FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

Real-time monitoring system for a building-like structure using wireless sensors

Thesis

Submitted to the Faculty of Fachhochschule Aachen and Centro de Ingenieria y Desarrollo Industrial

BY

Jorge Humberto De Anda Cuéllar

PRIMARY SUPERVISOR:

Dr. Eng. Josué Enríquez Zárate

CO-SUPERVISOR:

Dr. Eng. M. Sc. Gengis K. Toledo-Ramirez

In Partial Fulfillment of the requirements for the degree of Master of Science in Mechatronics

Santiago de Queretaro, Qro., Mexico, September 2018

Declaration of Autorship

I, Jorge Humberto De Anda Cuellar, declare that the thesis, ”Real-time monitoring system for a building-like structure using wireless sensors”, is the result of my own work. Any part of this dissertation has not been previously submitted, in part or whole, to any university or institution for a degree or other qualification.

I confirm that all consulted work from other is attributed and the source is always given. Where the work is done with the help of other, these sources of help have been acknowledged.

Date: ______________________

Sign: ______________________

To my parents
for being the fundamental pillar in everything I am, in all my education, both academically, as in life, for their unconditional support perfectly maintained through time

To Luisa,
for sharing her dreams with mine and putting all her faith, love and encouragement on me through adversity

Acknowledgements

I would like to express my immense gratitude to CONACYT for the scholarship and for supporting the study of my Master's studies at Queretaro, Mexico and Aachen, Germany.

I would like to thank my thesis supervisor Dr. Eng. Josué Enríquez Zárate and my co-supervisor Dr. Eng. M. Sc. Gengis K. Toledo-Ramirez for his guidance, encouragement and support during the development of this Thesis. Also, I would like to thank the Automated Systems Division at CIDESI

I would like to express my very great appreciation to Prof. Dr. rer. nat. Klaus-Peter Kämper and Prof. Dr.-Ing. Jörg Wollert for all their help and support during our studies at the FH Aachen.

I would like to offer my special thanks to Dr. Salvador Francisco Acuña Guzman and all the academic and administrative members at CIDESI that help me though my studies.

I would like to thank my parents whose love and guidance are with me in whatever I pursue.

I would like to thank to my brothers, Luis, Daniel and Estefania, for always being with me.

I would like to thank all my friends with whom I shared many experiences throughout the study of the Master in Mechatronics, for their friendship and advice.

Finally, I would like to express my most deepest gratitude to Luisa Teresa without her support, patience and love throughout my studies this work would not be possible

Abstract

Recently, there has been a trend on developing and testing Wireless Sensor Networks (WSNs) as part of a global inspection mechanism for civil structures. The Structural Health Monitoring (SHM) process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. On this Thesis a prototype of a Wireless Sensor Network (WSN) for the monitoring of civil structures is designed and constructed. First the theoretical background and state of the art is presented. Then a conceptual design is made based on the research of different microcontroller, wireless communication standards and sensors. Subsequently the prototype that consist of two parts: Sensor Node and Base Station, is built and programmed. A Monitoring System to visualize and post-process the data from the WSN is programmed. Finally, the Wireless Network System was mounted on a building-like structure and was excited using an Impact Hammer, the data acquired from the sensors is then compared with a FEM Modal Analysis to validate the results of the WSN.

Resumen

Recientemente, ha habido una tendencia en el desarrollo y prueba de Redes de Sensores Inalámbricas como parte de un mecanismo de inspección global para estructuras civiles. El proceso de monitoreo de salud estructural implica la observación de un sistema a lo largo del tiempo utilizando mediciones de respuesta dinámica muestreadas periódicamente por una serie de sensores, la extracción de características sensibles al daño de estas mediciones y el análisis estadístico de estas características para determinar el estado actual del sistema. En esta tesis se diseña y construye un prototipo de una Red de Sensores Inalámbricos para el monitoreo de estructuras civiles. Primero se presentan los antecedentes teóricos y el estado del arte. Luego se realiza un diseño conceptual basado en la investigación de diferentes microcontroladores, estándares de comunicación inalámbrica y sensores. Posteriormente, se construye y programa el prototipo que consta de dos partes: Sensor Node y Base Station. Se programa un Sistema de Monitoreo para visualizar y postprocesar los datos de la Red de Sensores Inalámbricos. Finalmente, el Sistema de Red Inalámbrica se montó en una estructura similar a un edificio y se excitó usando un Martillo de Impacto, los datos del acelerómetro luego se compararon con un Análisis Modal utilizando FEM para validar los resultados de la Red Inalámbrica.

Kurzfassung

In letzter Zeit werden Wireless Sensor Network (WSN) zur globalen Inspektion von Gebäuden, Brücken und anderen Infrastruktur Bauwerken entwickelt und getestet. Das Structural Health Monitoring (SHM) bedingt die Langzeitbeobachtung mit periodischer Probennahme von dynamischen Prozessen der Gebäude. Dies soll mit Sensoren erfolgen, um gefährliche Strukturveränderungen rechtzeitig zu erkennen. Mit statistischen Methoden und Vergleichenden Studien der Finite Elemente Methode FEM sollen diese Defekte erkannt werden. Im Rahmen dieser These wurde ein Prototyp eines WSN Konzipiert und hergestellt. Am Beginn wurde eine Studie zum Stand der Technik erstellt, danach eine Konzeptstudie zur Auswahl der geeigneten Mikrocontroller mit der Kabellosen Kommunikation. Ein Vollständiges System bestehen aus Sensor-Node und Basisstation wurde hergestellt, programmiert, in betrieb genommen sowie erfolgreich getestet. Ebenso wurde ein System zur Visualisierung und Nachbearbeitung der Daten programmiert. Das System wurde auf einem Gebäudemodell installiert und zu Testzwecken mit einem Impact Hammer erregt. Die so generierten Daten wurden mit Daten aus der FEM-Modalanalyse verglichen um das WSN zu validieren.

Contents

List of Figures

List of Tables

Acronyms

CAD Computer Aided Design

CIDESI Centro de Ingenieria y Desarrollo Industrial

FEM Finite Element Model

FFD Full Function Device

FFT Fast Fourier Transform

GAs Genetic Algorithms

GPS Global Positioning System

IIoT Industrial Internet of Things

IoT Internet of Things

MEMS (Microelectromechanical Systems

OSP Optimal Sensor Placement

RF Radio Frequency

RFD Reduced Function Device

RTP Real Time Processing

SBMCUs Single-Board Microcontroller Units

SHM Structural Health Monitoring

WPANs Wireless Personal Area Networks

WSNs Wireless Sensor Networks

WSN Wireless Sensor Network

Chapter 1

Introduction

In the context of Internet of Things (IoT), there has been an increasing interest in the adoption of emerging sensing technologies for the real-time applications such as Structural Health, Environmental and Traffic Monitoring Systems. The wireless monitoring is gaining popularity as there is no wiring required between the sensors and data acquisition systems. Recent improvements in Wireless and micro controller technologies have led to the development of various SHM systems. The SHM should observe the context and provide reliable information about the integrity of the structure.

WSNs are distributed systems composed by a network of tiny, battery powered sensor nodes with limited on-board processing, storage and radio capabilities. WSNs have been deployed for a wide range of applications, including environment monitoring, smart buildings, medical care, industrial and military applications. In a typical WSN deployment scenario, nodes sense and send their reports toward a processing center using a wireless interconnection network. Most of these networks are based on the IEEE 802.15.4 (ZigBee) standard, although the IEEE 802.15.1 (Bluetooth) standard has been used in some cases.

SHM refers to the process of implementing a damage detection and characterization strategy for civil structures. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. The context of the structure must remain in the domain specified in the design although this can be altered by normal aging due to usage, the action of the environment, and by accidental events like earthquakes.

1.1 Objective

Design and build a prototype of a Real-time monitoring system using a Wireless Sensor Network and test it on a build-like structure with the purpose of study the damage that real civil structures suffer by external forces as wind or earthquakes, in an online monitoring mode, through the use of an experimental platform.

1.1.1 Specific objectives

- Design the hardware architecture for the WSN
- Design the Software for Data acquisition on the WSN
- Build a Prototype of the Real-Time WSN
- Build a User Interface to Monitor, Post-process and visualize the data from the WSN
- Design a Computer Aided Design (CAD) model of the Building-like structure and perform a FEM modal analysis to know its natural frequencies.
- Test the prototype on a building-like structure and compare the experimental data with the FEM modal analysis to measure its performance

1.2 Justification

The monitoring of damage and control of civil structures in modern cities is a subject of great interest around the world. Recently, several events related with earthquakes have increased the interest in the use of sensors and actuators to establish or implement mechanism of monitoring health and structural control of civil structures. In this context, monitoring of important parameters of civil structures, like buildings, are required in order to improve their efficiency and even predict failures, premature maintenance and general overwatching when are submitted to forces, such as earthquakes or winds. The advances in WSN technologies has allowed an alternative to the monitoring in Real Time Processing (RTP) of the data allowing to reach a quick response of the actuator implemented to dissipate the energy of the perturbation forces and reduce the damage of the civil structure.

The monitoring health on-line of civil structures is a very useful tool to establish an analysis of the civil structure through the use of particular software, determine the type of damages and predict the failure in the structure in situ.

1.3 Scope

Due to time limitations in the Mexican-German Master Program the scope of this Thesis is to generate a review of the State of the art in Real-Time monitoring systems using wireless sensors networks applied in civil structures. Then a prototype will be build with the available equipment and materials in the Automated Systems Division at Centro de Ingenieria y Desarrollo Industrial (CIDESI). A three stories building-like structure will be build and a Modal Analysis will be performed using ANSYS. Experimental Data of the prototype mounted on the structure given a controlled excitation will be collected and then compared with the ANSYS model.

1.4 Hypothesis

It is possible to design and build a prototype of a real-time monitoring system using a wireless network of sensors and validate its performance by obtaining the natural frequencies from experimental data given by the accelerometers mounted on a building-like structure that is then compared with the frequencies obtained by a FEM Modal Analysis and to perform a monitoring of its structural behavior, with the goal of preventing possible damage due to external excitation forces.

1.5 Thesis Organization

The organization of this thesis is as follows. Chapter 2 presents a review on some of latest papers and publications, as well as, some of the WSNs academically and commercially available.

On Chapter 3, available microcontroller, wireless and accelerometers are researched, based on this a concept design is proposed. Chapter 4, presents some theoretical background to understand WSNs and the Zigbee protocol.

Chapter 5 describes all the Hardware used for the WSN prototype. The Base Station and Sensor Node are explained as well. Chapter 6, describes the code used for the Base Station and Sensor node. The Monitoring interface is explained and the front panel is shown.

On Chapter 7, The WSN system is validated using a building-like structure. Experimental data is sampled and received, then using the Fast Fourier Transform (FFT) the natural frequencies are obtained and compared with a FEM model. Chapter 8 presents a Real-Time System Proposal of a WSN System to be implemented on a Civil Structure. Chapter 9 gives a summary of this thesis as well as discusses on directions for future work.

1.6 System Requirements

The desired requirements of Wireless Sensor System are shown on next Section and are divided on Functional and Non-Functional Requirements.

1.6.1 Functional Requirements

FR0: The system nodes must be able to communicate wirelessly with other nodes and the base station.

FR1: The nodes must be able to use the SPI Communication Protocol.

FR2: The nodes must be able to use the UART Communication protocol.

FR3: The nodes must be able to use the I2C Communication protocol.

FR4: The User Interface should be able to show the data in Real-time.

FR5: The system must have digital and analog I/O. They are intended for communication between the sensors and the nodes.

FR6: The system must be able to store the nodes data on a log file.

FR7: Each node must have a high power-efficiency.

1.6.2 Non-Functional Requirements

NR0: The nodes should be as compact as possible.

NR1: The nodes should be low cost.

NR2: The user should be able to select the sampling rate of the nodes.

Chapter 2

State Of The Art

Wireless Sensor Networks continue to find application in an increasing number of areas. There is an increasing focus on systems to monitor and protect civil infrastructure (such as bridges,tunnels and buildings), power grids, pipeline infrastructure, wind turbines, etc. Networks of hundreds of sensor nodes are already being used to monitor large geographic areas for modeling and forecasting environmental pollution and flooding, collecting structural health information on bridges using vibration sensors, and controlling usage of water, fertilizers, and pesticides to improve crop health and quantity. This Chapter presents the latest and more important publications, patents and commercial equipment related to Real-time Wireless Sensor Networks and Structural Health Monitoring systems.

2.1 Wireless Sensor Networks and Structural Health Monitoring

Some of the most important papers regarding WSN were reviewed and brief description on each was written.

2.1.1 Wireless Sensor Data Collection based on ZigBee Communication

In [1] a WSN System for capturing human motion is developed. The systems consist of sensor elements which wirelessly transfers motion data to a receiver element. The sensor elements consist of a microcontroller, accelerometer(s) and a radio transceiver. The receiver element consists of a radio receiver connected through a microcontroller to a computer for real time sound synthesis. The wireless transmission between the sensor elements and the receiver element is based on the low rate IEEE 802.15.4/ZigBee standard.

2.1.2 Wireless sensor networks for active vibration control in automobile structures

In [2], Mieyeville et al. developed a WSN for active vibration control in automobile structures. The main objectives of this project are the identification and the integration of new intelligent active technologies in automotive systems so as to improve internal comfort (noise and vibrations). For this paper, they focused on the top-down design approach of WSNs for active vibration control that takes into account the hardware platform specificities at high levels of abstraction. Whereas most current studies are based on the physical deployment of one (sometimes more) hardware platform. They presented and demonstrated a design flow that enables, by simulation, the exploration of different WSN node architecture choices for a mechatronic application.

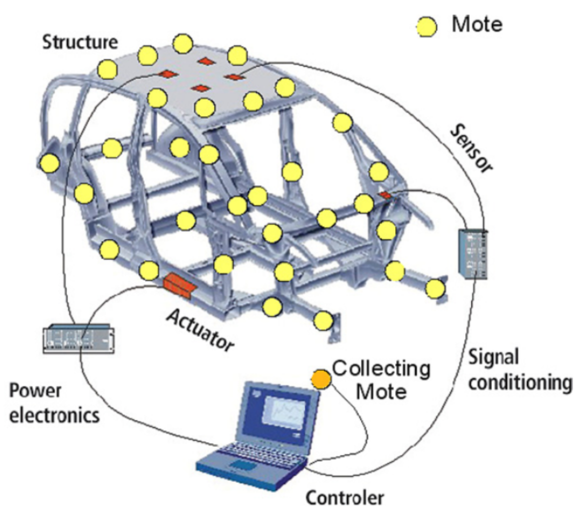


Figure 2.1: WSN System Implementation, taken from [2].

2.1.3 Remote Monitoring and Reconfiguration of Environment and Structural Health Using WSNs

On this paper Rekha et al. [3] developed a real-time embedded system, which provides a flexible and robust mechanism for monitoring and reconfiguration of SHM. The SHM system collects the periodic response measurements from an array of sensors. The damage-sensitive features are extracted from the data collected and a statistical analysis is conducted to determine the current state of system health. In case of emergency, the reconfiguration process should patch the differential image of the sensor software. A generic view of SHM is proposed as we can see on Figure 2.2.

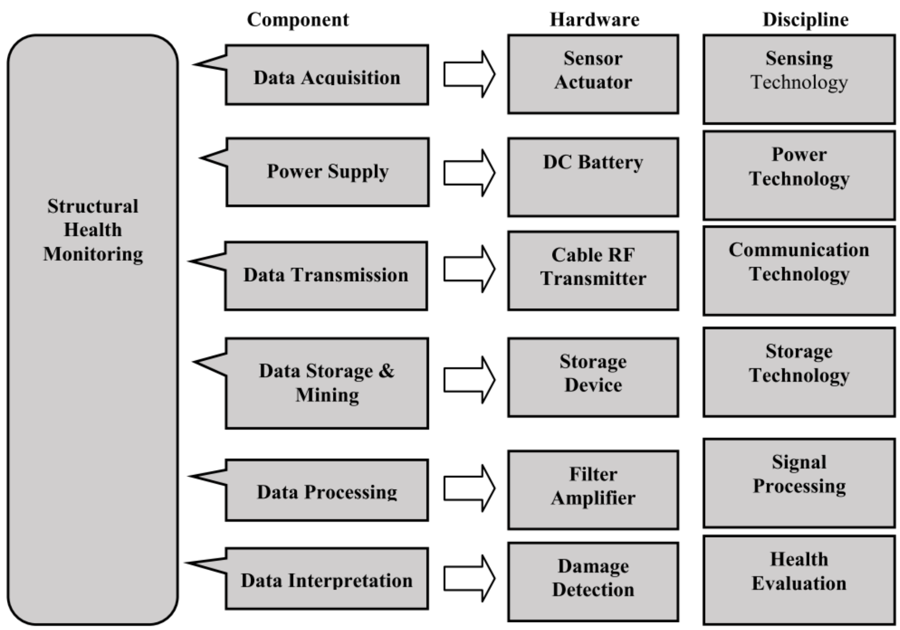


Figure 2.2: Generic View of Structural Health Monitoring System, taken from [3].

2.1.4 Decentralized civil structural control using real-time wireless sensing and embedded computing

On this paper [4], a prototype wireless structural sensing and control system is physically implemented and its performance verified in large-scale shake table tests. Wang et al. introduce the design of this prototype system and investigates the feasibility of employing decentralized and partially decentralized control strategies to mitigate the challenge of communication latencies associated with WSNs.

Closed-loop feedback control algorithms are embedded within the wireless sensor prototypes allowing them to serve as controllers in the control system. To validate the embedment of control algorithms, a 3-story half-scale steel structure is employed with magnetorheological (MR) dampers installed on each floor. Both numerical simulation and experimental results show that decentralized control solutions can be very effective in attaining the optimal performance of the wireless control system.

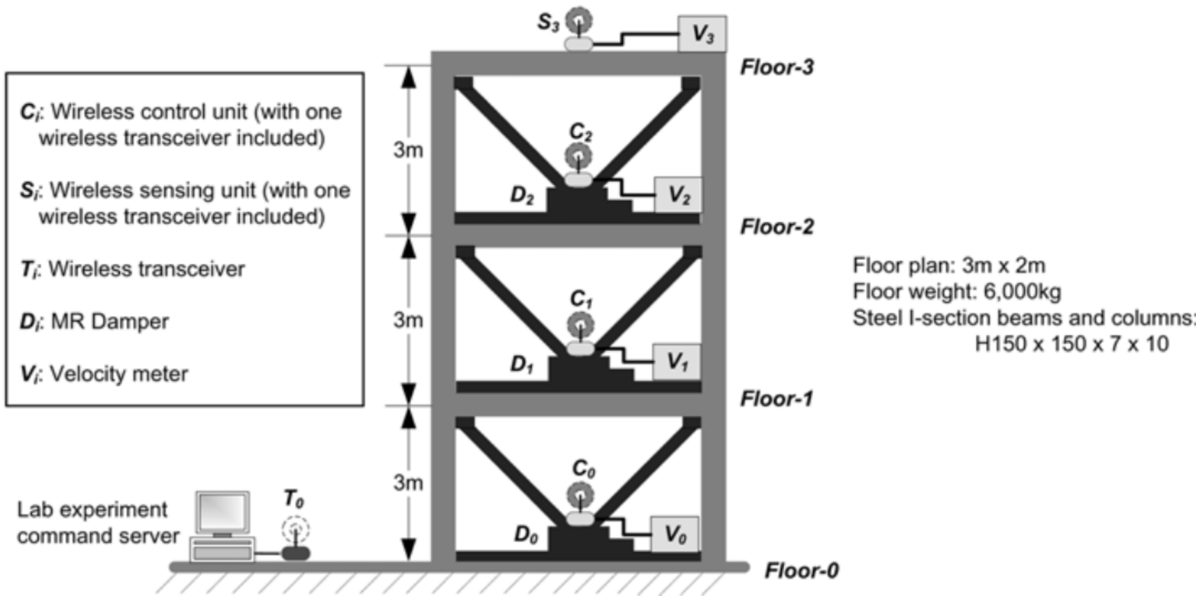
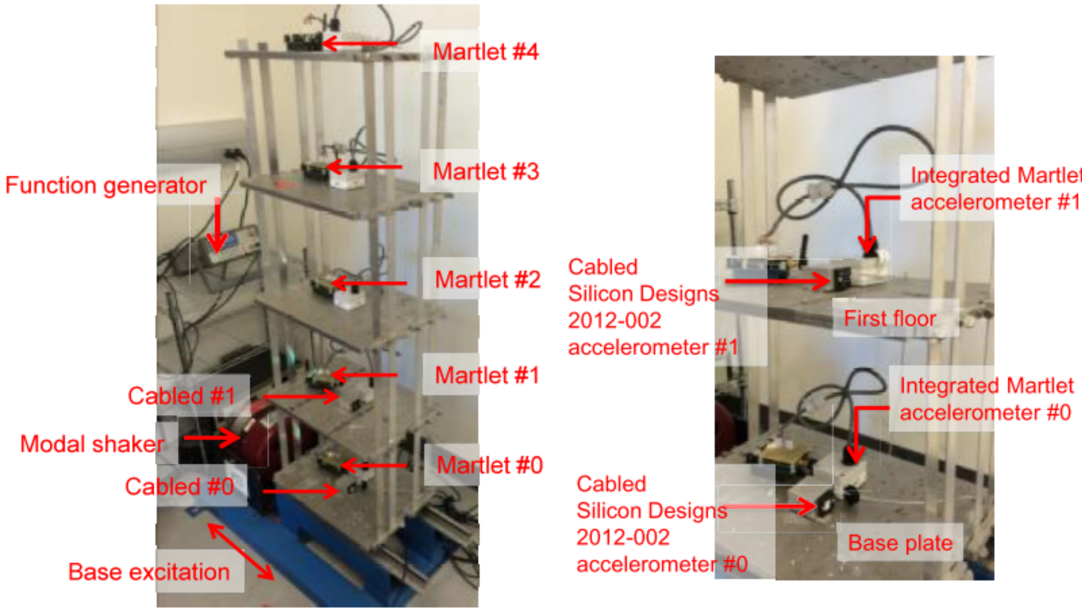


Figure 2.3: Illustration of the prototype wireless sensing and control system using a 3-story structure controlled by three MR dampers, taken from [4].

2.1.5 Design and Validation Of Acceleration Measurement using The Martlet Wireless Sensing System

This paper [5] reports the latest development of a low-cost wireless sensing node for SHM, named Martlet [6]. The performance of the wireless sensing system is validated through laboratory experiments. The integrated accelerometer wing is installed on a four-story aluminum shear- frame structure in the lab as we can see on Figure 2.4(a) y (b). The accuracy of the wireless acceleration measurement is evaluated with cabled accelerometers as reference. Furthermore, modal properties of the structure are extracted from the wireless acceleration measurement. Two Finite Element Model (FEM) updating approaches are applied for comparison, one minimizing modal dynamic residual and the other minimizing modal property difference between simulated and measurement results.



(a) Photo of complete experimental setup (b) Close-up view of experimental setup

Figure 2.4: Experimental setup using Martlet nodes on a four-story frame structure, taken from [5].

2.1.6 Active vibration suppression through positive acceleration feedback on a building-like structure

This paper [7] deals with the structural and dynamic analysis of a building-like structure consisting of a three-story building with one active vibration absorber. The base of the structure is perturbed using an electromagnetic shaker, which provides forces with a wide range of excitation frequencies, including some resonance frequencies of the structure. One beam-column of the structure is coupled with a PZT stack actuator to reduce the vibrations. The overall mechanical structure is modeled using Euler–Lagrange methodology and validated using experimental modal analysis and Finite Element Method (FEM) techniques. The active control laws are synthesized to actively attenuate the vibration system response via the PZT stack actuator, caused by excitation forces acting on the base of the structure. The control scheme is obtained using Positive Acceleration Feedback (PAF) and Multiple Positive Acceleration Feedback (MPAF) to improve the closed-loop system response. Some experimental results are included to illustrate the overall system performance.

2.1.7 Ground-borne vibration control in a building-like structure using multi-positive position feedback combined with sliding mode control

This paper [8] deals with the structural and dynamic analysis of a building-like structure consisting of a three-story building with one type of actuators, that is, a passive/active electromechanical actuator. The base of the structure is perturbed using an electromagnetic shaker, which provides forces with a wide range of excitation frequencies, including noisy excitations emulating traffic, underground railways and earth- quakes, common in Mexico City. The control scheme is obtained using multi-positive position feedback (MPPF) combined with sliding mode (SM) to improve the closed-loop system response, which is able to simultaneously attenuate the three vibration modes of the primary system. Some simulation and experimental results are included to illustrate the overall system performance.

