EEE3088F Design Project

Group 12

May 2020

Distribution Line Pole Monitor

Overview

The system outlined in this paper was designed to address the problem of undetected distribution line pole failure. This can be caused by many things such as corrosion due to exposure, car accidents, strong winds, etc. These failures lead to low- hanging power lines which can lead to serious injury or even death when people come into contact with them. Furthermore, there's the additional threat of property damage due to fires where low -hanging cables have broken insulation and no power breaks occur.

The proposed solution here is a pole monitoring system which can be mounted on top of each pole and make use of sensor data to determine the health of a pole and send an error message to the substation in the event of a fault.

Goals

1. **Measure** vibration, pole tilt, magnetic field and temperature information to determine the health of the pole.
2. **Generate** an error message when any of the parameters exceed the expected range.
3. **Transmit** error data to the substation via low power radio through a daisy chain.

Main Device Features

- Low-Power
- Low-Cost
- Able to transmit error data to substation within 10 minutes

Contributors to Final Design:

Low-power Wireless System:	***Contribution:***
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Micro-controller	***Contribution:***
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Power Supply	***Contribution:***
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Table 1: Group Contributions

End-User Specifications:

The end-user specifications for each subsystem are as follows:

System-Wide:

Lifespan - The system is required to have a lifespan of approximately 10 years and have a low maintenance requirement to avoid increasing costs.

Durability - Since the system would be placed outdoors, it should be rugged enough to withstand the elements (wind, fire, lightning, rain) for as long as the system is to remain on the pole.

Cost - The system is to cost no more than $25 (US).

Low Power Wireless:

Speed - This system is expected to have rapid transmission speeds such that any pole within range of the substation (50km) can have alerts sent from it in under 10 minutes via daisy-chain.

Range- The transceiver should should be able to transmit long and short messages over a distance of at least 400m in case a pole's sensor isn't working accurately,

Stability - Transmission stability is also a key consideration to minimize possible data loss/corruption

Cost- In order to not incur licensing fees, all data should be transmitted at ISM band frequencies. The cost of the whole system is subjected to 25$, therefore limited funding is available for the wireless communication aspect of the design.

Power consumption- Should consume the smallest amount of energy possible whilst being long range.

Micro-controller:

Speed - Needs to be able to process sensor data within a few ms to generate an error message as soon as a measurement is read to be beyond the specified threshold

Output Size - All data generated must be small enough (preferably no more than a KB to enable rapid transmission).

Security - Data should be encrypted to mitigate eavesdropping over the network.

Power Consumption - Should be able to put the entire system in “low power mode” to save energy when sensors do not read significant activity.

Diagnostics- Needs to generate a signal to be transmitted once in a specified time interval to check if each pole system is still operational otherwise an alert needs to be sent.

Memory - The microcontroller needs enough memory to temporarily store data for calculations without slowing down its processes

Compatibility - All devices should be compatible with the microcontroller

Flash Size - There needs to be sufficient on-board flash memory to save all the firmware

Power Supply

The system needs constant power to always be ready to receive readings from the sensors and taking the expected lifespan of the system, the power source would need to be somewhat renewable but also durability is a major concern.

A backup system is required in case there is a fault in the main system, and the power supply needs to have a large capacity for a low power system to run off for a long time.

Sensing

Accuracy:
All readings must be accurate and reliable as the sensors are responsible for obtaining all the input data.
Data:
Furthermore, the following data will be sufficient for determining pole faults:

Acceleration - This data will help determine whether or not the pole experienced unexpected movement, or moves in a direction that would clearly indicate a fault, i.e. the pole falling over
Vibration - This data can be used to check whether there was a break in the pole or if something collided with it. The data can be combined with acceleration data to determine if the pole has a fault and requires immediate attention
Temperature - The temperature can be used to detect any fires on the pole or in very close proximity to it. Time taken for a temperature increase can also be tracked to avoid false alarms, e.g we can measure a 10℃ increase over the space of one minute which is something that would likely be an issue.

Power Consumption - As data collection should be constant, the sensors should consume little enough power so as to not drain the supply.

Acceptance Test Procedures:

Low-Power Wireless:

Accuracy Test:

Generate a set of data and pass it through the low wireless network. Compare the packets that were sent to those that were received and a pass would be granted if the majority of the transmitted signal can be recovered and decoded accurately and without corruption. Doing the test in this manner will help discover any faulty transmitters.

Speed Test:

Similarly to the accuracy test, generate data to be passed through the network. If at any point within 50km, the transmitted signal takes longer than 10 minutes to reach the substation the test can be considered a failure. Otherwise, the speed test would pass.

