VIBRATION MONITORING USING SMART DATA NODE

WONG MUN LIK

UNIVERSITI SAINS MALAYSIA

2014

VIBRATION MONITORING USING SMART DATA NODE

by

WONG MUN LIK

Thesis submitted in fulfillment of the requirements for the
degree of Bachelor of Engineering (Electronic Engineering)

JUNE 2014

ACKNOWLEDGEMENT

This dissertation is dedicated to everyone who has contributed in the vibration monitoring field. The contribution from the past researchers has expanded the knowledge of vibration analysis in which the machine or plant assets can be managed more efficiently and effectively.

First of all, I would like to express my gratitude to Dr. Syed Sahal Nazli Alhady bin Syed Hassan, my project supervisor, for providing valuable guidance and advises in completing this project. His support has motivated me to overcome the challenges and move on from failures throughout the research period.

Nevertheless, I would like to thank Dr. Chong Fei Seong, as my industrial supervisor, for putting trust on me and granted me to do research for his company. The information and teaching from Dr. Chong has utterly expanded my knowledge and interest in the vibration monitoring field.

Also, I would like to thanks to my examiners, Dr. Aeizaal Azman bin Abd Wahab and Assc. Prof. Dr. Amylia bt Mat Sakim for spending their time to evaluate my thesis report and presentation.

Lastly, applauds and appreciations are dedicated to my family and fellow friends for helping me in completing this project indirectly. Their moral supports are the greatest motivation to me for continuing the effort to finish this project.

TABLE OF CONTENTS

CHAPTER 1- INTRODUCTION

CHAPTER 2-LITERATURE REVIEW

CHAPTER 3-METHODOLOGY

CHAPTER 4-RESULT AND DISCUSSION

CHAPTER 5-CONCLUSION

APPENDICES

APPENDIX A: Data Sheets

APPENDIX B: Program Code

LIST OF ABBREVIATIONS

AC	**Alternating Current**
ADC	**Analog-to-Digital Converter**
ARM	**Advanced RISC Machines**
CWT	**Continuous Wavelet Transform**
DAQ	**Data Acquisition**
DC	**Direct Current**
DFT	**Discrete Fourier Transform**
DWT	**Wavelet transformations**
FFT	**Fast Fourier Transform**
GND	**Ground**
LCD	**Liquid Crystal Display**
RISC	**Reduced Instruction Set Computer**
SI	**International Systems of Units**
SMD	**Surface Mount Device**
STFT	**Short Time Fourier transform**
UART	**Universal Asynchronous Receiver/Transmitter**

LIST OF FIGURES

LIST OF TABLE

Pemantauan Getaran Dengan Penggunaan Nod Data Pintar

Abstrak

Sistem pemantauan getaran untuk mesin adalah penting dalam industri kejuruteraan bagi memastikan mesin berada dalam keadaan baik. Rutin pemantauan adalah untuk mengumpul data getaran dengan menggunakan sensor dan memproses data dari domain masa ke dalam domain frekuensi. Biasanya, setiap mesin yang mahal seperti pendingin, mesin pembuatan secara automatik dan motor penjana elektrik memerlukan perkhidmatan pemantauan getaran dari semasa ke semasa untuk memastikan mesin berfungsi pada tahap yang optimum tanpa mengalami apa-apa kerosakan. Pada masa kini, sistem pemantauan getaran adalah mahal dan memerlukan alat analisis yang membebankan dan juga rumit. Oleh itu, objektif projek ini adalah untuk membina sebuah sistem terbenam yang murah dan mudah alih untuk sistem pemantauan getaran. Sistem terbenam ini termasuk model ADC AD7606-4, Nuvoton NUC140-LB mikorpengawal dan alata pengesan pecutan. Isyarat input sistem tersebut diperoleh daripada alat pengesan pecutan dan akan disampel oleh ADC menjadi data digital. Seterusnya, data digital ini akan disimulasikan dengan menggunakan modul pengaturcaraan MATLAB dalam komputer. Ketepatan data yang dikumpul akan disahkan dengan membandingkan hasil simulasi dalam MATLAB dengan keputusan yang ditunjukkan dalam osiloskop. Kesimpulannya, objektif utama projek ini telah tercapai. Kos pembinaan sistem ini adalah RM583.30 iaitu 27% kurang daripada bajet pembangunan. Di samping itu, objektif sekunder juga tercapai dengan had. Penanda aras ketepatan untuk sistem pemantauan getaran ini ialah 95%. Keputusan telah menunjukkan bahawa sistem pemantauan getaran ini adalah tepat dan konsisten hanya untuk isyarat DC di bawah -2V dan ke atas +2V dan untuk isyarat AC dari 1Hz sehingga 600Hz.

Vibration Monitoring Using Smart Data Node

Abstract

Vibration monitoring system for machine is important in engineering industry as to ensure that the machine is in good condition. Routine of the monitoring is to capture vibration data using sensor and process the data from time domain into frequency domain. Normally, every expensive machines such as chiller, automated manufacturing machine and motor-driven generator requires regular vibration monitoring service to make sure the machine is running at optimum performance without suffering from any damage. Nowadays, vibration monitoring systems are costly and require cumbersome analysis tools. Therefore, the objective of the project is to build an embedded system for vibration monitoring system at low cost and portable. This embedded system includes ADC model AD7606-4, Nuvoton NUC140-LB microcontroller board, and accelerometer. The input signal of the system is acquired from accelerometer and sampled by the ADC. The data is simulated by using MATLAB programming module in computer. The accuracy of the data captured is verified by comparing the simulation result in MATLAB with the result shown in oscilloscope. In conclusion, the primary objective of this project was achieved. The cost of building this system is RM583.30 which is 27% less than the development budget. Besides that, the secondary objective was also achieved with limitation. The benchmark of accuracy for this vibration monitoring system is 95%. The results have shown that the vibration monitoring system is accurate and consistent only for DC signal below -2V and above +2V and for the AC signal from 1Hz up to 600Hz.

