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Failure Data Acquisition System Based on WSN for Vehicle PHM Technology

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Abstract: Prognostic and health management (PHM) technology needs plenty of historical failure data to build accurate model for failure analysis, diagnostic and prognostic. However the existing data collection equipment is not flexible enough for special vehicle because of the wired connection or lack of real-time information feedback in real vehicle experiment. A new failure data acquisition system based on wireless sensor network is proposed to acquire the sufficient historical failure data for the development of vehicle PHM technology. The proposed system architecture consists of several wireless failure data acquisition (WFDA) nodes, a gateway node, monitoring software and probability density ratio (PDR) algorithm working on a base station. Compared with other related acquisition systems, the WFDA node is small enough and suitable for working in a narrow space inside the vehicle. A double-buffer resampling strategy is specifically developed in this node to solve the contradiction of high sampling rate and low wireless bandwidth. The PDR algorithm embedded in monitoring software is used to detect abnormal data and show researchers the analysis results which can be relied to change the test item in time. Experiments results in the laboratory preliminary verified the effectiveness of system.

Keywords: Vehicle Failure Data, Wireless Sensor Network, PHM, Vehicle Test, Abnormal Detection

1. Introduction

The integrity and complexity of modern system have been rapidly improved in recent years, and the cost of the development, production, maintenance and support also has great growth. Many factories and enterprises have a huge demand on system reliability since any minor fault will cause disastrous consequences. Therefore, Prognostics and Health Management (PHM) technologies have emerged as a key enabler to provide early indications of system faults and perform predictive maintenance actions [1].

PHM is a method that permits the reliability of a system to be evaluated in its actual life-cycle conditions, to determine the advent of failure, and mitigate the system risks [2]. For now, PHM has got rapid development and is widely applied in many fields, such as electronic system [3-4], vessel equipment [5], aircraft [6], unmanned system [7], large industrial equipment [8], structure monitoring [9].

In automobile industry, many researchers also have come up with the related PHM system [10-12]. Mark P. Zachos and Karl E. Schohl developed a mini-vehicle computer system—smart wireless internal combustion engine (SWICE) for the internal combustion engine maintenance of their fleet of tactical wheeled vehicles [10]. Eric Rabeno and Matt Hillegass put forward a health and usage monitoring system for Military ground vehicle power generating devices [11]. Sreerupa Das *et al*. described an extensible architecture for a Ground Vehicle Health and Usage which can be adopted to provide diagnostic and prognostic for vehicles by the on-board subsystem and off-board software component [12].

Whichever PHM system it is, the sufficient historical failure data are actually the most important resource for failure analysis, diagnostic and prognostic. However, the accumulation of failure data often take months or even years considering the fault propagation characteristics. To deal with this problem, two ways are discussed [13]: 1) using prototypes for data collection or 2) creating the failure progression unnaturally. Whereas, the increasingly complex modern systems pose new challenges for PHM. One of the most prominent problems is called No Fault Found (NFF) problem (related terminologies include “cannot duplicate,” “re-test OK,” and “trouble not identified) [14]. That is to say, many failure data gathered in the library or the testing bench could not fully reflect the equipment fault rule or the performance degenerating law, especially for the special vehicle working in complex environment. Consequently, the data collected in the actual vehicle test is necessary for data-analysis in order to build more exact prognostic models, which improves prognostic precision.

There are two common existing actual vehicle data acquisition equipment. One is vehicle data recording system used in vehicle working stage which has low processing performance and sampling rate. So, this kind of equipment can only be used to record whether the fault is generated but not supply adequate high frequency information for further prognostic analysis. The other one is a special test equipment used in vehicle test stage which is usually large and needs a great number of connecting wires. So, it is difficult to install and wire in such a narrow space inside the vehicle. In addition, this equipment could not show the test result in time and provide hints for the researchers in test site because of the fixed operation mode.

Wireless Sensor Network (WSN) provides a new method for solving above problem. WSN has been applied extensively in the fields of environmental monitoring, intelligent power plant, agricultural agriculture irrigation, etc. [15-17]. It has been also accepted in the field of condition monitoring and fault detection [18-21]. Shunfeng Cheng *et al*. developed a radio-frequency-based WSN system which can be used to detect anomalies, assess degradation, and predict failures. This system use RFID technology and on-board flash memory to transfer and store the data. The storage and transfer rate is not very high for the long-term field test [18]. Jan Neuzil *et al.* proposed a novel IWSN framework for machine condition monitoring based on splitting the data acquisition, classifier building and training between different units [19]. The system is realized in Crossbow WSN which is a Commercial-off-the-shelf (COTS) and not suitable for the vehicle test. Abel C. Lima-Filho *et al.* proposed an embedded WSN system to monitor dynamic torque and efficiency of induction motors [20]. Only useful monitoring information can be transferred and all signal processing is done locally in this system. In contrast to our approach, the system described in ref. [20] is just suitable to monitor, but do not offer data for further analysis.

Although the above WSN system has good performance in their applications, some shortcomings limit their development in vehicle test: a) Most COTS WSN system could not meet the requirement of vehicle test environment, such as high temperature and vibration. b) System size is not small enough for working in some narrow space. c) Some systems are only suitable for monitoring and could not offer high sample rate and real-time data transmission.