Similarly, the propagation time between poles should also be considered. A pass would be if the signal is successfully transmitted within 1.2 seconds so as to achieve the target of reaching all poles within 10 minutes.

Microcontroller:

Accuracy Test:

To test for the accuracy in the calculations of the microcontroller, readings will manually be taken from the controller and fed into the firmware. The results will be compared to results obtained from manual calculation and if the results are within 1% of each other, a pass will be granted for the test.

Power Switching Test:

Since the microcontroller will be switching the system between low and high power modes repeatedly, it is important to know if modes are correctly switched between. To test for this, the power consumption by each device should be measured and then compared to the rated normal and low power operation modes and if the measurements do not agree with the rated values, the test is a failure.

Device Communication Test:

The connection between the other devices in the system and the microcontroller needs to be tested to see if data is transmitted properly. Individually trigger all the sensors using known parameters. If the values obtained by the controller do not fall within device rating or if no data is received by the controller the test is a failure.

Power supply:

No-load test

Test whether the power supply supplies the desired voltage output under various conditions with no load. This will use the energy directly from the solar panel. This will test if the panel is able to power the system directly from the sunlight during the day. A pass will be if the system is able to run in this manner for at least 6 hours.

Load test

Test whether the power supply supplies the desired voltage output under various conditions with the load. This test will be done with the energy directly from the batteries. This test will check the ability of the batteries to power the system when there is sunlight e.g in a rainy condition or during the night.

A pass will be granted for the uninterrupted power supply for at least 18 hours.

Sensing:

Accelerometer Sensor Test Procedures

To test the accuracy of the accelerometer a moving test rig must be used. This test rig must induce a known acceleration on the device consistently. The Acceleration measured by the device must be accurate to the rated sensitivity of the device.
If the Acceleration measured is not accurate to the rated sensitivity of the device the accelerometer fails the Acceptance Test Procedure.

Vibration Sensor Test Procedure

To test the vibration sensor a vibrating test rig must be used. The test rig must vibrate at a constant frequency and magnitude. This frequency and magnitude must be changed at set intervals both increasing and decreasing the frequency and magnitude.
The vibration sensor must be placed on the test rig and must record the values of frequency and magnitude of the vibrations to the device's rated sensitivity.
Should the device measure the frequency and magnitude accurately to the rated values the device passes the acceptance test. If it does not read accurately to the rated values the device fails the acceptance test.

Temperature Sensor Test Procedure

To test the temperature sensor, it must be placed in water that is being heated from 0°C to 100°C or the boiling point of water. This test checks if the sensor will detect the changes in temperature accurately and if the sensor will be able to withstand the higher temperatures.

If the sensor reads the temperature consistently as the temperature increases, then it passes the acceptance test. If the temperature measured does not correspond to the water temperature or the sensor fails to measure the temperature the sensor fails the acceptance test.

System-Wide:

Perform a scaled test of the real-world scenario. Apply triggers to the sensors, e.g heat to the temperature sensor, of known values and check if an alert is successfully generated. A pass would be granted if the system generated accurate alerts within time proportional to 50km in 10 minutes.

System And Design Overview

Central Objective:

The goal of the system is to detect any faults in the pole by measuring environmental data and comparing that to the expected ranges for the values. If any of the measurements is out of range, an error is generated and transmitted via a daisy-chain to the substation.

Design Approach:

The entire system comprises four subsystems with two team members per subsystem. The initial phases of the design were dedicated to obtaining the end-user specifications, acceptance test procedures, sub-system interface information and sub-system specifications. The remainder of the time was used to create a conceptual design to meet those requirements.

Structure:

The basic system structure is illustrated below

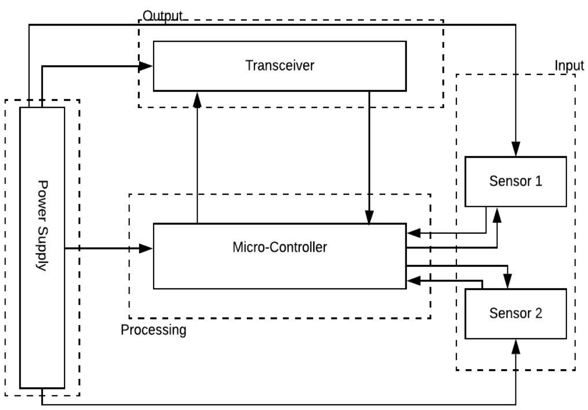


Figure 1: Block Diagram for the entire system

Cost Information

Item	Cost	Supplier
Sensing		
MAX6675	$1.00	Alibaba
LSM9DS1TR	$6.76	Digikey
Low-Power Wireless		
RMF95/96/97/98W transceiver	$4.30	HopeRF
Cable for antenna	$1.40	Takealot
Micro-controller		
Controller	$1.79	Mouser
Power - Supply		
Total Cost	*$9.73*	*see section for breakdown of materials
Total	*$24.98*	

