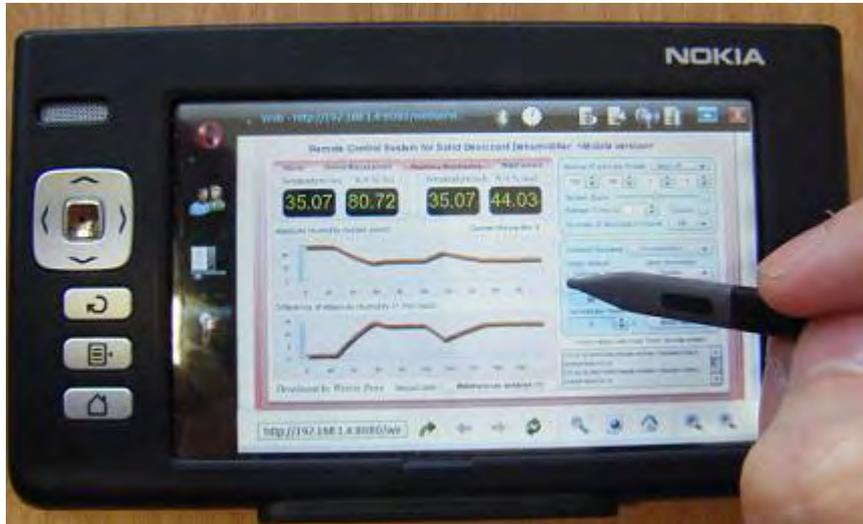
Figure 5.12 The real-time acquisition of waveforms of different working conditions using the option/function of the user interface of the PDA
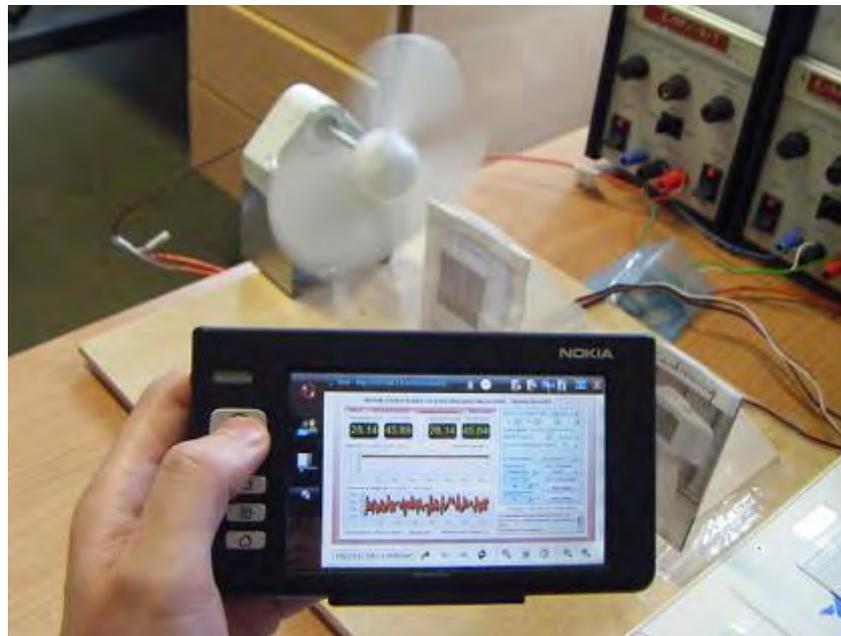
Figure 5.13 Remote control of rotation speed of the fan using the PDA and wireless Wi-Fi network

While utilising the PDA to tune the flow-rate of the air flowing through the dehumidifier, the fan's rotation speed and air's flow-rate varied with the control

commands of the PDA. Meanwhile, humidity and temperature of the air-conditioning unit changed due to the effect of the solid desiccant dehumidifier. According to the user's request/commands, the user is able to tune the dehumidifier's working conditions, such as humidity, temperature, and air's flow-rate, using the user interface of the PDA.

Figure 5.13 shows the remote control of rotation speed of the fan using the PDA and wireless Wi-Fi network. When the user adjusted the parameters via the user interface, the rotation speed of the fan changed soon. The working conditions data, such as humidity, temperature and flow-rate, varied as well, and were then displayed on the interface of the PDA.

5.5.2   Real-time Video Display and Remote Database Access using PDA

The real-time video/image, to display the operation of the air-conditioning system, was transmitted to the user interface of the PDA together with the working condition data of the dehumidifier, as shown in Figure 5.14.

Figure 5.14 Real-time video display based on video-decomposition technology using PDA and wireless Wi-Fi connectivity

When the Video Transfer function was switched on, the video/image was acquired by

the web camera connected to the server computer, and processed by Flex Media Server

(FMS), and then transferred to the user interface of the PDA through

video-decomposition. When Video-decomposition method was applied, the video was

converted into several single images with low resolution. The amount of displaying the

images per second is adjustable in the range of 1-24, which is determined by the user.

The user adjusted this amount to find out the optimal solution, such as resolution and

image bit (speed), to view the video smoothly.

When Database function is enabled on the PDA, the users can online view the history

data-files, which records the working conditions of solid desiccant dehumidifier,

utilising the PDA to access the database located in the server end. Figure 5.15 presents

the remote access to the database using the PDA.

Figure 5.15 Remote access to the My-SQL based database using PDA

The database is developed based on My-SQL database manager to record and manage

the working conditions data of solid desiccant dehumidifier. The database is associated

with the remote control system in the server via Open Database Connectivity (ODBC).

ODBC is a database interface, which allows the remote control system to access the

database and store the data into the database with security. When the system is running,

the working conditions data are logged into the database via ODBC connectivity in

real time. The users are able to utilise the PDA to access the history data within 24 hours in XML form. The experiment shows that the developed remote control system can effectively work to online access the working condition data of solid desiccant dehumidifier, and the applied remote communication methods enable end-users to remotely access the server to regulate the dehumidifier's working conditions and operating status.

5.6   Conclusion

This chapter investigates the issue of control and monitoring of solid desiccant dehumidifier for air conditioning. The control flow of the solid desiccant dehumidification can be summarised into three stages: start-up, steady operation, and overloaded/failure. The detailed specification of working conditions of the dehumidifier during the three stages has been listed in Table 5.1. The remote control system, which has been applied in the experimental environment, can effectively work in the above three stages to monitor and regulate the working conditions of the dehumidifier. Experimental results prove that the remote control system has been successfully developed and applied for controlling and monitoring the operation of the solid desiccant dehumidifier used in air-conditioning to maintain normal operation of dehumidification system.

Stage	Time (sec)	RH_{in} (g/m^3)	RH_{out} (g/m^3)	ΔH (g/m^3)	ΔH_c	Temp. (°C)	Speed (rpm)
Start-Up	0-30	32	32 - 23.5	0 - 8.5	0 - 0.26	35 - 35.5	1800 - 2400
Steady Operation	30-60	32	23.5	8.5	0.26	35.5	2400
Overload	60-90	32	23.5 - 28	8.5 - 4	0.26 − 0.13	35.5 - 34.9	2400 - 4500

Table 5.1 The specification of working conditions of the solid desiccant dehumidifier

Chapter 6   Remote Condition Monitoring of Thermo-Electric-Generations using Mobile Phones, GPRS Mobile Network and Cross-platform Communication

6.1   Introduction

A research project has been conducted with the support of Sustainable Construction iNET High Education Collaboration Fund to develop a novel building block of thermoelectric co-generation for electricity and hot water. The block uses heat energies from the exhaust gas of domestic boiler and solar radiation to generate electricity and also supply the heat energy in hot water for domestic use.

Thermo-Electric-Generations (TEGs) are made from thermoelectric modules which are solid-state integrated circuits that employ three established thermoelectric effects known as the Peltier, Seebeck and Thomson effects. It is the Seebeck effect that is responsible for electrical power generation. The energy from heat sources can be converted into electricity by such thermoelectric module in the presence of temperature difference.

The research reported in this chapter is a part of research project conducted by Nottingham Trent University (NTU) team, in collaboration with the project consortium members, University of Nottingham, and European Thermodynamics Ltd, a SME. Based on the Sustainable Construction iNET project, the author has developed a remote condition monitoring system for monitoring, controlling and recording the working conditions of Thermo-Electric-Generations. This chapter details the development of remote condition monitoring system with emphasis on data acquisition, decision-making for system control, and mobile communication.

6.2 Overview of the Remote Condition Monitoring System of Thermo-Electric-Generations

The remote condition monitoring system is developed in this research to monitor and control the working conditions of Thermo-Electric-Generations (TEGs). The system collects the data of working conditions from TEGs using the data I/O interfaces, and allows the users to utilise mobile devices, such as mobile phones, to access the data of the working conditions of TEGs via mobile phone network and Internet. The system is able to regulate the temperature of cold side of thermoelectric units used in TEGs automatically to ensure that TEGs function normally to output electricity continuously. Figure 6.1 presents the overall structure of the remote condition monitoring system of Thermo-Electric-Generations.
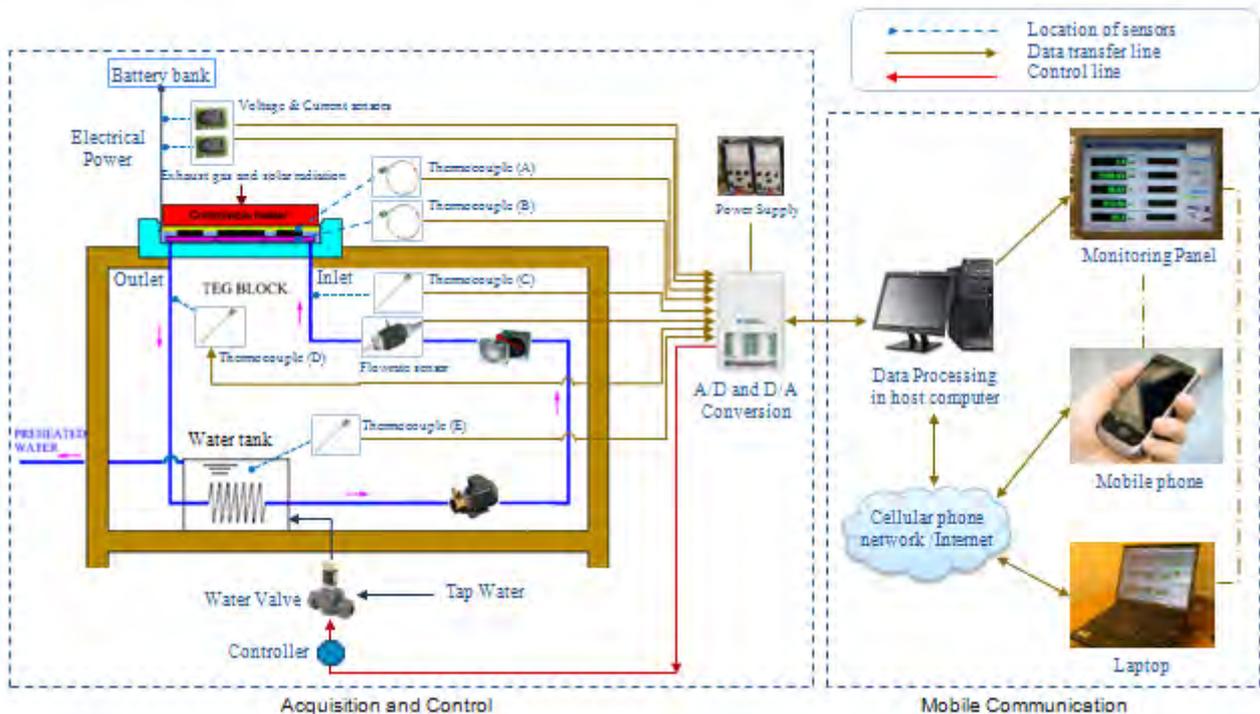
Figure 6.1 Structure of the remote condition monitoring system for Thermo-Electric-Generations (TEGs)

The remote condition monitoring system contains Thermo-Electric-Generations with thermoelectric units and water supply unit, data acquisition and control units, a desktop computer as the server, a mobile phone and relevant software.

Thermoelectric units utilise the thermoelectric effects, which converts temperature difference between the hot side and cold side into electricity. When there is a temperature difference on both sides, thermoelectric units generate electrical power. The hot side of thermoelectric units is supplied with heat energy using the exhaust gas from domestic boiler and solar radiation; the cold side of the thermoelectric units remains cooling using the recycled water, which flows through the surface of cold side, and is supplied by the water supply unit connected with the cold side.

The water supply unit includes a tank, pipes, a pump, a water valve, and a tap associated with domestic water. The water stored in the tank is driven by the pump and flows through the pipes. On one hand, the water is flowed into the cold side of thermoelectric units via the inlet to absorb the heat energy, which is generated by thermoelectric effects of thermoelectric units; on the other hand, the heated water flows out of the cold side of thermoelectric units via the outlet and is subsequently sent back to the tank. The water temperature of the tank increases due to the effect of the returned heat water.

The water temperature of the tank has a significant effect on the cooling of the cold side of thermoelectric units. If the water temperature of the tank is extremely high, the water flowing into of the cold side of thermoelectric units is unable to satisfy the requirement of cooling-down of the cold side. Therefore, the water temperature of the tank must be low enough to ensure that the thermoelectric units functions in the normal condition. To resolve the above-mentioned problem, the tap-water for domestic use will be injected into the tank to reduce the water temperature of the tank when the water temperature of the tank is extremely high and exceeds the upper limit set.

The amount of domestic water, to be injected into the tank, is controlled by the control unit, which manipulates the injection process of the domestic water by monitoring the water temperature of the tank and regulating the switch of the water valve. Once the water temperature of the tank is measured higher than the upper limit set, the water valve will be switched on and release domestic water into the tank immediately; meanwhile, the heat water in the tank will drain off the outlet of the tank. The drained water will supply its heat energy for domestic use, such as domestic heating. The control method with regard to the switch of the water valve is detailed in section *'6.3.3 System Control'* in this chapter.

The working conditions data of Thermo-Electric-Generations is acquired using thermocouples/sensors and data I/O interfaces. Several thermocouples/sensors are set up in Thermo-Electric-Generations to collect the working condition data, such as temperature, water flow-rate, and output voltage/current. These thermocouples/sensors are located at the following positions: the hot/cold side of the thermoelectric units, the inlet/outlet of the cold side of thermoelectric units, the inside of tank water, and the positive/negative poles of the electricity generated by thermoelectric units, as shown in Figure 6.1. The thermocouples/sensors simultaneously acquire the working conditions data, and then transfer the data to the computer via the analogue/digital input interfaces. The method of data acquisition is presented in the section *'6.3.1Data Acquisition'*.

The computer, as the system console, manages the monitoring and control process of TEGs. The computer works to process the data of working conditions in real time, and receive the control command from the operator/user, and to regulate the operation of the device/system. The computer is also used as the server to provide Web services for remote communication with the mobile phone.

The related application software has been developed using the following developing tools: (1) LabVIEW Developer Suite, a graphical programming environment, to develop the server-end applications for data acquisition and decision making (system control); (2) Adobe Flex Builder, a programming development environment, to develop the user interface and script for remote communication with the server; (3) Flex Media Server (FMS), to build the media-driven code to transfer video stream from the computer to mobile device in the client.

6.3 Technologies Applied

The remote condition monitoring system consists of the following four modules: data acquisition, data processing, system control and remote communication.

6.3.1 Data Acquisition

Data acquisition module collects the data of working conditions from Thermo-Electric-Generations using the data acquisition unit via the data I/O (Input/Output) interface. Data acquisition unit includes (1) five thermocouples associated with a signal conditioner, which acquire the temperature data of thermoelectric units, (2) voltage/current sensors, which measure the voltage and current of the electrical power generated by thermoelectric units, (3) a flow rate sensor, to measure the flow rate of the water passing through the pipes, and (4) a data acquisition (DAQ) card with the data I/O interfaces that convert the received data into the digital signal data and then transfer the data to the computer for the further processing. Figure 6.2 presents the above mentioned thermocouples and sensors, which are used in the monitoring process of working conditions of Thermo- Electric-Generations.
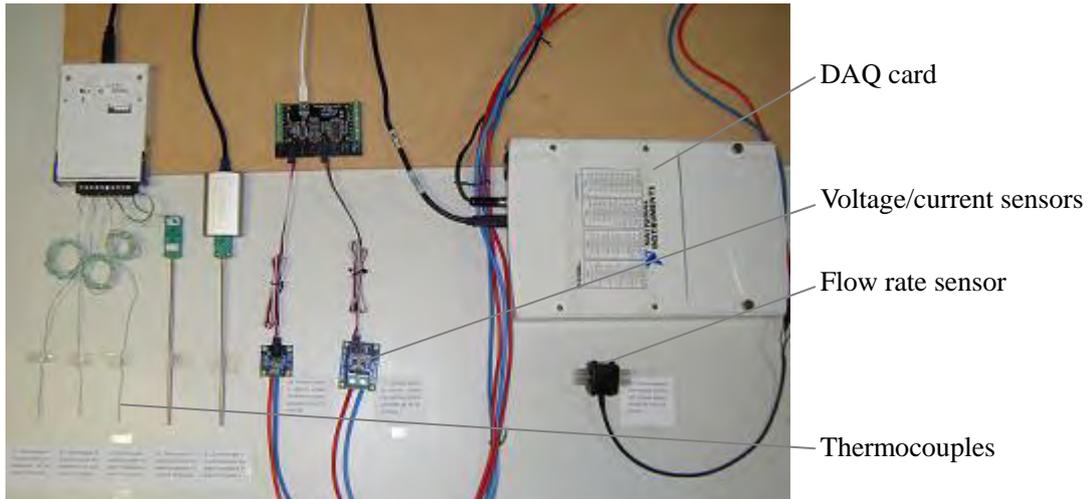
Figure 6.2 Data acquisition unit including thermocouples, sensors and
data acquisition card

Temperature measurement is conducted using the thermocouples with K-type miniature plugs/probes and a signal conditioner. The signal conditioner provides the temperature compensation for the cold-junction of the thermocouples, to ensure the accuracy of the measured temperature data; it also provides the amplification and filtering for the low-voltage signals generated by the thermocouples. The application of the signal conditioner reduces the error of the temperature measurement. The measurement error is less than 0.1% at 0-70 °C.

The high-precision voltage/current sensors and flow rate sensor are applied to acquire the output voltage/current and the flow rate of water, respectively. The acquired data are transmitted to the data acquisition card for further processing.

Data acquisition (DAQ) card uses data I/O communication interfaces, known as analogue input (AI) interface and digital counter (DC) interface, to acquire the analogue signal with physical information and then convert it into the digital signal, which can read by the computer.

The analogue input (AI) interface provides the functions of analogue input and differential calculation of signal; the sampling rate of analogue input interface is set 1 kHz and its data length is 1k. The digital counter (DC) interface utilises the pulse counting method to acquire the signal and provides the capability of high-speed computation of signal; the sampling rate of the digital counter is 80 kHz.

6.3.2 Data Processing

Data processing module is built to process the received data, and convert the analogue data into the physical quantities of working conditions of TEGs via A/D (analogue-to-digital) conversion, and then display the data/results on a monitor panel.

6.3.2.1 Pre-processing

In order to ensure the accuracy of the received data, the data are processed in the following procedure:

(1) The data are categorised into ten groups, and a group has 100 data.

(2) The data in each group are calculated to generate a root-mean-square (RMS) result;

(3) The mean of the RMS of ten groups is used as the data of working conditions at the time point.

The above method can effectively get rid of the odd/invalid data and ensure that the calculation error is not more than 1%.

6.3.2.2 A/D Conversion

A/D conversion is implemented to convert the analogue data into the real physical quantities of working conditions. Because the received data is not proportionally linear

with real physical quantities of working conditions, A/D conversion based on non-linearization is conducted in the following ways.

Equation 6.1 presents the A/D conversion of temperature condition. Within this equation, non-linearization calculation is conducted to convert the analogue data into actual temperature value.

$$\text{Temperature (°C)} = -2.0468 + 0.0367 * \text{SamplingValue} - 1.5955\text{E-}6 * \text{SamplingValue}^{2} \tag{6.1}$$

where the item 'SamplingValue' refers to the working condition data received from data acquisition unit, and 'Temperature' is the real temperature value that is gained using non-linearization calculation.

The obtained temperature data are further calculated to acquire the following physical quantities: heat energy and electrical power generated by the TEGs, and carbon dioxide emission saved.

Heat energy is acquired with the following formula:

$$Heat\ enegry\ (kJ) = c \times \rho \times G \times (T_{out} - T_{in}) \tag{6.2}$$

where, c is the heat capacity of water, 4.186kJ/kg°C, ρ is the water density, 1000kg/m^{3}, T_{out} is the water temperature of the outlet, T_{in} is the water temperature of the inlet, and G is the flow rate of water, m^{3}/s.

According to the mathematical model given by British Wind Energy Association (BWEA), carbon dioxide (CO_2) emissions saved is computed as follows:

$$CO_2\ emission\ saved\ (kg\ /\ hour) = 0.035 \times Electrical\ energy\ (kW \cdot h) \tag{6.3}$$

where Electrical energy is gained by multiplying electrical power by the time length of electrical power generation. Electrical power is acquired using the product of the output voltage and the output current.

6.3.2.3   Result Display on Monitoring Panels

The acquired data of working conditions of TEGs are subsequently displayed on the monitoring panels as shown in Figure 6.3. The monitoring panels are formed by several sub-panels such as primary panel and secondary panel, to provide the real-time display of the following data/information:

(1) the working conditions data shown in the primary panel, such as electrical power and heat energy generated by TEGs, CO_2 emission saved, and water temperature of the tank;

(2) the working conditions data shown in the secondary panel, including the temperature of hot/cold side of the thermoelectric units, the temperature of the inlet/outlet of the cold side of the thermoelectric units, output voltage and current, and flow rate of the water passing through the pipes;

(3) the control parameters in the control panel, such as the upper/lower limit of the water temperature of the tank, to tune the switch of the water valve;

(4) the real-time video, to display the image/video of operation of the TEGs;

(5) A/D conversion parameters, such as the linearization coefficients and the sampling rates of the system;

(6) data logging, to record the working conditions data of TEGs.
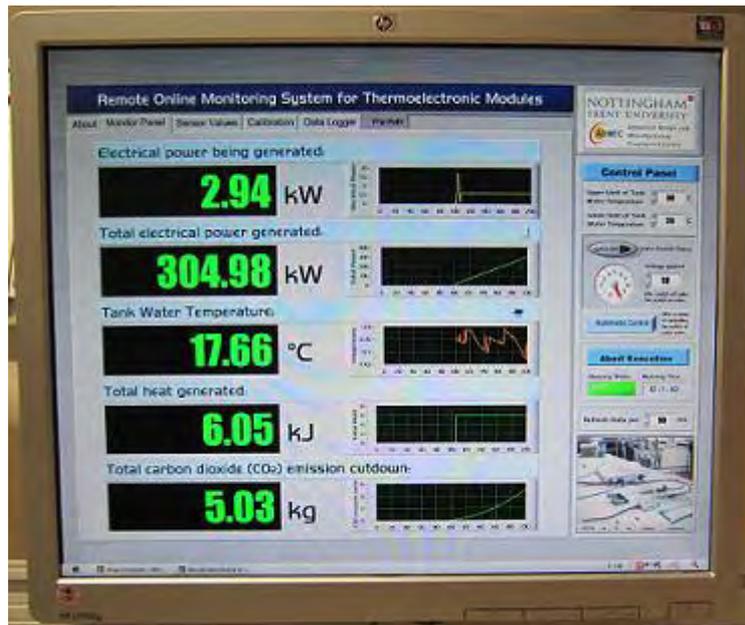
Figure 6.3 Real-time display of working conditions data in the primary
monitoring panel

Figure 6.4 Real-time display of working conditions data in the secondary
monitoring panels

Figure 6.3 presents the interactive interface of the primary panel, which displays the
parts of working conditions data of TEGs as well as the diagrams reflecting the
relation between the working conditions and the time. Figure 6.4 shows the interface
of the secondary panel, which displays the rest of the working conditions data of TEGs.
The control panel, on the right of the primary/secondary panel, is used to configure the

control parameters of the system/devices, and displays the system information, such as the operation status of the system, real-time video, etc.

6.3.3 System Control

The control unit for regulating the switch of the water valve is designed to inject domestic water into the tank to decrease the water temperature of the tank. The control unit, shown in Figure 6.5, includes a data acquisition (DAQ) card for outputting analogue voltage signal, a DC current amplifier, and an electric switch associated with the water valve.
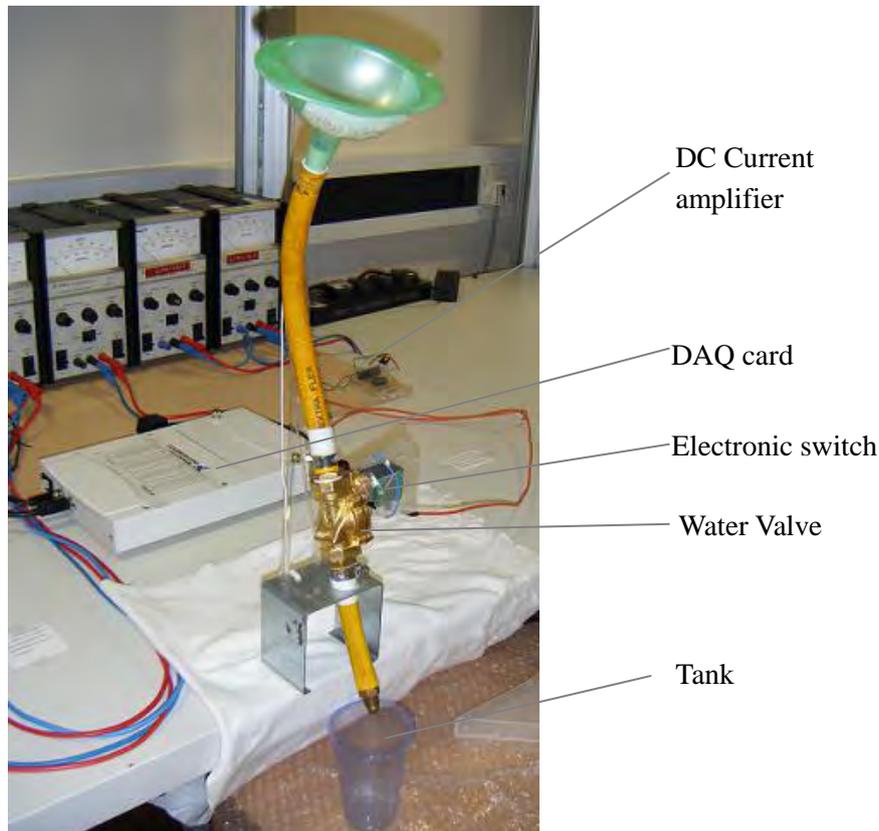
Figure 6.5.Control unit for regulating the water temperature of the tank

The DAQ card utilises the analogue output interface to convert the computer commands into analogue voltage signal, which is amplified by the DC amplifier and then transmitted to the electronic switch of the water valve. If the electric switch

receives a high voltage such as 10V the valve will be switched on; if the electric switch is given a low voltage such as 0V the valve will be turned off.

The DAQ card is able to programmatically output the analogue voltage signal in the range of 0-10V to regulate the electronic switch of the water vale, according to the measurement data of water temperature of the tank. When the water temperature of the tank is measured over the upper limit set, the DAQ card outputs the high voltage signal to the electric switch; subsequently, the valve is switched on and allows domestic water to be injected into the tank. When the water temperature of the tank decreases below the lower limit set, the DAQ card outputs the low voltage signal to the electric switch; the valve will then be switched off to stop the domestic water flowing into the tank.

The above control process can also be performed using the mobile phone. Since mobile communication has been applied as an important feature in this research, technicians/engineers are given the ability to remotely control the analogue output of the DAQ card and the switch of the water valve using the mobile phone via the cellular phone network. With regard to the details of control method using the mobile phone, please see '*Remote Communication*' section.

In order to secure the devices/system in the control process, a self-protection mechanism is built up within this module. Self-protection is implemented by monitoring the water temperature of the tank and the voltage applied on the electronic switch. In case that the water temperature of the tank is measured extremely high and cannot be adjusted and restored to the normal conditions, the mechanism of self-protection will be launched automatically. With the effect of this mechanism, the thermoelectric units and water supply unit will stop working. In the meantime, a warning message will appear on the monitor panel to alert the engineer/technician the current working conditions of the system.