This paper proposes a wireless failure data acquisition system which can provide enough support for the development of PHM system. Our system consists of some wireless failure data acquisition nodes, a gateway node, the monitoring software and related algorithm. Compared with the above mentioned systems, it has the following characteristics: a) This system is specifically developed for vehicle test which is small and adapted to harsh operation condition. b) The acquisition node realizes not only the high data acquisition and storage for further analysis but also real-time data transmission by resample strategy. c) Large amounts of normal data which have little contribution to modelling will be collected in vehicle test. However, researchers are most concerned about data before and after fault. So, they have to waste a lot of time to find the useful information from all collected data. The monitoring software and algorithm in this system not only could detect and display the abnormal data in time but also record the timing of the appearance of abnormal data for further analysis. So, the researchers can adjust the test content in time according to the analysis result.

This paper is organized as follows. In Section 2, the failure data acquisition system architecture is presented. In Section 3, the hardware and software of WFDA Node is described. In Section 4, the gateway node is proposed. In section 5, the experiment evaluation methodology is discussed. Finally, some conclusions end this paper.

2. Failure Data Acquisition System Architecture

The failure data acquisition system (FDAS) shown in Figure 1 is composed of several wireless failure data acquisition (WFDA) nodes, a gateway node, a monitoring software and related detection algorithm working in a base station which could be a laptop or a vehicle embedded computer.

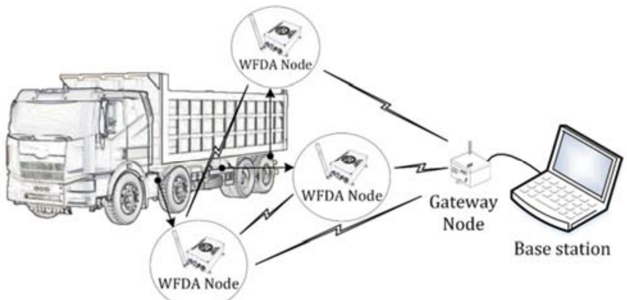


Figure 1. *Failure Data Acquisition System Architecture.*

The WFDA node is responsible to collect the vehicle operating data which is stored locally and concurrently sent to the gateway node. A double-buffer resampling strategy is developed to solve the contradiction of high sampling rate and low wireless bandwidth. The gateway node is utilized to receive data from WFDA nodes and transfer data to the base station through Ethernet bus. The monitoring software is used to send control commands and display received data. The probability density ratio algorithm embedded in the monitoring software detect abnormal data and show researchers the analysis results which can be relied to change the test item in time. The functional block is illustrated in Figure 2.

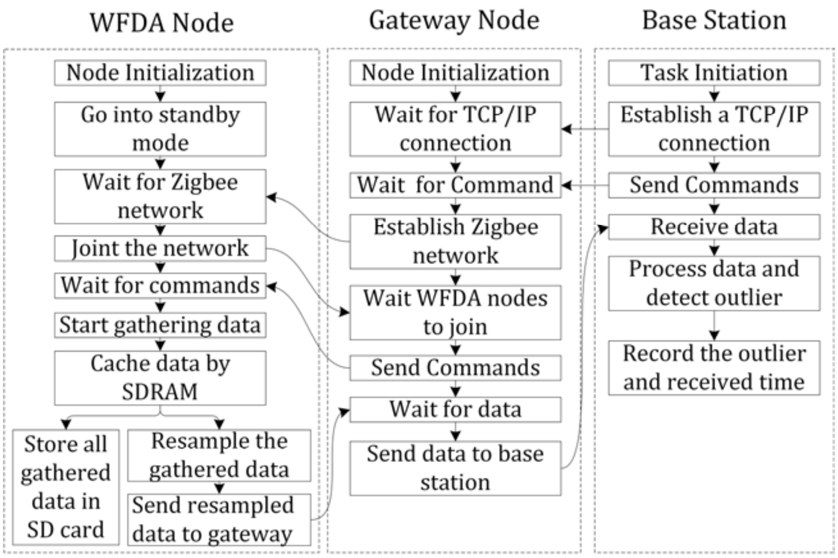


Figure 2. *Functional blocks of FDAS.*

3. Design of Wireless Failure Data Acquisition Node

The function of the WFDA Node is to gather all kinds of signals from vehicle intercom system, such as temperature, vibration, pressure and rotating speed. After this, the acquired data is stored into SD card and simultaneously transferred to the gateway node.

For PHM technology, the acquired fault data is used to build diagnostic and prognostic model. So, a high sample rate is needed to realize the frequency domain analysis or time-frequency domain analysis. However, the traditional wireless sensor network node has limited computational capabilities, which could not meet the demand of FDAS. In this paper, a new hardware and software architecture of WFDA node is proposed to solve the problem. FPGA is used as microcontroller to achieve the high-speed data flow. A double-buffer resampling strategy is developed for the real-time storage and transmission.

3.1. Hardware Design

The WFDA Node consists of A/D converter, microcontroller, SDRAM, EPCS, SD card and wireless module, as is shown in Figure 3.

