Development of Wireless Magnetoresistive Sensor Network for Unexploded Ordnance and Landmine Detection

by

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Abstract

This thesis summarizes the effort toward developing a passive/active magnetoresistive (MR) sensor array for unexploded ordnance (UXO) realized with wireless sensor network technology. In recent years, the rapid development and research on wireless sensor networks (WSN) has enabled application of WSN technology in a variety of areas. This thesis analyzed the characteristics and advantages of the WSN approach in detail and discussed the feasibility of WSN implementation in a UXO and detection system. An overall system design is given with the passive sensor array dedicated for large area magnetic field survey, and the active array for pin-point detection and target discrimination.

The initial design utilizes off-the-shelf components and software to minimize engineering costs. The design scheme of a distributed WSN node is introduced, with design of a WSN sensor platform based on the Silicon Labs C8051F912 microcontroller (MCU) and Si4431 radio frequency (RF) integrated circuit (IC) combination realized to operate on the 915MHz license free Industrial Scientific Medical (ISM) band. The passive sensor node is realized with the HMC5843 digital magnetometer IC and the active node is realized with HMC1053 magnetic sensor (both HMC sensors from

Honeywell) with customized analog circuits. The WSN is designed with master-slave state machine with star topology that supports up to 255 nodes per master node. The network protocol is comprised of a Si4431 physical layer, an EZMacPro media access control (MAC) layer, and a customized application layer.

The fabricated passive and active sensor node prototypes are compact and light weight. Lab testing demonstrates that the overall system performance goal has been met. A pilot production of the WSN nodes is proposed for field testing to further verify the effectiveness of the passive/active wireless MR sensor UXO/mine detection array.

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List of Acronyms

ADC	analog-to-digital converter
AMR	anisotropic magnetoresistance
CMR	colossal magnetoresistance
EM	electromagnetic
EMF	electromotive force
EMI	electromagnetic induction
EMR	extraordinary magnetoresistance
ERW	explosive remnants of war
FD	frequency domain
FSK	frequency shift keying
GMR	giant magnetoresistance
GPS	global positioning system
IC	integrated circuit
IED	improvised explosive device
ISM	industrial, scientific and medical
LOS	line of sight
MOSFET	metal–oxide–semiconductor field-effect transistor
OMR	ordinary magnetoresistance
OTS	off-the-shelf

P2P	point-to-point
PCB	printed circuit board
QFN	quad flat no leads
RF	radio frequency
RTC	real-time clock
SCL	serial clock
SDA	serial data line
SNR	signal-to-noise ratio
SPI	serial peripheral interface
SPS	sample per second
TD	time domain
UHF	ultra high frequency
USB	universal serial bus
UXO	unexploded ordnance

Chapter 1. Preface

Unexploded ordnance (UXO) and landmines are recognized as one of the world's most serious and dangerous environmental problems. Not only do the presence of UXO and landmines pose a life threatening situation to many people across the world, they also can significantly retard the reconstruction and development efforts in war-torn countries. The majority of the casualties caused by UXO and landmines are civilians and children, especially men who work in reconstruction areas which were once battlefields or military testing sites. According to *Landmine Monitor Report 2009*[1], around two-thirds of the countries in the world (119 countries) are affected to some extent by the landmine/UXO problem. Between 1999 and the end of 2008, *Landmine Monitor* collected information on 73,576 mines, explosive remnants of war (ERW) detonations, additionally improvised explosive devices (IED) were responsible for 17,867 death, 51,711 injuries, and 3,998 of unknown status, and the figure is most certainly under reported since it includes only recorded incidents. The figure also does not include casualties during conflicts.

The anti-personnel landmine is the weapon of choice for relatively underdeveloped countries, as the cost of a single landmine may be as low as US$3-10. Due to the cheap cost, there are two to five million landmines laid every year, while only 100,000 are being removed at a cost of $300 to $1,000 per mine. As for the UXO case, for the U.S. alone, there are currently more than 10 million acres of land on around 1400 sites that are thought to contain UXO [2]. With the danger involved with lingering

UXO, the land cannot be utilized for any productive activity. It is estimated that it would cost tens of billions of dollars to check and clear all of the possibly affected land in the U.S. alone.

There is currently a significant amount of research being performed in an attempt to develop methods to detect and clear these sites quickly and easily. To clear a site of UXO, the explosive must be detected first. This is typically done by performing a geophysical survey. A geophysical survey provides a complete map of any detectable geophysical anomalies across a wide area. Data collected can then is used to subdivide the area into smaller regions with high threat potential. Sensors of various types are currently used to detect metal objects on or below the ground. Since explosives normally contain metal, the explosives can be located by detecting, for example, perturbation in the earth magnetic field due to mine/UXO with ferrous materials.

A Wireless Sensor Network may be rapidly deployed over a wide geological area. With appropriate sensors integration they can be powerful tools in locating UXO, landmines, and other metallic objects.

1.1. Wireless Sensor Network Basics

1.1.1. Definitions

A wireless sensor network (WSN) is a novel type of self-organized network that bloomed in the late 1990s. It can be formed by a large number of compact and low cost sensor nodes with integrated sensing, processing, and wireless communication capability. The purpose of a WSN is to cooperatively monitor, sense, and gather any information about the environment or object under test and process this information, convey it to end users through multi-hop wireless channels. With WSN, the conventional data acquisition method has evolved from single wired sensor mode to highly integrated, miniaturized, automated, and interconnected "smart" network mode. WSNs can also be easily deployed to areas hard to reach or even to hazardous environments. It represents a novel information acquisition and processing technology and has drawn much attention from the research community.

1.1.2. Characteristics of Wireless Sensor Network

WSN can be deployed using air cargo to the area of interest to form a self-organized network. The sensor nodes cooperatively gather, process, and communicate information. Due to the requirements on dimensions, cost, and power, each sensor node only has access to very limited physical resources. The characteristics of a WSN can be summarized as:

Large Scale: To acquire precise real-time information, it is necessary to deploy a large number of sensor nodes to the area of interest, the number of nodes can be thousands or more. For example, with the nodes loaded on and deployed by aircraft, WSN can be deployed over thousands of acres of land for geological survey or oceanic environmental survey.

Energy Limitation: Every node in the network has access to limited energy. WSN typically functions in rural areas with a scarce population or even in a hazardous environment. Sometimes it is impossible to change the battery at a node and ultra-low power consumption is required to prolong the operation life of the network.

Self-organization: Self-organization including functions of auto network association, node and terminal identification, and hack prevention. Compared to a fixed point wireless network, the configuration of a WSN is similar to an ad hoc network, with the prerequisite of a suitable communication protocol for unmanned operation.

Self-management

In WSN, data processing is done within the nodes in order to reduce the data rate on the wireless medium, so that only the data related to other nodes are sent over the RF link. Data centric is another feature of WSN. Since the positions and deployment of the nodes are not pre-planned, it is possible that some nodes will become out of service due to errors or accidents during deployment. To ensure undisturbed services, redundant nodes must be included in WSN design. Moreover, data sharing and cooperation between nodes must be implemented to guarantee complete monitoring of the subject.

Different from ad hoc networks: WSN is similar to ad hoc network on the feature of distributed network. However, there are many differences between them. Generally speaking, WSN nodes have greater limited access to resources compared to handheld devices, but the computing requirement is only optional. When a computational task is needed, if cost of communication is low, it is possible to transfer the computing task to the sink node to improve overall performance.

1.1.3. WSN System Structure

WSN Networking Structure: WSN typically consist of sensor node, sink node, and management node. A great number of sensor nodes randomly scattered inside or around the sensing field, forms a network using the self-organize capability, real-time monitor and capture information of objects, and send data back to the sink node through multi-hopping or other mechanisms. The data can be processed during transmission, and then passed to the internet or via satellite to the management node. The end user can configure and manage the whole sensor network remotely, setting monitor tasks or change objectives "on the fly". A basic WSN network structure is shown in Figure 1.1.

Sensor nodes are usually micro embedded systems, have very limited processing power, memory storage, and communication capability. They are usually equipped with a small battery, a radio transceiver, and microprocessor used to control and process wireless data packages. Hardware and software at the sensor nodes are usually the key research area addressed when developing a specific WSN. On the other hand, sink nodes usually have better processing power, memory storage, and communication capability, and may have connectivity to an external network such as the internet, implementing interconnectivity between different protocols, disseminating tasks to the sensor nodes, and conveying the gathered data to an external network.

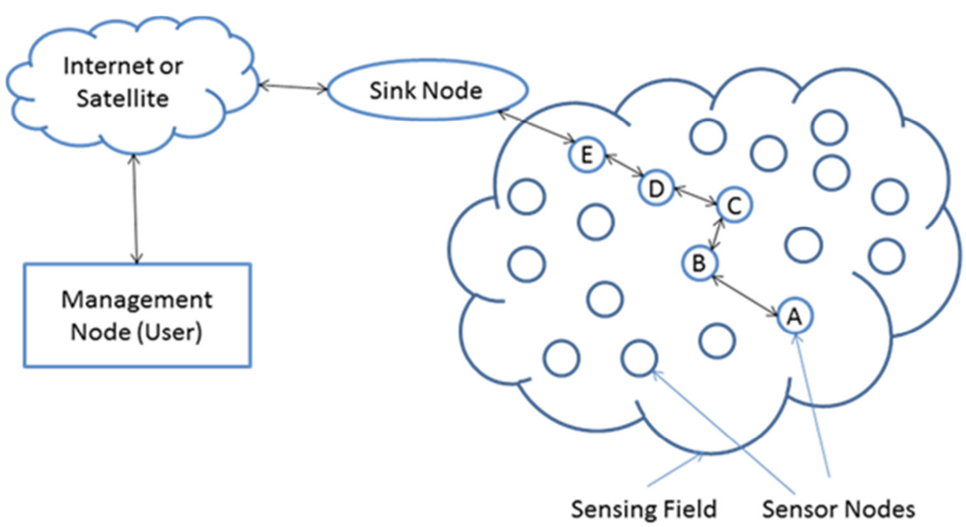

Figure 1.1 WSN network structure

WSN Sensor Node Structure: WSN has emerged as an independent computer network, and its basic unit is the node. Every node has its own sensor unit, processing unit and communication module. The functions of each node are to sense data, process data, and transmit data. A sensor node can have up to five major components as shown in Figure 1.2.

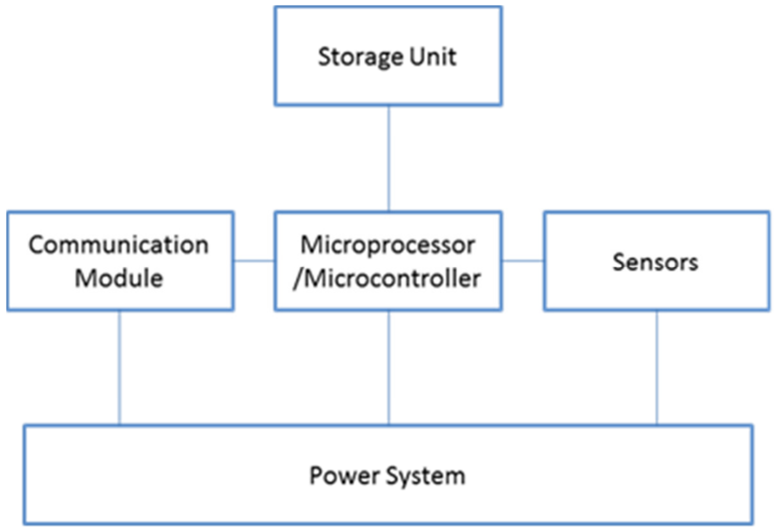

Figure 1.2 Major components of a sensor node

The microprocessor or microcontroller controls all processes and the behavior of the device and execute preprogramed codes. The storage unit stores the gathered and relayed data. Normally program and data uses different memory allocations. Sensors are the units used to gather information from the environment or data on a specific object. Communication modules are used to convey the data out to the external network and end users. The power system is usually a battery, with or without energy harvest devices.

1.1.4. WSN Protocol Stack

The protocol stack of a WSN utilizes simplified open system interface (OSI) model, it usually consists of Physical Layer, Data Link Layer, Network Layer, Transport Layer, and Application Layer as shown in Figure 1.3. Besides, the stack should also include power management platform, mobility management platform, and task management platform. These platforms enable the sensor node to work efficiently and utilize the least energy, thus prolonging system work life.

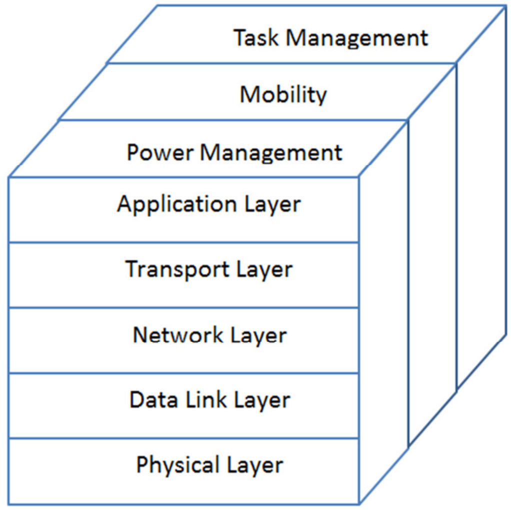

Figure 1.3 WSN protocol stack

Physical Layer: The Physical Layer consists of the basic hardware transmission technologies of a network such as signal modulation/demodulation, transmission and reception. The main functions of Physical Layer include frequency selection, signal modulation, and data encryption. For long range telecommunication, it is a critical component in terms of implementation complexity and energy consumption.

Data Link Layer: Data Link Layer is focused on solving multiple access problems. It provides the functions and procedures to transfer data between network entities without contention and might provide the means to detect and correct errors that may occur in the Physical Layer.

Network Layer: Network Layer takes care of the data routing from the Transportation Layer. With many sensor nodes scattered around the observation area, a routing protocol is necessary to be used for the communication between sensor nodes and sink node.

Transportation Layer: To ensure quality of service (QoS) of the WSN, Transportation Layer is utilized to maintain data stream throughout the WSN. Referring to the protocol diagram in Figure 1.3, when WSN needs to be connected to another type of network, the Transportation Layer allows the sink node to communicate with the task management node with conventional TCP or UDP protocols. However, since the sensor nodes have very limited power and memory resource, the WSN itself needs a resource efficient protocol.

Application Layer: Based on the task requirement of the WSN, different applications can be added to the Application Layer. It can include a series of application software for monitoring purposes. Because of their limited computing power, memory storage and communication capability, each individual sensor node can only acquire a very limited topology of the network, the protocol cannot be overly complicated. Meanwhile, WSN topology may be constantly changing, i.e. wireless mobile sensor network, with a requirement of dynamic networking resource reallocation, thus places even a higher requirement of the WSN protocol. The WSN protocol must also ensure each individual node forms a multi-hop data transportation network, and the current key research areas are Network Layer and Data Link Layer protocols.

1.1.5. Wireless Sensor Network Applications

WSN nodes have the capability of continuously gathering data, detecting events, and marking events, monitoring position, and controlling other nodes. These features plus the wireless communication capability ensures broad applications of WSNs. They can be applied in environmental monitoring and prediction, geological survey, health monitoring, smart homes, building monitoring, control of complex machinery, metropolitan traffic control, space exploration, garage management, industrial park safety, etc. A very important feature of WSN nodes is that they can be deployed to any designated area for different humanitarian missions including UXO and mine clearance missions. As the research and application of WSN deepens, WSN will have great impact on every aspect of human lives.