Chapter 1

Introduction

1.1 Background

Generally, machines with moving compartment generate vibration and consequently noise. From a handbook [1], machine vibration is simply the back and forth movement of machines or machine components. Any component that moves back and forth or oscillates is vibrating. Machine vibration can take various forms. A machine component may vibrate over large or small distances, quickly or slowly, and with or without perceptible sound or heat. Machine vibration can often be intentionally designed and so have a functional purpose. At other times, these vibration and noise can be destructive to the machine if it has reached the unsafe scale. Therefore, vibration monitoring is required to be performed to every machine regularly as to ensure the machine is either safe to be used or not. Vibration monitoring which is also known as condition monitoring is a technique to measure and evaluate the condition of plant assets and equipment especially machines, thus enabling better decisions to be made about maintenance activity.

However, the rapid development in engineering industry has improved the limitation of machine design from time to time as to reach higher specification, such as the speed and torque. Hence, the complex design of machinery has made the vibration monitoring service even more difficult to be carried out. So, the device for vibration monitoring must be reliable and accurate to ensure the data captured is always accurate and valid. This is because a few mistakes from the vibration monitoring system would probably cause a huge loss to the plant assets due to the facts that maintenance activity is expensive and also affects the production line.

Thus, this project is aimed to deliver a better solution to the industry in performing condition monitoring specially to motor-driven machine. This final year project is about developing an embedded system which can perform real time vibration signal processing. The main functions of this embedded system are to measure, analyze and store sampled data acquired from accelerometer. An accelerometer is a sensor that produces an electrical signal that is proportional to the acceleration of the vibrating component to which the accelerometer is attached.

In this embedded system, analog vibration data is acquired from accelerometer. Then, analog data is converted into digital data using ADC. A microcontroller is used to interface with the ADC and also allocate memory to store the digital data. Then, a computer is used to analyze and simulate the real time digital signal from microcontroller to produce a meaningful data that can be read by humans. At this point, FFT algorithm shall be applied to convert the time domain data into frequency domain data. Besides simulating and processing the digital data, the process will continue to store the data into a mountable memory for post processing.

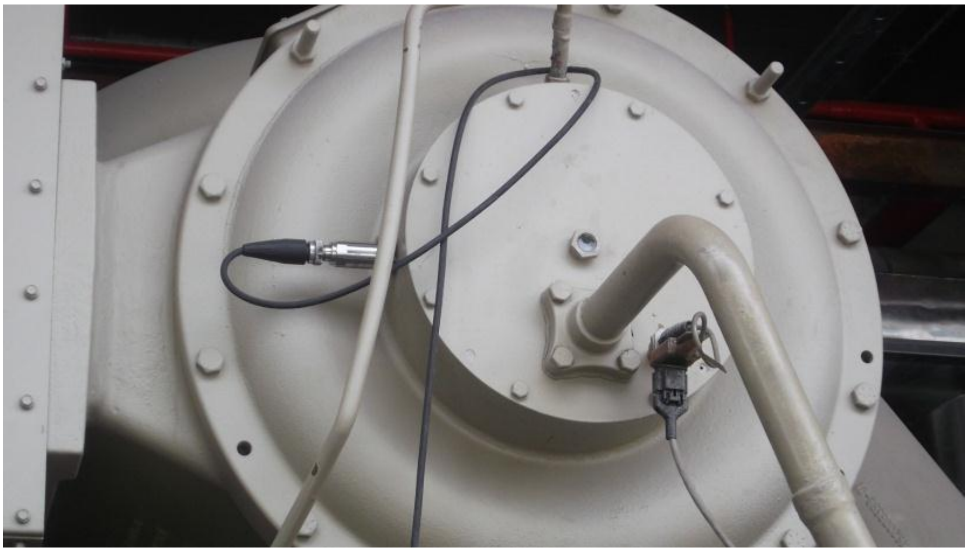


Figure 1.1: The front view of a chiller where accelerometer was probed at left side.

Figure 1.1 shows the way of doing condition monitoring on a chiller machine in X-axis direction. The vibration data is acquired by probing an accelerometer on the machine body. Overall, the accelerometer will be used to capture three-axis vibration data by changing the position of the sensor probe in reference to XYZ axis direction. In this case where simultaneous data acquisition is not possible, thus sampled data have to be stored for every axis for post processing individually. Figure 1.2 is showing the side view of a chiller machine. For certain cases, vibration of the machine body is required to be analyzed. Hence, it would be troublesome if the vibration monitoring system is large and heavy because it is required to be carried to perform vibration monitoring.

Figure 1.2: The side view of a chiller machine.

1.2 Problem Statement

From the previous section, the condition monitoring must utilize a reliable and accurate system to measure and evaluate the condition of a machine because a few mistakes or misjudgment would probably cause a huge loss to the plant assets. Therefore, the reliable and professional condition monitoring system often comes with high cost. Currently, the vibration measurement system tools or known as DAQ system that available in the market are very expensive which could cost up to RM 100,000.00 and above. In such case, it often requires a large amount of investment to purchase the monitoring system and undergo technical training courses. Nevertheless, most of the available DAQ systems are rather redundant, cumbersome, uneasy to be carried and not energy efficient. In some manufacturing plant or factory, there might be a problem to find space and power supply to setup the vibration monitoring system.

The two problems stated above are the main aims of this project, which are the issue of cost and portability. Therefore, the embedded system designed here shall be portable, stand-alone and low cost so that it can be mounted easily at any machine.

1.3 Objectives

The objectives of this project are as below:

1. To develop a stand-alone system that able to capture vibration data at a low cost (within RM 800).
2. To perform effective and accurate data analysis based on predefined preferences.

The meaning of stand-alone system is that it is able to function by itself without relying on other hardware, software or human controls. Therefore, this vibration monitoring smart data node must have the capability to measure, analyze and store data continuously at real time.

In order to achieve the second objective, a reliable microcontroller should be chosen in order to capture data more accurately. This system is developed using the Nuvoton NUC140-LB microcontroller board. Although this microcontroller board comes with a built-in ADC, a better model of ADC, AD7606-4 is used in this vibration monitoring system. The reason for this is that AD7606-4 has higher resolution (16-bits) which is more desirable for better accuracy.