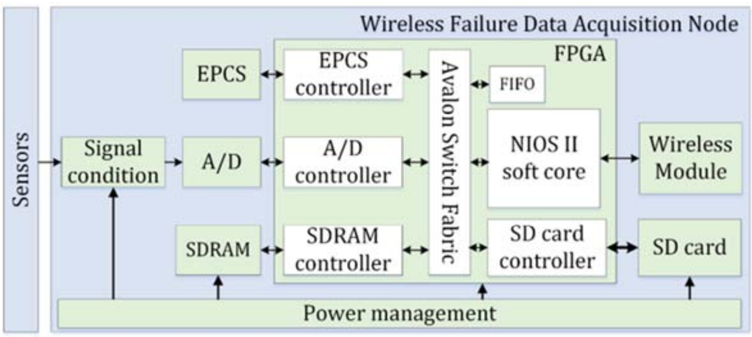


Figure 3. *A block diagram of the WFDA node.*

The Cyclone II FPGA is selected as the microcontroller which is an important part of the node including the A/D controller to control sampling, FIFO controller to buffer the acquired data, SD controller to storage data, NIOS soft core to control the whole system as a CPU. All controllers inside the FPGA communicate with each other through Avalon bus. In addition, the FIFO controller and SD controller specially designed by VHDL language are key components to realize the double-buffer strategy. Both of the controllers synchronously completed the data transmission and storage without taking CPU working time.

SDRAM provides space for program and data buffer. SD card supplies 8G storage space and features a maximum writing speed 2MB/s through SDIO communication mode because of the existing of SD card controller. A simplified FAT32 file system is utilized to manage the stored data.

Each WFDA node is powered by a rechargeable battery. The power management modules are LT3509 and TPS70245, which respectively provides 5V, 3.3V and 1.2V power supply. The wireless module could control the on-off of TPS70245 for cutting down power consumption when the nodes work in standby mode.

The JN51458 module from NXP corporation is chosen as the wireless module. This module is based on Zigbee protocol which has low power consumption, high security and flexible networking mode. This module is integrated with a 32bit CPU, RF component and other peripheral interfaces which can be used to join the network built by gateway node and receive the commands to realize data transmission.

The picture of the WFDA node has been shown in Figure 4. The size of this node is 70×40×30mm.

Figure 4. Picture of WFDA node.

3.2. Software Design

1) The strategy of storage and real-time transmission

Given that analysis requirement of some vehicle components, the highest sampling rate of each node is designed to be 1Msps in this WDFA node. What's more, the data resolution of A/D converter is 12 bit and 4 bit channel number is added for every sample data. So the highest data speed is 2MB/s and the writing speed of SD card has to meet the demand. However, the traditional soft control program can only reach several hundreds of kilobytes. Therefore, a SD controller designed by VHDL hardware language is proposed and a double-buffer strategy realized by FIFO and SDRAM is utilized for real-time storage. In addition, the transmission rate of wireless module is just 500kb/s, so it can not realize real-time transmission. For solving this problem, a resampling strategy is come up which could transfer the partial acquired data at regular intervals for real time observation. The data flow is shown in Figure 5.

The whole working process according to the data flow can be described from Process A to Process E.

Process A: A/D converter acquire data by 12bit/sample.

Process B: A/D controller send data to FIFO by 16bit at a time. FIFO size is 16kB.

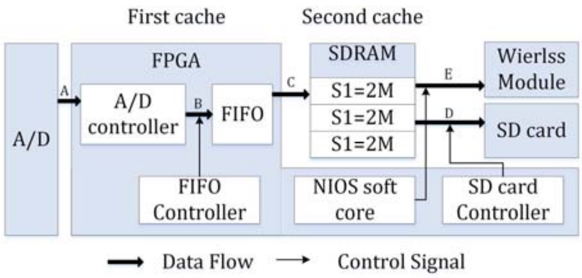


Figure 5. Block diagram of data flow.

Process C: Once FIFO controller receives the *read quest signal* (rdreq) which occurs by FIFO, data is read from FIFO to SDRAM. When the FIFO controller send 2M data, a signal is generated to tell SD controller read data from SDRAM.

Process D: SD controller write data to files in SD card by 2MB at a time. The file system used in this paper is different from the standard one considering the writing speed. We directly write the file information into the defined user table instead of the standard file allocation table. Moreover, the data is stored into specified block that each block size is 0.5kB. 2MB data is written in 4000 blocks at a time. Figure 6 shows the file system structure.

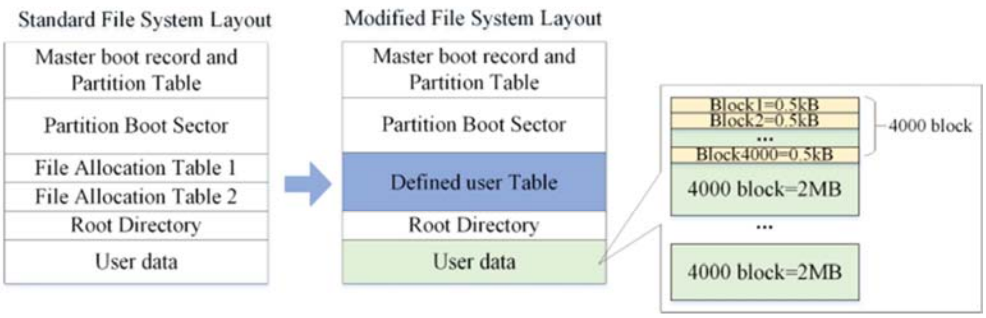


Figure 6. The modified file system.