1.1.6. Current Research on Wireless Sensor Networks

WSN technology bloomed in the late 1990s, and due to great application potential, it has become one of the most widely pursued research areas in the academic and industrial world.

The earliest WSN research effort was funded by NSF and DARPA, and was carried out by the University of California and Cornell University. Starting in the year 2000, many industrial researches on WSN have been reported including works from Intel [3] and Microsoft [4].

Nowadays, WSN research has gone through two stages of developments. The first stage is focused on the utilization of micro-electro-mechanism system (MEMS) technology and miniaturization of the nodes. The representing works including Wireless integrated network sensors [5] (WINS), and Smart Dust [6]. The second stage if research is mostly about the network itself and has become an active research area. From the network architecture point of view, every layer has to be studied separately to optimize the overall performance of the WSN. Current research is mainly focused on the Network Layer and Link Layer with special interests in establishing robust point-to-point (P2P) or meshed network through different MAC protocols.

1.2. Objectives

The ultimate goal of this research is to develop a distributed, mobile passive/active WSN array for UXO/mine detection. The highly sensitive magnetic sensor nodes are to form a sensor array to survey large areas with adequate resolution. The gathered data together with the GPS coordinate of the sensor node can be sent to the user terminal for target discrimination and mapping, thus providing critical data for further clearance efforts.

The first objective of this research is to develop a passive magnetoresistance sensor node by using a digital magnetometer sensor. The digital magnetometers have relatively small bandwidth and are mainly used to measure the earth magnetic field (DC) anomaly to detect the location of a UXO/mine. They are easier to build than an electromagnetic induction (EMI) system but do not have the frequency bandwidth necessary to discriminate among targets.

The second objective is to develop an active magnetic field sensor which can be used as an EMI system to provide additional information about the buried target. Over what is available using a simple magnetometers array, the additional information can enhance the ability to discriminate mines from clutter and other uninterested geologic anomalies.

1.3. Summary

This research is focused on the development of UXO/mine detection WSN using passive/active magnetic sensors and that provides an efficient way to locate and discriminate among potentially hazardous buried anomalies.

The overall structure of this thesis is arranged as follows:

Chapter 1 briefly describes the UXO/mine hazard, the background of WSN, and overall research objectives. Chapter 2 introduces the overall distributed detection system design, compares different detection technologies, and gives sensor node design and a work flow diagram. Chapter 3 explains the details of the hardware design of the sensor node, including schematics and PCB layout. Chapter 4 introduces sensor unit design for passive and active sensing using the magnetoresistance method. Chapter 5 gives preliminary test results prove the feasibility of WSN application in UXO and mine detection. Chapter 6 summarizes the research and gives suggestions for future work.

Chapter 2. Detection system and sensor node design

To take full advantage of a WSN, the distributed nodes network architecture is utilized. This approach distributes a task to an individual node, and the task is completed locally. For the passive system, due to the large size of the network, each sensor node gathers magnetic field data at its own rate (10sps typical) and sends the data to the sink node through multi-hop scheme. For the active EMI system, a central synchronization signal needs to be sent out by the sink node to reset/set the magnetic sensors for best sensitivity and resolution. Thus the active WSN array is relatively small in size but requires much higher sampling rate (50ksps) and consumes more power.

2.1. UXO/mine detection techniques

The development of UXO/mine detection techniques largely depends on the advances in various sensor systems. The current most popular technologies used are magnetometry, ground penetrating radar, and EMI. Among these, the prominent technologies are magnetometry and EMI sensors.

2.1.1. Magnetometry

Magnetometry is the technique of measuring and mapping patterns of magnetic field using magnetometers. A magnetometer is a passive sensor which uses the earth's magnetic field as an excitation source to measure an object's magnetic susceptibility. Magnetic sensor or magnetometers are widely used in geophysical survey research.

They can detect the disturbances in the surrounding static magnetic field i.e. earth magnetic field. Magnetic surveys have been one of the most successful techniques used for locating buried UXO/mines. When the sensor passes over ferrous metal objects such as UXO or mine, the field disturbance of the earth's magnetic field can be recorded by the sensor leading to target detection. Although magnetometers are easiest to use, since the magnetic sensor only measures passive field disturbances, they are prone to geologic noises and inefficient at determine target shapes.

2.1.2. EMI system

An EMI sensor is an active device that carries an excitation source and measures magnetic susceptibility and electrical conductivity depending on the frequency of excitation. The EMI sensor is relatively immune to geologic noise and has the capability to determine target shape, size and orientation. However, it is sensitive to sensor orientation and its false alarm rate is high due to metal fragments.

Conventional EMI systems are classified into time domain (TD) and frequency domain (FD) sensors based on the type of excitation. Time domain sensors use short duration current pulses to excite the transmitter coil and are referred to as pulsed EMI systems. The current pulses are usually increased to a certain level then abruptly shut off to induce an EMF in the buried object. TD detectors are usually preferred over FD detector for UXO/mine detection since the former method provides somewhat higher signal-to-noise ratio (SNR). The reason for this is that once the transmitter current in a TD is turned off only the signal from the buried object remains; whereas with FD system the transmitter is always on and its energy competes with the usually weak return from the buried object.

2.1.3. Ground penetrating radar

Ground Penetrating Radar (GPR) techniques have been highly developed in the past decade [7, 8] and have resulted in several commercial devices. It has been proven to reduce false alarm when used with other sensor technologies. Although it has the ability to determine target depth and shape, it performs poorly in any medium that has a high conductivity, such as wet and/or clay rich soils. Also, since the electromagnetic wave absorption rate of soil increases with frequency, GPR performance degrades when high frequency is necessary to achieve adequate resolution of small objects. In the case of UXO/mine detection, GPR can suffer from poor detection statistics due to clutter. Moreover, the GPR technique is not proven to be a standalone UXO sensor and must be used together with other sensor technologies. For more information on GPR, refer to reference [7, 8].

2.2. Overall system design

The proposed UXO detection system is comprised of many wirelessly interconnected nodes with passive and active magnetic field sensors. The passive system is designed to achieve simultaneous large area survey, while the active system works together with an EMI source to provide detailed target shape and depth information. This setup takes advantage of WSN features for maximized efficiency and accuracy, and provides maximum safety for the bomb disposal team. The overall system diagram is shown in Figure 2.1.

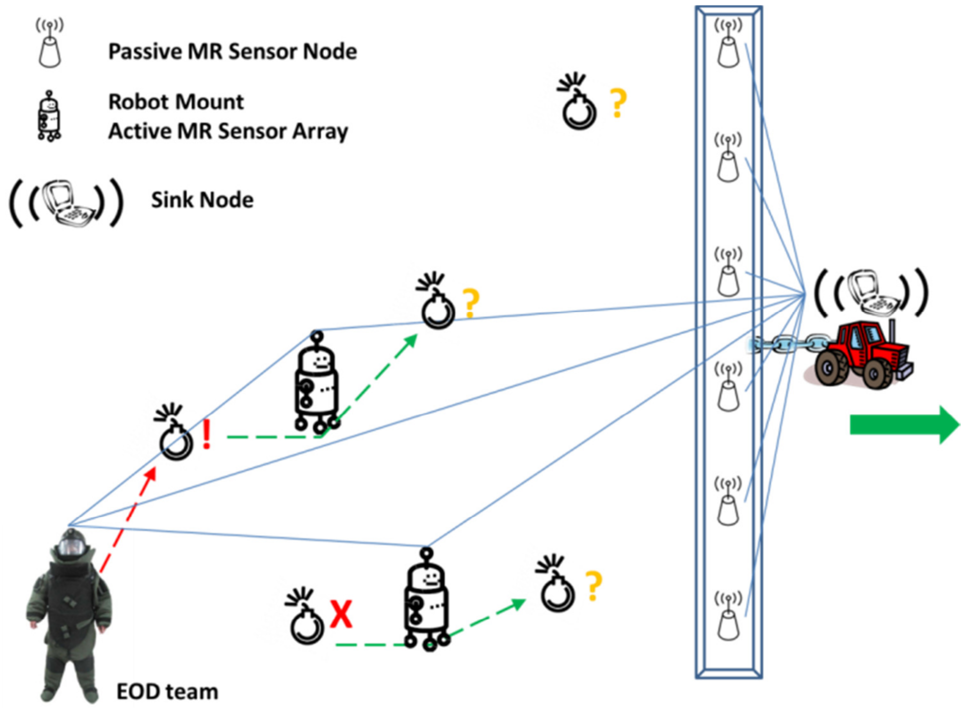

Figure 2.1 Overall UXO/mine detection system design

2.3. Magnetoresistance sensor basics

Magnetoresistance (MR) is the property of a material to change the value of its electrical resistance when an external magnetic field is applied. MR is measured as magneto-resistance ratio, and magnetic reluctivity defined as:

$$\eta = \frac{R_H + R_0}{R_0}$$

Where R_H is the resistance when magnetic field H interacts with the material, and R_0 the resistance when no magnetic field is applied. Depending on the angle between the applied field and current (0° when parallel, 90° when perpendicular), the MR is called longitudinal and transverse MR effect for parallel and perpendicular cases respectively. Based on the mechanism of MR, it can be categorized into two types, ordinary magnetoresistance (OMR), and extraordinary magnetoresistance (EMR).

OMR is caused by the enlarged electron scattering area due to introduction of external magnetic field. The effect is the same on ferrous and non-ferrous materials. For non-magnetic metals, MR effects at low fields are very small, although the effect can become quite large for high fields.

On the other hand, EMR is a unique property of ferromagnetic materials. The physical origin of the magnetoresistance effect lies in spin orbit coupling. The electron cloud about each nucleus deforms slightly as the direction of the magnetization rotates, and this deformation changes the amount of scattering undergone by the conduction electrons when traversing the lattice [9]. A simplified explanation can be given: when the materials is under magnetization saturation status, if the field and magnetization are oriented transverse to the current, then the electronic orbits are in the plane of the current, and there is a small cross-section for scattering, giving a low resistance state; if the field is parallel to the current, the electronic orbits are oriented perpendicular to the current, and the cross-section for scattering is increased, giving a high resistance state.

EMR can be further classified as anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), and colossal magnetoresistance (CMR). The materials and mechanisms for these three types of magnetoresistance are also distinctly different. The AMR is of particular interest in this research.

The ferromagnetic material utilized for AMR heads is NiFe (permalloy). This is due to the relatively large effect at room temperature ($\Delta\rho/\rho$ ~ 2%), and the low saturation fields (H_s ~ 5-10 Oe) required to obtain the AMR effect [9]. In order to properly utilize the AMR effect, the operating point (zero applied field) of the sensor has to be either on the increasing or decreasing slope of the AMR response (biasing).

Moreover, an external field may cause the operating point to drift, and cause “latch up”, thus frequency reset/set pulses must be implemented to guarantee accuracy.

2.4. Sensor node design

2.4.1. Passive MR Sensor node

The passive sensors can be installed on a linear or wheel line irrigation system, as shown in Figure 2.2 or similar structures, to form a passive magnetometer array and sweep a large area at once. This solution uses commercially available products and can provide a novel way to acquire large area magnetic field data with minimal modification of the carrier structures, as depicted in Figure 2.3.

Figure 2.2 Linear and wheel line irrigation system

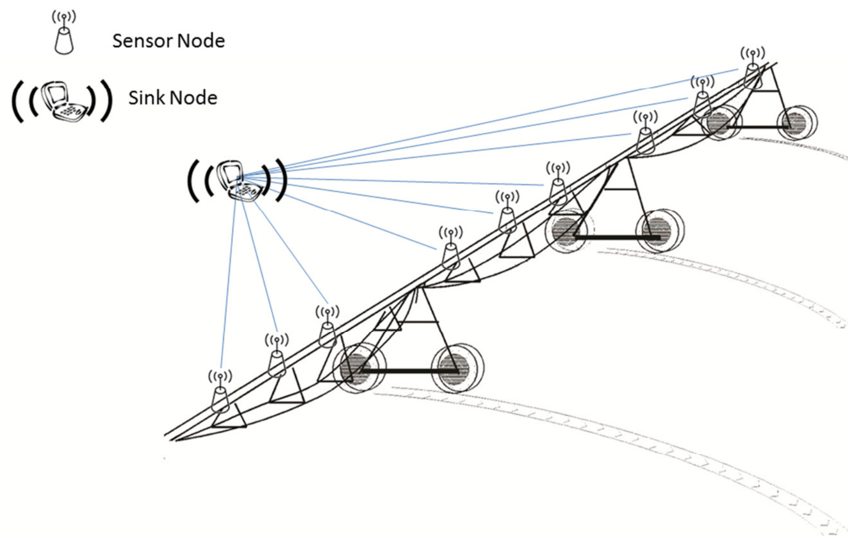

Figure 2.3 Diagram of passive MR sensor array installation

The passive sensor node is designed to be ultra-portable, ultralow-power, and with adequate communication range. Battery operation and compact size, as well as robustness are the major considerations. The sensor node design scheme is shown in Figure 2.4.

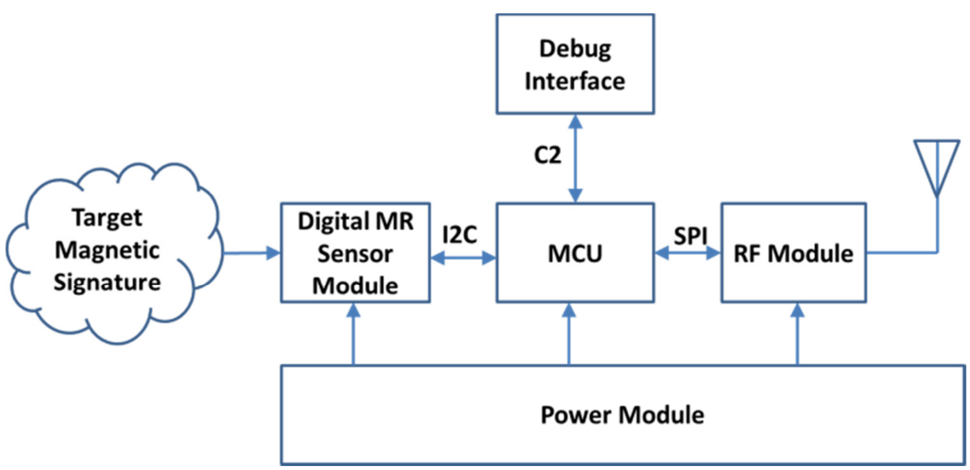

Figure 2.4 Passive sensor node design scheme

An off the shelf (OTS) digital MR sensor module is utilized in the passive sensor node. The digital MR sensor module should have amplification, set/reset/offset strap drive control, ADC, and digital communication, functions built in, so that no external analog circuit need be implemented. The passive MR sensing requires a lower sampling rate compared of the active system, thus on-chip ADC and control MCU on the digital sensor is acceptable. Since the sampling rate is relatively low (10sps typical), it is affordable to send all the data back to the sink node through the RF link (128kbps typical) for data processing. Assuming 16 bits (2bytes) data reading for each axis, the RF link can support up to $\frac{128k}{48\times10}\approx 266$ sensor nodes. The packet configuration of each data package is shown in Table 2-1.

Table 2-1 Data packet configuration

Preamble	Sync pattern	Payload length	Payload 3-axis MR reading	CRC
AA AA AA AA AA	2D D4	xx	xx xx xx	xx
5 bytes	2 bytes	1 byte	6 bytes	1 byte

The detailed realization of the passive sensor node is shown in Chapter 3.