1.4 Project Scope

The scope of this project is to assemble a reliable vibration monitoring system using available resources at low cost. The specification of the hardware implementation is shown in Table 1.1.

Table 1.1: Specification of the smart data node

Impedance	1MΩ, single ended BNC
Input Channel	Single channel for analog signals
Input Voltage Range	Configurable to ±5V, ±10V or ±15V
Resolution	16bit ADC
ICP/IEPE sensor supply	24V/4mA with AC or DC coupling
Sampling Frequency	10kHz

Referring to Table 1.1, the requirements for the data sampling frequency is 10kHz. The data sampling frequency is an important parameter for vibration monitoring system. Higher sampling frequency would result in higher resolution of the vibration signal. However, it also deteriorates the performance of the system because processor will take more time to compute a large amount of sampled data. Therefore, a good ADC and processor shall be chosen to achieve this target. Meanwhile, the other requirements stated in Table 1.1 can be achieved by using simple electronic components such as capacitors and resistors.

1.5 Report Outline

Overall, this thesis comprised of six main chapters which describes the full details of this vibration monitoring smart data node. The first chapter describes the background, problem statement, objectives, and project scope of this vibration monitoring system.

Chapter 2 describes about the past works done related to this project. Different methods of hardware and software implementation are discussed in this chapter. Also, the fundamental of vibration monitoring is briefly explained in this chapter to provide a better insight and understanding to readers.

Chapter 3 is about the methodology for implementing this project. This chapter focuses hardware and software implementation of this system. The process of development is described accordingly in this chapter. This chapter gives the details on how to construct the circuit and the method to implement the hardware. Besides that, it also covers the development of programming algorithms for the microcontroller and the MATLAB in order to realize this system.

Chapter 4 presents the result obtained from this vibration monitoring system along with discussion. This chapter shows the results for verifying the functionality and performance of this system. The result is analyzed to give comparison with the standard instruments.

Finally, Chapter 5 presents the conclusion of this project. The justification and final outcome of this project is stated in this chapter. Also, this chapter covers the limitation of this system whereby future development work is also included at the end of this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter presents the summary of past works by other researchers in related with this project. Apart from going through the result of past researches, the details and fundamental knowledge about this project are discussed briefly. This project involved embedded system design about vibration monitoring system. Therefore, other than hardware and software development, basic knowledge on vibration measurement and analysis is required in order to develop a better system. For better understanding, this chapter is divided into three parts, which are vibration analysis, FFT and embedded system design. The first topic is vibration analysis which gives a definition of vibration analysis and also the importance of vibration monitoring with supporting example. The second topic is FFT which give a general explanation of the fundamental FFT. Since there are many kinds of algorithms with different types of computing approaches, thus only a brief explanation is presented alongside the comparison with DFT. The last topic is related with embedded system design which is the most important part for this project. In order to realize this vibration monitoring system, a good understanding of the embedded system design is required. This topic includes some of the system designed in the past by other researchers. The result and performance of the past system designs are compared in order to build a better system for achieving the objectives of this project.

2.2 Vibration Analysis

In today’s industry, maintenance activity is one of the main concerns in the factory or plant management. This is due to the fact that maintenance activity requires high amount of cost in order to preserve the assets. In such case, maintenance of plant assets has been one of the hot research topics since the beginning of automated mass production in industry. In 2000, \$1.2 trillion was spent on maintaining the plant systems in the US [1]. Therefore, the budget for maintenance activity is likely to be one of the critical issues in any industry. Even though it is crucial for performing the maintenance, but it can be observed that most of the maintenance budget was spent on ineffective methods in the past. Apparently, there are many reasons of ineffectiveness, which give rise to the importance of vibration analysis [2].

The maintenance methods, which have been used in industry can be grouped into three categories. Different definitions and grouping can be found in different resources, but it is defined here as run-to-failure, preventive and predictive maintenance. The definitions of the three methods are described below [2].

Run-to-failure method, as the name refers, is to fix the system or machine when it is not able to operate any more due to a failure. This is the most expensive and least used method in industry today [1]. In the time of microprocessors and computerized automation, waiting for a system to fail and terminating the production is not relevant any more [2].

Preventive maintenance is the method to run maintenance in every decided period, or after certain amount of operating time of machinery, in order to prevent possible failures on the production line. This approach is especially applied to critical machinery, and the process can include lubrication, alignments, adjustments and replacements. The schedule can be decided upon past performance of equipment, statistical data or similar information. The cost of this maintenance method is still very high, since the equipment can be replaced even if there is no failure or defect by interrupting the production [2].

Predictive maintenance, which depends on current condition of the equipment, is the most efficient and least costly method of maintaining plant systems. By monitoring the mechanical condition of the critical equipment using parameters and indicators such as heat distribution [1], vibration patterns and acoustic characteristics continuously by the help of different sensors and measurement systems, maintenance can be applied at the exact time that is needed. This exact time can be decided upon efficiency and operating condition of the equipment that is being monitored. In addition to this, time-to-failure and possible amount of time that the monitored machinery will still be able to run can also be approximated [2].

The vibration analysis method that is implemented by this project belongs to predictive maintenance. To predict the condition of a machine, it is likely to implement a non-intrusive method for performing the vibration analysis in order to reduce the cost of maintenance. Apart from this, the tools and devices selected for predictive maintenance must be integrated with high level of accuracy and reliability. Any mistakes or miscalculation will lead to a misjudgment in the prediction of the machine, and hence maintenance activity is carried out ineffectively. On seeing this, the data capturing tools used must be highly accurate and reliable.