Process E: The NIOS soft core read 1 sample point every 2000 acquired samples from SDRAM, just like resampling. It is emphasized that all these 2000 samples have been stored in SD card as is shown in Process D. Once it has read up to 40 samples, the samples are sent to wireless module by SPI bus. Then the wireless module build the data frame and send it to the gateway node. The process can be described as Figure 7.

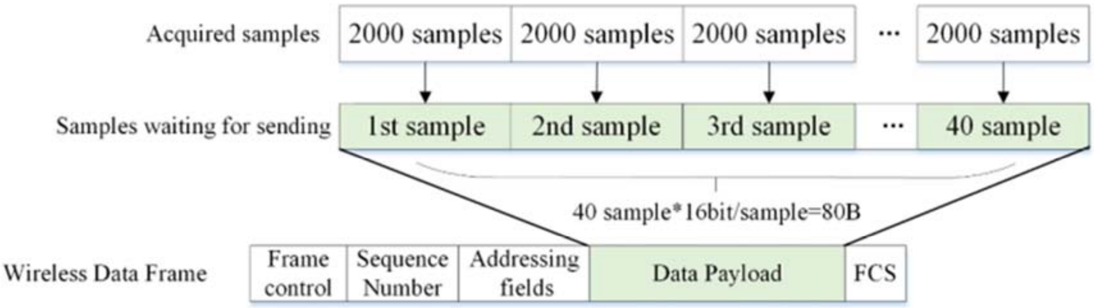


Figure 7. *The process of building data wireless data frame.*

2) Network communication strategy

The network topology takes a mesh shape with a coordinator and several routers in the network. The gateway node is configured as a coordinator and each WFDA node is configured as a router. The software of wireless communication is based on the jennic operating system (JENOS) which provides an interface that simplifies the programming of a range of operation with. The software architecture includes MAC layer, Zigbee pro stack layer and application layer from the bottom to top. This paper create four tasks in application layer for realizing basic function. App_taskRouter is a task for network function. App_taskMyEndpoint is a task for receiving commands. APP_TaskSendSensor is a task for sending acquired data. APP_TaskSendTopo is a task for sending topology information. The top-level design of programming is based on graphic pattern and partial program codes have been shown in Figure 8.