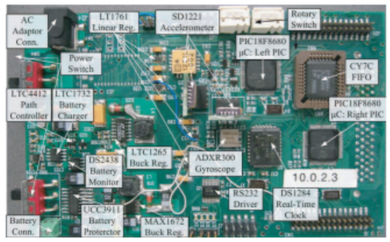
2.2 Wireless Sensor Networks Nodes and Equipment

On this Section the main WSN Nodes commercially and academically available were reviewed.

2.2.1 DuraNode: Wireless networked sensor for structural health monitoring

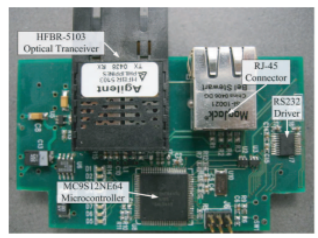
DuraNode [9] is a sensor node for real-time monitoring the health of civil engineering structures such as highway bridges and skyscrapers. It is specially designed to take civil engineers' requirements into account. To meet their requirements DuraNode has a dualmicrocontroller architecture sharing a FIFO memory. Evaluation shows that DuraNode has many distinguished features over other sensor nodes such as high power-efficiency, low jitter, and high network performance.

It consists of two boards: main board and daughter board. The main board itself can be used as a wireless sensor node, and we call this standalone operating mode wireless mode. As shown in Figure 2.5(a) and (b),the single board has everything a wireless sensor node may need, including microcontrollers, sensors, and a wireless communication interface. On the other hand, the daughter board, as shown in Figure 2.5(c), has only a microcontroller but two wired communication interfaces, namely Fast (10/100 Mbps) Ethernet and Optical. With the daughter board plugged in, DuraNode can send data through the wired communication interface in wired mode.



(a) Main board top view

(b) Bottom view



(c) Daughter board

Figure 2.5: Main board and Daughter board of DuraNode, taken from [9].

In addition, it can also use both wired and wireless interfaces in dual mode. As shown in Figure 2.6, DuraNode consists of four subsystems: Microcontroller, Communication, Power, and Sensor.

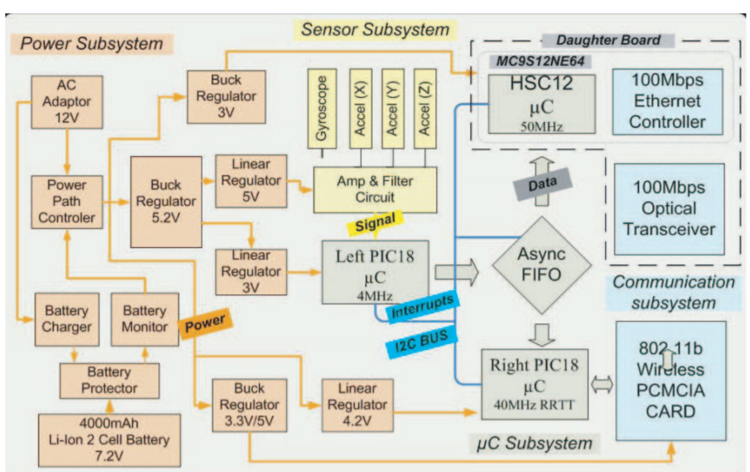


Figure 2.6: Top-level Block Diagram of DuraNode, taken from [9].

2.2.2 Mica2: Wireless Measurement System

Mica2 [10] , Fabricated by Crossbow Technology, is a third generation mote module used for enabling low-power, wireless, sensor networks. It is compatible with a wide range of sensors and data acquisition boards. The Mica 2 runs on TinyOS and uses an MPR400CB that is based on the Atmel ATmega 128L which supports Analog and Digital I/O, I2C, SPI and UART interfaces.

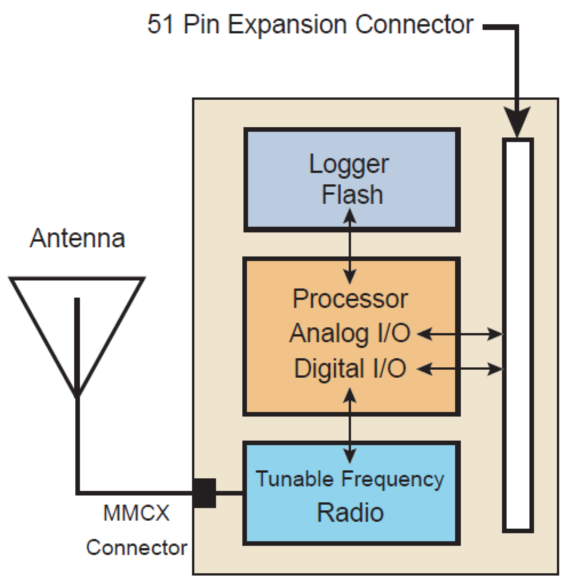


Figure 2.7: Mica 2 Block Diagram, taken from [10].

2.2.3 Imote2: High-performance Wireless Sensor Network Node

The Imote2 [11] is an advanced wireless sensor node platform. It is built around the low power PXA271 XScale CPU. The design is modular and stackable with interface connectors for expansion boards on both the top and bottom sides. The top connectors provide a standard set of I/O signals for basic expansion boards. The bottom connectors provide additional high-speed interfaces for application specific I/O. A battery board supplying system power can be connected to either side.

The Imote2 uses the CC2420 IEEE 802.15.4 radio transceiver from Texas Instruments. The CC2420 supports a 250kb/s data rate with 16 channels in the 2.4GHz band. The Imote2 platform integrates a 2.4GHz surface mount antenna which provides a nominal range of about 30 meters. For longer range a SMA connector can be soldered directly to the board to connect to an external antenna.

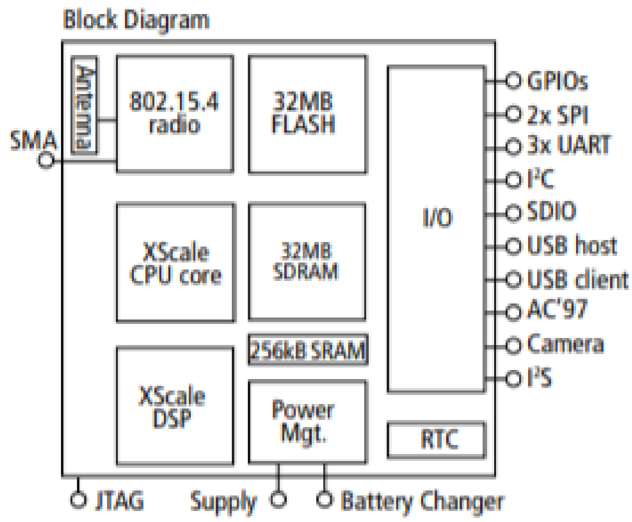


Figure 2.8: Imote2 Block Diagram, taken from [11].

2.2.4 MARTLET Wireless Sensing System

In this study[6], the authors propose a new wireless sensor node for adoption in Cyber-physical system (CPS) frameworks. While many wireless sensors have been proposed for monitoring and controlling civil infrastructure systems, the node proposed in this paper is specifically designed to emphasize two critical features for a CPS framework: high-speed computing and real-time deterministic functionality. The device is named Martlet1 and is shown in Figure 2.9

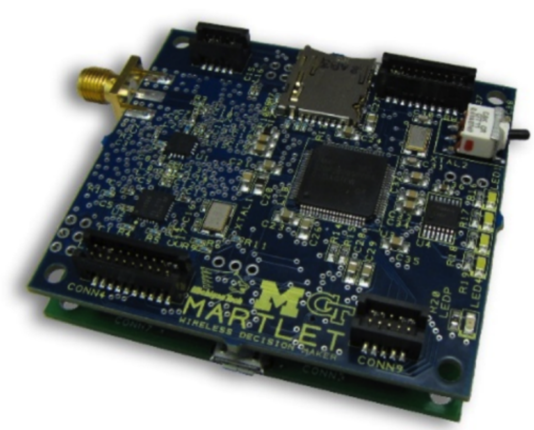


Figure 2.9: The Martlet wireless node baseboard, taken from [6].

A Texas Instruments Piccolo microcontroller, running up to 90 MHz clock frequency, is adopted in Martlet to execute onboard computation and data acquisition. The dual-core architecture of the microcontroller enables parallel tasks to be simultaneously performed on the main core and a programmable control law accelerator (CLA) core. In addition, the 32-bit floating-point math accelerator on the CLA enables faster and more accurate onboard computation. An onboard Micro SD card reader provides additional memory for data storage.

The Martlet's radio module is formed by pairing a TI CC2520 2.4 GHz IEEE 802.15.4 transceiver with a TI CC2591 RF front-end; the CC2591 is a programmable low noise amplifier for improved receiver sensitivity and power amplifier for amplification of the radio transmission power. In particular, the PA allows the communication range of the IEEE 802.15.4 transceiver to extend beyond 500 m line-of-sight.

2.2.5 National Instruments WSN-3226

The NI WSN-3226 is a four-channel, low-power, wireless voltage/resistance device that works with other NI WSN-32xx nodes and gateways to form a WSN. The NI WSN system consists of one or more NI WSN gateways, up to 36 NI WSN-32xx nodes per gateway, and multiple PCs or Programmable Automation Controllers (PACs) to receive and analyze the distributed sensor data

Figure 2.10: NI WSN-3326 Sensor Node., taken from[12].

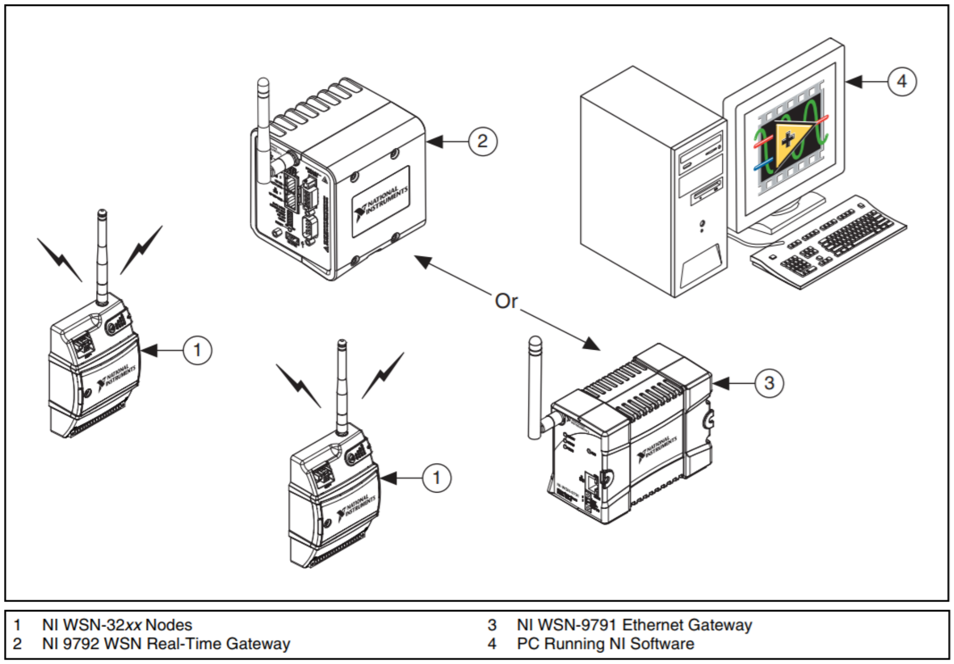


Figure 2.11: NI WSN System Components, taken from[12].

2.3 Real World Applications

On this Section the some real world implementations of SHM are shown.

2.3.1 Structural Health Monitoring of an Instrumented Building in Mexico with Accelerometers and GPS Sensors

This paper [13] presents the most significant results of the structural response of an instrumented building in Mexico during eight seismic events recorded between 2011 and 2013. A criterion for assessment of the structural health is proposed and the advantages of an automatic post-event structural warning system are discussed. The estimation of structural condition is based on five indicators: two related to intensity (peak ground acceleration and Arias intensity) and three related to structural response (interstorey drift ratio, seismic coefficient and percentage change in the fundamental frequencies corresponding to the horizontal components). When the structure is subjected to an earthquake, the records are analyzed by the warning system and a report is generated automatically. Changes in structural features can be detected and compared to their initial values to establish their state of damage.

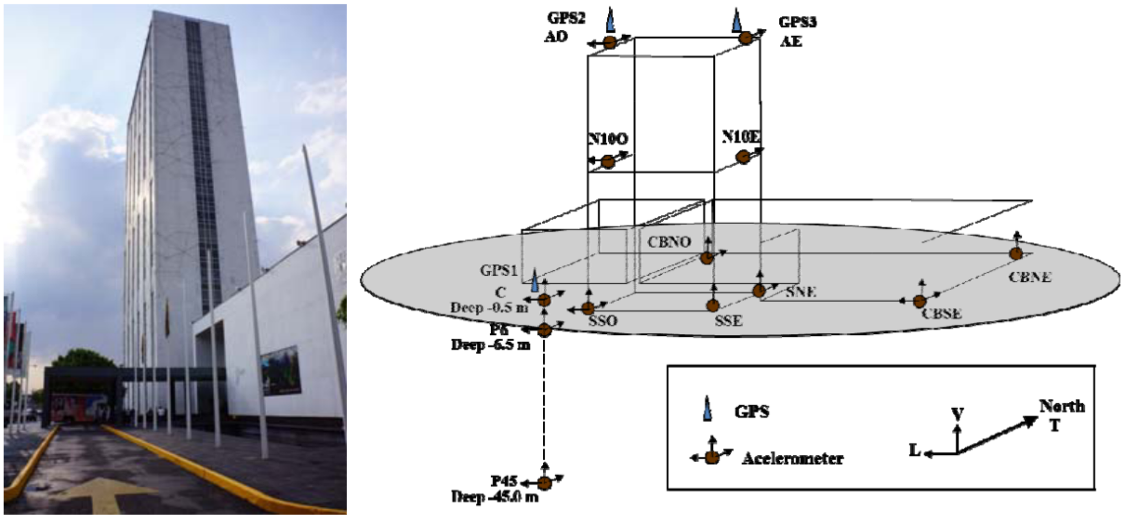


Figure 2.12: Overview of the building and instrumentation, taken from[13].

2.3.2 Seismic monitoring of a high-rise building in the Philippines

In the example presented in this case study [14], a seismic monitoring is performed inside a high-rise building in Taguig, in the southeastern portion of Metro Manila, close to Marikina Valley Fault System. Three MR3000SB devices are installed respectively at the foundation, middle and top floor of the structure. They have the following characteristics:

- Internal recorder and triaxial accelerometer.
- Internal AC/DC converter.
- Ethernet RJ45 connector.
- Horizontal installation.

The instruments constantly monitor the structure and raise instant warnings if the predefined acceleration thresholds are exceeded. Such exceedance may result in potential structural damage.

Chapter 3

Conceptual Design

After reviewing some of the available technologies and the current State of the Art of the WSN, on this chapter the parts and components for the WSN prototype are selected. The final goal of this chapter is to present a concept of the system. On Figure 3.1 the main parts of a WSN are shown, WSNs can be subdivided into two parts: Hardware and Software. The Hardware can be divided into three parts: Sensors, Wireless Communication Modules and the Microcontroller units.

First the most common and commercially available Single-Board Microcontroller Units (SBMCUs) are described and its characteristics are shown and then on Section 3.1.1.1 a comparison is made between them. Then on Section 3.1.2 the most common Wireless Communication protocols are review and its characteristics are summarize on Table 3.3. Then on Section 3.1.3, the characteristics of some accelerometers that could be use to gather data on the building-like structure that will be part thesis are shown. Finally, after selecting the components a concept design is developed.

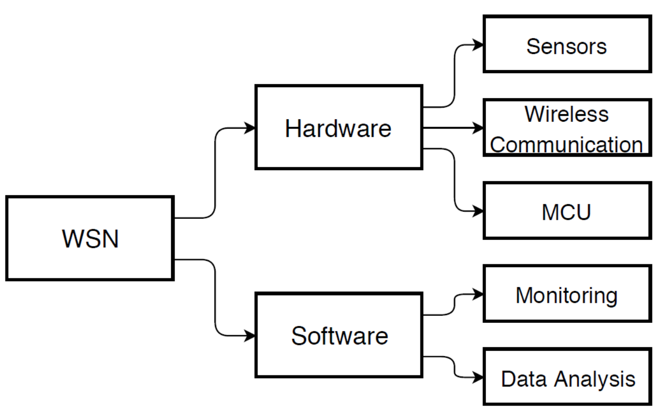


Figure 3.1: WSN Breakdown Structure.

3.1 Hardware Analysis

As part of the design process an analysis of the possible hardware that could be use for a WSN Node is made. First the characteristics of the parts conforming a WSN are described, later a comparison between the different parts researched is made.

3.1.1 Single-Board Microcontroller Units

There are many types of microcontrollers that could be used for this project. However, we are going to focus our research on the ones that comply with the following advantages over the rest of microcontrollers in the market:

1. Affordable.
2. Multi-platform.
3. Easy development environment.
4. Open-source.

The following SBMCUs were researched and considered:

- ***The Arduino Mega 2560:*** is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The Mega 2560 board has a number of facilities for communicating with a computer, another board, or other microcontrollers. The ATmega2560 provides four hardware UARTs for TTL (5V) serial communication, it also supports SPI and I2C.

  The numerous I/O options makes it flexible for different applications. An integrated development environment (IDE) is available from the Arduino website [15] for writing, debugging code and uploading to the board. The Arduino programming language is based on C/C++. It links against AVR Libc, a high quality C library for use with GCC on ATMEL AVR microcontrollers.

- ***The Raspberry Pi 3 Model B+:*** has a 64-bit quad core processor running at 1.4GHz, dual-band 2.4GHz and 5GHz wireless LAN, Bluetooth 4.2/BLE, and PoE capability via a separate PoE HAT. It also has 40 GPIO (general-purpose input/output), SPI, I2C, UART and PWM.

The Raspberry Pi 3 uses a Raspbian which is a Unix-like operating system. The Raspberry Pi can be programed by a great variety of languages like C/C++, Python, Java, Javascript and Perl between others.

- ***Tiva C Series TM4C123G LaunchPad:*** is a low-cost evaluation platform for ARM® Cortex™-M4F-based microcontrollers. The Tiva C Series LaunchPad has the following features: High Performance TM4C123GH6PM MCU, 80MHz 32-bit ARM Cortex-M4-based microcontrollers CPU, 256KB Flash, 32KB SRAM, 2KB EEPROM, Two Controller Area Network (CAN) modules, USB 2.0, Dual 12-bit 2MSPS ADCs, motion control PWMs, 8 UART, 6 I2C, 4 SPI, On-board In-Circuit Debug Interface (ICDI), USB Micro-B plug to USB-A plug cable.

  The TivaWare software provided with the Tiva C Series LaunchPad provides access to all of the peripheral devices supplied in the design. The Tiva C Series Peripheral Driver Library is used to operate the on-chip peripherals as part of TivaWare.

- ***ESP8266 Node MCU Wifi Dev Kit:*** is a self-contained WiFi networking solution offering as a bridge from existing micro controller to WiFi and is also capable of running self-contained applications. This module comes with a built in USB connector and a rich assortment of pin-outs. With a micro USB cable, you can connect NodeMCU devkit to your laptop and flash it without any trouble, just like Arduino. It is also immediately breadboard friendly. Wireless internet access can be added to any micro controller based design with simple connectivity (SPI/SDIO or I2C/UART interface).

  ESP8266EX is among the most integrated WiFi chip in the industry; it integrates the antenna switches, RF balun, power amplifier, low noise receive amplifier, filters, power management modules, it requires minimal external circuitry. It is compatible with the Arduino IDE wich make it easy to integrate with Arduino based projects.

3.1.1.1 Single-Board Microcontroller Units Comparison

A comparison between the different SBMCUs that are presented on Section 3.1.1 is shown in Table 3.1 and Table 3.2 where its more important characteristics regarding its use as a WSN node are compared.

Table 3.1: Single-Board Microcontroller Units Comparisson(Part 1)

Name	Maker	Processor	Clock Frequency	Dimensions (mm)	Flash (kb)
Arduino Mega 2560	Arduino	ATmega2560	16 MHz	101.6 x 53.3	256
Tiva C Series TM4C123G	Texas Instruments	TM4C123GH6PM	80 Mhz	50 x 57	256
Raspberry Pi Model 3	Raspberry Pi Fundation	BCM2837B0	1.4GHz	82 x 56	N/A
ESP8266 Node MCU Wifi Dev Kit	Espressif Systems	ESP8266EX	80 Mhz	48 x 24	512

Table 3.2: Single-Board Microcontroller Units Comparisson(Part 2)

Name	Digital I/O	Analog Inputs	Communication	Energy Consumption (mW)	Cost (USD)
Arduino Mega 2560	54	16	SPI, I2C, UART	400	30
Tiva C Series TM4C123G	43	2	SPI, I2C, UART, CAN	100	15
Raspberry Pi Model 3	40	0	SPI, I2C, UART	1900	35
ESP8266 Node MCU Wifi Dev Kit	17	1	SPI, I2C, UART, WIFI	462	8

3.1.2 Wireless Communication Standards

The technologies to be considered for WSN would be ZigBee (based on IEEE 802.15.4), Bluetooth (based on IEEE 802.15.1) and WiFi (based on IEEE 802.11). Other Radio Frequency (RF) technologies are available but only these three have the technical maturity for this kind of systems and low cost required for consumer products. The advantages and disadvantages of each technology are shown.

3.1.2.1 Zigbee (IEEE 802.15.4)

ZigBee is an specification of a joint of high level wireless communication protocols based on the wireless personal area network (PAN) standard IEEE 802.15.4. Its goal is the applications that require reliable communications, due to mesh topology, with low data transmission rate and longer lasting batteries.

ZigBee can be used in several types of applications such as automation and security control, remote control of electronic devices and WSNs.

The main characteristics and **advantages** that make it so suitable for these purposes are:

- *Low-Cost:* ZigBee devices are cheap as they do not need a high data rate and the microprocessor required for ZigBee devices is quite simple, due to the small size of the ZigBee MTU (Maximum Transmission Unit).
- *Mesh topology:* Provides a higher reliability because multiple transmission paths exist. This allow some nodes of the network to be asleep while others take the control of the propagation and avoid a whole network to block if one node gets down.
- *Low power consumption:* As multiple nodes can be asleep until they receive some information, they do not consume too much power and batteries can last for a long time.
- It is easy to install and it can be easily implemented. Setting up the network is very simple and up to 65,645 nodes can be implemented.

The **disadvantages** of the Zigbee protocol are:

- It is not secure like wifi based secured system, therefore its use is not recommended for private information.
- The Zigbee has low data transmission rate of 250 Kbps.
- It cannot be used as outdoor wireless communication system due to it has short coverage limited.

3.1.2.2 WiFi (IEEE 802.11)

WiFi uses RF to allow two devices to communicate with one another. The technology is most commonly used to connect Internet routers to devices like computers, tablets and phones; however, it can be used to connect together any two hardware components. WiFi is a local wireless network that runs of the 802.11 standards set forth by the Institute of Electrical and Electronics Engineers (IEEE).

Some characteristics and **advantages** of the Wi-Fi protocol are:

- Very high data rates. Latest WiFi standard versions such as 11n and 11ac deliver fast data connection rates of up to 433Mbps

- It is used to transfer any kind of data.
- It has been widely adopted.

The **disadvantages** of the Bluetooth protocol are:

- High energy consumption.
- Data transfer rate decreases (to individual computer) when number of clients or computers connected with wifi network increases.
- Wifi devices operate in full functionality and without any interruptions when they are within the range of the Access Point and receiving good signal strength. WiFi access is limited to about 30 to 100 meters.

3.1.2.3 Bluetooth (IEEE 802.15)

Bluetooth is a wireless technology standard for exchanging data over short distances (using short-wavelength UHF radio waves in the ISM band from 2.4 to 2.485 GHz) from fixed and mobile devices, and building personal area networks (PANs). Bluetooth is based on IEEE Standard 802.15.1 and has a data rate of 1 Mbps. Bluetooth has been developed for very short-range and is more suitable for applications with a middle data transmitting rate and non-stop services as file transfering and sound transmission.

Some characteristics and **advantages** of Bluetooth protocol are:

- Has a data transmission rate of up 1Mbps, which is faster than ZigBee but Slower than Wi-Fi
- It is used for voice and data transfer.
- It has been widely adopted compared to Zigbee which is less used.
- It allows only authorized devices to access and have control over resources to use a service before permitting it to do so.