Table 2: Costing information

Operation:

Interactions:

The sensors capture temperature, magnetic field, acceleration and gyroscopic and temperature data from the environment. At 10 second intervals, the microcontroller takes in the sensor data and checks if the measurements are within acceptable ranges. If any of the readings are outside the required threshold then an error message is generated and pushed to the transceiver which transmits the data to the next pole. In addition, a status message is sent out every 10 minutes to indicate whether the system is operational. Additionally when a signal is received from another device, the system takes in that signal and transmits it to the next device.

Interdependence:

All subsystems draw power from the power supply and the microcontroller handles data transmission throughout the system. Input data comes from the sensors and after processing data is sent as output via the transceiver. Data from the previous pole is also received via the transceiver and transmitted again.

Integration:

The on board data transmission will be done by the Serial Peripheral Interface (SPI) protocol. See the microcontroller section for more details.

Sensing

Temperature sensor

The temperature sensor we have chosen to use is the Digital MAXX6675 temperature sensor. This temperature sensor is a Type-K thermocouple to digital converter.

Accuracy

This version of the sensor has a measuring range of 0°C to +1024°C and a typical operating range of -20°C to +85°C. The Digital MAXX 6675 has cold junction compensation which aids the sensor in measuring more accurate readings. The sensor has an output of 12-bit resolution which resolves to 0.25°C increments. The optimal performance of this sensor is when both ends of the thermocouple are at the same temperature or close to it.

Sampling Rate

The intended sampling rate for this sensor will be a temperature check every 5 minutes. As this sensor is not required to operate constantly but rather check the environmental temperature periodically this will reduce power consumption and strain on the system.

Reason for using this sensor

This sensor is a good general-purpose thermocouple temperature sensor which can perform the required task easily. This sensor is also low cost and as this project is budget sensitive reducing the costs by using this sensor relieves stress in other areas that require more complex and expensive components.

Interfacing

The MAX6675 sensor has a simple 8 pin connection that can be used in conjunction with a µC as is needed. This device is SPI serial interface compatible. The pin set up and a connection set up can be seen in the figure below.

Typical Application Circuit

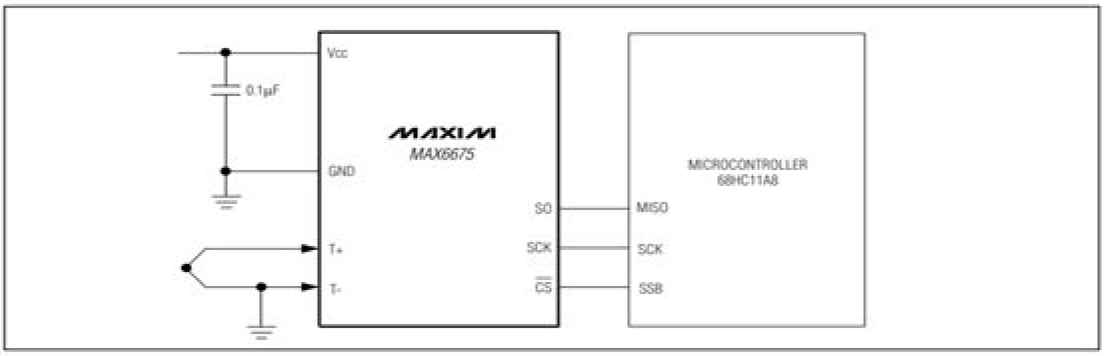


Figure 2: Recommended Configuration for SPI

Figure 3:Maximum Ratings

MAX6675

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

ABSOLUTE MAXIMUM RATINGS

Supply Voltage (V_{CC} to GND) .... -0.3V to +6V
SO, SCK, $\overline{CS}$, T-, T+ to GND .... -0.3V to V_{CC} + 0.3V
SO Current 50mA
ESD Protection (Human Body Model) .... ±2000V
Continuous Power Dissipation (T_A = +70°C)
8-Pin SO (derate 5.88mW/°C above +70°C) 471mW
Operating Temperature Range .... -20°C to +85°C
Storage Temperature Range .... -65°C to +150°C
Junction Temperature .... +150°C
SO Package
Vapor Phase (60s) .... +215°C
Infrared (15s) .... +220°C
Lead Temperature (soldering, 10s) .... +300°C