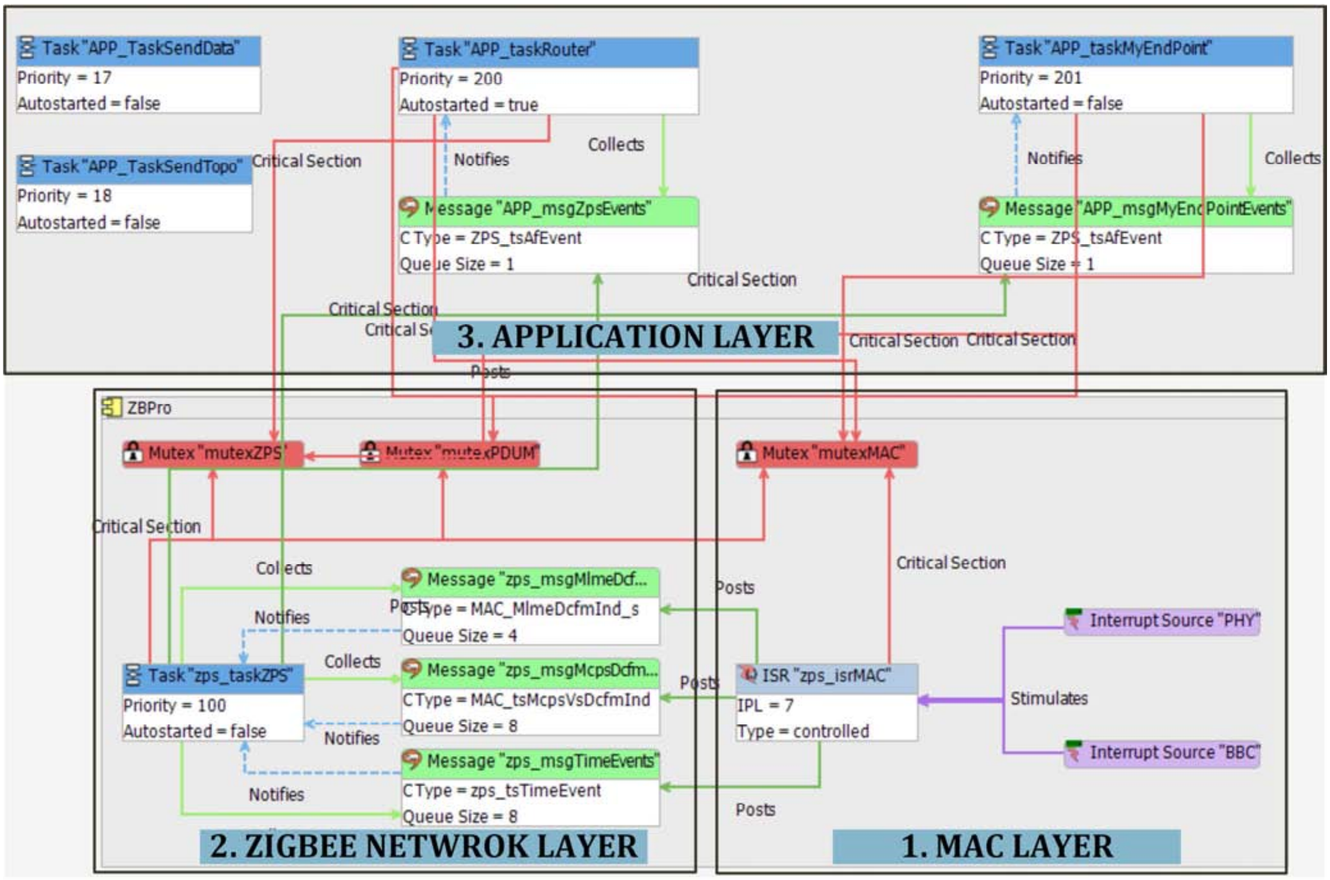


Figure 8. *Partial program codes of wireless module.*

4. Design of Gateway Node

The gateway node is equipped with wireless module, Ethernet interface module, flash module and power management module, as is shown in Figure 9. The Wiznet w550io module is selected as the Ethernet model. The function of this device is to build the test network, send commands and receive data which is transferred to base station through the Ethernet bus.

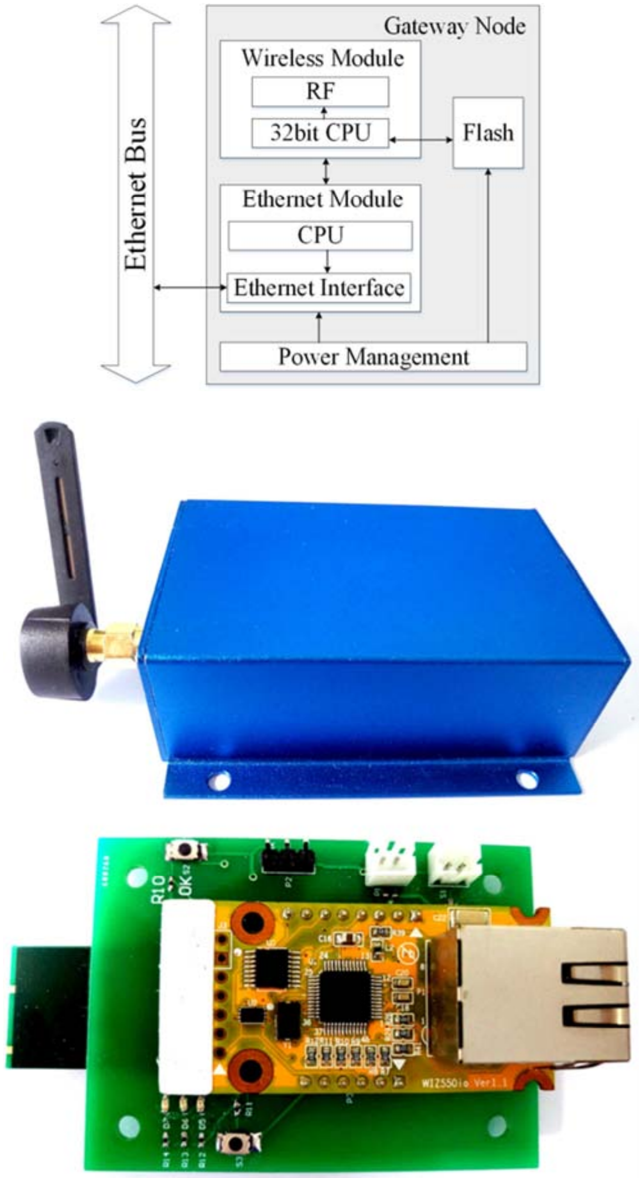


Figure 9. *Block diagram and picture of the gateway node.*

5. Design of Monitoring software and Algorithm

5.1. Monitoring Software

The monitoring software is developed by NI LabVIEW, a graphical programming environment which can be used to rapidly develop user interfaces for data visualization and user input with an easy-to-use drag-and-drop interface. Furthermore, LabVIEW also integrates graphical, text-based, and other programming approaches within a single environment to efficiently develop algorithms for data analysis and advanced control.

The monitoring software developed in this paper is composed by front panel and back panel. The front panel provides graphical indicators and waveforms to observe the data in real time. In the back panel, the program can be divided into three parts which are respectively data acceptance through Ethernet bus, data display, data analysis by probability density ratio algorithm.

5.2. Probability Density Ratio Algorithm

The PDR algorithm is a flexible tool which can detect fault using the normal information, so it needs not to know the type of outlier in advance. The probability patio density of the training samples and test samples can be utilized to describe abnormal condition, as is shown in (1).

$$\omega(x) = \frac{p(y)}{p(x)} \tag{1}$$

Where, y is the training sample series, and x is test sample series. $p(y)$ is training samples probability. $p(x)$ is test samples probability. $\omega(x)$ is the normal degree of test samples which would be near to 1 when the test samples is close to the training samples which are the normal status samples and would deviate from 1 when the test sample is abnormal.

In order to simply the calculation, the density patio module is converted into a linear module which can be described by (2).

$$\omega_\alpha(x) = \sum_{j=1}^{n} \alpha_j \psi_j(x) = \alpha^T \psi(x) \tag{2}$$

α is linear module parameter, $\psi(x)$ means basis function which is described by Gaussian Kernel Function $\exp\left(-\frac{\|x-y\|^2}{2\sigma^2}\right)$ in this paper. σ is the width argument. $\|x-y\|^2$ is the distance between test sample and normal sample.