In general, there are many techniques to perform vibration analysis which varies accordingly to the type of machinery. For instance, here is an example of vibration analysis to inspect machine's ball bearing. Rolling element bearings of different sizes are widely used in machinery in industrial applications. Generally, rolling element bearings are designed to withstand axial or radial pressure while minimizing the rotational friction by placing rolling elements such as cylinders or balls between inner and outer races. Besides that, there are different types of rolling element bearings such as thrust, axial, angular contact and deep groove ball bearings, but ball bearings are the cheapest among all of them. These ball bearings are widely applied in industry today, such as automated production line, electric motors, pumps and gear boxes. However, faults on these components such as misalignment, wear, cracks and pits, or lack of lubrication can result in machine malfunction and catastrophic failures, which yields a very high maintenance cost. For that reason, different methods of vibration analysis were developed for diagnosis of ball bearings' faults in order to reduce the occurrence of failures such as acoustic and vibration measurement techniques. Several examples for acoustic and vibration measurement techniques in frequency and time-domain with test results are presented by Tandon and Nakra [3], and Tandon and Choudhury [4]. Vibration measurements are the ones that are most widely used, compared to the other method, acoustic measurements [4].

Eventually, the ball bearings act as a source of vibration, even if there are no defects present and they are perfectly aligned and adjusted [4]. However, a defect in one of the elements of a ball bearing can cause a magnificent vibration. There are several types of defects that can occur on a ball bearing, such as cracks or pits on rotating surface or rolling elements, distributed defects such as roughness or misaligned races [4]. Those distributed or localized defects yield a general vibration pattern. These vibration patterns can be detected by a transducer, then analyzed and processed with processing algorithm, which enable the condition monitoring system to predict the condition of the machine whether it is safe to be used or not. By doing so, the condition monitoring system can prevent the occurrence of catastrophic failure before it damages the machine or interrupt the production [2].

In the presence of bearing defect, the vibration level is increased when a rolling element strikes to a defect position on one of the races, which creates an impulse. Since the rolling element bearing rotates, those impulses will be periodic with a certain frequency [5]. A model to describe the vibration pattern produced by a single point defect on the inner race is described by McFadden and Smith [5]. In case the defect occurs on the inner or outer race, how frequent each rolling element strikes to the defect is called "Ball-pass frequency" and determined by the bearing geometry and rotation speed [4]. Ball pass frequency can also be calculated theoretically, and compared to the detected measurements after the vibration signals have been processed. The comparison between the theoretical value and measured value can be an indicator of the performance of the machine. For further diagnosis, such as determining the size of the defect in the machine, ball pass frequencies and noise-free vibration pattern can be useful for being the benchmark [2].

The vibration signals captured from a machine with fault-free bearing, bearings with inner and outer race faults are given in Figure 2.1. As illustrated, the characteristics of the impulses that happen in a machine with defect on inner race or outer race are different. Impulses generated from a defect in outer race have approximately equal amplitudes at constant period. This is because the race is stationary with respect to the load zone; that is, each time a rolling element passes by the stationary defect on the outer race, equal amplitude impulses will be created. Meanwhile, impulses created from a defect on the inner race have different amplitudes but still being periodic. This behavior can be concluded as the impulses are amplitude modulated. In this case, the impulses happen due to the resonance from bearing elements, hence the impulse amplitude corresponds to the applied force on the ball bearing [2].

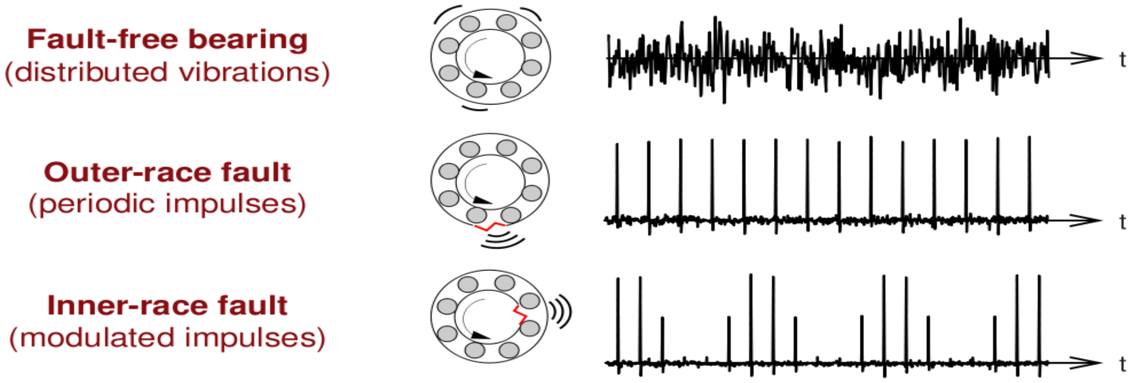


Figure 2.1: Examples of possible defects on a ball bearing and their vibration pattern. (Source: Figure 2.3 [2])

When the rotating inner race with a defect passes through the load zone, that is, a rolling element strikes to the defect which moves into and out of the load zone, modulated impulses will occur periodically at each shaft rotation. Therefore, the envelope of the impulses can be described as a function of load distribution [5]. However, the characteristic of vibration signals from a faulty bearing are not prominent due to the limitation measurement system, noise, distortions and disturbances. Thus, the purpose to build a vibration monitoring system with dedicated algorithm is to recover and enhance those signals by removing the undesired disturbances, as illustrated in Figure 2.2. Overall, the desired goal is to achieve vibration monitoring with minimum computational power, effort and complexity, without additional preprocessing applications such as filtering or envelope detection, and at a low cost [2].