2.4.2. Active MR Sensor node

Active MR Sensors are more challenging than the passive ones. To acquire detailed target information such as shape, depth, and material, EMI system must be used. Compatibility issues between active MR Sensor and the EMI system must be taken into consideration.

Due to the unique requirements of the active system, OTS components are not available. A specially designed analog circuit must be implemented to address this issue. The signal from the MR sensor needs to be amplified and sampled at much higher rate

(50ksps) in order to capture the EMI signature of the target. The sample rate also makes it impossible to send every data reading back to the sink node for processing, so that on-sensor processing capability must be implemented. The design scheme of the active sensor node is shown in Figure 2.5.

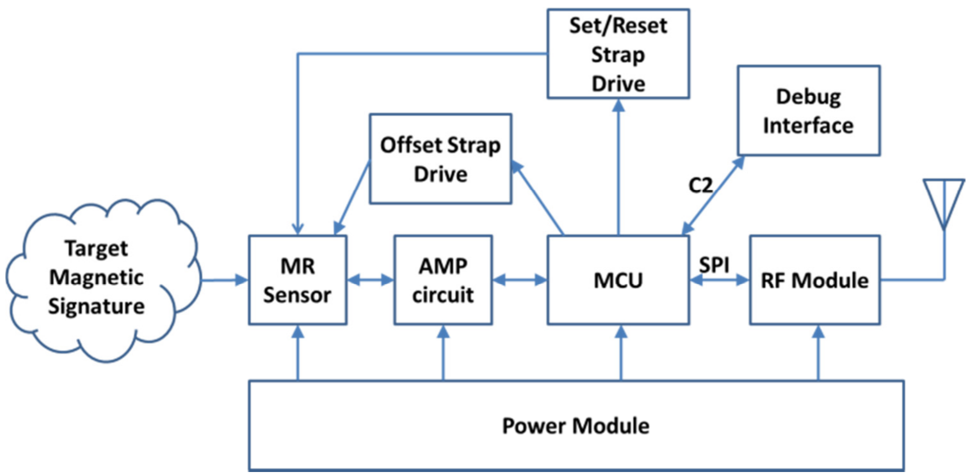

Figure 2.5 Active sensor node design scheme

The MR sensor used in the active node is a 3-axis AMR sensor. The analog signal gathered will be carefully conditioned before passed into the on-chip ADC of the MCU. A Set/Reset circuit is carefully designed to synchronize the Set/Reset impulse with the EMI pulses. An offset compensation circuit is also implemented for maximized system sensitivity and resolution. The data will be gathered by the MCU for exponential factor extraction. The extracted data is then sent back to the sink node for further processing.

2.5. Sensor node work flow

The WSN is design to work with master-slave architecture with sensor nodes as slaves and sink node as master. For the passive system, the sensor node is to achieve the solo function of gathering earth magnetic field information. Their small sizes and ultralow-power features make sure they can be easily deployed over a broad area or form a large array for UXO/mine survey purposes. While for the active system, due to the limited range of the EMI source, relatively high data processing requirements, and synchronization requirements, a smaller array is desired which provides better accuracy and discrimination capability. Both sensor systems can communicate with the same sink node. The sink node takes care of positioning, routing, network management and other complicated functions, and will be realized with off-the-shelf (OTS) USB transmitter and a laptop computer. The design of a passive and active sensor node is the main focus of this research.

In order to support network expandability, efficient node management, and low power consumption, a Contention Sensing Multiple Access (CSMA) scheme with automated query and acknowledge, is used. Multi-hop transmission is also supported for extended range. The overall work flow diagram of the CSMA scheme is shown in Figure 2.6 through Figure 2.8.

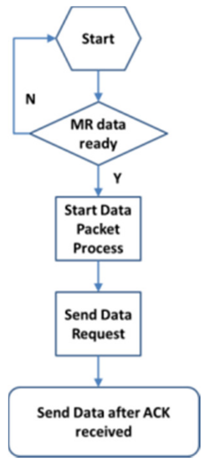

Figure 2.6 Data gather

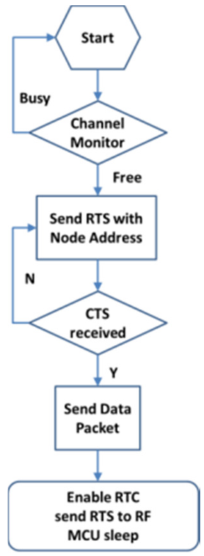

Figure 2.7 Data send

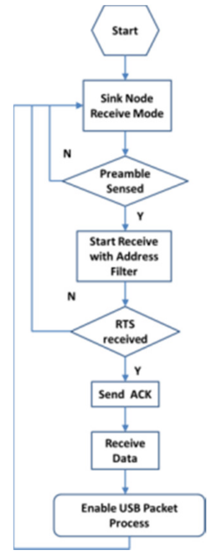

Figure 2.8 Data receive

2.6. Summary

In this chapter, the overall detection system design is briefly introduced. Different UXO/mine detection techniques are introduced and compared. Based on current detection technology, hybrid techniques are preferred to take advantage of different technologies. Then, the distributed passive/active WSN arrangement is introduced with detailed sensor node design schemes. Finally the sensor node work flow chart is given.

Chapter 3. Hardware design of wireless sensor platform

3.1. MR Sensor selection

There are generally five design parameters for WSN node development, low cost, proper microprocessor selection, ultra-low power, interference resistance, and miniaturization.

3.1.1. Low cost

Since WSN is typically comprised of large number of sensor nodes, and under many circumstances, the sensor nodes are one-time use only, the cost of sensor node directly impact the overall implementation of the WSN. As a result, lowering fabrication cost is the most important design parameter in designing WSN sensor nodes.

3.1.2. Microprocessor Selection

Due to the limitation on dimension, cost, and power, it is generally preferred to use microcontrollers (MCU) for system control and data processing. The data processing task on sensor nodes are typically minimal, microprocessors with powerful data processing capability are typically not suitable for sensor nodes. To choose a proper MCU, several factors have to be taken into consideration:

Interface performance: When deployed, the sensor node's MCU need to carry out many tasks simultaneously, including node device control, task management, energy calculation, function management, and etc., a suitable number of interfaces is required to accomplish all these tasks. The more tasks that need to be accomplished, the more interfaces will be required. Before purchasing the MCU, work flow of the sensor node need to be examined and planned carefully. One may calculate the total number of ports and interfaces based on the tasks, and select the MCU with proper size and functions. There are many OTS MCUs in the market that are suitable for WSN applications, for example, C8051F series from Silicon Labs, MSP430 from TI, R8C family from Renesas, and AVR series from Atmel.

Storage size and I/O ports: Storage size largely determines the size of program and data a MCU is capable of processing. System upgradability and expandability are important design factors for WSN, since not all the functions can be anticipated that need to integrate into the system. Upgradable firmware and expandable storage size guarantees the system can be improved over time.

Processor speed: For the passive sensor node, the processing power requirement is minimal. However, the active sensor node requires real-time sampling and data processing, thus the MCU must be able to process adequate data.

Power consumption: The method of deployment of the passive sensor requires ultralow-power features. A low sleep mode current is desirable for the design. Table 3-1 shows typical power consumption of several different MCUs.

Table 3-1 Power consumption comparison of several low-power MCUs

	C8051F912	ATtiny10	TI MSP
Wake up time (us)	2	N/A	5
Sleep mode current (uA)	0.01	0.1	3
Active mode current (uA/MHz)	160 (25MHz)	200 (12MHz)	45 (4MHz)
Supply voltage (V)	0.9-3.6	1.8-5.5	1.5-1.65V

3.1.3. Ultra-low Power and Energy Harvest Design

The widely distributed sensor nodes are required to gather data while transmitting data through the RF link. In general, the on board battery is the only energy source of the sensor, thus ultralow-power consumption is a very important technology for these sensor nodes. It is required that the power consumption of the node to be as low as possible. Toward this end, the components of choice must be low power, especially the sensor, MCU, and RF IC. The components are also desired to have low operation voltages. For constant current, lower supply voltage means lower power consumption. A proper battery is also an important factor and OTS batteries are the best of choice for reliability and availability. The different components must have a sleep mode so when not in use by the system, they can be switched to sleep mode independently.

3.1.4. Anti-interference Design

The signal to noise (SNR) ratio largely determines the sensitivity and performance of the detection system. There are two major sources of noise, radiated emission from external sources and conducted emission from the sensor itself. Radiated emission comes from external sources such as lightening, radiation from space, and other high power RF devices. The frequency spectrum expands from DC to UHF and higher. The radiated emission induces currents in the sensor circuit boards, leads, and sensors and disrupts the sensitivity. Self-interference comes from common mode interference, Electrostatic coupling interference, conducted interference coupling and other noises from internal sources.

To reduce system noise, several precautions must be taken into consideration including shielding and digital filtering. Metallic films can effectively radiation at

1000Hz and above. Metallic shields are transparent to magnetic field signals, and thus are applicable to this detection system. The metal shield also needs to be grounded properly to reduce coupled interferences. It is preferred to enclose the sensor node circuits inside a metal casing and of course leave the antenna outside the enclosure. Digital filtering is another effective method to improve the SNR of the system on the RF side. A built-in digital filter feature of the RF IC is desirable for the sensor node.

3.1.5. Miniaturization

Miniaturization is another important feature of WSN. The size of the sensor node largely depends on the MCU of choice. A high performance MCU with Small Outline Package (SOP), integrated ADC, and other digital peripherals is desired.

Sensor node design is a complicated and involves many design tradeoffs. Engineering principles and trade-offs is necessary to balance the above requirements and make the final product a success.

3.2. Sensor node hardware realization

Based on the above guidelines, a WSN node platform is design for both passive and active MR sensors. The platform utilizes MCU as central processing module, and includes sensor module, wireless communication module, power module, and other peripherals. A detailed explanation is given for each component of the passive and active sensor node. The overall platform scheme is shown in Figure 3.1.

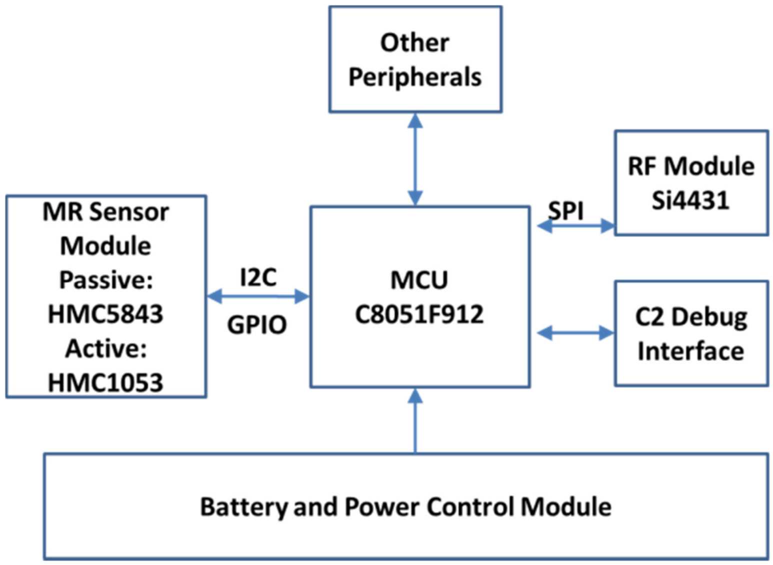

Figure 3.1 Design scheme of sensor node platform

The hardware of the sensor node platform uses a modular design. The MCU takes care of sensor operation, task management, function coordination, and data storage and processing. The sensor module measures the external magnetic field and generates a proportional voltage signal. The wireless communication module is responsible for data transmission between nodes and the power module provides power to all components. A Silicon Labs C2 interface is used as in-circuit-debugging interface for firmware update. A detailed component description is provided below.

3.2.1. Microprocessor Module Design

The MCU is the core of the sensor node. It controls and coordinates all components of the sensor node. Although there are many microprocessors in the market, only a few of them are suitable for use in WSN sensor node applications. The requirement of MCU include small size, high integration, ultralow-power, high processing speed, low cost, and support sleep mode. The microprocessors in the market can be categorized as microcontroller (MCU), Digital Signal Processor (DSP), Programmable Logic Controller (PLC), Advanced RISC Machine (ARM), and other specialty microprocessors. ARM processors have very powerful processing power and speed, but they are larger in size and require much higher power. DSPs are not designed as controllers and are generally used with other processors. MCUs are low power, small size, specialty in control, and are most suitable for WSN application. The MCU of choice is the high performance, ultralow-power C8051F912 MCU from Silicon Labs.

The C8051F912 is optimized for battery operated operations. It can operate as low as 0.9V supply, which make is possible to design a sensor node running on a single AA or AAA battery. It is capable of providing up to 25 million instructions per second (MIPS) throughput with 25 MHz clock, 768 bytes of on-chip RAM, and 16kB in-system programmable flash. It features 2μs wake-up time, 160μA/MHz active mode current, and as low as 10nA sleep mode current. It also has a built-in temperature sensor, 12-bit ADC, DC-to-DC converter, 16 port I/O (including I2C and UART), four general purpose 16-bit counter/timers, and Real-time clock (RTC). With advanced pipelined architecture, it is capable of processing adequate amount of data with common digital signal processing algorithm such as the Fourier transformation.

3.2.2. Wireless Communication Module Design

There are many short/medium range wireless technologies available for WSN such as Wi-Fi, Bluetooth, ZigBee, and sub-GHz industrial, scientific and medical (ISM) band technology. The priorities for choosing the most suitable wireless technology are range, power consumption, data rates, antenna size and interoperability. Compared with the most popular 2.4GHz technologies, sub-GHz wireless systems offer several advantages, including longer range, reduced power consumption, and lower deployment and operating costs.

A simple calculation according to the Friis Equation compares the path loss of 900MHz and 2.4GHz is given

$$Path\ Loss = 20 * \log \frac{4\pi d}{\lambda}$$

Where d is the distance and λ is the wavelength. The frequency difference can be translated as 8.5dB higher loss for 2.4GHz technology. Thus with same operation power, sub-GHz has roughly 2.7 times the range compared to 2.4GHz technology. Plus, sub-GHz provides superior penetration, slower fade, and less blocking effect.

For data rate consideration, although 2.4GHz provides higher data rate than sub-GHz (54Mbps vs. 128kbps), the excess data rate is not a necessary for either passive or active systems. The passive system only requires 480bps per node, the sub-GHz can very well support up to 200 nodes, which is more than sufficient. As for the active system, 2.4Mbps per node is required to send every data point through the RF link to the sink node for data processing. The 54Mbps bandwidth can only support up to 20 nodes, a large scale network is not economically acceptable.