6.3.4 Remote Communication

The remote communication module utilises the Wireless-based server-client
networking structure to realise the communication between the server and the client.
During the communication, Web Service is deployed in the server and is responsible to
receive the request from the client. While the user send a request with the control
commands to the server via Internet/cellular phone network, Web Service is able to
make a quick response by passing the request to the system modules such as data
processing/acquisition module for further processing; according to the request received,
the system modules conduct the classification and calculation, and then output the
commands to the control units to perform the required operation or control task.
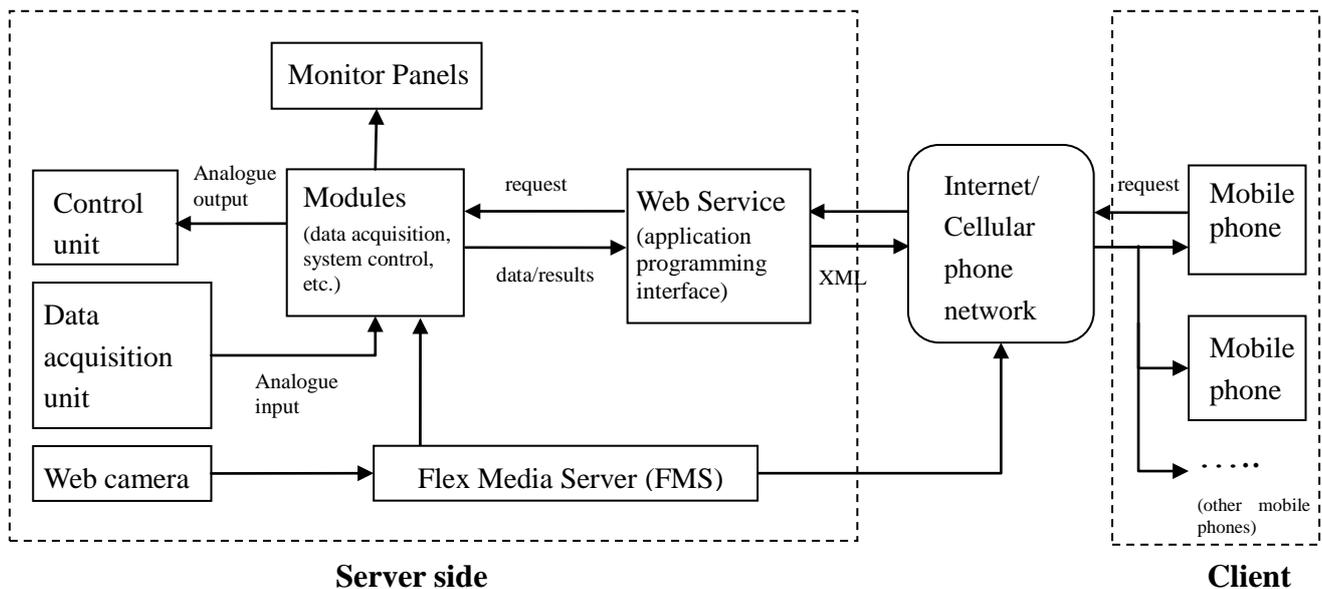
Figure 6.6 The structure of remote communication between server side and client side
using Internet, cellular phone network, and mobile phone

In the meantime, the working condition data of the Thermo-Electric-Generations are
acquired via the data acquisition unit and are passed to the monitor panels for real-time
display. As the response to the client-end user, the working condition data are to be
sent to the client in form of XML via Internet/cellular phone network. XML
(Extensible Mark-up Language) is an efficient and reliable data-carrier, which is used

in Web Service and conveyed over Internet. XML allows the data to be converted into
the standard web form and transferred to the client. Figure 6.6 shows the network
structure of remote communication between the server and the client using Internet and
cellular phone network.

The server-client network formed by the server computer and the client-end mobile
phone has been established, which is detailed in the following sub-sections:

6.3.4.1 Development of the Server

The server is located beside the TEGs and is connected with Internet. The server
includes a server computer, a monitor panel, a web camera, and an interface for
network communication. The web camera is used to capture the video/image of
operation of the TEGs.

The server computer provides the functions of real-time data acquisition/processing,
system control, and remote communication with the client-end mobile phone. The
above functions are implemented utilising the application software, which is coded
with the use of Labview Developer Suite.

The developed application software is composed of several programme blocks; each
programme block performs an independent function such as data acquisition. These
programme blocks use the uniform computer/networking resources, such as network
transmission protocols and application programming interfaces, to transfer the
data/information each other.

Among the programme blocks, the network-based shared variables (GSV), are applied
to transfer different types of data, such as two-dimensional waveforms, graphs, and
tables. As an important feature/function used in Labview, GSV can effectively

transmit the data/information to the application programming interface (API) of the server for the communication with the client.

The application programming interfaces, known as Java API, Google API, and Web Service, are used to create a remote connection between the server and the client. Web Service is applied in this research to realise such a connection to ensure the secure transmission and to acquire the compatibility of different computer languages/platforms.

The real-time video/image, to monitor the operation of the Thermo-Electric-Generations, is also to be sent to the client mobile phone together with the working condition data. The video is acquired via the web camera and then processed by Flex Media Server (FMS), which provides the powerful media-processing capability to convert the captured video into Flash stream and transfer the stream to the client.

6.3.4.2 Development of the Client

The client consists of the mobile phones. It allows many users to simultaneously access the server to acquire the information, such as data, table, image and video, using the mobile phones via cellular phone network such as GPRS. It also allows an authorised user such as the technician to log into the server as an administrator to control the operation of the Thermo-Electric-Generations located in the server by delivering the control commands. Such the control method is useful for the technician to remotely assess/examine the capability and reliability of the system control.

The application software in the client consists of the user interfaces and script, which are developed utilising Adobe Flex Builder and Open-plug programming environments. The user interfaces are applied to display the data of the working conditions of Thermo-Electric-Generations, such as the electrical power, heat energy, output

voltage/current, temperature, and flow rate. The user interface allows the user to configure the information required for accessing the server and to set up the control parameters related to the control of the devices/system.

The script, which is closely connected to the user interfaces, is responsible to pass the data/results received from the server to the user interface for the display, and, meanwhile, to transmit the user requests, such as the system parameters and control commands, to the server.

The communication with the server is implemented using Web Service, which utilises the same application programming interface as the server. On one hand, the client sends the request with user commands to the server via Web Service; on the other hand, the client resolves the responses, which is retrieved from the server in XML form, and then displays the data/results on the user interface.

6.4 Remote Condition Monitoring and Control using Nokia, HTC, and iPhone Mobile Phones via GPRS Cellular Phone Network

The developed remote condition monitoring system has been applied to monitor and control the working conditions of Thermo-Electric-Generations (TEGs) used in an experimental environment, as shown in Figure 6.7. The mobile phones, such as Nokia, HTC, and iPhone mobile phones, are applied in the client end to wirelessly access the working conditions data of TEGs.

The data acquisition hardware contains five K-type thermocouples associated with a signal conditioner, a voltage sensor, a current sensor, a flow rate sensor and a DAQ card. The sensors and thermocouples are set up to monitor the working conditions data, such as output voltage, output current, temperature and flow-rate of water.
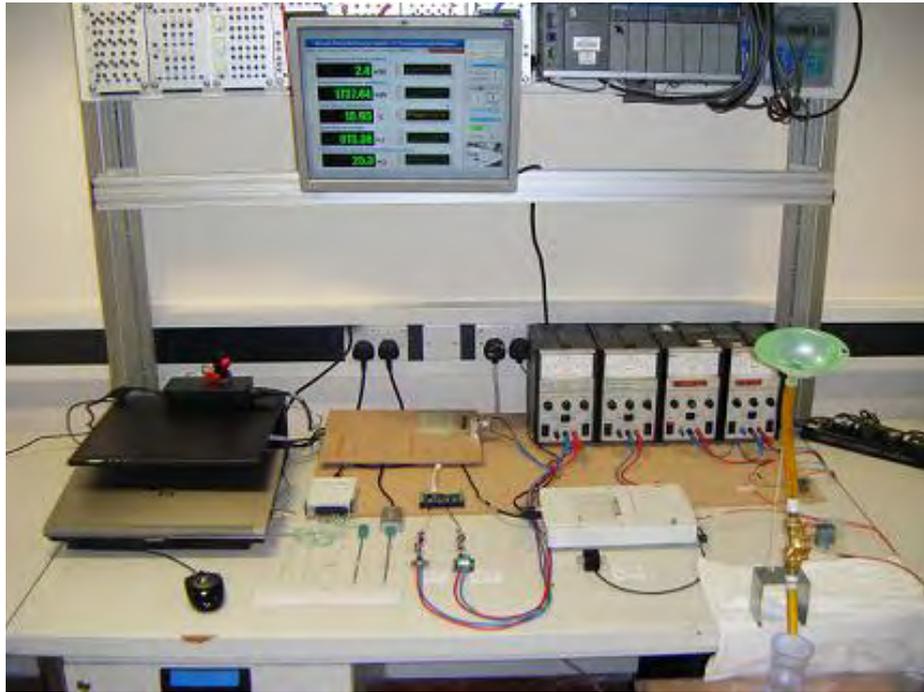
Figure 6.7 Remote Condition Monitoring System of Thermo-Electric-Generations in
an Experimental Environment

The DAQ card has the dual functions of data acquisition and control. On one side, the
DAQ card acquires the data of working conditions from the Thermo-Electric-
Generations via the thermocouples and sensors, and then transfer the digital (signal)
data to the computer for further processing. On the other hand, the DAQ card converts
the control commands received from the computer into the analogue output signal
which is subsequently transferred to the controlled device, such as the electric switch,
to conduct the control output required.

6.4.1 Remote Condition Monitoring and Control using Nokia Mobile Phone

When the system was in operation, the working conditions data of TEGs were
displayed on the monitor panel located in the server in real time. Using Nokia N900
mobile phone, the user wirelessly accessed the server computer to retrieve the working
condition data, which were then displayed on the user interface of the mobile phone

via GPRS cellular network and Internet. Figure 6.8 presents the real-time acquisition

of working condition data of TEGs using Nokia mobile phone. It is observed from the

Figure 6.8(a) that the water temperature of the tank was $17.71°c$, which was lower than

the upper limit set. By sending the requests to the server via the mobile phone, the user

can access the working condition data from different monitoring panels of the server.

Figure 6.8 (a) and (b) shows the user interfaces of the Nokia mobile phone, which

receives the working conditions data from the server's the primary panel and

secondary panel, respectively.

When the water temperature of the tank was measured higher than the limit set, the

commands for switching on the valve were automatically sent to the DAQ card, which

transferred the analogue signal with high voltage to the electric switch of the valve.

Subsequently, the valve was switched on and domestic water was injected into the tank

to reduce the water temperature of tank; meanwhile, the heat water in the tank was

drained off the tank via the outlet. When the water temperature of the tank dropped

down below 20°C, the valve was turned off with the effect of the shutdown command

of the system automatically.

(a)

(b)

Figure 6.8 Remote acquisition of working condition data from different
monitor panels of server computer using Nokia mobile phone

Figure 6.9 Remote control of the electric switch of the valve using Nokia
mobile phone

Although the control of working conditions of TEGs can be performed by the system
automatically, the technicians/engineers, in some circumstance, need to remotely

assess/examine the capability and reliability of the control system. To meet such the requirement/application, the system allows the authorised user to log into the server as the expert, which can adjust the control parameters of the system and regulate the working conditions of TEGs.

The control parameters/commands include 'Step control', 'Switch of the valve (On/Off)', 'Upper/lower limit of the water temperature of the tank', etc. These parameters/commands allow the user to remotely control the electric switch of the valve using mobile phone. Whilst 'Step control' was set 'Enabled' and 'Switch of the valve' was on, the electric switch associated with the valve was open and then the domestic water was injected into the tank, which is shown in Figure 6.9. While 'Switch of the valve' was off, the water valve was shut down shortly to stop the domestic water's injection.

Figure 6.10 Real-time display of the video that monitors the operation of TEGs
using Nokia mobile phone

While 'Remote Video' was enabled on mobile phone, the video for monitoring the operation of Thermo-Electric-Generations was broadcasted to the Nokia mobile phone, as shown in Figure 6.10.

6.4.2 Remote Condition Monitoring using HTC and iPhone Mobile Phones

The client allows many users to utilise the mobile devices to access the server. Furthermore, mobile cross-platform communication enables the mobile devices with different cellular phone operation systems to simultaneously access the working conditions data from the server.

Figures 6.11 and 6.12 present the remote acquisition of working conditions data from the primary/secondary panel of the server using HTC mobile phone, respectively. Figure 6.13 presents the real-time monitoring of working conditions data, such as electrical power, heat energy and water temperature of the tank, using iPhone mobile phone.

Figure 6.11 Remote acquisition of working condition data from the primary
panel of the server using HTC mobile phone

Figure 6.12 Remote acquisition of working condition data from the secondary
panel of the server using HTC mobile phone

Figure 6.13 Real-time acquisition of working conditions data of TEGs
using iPhone mobile phone
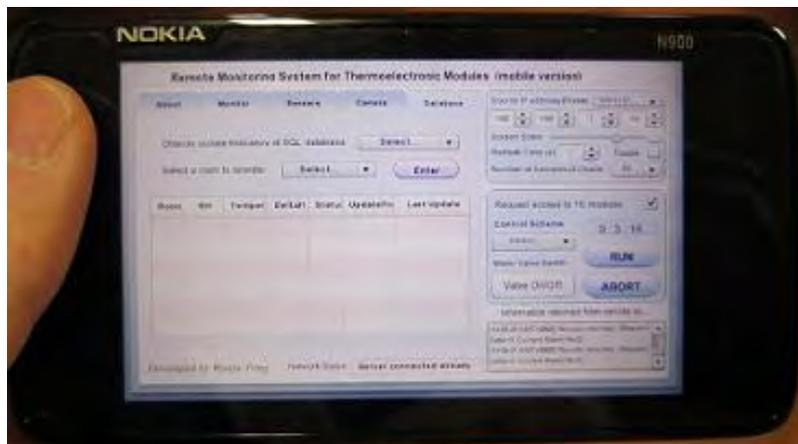
Figure 6.14 The user interface of MySQL-based database used in Nokia mobile phone

6.5   Concluding Remarks

The research reported in this chapter investigates the issues of monitoring and control
of working conditions of Thermo-Electric-Generations. The remote condition
monitoring is conducted based on sensor technology, data I/O interfaces and mobile
communication to acquire the physical quantities of working conditions of Thermo-
Electric-Generations. Using the mobile devices, such as Nokia mobile phone, the user
is able to wirelessly access the data of working conditions and control the system as an
expert via GPRS mobile phone network and Internet.

The MySQL-based database is built to log the data of working conditions into the
computer located in the server end. The database allows the user to acquire the
current/history data of working conditions by accessing the database page via the
Internet and/or mobile phone network. Figure 6.14 presents the user interface of
MySQL-based database used in Nokia mobile phone.

The remote condition monitoring system with the above technologies has been applied
to monitor and control the working conditions of TEGs used in the experimental
environment. Experimental result proves that the success of the development of the
system, which can be effectively utilised to monitor and control the actual working
conditions of the TEGs and maintain the normal operation of the system.

Chapter 7   Conclusions and Future Work

7.1   Conclusions

The PhD project entitled 'Remote online machine condition monitoring using advanced internet, wireless and mobile communication technologies' has been successfully completed and presented in this thesis. In the project, the sensory, fault diagnostic, wireless and mobile techniques have been applied; and the technologies developed have been successfully applied in three case studies in the areas including industrial gearbox, solid desiccant dehumidifier for air-conditioning, and thermo-electric-generations. The conclusions of this project can be drawn as follows.

1. The aim of this project has been successfully achieved by the successful implementation of objectives specified in section 1.2.

2. The conceptual model of online condition monitoring, which is presented in Chapter 3, forms the core platform of the system development of this project. The platform and its related technologies have been successfully proved by three applications, as detailed in Chapters 4, 5 and 6, and are summarised below.

Chapter	Applications	Successful application of the techniques of the conceptual module	Purpose of the application
4	Development of a remote real-time condition monitoring system of industrial gearbox	• The sensory and digital I/O interface techniques are applied to collect the working conditions data from the gearbox and extract the physical information about the gearbox (e.g. failure and wear) for data processing and fault diagnosis. • Real-time fault diagnostic techniques comprising of adaptive digital filtering and statistics-based feature analysis algorithms are used to extract gearbox's vibration signals from the contaminated signal source, identify the fault symptom of the gearbox in real time, and provide advice for decision making for maintenance. • Wireless communication techniques, including MXML-based mobile scripting, ActiveX controls, and Web Service, are applied to monitor and diagnose the working condition of the gearbox in real time via the Internet and wireless network, and enable the users to access the working condition data and diagnostic results from the server using PDAs and mobile phones • The Data-Socket technique for remote	To develop a system to remote online monitor and diagnose the working condition of an industrial gearbox using Internet, wireless and mobile technologies, and provide advice for decision making for maintenance.

		data-acquisition is able to transmit the working condition data of the gearbox from a dedicated data-acquisition computer to the server via the Internet and wireless network.	
5	Development of a remote control system of solid desiccant dehumidifier for air conditioning in low carbon emission buildings	• The sensory technique is applied to acquire working conditions data of solid desiccant dehumidifier, such as temperature, humidity and flow-rate, and convert the analogue data to physical quantities of the working conditions for decision making. • The linear control technique with digital I/O interfaces is used to control the operations of the system/devices, such as dehumidifier and the fan, by delivering the analogue output signals to the machine controllers. • Wireless communication techniques with MXML-based mobile scripting, ActiveX controls and Web Service, are utilised to remote control the working conditions of solid desiccant dehumidifier, and enable geographically dispersed users to access the working condition data from the server by sending the HTTP requests to the server via mobile devices, such as PDAs and mobile phones. • Database technique is applied using My-SQL database manager to record and online manage the working conditions data of solid desiccant dehumidifier.	To develop a remote system to control and monitor the working conditions of solid desiccant dehumidifier using wireless and mobile technologies
6	Development of an innovative remote online monitoring system of Thermo-Electric-Generations	• The sensory technique is applied to collect the working conditions data from Thermo-Electric-Generations (TEGs), such as flow-rate, temperature, voltage and current, via analogue input interfaces. • The process control technique is utilised to adjust the temperature of cold side of TE units and maintain the normal operation of TEGs system, by sending the commands/parameters to a control unit to regulate the switch of water valve. • Wireless communication techniques with mobile cross-platform features enable multiple mobile users to employ mobile phones with different mobile architecture and operation systems/platforms, to monitor and control the working conditions of the TEGs via the mobile phone network.	To develop a system to online monitor and control the working conditions of TEGs via the mobile phone network

3. The following major techniques greatly enhanced the technical advances of this project:

a. Labview, Adobe Flex and C-Plug (Open-Plugin) are appropriate tools for this research. With those tools, wireless and mobile techniques can be combined with data acquisition, fault diagnosis, decision making, and automated control, into a system for real-time condition monitoring. Due to Labview's multiple-threading execution and web-based distributed computing features, the system can quick extract the physical information from a machine monitored via data I/O interfaces, implement real-time fault diagnosis and decision making, and transmit the working condition data and diagnostic results in

HTTP-based response form to a web-based application programming interface of the server for remote communication. Using ActiveX controls and scripting tools of Adobe Flex and C-Plug, the client can effectively communicate with the server through wireless and mobile phone network, online retrieve and resolve the response received from the server, and display the machine condition data and analysis results on the client interface of mobile devices in real time.

b. The techniques of Web Service and TCP/IP based Data-Socket techniques are correct tools using in this project to enable the systems' wireless and mobile feature. The Web Service is used as an application programming interface of the server-end to publish the working condition data on the wireless and mobile phone network, while the client retrieves the working condition data in XML form via the wireless/mobile network by sending a HTTP request to the URL of Web Service of the server. The TCP/IP based Data-Socket is applied as a DSTP-based application programming interface to transmit the working condition data from the data-acquisition computer to the server computer through the wireless and mobile phone network.

c. Remote communication with mobile cross-platform feature enables the users to utilise multiple mobile devices with different mobile architectures and operation systems/platforms, such as mobile phones and PDAs, to access the working conditions data from the server via the wireless/mobile network. With the mobile cross-platform feature, existing applications/software can work on various mobile operating systems/platforms, known as Symbian, Maemo, Android, and iPhone iOS, without re-writing or modifying codes.

7.2   Contributions to Knowledge

Remote communication technologies make it possible to remote monitor, diagnose and

control the working conditions of machines. However, there have been few applications of integrating the Internet, wireless and mobile communication into the machine's condition monitoring so far.

The Integration of Internet and mobile/wireless communication into the condition monitoring system is a significant innovative feature of this research. Compared with the other forms of remote monitoring like remote panel/desktop using wired connection, the communication method provides a great deal more. The main characteristics that it brings with the system are detailed as follows:

- This research developed the remote condition monitoring approach, which is a novel contribution in this area. Within this approach developed, the Internet and wireless/mobile phone network are used to transfer the data/results among all the modules, from data acquisition, to data processing and decision making, then to maintenance activity. Such a communication method is particularly useful in the following situations:

  (1) When the monitored machine is located far from the monitoring centre and there is no necessary cable-connection between them, the machine's condition data cannot be transferred to the monitoring centre via the wired network.

  (2) Because the space/location required for network deployment is restricted, the machine is difficult to install the network cable (wire) to transfer data to the monitoring centre.

  One of common examples is that a gearbox is located at a remote place where the wired Internet connection is not available, e.g. the gearbox installed in the pump of a wastewater treatment plant is far from the monitoring centre and there is no wired Internet connection between them. In this circumstance, a dedicated data-acquisition computer, which is beside the gearbox, can be used to collect the working condition data from the gearbox and then transmit the data to the server computer located in the monitoring centre through the Internet and wireless

network. Thus the Internet and wireless network can serve as a communication bridge to transmit the gearbox's working conditions data to the monitoring centre.

- A remote online machine fault diagnostic scheme has been implemented using the adaptive filter with LMS algorithm and statistics-based feature analysis to fast extract the representative feature, i.e. vibration feature of the gearbox, from the contaminated vibration signals, for real-time identification of possible faults of the gearbox. Online diagnostic results are then used to schedule necessary maintenance activities. The user, such as a diagnostician, is enabled to remotely access the working conditions data and diagnostic results of the gearbox using mobile devices, such as mobile phone and PDA, and be alerted the gearbox's working conditions when a fault occurs.

- Although condition monitoring industrial gearbox is not a new topic, this research combines multiple advanced technologies including sensory, Internet and wireless techniques, which greatly advanced the gearbox condition monitoring techniques with remote online monitoring capacity, which has not been reported in the literature.

- At present, there is nothing available in the market involving solar Thermo-Electric-Generations (TEGs). Therefore, the remote online condition monitoring of TEGs is significantly innovative application. In this research, the remote online condition monitoring system has been successfully developed and applied to monitor and control the working conditions of TEGs. The users are able to utilise various mobile phones, such as Nokia, HTC and iPhone mobile phones, to access the data of working conditions, and regulate the operation status of TEGs via Internet and GPRS cellular phone network. The real-time video for monitoring the operation of the TEGs can be displayed on the user interface of mobile phones. Temperature control of the cold side of thermoelectric units used in TEGs is

performed automatically under the control of the system.

- The application of solid desiccant dehumidification with the electro-osmosis regeneration for air-conditioning unit is a novel contribution. The solid desiccant dehumidification is suitable for domestic use or small THICAC (Temperature and humidity independent control air-conditioning) units [19] and renewable energy applications, and typically for developing low/zero emission buildings. The remote control system of solid desiccant dehumidifier for air-conditioning unit has been developed. The system works to remotely monitor and control the internal conditions of air-conditioned buildings with a view to reducing carbon emissions. Mobile communication is utilised as an important feature in this research. The use of mobile devices provides the flexibility for remotely monitoring and controlling the working conditions of the solid desiccant dehumidifier.

7.3   Future Work

This research presented a remote online machine condition monitoring approach, which is applied for the monitoring, diagnosis and control of working conditions of machines. Due to the limitations of time, part of work was not undertaken as a part of the present study. On the basis of the achievements gained in this research, the further investigation could be conducted in the following ways to refine the design of the system and improve the performance of the system:

- Experimental investigation of artificially introduced defective gears in industrial gearbox

  In order to investigate the dynamic performance of defective gears at different load-conditions, the developed condition monitoring and fault diagnosis approach will be applied to detect the artificially introduced defects in gears of industrial

gearbox at different gear operations. Real-time/online fault diagnosis will be implemented using digital noise filtering, gear feature analysis and time-domain analysis. Digital noise filtering is used to extract gear features from the signals contaminated by noisy environments; gear feature parameters can be obtained using the statistics-related gear feature analysis. Steady and fluctuating load conditions will be studied in order to test the effect of load.

- Modified least-mean-square (LMS) algorithm

The least mean square (LMS) algorithm used in this research is one of the most popular algorithms for digital noise filtering due to its accuracy of reliability. The LMS algorithm utilises the gradient-search method to allow mean-square error to converge at minima. However, when solving the multiple-peak problems, gradient-search process cannot be achieved, so that the mean-square error cannot be converged using the gradient-search.

Evolutionary digital filtering (EDF) can be applied as modified least-mean-square (LMS) algorithm to overcome the shortcomings of the gradient-search in the multiple-peak problems. EDF is developed based on the evolutionary strategies with cloning and mating methods. Within this algorithm, Peak Ratio (PR) is used to evaluate the behaviour of EDF, while the Converge Speed (CS) and Peak Ratio (PR) are utilised to select the length of the optimal data.

- Data collection method using multi-sensor data fusion

For a complex system, a single sensor is incapable of collecting enough data for accurate condition monitoring and fault diagnosis of machines. Multiple sensors are needed in order to improve the accuracy of acquired data/information. When multiple sensors are used, data collected from different sensors may contain different partial information about the same machine condition. Now the problem

is how to combine all partial information obtained from different sensors for more accurate machine diagnosis and prognosis. The solution to this problem is known as multi-sensor data fusion.

Multi-sensor data fusion is capable of building an improved model for system estimation by using a set of independent data sources. It can make full use of data information to increase the ratio of signal-to-noise of signal, and to enhance the quality of data/information to improve the accuracy of diagnosis and prognosis. Data fusion can effectively increase the consistency of the extracted information by the use of multi-sensor to simultaneously monitor the working conditions of machines.

- Signal processing based on Novelty Detection

Novelty Detection (ND) is a self-learning approach to characterise the "normal" state of the gearbox. The application of Novelty Detection can greatly improve the accuracy of fault diagnosis of machines. Novelty Detection is a classification technique that recognises a presented data to be novel (i.e. new) or non-novel (i.e. normal). The training data for the novelty detection algorithm consists of the normal class which is often much easier to obtain. Since the degree of overlap is normally expected between different classes, classification problems have a probabilistic nature. Novelty detection involves estimating the probability-density–function (PDF) of a normal class from the training data and then estimating the probability that a new set of data belongs to the same class. In comparison to fuzzy logic, neural networks and genetic algorithms, the advantage of using this technique is that it could detect abnormalities in systems for new faults that have not been seen before.

Within this algorithm, the variation of voltage and load conditions may lead to the change of the rotational speed of gearbox, and hence, the period-based-time

domain averaging method used in this algorithm is not suitable to process the fluctuation signal of speed due to its phase error accumulation effectiveness that is arisen from round-off errors and frequency estimation errors. To solve this problem, the modified method of Period-based Time Domain Averaging could be utilised. This method can suppress the phase error accumulation effectiveness when processing the fluctuation signal of speed of gearbox.

- Improvement of the networking structure

In the developed remote monitoring system, data processing, Web server and Flash Media server have been integrated into a single server computer, but such the arrangement will affect performance of the system. Because the server requires a great number of computational resources for data processing, such as data collection, decision making and system control, the Web services and media communication are affected in some circumstance due to the lack of computational resources, e.g. the video display in the client will be delayed. Therefore, the Web server and Flash Media server could be arranged to deploy on a dedicated computer to allow maximum throughput. Figure 7.1 presents the improved structure of the server side.
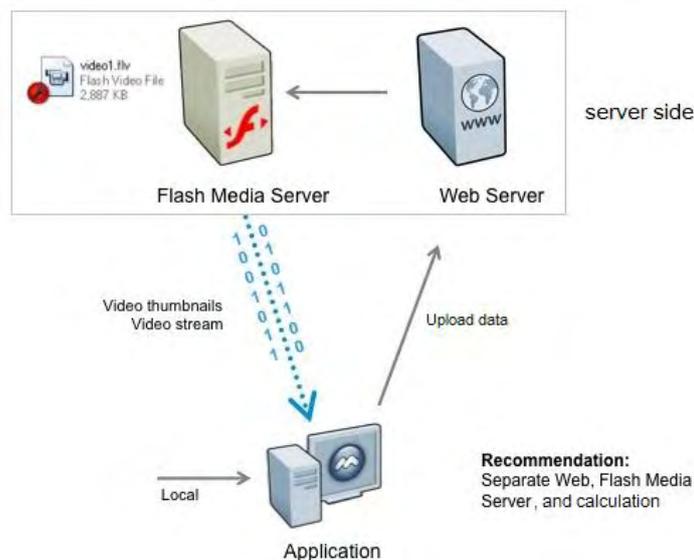

Figure 7.1 The improved server structure

References

[1]. http://en.wikipedia.org/wiki/Machine (accessed July 2011)

[2]. Chinmaya Kar and A.R. Mohanty, Multistage gearbox condition monitoring using motor current signature analysis and Kolmogorov–Smirnov test, Journal of Sound and Vibration, Volume 290, Issues 1-2, February 2006, p.p. 337-368

[3] Wilson Wang, An integrated classifier for gearbox system monitoring', Mechanical Systems and Signal Processing, Volume 23, Issue 4, May 2009, p.p. 1298-1312

[4] Li, L. & Lee, H. (2005). Gear fatigue crack prognosis using embedded model gear dynamic model and fracture mechanics, Mechanical Systems and Signal Processing, Vol. 20, p.p. 836-846.

[5] Gusumano, J.; Chelidze, D. & Chatterjee, A. (2002). Dynamical systems approach to damage evolution tracking, part 2: Model-based validation and physical interpretation, Journal of Vibration and Acoustics, Vol. 124, p.p. 258-264.

[6] Isermann, R. (1998). On fuzzy logic applications for automatic control, supervision, and fault diagnosis, IEEE Transactions on Systems, Man, Cybernetics, Part A, Vol. 28, p.p. 221-235.

[7] Yimin Shao, Kikuo Nezu, 'Design of Mixture de-nosing for detecting faulty bearing signals', Journal of Sound and Vibration 282 (2005) p.p. 899-917

[8] Rish, I; Brodie, M.; Ma, S.; Odintsova, N.; Beygelzimer, A.; Grabarnik, G. & Hernandez, K. (2005). Adaptive diagnosis in distributed systems, IEEE Transactions on Neural Networks, Vol. 16, p.p. 1088-1109

[9] Mansoori, E.; Zolghadri, M. & Katebi, S, A weighting function for improving fuzzy classification systems performance, Fuzzy Sets and Systems, Vol. 158, (2007). p.p. 583-591.

[10] Ishibuchi, H. & Yamamoto, Y. (2005). Rule weight specification in fuzzy rule-based classification systems, IEEE Transactions on Fuzzy Systems, Vol. 13, p.p. 428-435.

[11] Wang, W. 'A remote intelligent system for machinery condition monitoring',

IEEE Transactions on Fuzzy Systems, Vol. 16, (2008). No. 1, p.p. 110-122

[12] Uluyol, O.; Kim, K. & Nwadiognu, E. Synergistic use of soft computing technologies for fault detection in gas turbine engines, IEEE Transactions on Systems, Man, Cybernetics, Part C, (2006), Vol. 36, p.p. 476-484.