σ and α can be solved by the cross-validation method, so the final equation can be determined by (3)

$$\omega_\alpha(x) = \sum_{j=1}^{n} \alpha_j \exp\left(-\frac{\|x-y\|^2}{2\sigma^2}\right) \tag{3}$$

6. Experiment Validation

To verify the effectiveness of this system, this system is used to measure the simulation signal and show the storage, transmission and analysis results in our laboratory, as is shown in Figure 10.

The simulation data comes from Western Reserve University Bearing Data Centre which provides ball bearing test data of normal and faulty bearings [24]. The dataset includes acceleration data which was measured from the motor bearings. Part of the normal status data was chosen for training data. Part of the normal status data and part of the faulty status data was respectively chosen for testing data.

The testing data was output by NI PXI equipment which consists of PXI-1062Q chassis, PXI-8135 controller, PXIe-6558 analog input/output board. The output data was acquired by the WDFA node. Then the data was transferred to the gateway node. At last, the gate way node transferred data to the laptop as a base station. The data is displayed by monitoring software and analysed by PDR algorithm.

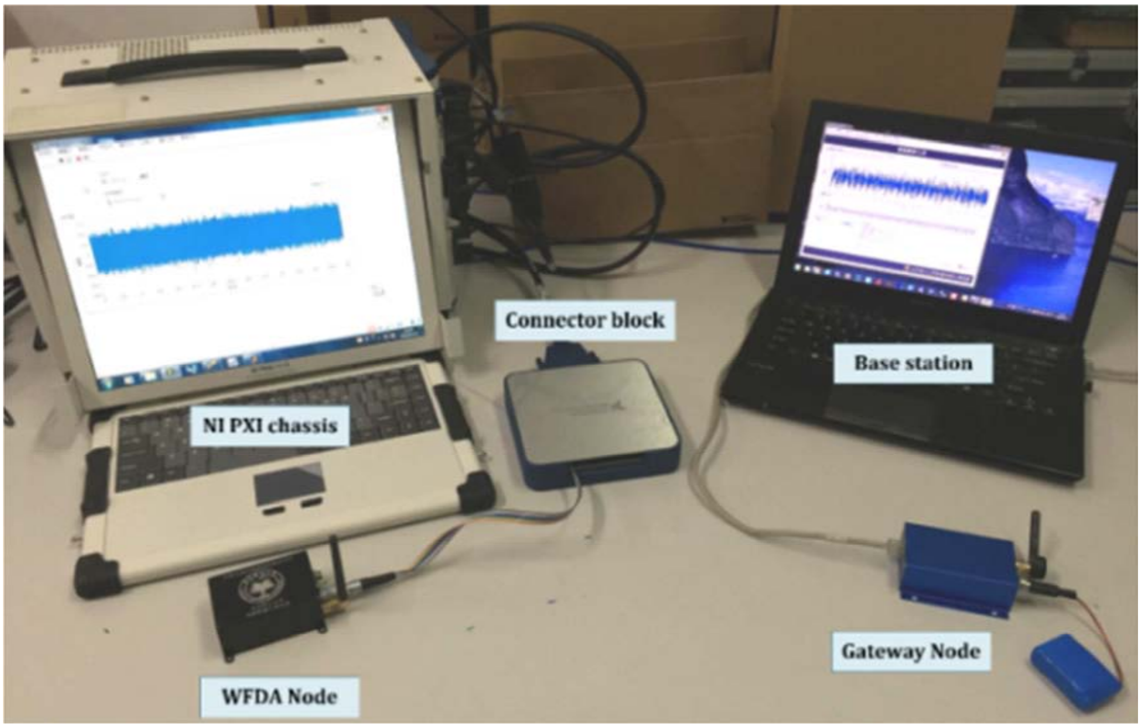


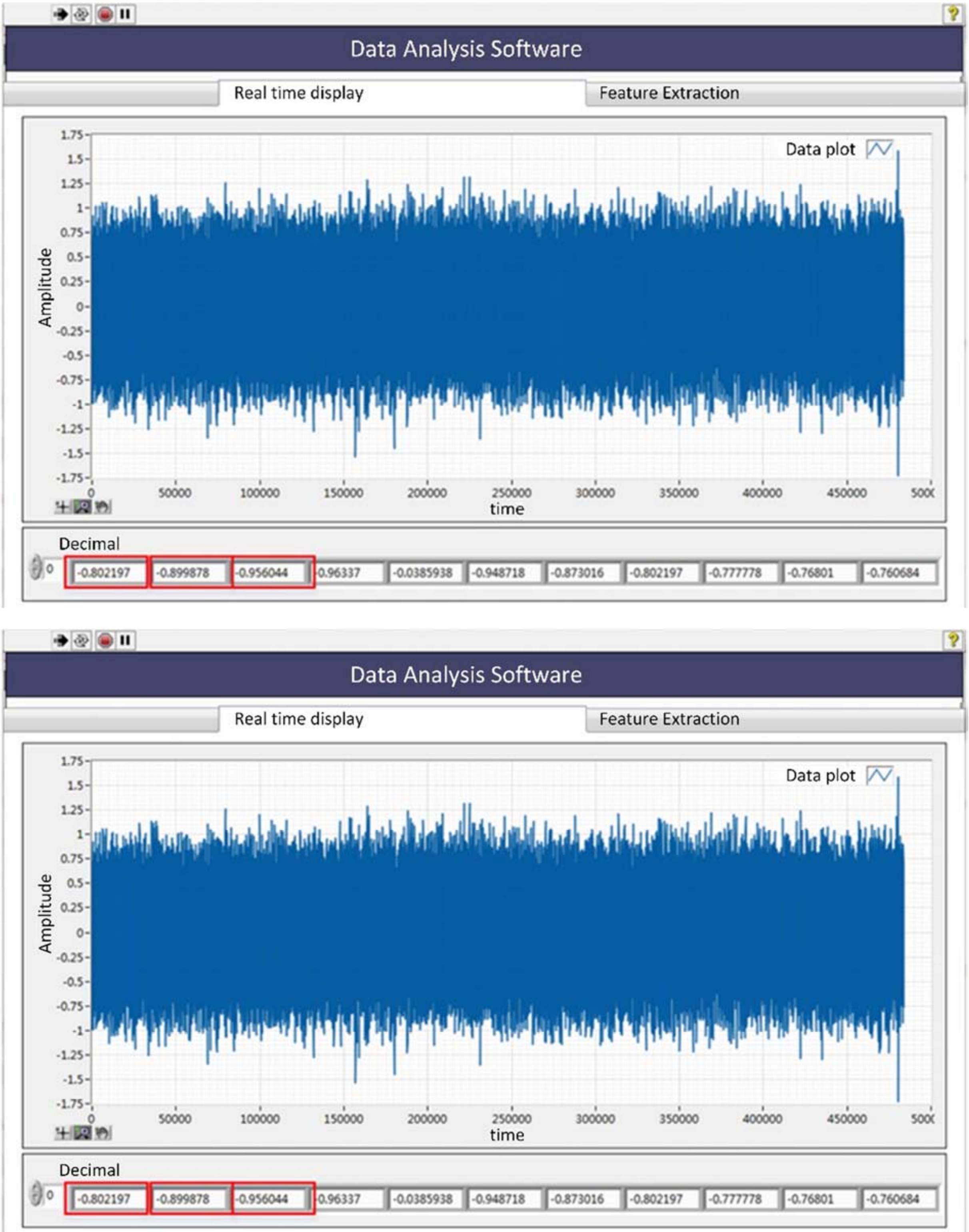
Figure 10. *The test environment.*

Experiment results show the effectiveness of the system from three aspects:

1) The storage result of SD card shown in Figure 11*a*. The storage data is shown in hexadecimal by WinHex software. The first resampled data is '3EB7'. '3' is the channel number and 'EB7' stands for the real voltage data. 'EB7' can be converted to decimal voltage data that is -0.802197 according to Max1308-datasheet. The display result of monitoring software shown in Figure 12b. The received data is same with the resampled data stored in SD card.

ADDRESS	DATA															
Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
00000000	3E	B7	3E	AC	3E	A3	3E	99	3E	90	3E	8A	3E	84	3E	7E
00000010	3E	7A	3E	77	3E	75	3E	73	3E	74	3E	75	3E	76	3E	79
00000020	3E	7D	The first resampled data						E	96	3E	A0	3E	A9	3E	B4
00000030	3E	C0	3E	CB	3E	D8	3E	E7	3E	F5	3F	04	3F	14	3F	25
00000040	3F	36	3F	48	3F	5A	3F	6D	3F	7F	3F	92	3F	A6	3F	BB
00000050	3F	CF	3F	E3	3F	F7	30	0C	30	20	30	34	30	49	30	5D
......									......							
00001F40	3E	8F	3E	87	3E	82	3E	7E	3E	79	3E	76	3E	75	3E	73
00001F50	3E	74	3E	75	3E	77	3E	7A	3E	7F	3E	84	3E	8A	3E	92
00001F60	3E	99	The second resampled data							C3	3E	CF	3E	DD	3E	EB
00001F70	3E	FA	3F	09	3F	1A	3F	2A	3F	3B	3F	4E	3F	60	3F	73
00001F80	3F	85	3F	99	3F	AD	3F	C1	3F	D5	3F	E9	3F	FD	30	13
......									......							
00003E80	3E	78	3E	75	3E	74	3E	73	3E	74	3E	76	3E	78	3E	7D
00003E90	3E	81	3E	86	3E	8D	3E	95	3E	9D	3E	A7	3E	B1	3E	BC
00003EA0	3E	C9	The third resampled data							00	3F	10	3F	21	3F	31
00003EB0	3F	44	3F	55	3F	69	3F	7C	3F	8E	3F	A1	3F	B5	3F	CA
00003EC0	3F	DE	3F	F2	30	08	30	1C	30	2F	30	44	30	57	30	6D

a) Storage data result.