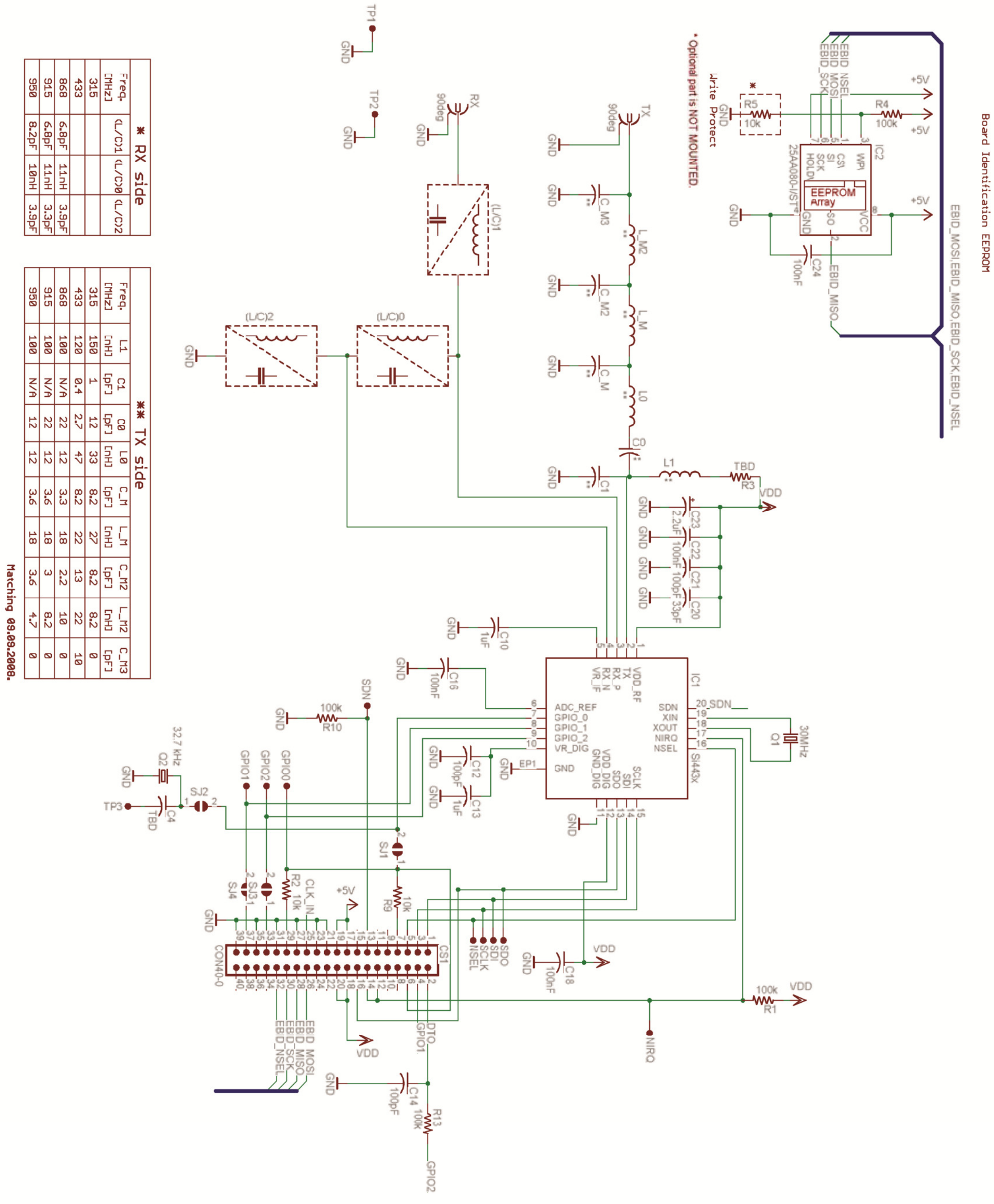

Figure 3.2 Reference design of Si4431

With all design considerations and to avoid compatibility issues, a sub-GHz RF IC Si4431 from Silicon Labs is chosen to be paired with the C8051F912 MCU as the RF module. It features small size (20-pin QFN package), ultralow-power (18.5 mA receive, 28 mA @ +13 dBm transmit), low voltage (1.8-3.6V), high sensitivity (–118 dBm), and moderate data rate (128kbps). In this design, the Si4431 is configured to work on 915MHz band, with FSK modulation, and 128kbps data rate. The MCU configures the Si4431 registers through SPI interface to control the state machine and determine the state of the device (idle, receive, or transmit).

Another major concern using this Silicon Labs combination setup is that Silicon Labs provides the EZMacPro library as a generic PHY and MAC layer protocol solution for their IC users. The EZMacPro fully utilize the built-in RF hardware of the Si4431, including digital modem, FIFO, fast frequency hopping and other capabilities. A reference design of the Si4431 is shown in Figure 3.2.

3.2.3. Sensor Module Design

Due to the different assignment of the passive and active method, different MR sensor implementations are used. The passive sensor module has an amplification circuit and other peripheral built in, while the active sensor requires a carefully designed analog circuit. The design details of the passive and active sensor modules are described in Chapter 4.

3.2.4. Power Management Module

Power source is a critical component of the sensor node. For reliable operation, it is required that each component of the sensor node is supplied with adequate and stable current. Battery or other power source is not able to achieve this, thus a voltage regulation circuit is required. The C8051F912 MCU has a built in DC-DC converting circuit, which allow operation from a single cell battery with a supply voltage as low as

0.9 V. Other specifications of the on-chip DC-DC converter include fully programmable output voltage range of 1.8 to 3.3 V, typical power output of 110mW max, and can be used for powering other devices in the system. These features allow the flexibility when interfacing to sensors and other components which typically require a higher supply voltage than a single-cell battery can provide. The DC-DC converter also supports programmable bypass mode for the ease of use with solar cells. During normal operation, if the dc-dc converter input voltage exceeds the programmed output voltage, the converter will stop switching and the external source (solar cell) will be used directly to power the circuit and charge the battery. Based on these features, a rechargeable AAA battery is used as the primary power source with energy harvest interface designed in case of prolonged operation requirement.

3.2.5. Other peripherals

Due to the time sensitive nature of the MR measurements, it is desired to have a real-time clock to track time for the sensor nodes to sleep and wake up and thereby save power. The C8051F912 has a built-in ultralow power 32-bit SmaRTClock (Real Time Clock) with alarm. The SmaRTClock has a dedicated 32 kHz oscillator that can be configured for use with or without a crystal. The SmaRTClock can operate directly from a 0.9–3.6 V battery voltage and remains operational even when the device goes into its lowest power down mode. The SmaRTClock output can be buffered and routed to a GPIO pin to provide an accurate, low frequency clock to other devices while the MCU is in its lowest power down mode.

I2C interface: The C8051F912 MCU also has built-in I2C capability. The I2C I/O interface is a two-wire, bi-directional serial bus. Data can be transferred at up to

100kbps as a master or slave. The interface makes it possible to connect the MCU with the HMC5843 digital MR sensor on chip level.

3.3. Sensor node performance

3.3.1. Power consumption

The power consumption of a WSN node is comprised of RF, MCU, and sensor power consumptions. The power consumption of the RF IC is shown in Table 3-2.

Table 3-2 Si4431 power consumption

Frequency	915MHz			
RF Status	Transmit (+1dBm)	Transmit (+13dBm)	Receive	Sleep
Current	18mA	28mA	18.5mA	800nA

The power consumption of the C8051F912 MCU is determined by the operation voltage and system clock frequency. The power consumption of C8051F912 under different modes is shown in Table 3-3.

Table 3-3 C8051F912 power consumption

Condition	VDD=1.8V			
MCU Status	Active F=24.5MHz	Active F=1MHz	Idle F=24.5MHz	Sleep with RTC
Current	4mA	265uA	2.1mA	0.6uA

The power consumption of the digital magnetometer HMC5843 is determined by supply sources, and measure modes. The detailed power consumption is shown in Table 3-4.

Table 3-4 HMC5843 power consumption

Condition	AVDD = 2.5 volts		
Sensor status	Measure mode	Idle mode	Sleep mode
Current	0.9mA	340uA	110uA

3.3.2. Battery life

Based on the power consumption, the maximum battery life can be calculated using Silicon Labs Battery Life Estimator. The simulated results are shown in Figure 3.3.

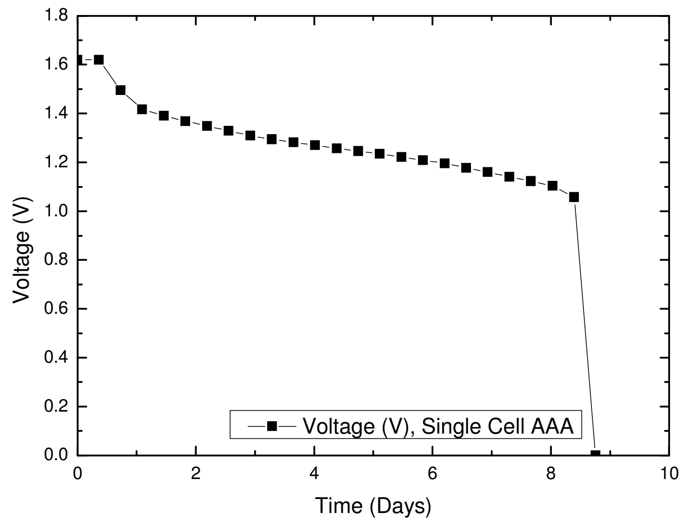

Figure 3.3 Estimated battery life of passive WSN node

3.3.3. Summary

In this chapter, hardware implementation of the WSN node is described. The overall system utilized modular design, and a detailed explanation is given for each module. The power consumption and estimated battery life is given for the passive system. It is shown that the overall system design conform to the WSN requirements.

Chapter 4. Magnetoresistance sensor module design

4.1. Passive MR Sensor module design

4.1.1. Earth magnetic field characteristic and field detection application

The earth's magnetic field (and the surface magnetic field) is approximately a magnetic dipole, with the magnetic field South Pole near the Earth's geographic North Pole and the other magnetic field North Pole near the Earth's geographic South Pole. This makes the compass usable for navigation and other application such as magnetometry for UXO and mine detection. A simple dipole model of earth magnetic field is shown in Figure 4.1 [10].

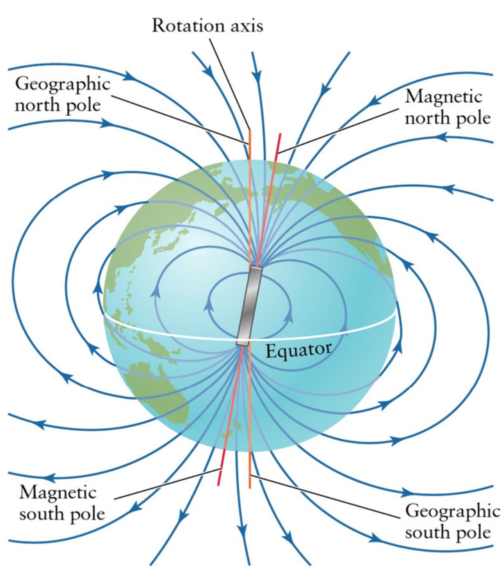

Figure 4.1 Earth magnetic field

Like any other magnetic field, earth magnetic field can be measured in magnetic field strength H or its vector components. The earth magnetic field is mainly generated inside the earth. The field strength is typically within 30000nT~60000nT and is almost constant within a few kilometers on earth surface, where large ferrous object can significant disturb the field strength. In geophysics, it is conventional to use nT as the unit for the earth's magnetic field strength measurement. The relationship between Tesla and Gauss, is $1T = \frac{1Wb}{m^2} = 10^4\ G(gauss) = 10^9 nT$. For field anomaly application such as UXO/mine detection, the sensor should be able to detect magnetic field in the nT range.

Due to the development of advanced magnetic field sensors, the microprocessor, and filtering technology, the combination of MR sensor with WSN is possible. With the advent of GMR and AMR sensors, there have been several interests in measuring the earth's magnetic field and perturbation thereof due to ferrous objects like mines and UXO.

4.1.2. Magnetic field sensor options

Magnetic field sensors, generally called magnetometers, are manufactured based on different physic principles. A brief review on different magnetic sensing principles is given here to provide a baseline for choosing different technology for UXO detection solution.

4.1.2.1. Coil sensors

Coils are the oldest means to measure variations of magnetic fields. According to Faraday's law, any change in the magnetic environment of a coil of wire will cause a voltage (EMF) to be induced in the coil. Thus by placing a coupled coil in a time varying magnetic field, the variation of the field can be recorded by the variation in the EMF generated by the coil.

Coils can only be used to measure time varying magnetic field. There are many implementations using the coil, such as the traffic light control sensor. The coils buried underneath the roadbed can sense the passing by vehicles. However, due to the large size and relatively high cost, coils are not ideally suited for use with WSN.

4.1.2.2. Fluxgate magnetometers

A fluxgate is a magnetometer developed based on Faraday's Law. A fluxgate magnetometer consists of a small, magnetically susceptible, core wrapped by two coils of wire. An alternating current is passed through one coil, driving the core through an alternating cycle of magnetic saturation. This alternating magnetic field induces an electrical current in the second coil, and this output current is measured by a detector. The fluxgate magnetometer has been around since WII, and their typical sensitivity nowadays are on the order of 0.5nT to 1nT. However, due to the coils and magnetic core involved, their sizes are relatively large, and costs from $5,000 to $10,000 are typical. For time spatial sampling of the magnetic field, the fluxgate magnetometers, because of its large size, is not ideal.

4.1.2.3. Hall Effect sensors

The most common magnetic sensing devices are solid-state Hall Effect sensors. A Hall Effect sensor is a transducer that varies its output voltage in response to changes in magnetic field. Hall Effect sensors are typically used to measure 10Oe to 1000Oe

Strong fields. Hall Effect can exist in both metals and semiconductors. The most common Hall Effect sensors are silicon based Hall Effect ICs with signal conditioning circuit build in the sensor. The typical sensitivity of silicon based Hall Effect sensors are around 5mV/V/Oe, and the minimum detectable magnetizing field is around 10Oe, which is much larger than earth's magnetic field (0.5Oe max).

4.1.2.4. Magnetoresistance sensors

Magnetoresistive (MR) sensors make use of the magnetoresistive effect, the property of a current-carrying magnetic material to change its resistivity in the presence of an external magnetic field. The MR sensors are typically made of film strips of ferromagnetic material called permalloy (19% Fe, 81% Ni) deposited on silicon substrates using a semiconductor fabrication process. The films are typically 150 to 500A (Angstrom) thick, 10-50um wide, and 500-1000um long. Their miniatures sizes, high sensitivity, and near immunity to EM noises make them ideal for use in a WSN.

As a result, the sensor of choice for our UXO/mine detection WSN is the MR sensor.

4.1.3. Passive MR Sensor module design

Many highly sensitive sensors capable of sensing small variation in Earth magnetic field are developed in recent years based on the MR mechanisms. Based on these sensors, it is possible to develop a UXO detection system with excellent spatial resolution. Another very desirable attribute of the MR sensor is its ability to read all three vector components of the earth's magnetic field, leading to improved discrimination capability over a single axis measure.

MR sensors can be used to detect the magnetic field anomalies caused by ferrous materials and these estimate the location of the object. The data gathered from a 3-axis magnetometer can be processed to extract complete magnetic field vector information.

For our passive MR sensor array, we used the HMC5843 3-axis digital magnetometer IC. A summary of HMC5843 features is listed in Table 4-1 and the system diagram of MR sensing unit is shown in Figure 4.2.