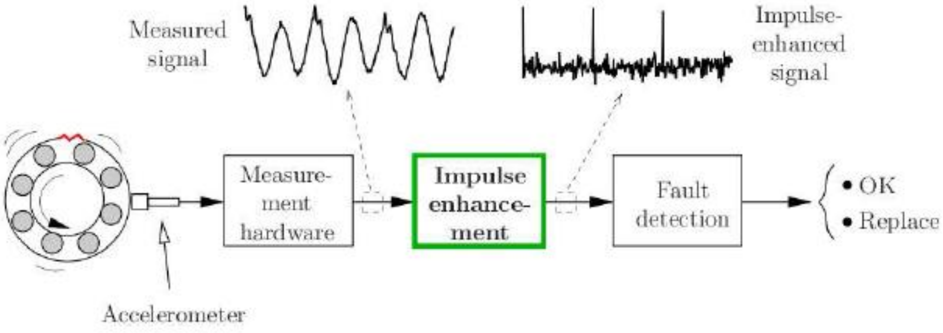


Figure 2.2: Fault Detection Process. (Source: Figure 2.4 [2])

Vibration amplitude may be measured as a displacement, a velocity, or acceleration. Vibration amplitude measurements may either be relative, or absolute. An absolute vibration measurement is one that is relative to free space. Absolute vibration measurements are made with seismic vibration transducers. Seismic vibration transducers include swing coil velocity transducers, accelerometers and velometers. On the other hand, a relative vibration measurement is relative to a fixed point on the machine. Relative vibration measurements are generally limited to displacement measurements, the displacement of the bearing journal relative to the bearings being the predominate example [6].

Displacement measurement is the distance or amplitude displaced from a resting position. The SI unit for distance is meter (m), although common industrial standards include mm and mils. Displacement vibration measurements are generally made using displacement eddy current transducers for detection of small gap changes [6].

Velocity is the rate of change of displacement with respect to change in time. The SI unit for velocity is meters per second (m/s), although common industrial standards include mm/s and inches/s. Velocity vibration measurements are generally made using either swing coil velocity transducers or acceleration transducers with either an internal or external integration circuit which provide useful information for vibration monitoring and balancing of rotating machinery [6].

Acceleration is the rate of change of velocity with respect to change in time. The SI unit for acceleration is meters per second^2 (m/s^2), although the common industrial standard is the g. Acceleration vibration measurements are generally made using accelerometers which works well for a wide range of frequency [6].

In short, accelerometer is best chosen for vibration monitoring system because it works well for a wide range of frequency with high degree of accuracy.

2.3 Fast Fourier Transform

This topic explains about the definition of FFT and the supporting details which related to vibration monitoring. There are many ways of transforming time domain to frequency domain, however FFT is chosen over others because it is simpler to be used in MATLAB. According to Franz Franchetti and Markus Puschel [7], FFT is an efficient algorithm to compute the DFT of an input vector. Efficient means that the FFT computes the DFT of an n-element vector in $O(n\log n)$ operations in contrast to the $O(n^2)$ operations required for computing the DFT by definition [7]. In other words, FFT reduces the computational steps of DFT.

In time domain, statistical parameters are evaluated by using data capturing system. These parameters can give some interesting information about potential defects. For instance, the peak and root mean square values are referred to the overall vibration level. These statistical parameters of measurements are simple to be calculated, but they are rather insensitive parameters for defect detection [8].

In frequency domain, potential defects can be detected by analyzing the frequency domain spectrum of the vibration signal. In order to calculate the frequency spectrum of a sampled time signal, the FFT algorithm can be used as a numerically efficient method [8]. FFT algorithm is one of the fastest and efficient computing methods to construct the frequency domain spectrum from time domain data.

Frequency domain spectrum analysis is widely applied in many industrial fields such that estimation of the instantaneous frequency is very important in many applications. For instances, in radar signal processing, it produces information about target’s range and cross-range position by evaluating the frequency of radar signal. Many instantaneous frequency estimators are based on the time-frequency representations. Conventionally, most commonly used representation are the FFT, STFT, the Wigner distribution and other quadratic reduced interference distributions, defined by the Cohen class [8].

The DFT is a ubiquitous tool in science and engineering especially in digital signal processing, communication, and high performance computing. Applications include spectral analysis, image compression, interpolation, solving partial differential equations, and many other tasks [7]. Here, an example is used to visualize between FFT and DFT. Given n real or complex inputs $x_0, \ldots, x_{n-1}$, the DFT is defined as

$$y_k = \sum_{0 \leq l < n}^{n} \omega_n^{kl} x_l \text{ , } 0 \leq k < n \tag{2.1}$$

with $\omega_n = exp(-2\pi i/n)$, $i = \sqrt{-1}$. Stacking the x_l and y_k into vectors $x = (x_0, \ldots, x_{n-1})T$

and $y = (y_0, \ldots, y_{n-1})T$ yields the equivalent form of a matrix-vector product:

$$y = DFT_n \times x, DFT_n = [\omega_n^{kl}], 0 \leq k, l < n \tag{2.2}$$

Referring to the two different ways in equation (2.1) and equation (2.2) of representing the DFT, FFT can be represented either as a sequences of summations or as a factorizations of the transform matrix, DFT_n [7]. To explain this FFT representation, assume an example that DFT_n in equation (2.2) can be factored into four matrices:

$$DFT_n = M_1 M_2 M_3 M_4 \tag{2.3}$$

Then equation (2.2) can be computed in four steps as

$$t = M_4 x \text{ ; } u = M_3 t; \; v = M_2 u; \; y = M_1 v. \tag{2.4}$$

If the matrices M_i are sufficiently sparse, which means it has many zero entries, the operations' count compared to a direct computation is decreased and equation (2.3) is called a FFT [7]. Looking at this example, the first FFT algorithm done by Cooley and Tukey in 1965 has reduced the runtime to O($n \log n$) for 2^n and marked the advent of digital signal processing [7]. This is one of the examples of FFT algorithm, but programming tool such as MATLAB is required to perform the computation.