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

(V_{CC} = +3.0V to +5.5V, T_A = -20°C to +85°C, unless otherwise noted. Typical values specified at +25°C.) (Note 1)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Temperature Error		$T_{THERMOCOUPLE}$ = +700°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-5		+5	LSB
			V_{CC} = +5V	-6		+6	
		$T_{THERMOCOUPLE}$ = 0°C to +700°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-8		+8	
			V_{CC} = +5V	-9		+9	
		$T_{THERMOCOUPLE}$ = +700°C to +1000°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-17		+17	
			V_{CC} = +5V	-19		+19	
Thermocouple Conversion Constant					10.25		µV/LSB
Cold-Junction Compensation Error		T_A = -20°C to +85°C (Note 2)	V_{CC} = +3.3V	-3.0		+3.0	°C
			V_{CC} = +5V	-3.0		+3.0	
Resolution					0.25		°C
Thermocouple Input Impedance					60		kΩ
Supply Voltage	V_{CC}			3.0		5.5	V
Supply Current	I_{CC}				0.7	1.5	mA
Power-On Reset Threshold		V_{CC} rising		1	2	2.5	V
Power-On Reset Hysteresis					50		mV
Conversion Time		(Note 2)			0.17	0.22	s
SERIAL INTERFACE							
Input Low Voltage	V_{IL}					0.3 x V_{CC}	V
Input High Voltage	V_{IH}			0.7 x V_{CC}			V
Input Leakage Current	I_{LEAK}	V_{IN} = GND or V_{CC}				±5	µA
Input Capacitance	C_{IN}				5		pF

Accelerometer\Magnetometer\Gyroscope

The sensor chosen for this was the LSM9DS1TR STMicroelectronics, 3-axis Accelerometer, Gyroscope, Magnetometer, Serial-I2C, Serial-SPI, 24 Pin LGA.

This sensor was chosen as it seemed to be an appropriate fit for the quantities that we need to measure while staying within our budget. The LSM9DS1TR sensor is a combination of three, 3-axis digital sensors packaged in a plastic Land Grid Array (LGA). This means that its is a compact 24 pin sensor which can sense: accelerations of ±4g, a full-scale magnetic field of ±12 gauss and an angular rate of ±500 dps.

This sensor is also cost effective. As this project is intended for this overall system to be mass produced, if these sensors are bought in bulk (in multiples of 4000 units) it would merely cost R63.84 per sensor including Vat. The LSM9DS1TR also has an ideal operating temperature range, from -45°C to +85°C. This is ideal as South Africa has quite a large temperature range over the country throughout the year. In summer some areas can reach ±40°C and in winter some areas can reach ±(-10°C). As well as the sensors will be placed in a water proof, tamper-proof casing at the top of a power line pole in direct sunlight. This will result in an increased average operating temperature as the casing will absorb the sun's heat and re-radiate it onto the sensor for a longer period of time while increasing the internal temperature inside the casing as there is no airflow. Making the maximum operating temperature of +85°C extremely beneficial.

The LSM9DS1TR also features the I2C serial bus interface which has a standard mode, fast mode (100 kHz to 400kHz) as well as an SPI serial standard interface. It also has the ability to operate the accelerometer and gyroscope in power-down mode separately which allows for better power management of the whole system. The sample rate is 30 Hz, as this is very close to real time. It samples at this rate with a 16-bit accuracy and producing a digital output.

It is due to the features stated above, as to why the LSM9DS1TR was chosen. It provides us with all the features that are needed and it does this while being within our given budget.