Table 4-1 Features of HMC5843 digital magnetometer IC

Ultra-low power	Low Voltage (2.5 to 3.3V), active mode current 0.9mA
Small Size	4.0x4.0x1.3mm surface mount LCC package
High resolution	120 $\mu gauss$
High sensitivity	1.0 mV/V/gauss
Integrated peripherals	Built-in ASIC circuits with amplification, strap drivers, offset cancellation, 12-bit ADC and an I2C interface

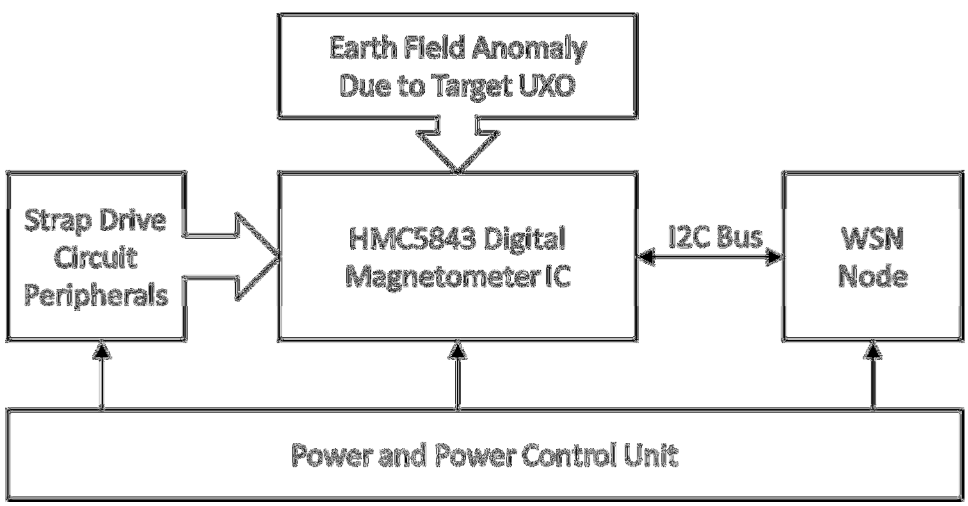

Figure 4.2 System diagram of passive MR sensing unit

Although the HMC5843 has amplification, strap drivers, offset cancellation, 12-bit ADC and an I2C serial bus interface built in, a few supportive components such as pull up resistors and reservoir capacitors have to be added for proper operation. The I2C interface with the host MCU must also be designed. The HMC5843 requires the I2C bus to be interfaced with the host MCU, as shown in Figure 4.3.

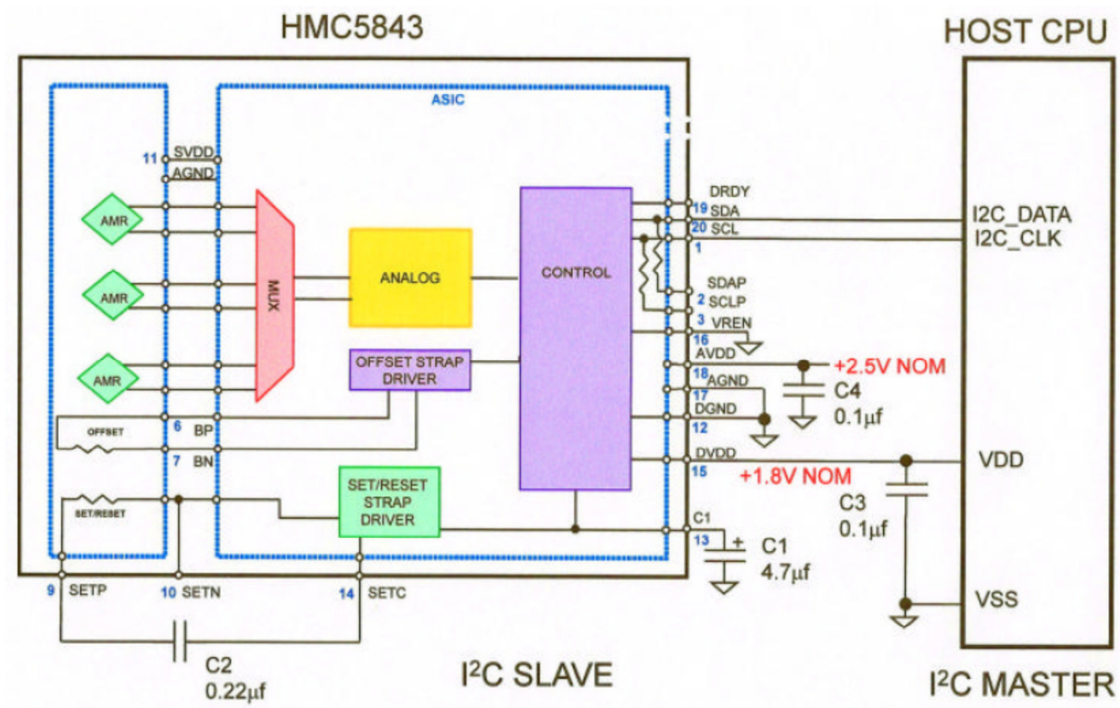

Figure 4.3 HMC5843 I2C schematic and reference design

For the MCU and RF module we used a Silicon Labs C8051F912 MCU and a Si4431 radio. This combination features ultralow power and voltage operation. A single AAA battery can support the module in full active mode (24.5 MHz clock) for over 7 days (refer to 3.3.2). The C8051F912 has an on-chip dc-dc converter to allow operation from a single cell battery with a supply voltage as low as 0.9 V. The DC-DC converter is configured to enable bypass mode when VBAT is greater than VDD for use with a solar panel. A power harvest interface is utilized for solar panel connection.

When the voltage supplied by the solar cell/battery combination reaches the designed output voltage, the DC-DC converter will bypass itself to operate at maximum efficiency. Since the DC-DC convertor is flexible with input voltage range, this allows for different combinations of batteries and solar cells for the system if other power source options are desired.

The Si4431 RF IC is connected to the MCU through serial peripheral interface (SPI) and is controlled by Silicon Labs EZMacPro library software. A PCB meander line antenna from Silicon Labs EZRadioPro reference design is used together with the Si4431 radio. The MCU also has a C2 interface for debugging and firmware update.

The HMC5843 digital magnetometer is connected to the MCU I/O ports P0.0 as serial data line (SDA) and P0.1 as serial clock (SCL) using I2C bus configuration. The I2C bus operates at 100kbps data rate with the C8051F912 MCU configured as master and HMC5843 configured as slave. A breadboard test is successfully carried out before the PCB design to verify the compatibility between the MCU and HMC5843. The final schematic of the passive WSN node is shown in Figure 4.4 and Figure 4.5.

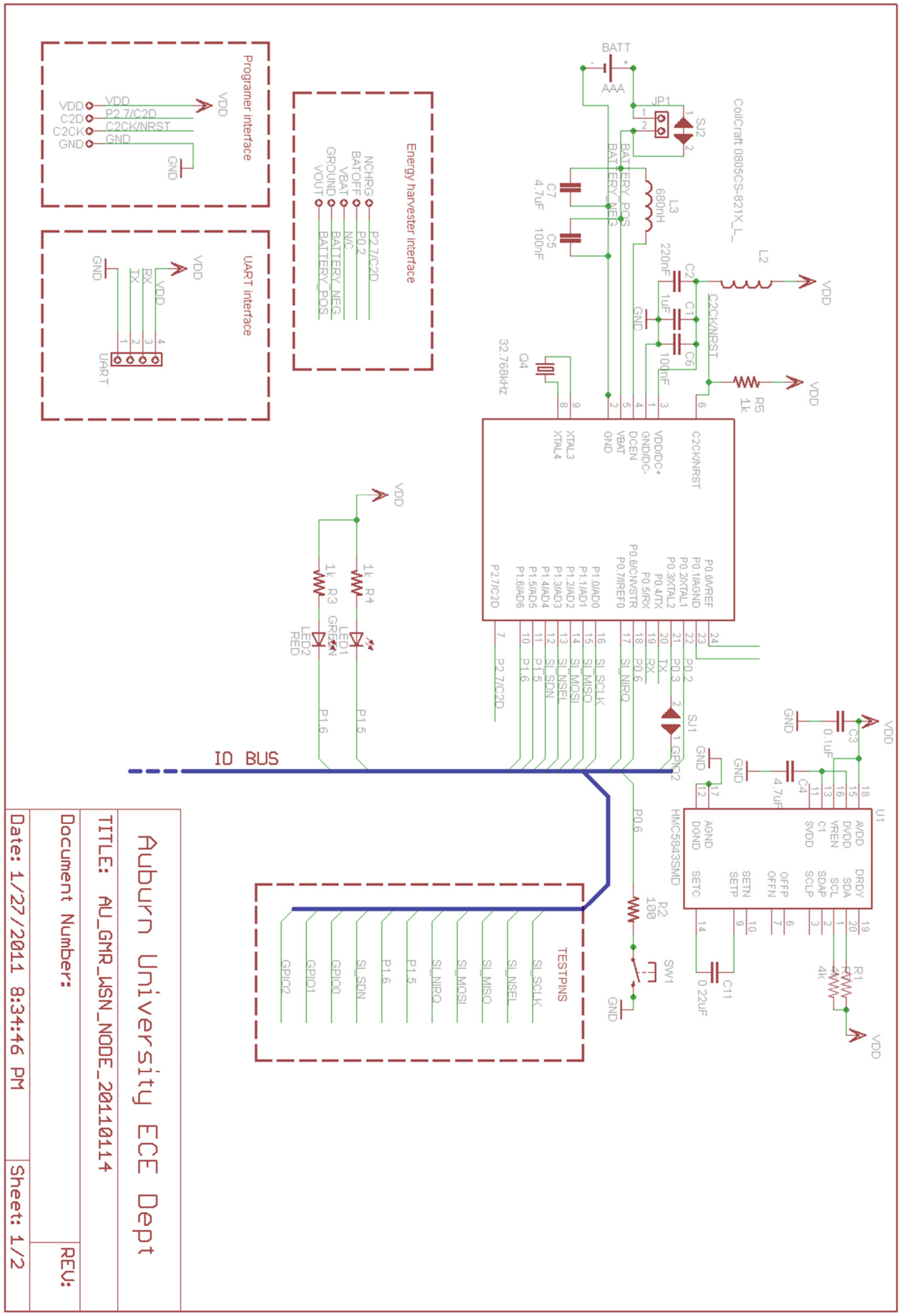

Figure 4.4 Passive WSN node scheme, MCU and MR sensor

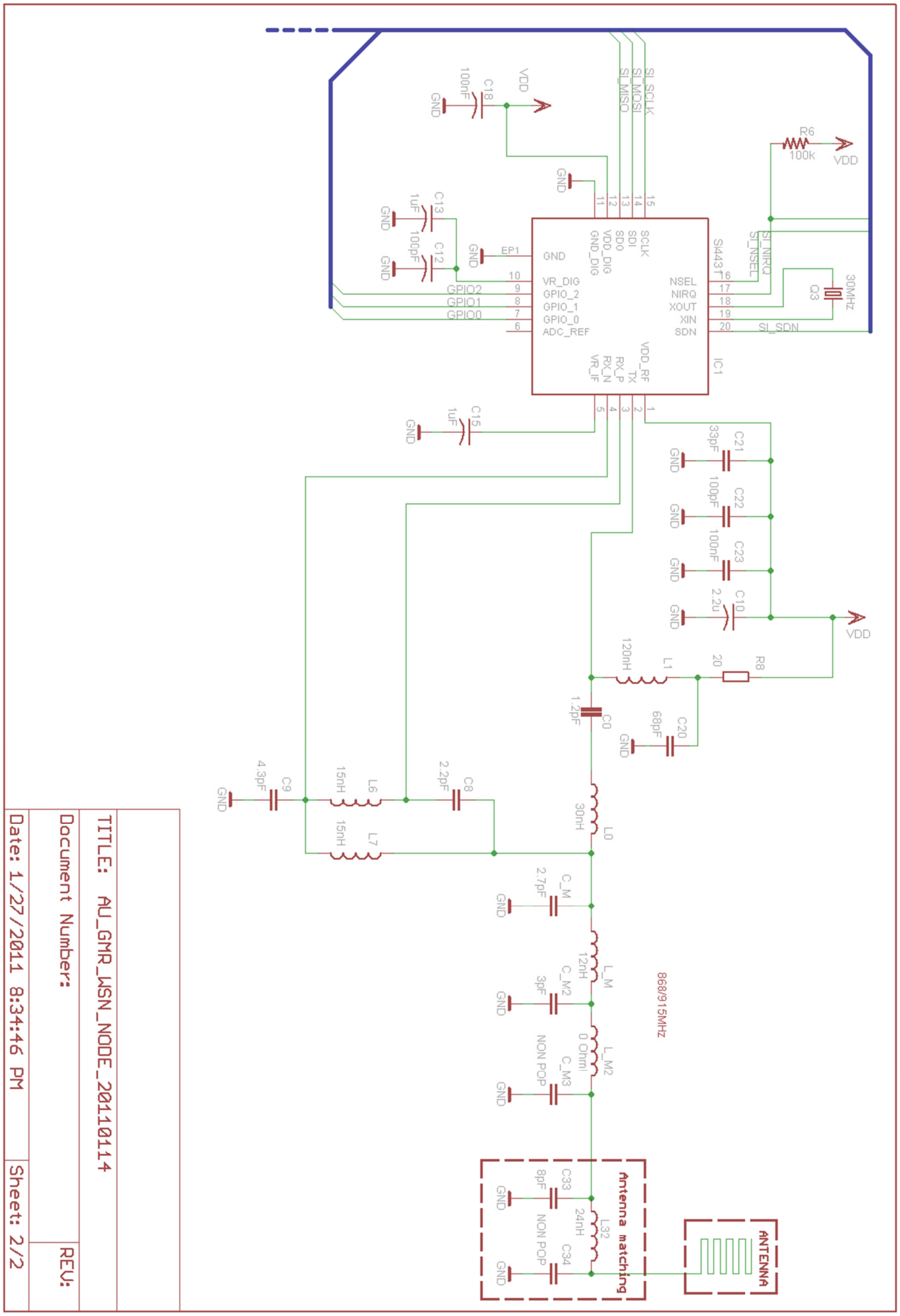

Figure 4.5 Passive WSN node scheme, RF

In order to keep the board to a minimal size as well as reduce in circuit interferences, we chose to use leadless Quad Flat No leads (QFN) based ICs and surface mount passive components that are sized down to 0402 based packages. An advantage to using standard surface mount components is that the board can be assembled on a larger scale using standard manufacture assembly lines for electronics because they are easily handled using automated 'pick and place' machines. Using components this small, hand-soldering is less than ideal for populating the board; therefore, we chose to use the reflow soldering technique. This method requires that a solder paste to be applied to each of the component pads on the circuit board. To place the correct solder paste in the right location, we chose to have a solder paste stencil made of 3mm thick clear Mylar for relatively low cost at Pololu Robotics and Electronics. Upon placing the components, the circuit board is place in an oven to flow the solder, which will harden when cooled. The final layout is shown in Figure 4.6. An unpopulated circuit board is shown in Figure 4.7 and a fully assembled board is shown in Figure 4.8. A X-ray inspection of the fully assembled board is also carried out using a phoenix PCBA inspector, the overall X-ray image and integrated relief are shown in Figure 4.9 and Figure 4.10