2.4 Embedded System Design

With rapid development of information technology which concentrates on computer technology, communication technology and software technology, embedded systems have been widely used in various industries. The application of embedded system has greatly promoted the industry productivity. Embedded system can be defined as stand-alone devices used to control, monitor, or assist the operation of equipment, machinery or plants [9]. Embedded system can be categorized into two parts which are embedded hardware and embedded software. Embedded hardware is the hardware implemented to execute the algorithms such as embedded microprocessor and peripheral function modules. Embedded software refers to the algorithms that are generated to drive the hardware to perform certain task, and in such case, the algorithms must be compatible with the hardware. Nowadays, the mainstream of embedded system design is aiming to achieve small size, high reliability, power efficiency and low cost. In the last decade, there has been a lot of researches on computer architecture design such as Reduced instruction set computing (RISC) architecture. Recently, ARM architecture platform has become the industry's leading supplier of microprocessor technology, offering the widest range of microprocessor cores to address the performance, power and cost requirements for almost all application markets. Therefore, ARM processor architecture has become the mainstream of embedded system design in today, which is also the core processor of the embedded system design for this project. Even though ARM processor has addressed most of the requirements of building an embedded system, however the operating system for setting up the embedded system still requires plenty of effort for development [9]. From the past, most of the computer users have already familiar with the use of Microsoft operating system, but most of the ARM processors only accept Linux operating system.

Since year 1996, Microsoft has developed embedded operating system, Windows CE for the ARM cores which is increasingly popular nowadays. Windows CE operating system launched by Microsoft is a 32-bit embedded operating system which has powerful compact, efficient, scalable, the main face of a wide range of embedded systems and products. The operating system has multithreaded, multitasking, full preemptive characteristics which is designed for a variety of hardware system to boost the performance of the core processor. For it to be applied in embedded system, the operating system must be compatible with the embedded hardware as well. Other than that, to establish a connection between operating systems and hardware devices, a driver program is needed which acts as a link between hardware and software [9]. In short, even though provided with a good operating system such as Windows CE, it is still difficult to realize an embedded system because researchers have to understand the architecture of ARM processor in order to build a compatible driver for interfacing purposes. According to Philip Koopman [10], many embedded systems have substantially different design constraints than desktop computing applications. No single characterization applies to the diverse spectrum of embedded systems. However, due to some combinations of cost pressure, long life-cycle, real-time requirements, reliability requirements, and design culture dysfunction can make it difficult to be successful in applying traditional computer design methodologies and tools to embedded applications. Hence, embedded systems in many cases must be optimized for life-cycle and business-driven factors rather than upgrading the computational performance. Currently, there is limited resources support for expanding embedded computer design to the scope of holistic embedded system design. However, knowing the strengths and weaknesses of current approaches can set expectations appropriately. It is necessary to identify the risk areas, and suggest ways in which the embedded system design can meet industrial needs. The following paragraphs discuss about some of the examples of embedded system design using ARM processor.

From the research of Giuseppe Merendino and et al. [11], a new microcontroller based embedded system was devoted to vibration analysis for fault diagnosis in rotating machine, that implements advanced methods for signal analysis, such as FFT and DWT, suitably adapted to run on a low-cost microcontroller which is a 32 bit, RISC architecture of ARM 9 core processor, STR912F44W model. This system makes use of micro-fabricated accelerometers as sensors to capture the data. The experimental results were obtained from a model of a rotating machine which allows easy emulation of common machine faults and defects. The results obtained clearly indicate that the system developed in this project features good diagnostic capabilities, such that different types of faults can be distinguished and recognized. The performance of the system was also tested by artificially synthesized signals which has shown satisfactory level of reliability. In this research, vibration signals were analyzed using time domain averaging, which is a heavy processing technique to extract periodic waveforms from noisy signals. However, this technique requires either signal pre-processing or sampling synchronization to be performed with ad-hoc hardware. On top of this, time domain analysis becomes difficult in the presence of multi-tone noisy signals. Therefore, signal analysis using time domain data is inefficient and redundant. Hence, signal analysis in the frequency domain was used for diagnostics. This is because different types of machine faults or defects produce specific deformations in the frequency spectrum harmonic components. For these reasons, the CWT was proposed as an approach of combining the advantages of both time and frequency domain analysis. Unfortunately, such an approach is very demanding in terms of computing resources, and hence direct implementation on microcontrollers is impossible to perform the diagnostic analysis. In a conclusion, this research has successfully designed an embedded system by applying the FFT algorithm to the data, and hence machine faults can be detected without considering the time domain data analysis [11].

The next example of embedded system design is similar to this project. From the research team of Huangcheng Guo and et al. [12], an embedded data acquisition system was designed to collect and analyze vibration signal. The analog-to-digital converter model used was AD7606, which is the same as the model used in this project. In their research, they have concluded that the embedded system was a success such that the data was simulated correctly. However, due to the limitation of the microcontroller, the ADC sampling frequency was not able to be fully utilized, and hence they suggested to integrate a DSP chip into the embedded system to afford adequate computational capability, so as to make the system independent in data processing and portable. Since the specification and the throughput rate of their embedded system was not mentioned, therefore comparison could not be made with the system designed here. But, without doubt, the circuit and signal conditioning in their research is clearly more complex than the circuit designed in this project [12].

2.5 Summary

From the past researches, all the designs and implementation have their own advantages and disadvantages. It is a good practice to go through the past works done by other researchers as the time for design, development and troubleshooting can be shorten by referring to their methodology. On top of that, the future works proposed by them are important findings where better design and ideas can be extracted from there. Therefore, development work shall be continued in order to improve the embedded system design for this vibration monitoring system.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter will be presenting the methodology of designing this vibration monitoring smart data node embedded system. This chapter is divided into six parts, which are list of devices, ADC implementation, circuit setup, data capture using microcontroller, data transmission, MATLAB simulation and finally implementation with verification.

This project consists of hardware and software development. The hardware development covers the first two phases of methodology, which are ADC implementation and circuit setup. Meanwhile, the software development covers the following three phases of methodology, which includes the data capture by microcontroller, data transmission and MATLAB simulation. After the hardware and software was developed accordingly, the vibration monitoring system was implemented on a strip board and the simulation result in MATLAB was verified.

In this project, a series of program algorithms were created in order to testify, verify and improve the system. Since the software development was divided into three individual stages, an individual module of algorithm was built for each phase. The main reason of building individual modules is to save time for troubleshooting by breaking down the algorithms into smaller compartments. Therefore, each phase must be tested and verified before proceeding to the next phase in order to prevent any error that might occur after assembling all the modules.