The **disadvantages** of the Bluetooth protocol are:

- Has a network range between 1 and 100 meters depending on radio class.
- Higher energy consumption compared to Zigbee
- Bluetooth connects up to 8 node only.

3.1.2.4 Wireless Communication Standards Comparison

A comparison between the different Wireless communication standards that are presented on Sections 3.1.2.1, 3.1.2.2 and 3.1.2.3 is shown in Table 3.3 where their more important characteristics are compared.

Table 3.3: Wireless Communication Standards Comparison, adapted from [16],[17],[18]

	Zigbee	**Wi-Fi**	**Bluetooth**
Range	70-100 meters	30-100 meters	10-100 meters
Network Topology	Ad hoc, Star, Tree, Mesh	Ad hoc, Point to hub	Ad hoc, Point to Point, Mesh
Operating Frequency	868 Mhz (Europe), 2.4 Ghz (worldwide)	2.4 and 5 Ghz	2.4 Ghz
Complexity (Device and Application Impact)	Low	High	High
Power Consumption	Very Low	High	Medium
Security	128-bit encryption	256-bit encryption	128-bit encryption
Max Data Rate	250 Kbps	433 Mbps	1 Mbps

3.1.3 Accelerometers

Accelerometers are capable of measuring acceleration, tilt, and vibration or shock, and, as a result, are used in a diverse range of applications from wearable fitness devices to industrial platform stabilization systems. There are hundreds of parts to choose from with a significant span in cost and performance.

Figure 3.2 shows a snapshot of a range of (Microelectromechanical Systems (MEMS) accelerometers and classifies each sensor based on key performance metrics for a specific application and the level of intelligence/integration accordoing to Analog devices [19]. A key focus is on next-generation accelerometers based on enhanced MEMS structures and signal processing.

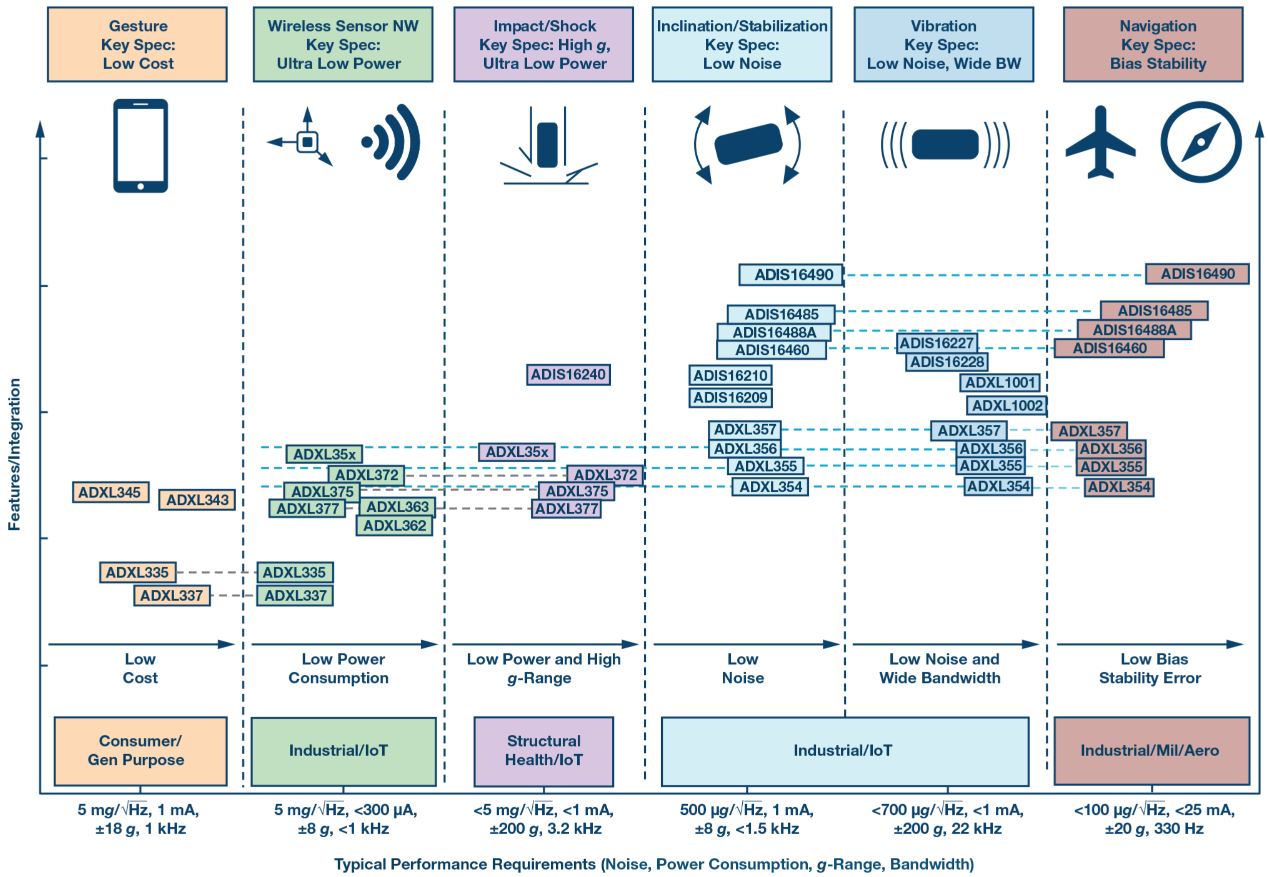


Figure 3.2: Application landscape for a selection of Analog Devices MEMS accelerometers, taken from [19].

A wide variety of accelerometers of different prices and characteristics exist, to narrow this research only devices that were available at CIDESI are considered. The three following accelerometers are researched and its characteristics described:

- **Triple Axis Accelerometer - MMA8452Q**:
  - 1.95 V to 3.6 V supply voltage
  - 1.6 V to 3.6 V interface voltage
  - $\pm 2g/\pm 4g/\pm 8g$ dynamically selectable full-scalell-scale
  - Output Data Rates (ODR) from 1.56 Hz to 800 Hz
  - 12-bit and 8-bit digital output
  - I^2C digital output interface (operates to 2.25 MHz with 4.7 kΩ pullup)
  - Two programmable interrupt pins for six interrupt sources

  - Three embedded channels of motion detection
  - Orientation (Portrait/Landscape) detection with set hysteresis
  - High Pass Filter Data available real-time
  - Current Consumption: 6 μA – 165μ A

- **Triple Axis Accelerometer - ADXL345**:
  - Ultralow power: as low as 23 μA in measurement mode and 0.1 μA in standby
  - Power consumption scales automatically with bandwidth
  - User-selectable resolution
  - Full resolution, where resolution increases with g range, up to 13-bit resolution at ±16g (maintaining 4 mg/LSB scale factor in all g ranges)
  - Embedded memory management system with FIFO technology minimizes host processor load
  - Supply voltage range: 2.0 V to 3.6 V
  - I/O voltage range: 1.7 V to VS
  - SPI (3- and 4-wire) and I2C digital interfaces
  - 10,000 g shock survival

- **Triple Axis Accelerometer and Gyroscope - MPU-6050**:
  - Three 16-bit analog-to-digital converters (ADCs) for digitizing the gyroscope outputs and three 16-bit ADCs for digitizing the accelerometer outputs.
  - Feature a user-programmable gyroscope full-scale range of ±250, ±500, ±1000, and $\pm 2000°/sec(dps)$ and a user-programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g.
  - Communication with all registers of the device is performed using either I2C at 400kHz or SPI at 1MHz
  - 10,000g shock tolerance
  - Operates from VDD power supply voltage range of 2.375V-3.46V.
  - Accelerometer normal operating current: 500μA
  - User self-test

3.2 Component Selection

After making an analysis of the main parts that could be used for the WSN, The best components are chosen according to the requirements laid out at the beginning of this chapter.

3.2.1 Single-Board Microcontroller Unit (SBMCU)

After describing the characteristics of 4 SBMCUs on Section 3.1.1, The Arduino Mega 2560 (Figure 3.3) was selected because its vast number of analog and digital I/O which make it flexible to integrate a wide number of sensors.

In spite of having bigger dimensions than the other compared SBMCUs its low energy consumption, versatility with a great number of Arduino shields available and an ample support by the open source community.

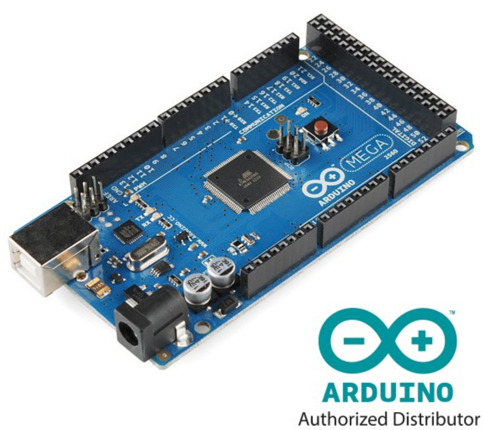


Figure 3.3: Arduino-Mega-2560, taken from [20].

3.2.2 Wireless Communication Standards

After analyze and research the advantages of Zigbee, Wi-fi and Bluetooth it can be seen that Zigbee is the best technology for our application. Zigbee has a bigger range and most important very low power consumption which is very important for WSN. In spite of having a slow data rate compared to Wi-fi and Bluetooth this is not a problem for this application.

Figure 3.4: Xbee Communication Module, taken from [21].

3.2.3 Accelerometers

According to the accelerometers available at CIDESI and described on Section 3.1.3, the ADXL345 is selected due to having a better resolution, range,bandwidth and lower energy consumption compared to the other usable accelerometers.

Several special sensing functions are provided. Activity and inactivity sensing detect the presence or lack of motion and if the acceleration on any axis exceeds a user-set level. Tap sensing detects single and double taps. Free-fall sensing detects if the device is falling. These functions can be mapped to one of two interrupt output pins. Low power modes enable intelligent motion-based power management with threshold sensing and active acceleration measurement at extremely low power dissipation.

Figure 3.5: ADXL345, taken from [22].

3.3 Concept of the System

After choosing each component according to the Hardware Analysis Section 3.1 a Layer Architecture is proposed, as it can be seen on Figure 3.6.

It consists of 5 layers:

1. The Sensor layer is where all the physical variables are measured.
2. The Data Acquisition Layer which consists on the digitalization of the sensors data or digital communication of the sensors (e.g., SPI,UART).
3. The Wireless Communication Layer is where the data from the Data Acquisition is send to the Base Station.
4. The Base Station Layer is in charge to gather all the data from the data acquisition nodes.
5. The Data Monitoring Layer is where all the data can be monitored and can be saved for further post-processing.

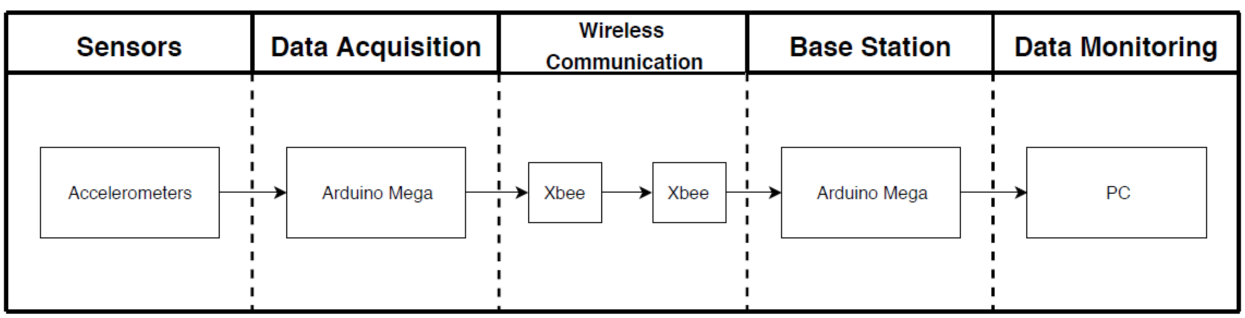


Figure 3.6: Layer Architecture.

Then on Figure 3.7 a complete concept of the entire system is introduced. Three sensor nodes are required since the proposed building-like structure has three floors, One base station to gather all the data from the nodes and finally a PC application to analyzing and monitoring the data.

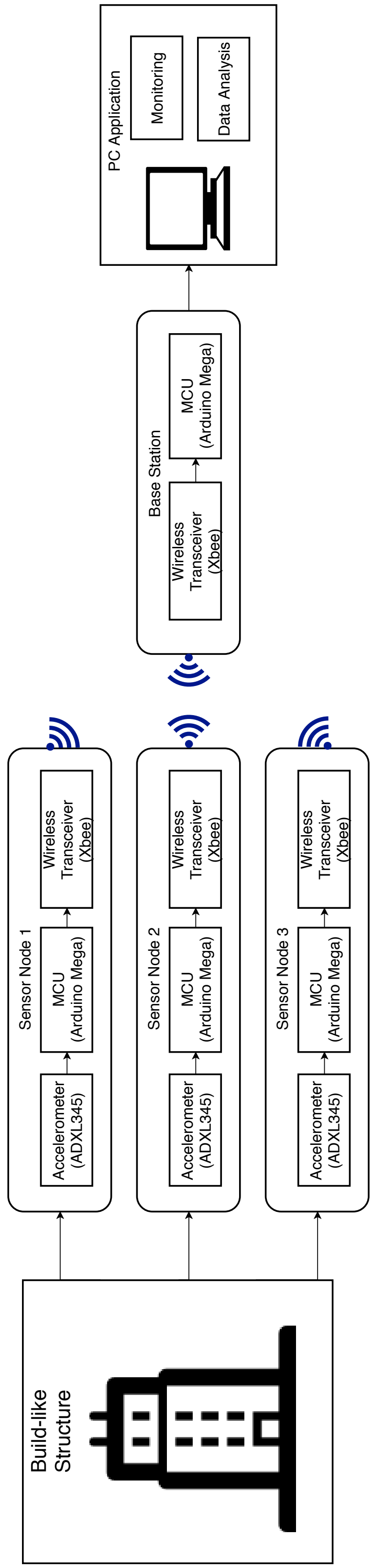


Figure 3.7: Complete System Concept.

Chapter 4

Theoretical Background

On this chapter, a brief introduction to the topics of WSNs, Zigbee Communication Protocol and Optimal Sensor Placement is presented.

4.1 Wireless Sensor Networks

While many sensors connect to controllers and processing stations directly (e.g., using local area networks), an increasing number of sensors communicate the collected data wirelessly to a centralized processing station. This is important since many network applications require hundreds or thousands of sensor nodes, often deployed in remote and inaccessible areas. Therefore, a wireless sensor has not only a sensing component, but also on-board processing, communication, and storage capabilities. With these enhancements, a sensor node is often not only responsible for data collection, but also for in-network analysis, correlation, and fusion of its own sensor data and data from other sensor nodes. When many sensors cooperatively monitor large physical environments, they form a WSN.

Sensor nodes communicate not only with each other but also with a base station (BS) using their wireless radios, allowing them to disseminate their sensor data to remote processing, visualization, analysis, and storage systems. For example, Figure 4.1 shows two sensor fields monitoring two different geographic regions and connecting to the Internet using their base stations.

The capabilities of sensor nodes in a WSN can vary widely, that is, simple sensor nodes may monitor a single physical phenomenon, while more complex devices may combine many different sensing techniques (e.g., acoustic, optical, magnetic). They can also differ in their communication capabilities, for example, using ultrasound, infrared, or radio frequency technologies with varying data rates and latencies.

While simple sensors may only collect and communicate information about the observed environment, more powerful devices (i.e., devices with large processing, energy, and storage capacities) may also perform extensive processing and aggregation functions. Such devices often assume additional responsibilities in a WSN, for example, they may form communication backbones that can be used by other resource-constrained sensor devices to reach the base station.

Finally, some devices may have access to additional supporting technologies, for example, Global Positioning System (GPS) receivers, allowing them to accurately determine their position. However, such systems often consume too much energy to be feasible for low-cost and low-power sensor nodes.

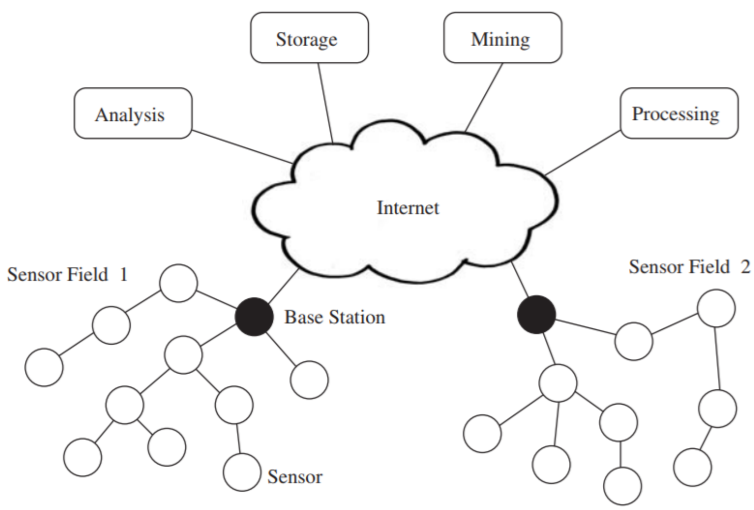


Figure 4.1: Conceptual example of a Wireless Sensor Network, adapted from [23].

4.1.1 Communication in a WSN

The well-known IEEE 802.11 (WiFi) family of standards was introduced in 1997 and is the most common wireless networking technology for mobile systems. It uses different frequency bands, for example, the 2.4-GHz band is used by IEEE 802.11b and IEEE 802.11g, while the IEEE 802.11a protocol uses the 5-GHz frequency band. IEEE 802.11 was frequently used in early WSNs and can still be found in current networks when bandwidth demands are high (e.g., for multimedia sensors). However, the high-energy overheads of IEEE 802.11-based networks makes this standard unsuitable for low-power sensor networks. Typical data rate requirements in sensor networks are comparable to the bandwidths provided by dial-up modems, therefore the data rates provided by IEEE 802.11 are typically much higher than needed. This has led to the development of a variety of protocols that better satisfy the networks' need for low power consumption and low data rates. For example, the IEEE 802.15.4 (Zigbee) protocol has been designed specifically for short- range communications in low-power sensor networks and is supported by most academic and commercial sensor nodes.

4.2 IEEE 802.15.4 Technology

The IEEE 802.15.4 wireless technology is a short-range communication system intended to provide applications with relaxed throughput and latency requirements in Wireless Personal Area Networks (WPANs). The key features of the IEEE 802.15.4 wireless technology are low complexity, low cost, low power consumption, low data rate transmissions, to be supported by cheap (either fixed or moving) devices. The main field of application of this technology is the implementation of WSNs: IEEE 802.15.4, in fact, can be considered the de facto standard for WSNs. The IEEE 802.15.4 Working Group focuses on the standardization of the bottom two layers of ISO/OSI protocol stack: Physical (PHY) and MAC. There are mainly two options for the upper layers definition: Zigbee protocol stack, specified by the industrial consortia ZigBee Alliance, and IPv6 over Low-power PAN (6LowPAN).

4.2.1 IEEE 802.15.4 Network Topologies and Operational Modes

To overcome the limited transmission range, multihop self-organizing network topologies are required. These can be realized taking into account that IEEE 802.15.4 defines two types of devices: the Full Function Device (FFD) and the Reduced Function Device (RFD). The FFD contains the complete set of MAC services and can operate as either a network coordinator (hereafter also denoted as WPAN coordinator) or as a simple network device. The RFD contains a reduced set of MAC services and can operate only as a network device.

Two basic topologies are allowed, but not completely described by the standard since definition of higher layers functionalities are out of the scope of IEEE 802.15.4: the star topology, formed around an FFD acting as a WPAN coordinator, which is the only node allowed to form links with more than one device, and the peer-to-peer topology, where each device is able to form multiple direct links to other devices so that redundant paths are available. An example of both the IEEE 802.15.4-compliant network topologies is shown in Figure 4.2.

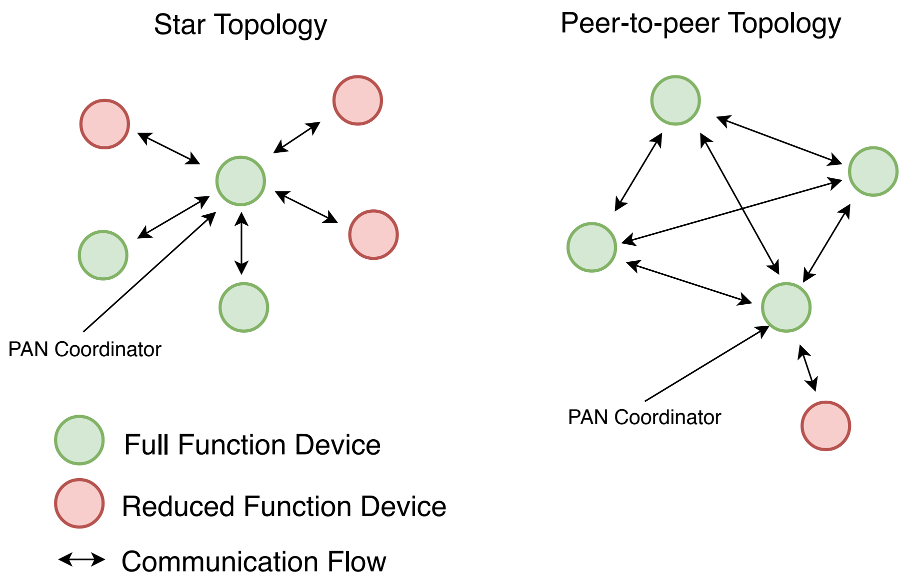


Figure 4.2: The two IEEE 802.15.4-compliant network topologies: star and peer-to-peer topologies, adapted from [24].

Star topology is preferable when the coverage area is small and a low latency is required by the application. In this topology, communication is controlled by the WPAN coordinator that acts as network master, sending packets, denoted as beacons, for synchronization and device association. Network devices are allowed to communicate only with the WPAN coordinator and any FFD may establish its own network by becoming a WPAN coordinator according to a predefined policy.A network device wishing to join a star network listens for a beacon message and, after receiving it, the network device can send an association request back to the WPAN coordinator, which allows the association or not. Star networks support also a non- beacon-enabled mode. In this case, beacons are used only for the purpose of association, whereas synchronization is achieved by polling the WPAN coordinator for data on a periodic basis.

Peer-to-peer topology is preferable when a large area has to be covered and latency is not a critical issue. This topology allows the formation of more complex networks and permits any FFD to communicate with any other FFD within its transmission range via multiple hops. Each device in a peer-to-peer structure needs to proactively search for other network devices. Once a device is found, the two devices can exchange parameters to recognize the type of services and features each supports. However, the introduction of multihop requires additional device memory for routing tables.

4.3 Optimal Sensor Placement

Generally for obtaining more information, more sensors have to be placed at the nodes of the structure. Placing a number of sensors is uneconomical and not possible in reality. Hence limiting the number of sensors comes into consideration. This process of limiting the sensors and placing them only at certain important nodes is termed as "Optimal Sensor Placement (OSP)" in structures.

Six different optimal sensor placements in buildings , namely Effective Independence (EFI), Optimal Driving Point (ODP), Non-Optimal Driving Point (NODP), Effective Independence Driving Point Residue (EFI-DPR), Singular Value Decomposition (SVD) and the Sensor Set Expansion (SSE) methods, have been introduced by Pelin Gundes Bakir[25].

4.3.1 Rules for Sensor Placement

There are five key considerations for determining sensor placement in mapping studies [26]. While every combination of environment and product specifications is unique, these rules are applicable to almost every situation.

- **Rule 1-Map the extremes:** To do an effective mapping, we must be sure to place sensors in the geometric extremes of the space. We must also be sure to place sensors in the locations that will experience the extremes. Mapping the extremes captures the worst-case conditions of the space and helps ensure we collect data from the entire space.
- **Rule 2-Map in three dimensions.**
- **Rule 3-For large spaces, map storage only:** As a space gets larger, it is not necessary to map hallways and access areas. We only need to map areas where product is actually stored.
- **Rule 4-Identify and address variables:** The process of identifying variables is recognizing the potential heat sources or areas of heat differences in the environment to be mapped.

- **Rule 5-If it's worth mapping, it's worth monitoring:** Identify the hot spots and cold spots, and then select a monitoring strategy to account for these known areas of concern. This may be accomplished by monitoring these spots directly, or by finding representative spots.