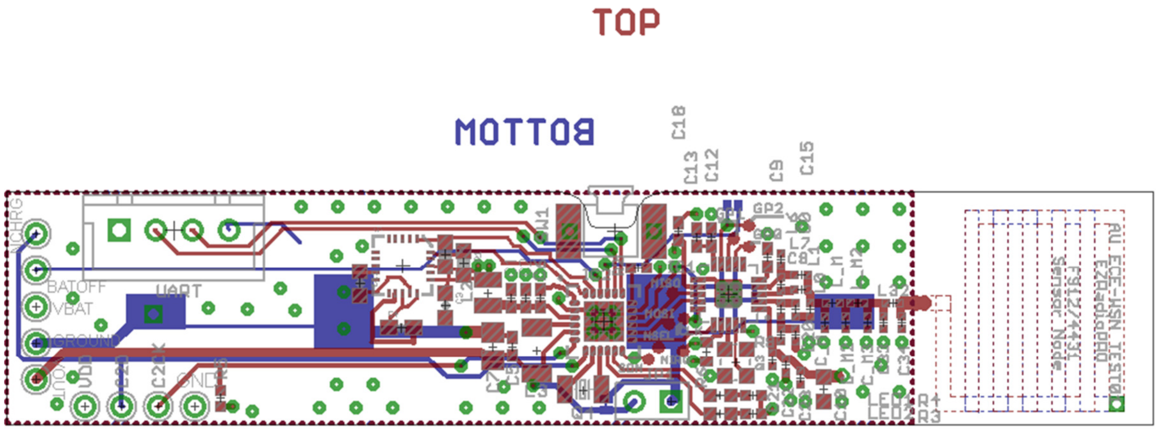

Figure 4.6 Passive node PCB layout

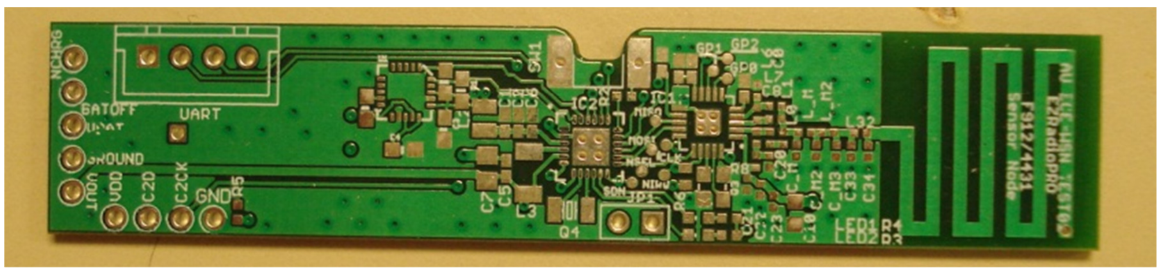

Figure 4.7 Fabricated passive node PCB

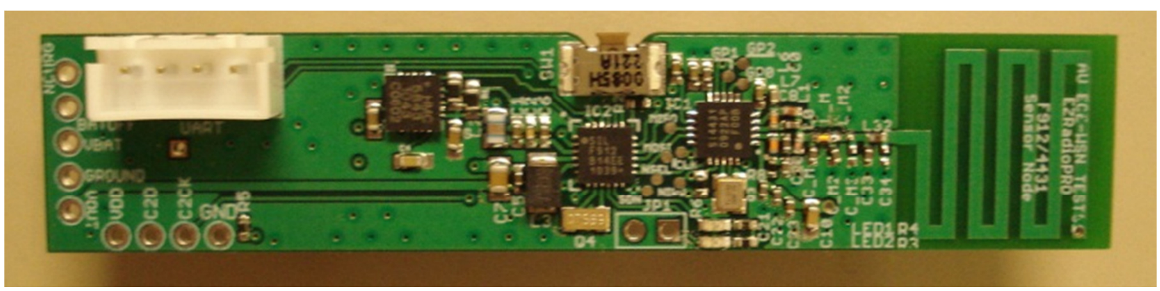

Figure 4.8 Assembled passive node

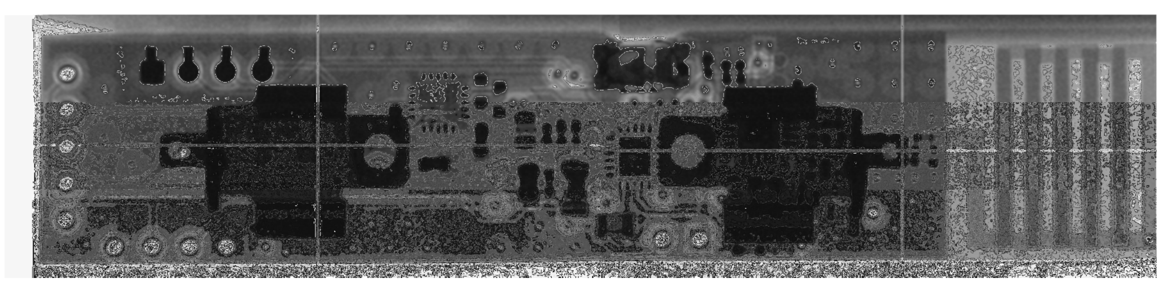

Figure 4.9 X-ray inspection of assembled passive node

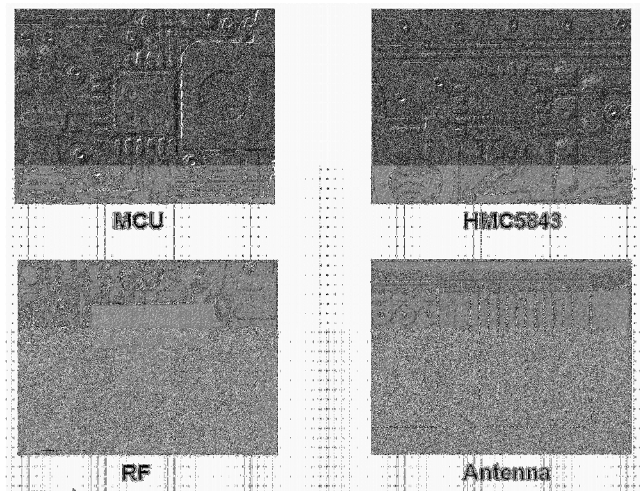

Figure 4.10 X-ray integrated relief of passive node components

The X-ray results shown a few minor soldering defects possibly introduced during assembly process and will be improved in further prototyping iterations.

4.2. Active MR Sensor module design

4.2.1. EMI system

Time-varying electric currents produce time-varying magnetic fields, and according to Faraday's law, this field will induce eddy currents in any nearby conductive and/or permeable object. The eddy currents in turn generate a secondary time-varying magnetic field which can be detected using a magnetic field sensor. The received signal may be used to acquire information regarding the UXO/mine target and ultimately used for discrimination purposes. The above electromagnetic interaction may be referred to as electromagnetic induction (EMI) phenomenon. Typical components of an EMI system are shown in Figure 4.11 and include a transmitter and receiver and buried object or objects.

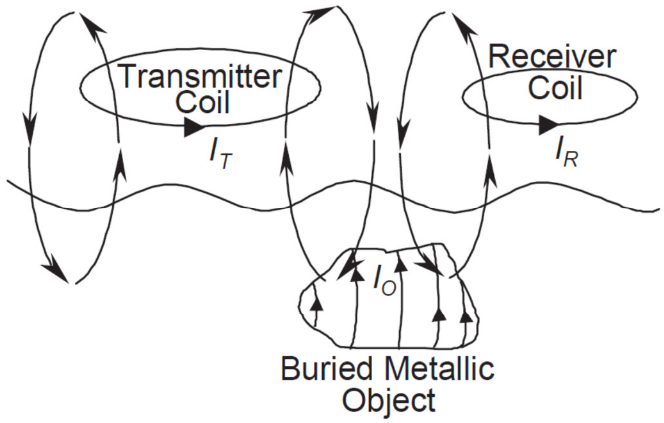

Figure 4.11 Typical EMI system setup

As shown in the figure, the typical EMI system implementations use coils as transmitter and receiver. However, as stated in 4.1.2.1, coils are costly and bulky and not ideally suitable for WSN applications, thus MR sensors are used to replace the receiver coils in our design.

4.2.2. The magnetoresistive effect

In sensors employing the MR effect, the resistance of the sensor changes with $cos^2\theta$ relationship under the influence of a magnetic field:

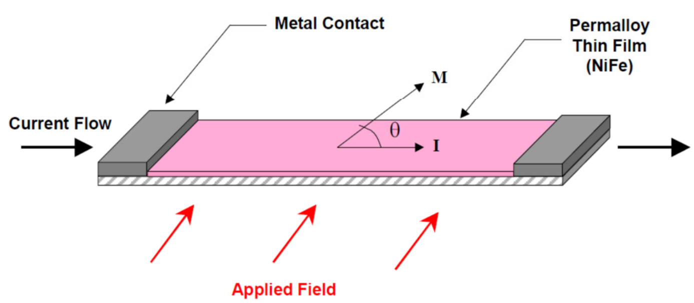

Figure 4.12 AMR Element [11]

$$R = R_O + \Delta R_O cos^2\theta \qquad (4\text{-}1)$$

It can be shown that

$$\sin^2\theta = \frac{H^2}{{H_O}^2} \text{ for } H \leq H_O \tag{4-2}$$

and

$$\sin^2\theta = 1 \text{ for } H > H_O \tag{4-3}$$

where Ho can be regarded as a material constant comprising the demagnetizing and anisotropic fields and θ is the angle between the magnetic moment (M) vector and the current flow (I). Figure 4.12 [11] shows the Permalloy element with field and current applied.

Applying equations (4-2) and (4-3) to equation (4-1) leads to:

$$R = R_O + \Delta R_O\left(1 - \frac{H^2}{{H_O}^2}\right) \text{ for } H \leq H_O \tag{4-4}$$

and

$$R = R_O \text{ for } H > H_O \tag{4-5}$$

which clearly shows the non-linear nature of the MR effect.

4.2.2.1. Linearization

In order to be used for UXO detection application, the AMR sensors need to be configured with in a linear range. The MR effect can be linearized by depositing aluminum stripes (Barber poles) on top of the permalloy strip at an angle of 45° to the strip axis as shown in Figure 4.13. As aluminum has a much higher conductivity than permalloy, the effect of the Barber poles is to rotate the current direction through 45°, forming a saw-tooth shaped current flow, and effectively changing the rotation angle of the magnetization relative to the current from α to $\alpha - 45°$.

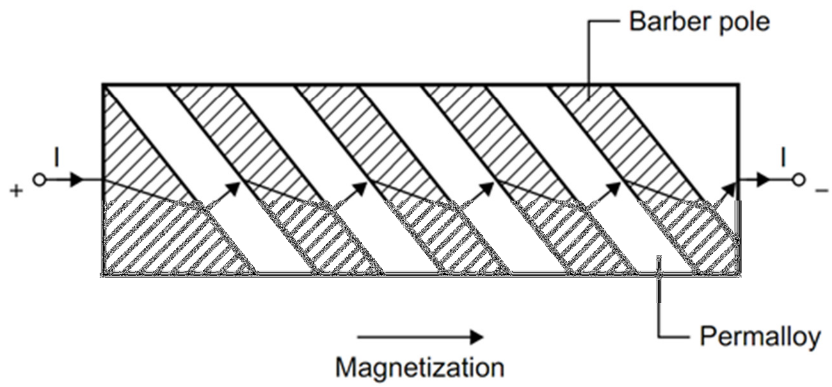

Figure 4.13 Linearization of the MR effect [11]

A Wheatstone bridge configuration is also used for linearized applications as shown in Figure 4.14. In one pair of diagonally opposed elements, the Barber poles are at +45° to the strip axis, while in another pair they are at −45°. A resistance increase in one pair of elements due to an external magnetic field is thus matched by a decrease in resistance of equal magnitude in the other pair. The resulting bridge imbalance is then a linear function of the amplitude of the external magnetic field in the plane of the permalloy strips, normal to the strip axis.

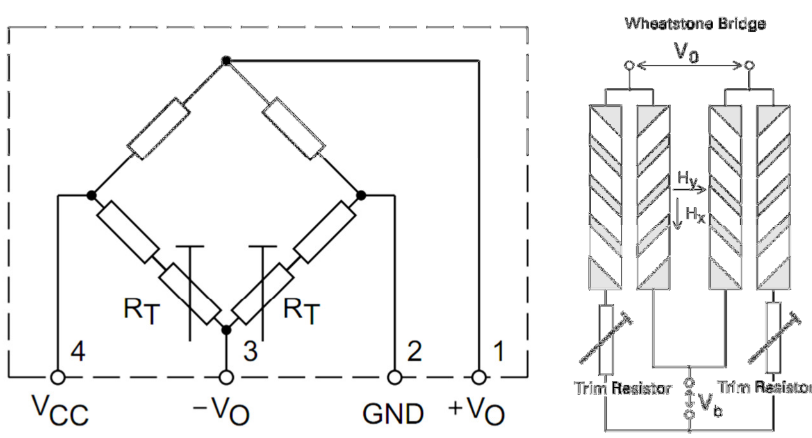

Figure 4.14 Wheatstone bridge configuration [11]

4.2.2.2. Set/reset function

One undesirable characteristic of the wheatstone bridge MR sensor is that strong magnetic fields can disrupt the magnetic domains of the film particles from a smooth factory orientation to arbitrary directions thus causing a non-linear responses. Accuracy and resolution of these sensors will suffer until the film magnetic domains are reset to recreate a uniform orientation. Figure 4.15 shows three examples of magnetic orientation of the film domain structure.

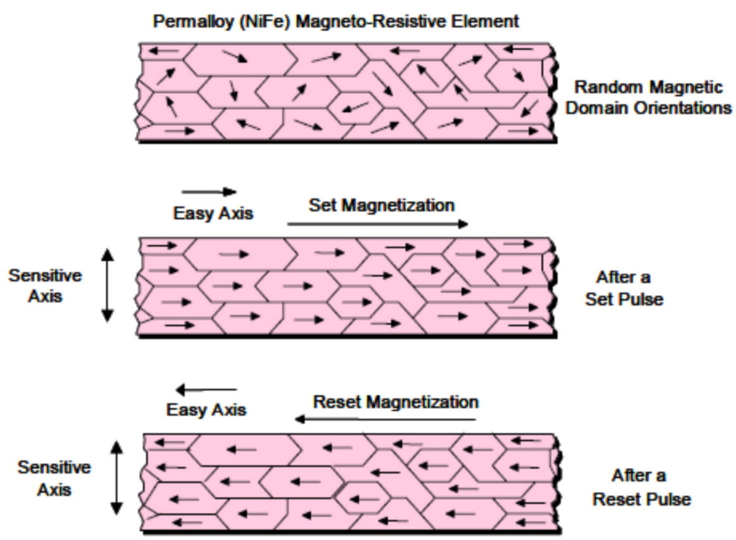

Figure 4.15 MR magnetic domain for set/reset [11]

The alignment of the magnetic domains is up along the easy axis of the material while the sensitive axis is perpendicular to the easy axis direction which is the driving function of the MR characteristic curve as shown in Figure 4.16.

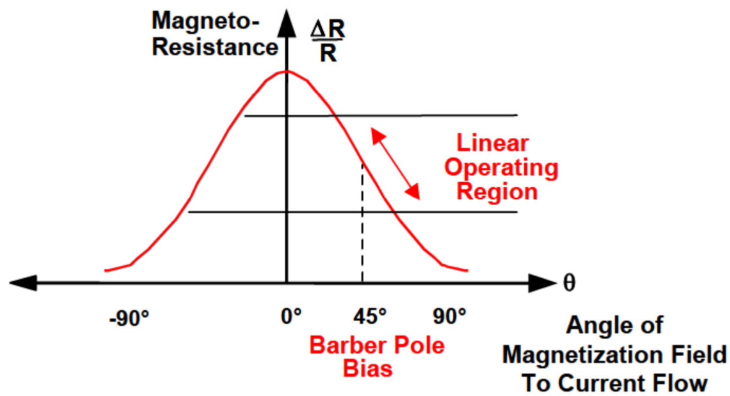

Figure 4.16 Typical MR characteristic curve [11]

Due to the large current used in the active detection system, especially the EMI source, a set/reset circuit must be implemented to acquire accurate and sensitive secondary magnetic field data.