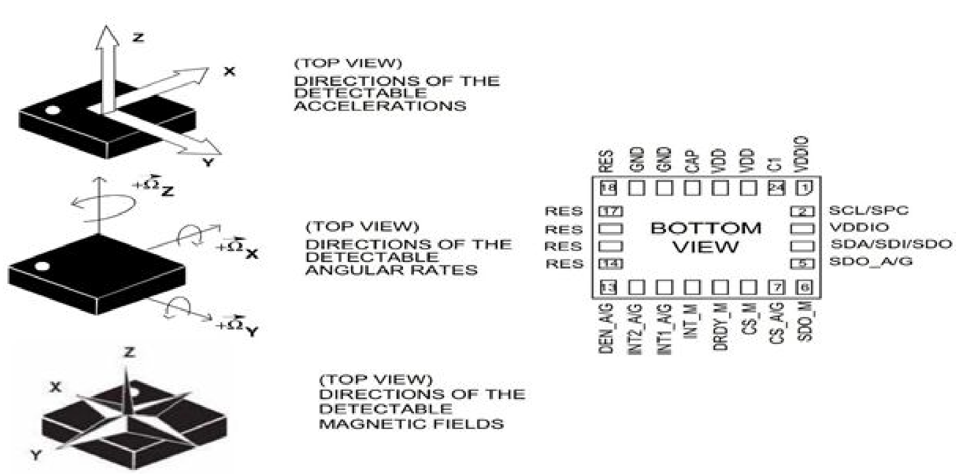


Figure 4: Pin Out

Pin #	Name	Function
1	VDDIO(1)	Power supply for I/O pins
2	SCL/SPC	I^2C serial clock (SCL) / SPI serial port clock (SPC)
3	VDDIO(2)	Power supply for I/O pins
4	SDA/SDI/SDO	I^2C serial data (SDA) SPI serial data input (SDI) 3-wire interface serial data output (SDO)
5	SDO_A/G	SPI serial data output (SDO) for the accelerometer and gyroscope I^2C least significant bit of the device address (SA0) for the accelerometer and gyroscope
6	SDO_M	SPI serial data output (SDO) for the magnetometer I^2C least significant bit of the device address (SA0) for the magnetometer
7	CS_A/G	SPI enable I^2C/SPI mode selection for the accelerometer and gyroscope (1: SPI idle mode / I^2C communication enabled; 0: SPI communication mode / I^2C disabled)
8	CS_M	SPI enable I^2C/SPI mode selection for the magnetometer (1: SPI idle mode / I^2C communication enabled; 0: SPI communication mode / I^2C disabled)
9	DRDY_M	Magnetic sensor data ready
10	INT_M	Magnetic sensor interrupt
11	INT1_A/G	Accelerometer and gyroscope interrupt 1
12	INT2_A/G	Accelerometer and gyroscope interrupt 2
13	DEN_A/G	Accelerometer and gyroscope data enable
14	RES	Reserved. Connected to GND.
15	RES	Reserved. Connected to GND.
16	RES	Reserved. Connected to GND.
17	RES	Reserved. Connected to GND.
18	RES	Reserved. Connected to GND.
19	GND	0 V supply
20	GND	0 V supply
21	CAP	Connected to GND with ceramic capacitor(3)
22	VDD(4)	Power supply
23	VDD(5)	Power supply
24	C1	Capacitor connection (C1 = 100 nF)

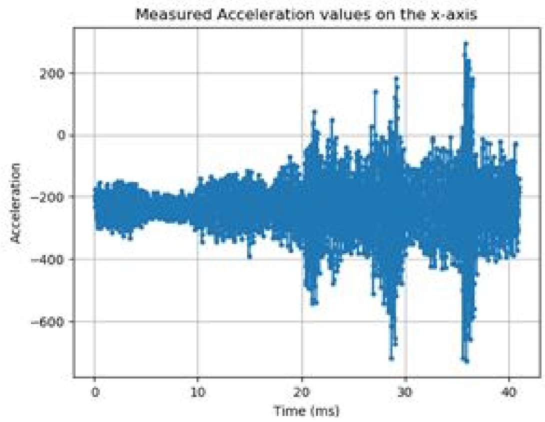
Figure 5: Pin description

Symbol	Parameter	Test conditions	Min.	Typ.(1)	Max.	Unit
Vdd	Supply voltage		1.9		3.6	V
Vdd_IO	Module power supply for I/O		1.71		Vdd+0.1	
Idd_XM	Current consumption of the accelerometer and magnetic sensor in normal mode (2)			600		µA
Idd_G	Gyroscope current consumption in normal mode(3)			4.0		mA
Top	Operating temperature range		-40		+85	°C
Trise	Time for power supply rising(4)		0.01		100	ms
Twait	Time delay between Vdd_IO and Vdd(4)		0		10	ms