This project is utilising a Nuvoton NUC140-LB microcontroller board and an ADC model AD7606-4 to form an embedded system for vibration monitoring. The block diagram of the overall system is shown in Figure 3.1.

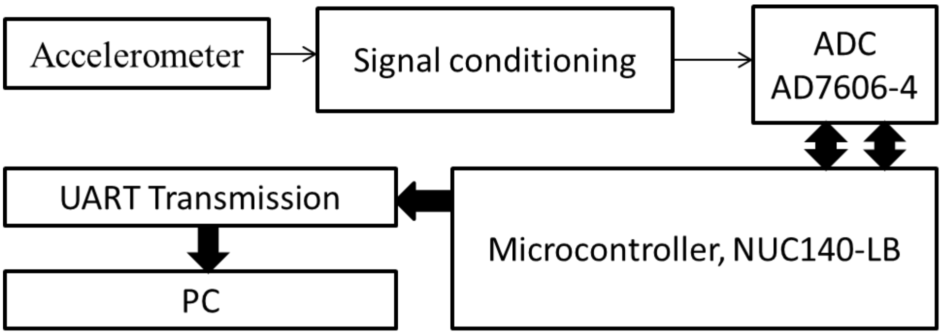


Figure 3.1: Block diagram of vibration monitoring system.

The flow of the hardware and software development is displayed in Figure 3.2. A total of six phases were done sequentially for developing this vibration monitoring smart data node.

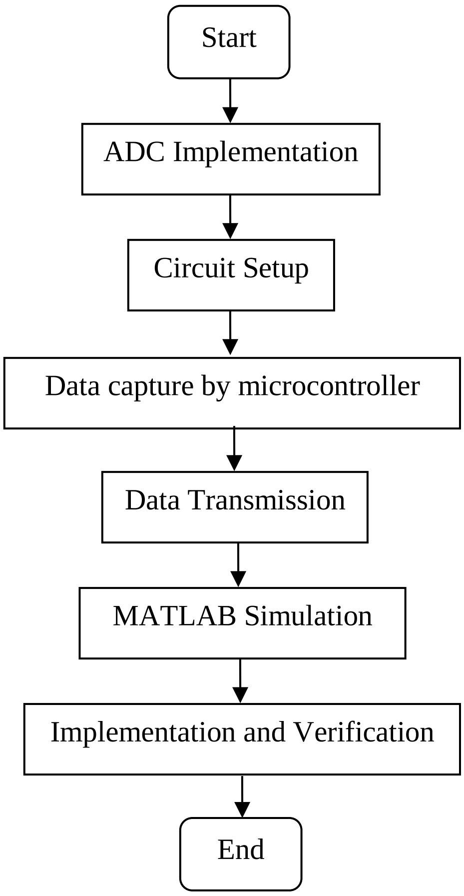


Figure 3.2: Flow chart of hardware and software development.

3.2 List of Device

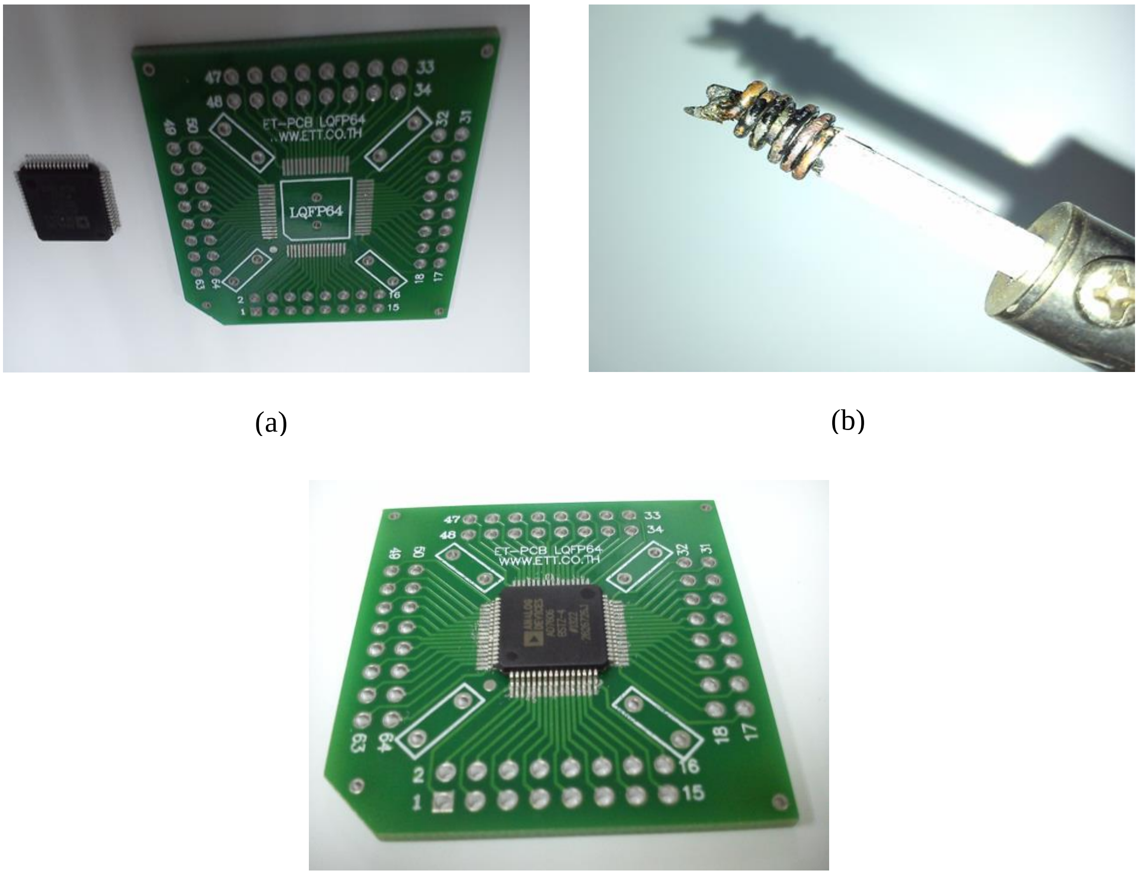
This section is presenting a list of devices and also the instruments involved in carrying out experiment and troubleshooting in order to realise this system.