[13] K Nezu, Y Shao: 'Extracting symptoms of bearing faults from noise using a non-linear neural filter', Proceedings of Mechanical Engineering, Vol. 216 Part I: J Systems and Control Engineering, 2002

[14] XI Yu-jie, MA Bo, FENG Kun 'Adaptive Filtering Algorithm in Fault Diagnosis of Rolling Bearings', Bearing, May, 2011

[15] Huaqing Wang , Peng Cheng, 'Fault diagnosis for a rolling bearing used in a reciprocating machine by adaptive filtering technique and fuzzy neural network', Journal of WSEAS transactions on systems archive, Volume 7 Issue 1, January 2008

[16] Xue, Q., Hu, Y.H., Tompkins, W.J.; 'Neural-network-based adaptive matched filtering for QRS detection', Biomedical Engineering, IEEE Engineering in Medicine and Biology Society, Volume: 39 Issue:4, 2002, p.p. 317-329

[17] http://www.eminnovation.org.uk/construction/Page.aspx?SP=4392 (accessed July 2011)

[18] Christine A. Ennis , 'CFCs (Chlorofluorocarbons)', World Meteorological Organization. (2003), Scientific Assessment of Ozone Depletion, 2002.

[19] Pan Zhixin, Zhang Zhihong, Li Dan, Jia Yugui, Pan Binyao, 'Study of Temperature and Humidity Independent Control Air-Conditioning System', Bioinformatics and Biomedical Engineering, (iCBBE) 2011 5th International Conference, May 2011, p.p. 1-4

[20] http://www.c-f-c.com/supportdocs/cfcs.htm (accessed July 2011)

[21] California Energy Commission, 'A guide to photovoltaic (pv) system design and installation', Energy Technology Development Division, 1516 Ninth Street, Sacramento, California 95814

[22] Thermoelectric /Peltier cooling: (accessed July 2011)

http://www.inbthermoelectric.com/peltier-cooling-and-seebeck-effect.html

[23] History of Thermo electrics: http://www.customthermoelectric.com/History.html (accessed July 2011)

[24] Stimulation Innovation Success programme: http://www.ntu.ac.uk/business_professions/research_consultancy/stimulating_innovation_success/index.html   (accessed July 2011)

[25] A.K. Garga, B.T. Elverson, D.C. Lang, AR modeling with dimension reduction for machinery fault classification, in: Critical Link: Diagnosis to Prognosis, Haymarket, 1997, pp. 299–308.

[26] Y. Zhan, V. Makis, A.K.S. Jardine, Adaptive model for vibration monitoring of rotating machinery subject to random

deterioration, Journal of Quality in Maintenance Engineering 9 (2003) p.p. 351–375.

[27] W.J. Wang, J. Chen, X.K. Wu, Z.T. Wu, The application of some non-linear methods in rotating machinery fault diagnosis, Mechanical Systems and Signal Processing 15 (2001) p.p. 697–705.

[28] W.J. Wang, R.M. Lin, The application of pseudo-phase portrait in machine condition monitoring, Journal of Sound and Vibration 259 (2003) p.p. 1–16.

[29] T. Koizumi, N. Tsujiuchi, Y. Matsumura, Diagnosis with the correlation integral in time domain, Mechanical Systems and Signal Processing 14 (2000) p.p. 1003–1010.

[30] W.J. Wang, Z.T. Wu, J. Chen, Fault identification in rotating machinery using the correlation dimension and bispectra, Nonlinear Dynamics 25 (2001) p.p. 383–393.

[31] Q. Zhuge, Y. Lu, Signature analysis for reciprocating machinery with adaptive signal-processing, Proceedings of the Institution of Mechanical Engineers Part C—Journal of Mechanical Engineering Science 205 (1991) p.p. 305–310.

[32] N. Baydar, Q. Chen, A. Ball, U. Kruger, Detection of incipient tooth defect in helical gears using multivariate statistics, Mechanical Systems and Signal Processing 15 (2001) p.p. 303–321.

[33] R.R. Schoen, T.G. Habetler, Effects of time-varying loads on rotor fault detection in induction machines, IEEE Transactions on Industry Applications 31 (1995) p.p. 900–906.

[34] R.G.T. De Almeida, S.A. Da Silva Vicente, L.R. Padovese, New technique for evaluation of global vibration levels in rolling bearings, Shock and Vibration 9 (2002) p.p. 225–234.

[35] Z. Liu, X. Yin, Z. Zhang, D. Chen, W. Chen, Online rotor mixed fault diagnosis way based on spectrum analysis of instantaneous power in squirrel cage induction motors, IEEE Transactions on Energy Conversion 19 (2004) p.p. 485–490.

[36] D. Ho, R.B. Randall, Optimisation of bearing diagnostic techniques using simulated and actual bearing fault signals, Mechanical Systems and Signal Processing 14 (2000) p.p. 763–788.

[37] R.B. Randall, J. Antoni, S. Chobsaard, The relationship between spectral correlation and envelope analysis in the diagnostics of bearing faults and other cyclostationary machine signals, Mechanical Systems and Signal Processing 15 (2001) p.p. 945–962.

[38] J.R. Stack, R.G. Harley, T.G. Habetler, An amplitude modulation detector for fault diagnosis in rolling element bearings, IEEE Transactions on Industrial Electronics 51 (2004) p.p. 1097–1102.

[39] G.W. Blankenship, R. Singh, Analytical solution for modulation sidebands associated with a class of mechanical oscillators, Journal of Sound and Vibration 179 (1995) p.p. 13–36.

[40] M.A. Minnicino, H.J. Sommer, Detecting and quantifying friction nonlinearity using the Hilbert transform, in: Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological System III, vol. 5394, Bellingham, 2004, pp. p.p. 419–427.

[41] S. Goldman, Vibration Spectrum Analysis: A Practical Approach, Industrial Press, Vol2, New York, 1999.

[42] C.M. Harris, A.G. Piersol, Harris' Shock and Vibration Handbook, McGraw-Hill, Vol4, New York, 2002.

[43] N.T. van der Merwe, A.J. Hoffman, A modified cepstrum analysis applied to vibrational signals, in: Proceedings of 14th International Conference on Digital Signal

Processing (DSP2002), vol. 2, Santorini, Greece, 2002, pp. 873–876.

[44] C.-C. Wang, G.-P.J. Too, Rotating machine fault detection based on HOS and artificial neural networks, Journal of Intelligent Manufacturing 13 (2002) p.p. 283–293.

[45] L. Xiong, T. Shi, S. Yang, R.B.K.N. Rao, A novel application of wavelet-based bispectrum analysis to diagnose faults in gears, International Journal of COMADEM 5 (2002) 31–38.

[46] D.-M. Yang, A.F. Stronach, P. Macconnell, J. Penman, 'Third-order spectral techniques for the diagnosis of motor bearing condition using artificial neural networks', Mechanical Systems and Signal Processing 16 (2002) p.p. 391–411.

[47] B.E. Parker, H.A. Ware, D.P. Wipf, W.R. Tompkins, B.R. Clark, E.C. Larson, H.V. Poor, Fault diagnostics using statistical change detection in the bispectral domain, Mechanical Systems and Signal Processing 14 (2000) p.p. 561–570.

[48] T.W.S. Chow, G. Fei, Three phase induction machines asymmetrical faults identification using bispectrum, IEEE Transactions on Energy Conversion 10 (1995) p.p. 688–693.

[49] N. Arthur, J. Penman, Inverter fed induction machine condition monitoring using the bispectrum, in: Proceedings of the IEEE Signal Processing Workshop on Higher-Order Statistics, Banff, Alta., Canada, 1997, pp. 67–71.

[50] W. Li, G. Zhang, T. Shi, S. Yang, Gear crack early diagnosis using bispectrum diagonal slice, Chinese Journal of Mechanical Engineering 16 (2003) p.p. 193–196 (English Edition).

[51] A.C. McCormick, A.K. Nandi, Bispectral and trispectral features for machine condition diagnosis, IEE Proceedings—Vision, Image and Signal Processing 146 (1999) p.p. 229–234.

[52] L. Qu, X. Liu, G. Peyronne, Y. Chen, The holospectrum: A new method for rotor surveillance and diagnosis, Mechanical Systems and Signal Processing 3 (1989) p.p. 255–267.

[53] C.B. Yu, H.B. He, Y. Xu, F.L. Chen, Identification method of acoustic information

flow of bearing state, in: Condition Monitoring '97, 1997, pp. 311–315.

[54] Y.D. Chen, R. Du, Diagnosing spindle defects using 4-D holospectrum, Journal of Vibration and Control 4 (1998) p.p. 717–732.

[55] L. Qu, D. Shi, Holospectrum during the past decade: Review & prospect, Zhendong Ceshi Yu Zhenduan/Journal of Vibration, Measurement & Diagnosis 18 (1998) p.p. 235–242 (in Chinese).

[56] M.H. Hayes, Statistical Digital Signal Processing and Modeling, Wiley, New York, 1996.

[57] C.K. Mechefske, J. Mathew, Fault detection and diagnosis in low speed rolling element bearing. Part I: The use of parametric spectra, Mechanical Systems and Signal Processing 6 (1992) 297–307.

[58] J.P. Dron, L. Rasolofondraibe, C. Couet, A. Pavan, Fault detection and monitoring of a ball bearing benchtest and a production machine via autoregressive spectrum analysis, Journal of Sound and Vibration 218 (1998) p.p. 501–525.

[59] J.R. Stack, T.G. Habetler, R.G. Harley, Bearing fault detection via autoregressive stator current modeling, IEEE Transactions on Industry Applications 40 (2004) 740–747.

[60] M.J.E. Salami, A. Gani, T. Pervez, Machine condition monitoring and fault diagnosis using spectral analysis techniques, in: Proceedings of the First International Conference on Mechatronics (ICOM '01), vol. 2, Kuala Lumpur, Malaysia, 2001, pp. p.p. 690–700.

[61] W.J. Wang, P.D. McFadden, Early detection of gear failure by vibration analysis I. Calculation of the time–frequency distribution, Mechanical Systems and Signal Processing 7 (1993) p.p. 193–203.

[62] F.A. Andrade, I. Esat, M.N.M. Badi, Gearbox fault detection using statistical methods, time–frequency methods (STFT and Wigner–Ville distribution) and harmonic wavelet—A comparative study, in: Proceedings of the COMADEM '99, Chipping Norton, 1999, pp. 77–85.

[63] Q. Meng, L. Qu, Rotating machinery fault diagnosis using Wigner distribution,

Mechanical Systems and Signal Processing 5 (1991) p.p. 155–166.

[64] M.-C. Pan, H. Van Brussel, P. Sas, B. Verbeure, Fault diagnosis of joint backlash, Journal of Vibration and Acoustics, Transactions of the ASME 120 (1998) p.p. 13–24.

[65] I.S. Koo, W.W. Kim, The development of reactor coolant pump vibration monitoring and a diagnostic system in the nuclear power plant, ISA Transactions 39 (2000) p.p. 309–316.

[66] N. Baydar, A. Ball, A comparative study of acoustic and vibration signals in detection of gear failures using Wigner–Ville distribution, Mechanical Systems and Signal Processing 15 (2001) p.p. 1091–1107.

[67] L. Cohen, Time–frequency distribution-A review, Proceedings of the IEEE 77 (1989) p.p. 941–981.

[68] P. Bonato, R. Ceravolo, A. De Stefano, M. Knaflitz, Bilinear time–frequency transformations in the analysis of damaged structures, Mechanical Systems and Signal Processing 11 (1997) p.p. 509–527.

[69] S. Gu, J. Ni, J. Yuan, Non-stationary signal analysis and transient machining process condition monitoring, International Journal of Machine Tools and Manufacture 42 (2002) p.p. 41–51.

[70] P. Loughlin, F. Cakrak, L. Cohen, Conditional moments analysis of transients with application to helicopter fault data, Mechanical Systems and Signal Processing 14 (2000) p.p. 511–522.

[71] R.K. Young, Wavelets Theory and Its Applications, Kluwer Academic Publishers, Boston, 1993.

[72] W.J. Staszewski, G.R. Tomlinson, Application of the wavelet transform to fault detection in a spur gear, Mechanical Systems and Signal Processing 8 (1994) p.p. 289–307.

[73] W.J. Wang, P.D. McFadden, Application of wavelets to gearbox vibration signals for fault detection, Journal of Sound and Vibration 192 (1996) p.p. 927–939.

[74] R. Rubini, U. Meneghetti, Application of the envelope and wavelet transform analyses for the diagnosis of incipient faults in ball bearings, Mechanical Systems

and Signal Processing 15 (2001) p.p. 287–302.

[75] G.Y. Luo, D. Osypiw, M. Irle, On-line vibration analysis with fast continuous wavelet algorithm for condition monitoring of bearing, Journal of Vibration and Control 9 (2003) 931–947.

[76] N. Aretakis, K. Mathioudakis, Wavelet analysis for gas turbine fault diagnostics, Journal of Engineering for Gas Turbines and Power 119 (1997) p.p. 870–876.

[77] G.O. Chandroth, W.J. Staszewski, Fault detection in internal combustion engines using wavelet analysis, in: Proceedings of the COMADEM '99, Chipping Norton, 1999, pp. 7–15.

[78] G. Dalpiaz, A. Rivola, Condition monitoring and diagnostics in automatic machines: Comparison of vibration analysis techniques, Mechanical Systems and Signal Processing 11 (1997) 53–73.

[79] N. Baydar, A. Ball, Detection of gear failures via vibration and acoustic signals using wavelet transform, Mechanical Systems and Signal Processing 17 (2003) p.p. 787–804.

[80] P.S. Addison, J.N. Watson, T. Feng, Low-oscillation complex wavelets, Journal of Sound and Vibration 254 (2002) p.p. 733–762.

[81] Y.-G. Xu, Y.-L. Yan, Research on Haar spectrum in fault diagnosis of rotating machinery, Applied Mathematics and Mechanics 12, (1991) 61–66 (English Edition).

[82] H.K. Tonshoff, X. Li, C. Lapp, Application of fast Haar transform and concurrent learning to tool-breakage detection in milling, IEEE/ASME Transactions on Mechatronics 8 (2003) p.p. 414–417.

[83] A.J. Miller, K.M. Reichard, A new wavelet basis for automated fault diagnostics of gear teeth, in: Inter-Noise 99: Proceedings of the 1999 International Congress on Noise Control Engineering, vols. 1–3, Poughkeepsie, 1999, pp. 1597–1602.

[84] D. Boulahbal, F. Golnaraghi, F. Ismail, Amplitude and phase wavelet maps for the detection of cracks in geared systems, Mechanical System and Signal Processing 13 (1999) p.p. 423–436.

[85] G. Meltzer, N.P. Dien, Fault diagnosis in gears operating under non-stationary

rotational speed using polar wavelet amplitude maps, Mechanical Systems and Signal Processing 18 (2004) p.p. 985–992.

[86] C. Wang, R.X. Gao, Wavelet transform with spectral post-processing for enhanced feature extraction, IEEE Transactions on Instrumentation and Measurement 52 (2003) p.p. 1296–1301.

[87] G.G. Yen, K.-C. Lin, Wavelet packet feature extraction for vibration monitoring, IEEE Transactions on Industrial Electronics 47 (2000) p.p. 650–667.

[88] S. Zhang, J. Mathew, L. Ma, Y. Sun, Best basis-based intelligent machine fault diagnosis, Mechanical Systems and Signal Processing 19 (2005) p.p. 357–370.

[89] H.A. Toliyat, K. Abbaszadeh, M.M. Rahimian, L.E. Olson, Rail defect diagnosis using wavelet packet decomposition, IEEE Transactions on Industry Applications 39 (2003) p.p. 1454–1461.

[90] H. Yang, J. Mathew, L. Ma, Fault diagnosis of rolling element bearings using basis pursuit, Mechanical Systems and Signal Processing 19 (2005) p.p. 341–356.

[91] J. Lin, M.J. Zuo, K.R. Fyfe, Mechanical fault detection based on the wavelet de-noising technique, Journal of Vibration and Acoustics 126 (2004) p.p. 9–16.

[92] Z.K. Peng, F.L. Chu, Application of the wavelet transform in machine condition monitoring and fault diagnostics: A review with bibliography, Mechanical Systems and Signal Processing 18 (2004) p.p. 199–221.

[93] A. Siddique, G.S. Yadava, B. Singh, Applications of artificial intelligence techniques for induction machine stator fault diagnostics: Review, in: Proceedings of the IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, New York, 2003, pp. 29–34.

[94] M.J. Roemer, C. Hong, S.H. Hesler, Machine health monitoring and life management using finite element-based neural networks, Journal of Engineering for Gas Turbines and Power—Transactions of the ASME 118 (1996) p.p. 830–835.

[95] E.C. Larson, D.P. Wipf, B.E. Parker, Gear and bearing diagnostics using neural network-based amplitude and phase demodulation, in: Proceedings of the 51st Meeting of the Society for Machinery Failure Prevention Technology, Virginia Beach, VA, 1997,

pp. 511–521.

[96] B. Li, M.-Y. Chow, Y. Tipsuwan, J.C. Hung, Neural-network-based motor rolling bearing fault diagnosis, IEEE Transactions on Industrial Electronics 47 (2000) p.p. 1060–1069.

[97] Y. Fan, C.J. Li, Diagnostic rule extraction from trained feed-forward neural networks, Mechanical Systems and Signal Processing 16, (2002) p.p. 1073–1081.

[98] B.A. Paya, I.I. Esat, M.N.M. Badi, Artificial neural network based fault diagnostics of rotating machinery using wavelet transforms as a pre-processor, Mechanical Systems and Signal Processing 11 (1997) p.p. 751–765.

[99] B. Samanta, K.R. Al-Balushi, Artificial neural network based fault diagnostics of rolling element bearings using time-domain features, Mechanical Systems and Signal Processing 17 (2003) p.p. 317–328.

[100] J.K. Spoerre, 'Application of the cascade correlation algorithm (CCA) to bearing fault classification problems', Computers in Industry 32 (1997) p.p. 295–304.

[101] D.W. Dong, J.J. Hopfield, K.P. Unnikrishnan, Neural networks for engine fault diagnostics, in: Neural Networks for Signal Processing VII, New York, 1997, pp. p.p. 636–644.

[102] C.J. Li, T.-Y. Huang, Automatic structure and parameter training methods for modeling of mechanical systems by recurrent neural networks, Applied Mathematical Modelling 23 (1999) p.p. 933–944.

[103] P. Deuszkiewicz, S. Radkowski, On-line condition monitoring of a power transmission unit of a rail vehicle, Mechanical Systems and Signal Processing 17 (2003) p.p. 1321–1334.

[104] R.M. Tallam, T.G. Habetler, R.G. Harley, Self-commissioning training algorithms for neural networks with applications to electric machine fault diagnostics, IEEE Transactions on Power Electronics 17 (2002) p.p. 1089–1095.

[105] Y.H. Yoon, E.S. Yoon, K.S. Chang, Process fault diagnostics using the integrated graph model, in: On-Line Fault Detection and Supervision in the Chemical Process Industries, Oxford, 1993, pp. 89–94.

[106] C.H. Hansen, R.K. Autar, J.M. Pickles, Expert systems for machine fault diagnosis, Acoustics Australia 22 (1994) p.p. 85–90.

[107] M.F. Baig, N. Sayeed, Model-based reasoning for fault diagnosis of twin-spool turbofans, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 212 (1998) p.p. 109–116.

[108] Z.Y. Wen, J. Crossman, J. Cardillo, Y.L. Murphey, Case base reasoning in vehicle fault diagnostics, in: Proceedings of the International Joint Conference on Neural Networks 2003, vols. 1–4, New York, 2003, pp. 2679–2684.

[109] M. Bengtsson, E. Olsson, P. Funk, M. Jackson, Technical design of condition based maintenance system—A case study using sound analysis and case-based reasoning, in: Maintenance and Reliability Conference—Proceedings of the Eighth Congress, Knoxville, USA, 2004.

[110] M.L. Araiza, R. Kent, R. Espinosa, Real-time, embedded diagnostics and prognostics in advanced artillery systems, in: 2002 IEEE Autotestcon Proceedings, Systems Readiness Technology Conference, New York, 2002, pp. 818–841.

[111] D.L. Hall, R.J. Hansen, D.C. Lang, The negative information problem in mechanical diagnostics, Journal of Engineering for Gas Turbines and Power—Transactions of the ASME 119 (1997) p.p. 370–377.

[112] M. Stanek, M. Morari, K. Frohlich, Model-aided diagnosis: An inexpensive combination of model-based and case-based condition assessment, IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews 31 (2001) p.p. 137–145.

[113] R.G. Silva, R.L. Reuben, K.J. Baker, S.J. Wilcox, Tool wear monitoring of turning operations by neural network and expert system classification of a feature set generated from multiple sensors, Mechanical Systems and Signal Processing 12 (1998) p.p. 319–332.

[114] H.R. DePold, F.D. Gass, The application of expert systems and neural networks to gas turbine prognostics and diagnostics, Journal of Engineering for Gas Turbines and Power 121 (1999) p.p. 607–612.

[115] B.-S. Yang, T. Han, Y.-S. Kim, Integration of ART-Kohonen neural network and case-based reasoning for intelligent fault diagnosis, Expert Systems with Applications 26 (2004), p.p. 387–395.

[116] C.K. Mechefske, Objective machinery fault diagnosis using fuzzy logic, Mechanical Systems and Signal Processing 12 (1998), p.p. 855–862.

[117] G.C. Collins, J.R. Bourne, A.J. Brodersen, C.F. Lo, Comparison of rule-based and belief-based systems for diagnostic problems, in: Proceedings of the Second International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems (IEA/AIE—89), vol. 2, New York, USA, 1989, pp. p.p. 785–793.

[118] R. Du, K. Yeung, Fuzzy transition probability: A new method for monitoring progressive faults. Part 1: The theory, Engineering Applications of Artificial Intelligence 17 (2004) 457–467.

[119] S. Zhang, T. Asakura, X.L. Xu, B.J. Xu, Fault diagnosis system for rotary machine based on fuzzy neural networks, JSME International Journal. Series C: Mechanical Systems, Machine Elements and Manufacturing 46 (2003) p.p. 1035–1041.

[120] T.I. Liu, J.H. Singonahalli, N.R. Iyer, Detection of roller bearing defects using expert system and fuzzy logic, Mechanical Systems and Signal Processing 10 (1996) p.p. 595–614.

[121] S.H. Chang, K.S. Kang, S.S. Choi, H.G. Kim, H.K. Jeong, C.U. Yi, Development of the on-line operator aid system OASYS using a rule-based expert system and fuzzy logic for nuclear power plants, Nuclear Technology 112 (1995) p.p. 266–294.

[122] A.K. Garga, K.T. McClintic, R.L. Campbell, C.C. Yang, M.S. Lebold, T.A. Hay, C.S. Byington, Hybrid reasoning for prognostic learning in CBM systems, in: 2001 IEEE Aerospace Conference Proceedings, vols. 1–7, New York, 2001, pp. 2957–2969.

[123] D.B. Fogel, An introduction to simulated evolutionary optimization, IEEE Transactions on Neural Networks, 5 (1994) p.p. 3–14.

[124] S. Sampath, S. Ogaji, R. Singh, D. Probert, Engine-fault diagnostics: An

optimisation procedure, Applied Energy 73 (2002) p.p. 47–70.

[125] Z.Y. Chen, Y.Y. He, F.L. Chu, J.Y. Huang, Evolutionary strategy for classification problems and its application in fault diagnostics, Engineering Applications of Artificial Intelligence, 16 (2003) p.p. 31–38.

[126] Y.-C. Huang, C.-M. Huang, Evolving wavelet networks for power transformer condition monitoring, IEEE Transactions on Power Delivery 17, (2002) p.p. 412–416.

 [128] Lee WeiPo, Deploying personalized mobile services in an agent-based environment, Expert Systems with Applications,1 194-1207,32, 2007

[129] http://www.adobe.com/products/flex/features/flex_builder/ (accessed July 2011)

[130] http://www.admec.ntu.ac.uk/admecentre/software/facilities%201software.htm (access on 01/08/2011)

[131] Jaehun Joo, Sang M. Lee, Adoption of the Semantic Web for overcoming technical limitations of knowledge management systems, Expert Systems with Applications, Volume 36, Issue 3, Part 2, April 2009, Pages 7318-7327

[132] http://powermagpie.open.ac.uk/ (access on 01/07/2011)

[133] http://www.joseki.org/ (access on 01/07/2011)

[134] http://www.aifb.uni-karlsruhe.de/about.html (access on 01/07/2011)

[135] http://projects.kmi.open.ac.uk/akt/ontoweaver/ (access on 01/07/2011)

Appendixes

Appendix (A) presents the development of the remote online condition monitoring software of industrial gearbox. The approach of developing gearbox condition monitoring software is also applied to develop the condition monitoring software of solid desiccant dehumidifier and Thermo-Electric-Generations (TEGs). Appendix (B) presents the development of remote control system software for solid desiccant dehumidifier used in air-conditioning with the emphasis on the system control and database management. Appendix (C) presents the work flow of the remote condition monitoring software for Thermo-Electric-Generations, and shows several photos and pictures related to remote condition monitoring of the system.

Appendix (A): Development of the Remote Online Machine Condition Monitoring System Software

A.1 Overview of the Software

The remote online machine condition monitoring system software consists of the three modules: Server, Client, and Remote data-acquisition. Figure A.1 presents the work flow of the software including the above three modules.

The Server module is the core of the remote online condition monitoring system software. It is deployed in the server computer and responsible for manipulating and managing the operation of the system. The Server module not only provides the online signal processing and fault diagnostic functions, but also has the remote communication capability, such as data transmission via the Internet and wireless/mobile phone network. It allows multiple mobile devices via the Client modules to connect the server computer concurrently.

Considering that the processing capability of mobile devices such as PDAs or mobile phones is usually lower than the server computer, the Client module for the mobile devices is only used to access the data/information from the Server module and to display the data/information in the user interfaces of the mobile devices. That is, the complex calculations, such as data processing and fault diagnosis, are fully undertaken by the Server module.

Although the Server module has the data acquisition capability, it cannot be used to acquire the working conditions data from a remote machine, e.g. the monitored machine, such as the gearbox, is installed at a place far from the server computer. To resolve the above problem, the Remote data-acquisition module is developed and deployed in a dedicated data-acquisition computer, besides the monitored machine, to perform the data acquisition task of the machine.

Server module
(deployed in server computer)

Client module
(downloaded to the client mobile devices)

Remote Data-acquisition module
(deployed in the data-acquisition computer)

Initialisation

Launch Web server

Check network connection (listen to Web port: 8080)

Send a request

Connect the server

Initialisation

Launch Data-socket server

Check Data-socket connection (port: 8000)

Connect the data-acquisition computer

Remote data acquisition?

Y

N

Data acquisition and Processing

Data acquisition and Processing

Display data, results, and waveform

Transfer data

Decision Making (e.g. digital filter, feature analysis)

Continue?

Y

N

Close

Warning

Y

Faults?

N

Inform users the analytical results by e-mail

Display data/results, and waveform

Schedule the necessary maintenance

Write data into XML

Return a response

Read the response and resolve data

Log data into a data file

Display data, results, and waveform

Continue?

Y

N

Continue?

Y

N

Close

Close

Figure A.1 The work flow of the remote online machine condition monitoring system software

The Remote data-acquisition module is capable of acquiring the working condition data from the machine, and transmitting the data to the Server module located in the server computer via the Data-socket connectivity for further processing and analysis.

In this research, the server computer refers to the computer with the Web Server. Although the data-acquisition computer with the Data-socket Server is also a server computer, it is called the data-acquisition computer to avoid the confusion about the server computers.

The development of the software with above three modules is detailed in the following sections.

A1.1   The Development of the Server Module

The server module is developed using Labview Professional graphic programming environment. It consists of the following five programme blocks: data acquisition/processing, fault diagnosis, data logger, remote communication using Web services and Data-socket. These programme blocks utilise the uniform computational/networking resources, such as data I/O interfaces, device drivers, and Web programming interfaces, and transmit the data/information each other. Among these programme blocks, the network-based shared variables (GSV), are applied as the data carried to transfer different types of data, such as integer/floating point, graphs and tables.

- **Data Acquisition/Processing**

The data acquisition/processing block is built using Labview's DAQmx control panel, as shown in Figure A.2, to acquire the working conditions data from the sensors and

convert the received analogue data into the quantities of the working conditions. In the DAQmx control panel, the DAQ Assistant function is used to collect floating-point data (samples) from the analogue input channels allocated to sensors. Taking the acquisition of vibration data of an accelerometer as an example, the data-acquisition process is detailed in the following ways.
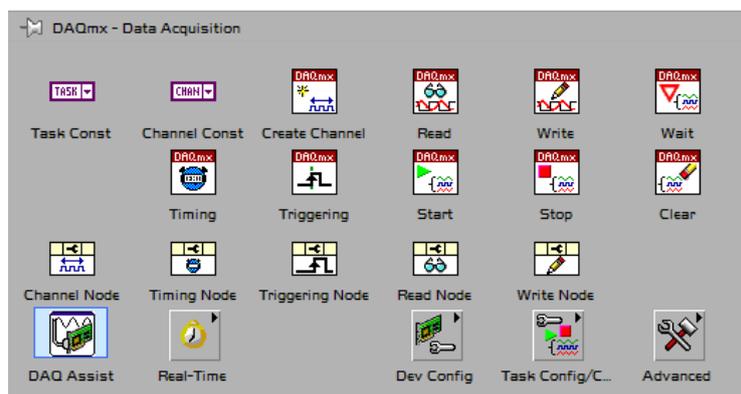

Figure A.2 DAQmx control panels

The data acquisition of the accelerometer starts with the configuration of the DAQ Assistant function's properties (parameters), which includes Task/Channels In, Rate, Number of Samples and Data. These properties/parameters are applied as the application programming interface (API) of the data-acquisition card by configuring a task that contains a single analogue input channel to acquire the data (samples) from the accelerometer.