4.3.2 Sensor Placement using Genetic Algorithms

The use of Genetic Algorithms (GAs) seemed to be an effective approach to sensor placement problems. GAs are adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. GAs are a type of optimization algorithm, meaning they are used to find the optimal solution to a given computational problem that maximizes or minimizes a particular function. They imitate the biological processes of reproduction and natural selection to solve for the "fittest" solutions. The "traditional" GA is composed of a fitness function, a selection technique, and crossover and mutation operators which are governed by fixed probabilities.

Chapter 5

Hardware of the Wireless Sensor Network

On Chapter 3 a conceptual design for the WSN system was proposed. The two basic hardware systems are the sensor nodes and the base station, on this chapter the methodology and components used to develop both hardware systems are described. First, all the components used in the complete system are shown, then an individual description and schematics of the Sensor node and the Base Station are presented.

5.1 Wireless Sensor Network Components

On this Section all the Components that are part of the WSN system proposed on this thesis are reviewed, described and analyzed.

5.1.1 Accelerometer: ADXL345

A tri-axial accelerometer ADXL 345 from Analog Device is selected as the sensing component. The ADXL345 uses a MEMS accelerometer and has a maximum measurement range of ±16 g in all three directions with 13 bit resolution. The sampling rate is user selectable from 6.25 Hz to 3200 Hz. The accelerometer has low power consumption, requiring about 40 μA in measurement mode and 0.1 μA in standby mode (25 °C, 2.5V)[27]. The Datasheet of the Accelerometer with all the specifications can be seen on Apendix A.

On this thesis the SparkFun Triple Axis Accelerometer - ADXL345 is used since the accelerometer is mounted on a PCB and a standard Breakaway Male Header that can be welded to have access to the PINs as we can se on Figure 5.1.

Figure 5.1: SparkFun Triple Axis Accelerometer Breakout- ADXL345, taken from [22].

The Sparkfun ADXL345 Breakout board has eight pins, the description of each pin is given on Table 5.1. No interrupts is used for the WSN proposed on this Thesis and the communication protocol, the supply voltage range (VCC) has to be between 2.0V and 3.6V.

Table 5.1: Pin Function Descriptions of the ADXL345

Pin Name	Description
GND	Ground
VCC	Supply Voltage
CS	Chip Select
INT1	Interrupt 1 Output
INT2	Interrupt 2 Output
SDO	Serial Data Output
SDA	Serial Data (I2C)/Serial Data Input (SPI)
SCL	Serial Communications Clock

The ADXL 345 has an internal ADC, due to this the accelerometer has a digital output through SPI or I2C Communication. On this WSN prototype I2C communication is used. Figure 5.2 shows a schematic of a I2C connection between the accelerometer and a microcontroler.

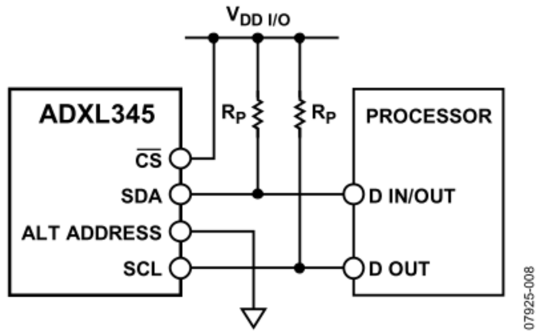


Figure 5.2: I2C Connection Diagram [22].

5.1.2 Single-Board Microcontroller Units: Arduino Mega 2560

The characteristics of the Arduino Mega 2560 have already been mentioned on Section 3.1.1. For the WSN nodes and base station the Serial1 port and I2C communication are used. The Arduino mega also has the capability to supply 5v and 3.3v, this is used to power the Xbee and the Accelerometer respectively. The Arduino Mega can be supplied through the Vin pin with a voltage between 7V and 12V. On Appendix B a detailed Pinout of the Arduino Mega 2560 can be found.

5.1.3 Wireless Communication Device: XBee Series 1

An XBee Series 1(S1) with 802.15.4 stack from Digi International Inc. is adopted as the wireless transmission module. It has a dedicated microcontroller for wireless data transmission. These modules take the 802.15.4 standard (the basis for Zigbee) and wrap it into a simple to use serial command set. These modules allow very reliable and simple communication between microcontrollers, computers and any system with serial port, Point to point and multi-point networks are also supported.

Current consumption during transmission and reception is 50 mA at 3.3V. The power-down current is less than 10 μA at 3.3V. The maximum transmission rate over-the-air is 250 kb/s. The maximum transmission range is 90 meters (Appendix C). Note that an enhanced version of XBee S1 is also available which has maximum transmission range 1600m. The tradeoff is higher current consumption (250 mA at 3.3V) during transmission.

The Xbee Modules from Digi can be configured using the XCTU Software from Digi. XCTU is a free multi-platform application designed to enable developers to interact with

Digi RF modules through a graphical interface. XCTU includes all of the tools a developer needs to quickly get up and running with XBee. Unique features like graphical network view, which graphically represents the XBee network along with the signal strength of each connection, and the XBee API frame builder, which intuitively helps to build and interpret API frames for XBees being used in API mode.

To connect the Xbee modules with the XCTU software, the data from the Xbee was redirected through the Arduino using the code on Listing 5.1. This was done to avoid the use of a Xbee Explorer USB, so no extra hardware was needed to configure the Xbee modules.

```
void setup() {
  Serial1.begin(115200);
  Serial.begin(115200);
}

void loop() {

  if(Serial.available())
    {
      Serial1.write(Serial.read());
    }

  if(Serial1.available())
    {
      Serial.write(Serial1.read());
    }
}
```

Listing 5.1: Code to connect Xbee with XCTU software through an arduino

5.1.4 XBee Arduino Shield

To easily connect the Xbee module and the Arduino, the SparkFun XBee Shield is used. The shield (5.3) form-factor mates directly with any dev board that has an Arduino standard footprint and equips it with wireless communication capabilities using the popular XBee module. This unit works with all XBee modules including the Series 1 and 2, standard and Pro versions.

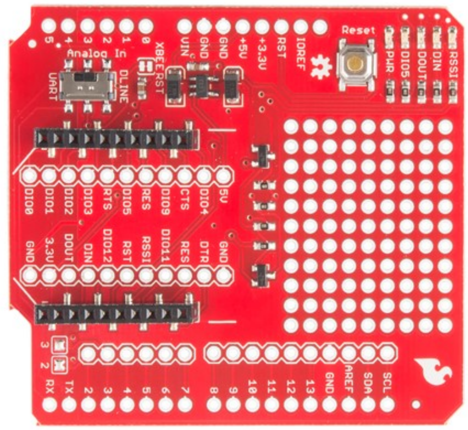


Figure 5.3: Xbee Arduino Shield, taken from [22].

The serial pins (DIN and DOUT) of the XBee are connected through an DPDT switch, which allows to select a connection to either the UART pins (D0, D1) or any digital pins on the Arduino (D2 and D3 default). Power is taken from the 5V pin of the Arduino and regulated on-board to 3.3VDC before being supplied to the XBee. The shield also takes care of level shifting on the DIN and DOUT pins of the XBee.

The board also includes LEDs to indicate power and activity on DIN, DOUT, RSSI, and DIO5 pins of the XBee. The Arduino's reset button is brought out on the shield, and a 9x11 grid of 0.1" holes are available for prototyping.

5.2 Base Station

The Base Station is composed of three elements Arduino Mega 2560, Xbee Arduino Shield and Xbee Series 1. The Base Station is in charge of receiving all the data from the sensor nodes and send it to the PC for monitoring and post-processing. On Figure 5.4 an actual image of the Base Station is shown.

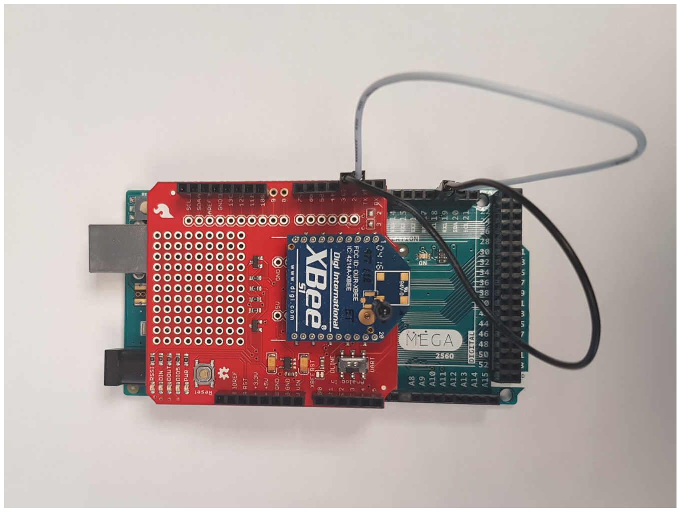


Figure 5.4: Image of the Built Base Station.

The data is received by the Xbee module and sent to the Serial port 1 of the Arduino, then the arduino Arduino sends the data to the Serial port 0 that is connected to a serial to USB converter. On Figure 5.5 a schematic of the connection of the different communication used between components on the Base Station is shown. A detailed pin to pin schematic can be seen on Appendix D.1

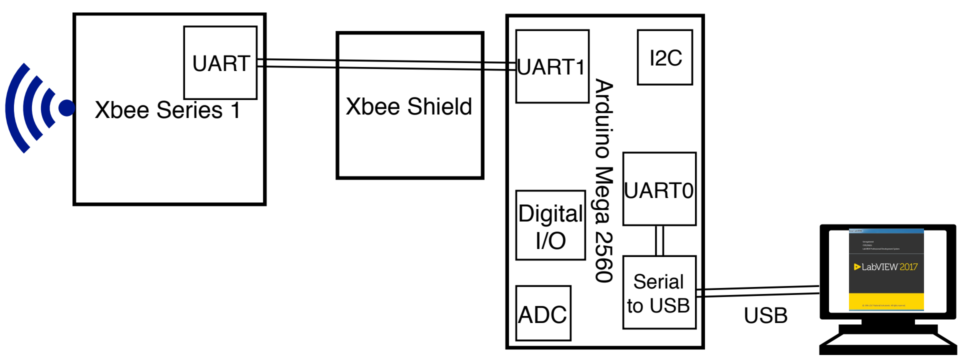


Figure 5.5: Base Station Communication Schematic.

The Xbee module of the Sensor Node is configured with the following parameter using the XCTU software: PAN ID=3332, Coordinator Enable= 1 (This set the Xbee module as Coordinator), Interface Data Rate=57600, API Enable=0 (AT mode Activated).

5.3 Sensor Node

The sensor station consists on 3 essential components: Arduino Mega 2560, Xbee Arduino Shield and Xbee Series 1. Also multiple sensors can be added but for this Thesis only an Accelerometer ADXL345 is used. The sensor node is in charge of receiving and gathering all the data from the sensors and send it to the Base Station. On Figure 5.6 an actual image of the Sensor Node is shown.

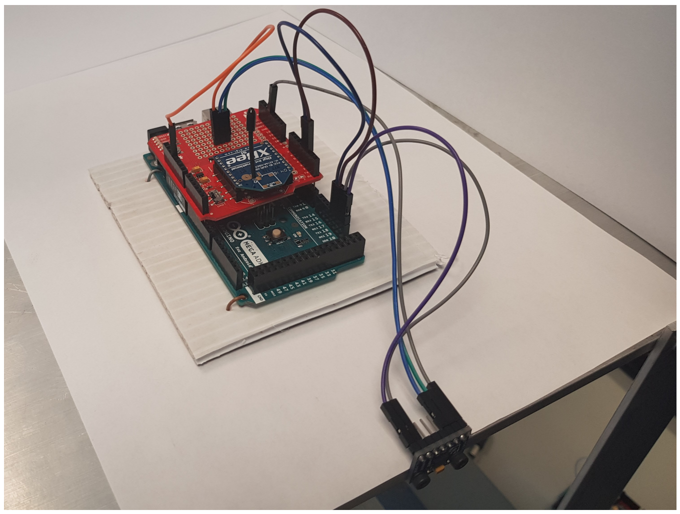


Figure 5.6: Current Image of the Built Sensor Node.

The accelerometer sends all the data through I2C bus to the Arduino Mega 2560. Then the Arduino sends the data through the Serial Port 1 to the Xbee Arduino Shield where it is redirected to the Xbee, The Xbee then transmits the data wirelessly to the Base Station. On Figure 5.7 a schematic of the connection of the different communication used between components is shown. A detailed pin to pin schematic can be seen on Appendix D.2

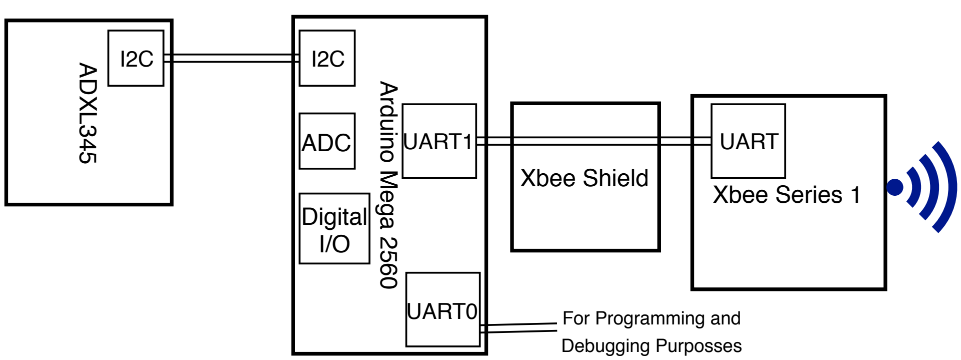


Figure 5.7: Sensor Node Communication Schematic.

The Xbee module of the Sensor Node is configured with the following parameter using the XCTU software: PAN ID=3332, Coordinator Enable= 0 (This set the Xbee module as a End-device), Interface Data Rate=57600, API Enable=0 (AT mode Activated).

5.4 Energy Consumption

The constraint most often associated with sensor network design is that sensor nodes operate with limited energy budgets. Typically, they are powered through batteries, which must be either replaced or recharged (e.g., using solar power) when depleted. For some nodes, neither option is appropriate, that is, they will simply be discarded once their energy source is depleted . Whether the battery can be recharged or not significantly affects the strategy applied to energy consumption. For non-rechargeable batteries, a sensor node should be able to operate until either its mission time has passed or the battery can be replaced. The length of the mission time depends on the type of application, for example, scientists monitoring glacial movements may need sensors that can operate for several years while a sensor in a battlefield scenario may only be needed for a few hours or days. As a consequence, the first and often most important design challenge for a WSN is energy efficiency. This requirement permeates every aspect of sensor node and network design [23]. Due to time constrains the WSN was powered through USB, a future work an Energy Consumption analysis and the use of a Lipo Battery is recommended.

5.5 Hardware Cost

On Table 5.2, the cost of all the components that integrate the Wireless Sensor network is shown. The cost is for a Sensor Node, for a Base Station the cost of the accelerometer would have to be subtracted.

Table 5.2: Cost of the Components that Integrate the WSN

Quantity	**Device**	**Cost (USD)**
1	Accelerometer ADXL345	$9.95
1	Arduino Mega 2560	$18.99
1	XBee Series 1 Module	$24.95
1	XBee Arduino Shield	$14.95
1	7.4V 5200mAh Lipo Battery	$22.79
	Total	$91.63

Chapter 6

Software of the Wireless Sensor Network

After designing and building a prototype of the WSN on Chapter 5, the next step is to describe the software used on the Base Station and the Sensor Node as well as the software use for the Monitoring interface. First the software used for the Base Station and Sensor Node is described, then the Monitoring user interface is described and explained.

6.1 Base Station

The only task for the Base Station is to receive the Data from the Sensor Node and afterwards send it to the monitoring interface. The idea was to have a Star topology network but since only one Sensor node was built, the connection between the Sensor Node and the Base Station is configured as peer-to-peer. The serial data rate is configured at 56000 bauds.

On Figure 6.1 a Sequence diagram of the Base Station is shown. The serial ports are first initialized with the function *Serial.begin()* and then if there is data available in any of the serial ports, the data is redirected to the other serial port e.g. there is data on Serial port 1, data is read using *Serial1.read()* and then written on Serial port 0 using *Serial.write()*. The complete code can be found on Appendix E.1.

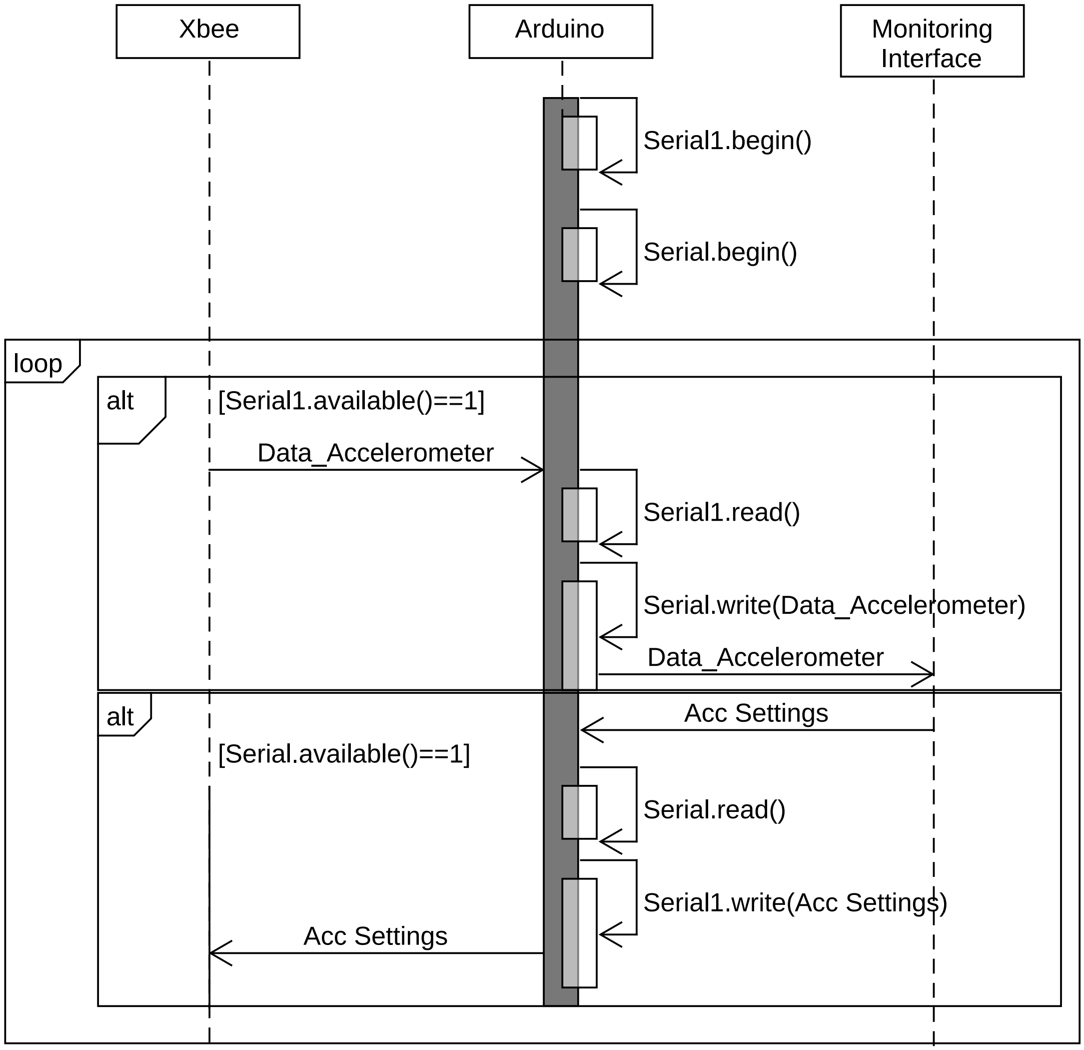


Figure 6.1: Base Station sequence diagram

6.2 Sensor Node

The Sensor Node task is to sample data from the accelerometers continuously, then this data is sent to the Base Station. The serial data rate is configured at 56000 bauds and the I2C clock is set at 400kHz. On Figure 6.2 a Sequence diagram of the Base Station is shown.

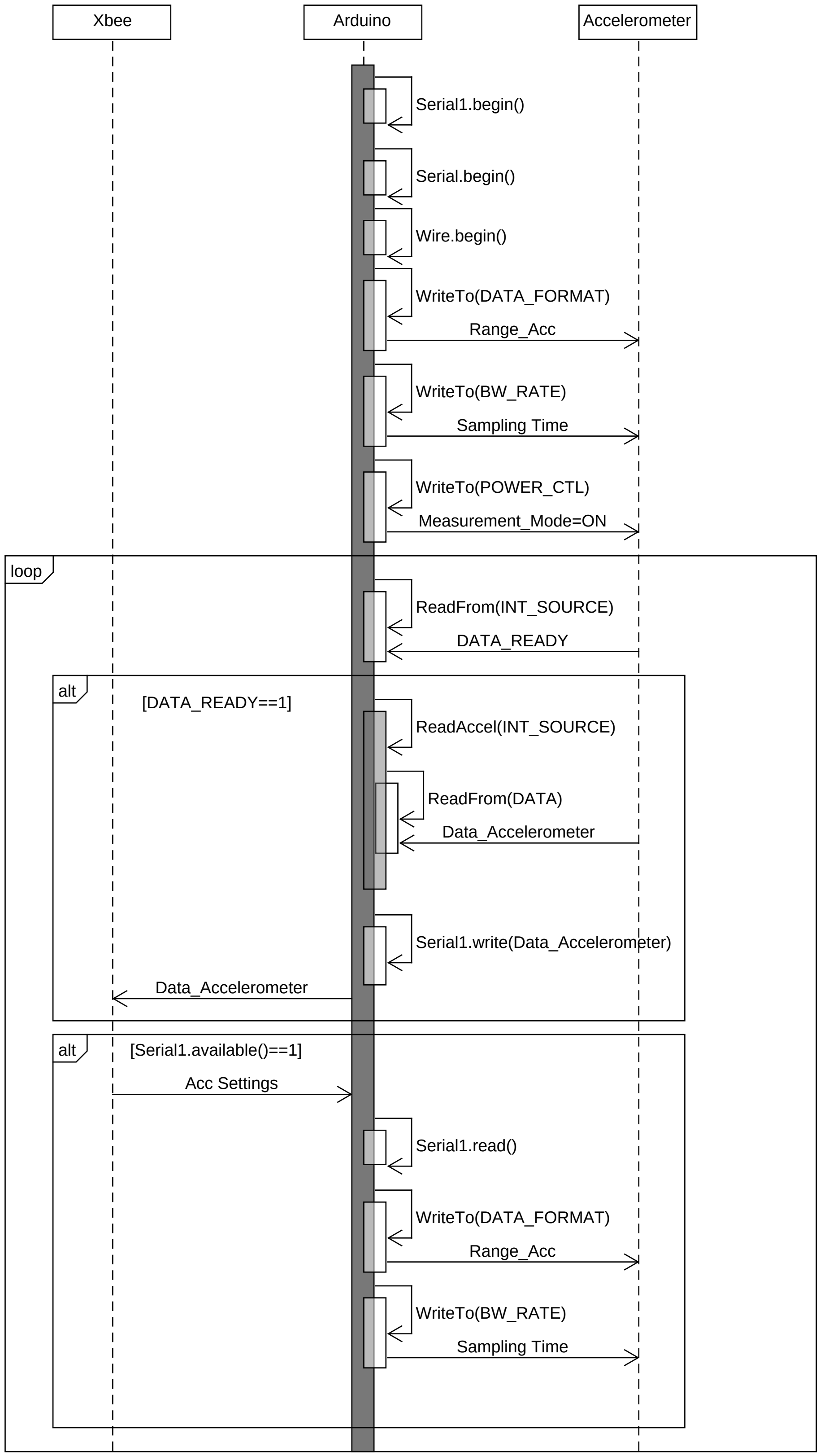


Figure 6.2: Sensor Node sequence diagram.

The serial ports are initialized, as well as the I2C communication protocol. Then the default sampling time, range and mode of the accelerometer are set on the accelerometer registers(Table 6.1). The DATA_READY flag is checked continuously, if the flag is set then the acceleration is read on the DATA registers (0x32-0x37) and sent to the Xbee through the Serial port 1. If there is incoming data from the Serial port 1, is an indicator that the Monitoring interface is sending a new Sampling Rate and Range for the accelerometer. The complete code can be found on Appendix E.2.