4.2.3. Active MR Sensor module design

In the active MR sensor design, we used a HMC1053 3-axis magnetic sensor. The HMC1053 is a MR sensor designed for low field magnetic sensing. The advantage of the HMC1053 sensor is in the near-perfectly orthogonal sensors on a single chip with shared set/reset and offset coils/straps included. The HMC1053 allows for a much faster sampling rate than is available with the HMC5843 (50sps max). The HMC1053 is designed to be sampled with the built-in ADC of the C8051F912 MCU, which is capable of sampling at 75ksps and this should provide adequate resolution for target discrimination. To function properly, the HMC1053 also requires auxiliary signal conditioning, amplification, and a set/reset circuit. A summary of HMC1053 features is listed in Table 4-2 and the system diagram of MR sensing unit is shown in Figure 4.17.

Table 4-2 Features of HMC1053 3-axis magnetic sensor

Ultra-low power	Low Voltage (1.8V to 20V), active mode current 0.5mA
Wide bandwidth	DC to 5MHz
High resolution	120 $\mu gauss$
High sensitivity	1.0 mV/V/gauss
Low noise	50 nV/sqrt Hz @ 1kHz

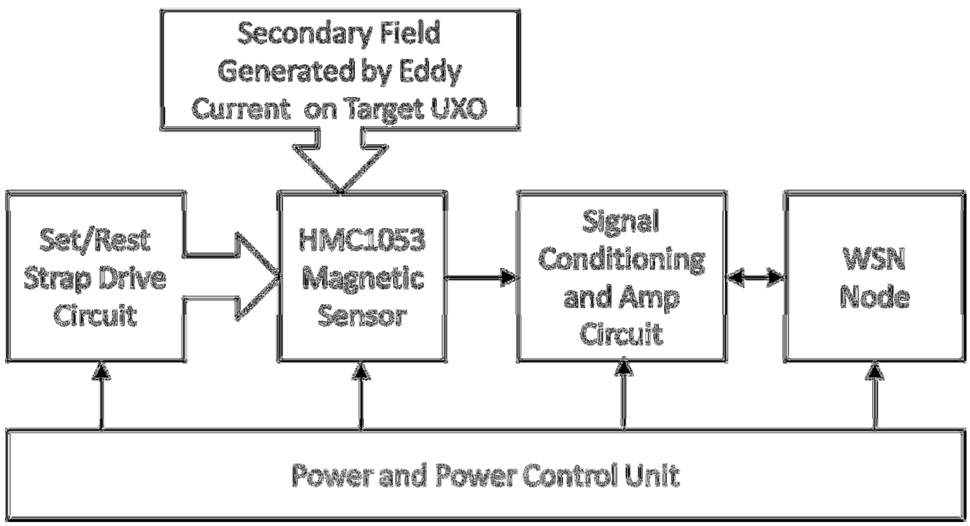

Figure 4.17 System diagram of active MR sensing unit

Although the set/reset and offset straps are built-in, unlike the HMC5843 digital magnetometer, the HMC1053 requires an external analog circuit for amplification, signal conditioning, set/reset drive, and offset drive circuit.

The offset strap allows for several modes of operation when a direct current is driven through it, including: 1) Subtraction (bucking) of an unwanted external magnetic field, 2) nulling of the bridge offset voltage, 3) Closed loop field cancellation, and 4) Auto-calibration of bridge gain.

The set/reset strap can be pulsed with high currents for the following benefits: 1) Enable the sensor to perform high sensitivity measurements, 2) Flip the polarity of the bridge output voltage, and 3) Periodically used to improve linearity, lower cross-axis effects, and temperature effects.

A reference design of the amplification circuit is shown in Figure 4.18.

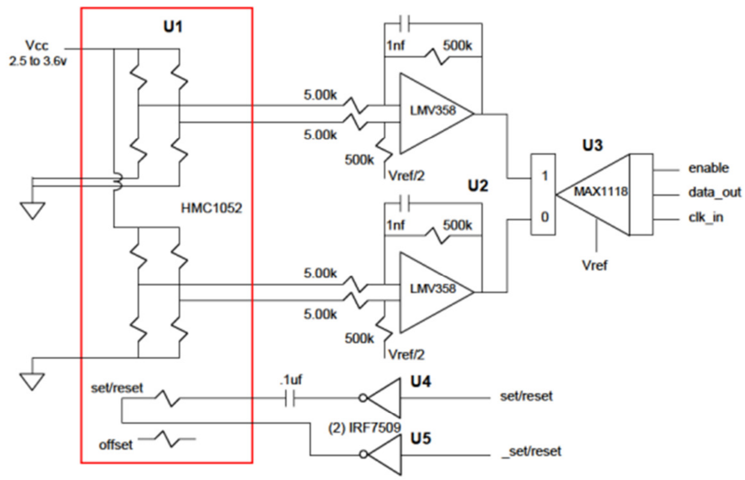

Figure 4.18 Reference design of amplification circuit

In our design, the LMV358 Op-Amps are replaced with a four channel LMV934 low voltage Op-Amp. Three out of the four channels are used to amplify the 3-axis signal from the HMC1053. The output from the Op-Amp is connected to three I/O ports of the MCU for 12-bit ADC.

An H-bridge set/reset circuit is implemented in this design. A reference design is shown in Figure 4.19. A SOT-353 inverter and a pair of IRF7507 MOSFET are used instead of the components shown in the reference design.

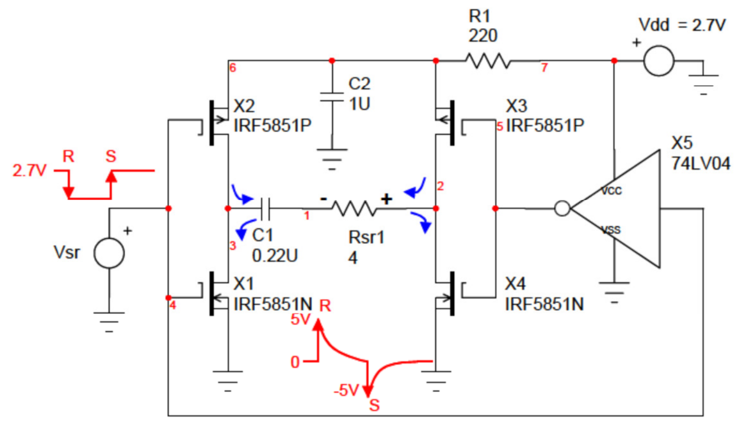

Figure 4.19 H-bridge Reference design of set/reset circuit

A breadboard test of the analog circuit has been implemented, and shows expected performance of the components. The set/reset circuit can provide up to 0.6A on each set/reset strap which is sufficient to align the sensor to the desired easy axis, as shown in Figure 4.20.

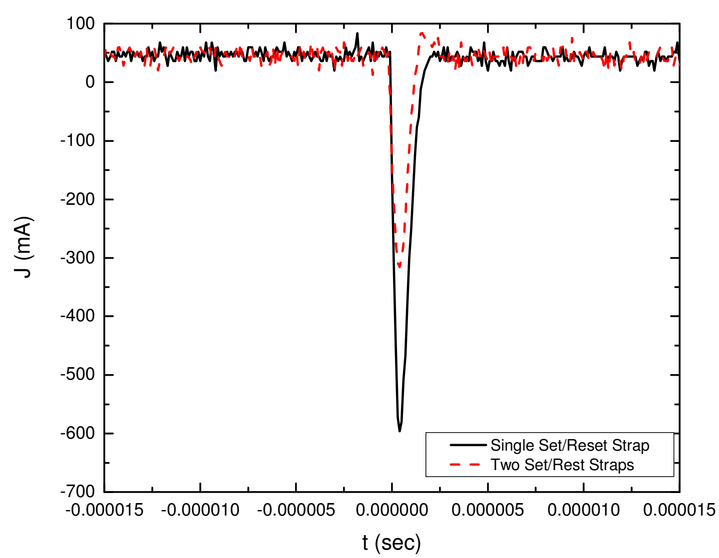

Figure 4.20 H-bridge set/reset current test

Based on the reference designs and breadboard implementation, the circuit scheme design is shown in Figure 4.21 and Figure 4.22.

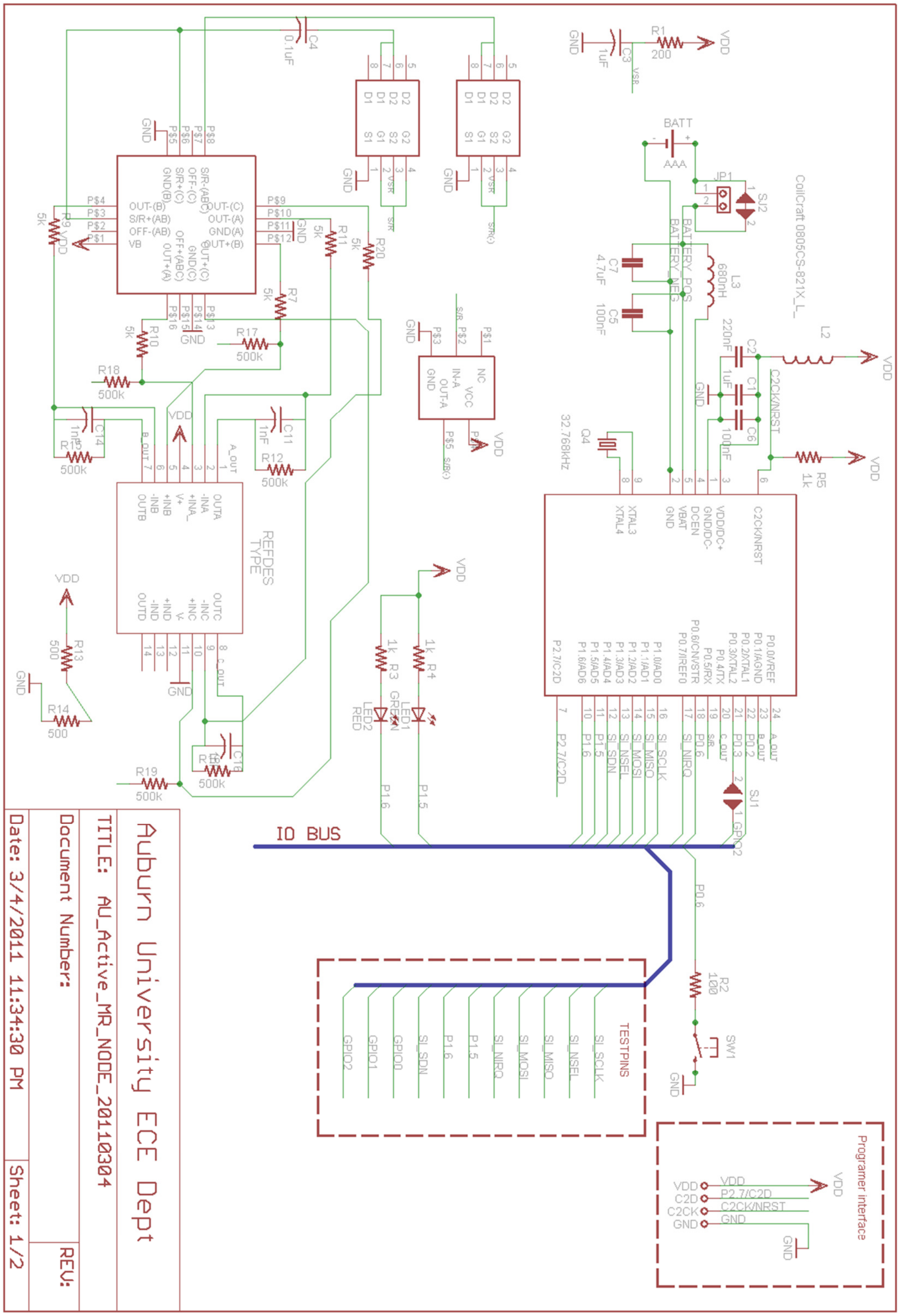

Figure 4.21 Active node scheme, MCU and analog circuit

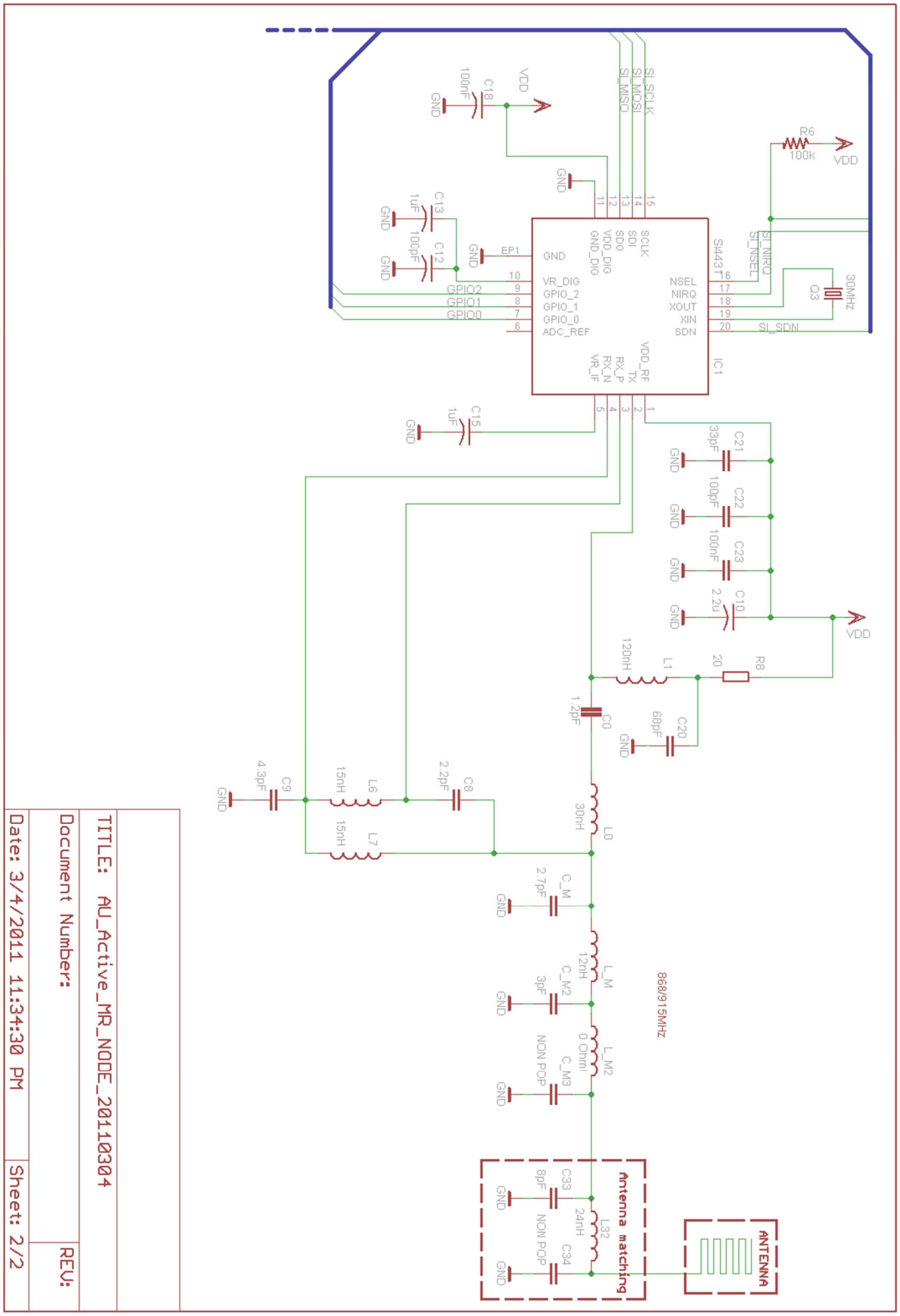

Figure 4.22 Active node scheme, RF

Following the same reflow procedures as the passive WSN node, the designed active WSN node solder paste stencil is ordered from Pololu Robotics and Electronics. The PCB board layout shown in Figure 4.23 is ordered from Advanced Circuits.