The property 'Task/Channels In' is used to allocate an analogue input channel to the accelerometer. When the accelerometer is connected to the data acquisition card and recognised by the computer, a virtual channels' list including the accelerometer channel is generated by the DAQ Assistant function automatically. The analogue input channel is determined as 'AI_0_accelerometer' by selecting/specifying the name of the channel from the virtual channels list.

The property 'Rate' is applied to determine the sampling rate of data (samples) per

channel per second. Based on the signal sampling theory, i.e. the sampling rate of data must be more than twice the maximum frequency/rate of the analogue input signals, the property 'Rate' is identified as 2K per channel, which is five times of the maximum frequency of the accelerometer signals. The property 'Number of Samples' is set 2K.

The property 'Data' contains the data (samples) received from the accelerometer via the data acquisition card. The DAQ Assistant function scales the data to the data acquisition card using the custom scaling, which is applied to the accelerometer channel.

The received analogue data are converted utilising the A/D (analogue-to-digital) conversion into the quantities of accelerometer's vibration conditions, which are then transferred to the Spectrum Measurement function for power spectrum calculation. The A/D conversion is conducted by applying the Mathematical function to calculate the product of the analogue data and a linear conversion coefficient.
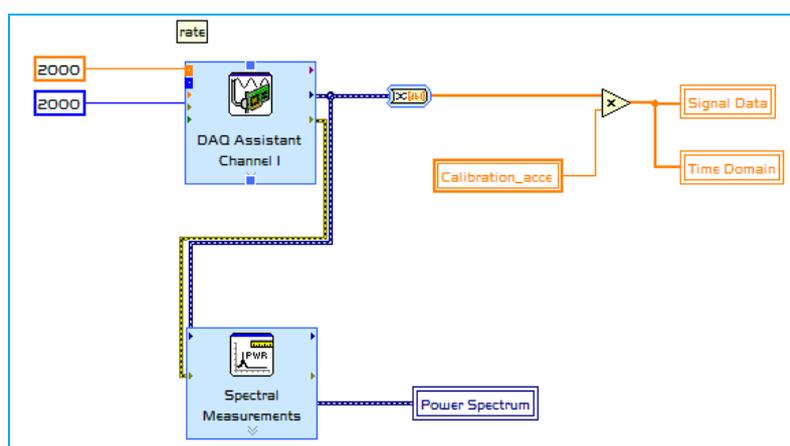
Figure A.3 Configure the analogue input channel and the sampling rate of samples for the accelerometer and generate a power spectrum

Figure A.3 presents the code of the accelerometer's data acquisition/processing. It utilises the DAQ Assistant function to configure a task that contains a single analogue

input channel and convert the acquired analogue data into the quantities of vibration conditions.

- **Fault Diagnosis**

Fault diagnosis consists of the following five steps: (1) the digital filtering; (2) statistics-based feature analysis; (3) the data/results display; (4) issuing a warning when a fault occurs; (5) informing the users, such as diagnosticians, the diagnostic results.

The first step of fault diagnosis is the digital filtering, which utilises the adaptive filter to extract the gear signal from the signal d(n), which is contaminated by the noise environment.
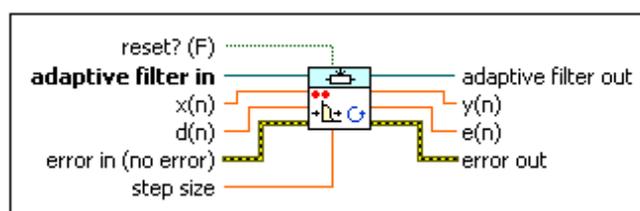
Figure A.4 Adaptive filter function

The adaptive filter is created using the Adaptive Filter function (see Figure A.4). The adaptive filter applies the least mean squares (LMS) to filter an input signal d(n) and updates the coefficients of the adaptive filter iteratively. x(n) as the reference noise signal is input to the adaptive filter to calculate the machine noise y(n). The error signal e(n) is calculated as e(n)=d(n)-y(n), which measures the difference between the input and the output of adaptive filter. On the basis of this measure, the adaptive filter adjusts the filter coefficients w(n) to reduce the error e(n). When the mean-square of the error e(n) converges at minima, the error e(n) becomes close to the gear signal S. Thus, the noise is eliminated from the signal d(n) and the gear signal S is obtained.
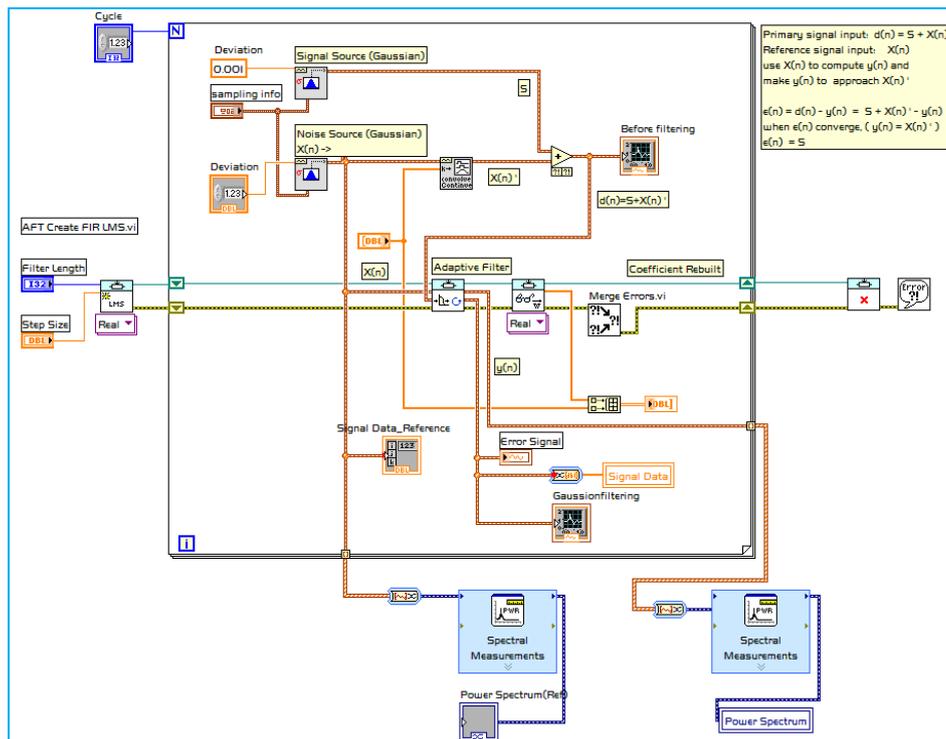
Figure A.5 the code of digital filtering using Adaptive Filter function with LMS algorithm

Figure A.5 presents the code of the digital filtering utilising the Adaptive Filter function with LMS algorithm to remove noise signals from the input signal d(n) and output the filtered signal via the global shared variable (GSV) for further feature analysis.

The second step of fault diagnosis is the statistics-based gear feature analysis, which uses the feature parameters to calculate the impulse energy/feature of gear. The feature parameters contain crest factor, impulse factor, kurtosis factor, clearance factor and root-mean-square (RMS) (There are many parameters with regard to the gear feature, but the above five parameters used can more accurately describe the gear feature than others, such as shape factors and peak value. When a fault occurs, the five parameters rapidly change with the load conditions. Therefore, they are applied to identify the gear symptom such as failure and wear).
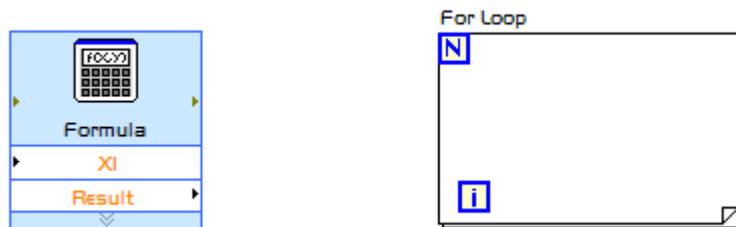
Figure A.6 the Formula Express function and the For-loop function

The calculation of the feature parameters is performed using the Formula Express and For-loop functions (see Figure A.6). The Formula Express function processes input variables and performs mathematical operations on the input variables; the For-loop function controls the repetitive operations of the formulas and/or functions by executing a sub-diagram a set number of times. Taking root-mean-square as an example, the calculation of the feature parameter is detailed in the following steps:

(1) The equation of root-mean-square, i.e. $x_{rms} = \sqrt{\dfrac{1}{N}\sum\limits_{i=0}^{N-1} x_i^2}$, is input to the Formula Express function according to the syntax/rule of Labview mathematical functions.

(2) With the For-loop function, the equation in the step (1) is calculated iteratively to obtain the root-mean-square of signals. Figure A.7 presents the code for calculating root-mean-square of time-serial signals.

(3) The acquired root-mean-square is passed via the global shared variables (GSV) to the numeric indicator in the software interface for real-time display.

(4) The time-waveform of root-mean-square is then displayed in the software interface by transferring the quantity of root-mean-square to a Waveform Graph function.

The above procedure is also used to calculate the rest of feature parameters, i.e. kurtosis factor, crest factor, impulse factor and clearance factor, and to display these parameters in the software interface via the controls/indicators. Figure A.8 presents the code of displaying the working conditions data, feature parameters, and associated time-waveforms. In the code, the procedure for calculating and displaying the feature

parameters is encoded into a sub-programme; by calling this sub-programme, the feature parameters are obtained and subsequently passed to the software interface for real-time display.
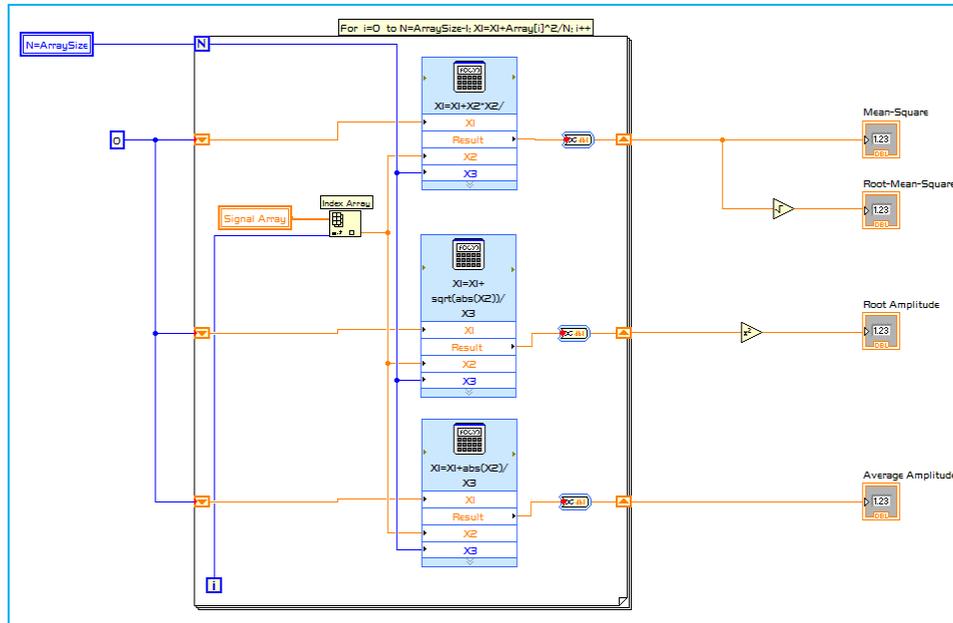

Figure A.7 the source code of calculating Root-Mean-Square of signals
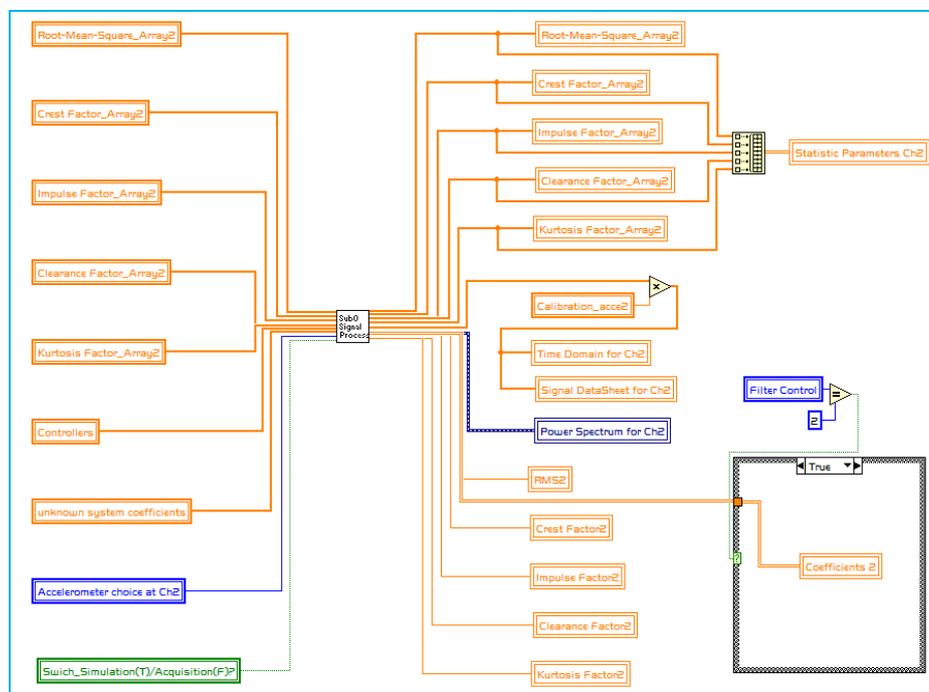

Figure A.8 the source code of displaying the working conditions data, gear feature parameters, and time-waveforms

When any of the feature parameters exceeds the upper limit set, the system declares that a fault such as failure or wear is discovered; a warning message then appears in the message window of the software interface immediately. The code, shown in Figure A.9, employs the feature parameters to identify the fault and issue the advanced warnings. Each feature parameter is used to compare with its pre-set upper limit to generate a Boolean value, which is used as a criterion to identify whether the gearbox has a fault.
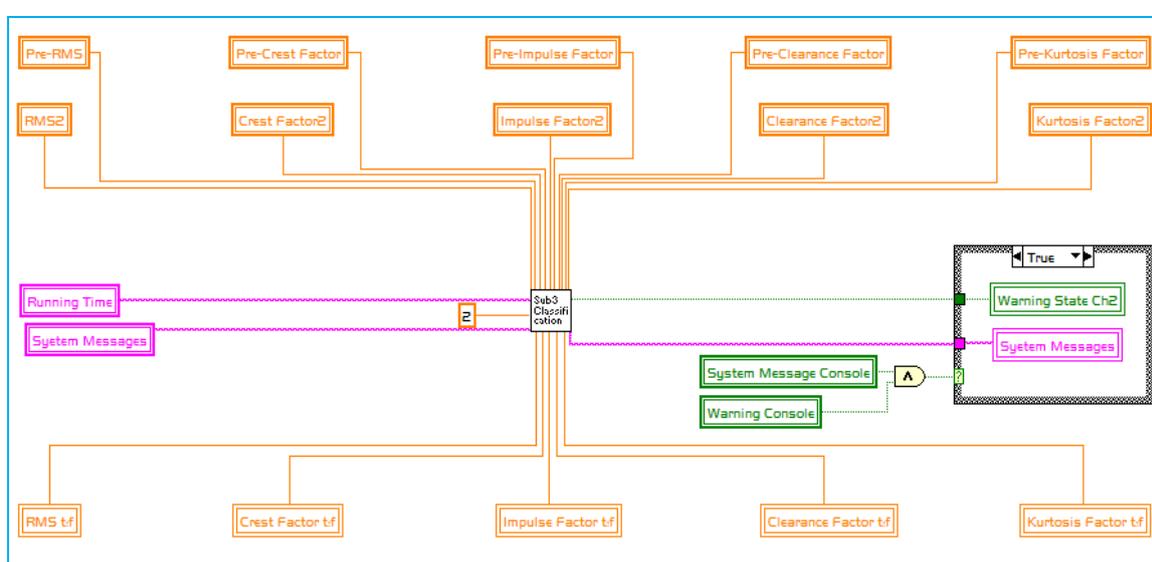
Figure A.9 the source code of identifying the fault and issuing the advanced warnings

Figure A.10 presents the Server module's real-time processing interface, which is built using the ActiveX controls/indicators of the Labview Front Panel toolbars, such as numeric and graph indicators. In the data processing interface, a number of data/information was displayed, including the working condition data (torque and rotation speed of driving/driven shafts, and vibration data of the accelerometers), gear feature parameters, time/frequency domain data, and the warning message. The warning message contains the change of gear feature, the time when a fault occurs, and the times of warnings.
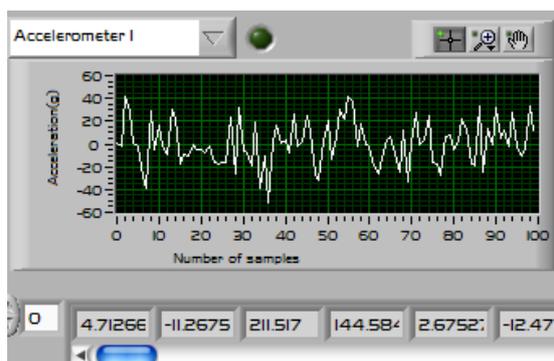
(a) the online display of working conditions data and its time-waveform
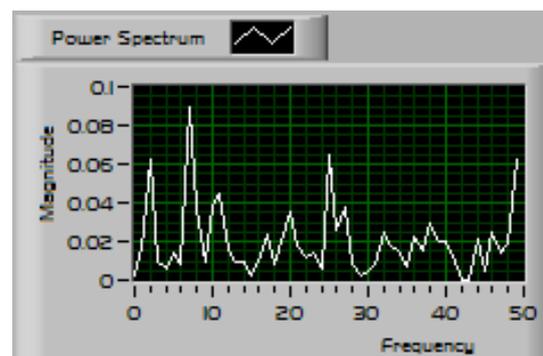
(b) the online display of frequency-waveform
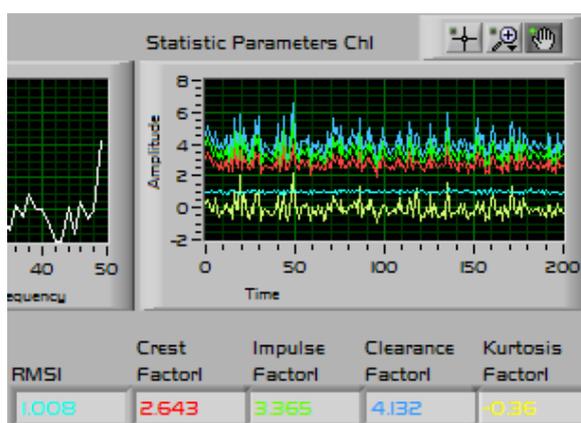
(c) the online display of feature parameters and their time-waveform
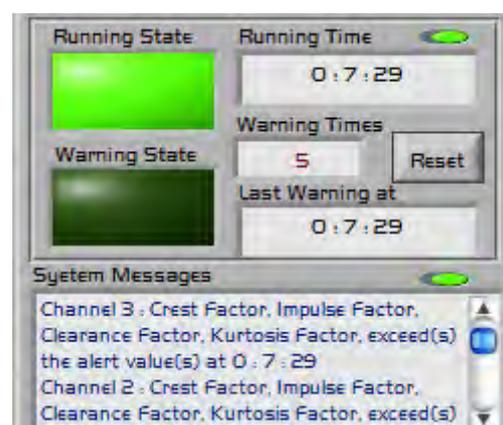
(d) issuing the warnings in real time

Figure A.10 the online display of the machine working conditions and analysis results in the software interface

The working conditions data/results, which are shown in Figure A.10, were obtained in the actual industrial environment. For more details about the results and discussion, please see section 4.5 in Chapter 4.

The last step of fault diagnosis is to send the warning message together with the analysis result to the diagnostician and users to alert the working conditions of the machine, so that the required maintenance may be scheduled according to the obtained diagnostic result.

The warning message is sent to the diagnostician/users in the e-mail form via the SMTP (Simple Mail Transfer Protocol) connectivity. The SMTP connectivity is

created by the SMTP E-mail function, which employs the MIME (Multipurpose Internet Mail Extensions) format to encode an e-mail; within this e-mail, the data file, including the working conditions data and analysis results, can be transferred via the MIME format over the Internet.

Figure A.11 presents the SMTP E-mail function with the following main properties (parameters): mail server, recipients, message, subject, and file path. These properties are configured in the following ways:
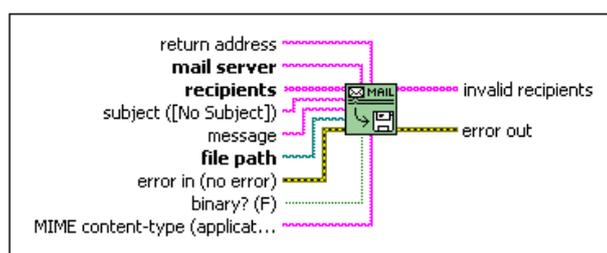

Figure A.11 SMTP E-mail function

(1) The property 'mail server' is used to determine the SMTP server for sending e-mails, including the attached data file, using the Simple Mail Transfer Protocol (SMTP). Figure A.12 presents the SMTP server's configuration, which includes the name of a SMTP server provided by the Netease (Netease is a supplier of free e-mail services), the port number of the SMTP server, and the authentication protocol with Secure Socket Layer (SSL).

Figure A.12 the SMTP server information

(2) The property 'recipients' contains the email addresses of the users, to be informed the analysis results by e-mail when a fault is identified. Each e-mail address is added before sending the e-mail. Figure A.13 presents the e-mail notification interface, which is built to configure the users' e-mail addresses and message contents.
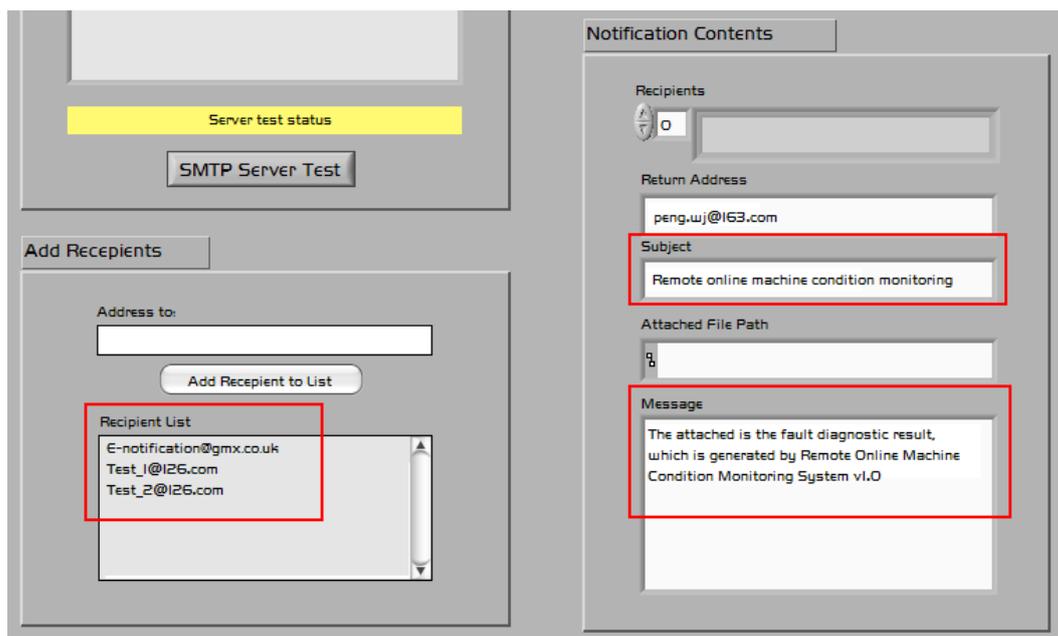

Figure A.13 Configure the recipiants' email addresses and message contents in the e-mail notification interface of the Server module

(3) The properties 'message' and 'subject' are utilised to specify the message text and subject of the e-mail, respectively. The message text consists of the warning message and custom message. The warning message is generated by the Server module when a fault occurs. For example, when a feature parameter is greater than the upper limit, a warning message with regard to this situation will be shown in the message window of the software interface. In order to avoid the interference of false warnings due to the transient signals of the machine, the warning will be further validated. If the subsequent 50 warnings are identical within a minute, these warnings will be generated to a report as part of the message text of the e-mail. For the custom message and the subject, they are identified via the e-mail

notification interface built in the Server module, as shown in the Figure A.13.

(4) The property 'file path' is used to set the path of the data file, to be attached in the e-mail. This data file contains the machine condition data and analysis results, such as time/frequency data, feature parameters, torque and rotation speed of the gearbox. When the system operates, these data/results will be automatically logged into the data file. The generation of the data file is detailed in the following sub-section 'Data Logger'.
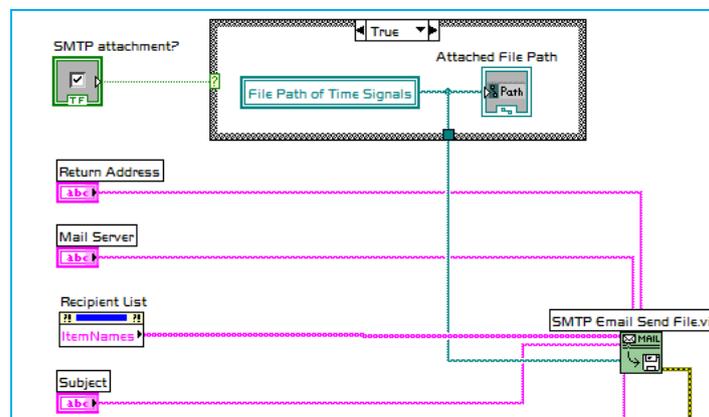
(a)
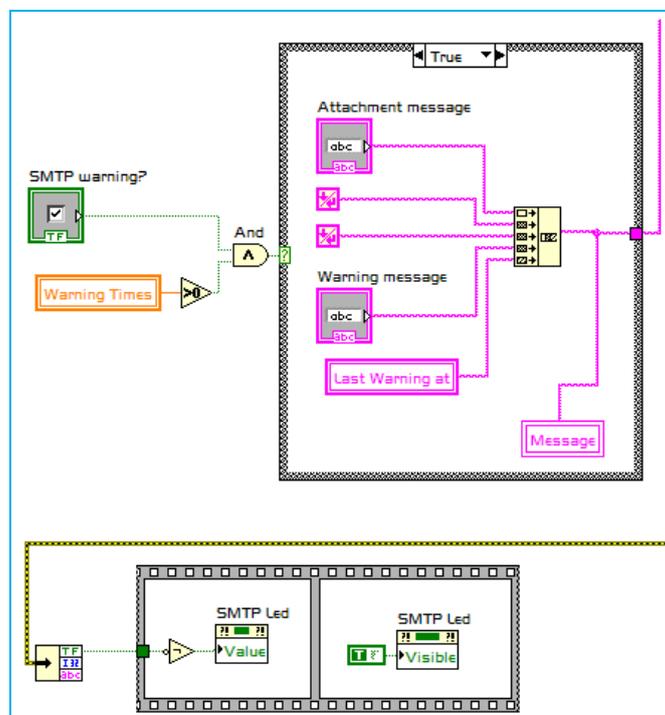
(b)

Figure A.14 the codes of sending a warning together with the diagnostic result to the

user via SMTP email connectivity

Figure A.14 presents how to utilise the SMTP E-mail function to send a warning message with the analysis result to the user.

- **Data Logger**

This programme block is developed to log the working condition data and analysis results into a data file, and allow the data/results to be read out from the data file and displayed in the data logging interface when the user needs to view the past data and results.
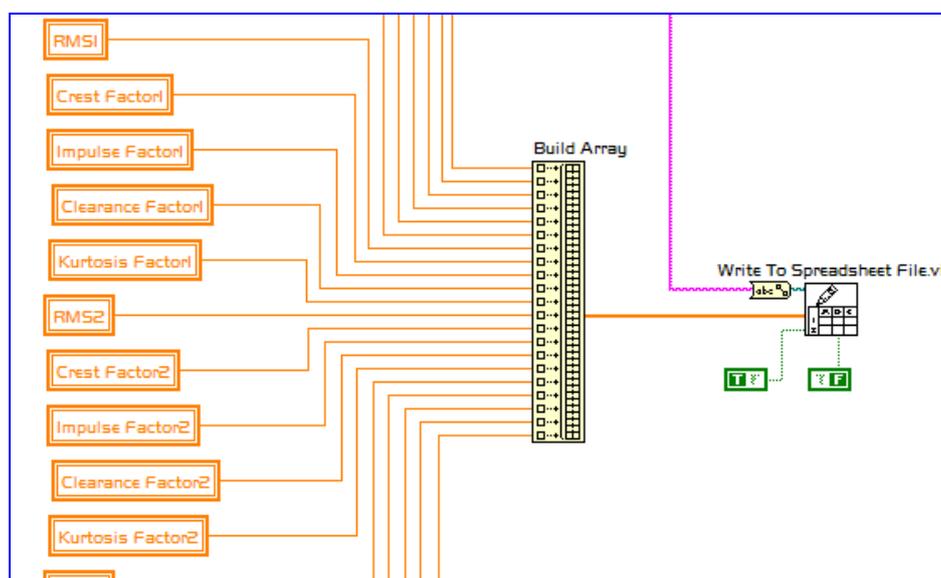

Figure A.15 the source code of writing the working condition data and analysis results into a data file readable by most spread-sheet applications

The process of logging the data into a file is performed using the Write To Spread-sheet File function. Before applying the Write To Spread-sheet File function, the data to store are required to be converted into the one-dimensional array form. Using the Build Array function, the data/results are processed to an array, which is transferred to the Write To Spread-sheet File function for building the data file. The data file is stored in a position of the server computer and it can be open by the

spread-sheet applications such as the Microsoft Excel. Figure A.15 presents the code of writing the working condition data and analysis results into a data file using the Write To Spread-sheet File function.

The process of extracting the data from the data file is performed by combining the Read from Spread-sheet File function and the Waveform Graph function. When a user such as a diagnostician views the past working condition data, the data file are first loaded using the Read from Spread-sheet File function, and then the working condition data and analysis results are read out and displayed in the time-waveform form via the Waveform Graph functions. The data file can be open by the spread-sheet applications.