Table 6.1: Map of the registers used of the ADXL345 accelerometer

Name	**R/W**	**Address**	**Function**
BW_RATE	R/W	0x2C	Sampling Time Selection Register
DATAX	R	0x32-0x33	X-Axis Data
DATAY	R	0x34-0x35	Y-Axis Data
DATAZ	R	0x36-0x37	Z-Axis Data
DATA_FORMAT	R/W	0x31	Data Format Control
POWER_CTL	R/W	0x2D	Power-Saving Features Control
INT_ENABLE	R/W	0x2E	Interrupt Enable Control
INT_SOURCE	R	0x30	Source of Interrupts

6.2.1 Moving Average Filter

The moving average filter operates by averaging a number of points from the input signal to produce each point in the output signal. The moving average filter is optimal for a common problem, reducing random white noise while keeping the sharpest step response. In equation form, this is written:

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i+j] \tag{6.1}$$

The moving average filter was implemented on the Sensor Node using the Arduino library *movingAvg.h*, the moving average filter is used to smooth and remove high frequency noise from the accelerometer data. On Figure 6.3 a comparison between the filtered and unfiltered data is shown.

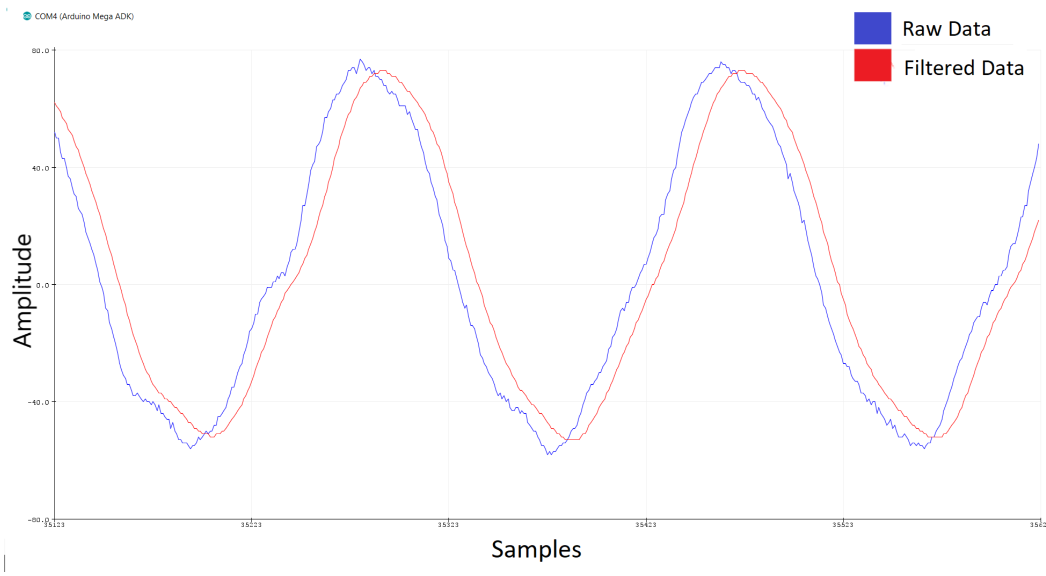


Figure 6.3: Comparison between filtered and unfiltered data.

6.2.2 I2C Communication

As mentioned before the communication between the Arduino and the accelerometer is done through the I2C communication protocol, for this purpose the Arduino library *Wire.h* is used. Two functions were created to facilitate the writing(Listing 6.2) and reading(Listing 6.1).

```
void readFrom(int device, byte address, int num, byte _buff[])
{
  Wire.beginTransmission(device);
  Wire.write(address);
  Wire.endTransmission();
  Wire.beginTransmission(device);
  Wire.requestFrom(device, num);

  int i = 0;
  while (Wire.available())
  {
    _buff[i] = Wire.read();
    i++;
  }
  Wire.endTransmission();
}
```

Listing 6.1: *readFrom* function to communicate to the accelerometer

```

  void writeTo(int device, byte address, byte val)
{
  Wire.beginTransmission(device);
  Wire.write(address);
  Wire.write(val);
  Wire.endTransmission();
}
```

Listing 6.2: *writeTo* function to communicate to the accelerometer

6.3 Monitoring System

After the Base Station gets accelerometer data from the Sensor Node, the data is then sent to a Monitoring System. The Monitoring system facilitates the user to visualize the data, save the accelerometer data to a TDMS file, configure serial settings, configure accelerometer settings. A post-processing is as well done through the Monitoring system.

The Monitoring system is programed using LabVIEW from National Instruments. The front panel consists on 4 parts(Figure 6.4):

1. Serial settings: on this part the user can set the COM port used, data rate, parity, read data. Also, the user can visualize the number of bytes incoming as well as the error codes corresponding to the Serial port.

2. Accelerometer settings: On this part the user can set the range and sample rate of the accelerometer.

3. Save File settings: On this part the user can define the path to the data file and decide if he wants to save the data.

4. Graphic data visualization: On this part the user can visualize on the accelerometer tab the value of each acceleration axis. Then on the Data Z,Y,X tab the user can visualize the FFT, Velocity and Displacement corresponding on that axis.

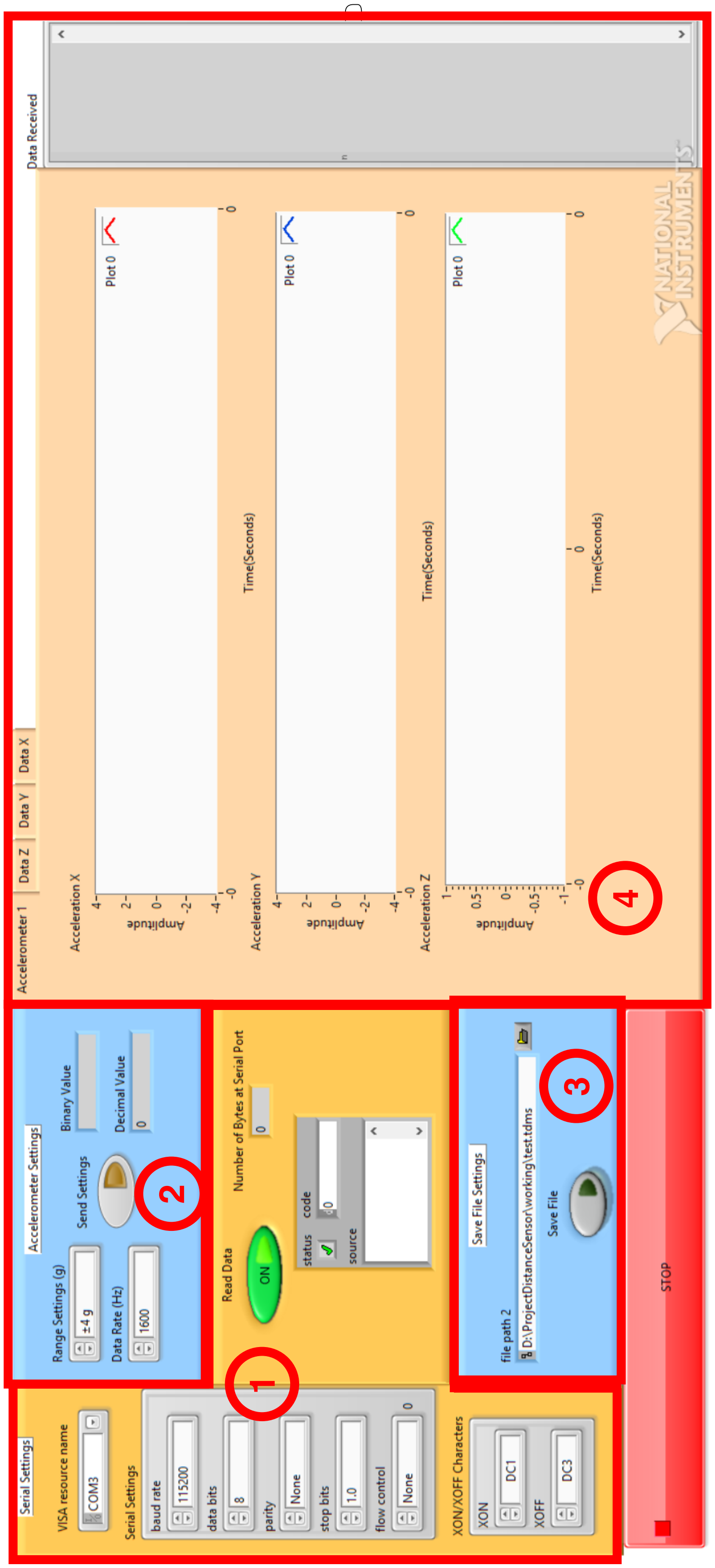


Figure 6.4: Front Panel Monitoring Interface: 1) Serial settings 2) Accelerometer settings 3) Save File settings 4) Graphic data visualization

A Producer/Consumer design pattern is used to obtain the data from the accelerometer as fast as possible. The Producer/Consumer is geared towards enhanced data sharing between multiple loops running at different rates. The Producer/Consumer pattern is used to decouple processes that produce and consume data at different rates. The Producer/Consumer pattern's parallel loops are broken down into two categories; those that produce data, and those that consume the data produced. Data queues are used to communicate data between loops in the Producer/Consumer design pattern. These queues offer the advantage of data buffering between producer and consumer loops.

Chapter 7

System Validation on Building-like Structure

To validate the WSN system a Building-like structure is designed. Then using the CAD model a modal analysis is performed on ANSYS to know the modal frequencies. The building-like structure is constructed and the WSN system is mounted on the building-like structure. Using an impact-hammer to excite the structure, data from the accelerometer is gathered and post-processed. Finally the data from the accelerometer is compared with the modal analysis.

7.1 Building-like Structure Design and Construction

To measure the performance of the accelerometers on SHM a scale-like structure, representing the dynamics of a 3-story building is designed. The structure consists of only two different parts: the plates that represent the floors and the beams that represent the columns that support the floors.

Table 7.1: Weight of the Building-like Structure

Quantity	**Part**	**Weight**
4	Aluminum Plate	1.55kg
4	Aluminum Column	0.51kg
Total		8.24kg

The floors are made of aluminum plate and have a length and width of 300mm x 300mm and a thickness of 1/4 in. The weight of each plate is 1.55kg. The columns are made of aluminum sheet and have a length and width of 1200mm x 50.8mm and a thickness of 1/8 in. The weight of each column is 0.51kg. The total weight of the structure is 8.24kg.

M3x15mm screws are use to join the columns, each floor is join to each column by two screws. On Figure 7.1 an image of the CAD model made on SolidWorks is shown. The detailed drawings of the Building-like Structure can be found on appendix F. The Structure was made on the Machining lab at CIDESI

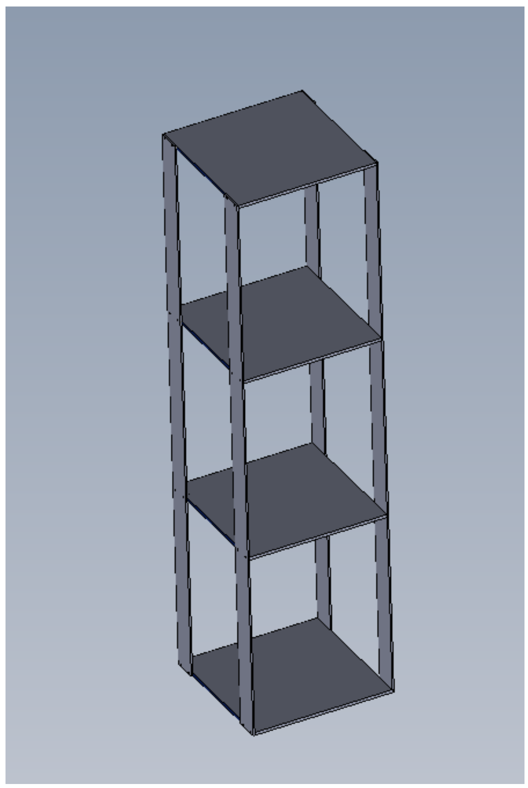
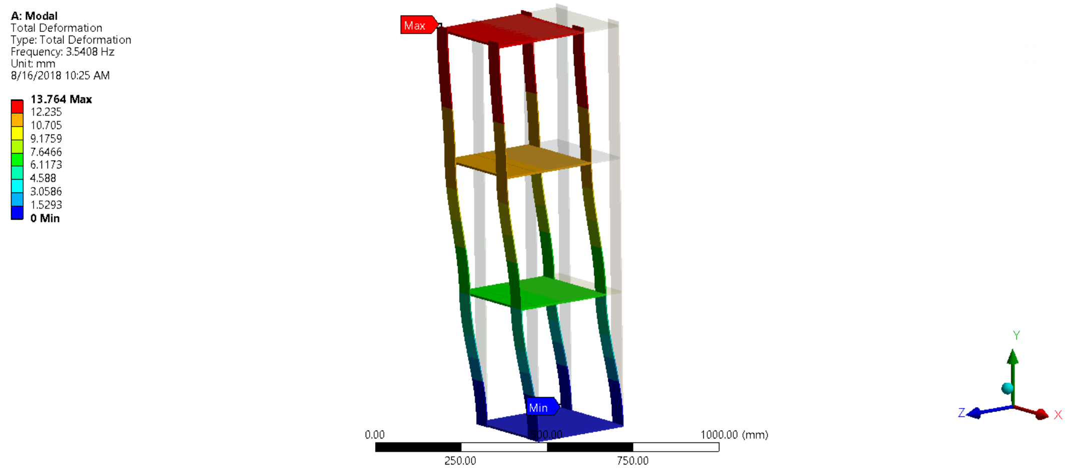


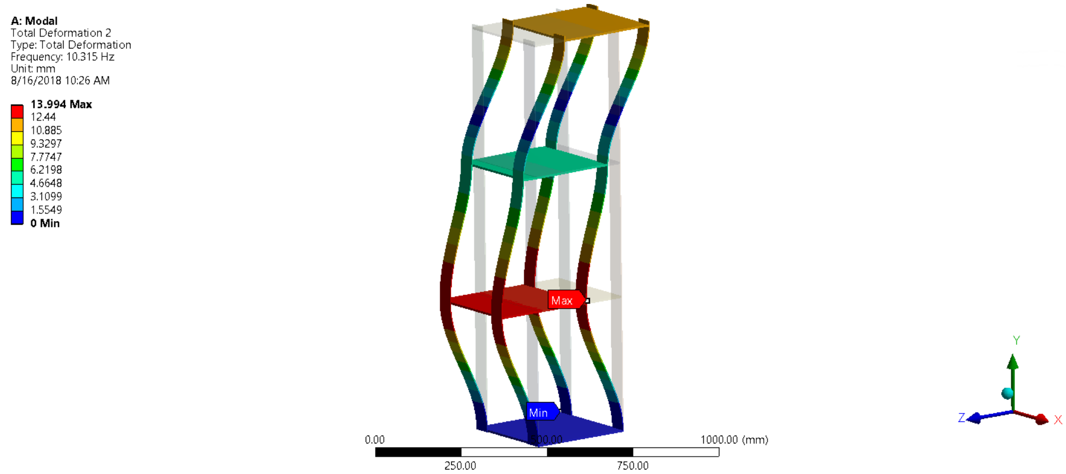
Figure 7.1: 3D CAD Model of the Building-like Structure.

7.2 Modal Analysis

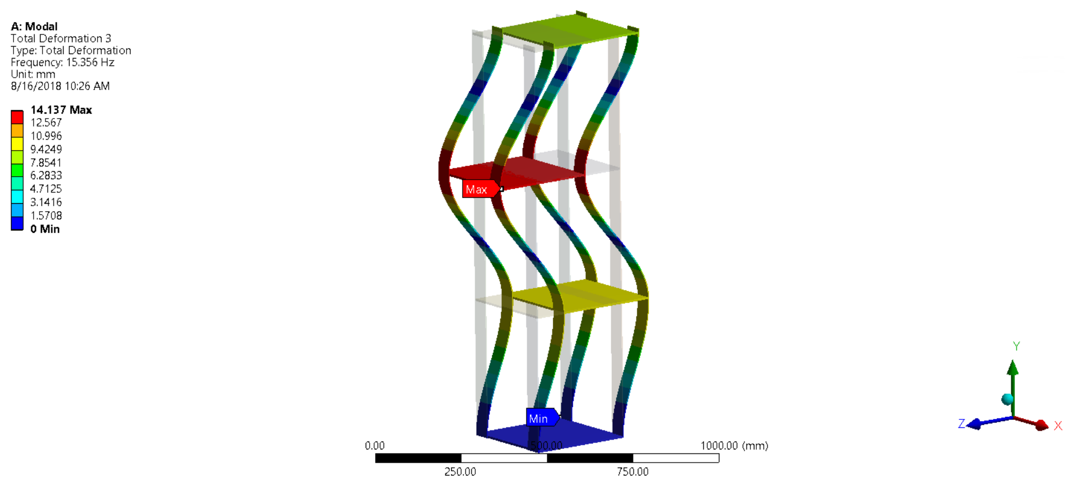
Using the CAD Model a FEM Modal Analysis was performed on ANSYS to know the structure resonance frequencies. A simplified model was made by not taking into consideration the screws, the union between the plate and the columns was considered to be perfect. The first 3 mode shapes are shown on Figure 7.2 and the first three resonance frequencies are shown in Table 7.2



(a) First Mode.



(b) Second Mode.



(c) Third Mode.

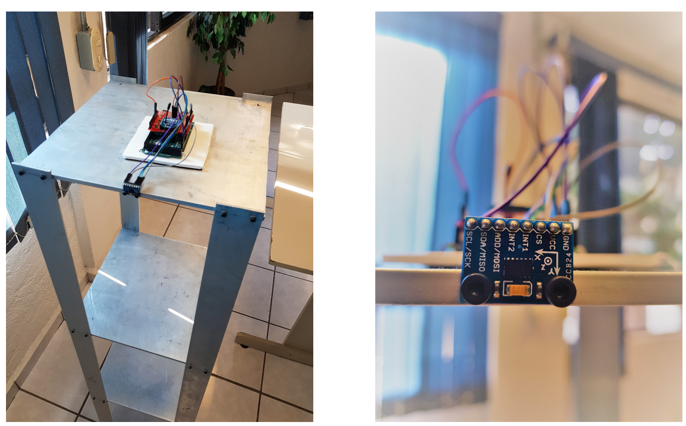
Figure 7.2: First three Mode Shapes.

Table 7.2: Resonance Frequencies obtained from the FEM Modal Analysis.

Mode	**Frequency [Hz]**
1.	3.54
2.	10.31
3.	15.35

7.3 Experimental Data from the WSN

The original plan was to have three Sensor nodes, one mounted on each floor, but due to budget issues only one Sensor node with an accelerometer was mounted on the top floor using M3x10mm screws. On Figure 7.3 the Sensor Node and the Accelerometer mounted on the Building-like Structure can be seen.



(a) Top view of the WSN mounted on the Building-like Structure

(b) View of the Accelerometer mounted on the Building-like Structure

Figure 7.3: Sensor Node an Accelerometer mounted on the Building-like Structure.

Impulse testing of the dynamic behavior of mechanical structure involves striking the test object with a force-instrumented hammer at one point, and measuring the resultant motion with a fixed accelerometer. The hammer used to excite the structure was a 086C03 made by PCB Piezotronics, Inc.(Figure 7.4).

Figure 7.4: 086C40 Impact Hammer used to excite the Building-like structure and its different tips, taken from [28].

Integration of the acceleration signal yields velocity compliance, impedance, and mobility. The hammer impulse consists of a nearly-constant force over a broad frequency range, and is therefore capable of exciting all resonance frequencies in that range. The hammer, size, length, material and velocity at impact determine the amplitude and frequency content of the force impulse. The response curves of the 086C40 Impact Hammer used for this experiment can be seen on Figure 7.5

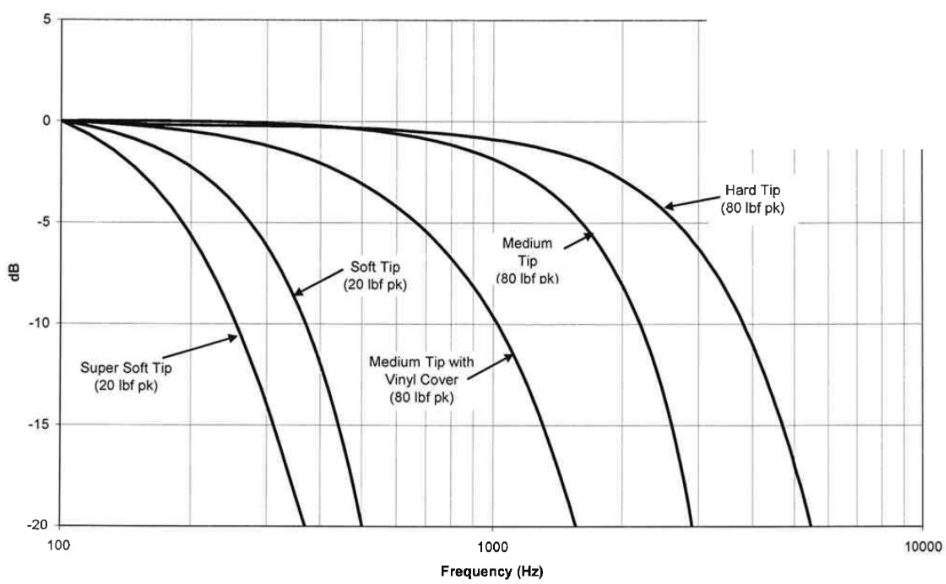


Figure 7.5: 086C40 Impulse Hammer Response Curves according to the used tip, taken from [28].

7.3.1 Experimental Setup

The Structure was excited using the 086C40 Impact Hammer with the Medium Impact Tip (Figure 7.5). The Structure was hit on each floor one time on the places marked on

Figure 7.6, the force from the impact was recorded using an Oscilloscope Tektronix TBS 1102B-EDU. The response from the impact was recorded by the accelerometer connected to the Sensor Node. Then the Base Station received the data from the Sensor Node and sent it to the monitoring interface on LabVIEW for post-processing. Sampling rate of the accelerometer was set at 400Hz, using a 10 bit. The accelerometer range was set at +/- 4g, resulting in a resolution of 7.8mg/LSB .On Figure 7.6 all the parts of the experimental setup is shown.

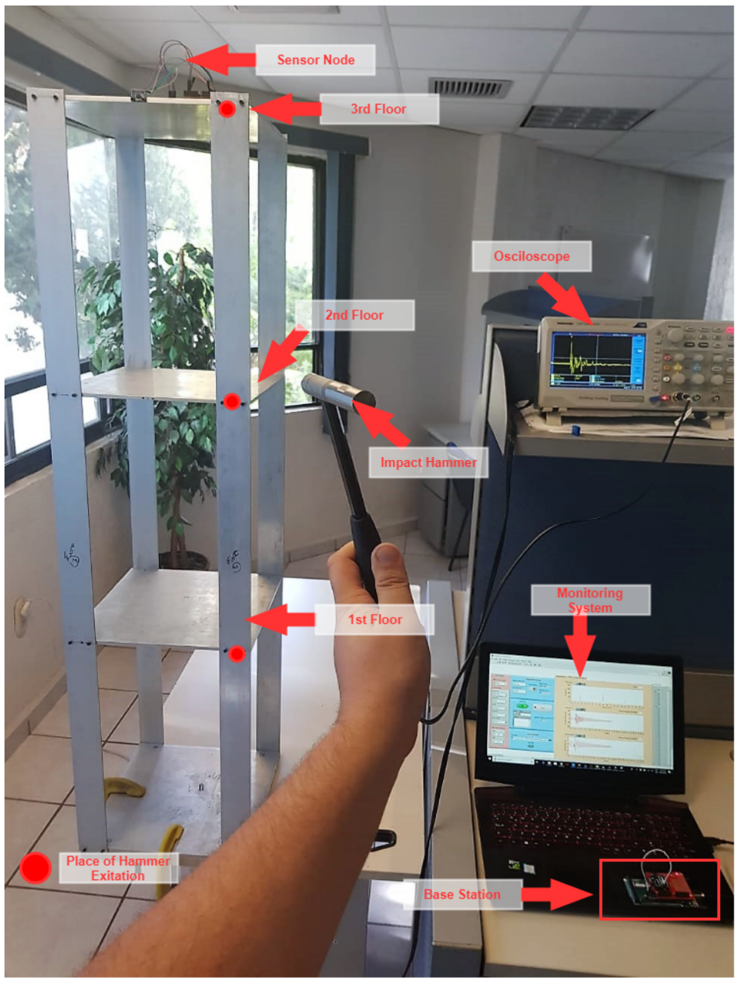


Figure 7.6: Experimental Setup to excite the Building-like structure.