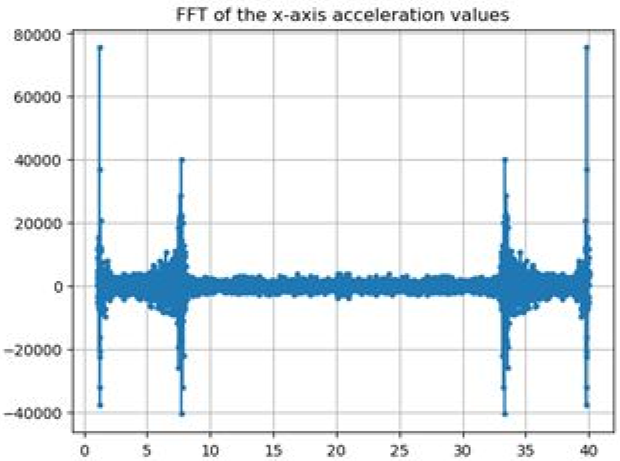
Figure 6: Max Ratings

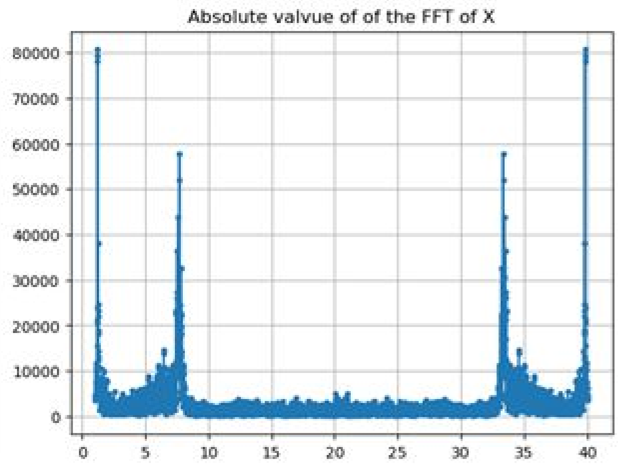
Single Axis Accelerometer Simulations

This figure shows the test samples of accelerations along the x-axis. The test samples were taken over a period of 40ms.



Below is the Fast Fourier Transform and the magnitude of the Fourier Transform function for the x-axis.





Low-power wireless

Introduction

The low-power wireless design is a crucial part of the system as it is responsible for the transmission of data across the individual devices. Low-power wireless communication and technology range from Bluetooth, to WIFI, to ANT, and to many others. Each technology has its own pitfalls as well as advantages, relating to power consumption, cost, physical size, range, and operating frequency. The technology chosen for this design is that of the Ultra-Long-Range(LoRa) transceiver modules. Namely, the RFM95 Ultra-long Range Transceiver Module.

Below are some of the key product features of the RMF95 transceiver:

- LoRa™ Modem.
- 168 dB maximum link budget.
- +20 dBm - 100 mW constant RF output vs. V supply.
- +14 dBm high efficiency PA.
- Programmable bit rate up to 300 kbps.
- High sensitivity: down to -148 dBm.
- Bullet-proof front end: IIP3 = -12.5 dBm.
- Excellent blocking immunity.
- Low RX current of 10.3 mA, 200 nA register retention.
- Fully integrated synthesizer with a resolution of 61 Hz.
- FSK, GFSK, MSK, GMSK, LoRa™ and OOK modulation.
- Built-in bit synchronizer for clock recovery.
- Preamble detection.
- 127 dB Dynamic Range RSSI.
- Automatic RF Sense and CAD with ultra-fast AFC.
- Packet engine up to 256 bytes with CRC.
- Built-in temperature sensor and low battery indicator.
- Modue Size：16*16mm

(HopeRF RFM95W datasheet, page 1)

Design Approach

Our design needed to feature a system which could communicate over long distances in a way that was inexpensive, unrestrained, and reliable and LoRa was the best option with all the constraints being put into account.

Protocol selection

LoRa is ideal for providing intermittent low data rate connectivity over long distances. The radio interface has been designed to enable extremely low signal levels to be received, and as a result even low power transmissions can be received at significant ranges.

LoRa technology key features:

-Long range

-Millions of nodes

-Long battery life: almost 10 years

In order to communicate with the microcontroller, a serial interface/protocol needs to be utilized. The desired protocol which is supported by the RFM95 Transceiver is the Serial Peripheral Interface. SPI is an interface bus that operates at full-duplex, allowing for simultaneous receiving and sending of data. Therefore, it is known for its high synchronous data transfer speeds.

SPI communicates through 4 ports:

- MOSI – Master Output-Slave Input
- MISO – Master input-slave output
- SCLK – Serial Clock, (by master device)
- NSS/CS – Slave enabled signal or Chip select

8 bits of data are transmitted individually subjected to the slave enabled signal and shift register pulse of the master device. The most significant bit (MSB) comes first and the least significant bit (LSB) last.