Figure A.16 presents the code of extracting the data/results from a data file. Figure A.17 presents the code of displaying the data/results as the time-waveform in the data logging interface.

Figure A.16 the source code of extracting the working conditions data and analysis results from a data file

Figure A.17 the source code of displaying the working conditions data and analysis results in the data logging interface
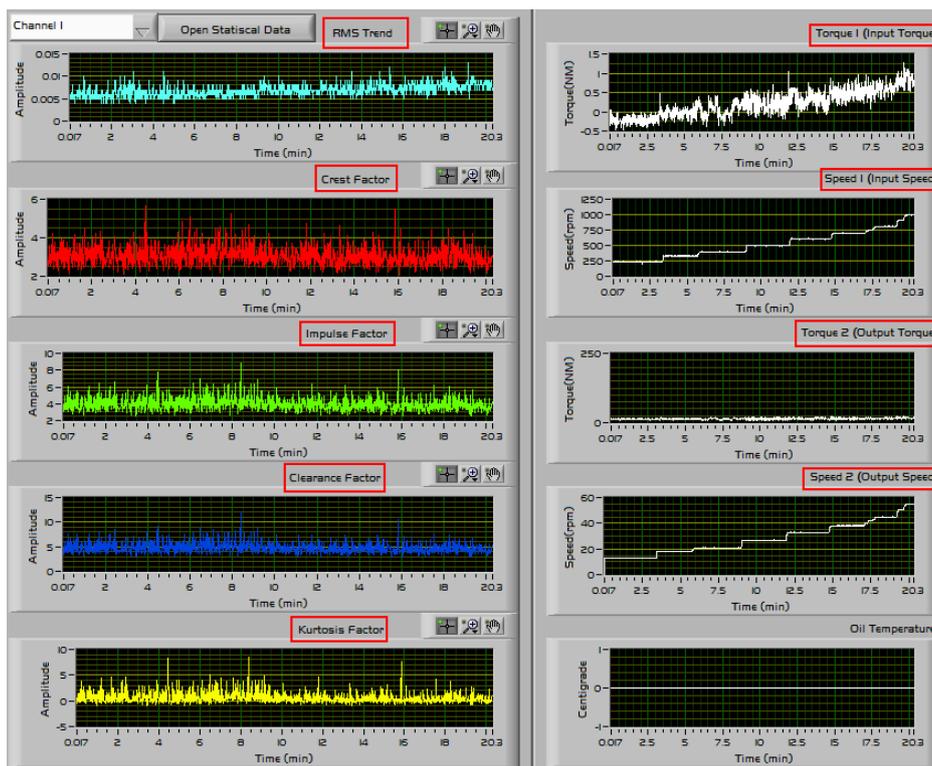
Figure A.18 the display of the time-waveform graphs of the working conditions data and analysis results in the data logging interface

The data logging interface of the Server module is built to display the working condition data and analysis results, which are extracted from the history data file, as

shown in Figure A.18. The working conditions data include the torque and rotation speed of the driving/driven shafts of the gearbox and time/frequency data; the analysis results include gear feature parameters and warning messages. The related waveform graphs reflect the variance of the data/results with time.

• **Remote Communication using the Web Services**

This programme block aims to provide an approach, which allows the mobile users to remotely access the working condition data and analysis results from the server computer, and to regulate the working conditions of machines by sending the control commands/parameters to the server computer through the Internet and wireless network. To realise this aim, the Web Service is applied as application programming interface to send and receive data between the server computer and the client mobile devices.

The implementation of the Web Service consists of the following two steps:
  (1) To develop the Web service application with the XML standard;
  (2) To deploy the Web service application as a Web Service in Labview.

▪ Development of the Web Service Application

The development of the Web service application starts by processing the data with the XML standard. Using the following Labview XML syntax, the data/information, such as working conditions data, gearbox feature parameters, and system message, can be written as the XML code.

```
<?xml version='1.0' standalone='yes' ?>
<Heading>
      <Record_1>
          <Val>
                data_1
```

```
        </Val>
    </Record_1>
    <Record_2>
        <Val>
            data_2
        </Val>
    </Record_2>
    <Record_3>
    ……
</Heading>
```

In the XML syntax, 'data_1' and 'data_2' refer to the data/information to be written into the XML. The tags <Record_1> and </Record_1> are used to define a record that contains 'data_1'; the tags <Record_2> and </Record_2> use the same method to define a record for 'data_2'. The tags <Heading> and </Heading> specify a heading of the XML code including the records.
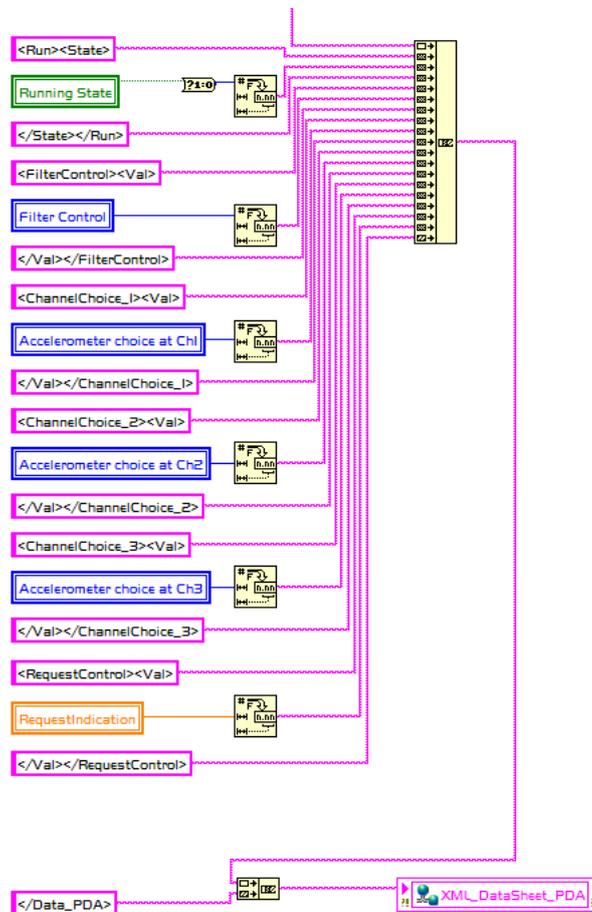
Figure A.19 the code of writing data into XML

Using the above XML syntax, the data/information is written as the XML code, as shown in Figure A.19. Because the XML code is transmitted in the form of a single string, the data/information are first processed to the strings form using the Number to String function, and then are concatenated into a single output string using the Concatenate Strings function. The output string is called the XML code.

Sending the XML code over the Internet is performed utilising the Write Response function and the Flash Out function. The XML code as the response to users is transferred to the Write Response function and is then written into a buffer in memory. When the server receives a user request and the XML output mode is enabled, the response, i.e. the XML code, which remains in the buffer, is sent by the Flash Out function to the client. Figure A.20 presents the code of transferring the XML over the Internet.
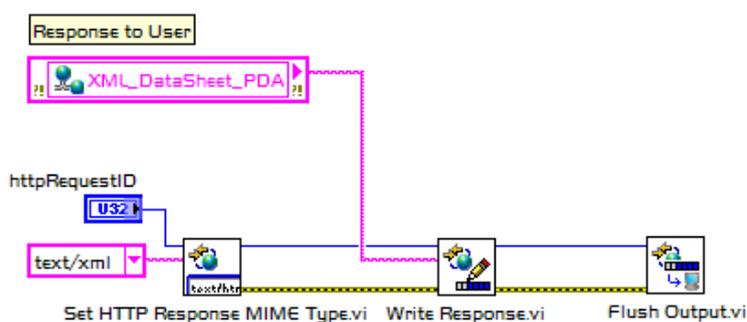
Figure A.20 the code of transferring the XML over the Internet

- Deploying the Web service application as a Web Service

Once the Web service application is built, it must be deployed as a Web Service, so that the server, i.e. Web Server, can communicate with the client via the Web service application.
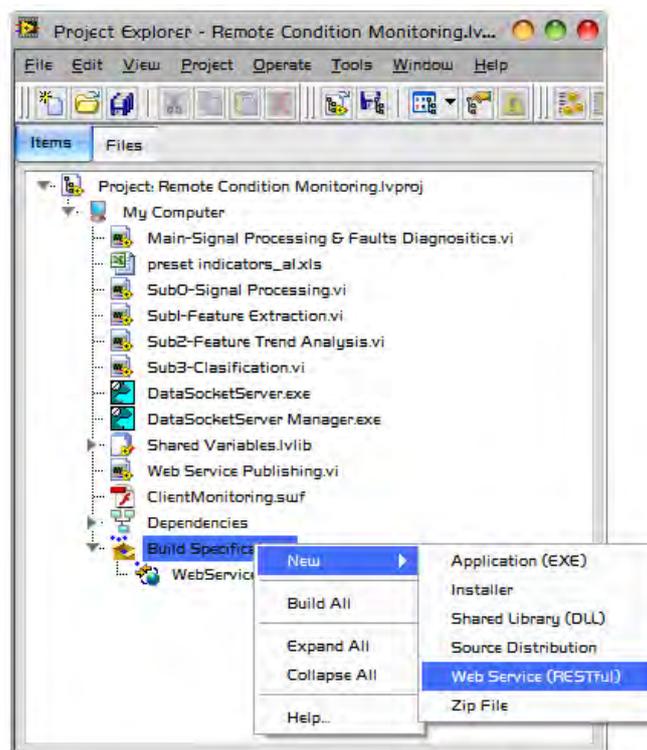
Figure A.21 Configure and deploy the Web service application from the Build Specifications menu

The configuration and development of the Web service application starts with the settings in the Build Specifications section of the LabVIEW Project Explorer, as shown in Figure A.21. The settings in the Build Specifications dialog for Web Services determine how a remote user interacts with the Web service application once it has been deployed.

In the Information category of the Build Specifications dialog (Figure A.22), the following three parameters are configured: the service name, the build specification name and destination directory. The first parameter specified in the dialogue window is the service name. Because we can configure multiple services for a single Web service application, the service name is specified to differ from the names of other services. The next parameter specified is the destination directory, which assigns a location in the server computer to the Web service application. The build specification name is identified as the same as the service name.
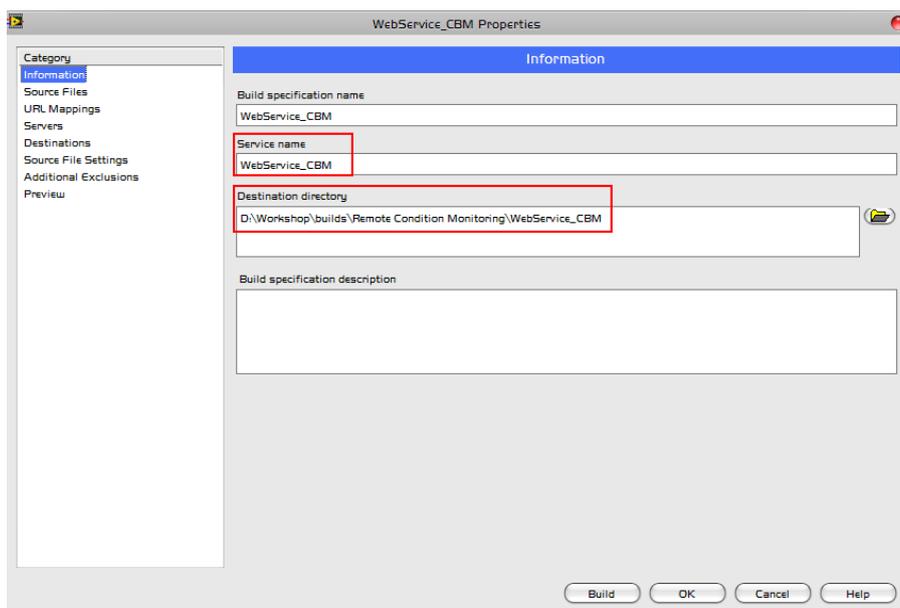
Figure A.22 Specifying the Service name, Build Specification name, and Destination directory from the Information category of the Build Specification

In Source Files category, the Web service application is deployed as a Web Service, as shown in Figure A.23 (The settings of other categories, such as the URL mapping category, are detailed in the section 'Development of the Client module').
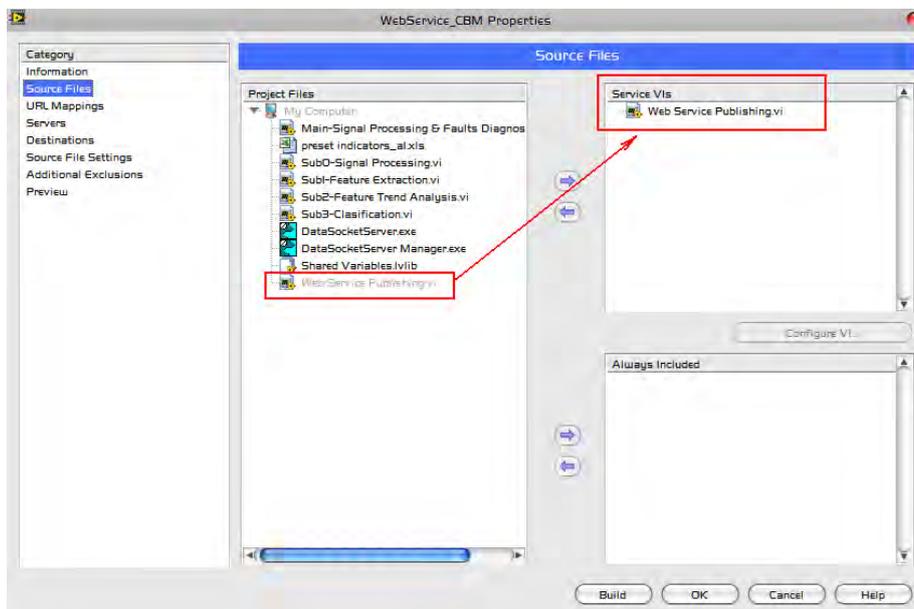

Figure A.23 Deploying the Web service application as a Web Service
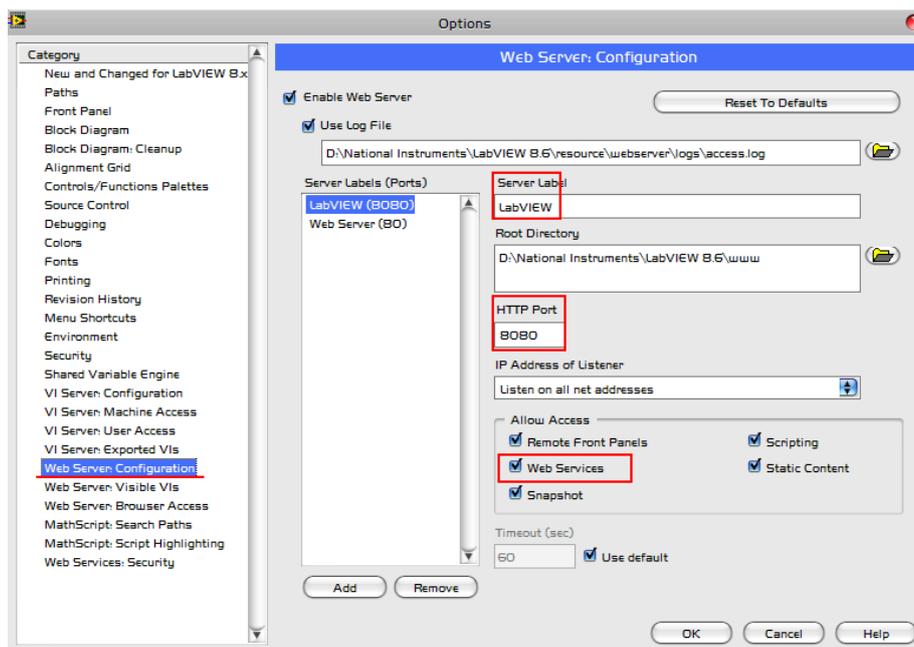
Figure A.24 Configure Web Service in Labview Web Server from the Options dialog window

After the Web service application is deployed as a Web Service, the Web Service is enabled in the Web Server to allow the access to the Web Server. Figure A.24 shows the Web Server's configuration, which utilises the port 8080 as the default port of the Web Service and 'Labview' as the name of the Web server, and allows the Web Service to access the Web Server.

- **Remote communication using Data-socket**

This programme block is built to acquire working conditions data from the Remote Data-acquisition module (see section 'Development of Remote Data-acquisition Module) deployed in the data-acquisition computer. When the machine to be monitored is located at a position far from the server computer, the function that this block brings with is particularly useful.

The data acquisition from the Remote Data-acquisition module is implemented using the Data-socket Read function. The Data-socket Read function utilises the Data-socket

API, i.e. Data-socket properties/parameters, to read data from the Remote Data-acquisition module. Figure A.25 presents the Data-socket Read function with the following the main properties: connection in, type, timeout, and data.
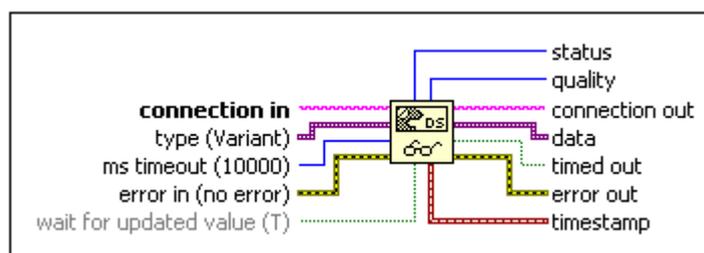

Figure A.25 the Data-socket Read function

The property 'connection in' identifies the data source's URL (Uniform Resource Locator), which consists of the transfer protocol, the physical location of the data source, and the tag. The transfer protocol is specified as the Data-socket Transfer Protocol (DSTP), which is used to transmit working conditions data at high rates across the Internet. The physical location of the data source contains the IP address and the port number of the data source. Because the data-acquisition computer is the data source of the Data-socket, the address of the data-acquisition computer is identified as the physical location of the data source, i.e., '152.71.146.80:8000'. The tag is used to identify the location of the data to read from the data source.

The property 'type' specifies the types of data to read as well as the data output terminal. The data types are defined as 'Variant', which can be any type, such as the string and floating-point. The output data type is in line with the data input type. The property 'data' is the result of the read.

Figure A.26 presents how to read data from the data source, i.e. the data-acquisition computer, using the Data-socket Read function. The parameter 'timeout' is set 1000ms (1 second), and 'wait if wait for updated value' is True. If an updated value is unavailable in the connection buffer within the specified time, an error code will occur

in the software interface.
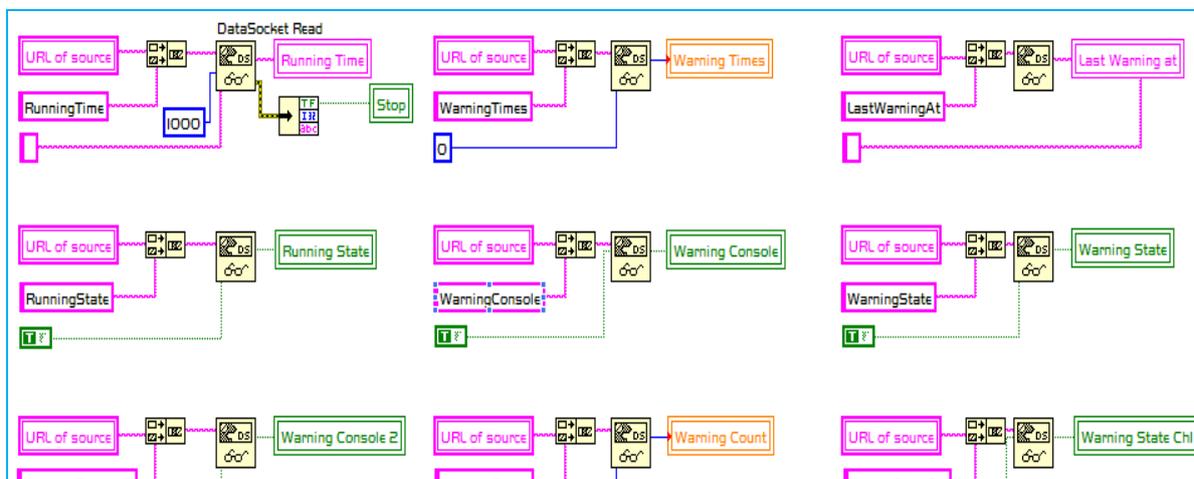
Figure A.26 Acquire data from the data-acquisition computer using the Data-socket Read function

A1.2 Development of the Client Module

The second part of the remote online machine condition monitoring system software is the Client module, which is applied to communicate with the Server module and to pass the data/results to diagnosticians for the maintenance work. The development of the Client module includes the following two steps:

(1) To develop the script and user interface of the Client module;

(2) To deploy the Client module in the Web Server.

- Development of the Script and User Interface

The script and user interfaces of the Client module are developed using MXML programming language. MXML language provides a number of syntax and commands related to the Web Service. Using these syntax and commands, the client can send requests to the Web Server via the Web Service, and receive responses returned from the Web Server in the form of XML and display the data/results in the user interfaces.

The following code is placed at the beginning of the script to build a connection to the Web Server.

```
1  <?xml version="1.0" encoding="utf-8"?>
2
3  <mx:Application xmlns:mx="http://www.adobe.com/2006/mxml" la
4      <mx:HTTPService id="LabVIEW" url="{inputValues}"
5          result="resultHandler(event)"
6          fault="faultHandler(event)"
7          />
```

In this code, the class 'HTTPService' is utilised to define a Web Service of the client. The tag <mx:HTTPService> represents a Web Service's object, which consists of four parts: the object ID, a specified URL, a result event , and a fault. The object ID is defined as 'Labview'.

The URL refers to the server's HTTP address (Figure A.27), which is used to send requests to a specific interface of the server (Web Server). With the URL, we can transfer the commands/parameters as requests to the server to perform the required operation of the system.
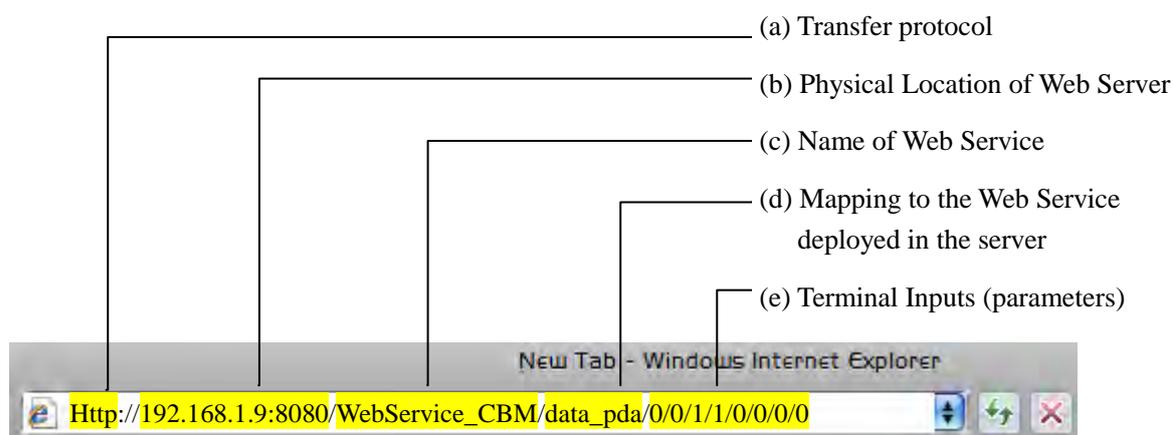

Figure A.27 the components of the URL

The URL includes the five parts: the transfer protocol, the physical location of the

server, the Web Service name of the server, mapping to the Web Service of the server, and the terminal inputs. The transfer protocol is identified as Hypertext Transfer Protocol (HTTP); the physical location of the server is specified using IP address 192.168.1.9 and the port number 8080; the Web Service name of the server is defined as 'WebService_CBM'; the mapping to the Web Service of the server is specified as 'data_pda', which defines a custom route to invoke the Web service application deployed in the server; the terminal inputs include parameters/commands to be passed to the Web service application invoked. The terminal inputs need to be configured in the server to map the inputs from URL to the Web service application. For the process of mapping the terminal inputs to the Web service application, please see the sub-section 'Development of the Client Module in the Web Server'.

Based on the above interpretation, the URL is described using the variable 'inputValues' in the following code.

```
private function UpdateInputValues():void{
    inputValues="http://" + ServerIP + ":8080/WebService_CBM/data_pda"+"/"
    +Request+"/"+Run+"/"+SelectChannel+"/"+SelectStatistic+"/"+FilterControl+"/"
    +Accelerometer1Channel+"/"+Accelerometer2Channel+"/"+Accelerometer3Channel;
}
```

In this code, the variable 'inputValue' that represents the URL utilises eight terminal inputs as the commands to regulate the operation of system/devices. These terminal inputs are defined as the numeric amounts, such as 0 and 1, which correspond to the specific control actions; they are sent as the URL extension to the server. The functionality of the eight terminal inputs is detailed in the table A1.1.

	Terminal inputs	Commands	Actions
1	Request	1	Make a connection to the server
		0	Disconnect from the server

2	Run	1	Start to receive data from the server, update the data as per the specified time interval, and display data/results in the user interface
		0	Stop receiving and displaying data/results
3	SelectChannel	0	Do not display the time/frequency domain waveform
		1	Display the time/frequency domain waveform of the signals acquired from the Channel 1
		2	Display the time/frequency domain waveform of the signals acquired from the Channel 2
		3	Display the time/frequency domain waveform of the signals acquired from the Channel 3
4	SelectStatistic	0	Do not display feature parameters
		1	Display the data/time-waveform of Crest factor
		2	Display the data/time-waveform of Impulse factor
		3	Display the data/time-waveform of Clearance factor
		4	Display the data/time-waveform of Kurtosis factor
		5	Display the data/time-waveform of RMS factor
5	FilterControl	0	Do not use digital filter
		1	Enable the ButterWorth Filter (IIR)
		2	Enable the Adaptive Filter with LMS
6	Accelerometer1Channel	0	Do not assign the accelerometer to Channel 1
		1	Assign Accelerometer 1 to Channel 1
		2	Assign Accelerometer 2 to Channel 1

		3	Assign Accelerometer 3 to Channel 1
7	Accelerometer2Channel	0	Do not assign the accelerometer to Channel 2
		1	Assign Accelerometer 1 to Channel 2
		2	Assign Accelerometer 2 to Channel 2
		3	Assign Accelerometer 3 to Channel 2
8	Accelerometer3Channel	0	Do not assign the accelerometer to Channel 3
		1	Assign Accelerometer 1 to Channel 3
		2	Assign Accelerometer 2 to Channel 3
		3	Assign Accelerometer 3 to Channel 3

Table A1.1 the functionality of the terminal inputs used in the URL

For example, when eight terminal inputs are identified as '1/0/0/0/0/1/2/3', it means that the client attempts to access the Web Server and allocate the accelerometers 1/2/3 to the analogue input channels 1/2/3, respectively, via the Web Service.

When the send() method of the Web Service object is called, it makes an HTTP request to the Web Server via the specified URL, and then the terminal inputs as the URL extension are passed to the Web Server. The following code shows how to send a request to the Web Server using the send() method. In this code, the send() method is repetitively operated with the control of a timer, so that the requests with terminal inputs can be sent to the server continuously.

```
private function setInputValues():void{
    UpdateInputValues();
    LabVIEW.send();
    timer = new Timer(Refresh_Rate.valueOf());
    timer.addEventListener(TimerEvent.TIMER, timerEvent);
    timer.start();
}
```

After a request is sent to the Web Server, a HTTP response is returned immediately. When the client receives the response returned, it resolves the response using the Result event immediately, and then passes the resolved data/results to the user interface for display.