7.3.2 Results

After obtaining the accelerometer data from the excitation of each floor a 6th order Butterworth highpass filter with cutoff frequency of 1Hz is applied to eliminate the signal offset. The conversion of time series data into frequency domain by FFT was performed to perceive the natural frequencies. Also to know the velocity and displacement of the structure integration and double integration was done respectively. The force applied on each floor was 244N for the first floor (Figures 7.7), 186N for the second floor (7.9) and 231N for the third floor (7.11). The acceleration, velocity, displacement and Frequency spectrum of each floor can be seen on Figures 7.8, 7.10 and 7.12

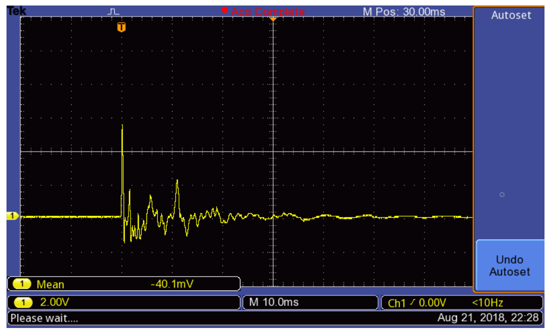
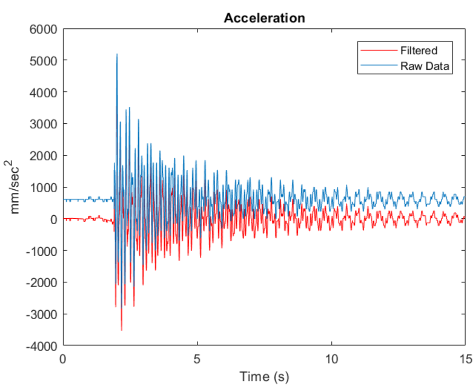
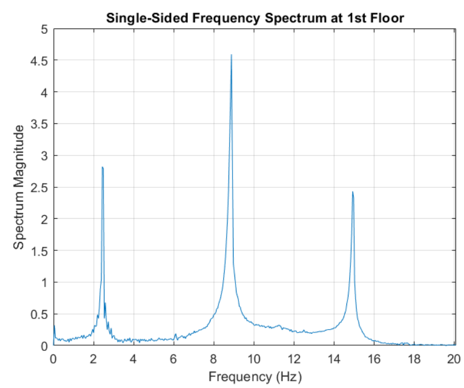


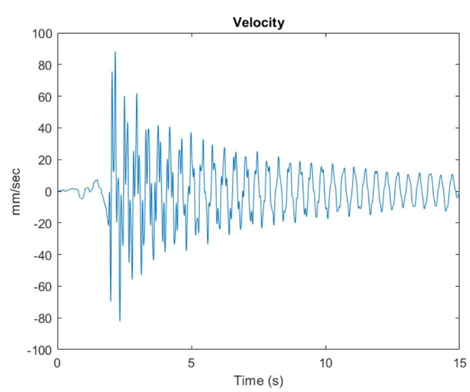
Figure 7.7: Force of 244N applied at first floor



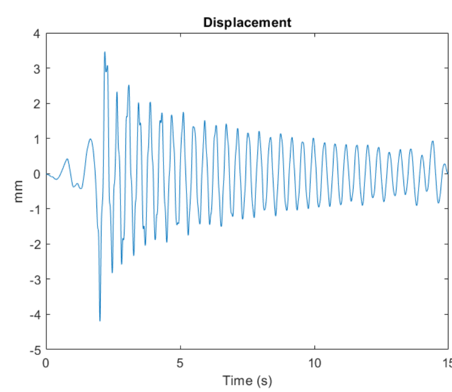
(a) Acceleration comparison between filtered and unfiltered data



(b) Frequency spectrum of first floor response



(c) Velocity of first floor reponse



(d) Displacement of second floor reponse

Figure 7.8: Results of the excitation at First Floor.

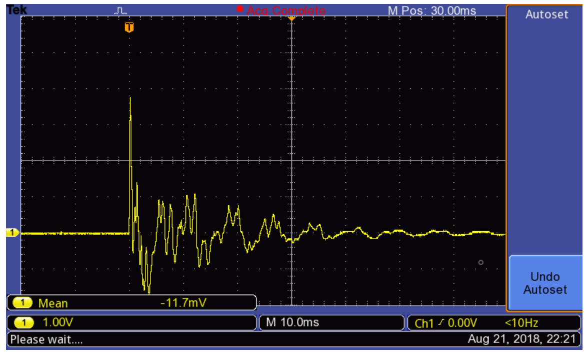
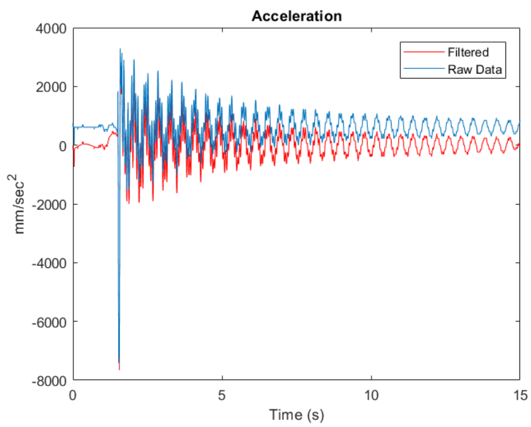
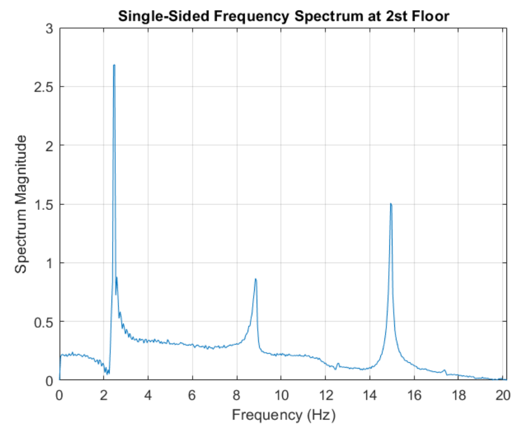


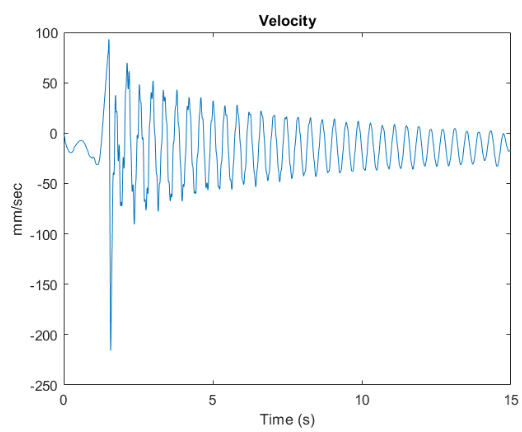
Figure 7.9: Force of 186N applied at second floor.



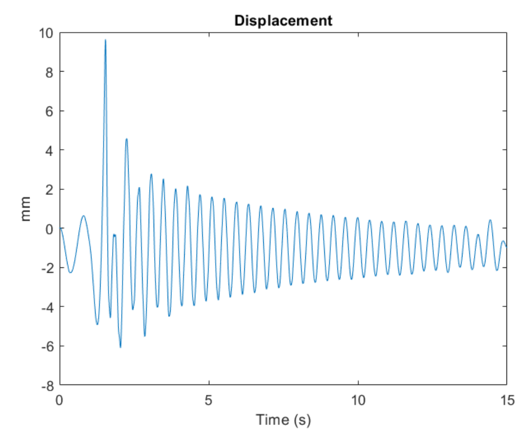
(a) Acceleration Comparison between Filtered and Unfiltered Data



(b) Frequency spectrum of second floor response



(c) Velocity of second floor reponse



(d) Displacement of second floor reponse

Figure 7.10: Results of the excitation at Second Floor.

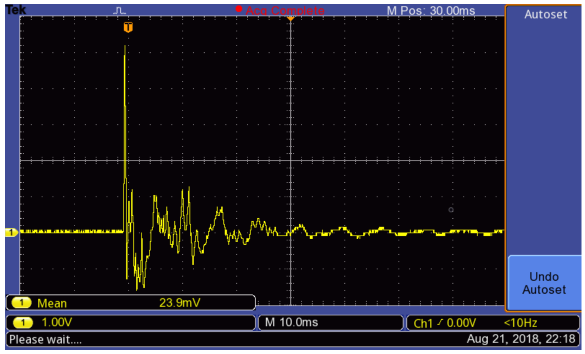
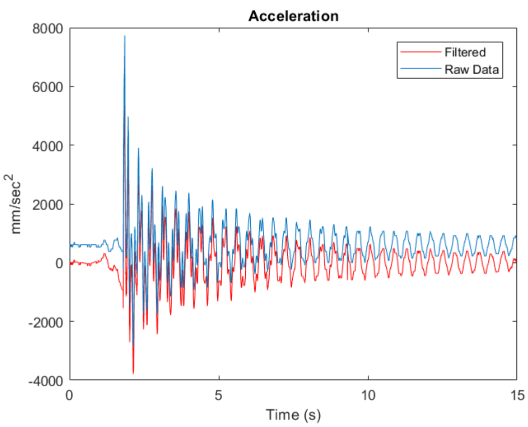
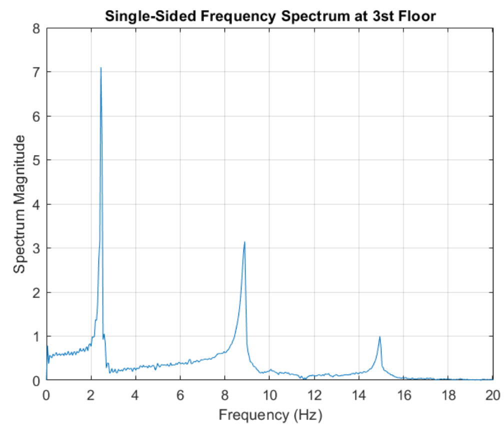


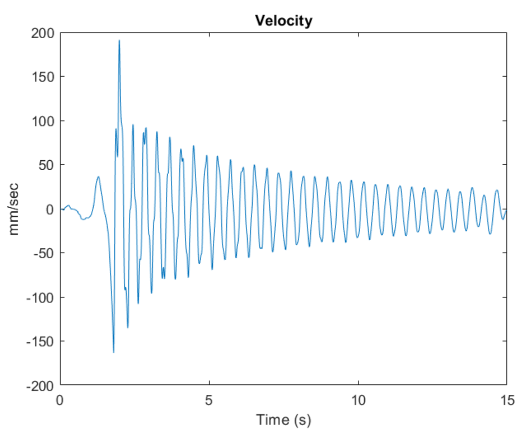
Figure 7.11: Force of 231N applied at third floor.



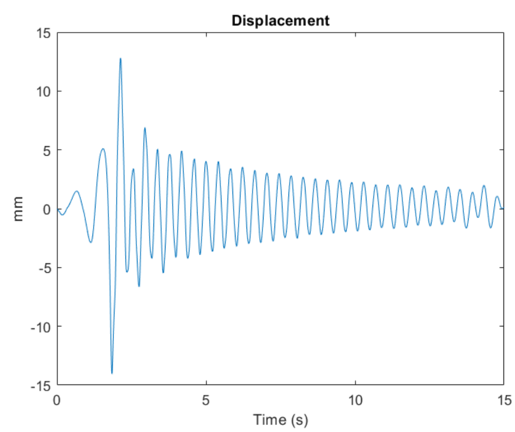
(a) Acceleration Comparison between Filtered and Unfiltered Data



(b) Frequency spectrum of third floor response



(c) Velocity of third floor reponse



(d) Displacement of third floor reponse

Figure 7.12: Results of the excitation at Third Floor.

Table 7.3: Resonance Frequencies obtained by experimental data.

Mode	Frequency [Hz]
1.	2.34
2.	8.91
3.	14.83

7.4 Comparison between Experimental data and FEM Modal Analysis

Table 7.4 compares the modal frequencies obtained from experimental results and the FEM Modal Analysis. The natural frequencies of the FEM Modal Analysis are close to the experimental results. The approach between the results demonstrate the ability of the wireless accelerometer to measure accelerations accurately.

Table 7.4: Comparison between Experimental data and FEM Modal Analysis

	Experimental Results	FEM Modal Analysis Results
Mode	**Frequency [Hz]**	**Frequency [Hz]**
1.	2.34	3.54
2.	8.91	10.31
3.	14.83	15.35

The difference between the results was believe to be due to the simplified model used for the FEM Modal Analysis. The model did not take into account the screws and the unions between the floors and the columns were modeled as perfect under ideal conditions.

Chapter 8

Real World System Concept for Civil Structure

The WSN System described on Chapters 5 and 6 was only an academic prototype. On this Chapter a Real-time WSN that could be implemented on a real world civil structure is proposed, for that purpose some changes to the previous conceptual design mentioned on Chapter 3 would have to be performed. On this Chapter a brief introduction to the new proposed hardware is made and at the end a System Concept is shown.

8.1 Proposed Changes to the Sensor Node

The hardware changes to the Sensor Node are as follow:

- Accelerometer: The ADXL1001 deliver ultralow noise density over an extended frequency range with two full-scale range options, and are optimized for industrial health usage monitoring sytems and vibration applications. The ADXL1001 ($\pm 100g$) has typical noise densities of 30 ug/$\sqrt{Hz}$, respectively. Both accelerometer devices have stable and repeatable sensitivity, which is immune to external shocks up to 10,000 g.

- GPS: The idea of adding a GPS is to have a timestamp with of the data sampled by the sensor and to relate the movement of a Civil Structure to the real world.

8.2 Proposed Changes to the Base Station

The hardware changes to the Base Station are as follow:

- CompactRIO System: Provide high-performance processing capabilities, sensor-specific conditioned I/O, and a closely integrated software toolchain that make them ideal for Industrial Internet of Things (IIoT), monitoring, and control applications. CompactRIO Overcomes the traditional challenges of programming heterogeneous architectures with NI Linux Real-Time, the LabVIEW FPGA Module, and the NI-DAQmx driver. With this combination, it is possible to develop faster systems. Focus on solving problems, not low-level programming tasks, with integrated user-friendly software that reduces risk, enhances productivity, and eliminates the need to create and maintain I/O drivers, OSs, and other middleware.
- Cloud Data Logging: The CompactRIO System is able to store data directly to the cloud. This would allow the Monitoring System to be in a remote area.

8.3 Concept of the Proposed System

The Real-Time concept design with the changes proposed on Section 8.1 and 8.2 can be seen on Figure 8.1. The number of Sensor Nodes depends on the application and has to be decided using Optimal Sensor Placement Techniques. An Industrial grade accelerometer (ADXL1001) is used instead of the general purpose accelerometer used before (ADXL345). Also the Base Station uses a CompactRIO system that allow for Real-Time applications and runs over NI Linux Real-Time, this system allow us to save data to the cloud to be Monitored remotely.

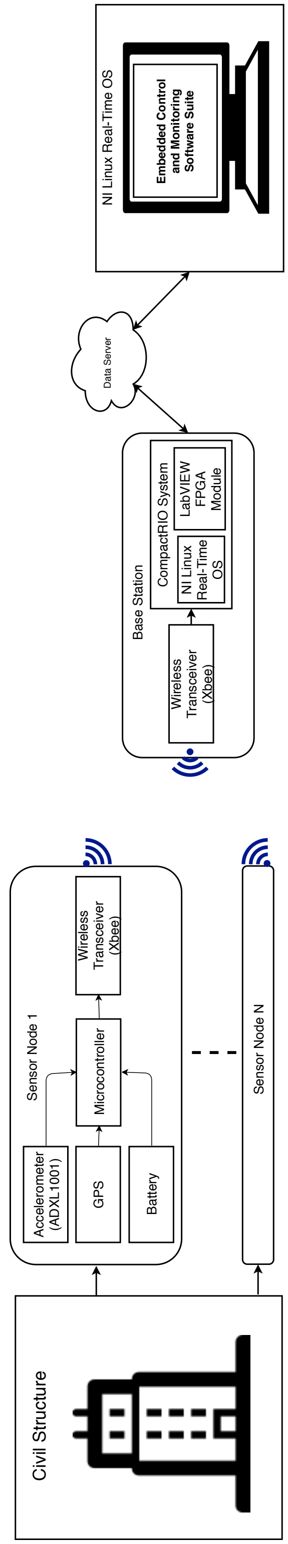


Figure 8.1: Real-time Wireless Sensor Network System Concept.

Chapter 9

Conclusions

The wireless monitoring of civil structures is a very useful tool to establish an analysis of buildings through the use of sensors to determine the type of damages and predict the failure of the structure. An insight of multiple state of the art available technologies was given.

A conceptual design to implement a wireless sensor network on a three story building-like structure was proposed after reviewing wireless technologies, communication protocols, microcontrollers and accelerometers. But due to budget issues only a part of the system could be implemented.

Taking into consideration the Conceptual Design a prototype of the Base Station and Sensor Node was built and designed successfully. A Monitoring interface to visualize and post-process the data was also created using LabVIEW.

To validate the data from the WSN the natural frequencies from the structure were obtained experimentally using the accelerometer data and through a FEM Modal Analysis. Both results were relatively close which means that the WSN system can provide accurate acceleration measurements from dynamic structures.

9.1 Future Work

The future research directions are detailed below:

- Applying the wireless sensor network to other applications should be explored, i.e. wind turbine monitoring and vibration control system. The low cost and low power wireless sensor network platform with flexible interfaces is appealing to such applications.
- Each wireless sensor node has certain computational power and this computational capability will continue to grow with the rapid development of sensor hardware. Utilizing the computational capability more efficiently and effectively requires continuous research effort.
- A test on an actual civil structure would give the system more reliability. For this task more sensor nodes would have to be implemented and even more sensors could be use e.g. GPS.
- The Base Station currently sends the data to the Monitoring Interface through a Wire, it would be a great addition to connect the Base Station to the Internet wirelessly and send the data to the Cloud. On this manner the Monitoring Interface could be used in any place.
- Implementation of a full system through the use of a Monitoring based scheme and Real-time data manipulation.

Bibliography

[1] J. Torresen, E. Renton, and A. R. Jensenius, "Wireless Sensor Data Collection based on ZigBee Communication," *Proceedings of the 2010 Conference on New Interfaces for Musical Expression (NIME 2010)*, pp. 368–371, 2010.

[2] F. Mieyeville, M. Ichchou, G. Scorletti, D. Navarro, and W. Du, "Wireless sensor networks for active vibration control in automobile structures," *Smart Materials and Structures*, vol. 21, no. 7, 2012.

[3] K. S. Rekha, T. H. Sreenivas, and A. D. Kulkarni, "Remote Monitoring and Reconfiguration of Environment and Structural Health Using Wireless Sensor Networks," *Materials Today: Proceedings*, vol. 5, no. 1, pp. 1169–1175, 2018.

[4] Y. Wang, R. A. Swartz, J. P. Lynch, K. H. Law, L. K.-C., and L. C.-H., "Decentralized civil structural control using a real-time wireless sensing and control system," *4th World Conference on Structural Control and Monitoring (4WCSCM)*, vol. 3, no. 3, pp. 321–340, 2006.

[5] X. Dong, D. Zhu, and Y. Wang, "Design and Validation Of Acceleration Measurement using The Martlet Wireless Sensing System," *Proceedings of the ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, pp. 1–9, 2014.

[6] M. Kane, D. Zhu, M. Hirose, X. Dong, B. Winter, M. Häckell, J. P. Lynch, Y. Wang, and A. Swartz, "Development of an extensible dual-core wireless sensing node for cyber-physical systems," no. April 2014, p. 90611U, 2014.

[7] J. Enríquez-Zárate, G. Silva-Navarro, and H. F. Abundis-Fong, "Active vibration suppression through positive acceleration feedback on a building-like structure: An experimental study," *Mechanical Systems and Signal Processing*, vol. 72-73, pp. 451–461, 2016.

[8] J. Enríquez-Zárate and G. Silva-Navarro, "Ground-borne vibration control in a building-like structure using multi-positive position feedback combined with sliding mode control," *Noise Control Engineering Journal*, vol. 64, no. 5, 2016.

[9] C. Park, Q. Xie, P. H. Chou, and M. Shinozuka, "DuraNode: Wireless networked sensor for structural health monitoring," *Proceedings of IEEE Sensors*, no. October 2005, pp. 277–280, 2005.

[10] "Mica 2 datasheet." `https://www.eol.ucar.edu/isf/facilities/isa/internal/CrossBow/DataSheets/mica2.pdf`. Accessed on 18-05-2018.

[11] "Imote2 wireless sensor datasheet." `http://wsn.cse.wustl.edu/images/e/e3/Imote2{_}Datasheet.pdf`. Accessed on 18-05-2018.

[12] "User Guide and Specifications NI WSN-3226 NI Wireless Sensor Network." `http://www.ni.com/pdf/manuals/373007b.pdf`. Accessed on 2018-05-30.

[13] D. Muriá-Vila, J. Camargo, and B. Aldama, "Structural Health Monitoring of an Instrumented Building in Mexico with Accelerometers and GPS Sensors," in *The 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, vol. 17, pp. 285–303, 2013.

[14] B. SYSCOM, "Case study - Monitoring of a building in the Philippines," Tech. Rep. April, 2018.

[15] "Arduino - Software." `https://www.arduino.cc/en/Main/Software`. Accessed on 2018-06-05.

[16] M. Deseada Gutierrez, *Indoor Location Systems Based on Zigbee networks*. PhD thesis, Mikkelin University of Applied Sciences, 2012.

[17] N. V. Rajeesh Kumar, C. Bhuvana, and S. Anushya, "Comparison of ZigBee and Bluetooth wireless technologies-survey," *2017 International Conference on Information Communication and Embedded Systems, ICICES 2017*, no. Icices, pp. 1–4, 2017.

[18] J. Kooker, "Bluetooth, ZigBee, and Wibree:A Comparison of WPAN Technologies," p. 4, 2008.

[19] C. Murphy, "Choosing the Most Suitable MEMS Accelerometer for Your Application—Part 1 — Analog Devices," 2018.

[20] "Arduino Mega Image." `http://arduino.cl/arduino-mega-2560/`. Accessed on 2018-06-30.

[21] "Image of the Wireless Xbee." `https://www.digi.com/products/xbee-rf-solutions/2-4-ghz-modules`. Accessed on 2018-06-30.

[22] "ADXL345 Sparkfun Image." `https://www.sparkfun.com/products/9836`. Accessed on 2018-06-30.

[23] W. Dargie and C. Poellabauer, *Fundamentals of Wireless Sensor Networks*. Wiley, 2010.

[24] C. Buratti, M. Martaló, R. Verdone, and G. Ferrari, *Sensor Networks with IEEE 802.15.4 Systems*. Springer, 2011.

[25] P. G. Bakir, "Evaluation of Optimal Sensor Placement Techniques for Parameter Identification in Buidlings," *Mathematical and Computational Applications*, vol. 16, no. 2, pp. 456–466, 2011.

[26] Vaisala, "5 Rules of Sensor Placement in Validation / Mapping Applications," tech. rep., Vaisala Oyj, 2014.

[27] Analog Devices, *ADXL345 Datasheet*.

[28] PCB Piezotronics, Inc., *086C03 Impact Hammer Datasheet*.

Appendices

Appendix A

ADXL345 Datasheet

ANALOG DEVICES

3-Axis, ±2 *g*/±4 *g*/±8 *g*/±16 *g* Digital Accelerometer

ADXL345

FEATURES

- **Ultralow power: as low as 40 μA in measurement mode and 0.1 μA in standby mode at V_S = 2.5 V (typical)**
- **Power consumption scales automatically with bandwidth**
- **User-selectable resolution**
  - **Fixed 10-bit resolution**
  - **Full resolution, where resolution increases with *g* range, up to 13-bit resolution at ±16 *g* (maintaining 4 m*g*/LSB scale factor in all *g* ranges)**
- **Embedded, patent pending FIFO technology minimizes host processor load**
- **Tap/double tap detection**
- **Activity/inactivity monitoring**
- **Free-fall detection**
- **Supply voltage range: 2.0 V to 3.6 V**
- **I/O voltage range: 1.7 V to V_S**
- **SPI (3- and 4-wire) and I²C digital interfaces**
- **Flexible interrupt modes mappable to either interrupt pin**
- **Measurement ranges selectable via serial command**
- **Bandwidth selectable via serial command**
- **Wide temperature range (−40°C to +85°C)**
- **10,000 *g* shock survival**
- **Pb free/RoHS compliant**
- **Small and thin: 3 mm × 5 mm × 1 mm LGA package**

APPLICATIONS

- **Handsets**
- **Medical instrumentation**
- **Gaming and pointing devices**
- **Industrial instrumentation**
- **Personal navigation devices**
- **Hard disk drive (HDD) protection**
- **Fitness equipment**

GENERAL DESCRIPTION

The ADXL345 is a small, thin, low power, 3-axis accelerometer with high resolution (13-bit) measurement at up to ±16 *g*. Digital output data is formatted as 16-bit twos complement and is accessible through either a SPI (3- or 4-wire) or I²C digital interface.