The protocol of SPI is relatively simple compared to protocols such as I2C where slave addressing systems are more complex. Furthermore, SPI is faster than both I2C and UART. Moreover, data is transferred continuously as there are no start and stop bits, which cause interruptions. Lastly, separate MOSI and MISO allow for bi-directional data transmission, which is a huge advantage.

A pitfall of using SPI is that it uses many physical pins and four communication lines. However, this is not a problem for this design.

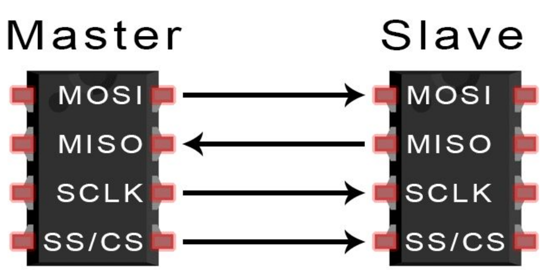


Figure 7: A general master-slave protocol
(Basics, 2020)

Range and signal Propagation

Receiver and Transmitter Gain

Using Friis Transmission formula you can determine the amount of gain to maintain communication range. This formula only holds for free-space propagation but it gives us a good overview of the importance of antenna gain for ensuring the maximum received to transmitted power.

$$\frac{P_r}{P_t} = \frac{c^2 g_t g_r}{(4\pi f)^2}$$

$P_r \equiv \textit{received power}\,[W]$

$P_t \equiv \textit{transmitted power}\,[W]$

$c \equiv \textit{speed of light}\left[\frac{m}{s}\right]$

$g_t \equiv \textit{transmit antenna gain}\left[\frac{W}{W}\right]$

$g_r \equiv \textit{receive antenna gain}\left[\frac{W}{W}\right]$

$f \equiv \textit{cyclic frequency}\,[Hz]$

$r \equiv \textit{communication range}\,[m]$

Figure 8: Relationship between gain and range

(Antenna Design Gain and Range, 2020)

Furthermore, antenna gain can be related to physical size. The relationship below depicts this, where A is the antenna area, g is the gain and λ is the wavelength.

$$A = \frac{g\lambda}{4\pi}$$

(Antenna Design Gain and Range, 2020)

Antenna power gain is also achieved by focusing the antenna. To increase our signal power, we focus our antenna in the direction needed. This gives us a relationship between the gain which is defined as the antenna’s electrical efficiency multiplied by its directivity.

Models for signal transmission

Path loss models are used to analyze the way in which signals are degraded due to distance. Signals cannot be reconstructed if they are too degraded. In a simplified model, the energy at the receiver is proportional to the distance squared between the receiver and transmitter.

However, this model ignores refraction and absorption effects, meteorology, temperature as well as multipath interference. Moreover, objects in Urban areas may block the signal path causing it to scatter.

Our design was made for rural areas so this may be less of a problem. A more accurate model is the Rayleigh fading model which assumes that transmission channels are distributed randomly via a Rayleigh distribution. This model helps to account for signal interference in urban areas.

Bit-Error-Rate

The BER refers to the number of errors for a unit time. It can also be described as the probability of an error. The BER can be reduced in the following ways:

Reduced Bandwidth: Due to this we will receive lower interference and lower noise levels. Therefore, this system's signal to noise ratio will be improved. The pitfall of this is that it results in a reduction of data throughput.

Increased transmitter power: This increases the power per bit. The limitations of this is that we are operating within the ISM band and have a power consumption budget.

Lowering the order modulation: This comes with a cost of data throughput.

Link Budget and Signal Amplification

The link budget needs to be high for us to be able to send messages between neighboring sensor nodes, taking into account all the obstacles that may be in between the poles.

This should be possible in both rural and urban areas. If the link budget is used up we won't be able to relay messages between the poles and the next receiver will just receive noise. The RMF95W has a link budget of 168dB.

The antenna on the sensor transmits data to a communication device attached to a nearby utility pole and to make the antenna(reducing costs) , we can use antenna cables and the length of the antenna was calculated to be 8.2cm for a frequency of 868Hz which is the allowed frequency in SA by the LoRa alliance.A wire antenna would be better to use than a coil antenna as it has an RSSI of -50 when tested. Follow the link (https://www.youtube.com/watch?v=8SfKb0d9z0M&list=PLmL13yqb6Oxc3FvWz4XewMl8OXsV5iqON&index=6) to see how tests were conducted. The transceiver is attached to the antenna feed via a connector. That connection is usually a BNC or SO-239 type connector on the transceiver.