If the response fails to be received, the client will launch the Fault event to return an error code, and pass this code to the message window of the user interface to inform the user current status. For instance, if the code 0 appears in the user interface, it means that the physical location of the server, such as the IP address or the port number of the server is incorrect, and then the user is alerted to re-assign the physical location of the server. Figure A.28 presents the user interface of the client when a response is returned.
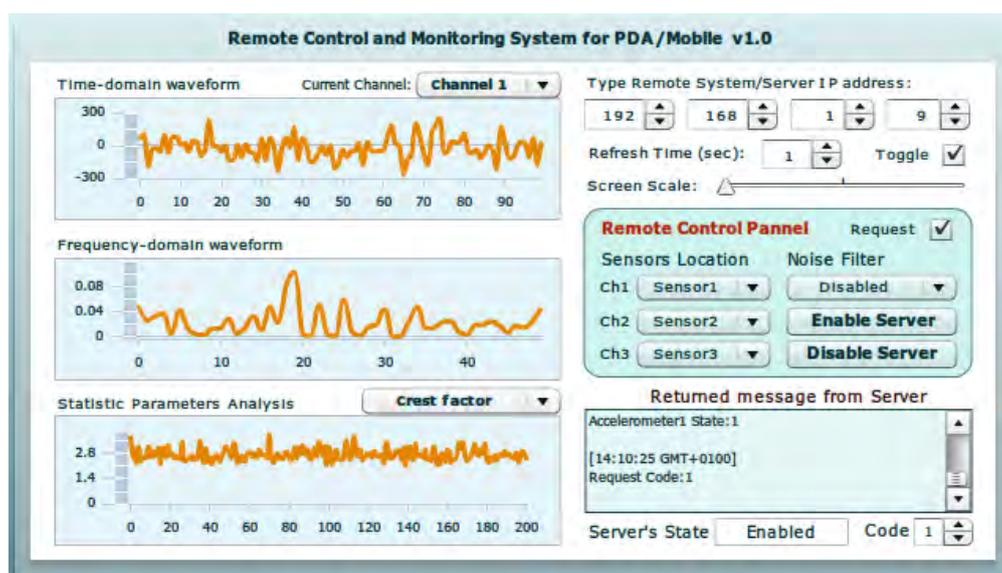
Figure A.28 the user interface of the client when a request is sent

Because the response is returned in the XML form to the client, the user is allowed to utilise the Web page to view the data/results included in the response in the XML form. Figure A.29 shows the XML data sheet, which is returned from the Web Server, when a request is sent to the server.
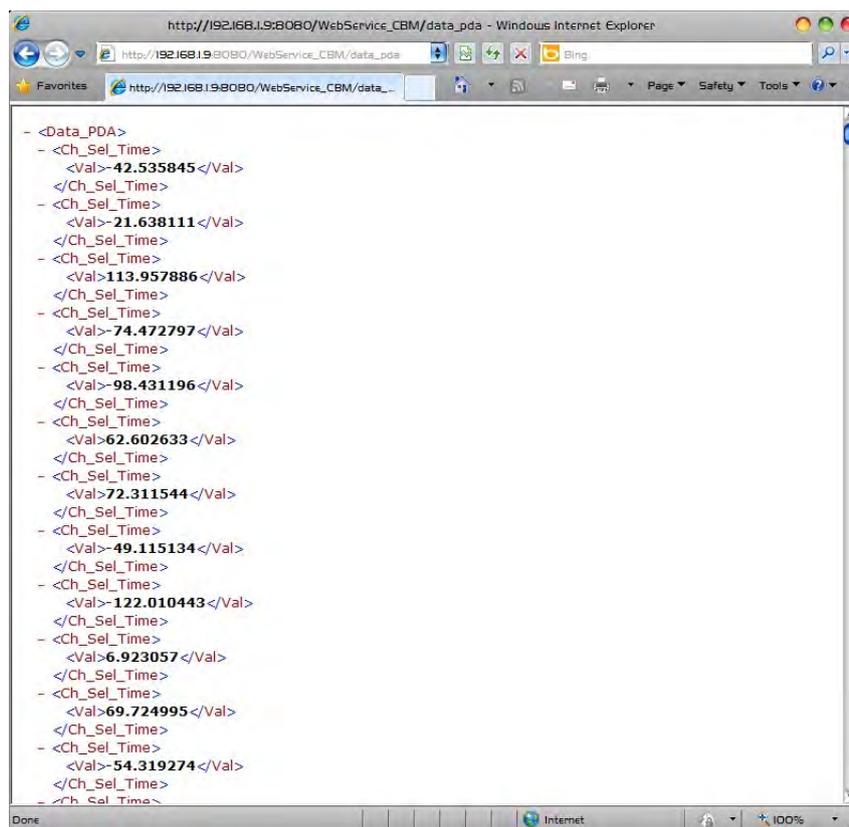
Figure A.29 the XML data sheet returned from the server when a request is sent

The developed script and user interface are saved in the form of Flash page or mobile phone code using the Open-plug add-on to the server.

- Deployment of the Client Module in the Web Server

After the Client module is developed, it may be deployed in the Web Server. The advantage of such a development is that the Client module is not necessary to pre-install in the client mobile device, such as a PDA or mobile phone. When a request is sent to the server, the Client module can be downloaded as a static content to the client in HTTP page form; and then client utilises the Web browser embedded in the mobile device to build a user interface. With the RESTful-based Web Service, the data/information is transmitted to the client and displayed via data resolving in the user interface.

Figure A.30 presents how to deploy the Client module in the Web Server from the Labview's Building Specification dialog. In the Sources Files category, the Client module is deployed as the static content in the Web Server.
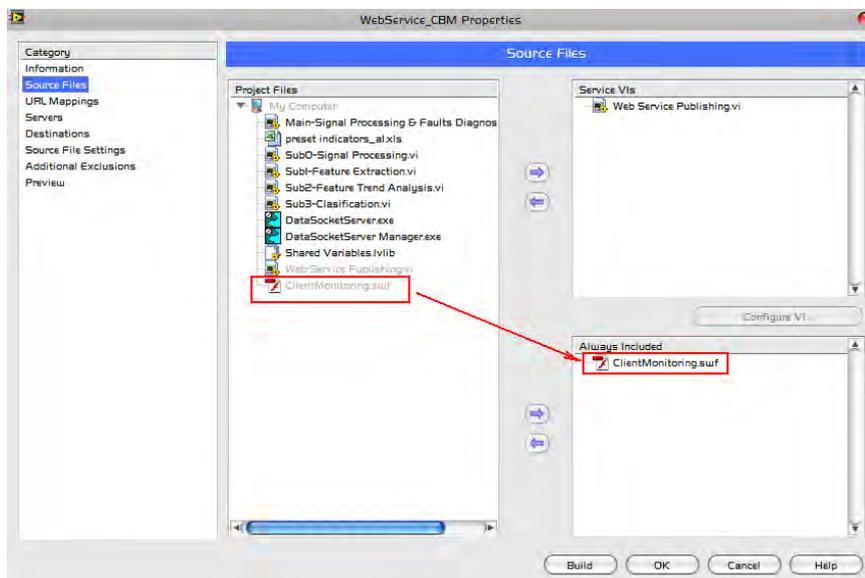
Figure A.30 Deploy the Client module in Labview Web server

In the URL mappings dialog, the terminal inputs are configured to map the inputs from the URL to the Web service application. After selecting a Web service application to run as a Web method VI (application), the URL extension including terminal inputs is entered to point to the Web service application. Figure A.31 shows how to map the terminal inputs from the URL to the Web service application.
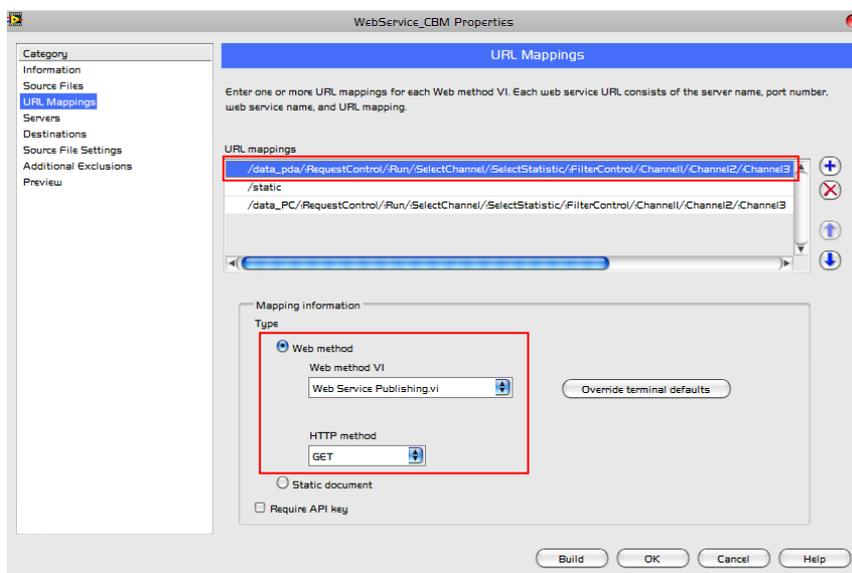
Figure A.31 Mapping the terminal inputs to the Web Service and customize routes to specific Web Service application using the URL mappings dialog

In order to send the terminal inputs to the Web service application, the Web Server needs to determine the method of data transmission. GET is specified as a HTTP method to allow data to be passed in via variables, which extend the URL by adding commands of requests.

A1.3   Development of the Remote Data-acquisition Module

The Data-acquisition module, as the last part of the remote online machine condition monitoring system software, is developed to collect the working conditions data from a remote machine, and transmit the data to the Server module at high rate to ensure that the server acquires up-to-date data of the remote machine.

The development of the Remote Data-acquisition module consists of the two steps:

(1) To develop a data acquisition block to collect working conditions data of a machine. (the block is developed applying the same method as the data acquisition block of the Server module, and hence, the development process is not discussed repeatedly)

(2) To develop a remote communication block to transmit the working conditions data from the data-acquisition computer to the server computer.

Because the Web Service cannot meet the demand of the high-rate transmission of a great number of data, the Labview Data-socket is utilised to perform the data communication between the data-acquisition computer and the server computer, providing the high-performance programing interfaces.

The data communication with the Data-socket requires a Data-socket Server. The data

to send are first written to the Data-socket Server, and then transmitted to the Data-socket programme block of the Server module (see section 'Development of the Server Module').

The Data-socket programme block of the Server module is the 'client' of the Data-socket Server; using the Data-socket Server Manager, the Server module can be configured to allow the access to the Data-socket Server. In the Default Readers section of the Data-socket Server Manager dialog, as shown in Figure A.32, the physical location of the Server module is added to the Hosts list as a host, which is enabled to read data from the Data-socket Server.
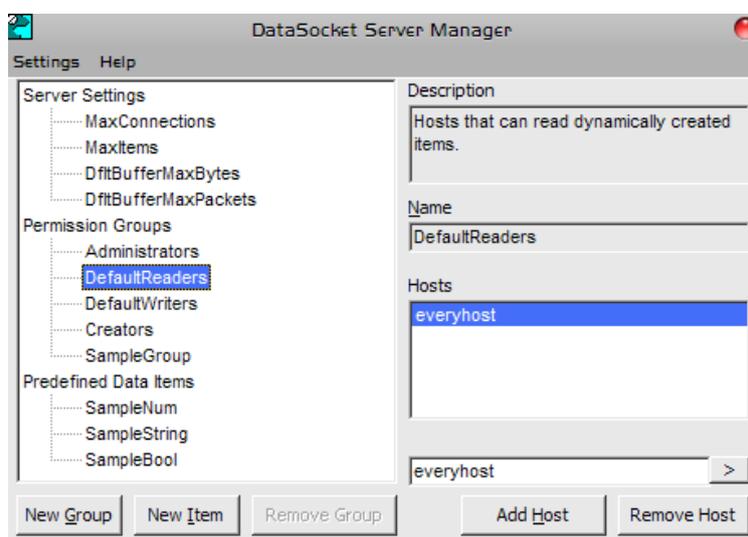
Figure A.32 the Data-socket Server Manager

The process of sending data to the Data-socket Server is performed combining the Data-socket Open function and the Data-socket Write function. The Data-socket Open function makes a Data-socket connection and identifies the buffering of writing data to data targets using the property 'Buffered Read/Write'; the Data-socket Write function then writes data into the specified data targets. The above-mentioned data target refers to the URL of the Data-socket Server, e.g. 'dstp://152.71.146.80:8000/Running Time', which includes the transfer protocol, the physical location of the Data-socket Server, and the tag of the data to write.
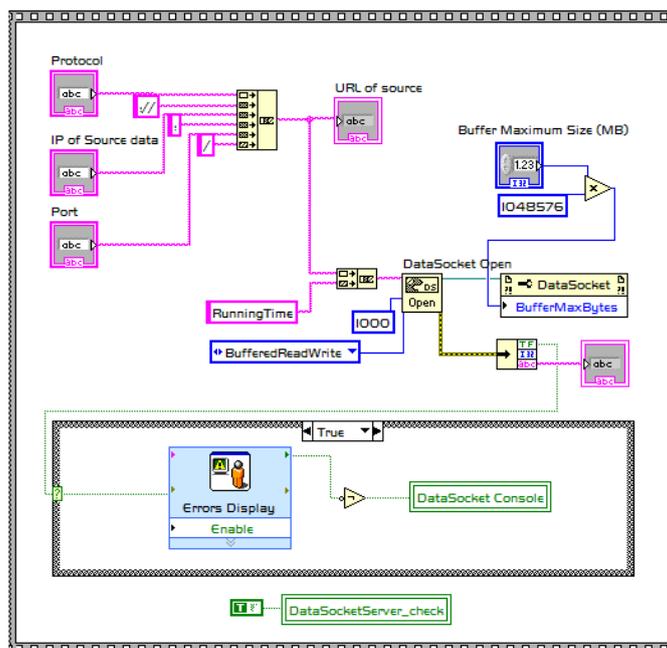
Figure A.33 the source code of making Data-socket connectivity and specify the buffering of writing data to the data targets

Figure A.33 presents how to utilise the Data-socket Open function to build a Data-socket connection and identify the buffering of writing data to data targets. The maximum buffering size is 1048MB, which is specified large enough to prevent the data loss from the Data-socket Server. Figure A.34 presents how to write the working conditions data into the specified data targets.

Figure A.34 the source code of writing the data into the data targets
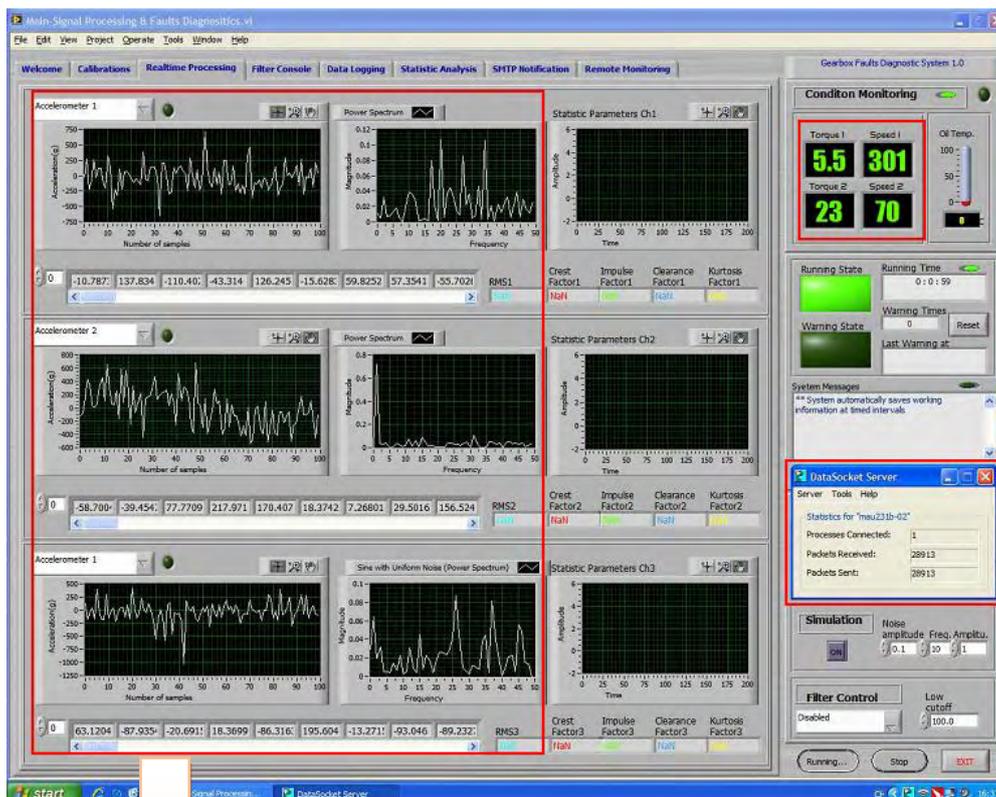
Figure A.35 To acquire the machine conditions data and transfer the data to the Server module when the Data-socket Server is applied
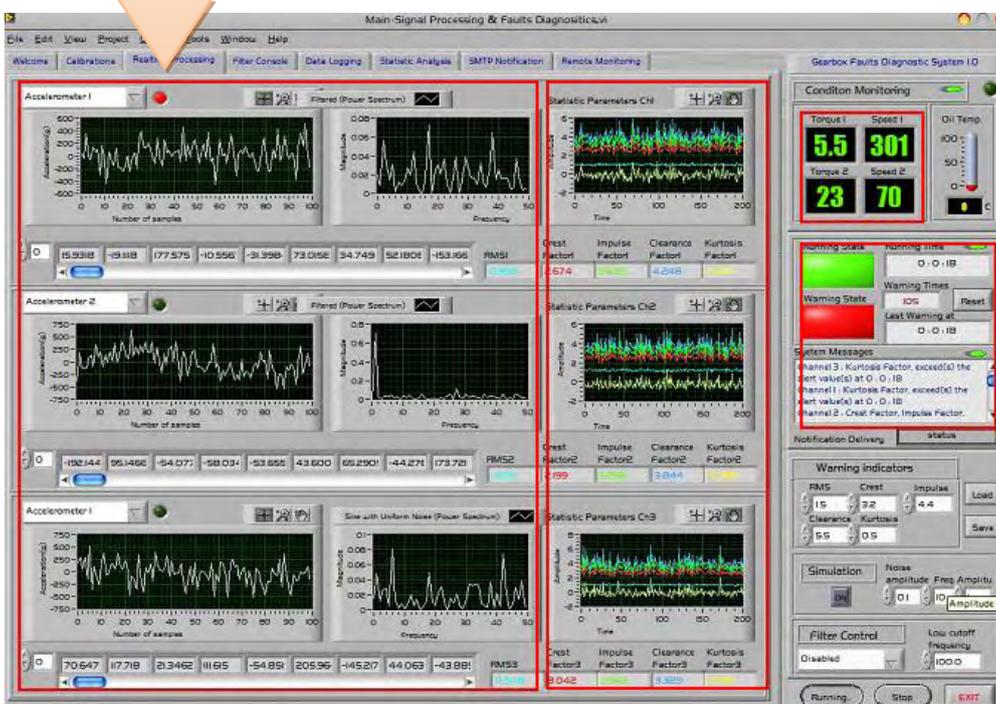
Figure A.36 Utilising the Server module to receive, process and diagnose the machine conditions data

Figures A.35 and A.36 present the real-time data acquisition/processing interfaces of the Remote Data-acquisition module and the Server module, respectively. When the Data-socket Server is operated in the Remote data-acquisition module, the working conditions data, such as torque, rotation speed, and vibration data, are acquired from the machine and then transmitted to the Server module; the Server module online processes and analyses the received working condition data, and pass the analytical results to the system message window in the interface of the Server module. In the meantime, the working condition data and relevant time-waveform are displayed in both the Server module and the Remote data-acquisition module in real time.

Appendix (B) Development of the Remote Control System Software of Solid Desiccant Dehumidifier for Air Conditioning

The remote control system software of solid desiccant dehumidifier for air conditioning has been developed, which consists of Server module, Client module, and the Database. The Server module includes the following programme blocks:

(1) Data acquisition/processing, to collect the working conditions data form solid desiccant dehumidifier and convert the received analogue data into the quantities of the working conditions.

(2) System control for decision making. When the fault, such as the overload of solid desiccant dehumidifier, is discovered, the system decelerates the fan's rotation speed to reduce the air-flow rate passing through solid desiccant dehumidifier automatically until the overload factor (ΔH) returns to rated working range.

(3) Remote communication via Web Service, to allow the user to remote access the working conditions data from the server, and control the working conditions of solid desiccant dehumidifier via the Internet and wireless network.

The Client module including the user interfaces and script is developed to communicate with the Server module, and to control and monitor the working conditions of solid desiccant dehumidifier using mobile devices via the Internet and wireless network.

The Database is built using the My-SQL database manager to record and manage the working conditions data of solid desiccant dehumidifier. The database is connected with the Server module via ODBC (Open Database Connectivity). It allows mobile users to access the data/results from the database using the Client module.

Server module
(deployed in server computer)

Client module
(downloaded to the client mobile devices)

```
                   Initialisation
                         │
                         ▼
                 Launch Web server
                         │
                         ▼
           Check network connection  ◄── Send a    Connect the server ◄──
           (listen to Web port: 8080)    request
                         │
                         ▼
             Data acquisition and
                  Processing
                         │
                         ▼
                 Decision Making
                         │
                         ▼
                 Y
   Warning ◄──────────  Faults?
      │                    │ N
      ▼                    ▼
  System control ──►  Display data/results,
                        and waveform
                         │
                         ▼
              Log data into the database
                         │
                         ▼
             Write data into XML  ── Return a ──►  Read the response and
                                     response        resolve data
                         │                                │
                         │                                ▼
                         │                          Display data/results,
                         │                          waveform, and
                         │                          database
                         │                                │
                         ▼                                ▼
                 Y                               Y
   ◄──────────  Continue?                        Continue? ──────────►
                    │ N                              │ N
                    ▼                                ▼
                  Close                            Close
```

Figure B.1 The work flow of the remote control system software
of solid desiccant dehumidifier for air-conditioning

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Figure B.1 presents the working flow of remote control system software of solid desiccant dehumidifier for air-conditioning.

The development of the blocks (1) and (4) of the Server module and the Client module utilise the same programming approaches as the following blocks/modules within the remote online condition monitoring software presented in Appendix (A): Data-acquisition/processing block, Remote communication using Web Service block, and the Client module. Therefore, the development of these blocks is not discussed (the source codes are presented only).

- **Data acquisition/processing**

Figures B.2 and B.3 present the source code for acquiring the air humidity and temperature data of the inlet/outlet of solid desiccant dehumidifier and converting the received analogue data into the quantities of humidity and temperature, respectively.

Figure B.4 presents the source code of acquiring fan's rotation speed data and converting analogue data into the quantity of fan's rotation speed.
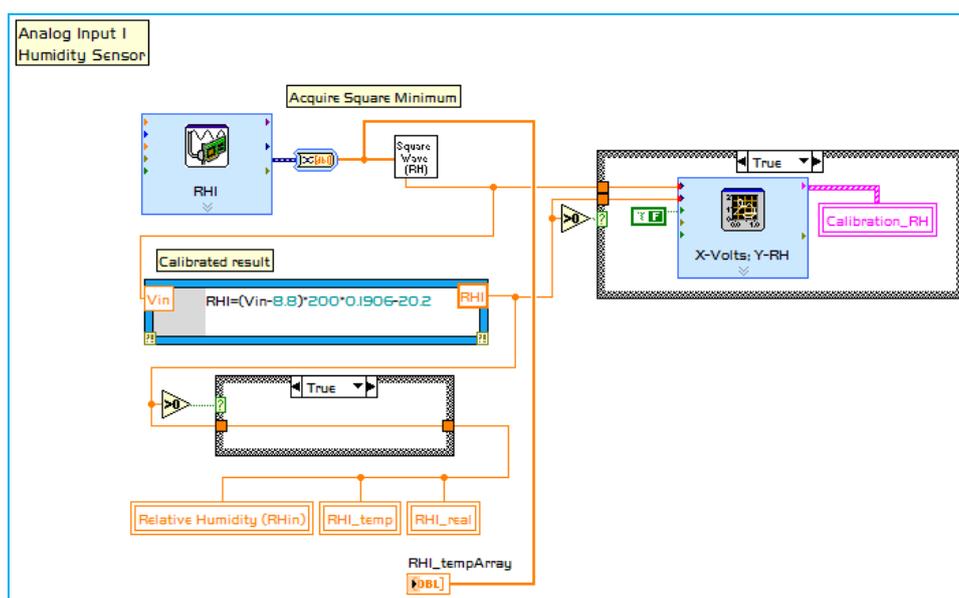
Figure B.2 the source code of acquiring the air humidity data of the inlet/outlet of solid desiccant dehumidifier and converting the received analogue data into the humidity quantity
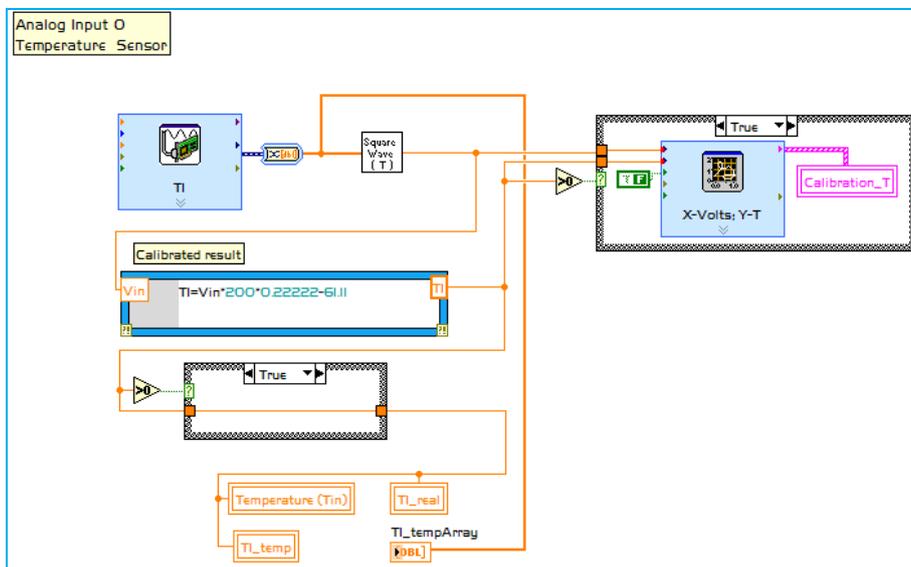
Figure B.3 the source code of acquiring the temperature data of the inlet/outlet of solid desiccant dehumidifier and converting the received analogue data into the temperature quantity
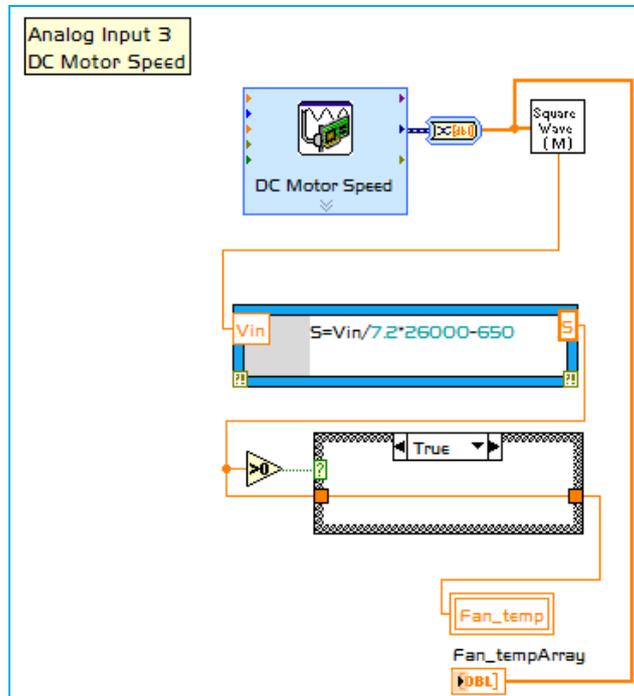
Figure B.4 the source code of acquiring the fan's rotation speed data of solid desiccant dehumidifier and converting the received analogue data into the fan's rotation speed

Figure B.5 presents the code of displaying the working condition data, such as humidity, temperature, and fan's rotation speed, and associated time-waveforms in the software interface.
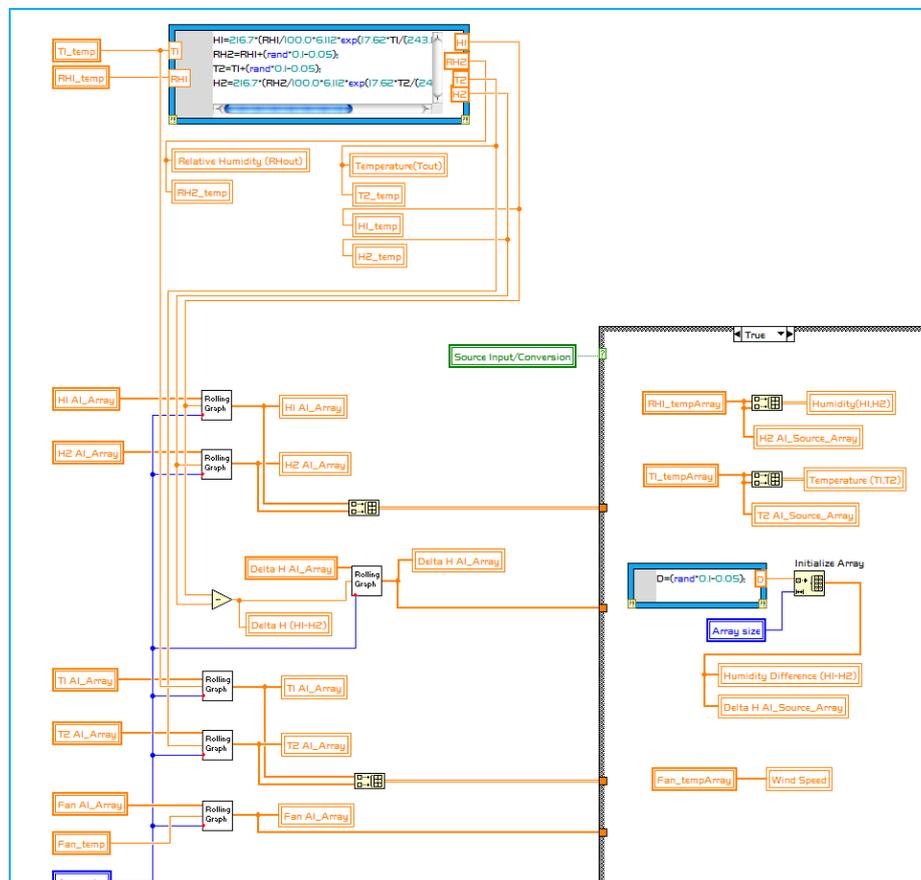
Figure B.5 the code of displaying the working condition data and associated time-waveforms in the software interface

- **System Control for Decision-making**

The system control is implemented based on the change of air humidity in the solid desiccant dehumidifier, which is denoted as ΔH. ΔH is computed as $\Delta H = H_{in} - H_{out}$, which measures the difference of air humidity between the inlet and the outlet of solid desiccant dehumidifier (H_{in} and H_{out} are acquired in Data acquisition/processing block).

When ΔH is less than the lower limit set, the air-flow rate passing through solid

desiccant dehumidifier is over fast, so that the amount of air-flow in solid desiccant dehumidifier exceeds the maximum capability that solid desiccant dehumidifier could afford to. The above situation is called the overload or fault of solid desiccant dehumidifier.

Once the overload of solid desiccant dehumidifier is identified, the system immediately slows down the fan's rotation speed to decrease the air-flow rate through solid desiccant dehumidifier until ΔH restores to the rated value. The system control process is conducted in the following steps:

(1) ΔH is acquired by calculating the difference of H_{in} and H_{out}. The calculation of ΔH is performed using the Formula Express function;

(2) The acquired ΔH is used to compare with the lower limit set: If ΔH is less than the limit, then the overload of solid desiccant dehumidifier is identified and a warning message appears in the software interface; subsequently, the fan's rotation speed is decelerated by 5 per cent to reduce the amount of air-flow in solid desiccant dehumidifier (the deceleration of the fan is performed in steps (3) and (4). If the ΔH is not less than the lower limit, then go back to the step (1) to re-calculate ΔH.