The ADXL345 is well suited for mobile device applications. It measures the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion or shock. Its high resolution (4 m*g*/LSB) enables measurement of inclination changes less than 1.0°.

Several special sensing functions are provided. Activity and inactivity sensing detect the presence or lack of motion and if the acceleration on any axis exceeds a user-set level. Tap sensing detects single and double taps. Free-fall sensing detects if the device is falling. These functions can be mapped to one of two interrupt output pins. An integrated, patent pending 32-level first in, first out (FIFO) buffer can be used to store data to minimize host processor intervention.

Low power modes enable intelligent motion-based power management with threshold sensing and active acceleration measurement at extremely low power dissipation.

The ADXL345 is supplied in a small, thin, 3 mm × 5 mm × 1 mm, 14-lead, plastic package.

FUNCTIONAL BLOCK DIAGRAM

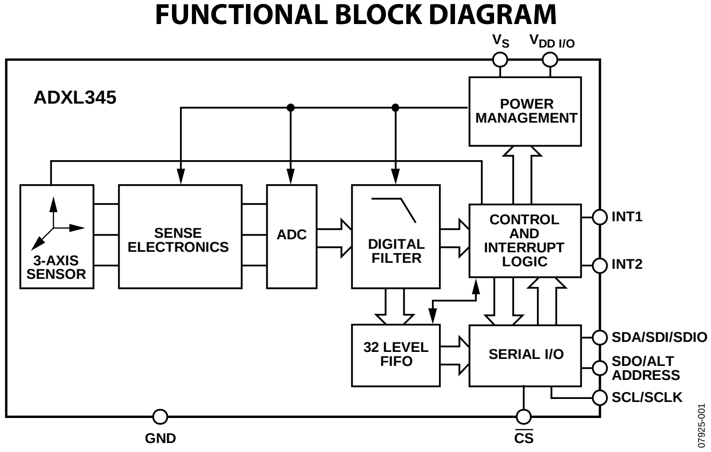


Figure 1.

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781.329.4700 www.analog.com
Fax: 781.461.3113

SPECIFICATIONS

T_A = 25°C, V_S = 2.5 V, $V_{DD\ I/O}$ = 1.8 V, acceleration = 0 *g*, C_S = 1 µF tantalum, C_{IO} = 0.1 µF, unless otherwise noted.

Table 1. Specifications[1]

Parameter	Test Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range	User selectable		±2, ±4, ±8, ±16		*g*
Nonlinearity	Percentage of full scale		±0.5		%
Inter-Axis Alignment Error			±0.1		Degrees
Cross-Axis Sensitivity[2]			±1		%
OUTPUT RESOLUTION	Each axis				
All *g* Ranges	10-bit resolution		10		Bits
±2 *g* Range	Full resolution		10		Bits
±4 *g* Range	Full resolution		11		Bits
±8 *g* Range	Full resolution		12		Bits
±16 *g* Range	Full resolution		13		Bits
SENSITIVITY	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	±2 *g*, 10-bit or full resolution	232	256	286	LSB/*g*
Scale Factor at X_{OUT}, Y_{OUT}, Z_{OUT}	±2 *g*, 10-bit or full resolution	3.5	3.9	4.3	m*g*/LSB
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	±4 *g*, 10-bit resolution	116	128	143	LSB/*g*
Scale Factor at X_{OUT}, Y_{OUT}, Z_{OUT}	±4 *g*, 10-bit resolution	7.0	7.8	8.6	m*g*/LSB
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	±8 *g*, 10-bit resolution	58	64	71	LSB/*g*
Scale Factor at X_{OUT}, Y_{OUT}, Z_{OUT}	±8 *g*, 10-bit resolution	14.0	15.6	17.2	m*g*/LSB
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	±16 *g*, 10-bit resolution	29	32	36	LSB/*g*
Scale Factor at X_{OUT}, Y_{OUT}, Z_{OUT}	±16 *g*, 10-bit resolution	28.1	31.2	34.3	m*g*/LSB
Sensitivity Change Due to Temperature			±0.01		%/°C
0 *g* BIAS LEVEL	Each axis				
0 *g* Output for X_{OUT}, Y_{OUT}		−150	±40	+150	m*g*
0 *g* Output for Z_{OUT}		−250	±80	+250	m*g*
0 *g* Offset vs. Temperature for x-, y-Axes			±0.8		m*g*/°C
0 *g* Offset vs. Temperature for z-Axis			±4.5		m*g*/°C
NOISE PERFORMANCE					
Noise (x-, y-Axes)	Data rate = 100 Hz for ±2 *g*, 10-bit or full resolution		<1.0		LSB rms
Noise (z-Axis)	Data rate = 100 Hz for ±2 *g*, 10-bit or full resolution		<1.5		LSB rms
OUTPUT DATA RATE AND BANDWIDTH	User selectable				
Measurement Rate[3]		6.25		3200	Hz
SELF-TEST[4]	Data rate ≥ 100 Hz, 2.0 V ≤ V_S ≤ 3.6 V				
Output Change in x-Axis		0.20		2.10	*g*
Output Change in y-Axis		−2.10		−0.20	*g*
Output Change in z-Axis		0.30		3.40	*g*
POWER SUPPLY					
Operating Voltage Range (V_S)		2.0	2.5	3.6	V
Interface Voltage Range ($V_{DD\ I/O}$)	V_S ≤ 2.5 V	1.7	1.8	V_S	V
	V_S ≥ 2.5 V	2.0	2.5	V_S	V
Supply Current	Data rate > 100 Hz		145		µA
	Data rate < 10 Hz		40		µA
Standby Mode Leakage Current			0.1	2	µA
Turn-On Time[5]	Data rate = 3200 Hz		1.4		ms
TEMPERATURE					
Operating Temperature Range		−40		+85	°C
WEIGHT					
Device Weight			20		mg

[1] All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.
[2] Cross-axis sensitivity is defined as coupling between any two axes.
[3] Bandwidth is half the output data rate.
[4] Self-test change is defined as the output (*g*) when the SELF_TEST bit = 1 (in the DATA_FORMAT register) minus the output (*g*) when the SELF_TEST bit = 0 (in the DATA_FORMAT register). Due to device filtering, the output reaches its final value after 4 × τ when enabling or disabling self-test, where τ = 1/(data rate).
[5] Turn-on and wake-up times are determined by the user-defined bandwidth. At a 100 Hz data rate, the turn-on and wake-up times are each approximately 11.1 ms. For other data rates, the turn-on and wake-up times are each approximately τ + 1.1 in milliseconds, where τ = 1/(data rate).

ABSOLUTE MAXIMUM RATINGS

Table 2.

Parameter	Rating
Acceleration	
Any Axis, Unpowered	10,000 *g*
Any Axis, Powered	10,000 *g*
V_S	−0.3 V to +3.6 V
$V_{DD\ I/O}$	−0.3 V to +3.6 V
Digital Pins	−0.3 V to $V_{DD\ I/O}$ + 0.3 V or 3.6 V, whichever is less
All Other Pins	−0.3 V to +3.6 V
Output Short-Circuit Duration (Any Pin to Ground)	Indefinite
Temperature Range	
Powered	−40°C to +105°C
Storage	−40°C to +105°C

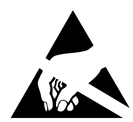
Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

THERMAL RESISTANCE

Table 3. Package Characteristics

Package Type	θ_{JA}	θ_{JC}	Device Weight
14-Terminal LGA	150°C/W	85°C/W	20 mg

ESD CAUTION



ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

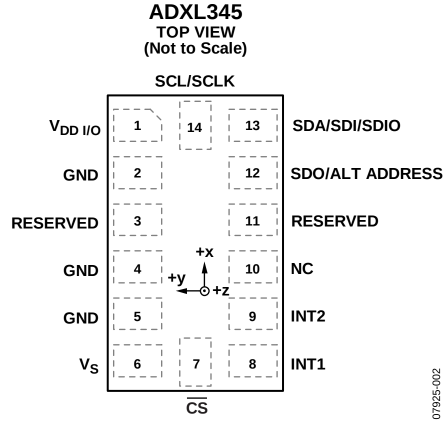


Figure 2. Pin Configuration

Table 4. Pin Function Descriptions

Pin No.	Mnemonic	Description
1	$V_{DD\ I/O}$	Digital Interface Supply Voltage.
2	GND	Must be connected to ground.
3	Reserved	Reserved. This pin must be connected to V_S or left open.
4	GND	Must be connected to ground.
5	GND	Must be connected to ground.
6	V_S	Supply Voltage.
7	$\overline{CS}$	Chip Select.
8	INT1	Interrupt 1 Output.
9	INT2	Interrupt 2 Output.
10	NC	Not Internally Connected.
11	Reserved	Reserved. This pin must be connected to ground or left open.
12	SDO/ALT ADDRESS	Serial Data Output/Alternate I^2C Address Select.
13	SDA/SDI/SDIO	Serial Data (I^2C)/Serial Data Input (SPI 4-Wire)/Serial Data Input and Output (SPI 3-Wire).
14	SCL/SCLK	Serial Communications Clock.

Appendix B

Arduino Mega 2560 Pinout

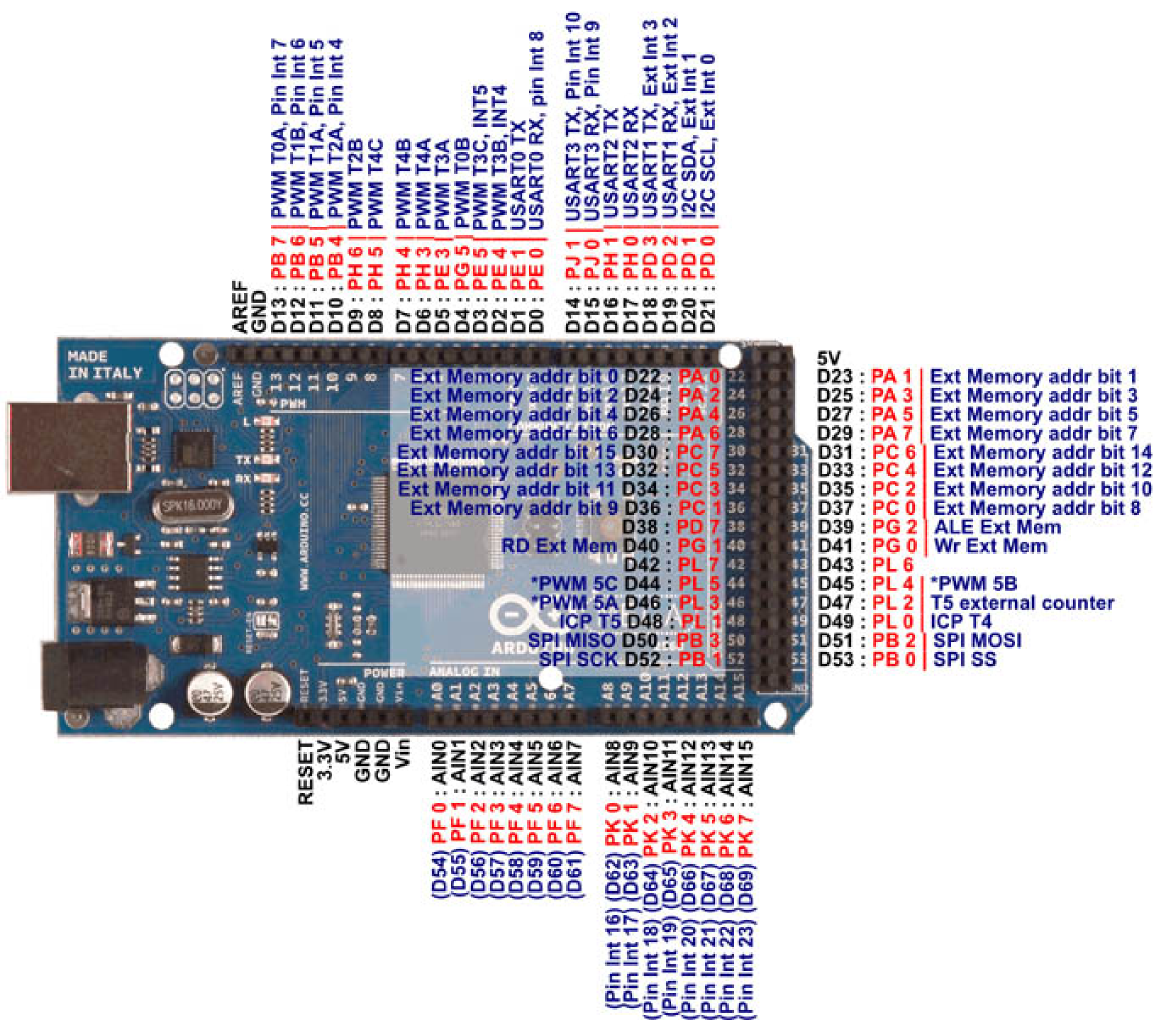


Figure B.1: Arduino Mega 2560 Pinout

Appendix C

XBee 1mW Trace Antenna - Series 1 (802.15.4) Datasheet

1. XBee®/XBee-PRO® RF Modules

The XBee and XBee-PRO RF Modules were engineered to meet IEEE 802.15.4 standards and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between devices.

The modules operate within the ISM 2.4 GHz frequency band and are pin-for-pin compatible with each other.

Key Features

Long Range Data Integrity

XBee

- Indoor/Urban: up to 100’ (30 m)
- Outdoor line-of-sight: up to 300’ (90 m)
- Transmit Power: 1 mW (0 dBm)
- Receiver Sensitivity: -92 dBm

XBee-PRO

- Indoor/Urban: up to 300’ (90 m), 200' (60 m) for International variant
- Outdoor line-of-sight: up to 1 mile (1600 m), 2500' (750 m) for International variant
- Transmit Power: 63mW (18dBm), 10mW (10dBm) for International variant
- Receiver Sensitivity: -100 dBm

RF Data Rate: 250,000 bps

Advanced Networking & Security

Retries and Acknowledgements

DSSS (Direct Sequence Spread Spectrum)

Each direct sequence channels has over 65,000 unique network addresses available

Source/Destination Addressing

Unicast & Broadcast Communications

Point-to-point, point-to-multipoint and peer-to-peer topologies supported

Low Power

XBee

- TX Peak Current: 45 mA (@3.3 V)
- RX Current: 50 mA (@3.3 V)
- Power-down Current: < 10 µA

XBee-PRO

- TX Peak Current: 250mA (150mA for international variant)
- TX Peak Current (RPSMA module only): 340mA (180mA for international varian
- RX Current: 55 mA (@3.3 V)
- Power-down Current: < 10 µA

ADC and I/O line support

Analog-to-digital conversion, Digital I/O

I/O Line Passing

Easy-to-Use

No configuration necessary for out-of box RF communications

Free X-CTU Software
(Testing and configuration software)

AT and API Command Modes for configuring module parameters

Extensive command set

Small form factor

Worldwide Acceptance

FCC Approval (USA) Refer to Appendix A [p64] for FCC Requirements.
Systems that contain XBee®/XBee-PRO® RF Modules inherit Digi Certifications.

ISM (Industrial, Scientific & Medical) **2.4 GHz frequency band**

Manufactured under **ISO 9001:2000** registered standards

XBee®/XBee-PRO® RF Modules are optimized for use in the United States, Canada, Australia, Japan, and Europe. Contact Digi for complete list of government agency approvals.

Specifications

Table 1-01. Specifications of the XBee®/XBee-PRO® RF Modules

Specification	XBee	XBee-PRO
Performance		
Indoor/Urban Range	Up to 100 ft (30 m)	Up to 300 ft. (90 m), up to 200 ft (60 m) International variant
Outdoor RF line-of-sight Range	Up to 300 ft (90 m)	Up to 1 mile (1600 m), up to 2500 ft (750 m) international variant
Transmit Power Output (software selectable)	1mW (0 dBm)	63mW (18dBm)* 10mW (10 dBm) for International variant
RF Data Rate	250,000 bps	250,000 bps
Serial Interface Data Rate (software selectable)	1200 bps - 250 kbps (non-standard baud rates also supported)	1200 bps - 250 kbps (non-standard baud rates also supported)
Receiver Sensitivity	-92 dBm (1% packet error rate)	-100 dBm (1% packet error rate)
Power Requirements		
Supply Voltage	2.8 – 3.4 V	2.8 – 3.4 V
Transmit Current (typical)	45mA (@ 3.3 V)	250mA (@3.3 V) (150mA for international variant) RPSMA module only: 340mA (@3.3 V) (180mA for international variant)
Idle / Receive Current (typical)	50mA (@ 3.3 V)	55mA (@ 3.3 V)
Power-down Current	< 10 µA	< 10 µA
General		
Operating Frequency	ISM 2.4 GHz	ISM 2.4 GHz
Dimensions	0.960" x 1.087" (2.438cm x 2.761cm)	0.960" x 1.297" (2.438cm x 3.294cm)
Operating Temperature	-40 to 85º C (industrial)	-40 to 85º C (industrial)
Antenna Options	Integrated Whip, Chip or U.FL Connector, RPSMA Connector	Integrated Whip, Chip or U.FL Connector, RPSMA Connector
Networking & Security		
Supported Network Topologies	Point-to-point, Point-to-multipoint & Peer-to-peer	
Number of Channels (software selectable)	16 Direct Sequence Channels	12 Direct Sequence Channels
Addressing Options	PAN ID, Channel and Addresses	PAN ID, Channel and Addresses
Agency Approvals		
United States (FCC Part 15.247)	OUR-XBEE	OUR-XBEEPRO
Industry Canada (IC)	4214A XBEE	4214A XBEEPRO
Europe (CE)	ETSI	ETSI (Max. 10 dBm transmit power output)*
Japan	R201WW07215214	R201WW08215111 (Max. 10 dBm transmit power output)*
Austraila	C-Tick	C-Tick

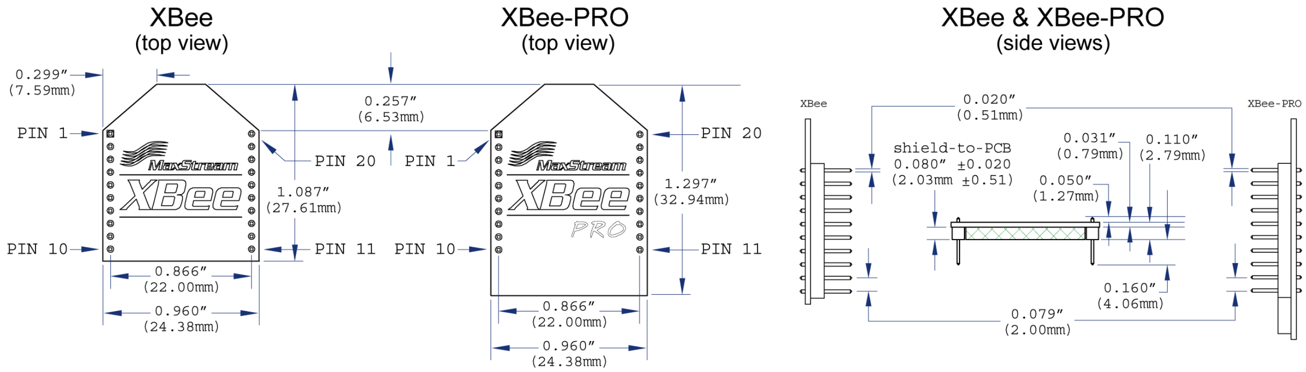
* See Appendix A for region-specific certification requirements.

Antenna Options: The ranges specified are typical when using the integrated Whip (1.5 dBi) and Dipole (2.1 dBi) antennas. The Chip antenna option provides advantages in its form factor; however, it typically yields shorter range than the Whip and Dipole antenna options when transmitting outdoors.For more information, refer to the "XBee Antennas" Knowledgebase Article located on Digi's Support Web site

Mechanical Drawings

Figure 1-01. Mechanical drawings of the XBee®/XBee-PRO® RF Modules (antenna options not shown)

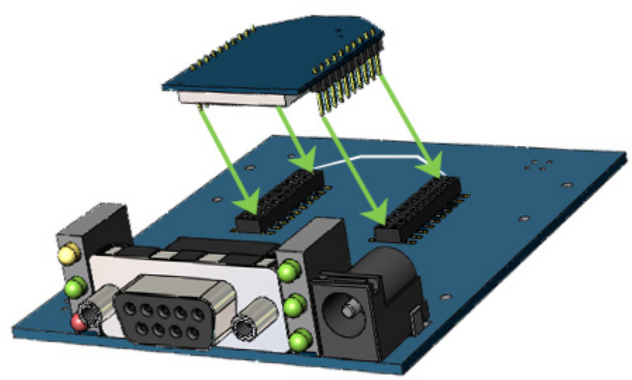
The XBee and XBee-PRO RF Modules are pin-for-pin compatible.



Mounting Considerations

The XBee®/XBee-PRO® RF Module was designed to mount into a receptacle (socket) and therefore does not require any soldering when mounting it to a board. The XBee Development Kits contain RS-232 and USB interface boards which use two 20-pin receptacles to receive modules.

Figure 1-02. XBee Module Mounting to an RS-232 Interface Board.



The receptacles used on Digi development boards are manufactured by Century Interconnect. Several other manufacturers provide comparable mounting solutions; however, Digi currently uses the following receptacles:

- Through-hole single-row receptacles -
  Samtec P/N: MMS-110-01-L-SV (or equivalent)
- Surface-mount double-row receptacles -
  Century Interconnect P/N: CPRMSL20-D-0-1 (or equivalent)
- Surface-mount single-row receptacles -
  Samtec P/N: SMM-110-02-SM-S

Digi also recommends printing an outline of the module on the board to indicate the orientation the module should be mounted.

Pin Signals

Figure 1-03. XBee®/XBee-PRO® RF Module Pin Numbers

(top sides shown - shields on bottom)

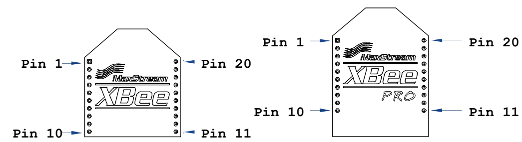


Table 1-02. Pin Assignments for the XBee and XBee-PRO Modules
(Low-asserted signals are distinguished with a horizontal line above signal name.)