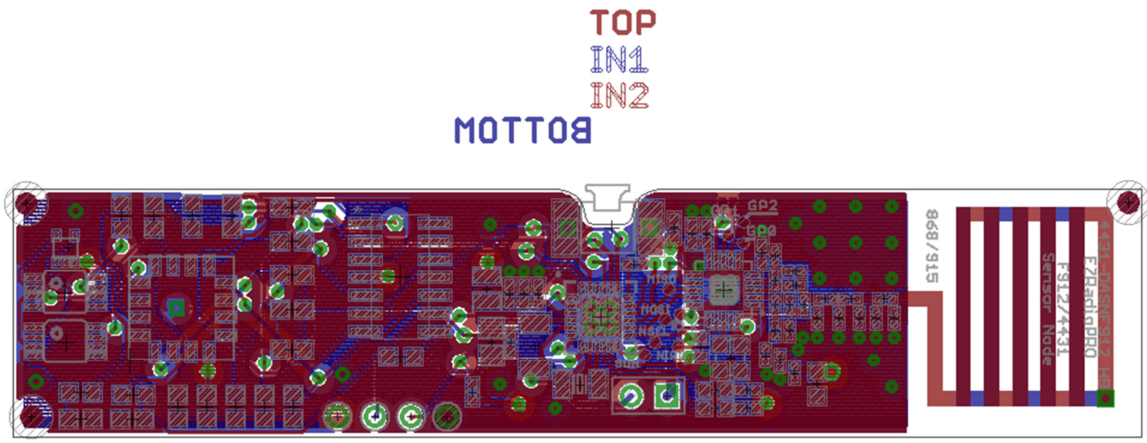

Figure 4.23 Active node layout

An unpopulated circuit board is shown in Figure 4.24 and a fully assembled board is shown in Figure 4.25. An X-ray overall inspection is shown in Figure 4.26 and an integrated relief of MCU, RFIC, MR sensor, and antenna is shown in Figure 4.27.

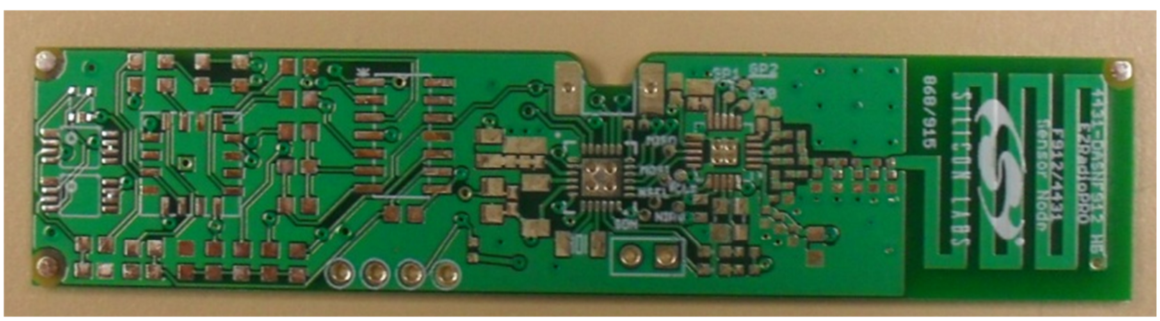

Figure 4.24 Fabricated active node PCB

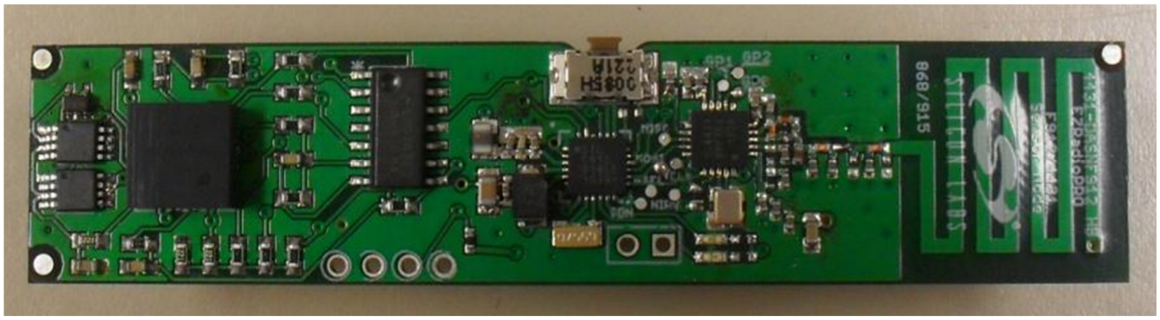

Figure 4.25 Assembled active node

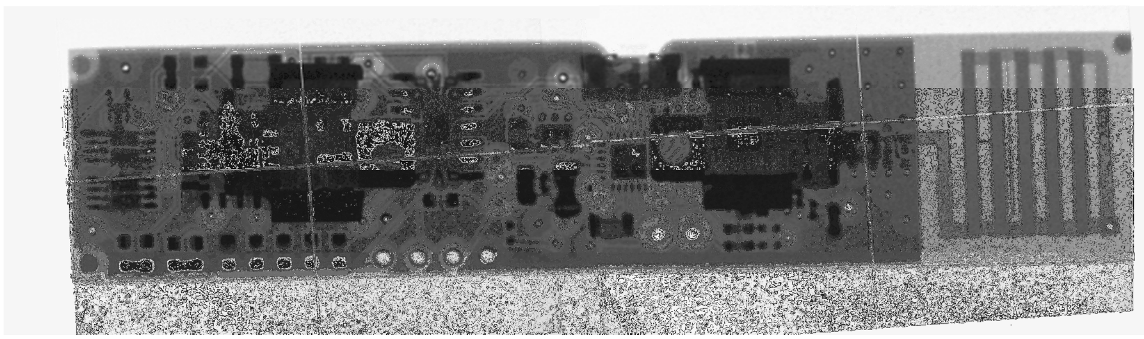

Figure 4.26 X-ray inspection of assembled active node

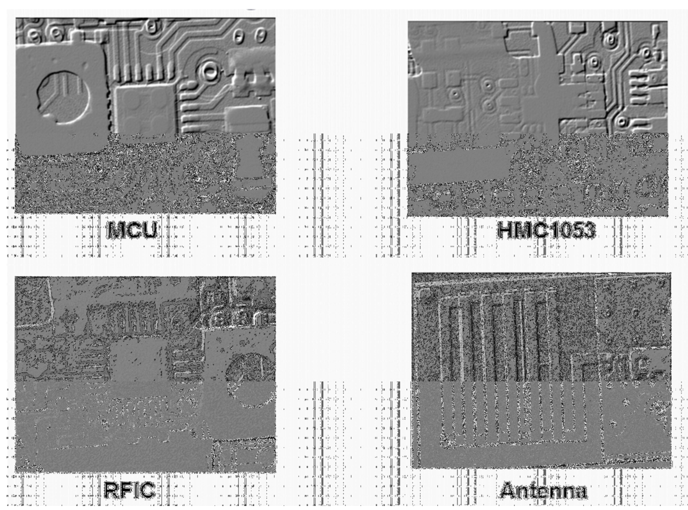

Figure 4.27 X-ray integrated relief of active node components

The X-ray result shows a few defects including several shorts and mistakes in antenna layout and will be fixed in further prototyping iterations.

4.3. Preliminary results

Preliminary results of a magnetic pen and a 60mm mortal shell with a breadboard prototype of the HMC1051 MR WSN node are taken. MR sensor can detect the magnetic field disturbance when ferrous objects enter its vicinity. The disturbance is measured in term of voltage variation across the Wheatstone bridge and converted into digital signal by the on-chip ADC. The magnitude of signal depends on the distance between the object and the sensor, the closer the object, the stronger the signal.

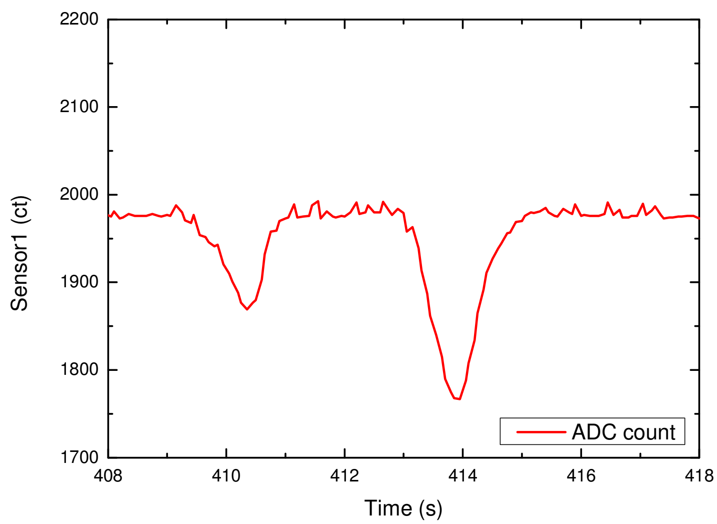

Figure 4.28 Response of a magnetic pen (10cm)

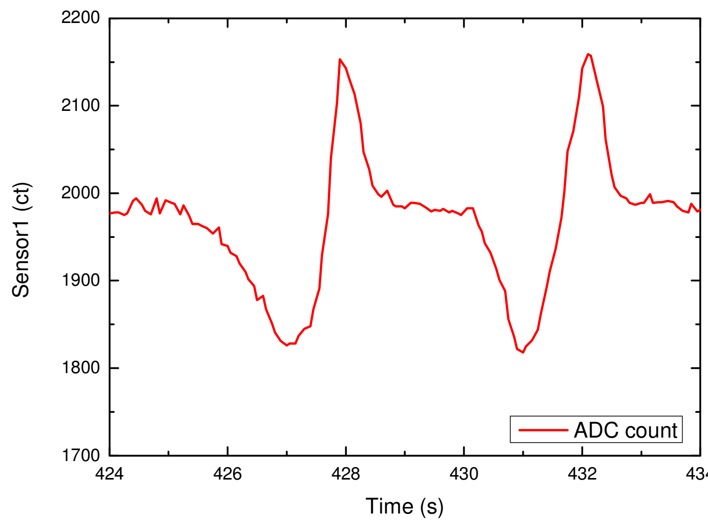

Figure 4.29 Response of a 60mm mortal shell (10cm)

As shown in Figure 4.28 and Figure 4.29, the response of a magnetic pen and a 60mm mortal shell 10 cm away from the sensor can have as strong as 150-200 ADC count, with significant different signal signatures such as amplitudes and pulse shapes.

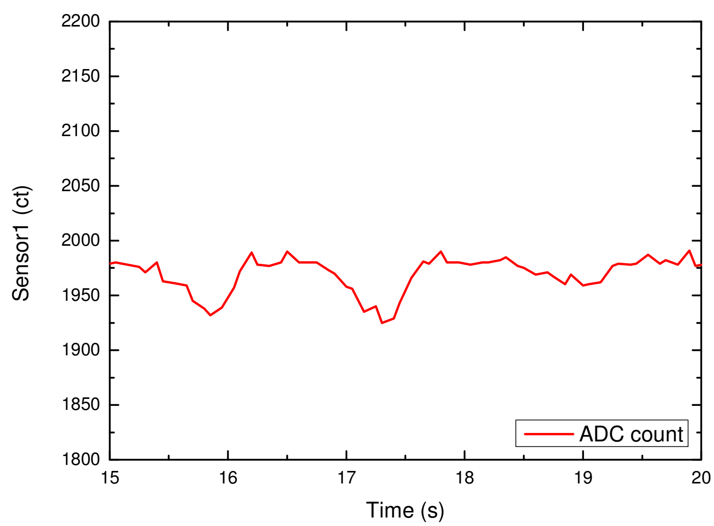

Figure 4.30 Response of a magnetic pen (20cm)

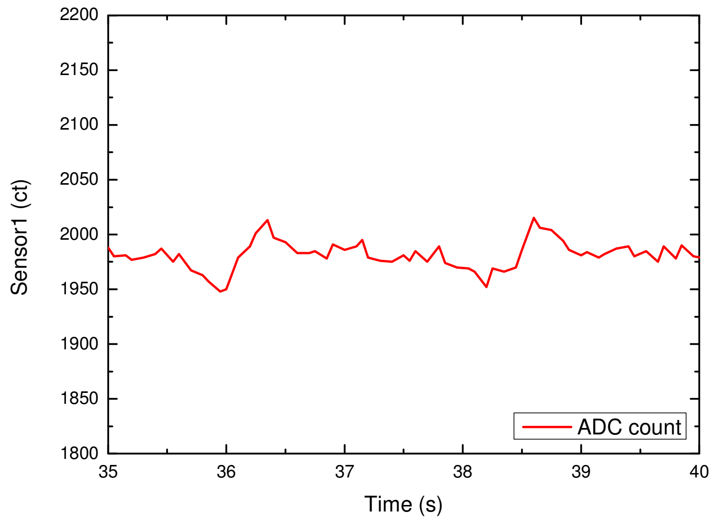

Figure 4.31 Response of a 60mm mortal shell (20cm)

Also shown in Figure 4.30 and Figure 4.31, the response of a magnetic pen and a 60mm mortal shell 20 cm away from the sensor have only about 50 ADC counts, which suggests the signal strength decays significantly with increased distance.

4.4. Summary

In this chapter, detailed design schemes of active and passive WSN node are given. Different MR sensors are chosen for active and passive detection systems. A detailed explanation of the corresponding circuits and components for the passive and active sensor nodes is also provided. Some preliminary data gathered with the wireless MR sensor is also presented which verifies the feasibility of the system design.

Chapter 5. Conclusion and future work

In this thesis, based on our understanding of WSN technology, a wireless magnetoresistive sensor network is designed to be used for UXO and landmine detection. Chapter 1 and 2 provided a brief background and introduction to UXO mine detection and WSN technologies followed by Chapter 3 that provided an overall system design of the passive/active WSN detection system as well as a detailed design of the wireless sensor node platform. Chapter 4 focused on the design and realization of the sensor node hardware.

This thesis also summarizes efforts toward hardware development for the active and passive WSN UXO detection system. A wireless sensor array is designed that is comprised of identical sensor nodes. The nodes utilize multi-hopping and are CSMA enabled and overall the system satisfied design criterion for UXO/mine detection system. The detailed overall system design and implementation plan is provided. The sensor node employs a modular design scheme. The detailed design requirement and realization of each module is given. A sensor platform based on the C8051F912 and Si4431 combination is presented. With the customized active or passive sensor module circuit, a passive/active WSN can be formed that cooperatively detects magnetic field anomalies caused by UXO or mines.

To the best of our knowledge, this work is the first effort utilizing WSN technology for UXO and mine detection. All the components used are off-the-shelf products. Due to time constraints, the project is still under development, additional testing is planned as a future activity.

The communication range of the sensor node platform is much less than handbook data. Improvements on antenna design, antenna matching network, and assembly technique are required to address this issue. With the sensor nodes assembled at the moment, it is impossible to test the robustness of the RF link of the entire WSN. Pilot production of the sensor nodes together with large scale WSN test bed are required to verify the effectiveness of the entire network. The WSN protocol has much room for improvement. As the scale of the WSN grows, it is possible that the current MAC protocol stack may not be able to provide sufficient system capacity (255 nodes per sink node). Clustered topology may be investigated and employed to solve this problem. Field testing of the passive/active UXO and mine detection system is required to verify the overall effectiveness of the system.

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