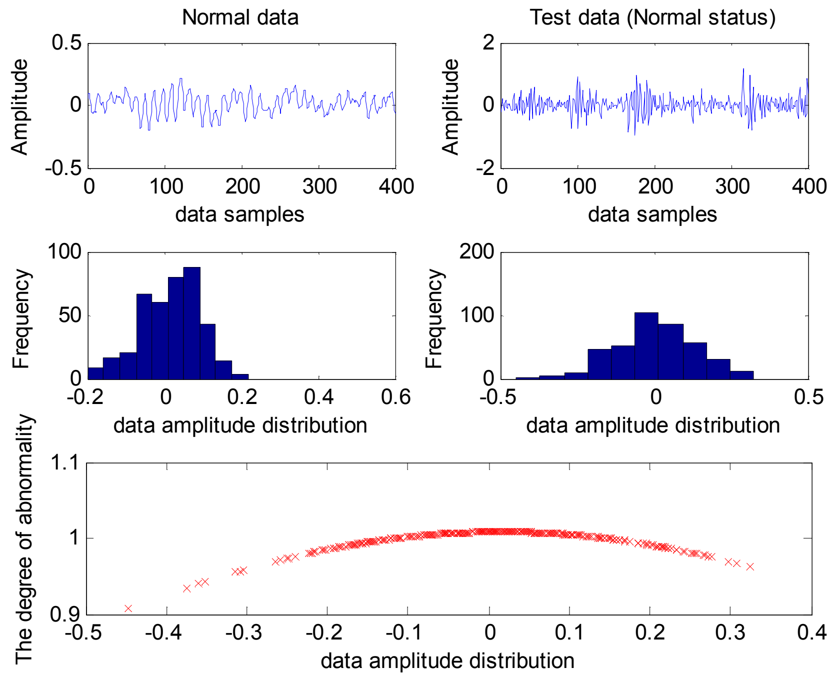


b) data display result.

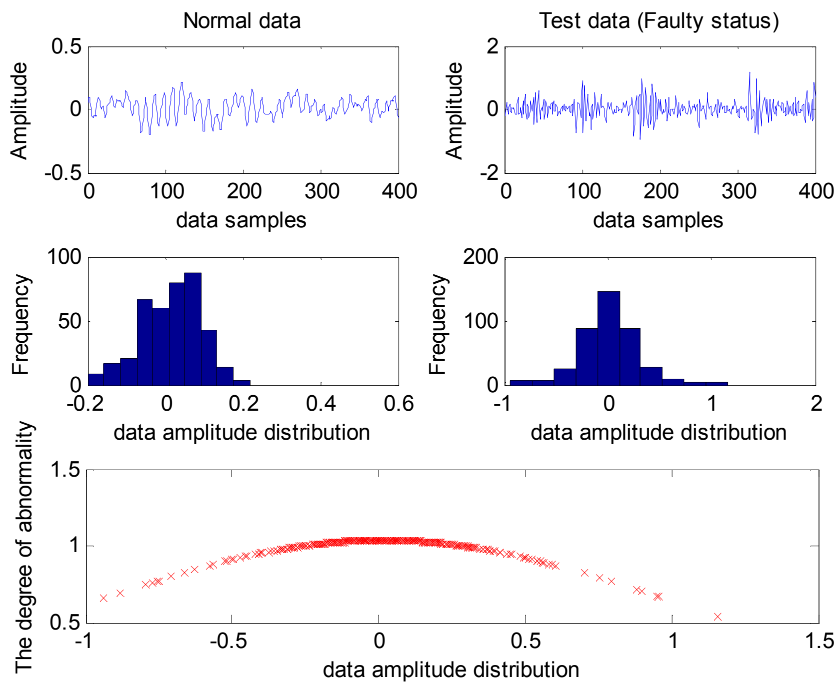
Figure 11. *Test result*

The analysis result of PDR algorithm shown in Figure 12a-b. In Figure 12*a*, the top two pictures are respectively signal waveform of training data and test data. The middle two pictures represents the frequency distribution of data. The bottom picture is the PDR value. In this picture, the normal status data is used as training data and the PDR result is close to 1 which also represents the training data is normal.

In Figure 12*b*, the fault status data is used as training data and the PDR result deviates from 1 which also represents the training data is abnormal.



a) normal test data analysis result of PDR algorithm.



b) fault test data analysis result of PDR algorithm.

Figure 12. *Analysis result of PDR algorithm.*

7. Conclusion

The sufficient historical failure data acquired in real environment is the most important resource for the development of vehicle PHM technology. Moreover, a flexible and robust data acquisition system is the premise to getting the resource. A wireless failure acquisition system is proposed in this paper. The system is composed of several wireless failure data acquisition nodes, a gateway node, the monitoring software and related algorithm working in a base station. The WFDA node is responsible to collect the vehicle operating data which is stored at local and concurrently send to the gateway node. The gateway node is utilized to receive data from WFDA node and transfer data to the base station through Ethernet bus. The monitoring software is used to send out control commands and display received data. The probability density ratio algorithm embedded in monitoring software could detect abnormal data and show researchers the analysis results which can be relied to change the test item in time. Experiment results show the effectiveness of the system.

Compared with other related systems, this system is specifically developed for vehicle test. The node is small and adapts to harsh operation condition. A double-buffer resampling strategy is developed to solve the contradiction of high sampling rate and low wireless bandwidth which could realise real-time storage and display in condition of high sample rate. The monitoring algorithm can analyse the abnormal data in time and the researchers can adjust the test content according to the analysis result. What's more, the system can be easily modified to a long-term monitoring vehicle system.

In the future work, this system will be tested in a real vehicle by collecting AMT system parameters.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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