Pin #	Name	Direction	Description
1	VCC	-	Power supply
2	DOUT	Output	UART Data Out
3	DIN / $\overline{\text{CONFIG}}$	Input	UART Data In
4	DO8*	Output	Digital Output 8
5	$\overline{\text{RESET}}$	Input	Module Reset (reset pulse must be at least 200 ns)
6	PWM0 / RSSI	Output	PWM Output 0 / RX Signal Strength Indicator
7	PWM1	Output	PWM Output 1
8	[reserved]	-	Do not connect
9	$\overline{\text{DTR}}$ / SLEEP_RQ / DI8	Input	Pin Sleep Control Line or Digital Input 8
10	GND	-	Ground
11	AD4 / DIO4	Either	Analog Input 4 or Digital I/O 4
12	$\overline{\text{CTS}}$ / DIO7	Either	Clear-to-Send Flow Control or Digital I/O 7
13	ON / $\overline{\text{SLEEP}}$	Output	Module Status Indicator
14	VREF	Input	Voltage Reference for A/D Inputs
15	Associate / AD5 / DIO5	Either	Associated Indicator, Analog Input 5 or Digital I/O 5
16	$\overline{\text{RTS}}$ / AD6 / DIO6	Either	Request-to-Send Flow Control, Analog Input 6 or Digital I/O 6
17	AD3 / DIO3	Either	Analog Input 3 or Digital I/O 3
18	AD2 / DIO2	Either	Analog Input 2 or Digital I/O 2
19	AD1 / DIO1	Either	Analog Input 1 or Digital I/O 1
20	AD0 / DIO0	Either	Analog Input 0 or Digital I/O 0

* Function is not supported at the time of this release

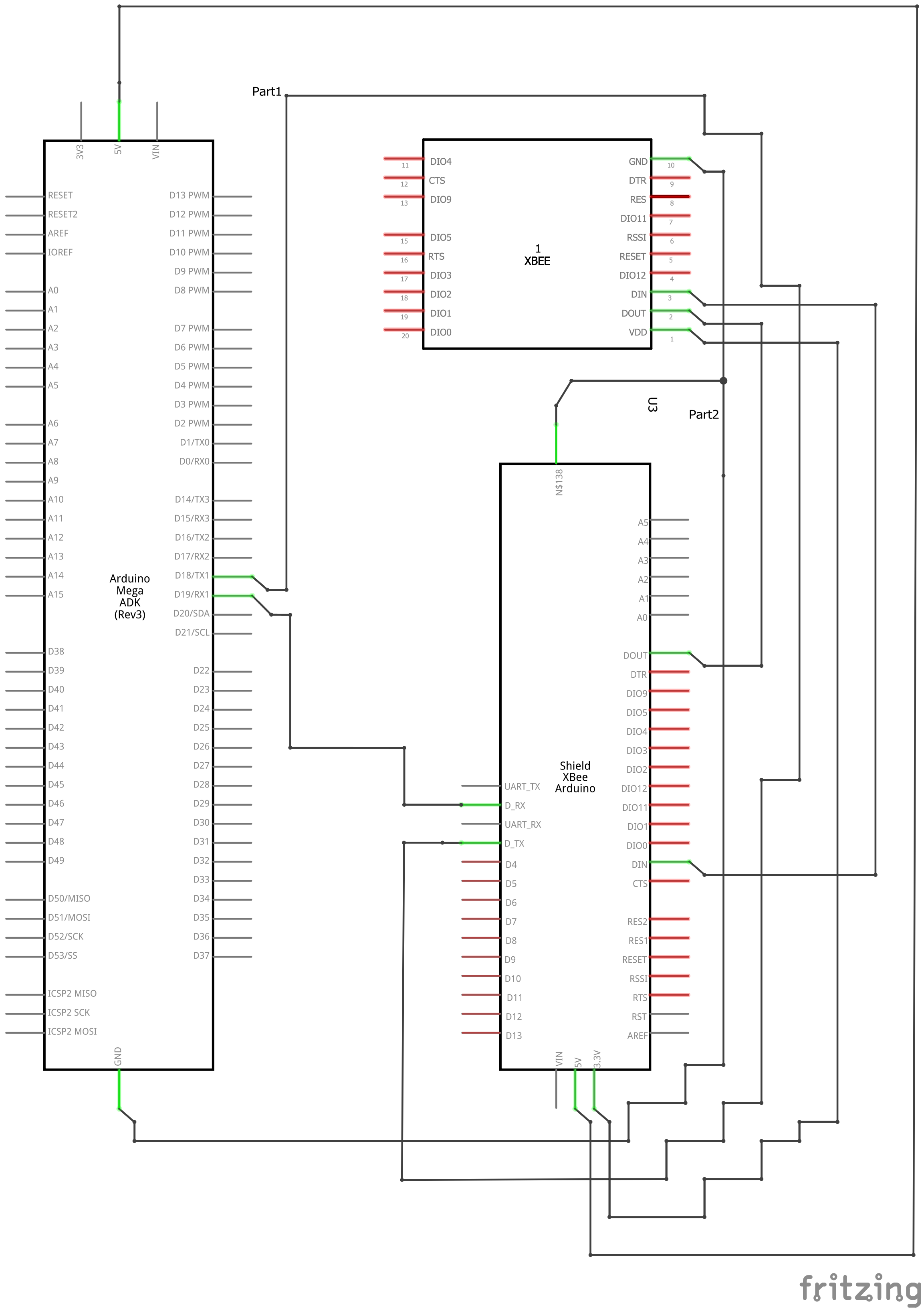
Design Notes:

- Minimum connections: VCC, GND, DOUT & DIN
- Minimum connections for updating firmware: VCC, GND, DIN, DOUT, RTS & DTR
- Signal Direction is specified with respect to the module
- Module includes a 50k Ω pull-up resistor attached to $\overline{\text{RESET}}$
- Several of the input pull-ups can be configured using the PR command
- Unused pins should be left disconnected

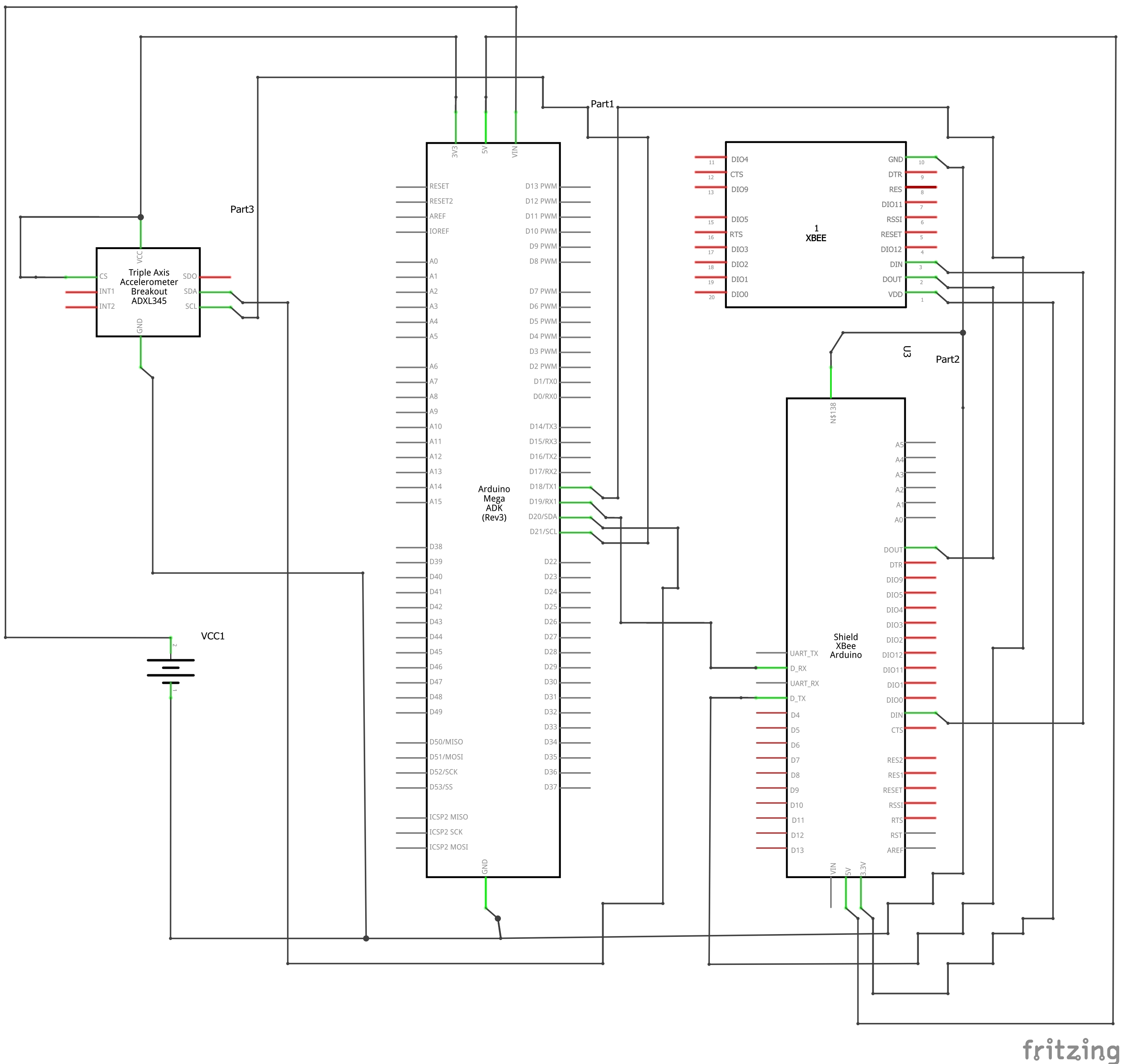
Appendix D

Sensor Node and Base Station Schematics

D.1 Base Station Complete Schematic



D.2 Sensor Node Complete Schematic



Appendix E

Code use for the WSN

E.0.1 Code used for the Base Station

```

void setup()
{
  Serial1.begin(57600);
  Serial.begin(57600);
}

void loop()
{
  if (Serial1.available())
  {
    Serial.write(Serial1.read());
  }
  else if (Serial.available())
  {
    Serial1.write(Serial.read());
  }
}

```

Listing E.1: Code used for the Base Station

E.0.2 Code used for the Sensor Node

```

#include <Wire.h>
#include <movingAvg.h>



movingAvg avgX(20);
movingAvg avgY(20);
movingAvg avgZ(20);

const int DEVICE_ADDRESS = (0x53); //Device Address


//ADXL345 Register Addresses
byte POWER_CTL = 0x2D;
byte DATA_FORMAT = 0x31; // Range Selection Register
byte BW_RATE = 0x2C;    // Bandwith Rate Selection Register
byte DATAX0 = 0x32;    //X-Axis Data 0
byte DATAX1 = 0x33;    //X-Axis Data 1
byte DATAY0 = 0x34;    //Y-Axis Data 0
byte DATAY1 = 0x35;    //Y-Axis Data 1
byte DATAZ0 = 0x36;    //Z-Axis Data 0
byte DATAZ1 = 0x37;    //Z-Axis Data 1
byte INT_ENABLE = 0x2E;
byte INT_SOURCE = 0x30;

//Data Buffers
char Data[50];
char DataAvg[50];
byte _buff[6];
byte Data_Ready[1];

//Acceleration Data
struct AccelData {
int X ;
int Y;
int Z;
};

AccelData Accel1;


```

```
void setup()
{
Serial.begin(57600);
Serial1.begin(57600);
//Serial.println("Initializing");
avgX.begin();
avgY.begin();
avgZ.begin();
Wire.setClock(400000);
Wire.begin();

//Default Settings
writeTo(DEVICE_ADDRESS, DATA_FORMAT, 0x01); //Set the ADXL345 on  +- 4G
writeTo(DEVICE_ADDRESS, BW_RATE, 0x0C);     //Set Sampling Rate at 400Hz
writeTo(DEVICE_ADDRESS, POWER_CTL, 0x08);   //Set the ADXL345 on Measurement Mode
}



void loop()
{

readFrom(DEVICE_ADDRESS, INT_SOURCE, 1, Data_Ready);

  if ( (Data_Ready[0] & 0x80) == 0x80)
  {

    Accel1 = readAccel(); //Leer aceleracion x, y, z

    //Moving Average Filter
    int avg_x = avgX.reading(Accel1.X);
    int avg_y = avgY.reading(Accel1.Y);
    int avg_z = avgZ.reading(Accel1.Z);

    // sprintf(Data, "%d,%d,%d \n", Accel1.X, Accel1.Y, Accel1.Z);

    sprintf(DataAvg, "%d,%d,%d \n", avg_x, avg_y, avg_z);
    Serial1.write(DataAvg);

    //Serial1.write(Data);
    //Serial.print(DataAvg );
    // Serial.print(Data );
  }
```

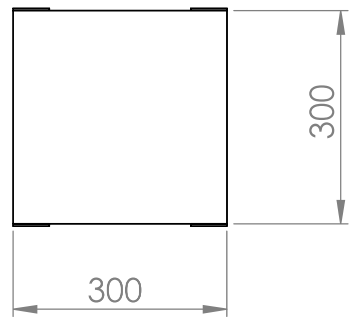
```

    else if (Serial1.available())
    {
      byte incomingByte = Serial1.read();

      if (incomingByte > 0 || incomingByte < 254 )
      {
        Serial.print("Received: ");
        Serial.println(incomingByte, DEC);
        byte SamplingRate = incomingByte & 0x0F; // Mask 00001111b
        byte AccelRange = (incomingByte & 0x30) >> 4;  // Mask 00110000b and then Shift 000000XX

        writeTo(DEVICE_ADDRESS, POWER_CTL, 0x00);  //Set the ADXL345 on Standby Mode
        writeTo(DEVICE_ADDRESS, DATA_FORMAT, AccelRange); //Set the Desired Range
        writeTo(DEVICE_ADDRESS, BW_RATE, SamplingRate);  //Set the Desired Sampling Rate
        writeTo(DEVICE_ADDRESS, POWER_CTL, 0x08);  //Set the ADXL345 on Measurement Mode

      }
    }
  }

  AccelData  readAccel() {

  uint8_t numBytesToRead = 6;
  AccelData DataReceived;


  readFrom(DEVICE_ADDRESS, DATAX0, numBytesToRead, _buff);

  //Read the register values ant converts to interger (Each axis has 10bits, on 2 Bytes)
  DataReceived.X = (((int)_buff[1]) << 8) | _buff[0];
  DataReceived.Y = (((int)_buff[3]) << 8) | _buff[2];
  DataReceived.Z = (((int)_buff[5]) << 8) | _buff[4];

  return DataReceived;

  }

```

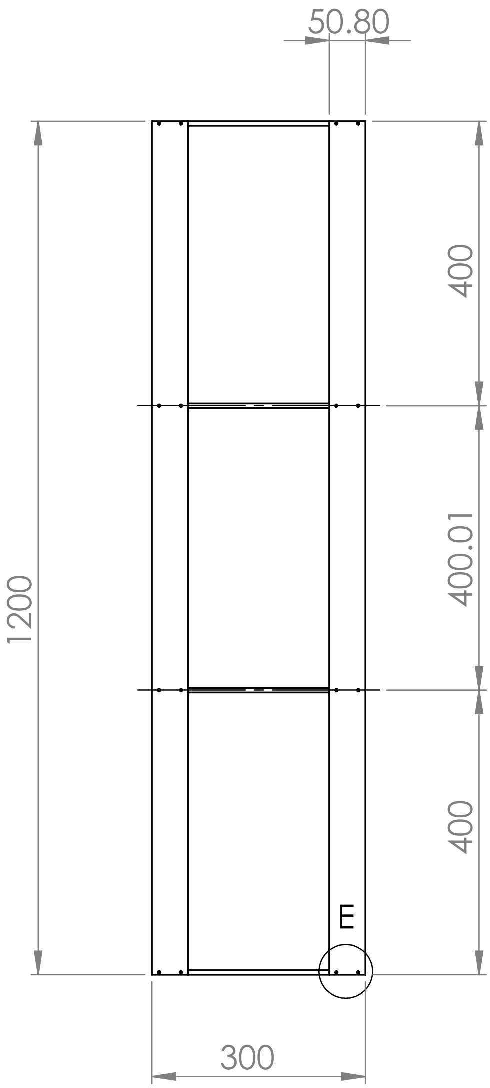
```
//Writing Function
void writeTo(int device, byte address, byte val) {
Wire.beginTransmission(device);
Wire.write(address);
Wire.write(val);
Wire.endTransmission();
}

//Reading Function
void readFrom(int device, byte address, int num, byte _buff[]) {

  Wire.beginTransmission(device);
  Wire.write(address);
  Wire.endTransmission();

  Wire.beginTransmission(device);
  Wire.requestFrom(device, num);

  int i = 0;
  while (Wire.available())
    {
      _buff[i] = Wire.read();
      i++;
    }
  Wire.endTransmission();
}


```

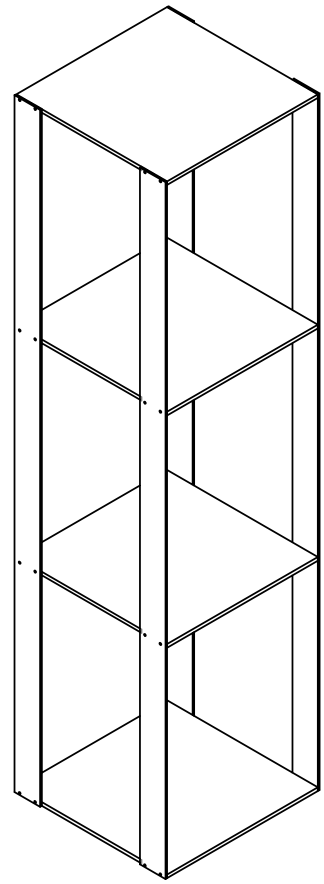
Listing E.2: Code used for the Sensor Node

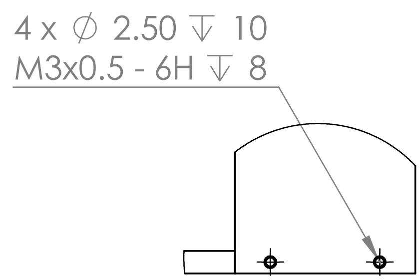
Appendix F

Building-like Structure Technical Drawings









DETALLE E
ESCALA 1 : 2

SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:	ACABADO:	REBARBAR Y ROMPER ARISTAS VIVAS	NO CAMBIE LA ESCALA — REVISIÓN

	NOMBRE	FIRMA	FECHA
DIBUJ.			
VERIF.			
APROB.			
FABR.			
CALID.			

TÍTULO:

Estructura

MATERIAL:

N.º DE DIBUJO

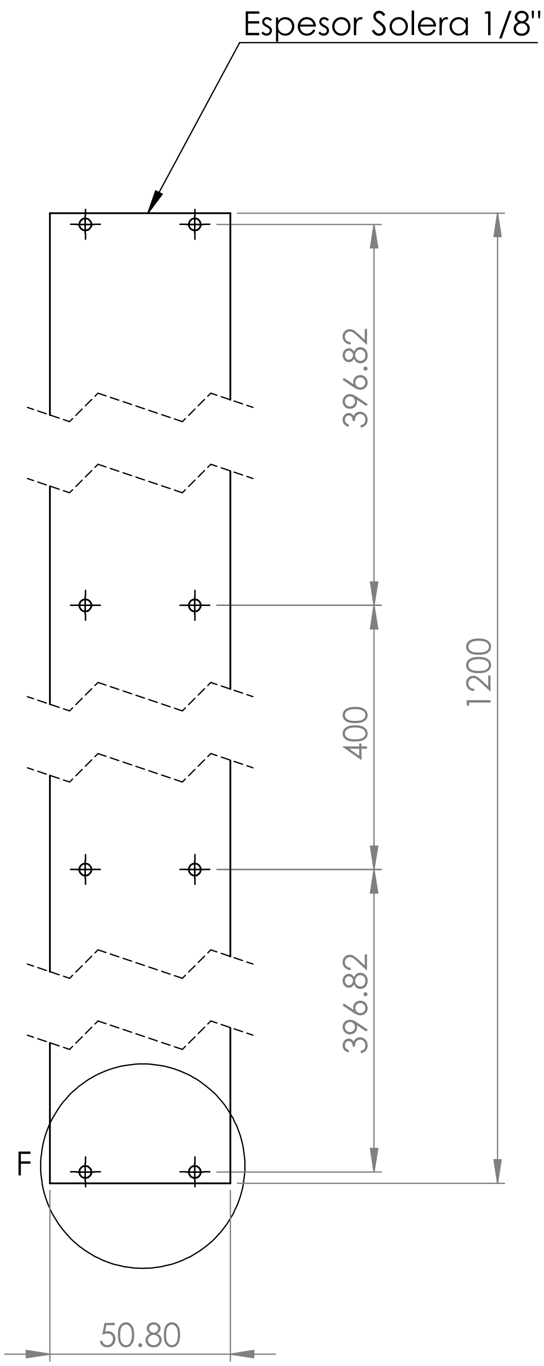
Planos

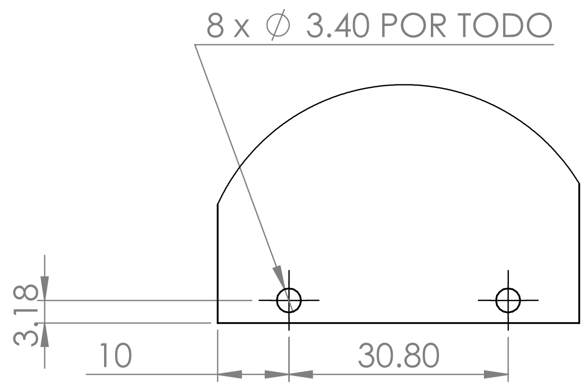
A4

PESO:

ESCALA:1:20

HOJA 1 DE 1





DETALLE F
ESCALA 1 : 1

4 Piezas

SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:	ACABADO:	REBARBAR Y ROMPER ARISTAS VIVAS	NO CAMBIE LA ESCALA	REVISIÓN

	NOMBRE	FIRMA	FECHA
DIBUJ.			
VERIF.			
APROB.			
FABR.			
CALID.			

TÍTULO: **Solera**

MATERIAL:

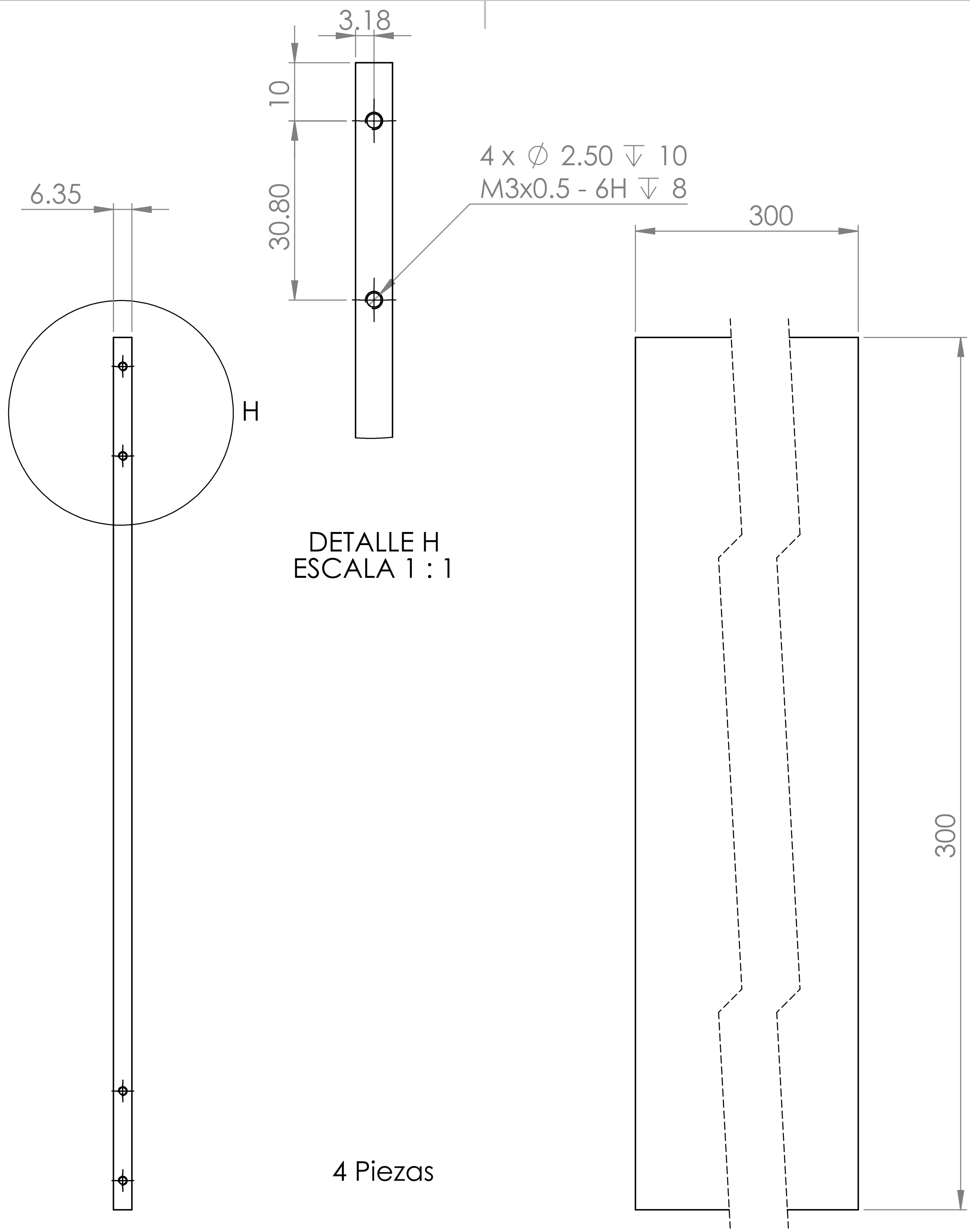
PESO:

N.º DE DIBUJO: **Planos**

A4

ESCALA:1:20

HOJA 1 DE 1



SI NO SE INDICA LO CONTRARIO:
LAS COTAS SE EXPRESAN EN MM
ACABADO SUPERFICIAL:
TOLERANCIAS:
LINEAL:
ANGULAR:

ACABADO:

REBARBAR Y ROMPER ARISTAS VIVAS

NO CAMBIE LA ESCALA

REVISIÓN

	NOMBRE	FIRMA	FECHA
DIBUJ.			
VERIF.			
APROB.			
FABR.			
CALID.			

MATERIAL:

PESO:

TÍTULO:

Placa

N.º DE DIBUJO

Planos

A4

ESCALA:1:5

HOJA 1 DE 1