Table 3.1: List of components and devices.

Type	**Model**		**Quantity**	**Price**
ADC	AD7606-4		1	RM 88.00
Microcontroller	NUC140-LB		1	RM490.00
Electronic Components	Resistor:	100Ω	3	RM 0.30
		300Ω	1	RM 0.10
		1kΩ	10	RM 1.00
	Capacitor	100nF	4	RM 0.80
		1µF	4	RM 0.80
		10µF	4	RM 0.80
	Voltage Regulator	LM317	1	RM 1.50
Oscilloscope	DSO-X 2002A		1	Free
Multimeter	Agilent U1232A		1	Free
			Total	RM 583.30

3.3 ADC Implementation

The ADC model for this vibration monitoring system is AD7606-4. This AD7606 model has a data resolution of 16-bits with configurable bipolar analogue input ranges. Besides of the high data resolution, the sampling frequency of this ADC can goes up to 200k samples per second for each input channel. On top of this, the AD7606 has 4-channel simultaneous sampled inputs capability. However, this project is only using single input channel for data conversion, thus the other three channels are not used and connected to GND. In short, this AD7606 is sufficient to achieve high accuracy and reliability for a data capturing system. However, the ADC model is a SMD which requires surface-mount technology to implement this chip. Therefore, the ADC chip could not be implemented easily using normal soldering gun. The chip implementation was illustrated in Figure 3.3.



(a)

(b)

(c)

Figure 3.3: The SMD chip implementation.

Referring to Figure 3.3(a), the pin distance of the ADC is 0.5mm. It is unlikely to perform a small scale soldering without the proper instrument. Instead of buying expensive equipment for SMD soldering, this SMD implementation was done using copper wire and a cheap soldering gun [13]. Referring to Figure 3.3(b), copper wire with the front end sharpened was coiled up around the soldering head. This copper wire has a very high heat conductivity, whereby the size of soldering head was greatly refined by using the copper wire coil as the soldering head. Hence, the cost for SMD chip implementation was reduced using this method. The 64 pins of ADC chip were soldered successfully as shown in Figure 3.3(c).

3.4 Circuit Setup

The NUC140-LB board is a 32-bit microcontroller with embedded ARM Cortex-M0 processor core for industrial control and applications which need rich communication interfaces [14]. The processor clock for this board runs at 50MHz. On top of this, this board comes with its own compiler, Keil µVision which is a C/C++ environment coding programmer. Besides that, it is convenient and easy to be used because program code can be directly flashed into the microcontroller board through USB connection. This board also has built-in flash memory for data storage. Therefore, the circuit conditioning for this microcontroller is not necessary which has reduced the time for hardware development. The circuit connection for this system is constructed in reference to the AD7606 datasheet [15]. The circuit diagram for this vibration monitoring system is shown in Figure 3.4. The first connection setup on breadboard for circuit testing is built as shown in Figure 3.5.

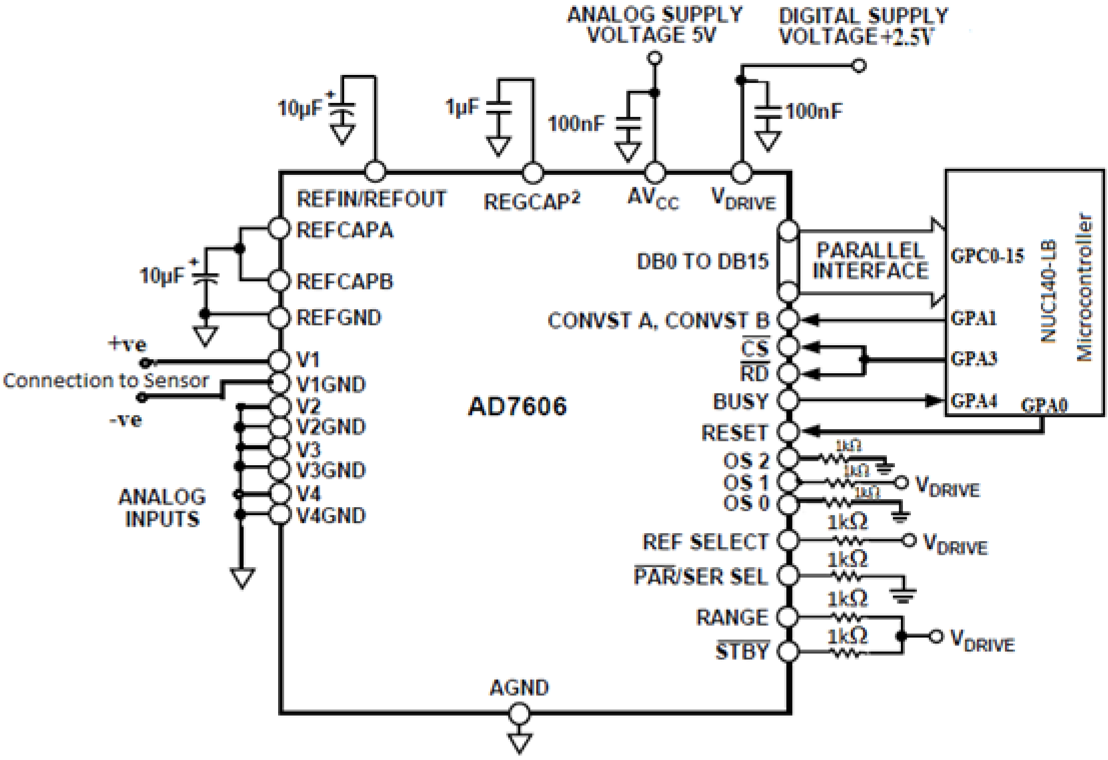


Figure 3.4: Circuit diagram of AD7606 and NUC140-LB microcontroller.
(Source: Figure 43 [15])