(3) While the fault (overload) is discovered, the fan's deceleration is immediately implemented using the analogue output method. The following equation is used to calculate the analogue output voltage that supplies the fan's motor:

$$OutputV = (1 - FanSpeed * 0.95 / 3600) * 5$$

The equation derives from analysing the linear relation between the Fan's rotation speed and the analogue voltage supplied to the fan (see Table B.1). In this equation, 'FanSpeed' refers to the fan's rotation speed, which is gained in the Data Acquisition/processing block; 'OutputV' is the analogue output voltage, to supply the fan's motor. The calculation of the equation is performed using the Mathematical function.

(4) The variable 'OutputV' is then transferred to the DAQ Assistant function, which utilises the analogue output interface (AO) of the data-acquisition card to output the specified voltage quantity to the fan's motor. Thus, the fan' rotation speed is slowed by 5 per cent with the effect of the specified output voltage.

Fan's rotation speed (RPM)	Fan's analogue voltage (DCV)
0	5
720	4
1440	3
2160	2
2880	1
3600	0

Table B.1 The table of comparison between the Fan's rotation speed and the analogue voltage supplied to the fan

The above steps are operated repetitively under the automated control of system. If the fan's rotation speed has been reduced by 5 per cent and ΔH remains less than the lower limit, the fan will decrease the rotation speed by 5 per cent again until ΔH restores to the rated value.

When the fan's rotation speed is decreased to approach zero, the fan and solid desiccant dehumidifier will both be controlled to stop working (air-flow can still pass through solid desiccant dehumidifier and is conveyed to air-conditioning). The 0 DCV of analogue voltage will be outputted to the fan motor and solid desiccant dehumidifier via the analogue output interfaces of the data-acquisition card, to stop the operation of solid desiccant dehumidification.

Figure B.6 presents how to control the fan's rotation speed using Labview functions and analogue output interface of the DAQ card.
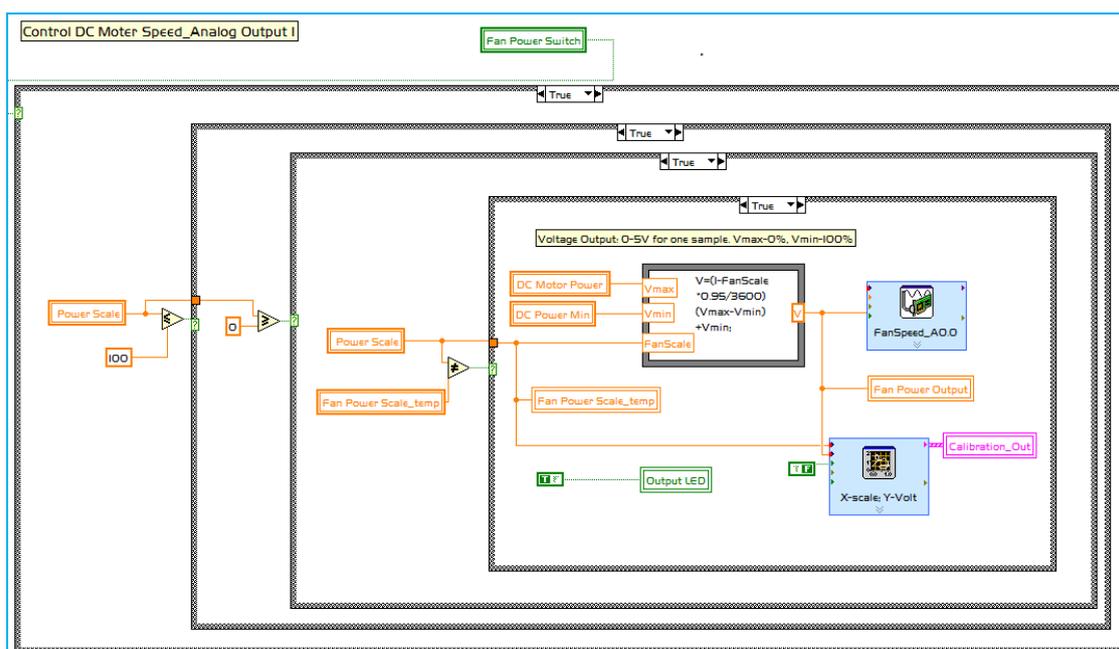
Figure B.6 the source code of controlling the fan's rotation speed using Labview functions and analogue output interface of the DAQ card

- **Database Management**

The database is established based on the My-SQL database manager (Figure B.7) to record and manage the working conditions data of solid desiccant dehumidifier. The database is associated with the Server module via Open Database Connectivity (ODBC).

ODBC is a database interface, which allows the Server module to access the database and record the data into the database with security. When the system is running, the working conditions data are logged into the database via the ODBC connectivity in real time. The users are able to utilise mobile devices to access the history data in XML form through the Internet and wireless/mobile phone network. Figure B.8 presents the configuration of ODBC in the database.

Accessing the database via ODBC is conducted using the LabSQL functions. The LabSQL functions utilise the ADO (ActiveX database objects) method to access the

database and operate the records in the database. The following steps detail how to add a record into the database.

- To create an ADO connection to the database using the ADO Connection Create function;

- To specify the data source of ODBC (see Figure B.8) in the ADO Connection Open function;

- To open the ADO connection using the ADO Connection Open function;

- To execute a query command and create a record-set in the database utilising the ADO Record-set Create function;

- To open the record-set using the ADO Record-set Open function and entre the SQL command of adding a record via the Command Text parameter.

- To add a new record to the record-set using the ADO Record-set Add New function;

- To close the record-set and the connection using the ADO Record-set/Connection functions.

Figure B.7 the My-SQL based database to record and manage the working condition data of solid desiccant dehumidifier
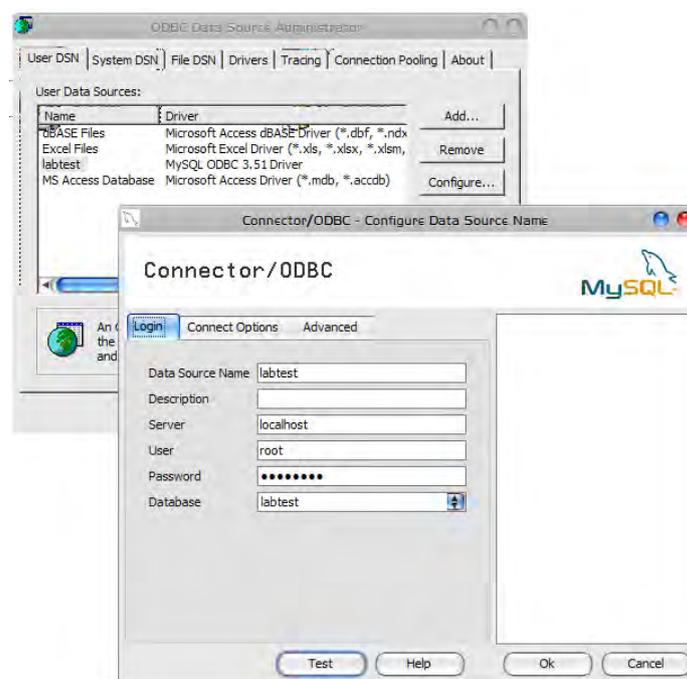
Figure B.8 the configuration of Open Database Connectivity (ODBC)

Figures B.10 - B.21 present the photos images with regard to the development of the remote control software for solid desiccant dehumidifier.

Figures B.10 - B.16 presents the interfaces/blocks of the Server module, including start-up, A/D (analogue-to-digital) conversion, video capture, data logging, off-line analysis, real-time processing, and sensor calibration.

Figures B.17 – B.21 present the interfaces of the Client module and the process of monitoring/controlling the working conditions of the system.
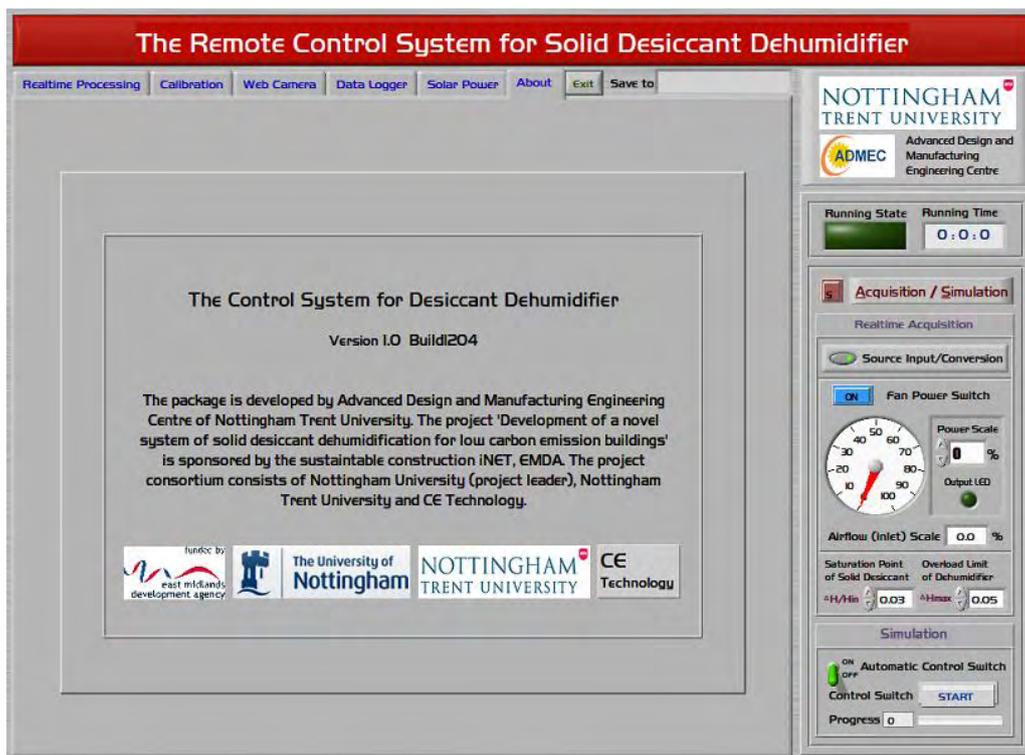
Figure B.10 Start-up interface of remote control system of solid desiccant
dehumidifier for air-conditioning
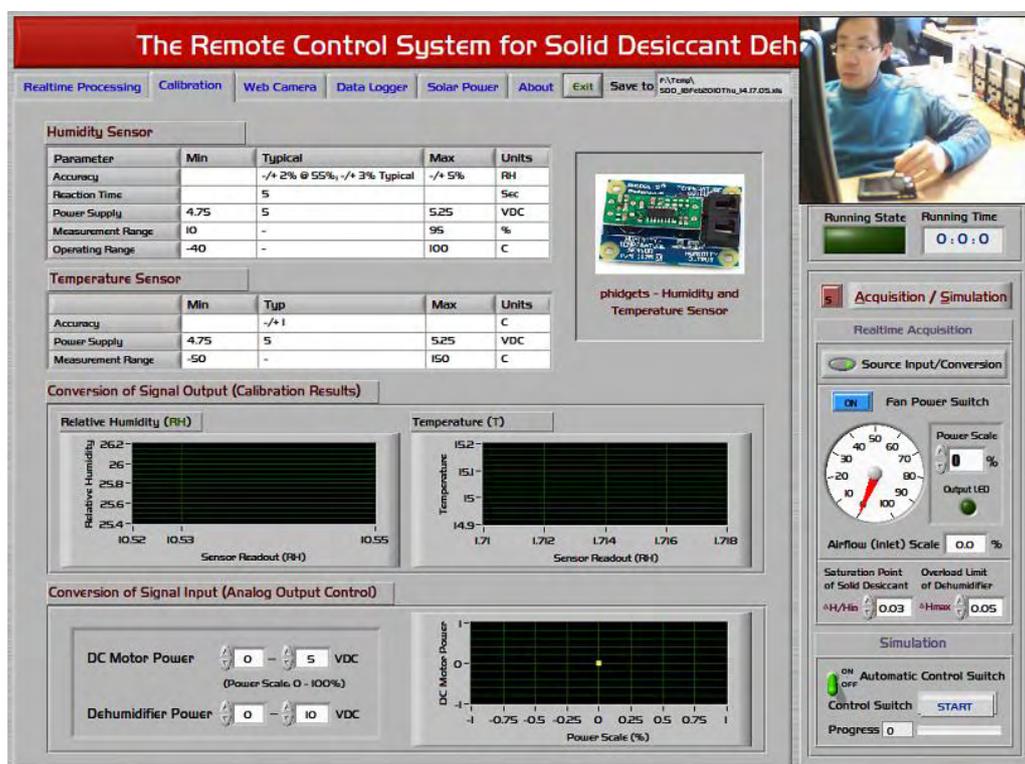
Figure B.11 A/D (analogue-to-digital) Conversion interface of remote control system
of solid desiccant dehumidifier for air-conditioning
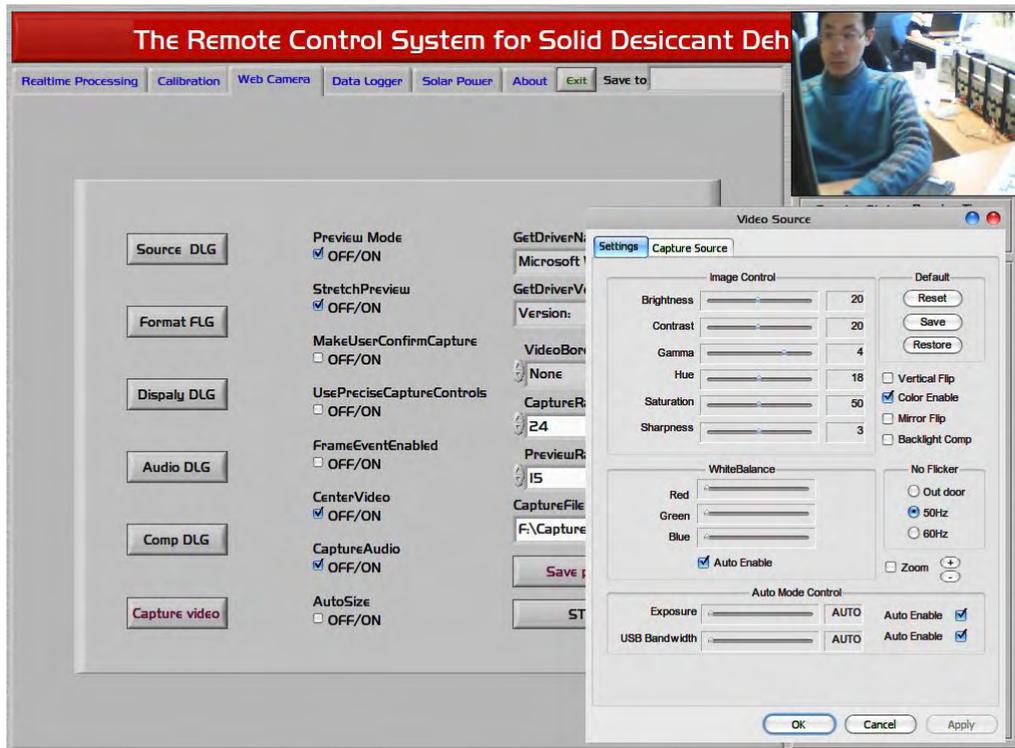
Figure B.12 Video Capture interface of remote control system of solid desiccant dehumidifier for air-conditioning
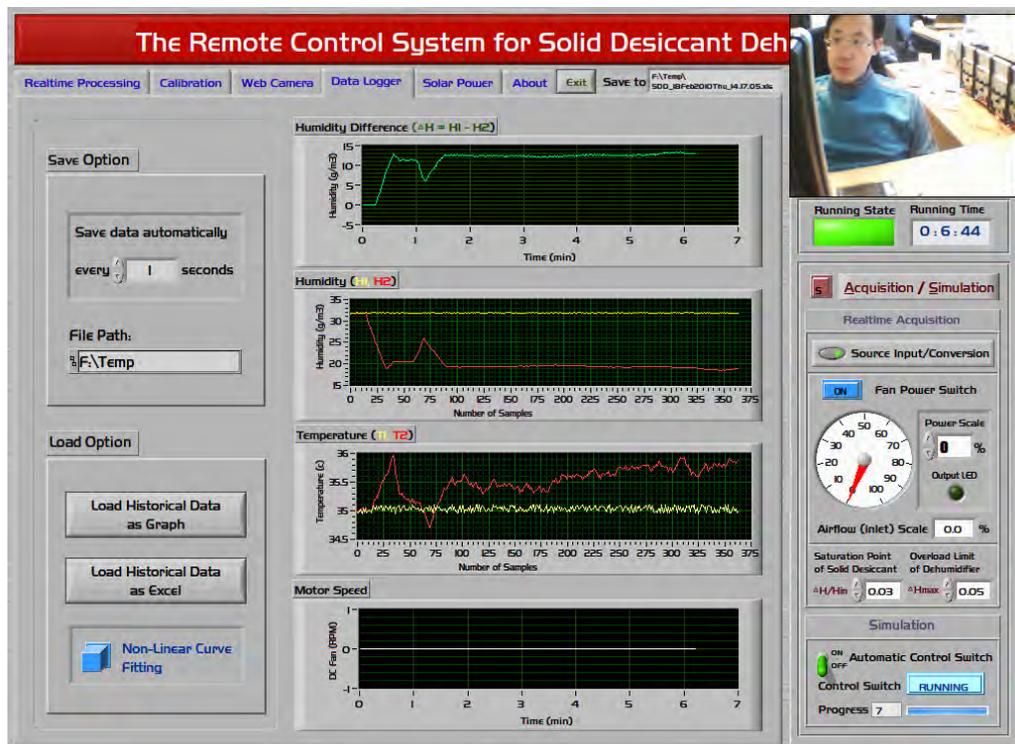
Figure B.13 Data Logging interface of remote control system of solid desiccant dehumidifier for air-conditioning
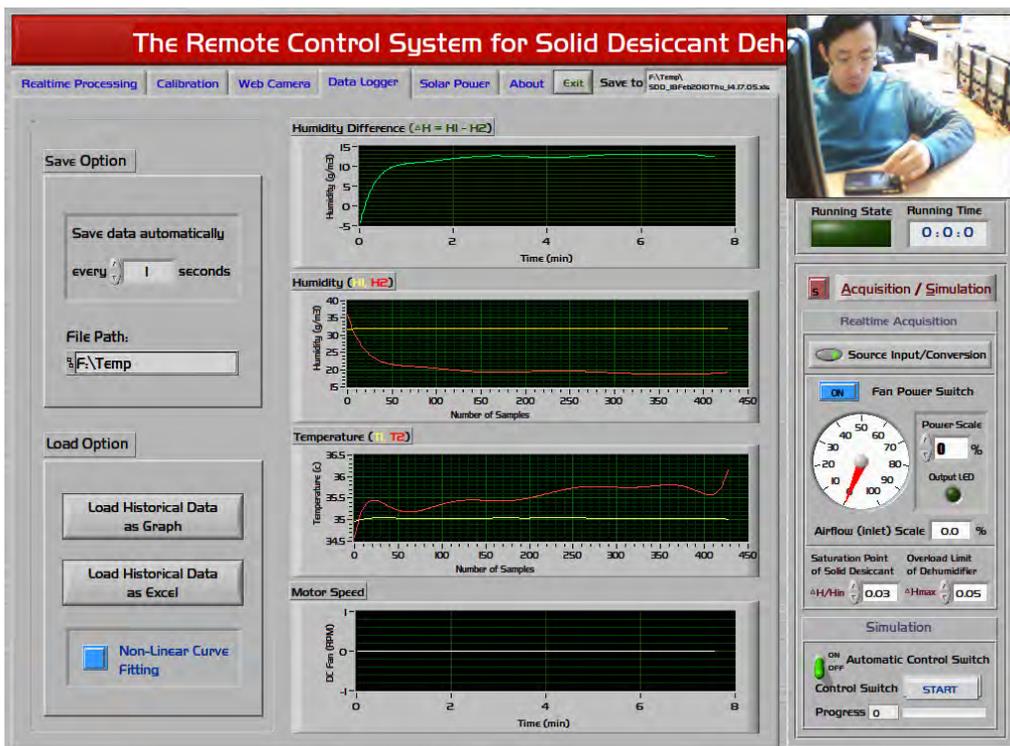
Figure B.14 Off-line Analysis interface of remote control system of solid desiccant dehumidifier for air-conditioning
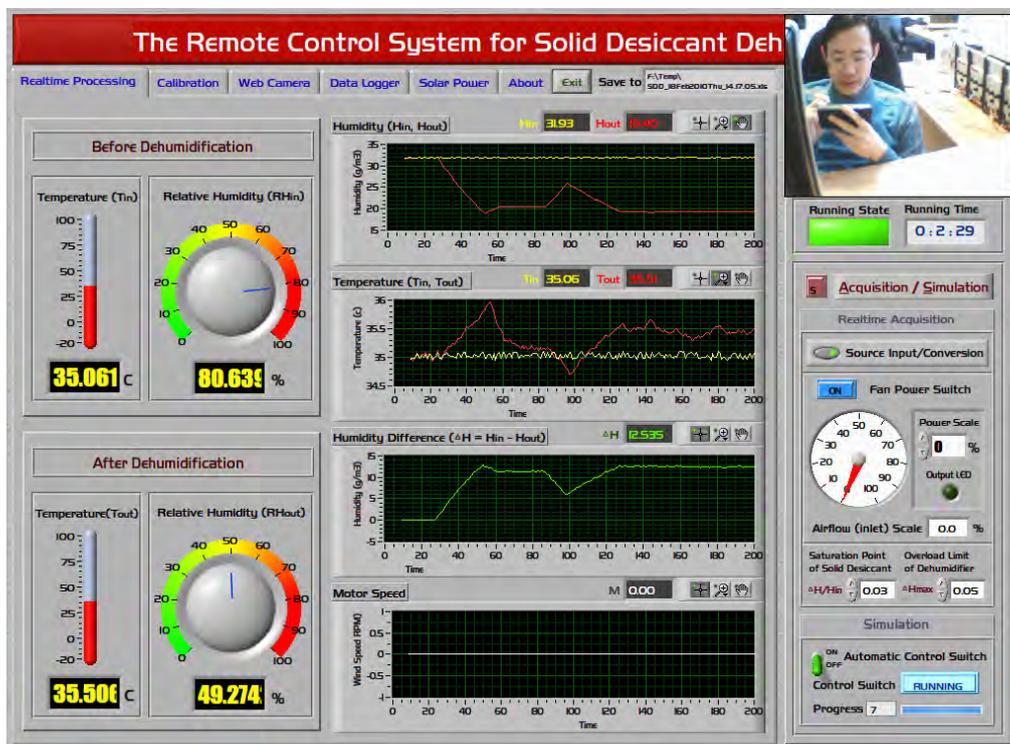
Figure B.15 Real-time processing interface of remote control system of solid desiccant dehumidifier for air-conditioning
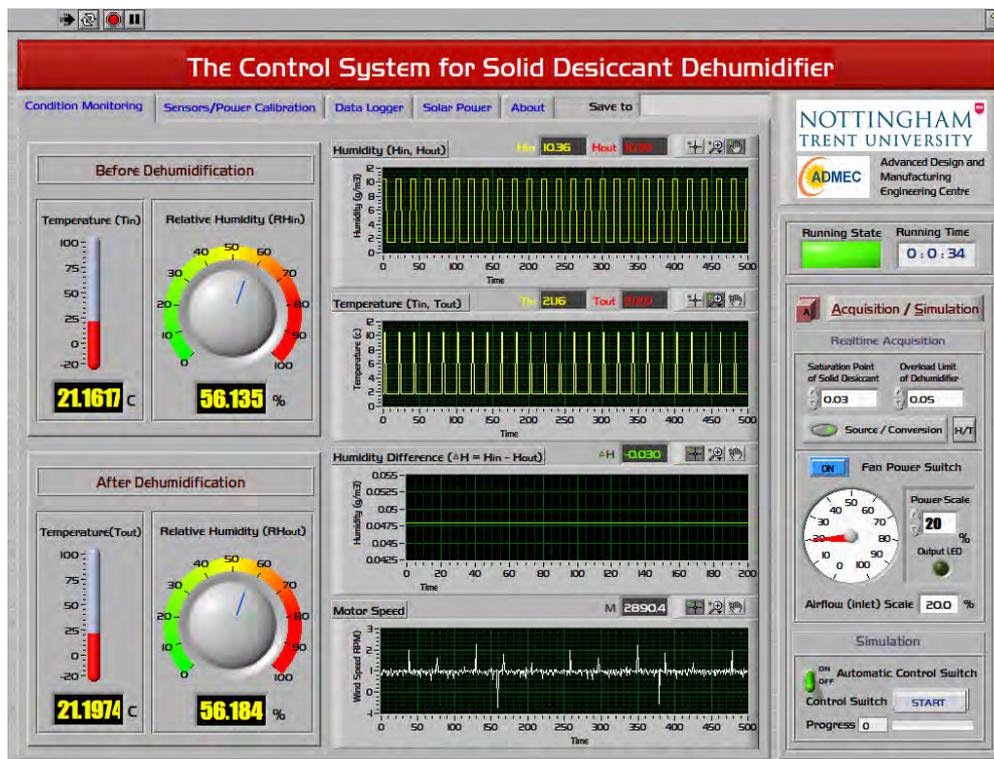
Figure B.16 Sensor calibration interface of remote control system of solid desiccant dehumidifier for air-conditioning
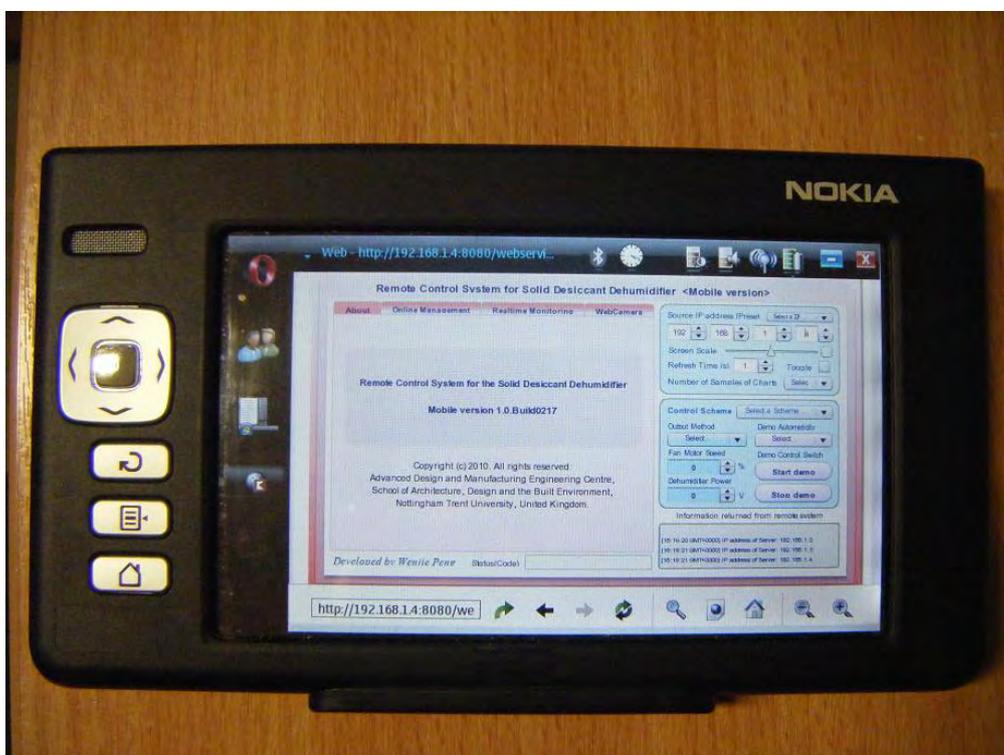
Figure B.17 Start-up interface of remote control system of solid desiccant dehumidifier for air-conditioning (Client)
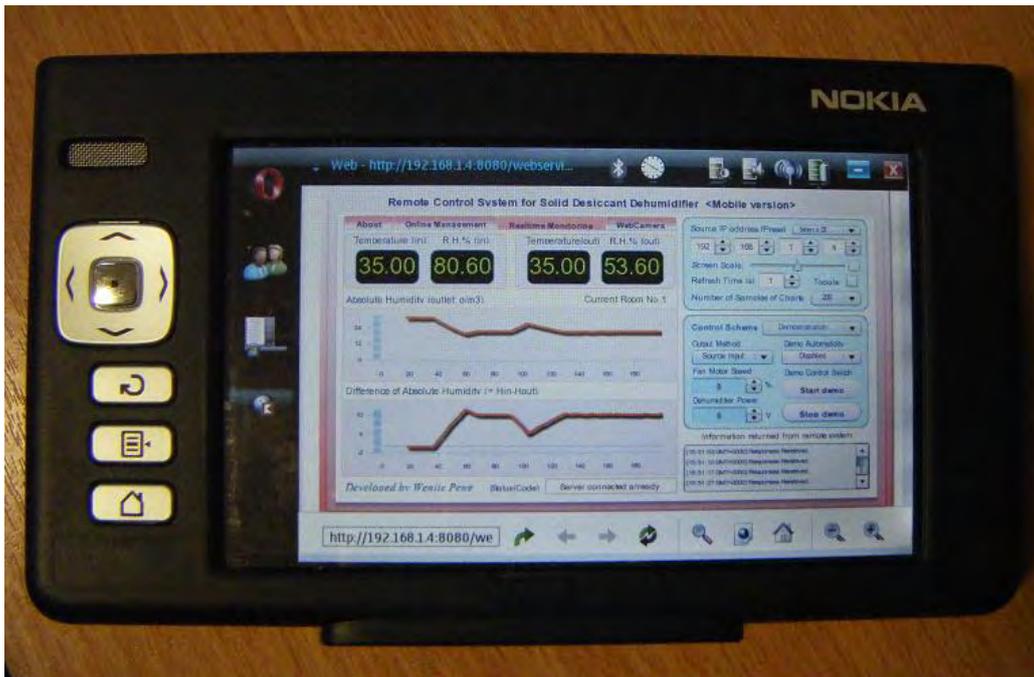
Figure B.18 Real-time monitoring interface of remote control system of solid desiccant dehumidifier for air-conditioning (Client)
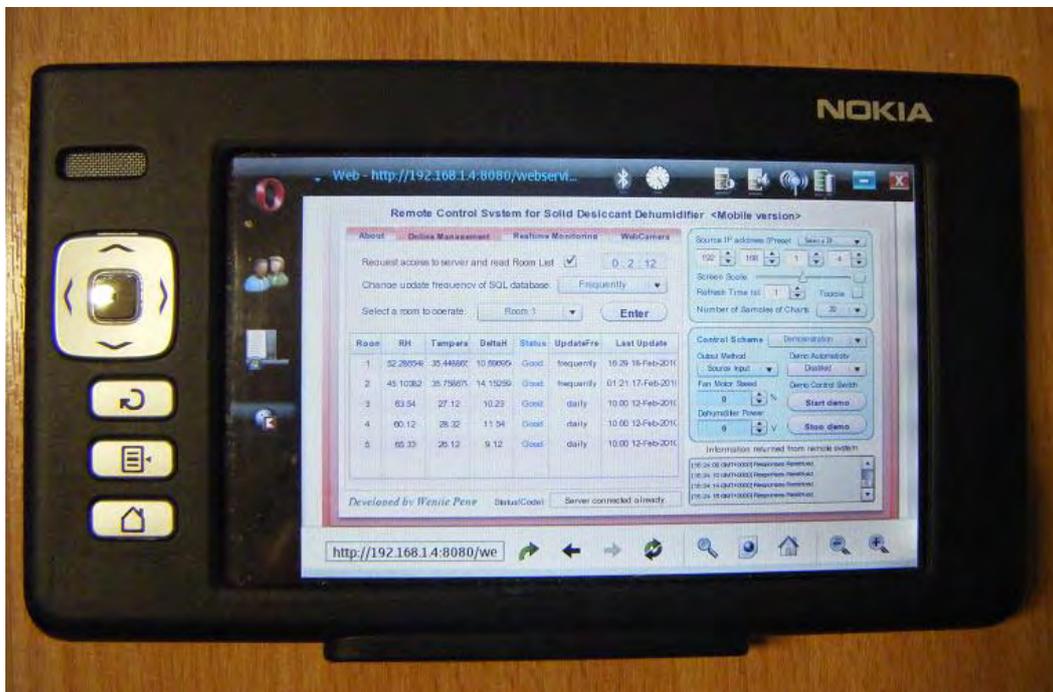
Figure B.19 Data management interface of remote control system of solid desiccant dehumidifier for air-conditioning (Client)

Figure B.20 remote video monitoring interface of remote control system of solid desiccant dehumidifier for air-conditioning (Client)
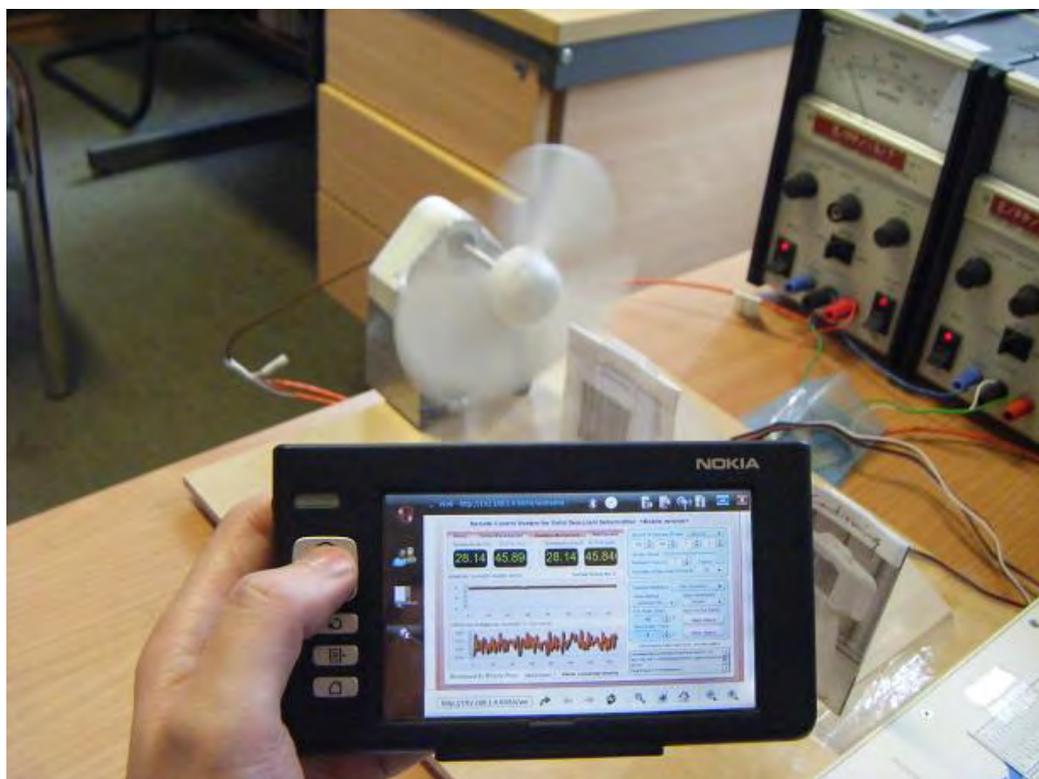
Figure B.21 Remote control interface of remote control system of solid desiccant dehumidifier for air-conditioning (Client)

Appendix (C) Development of the Remote Condition Monitoring Software for Thermo-Electric-Generations

The remote condition monitoring software of Thermo-Electric-Generations (TEGs) contains the Server and the Client module. Figure C.1 presents the work flow of the remote condition monitoring software of TEGs.

The Server module consists of the following programme blocks:

(1) Data acquisition, to collect the working conditions data form Thermo-Electric -Generations and convert the received analogue data into the quantities of the working conditions.

(2) System control for decision-making. System control is implemented based on the change of the water temperature of the tank. Once the water temperature of the tank is measured higher than the upper limit set, the water valve will be switched on and domestic water will be injected into the tank to reduce the water temperature of the tank.

(3) Remote communication via Web Service, to allow the user such as diagnosticians to remote access the working conditions data from the server, and regulate the working conditions of Thermo-Electric-Generations via the Internet and mobile phone network.

The Client module is developed to communicate with the Server module, and to monitor the working conditions of Thermo-Electric-Generations using mobile devices, such as mobile phones and PDAs.

Server module
(deployed in server computer)

Client module
(downloaded to the client mobile devices)

Initialisation

Launch Web server and FMS

Check network connection
(listen to Web port: 8080)

Send a request

Connect the server

Data acquisition and Processing

Decision Making

Warning

Faults?   Y

N

System control

Display data/results, and waveform

Log data into the database

Write data into XML

Return a response

Read the response and resolve data

Generate stream video

Return a stream

Display data/results, waveform, and video stream

Continue?   Y

N

Close

Continue?   Y

N

Close

Figure C.1 The work flow of the remote condition monitoring
software of Thermo-Electric-Generations

Figures C.2 - C.14 present the photos images about the development of the remote online condition monitoring software of TEGs. Figures C.2 - C.6 presents the interfaces/blocks of the Server module, including start-up, real-time processing, sensor calibration, A/D (analogue-to-digital) conversion, video capture, and data logging. Figures C.7 – C.14 present the interfaces of the Client module and the process of monitoring/controlling the working conditions of the system.
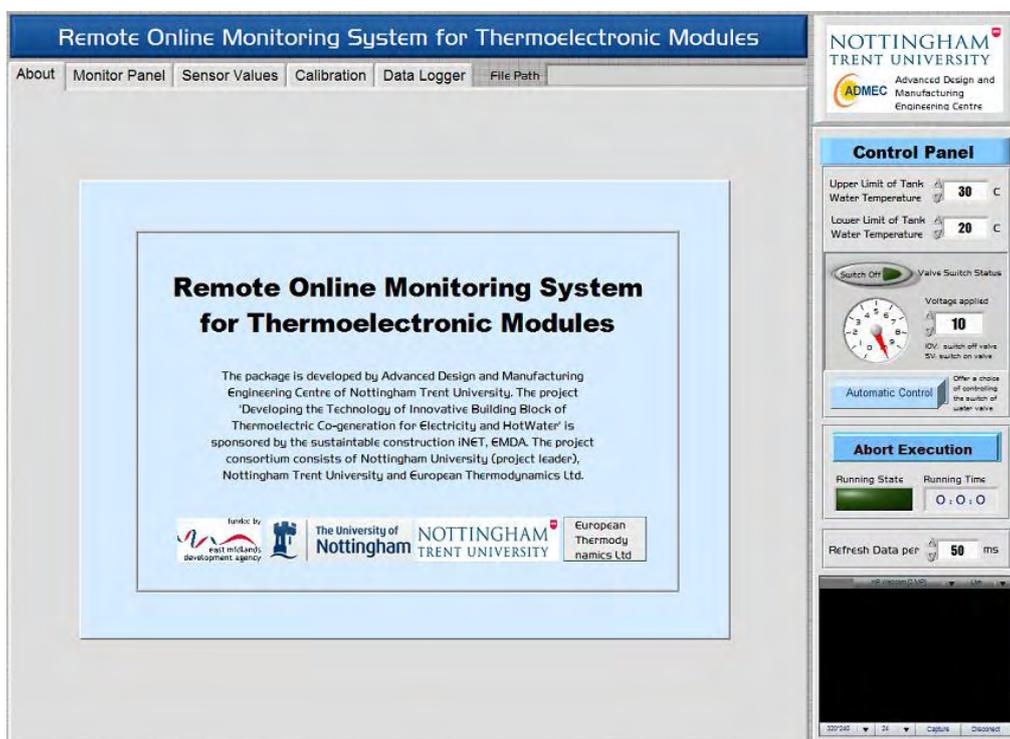
Figure C.2 Start-up interface of remote condition monitoring software of
Thermo-Electric-Generations
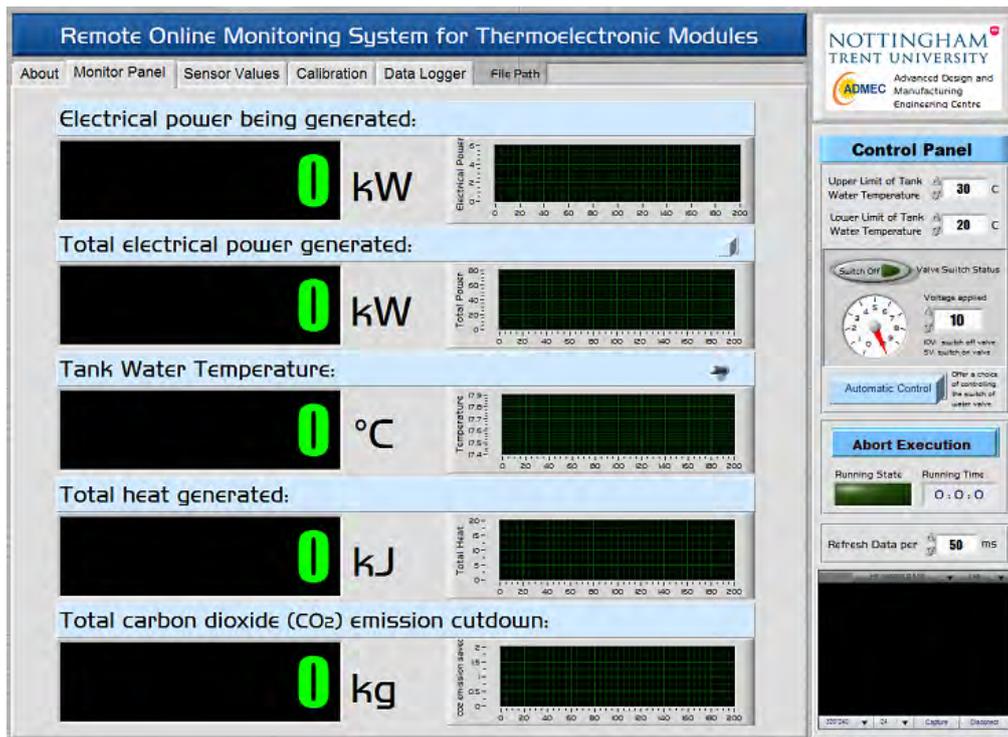
Figure C.3 Real-time processing interface (I) of remote condition monitoring software
of Thermo-Electric-Generations
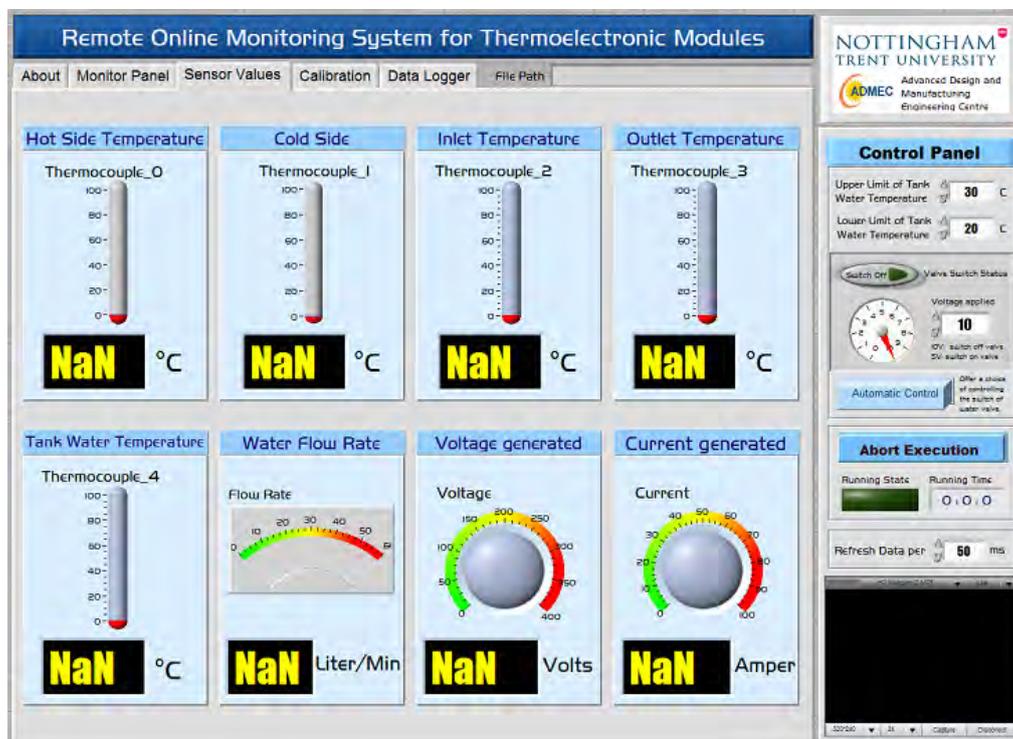
Figure C.4 Real-time processing interface (II) of remote condition monitoring software
of Thermo-Electric-Generations
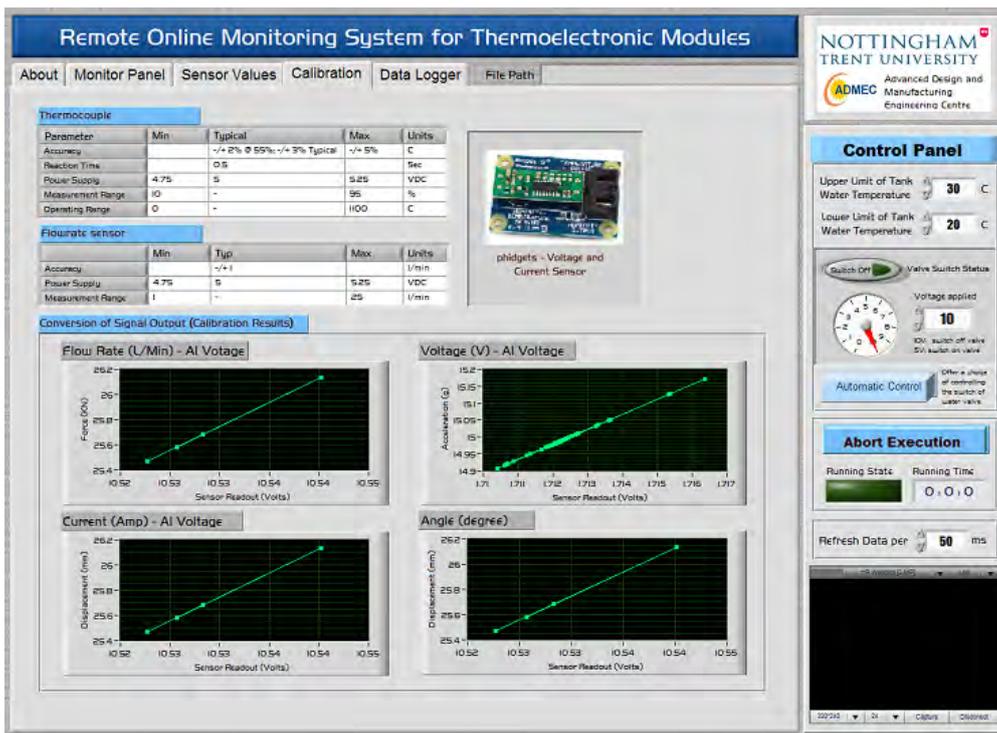
Figure C.5 Digital conversion interface of remote condition monitoring software of Thermo-Electric-Generations
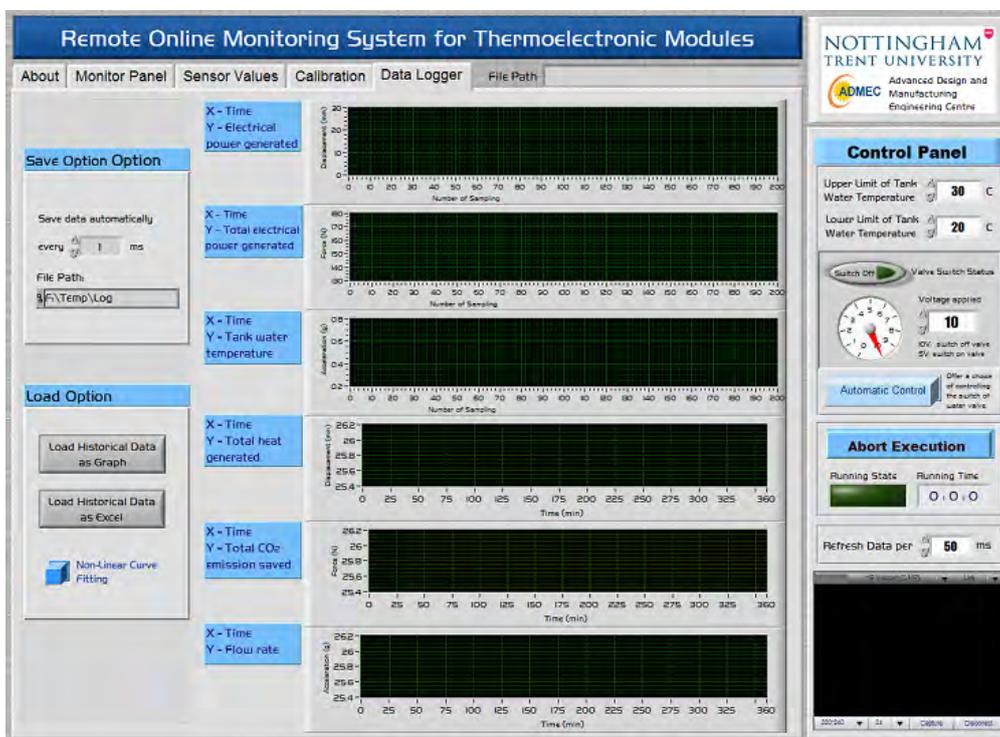

Figure C.6 Data logging interface of remote condition monitoring software of Thermo-Electric-Generations
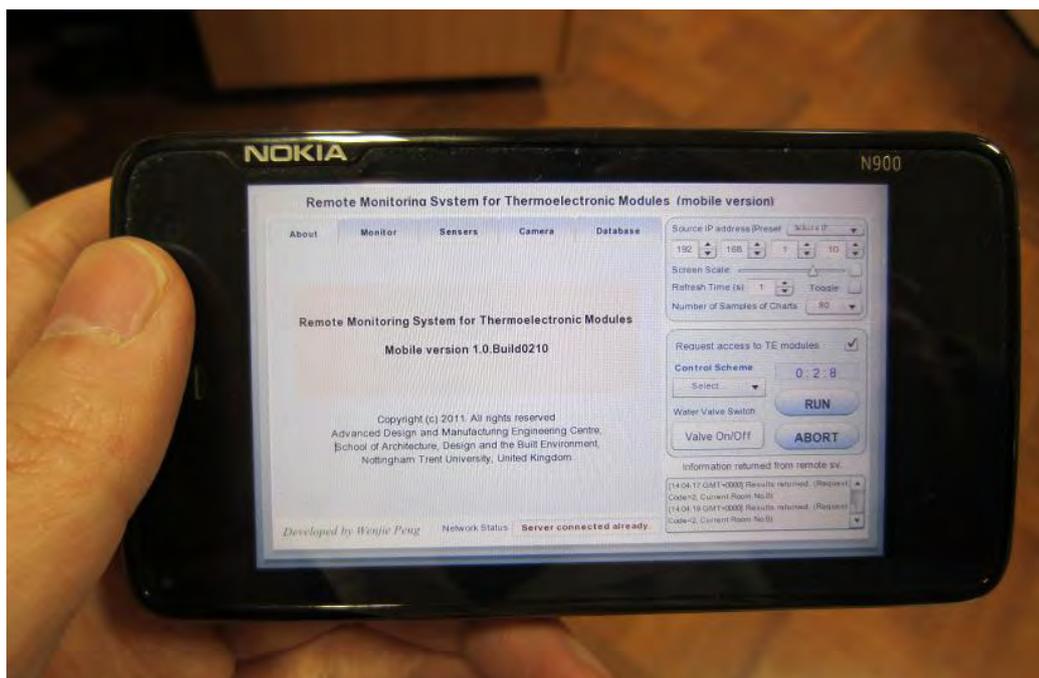
Figure C.7 Start-up interface of remote condition monitoring software of
Thermo-Electric-Generations (Client)
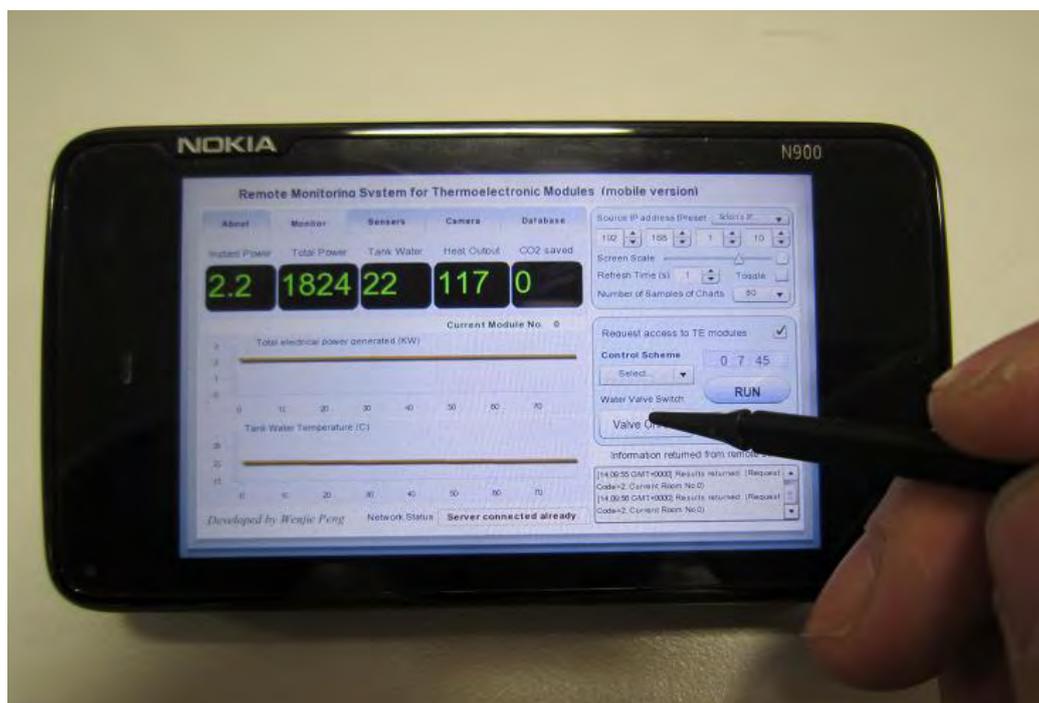
Figure C.8 real-time processing interface of remote condition monitoring software of
Thermo-Electric-Generations (Client)

Figure C.9 Real-time video display of Thermo-Electric-Generations using Nokia mobile phone

Figure C.10 Remote control of working conditions of Thermo-Electric-Generations using Nokia mobile phone
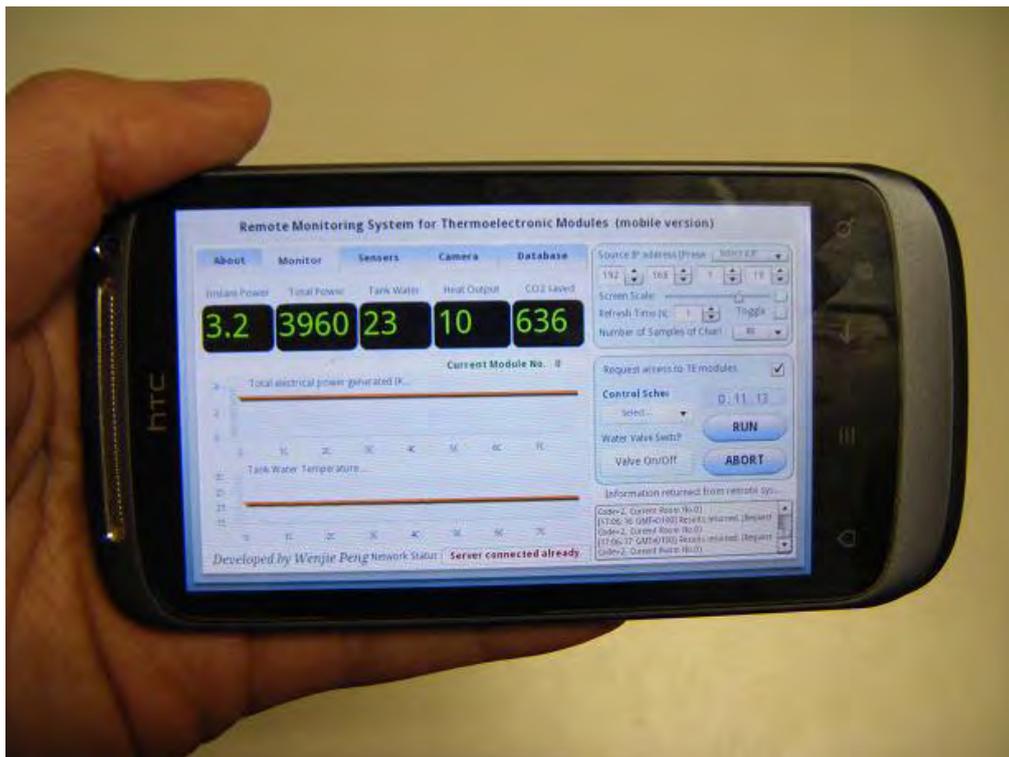
Figure C.11 Real-time processing interface of remote condition monitoring software of Thermo-Electric-Generations using HTC mobile phone


Figure C.12 Real-time acquisition interface of remote condition monitoring software for Thermo-Electric-Generations using HTC mobile phone

Figure C.13 Real-time processing interface of remote condition monitoring system for Thermo-Electric-Generations using HTC mobile phone
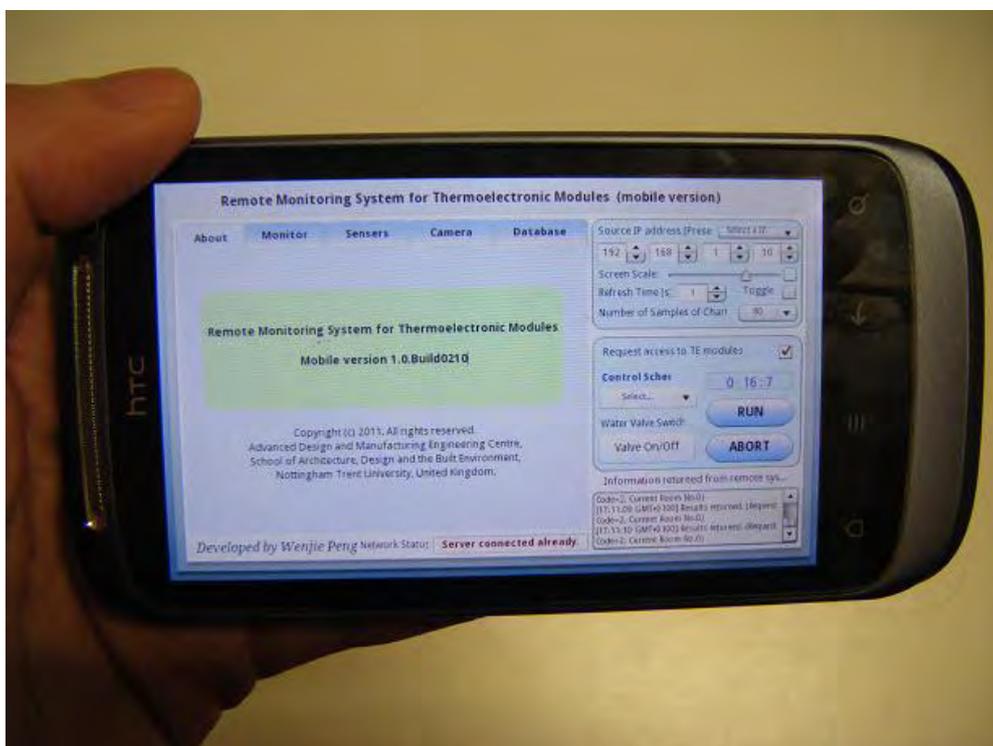

Figure C.14 Real-time processing interface of remote condition monitoring software for Thermo-Electric-Generations using HTC mobile phone