The RFM95W has 3 power amplifiers. Two of those, connected to RFO_LF and RFO_HF, can deliver up to +14 dBm, are unregulated for high power efficiency and can be connected directly to their respective RF receiver inputs via a pair of passive components to form a single antenna port high efficiency transceiver.

The 3rd PA, is connected to the PA_BOOST pin and is able deliver up to +20 dBm via a dedicated matching network.(HopeRF RFM95/96/97/98W datasheet , page20)

Power Consumption

The supply voltage of the RMF95W is 3.3V. We needed to choose a transceiver that had a good bandwidth (125kHz) and consumed very little energy as we do not have a lot of power with the batteries. The transceiver has multiple modes of operation shown in the table below taken from (HopeRF RFM95/96/97/98W datasheet , page15). Table labelled table 51.

Symbol	Description	Conditions	Min	Typ	Max	Unit
IDDSL	Supply current in Sleep mode		-	0.2	1	uA
IDDIDLE	Supply current in Idle mode	RC oscillator enabled	-	1.5	-	uA
IDDST	Supply current in Standby mode	Crystal oscillator enabled	-	1.6	1.8	mA
IDDFS	Supply current in Synthesizer mode	FSRx	-	5.8	-	mA
IDDR	Supply current in Receive mode	*LnaBoost* Off, higher bands *LnaBoost* On, higher bands Lower bands	- - -	10.8 11.5 12.1	- - -	mA
IDDT	Supply current in Transmit mode with impedance matching	RFOP = +20 dBm, on PA_BOOST RFOP = +17 dBm, on PA_BOOST RFOP = +13 dBm, on RFO_LF/HF pin RFOP = + 7 dBm, on RFO_LF/HF pin	- - - -	120 87 29 20	- - - -	mA mA mA mA

Figure 9: Maximum Ratings

In transmit mode power consumption is optimized by enabling RF, PLL and PA blocks only when packet data needs to be transmitted and the sequencer ensures that very little time is spent in this mode which also helps with power consumption.

When the radio is in standby mode, power consumption is reduced.

The transceiver has the ability to fill and empty the FIFO in Sleep/Standby mode, therefore ensuring maximum power consumption and adding more flexibility for the software.

The RFM95W transceiver has packet filtering which makes sure that only useful packets are made accessible to the uC, this lowers the system’s energy use.

In listen mode, the transceiver stays in Low Power mode(LPM) most of the time which results in very low average power consumption.

Message/Packet Designs

Messages travel from the sensor node - gateway - cloud- substation. One gateway can have multiple can be used by many sensor nodes. Our transceiver should be able to send messages between 4-10 kb/s and local messages which are unique and have a 16-bit sensor node ID number as well as an 8 bit number representing the distance from our sensor node to the gateway.

Spreading factor

Symbol rate is the speed at which information is sent.The spreading factor is (nominal symbol rate/ chip rate) and represents the number of symbols sent per bit of information. Lower spreading factor means data is transmitted faster.(HopeRF RFM95/96/97/98W datasheet , page24)

Coding Rate

To improve the quality of the link, LoRa utilizes cyclic error coding to perform forward error detection and correction. Such error coding incurs a transmission overhead. The higher the coding rate the faster the transmission (HopeRF RFM95/96/97/98W datasheet , page24)

Signal Bandwidth

Higher signal bandwidth allows the use of a higher and efficient data rate, this in turn reduces time of transmission but this will reduce sensitivity. (HopeRF RFM95/96/97/98W datasheet , page25)

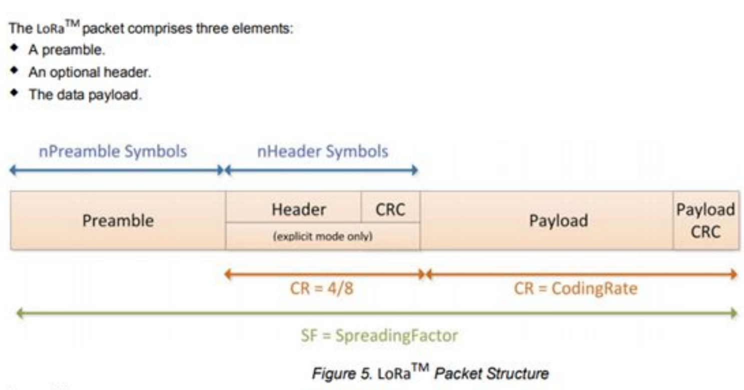


Figure 10: Packet Structure

The preamble (length is 12 symbols) is used to synchronize the receiver with the incoming data flow.The header gives us information such as the payload length(64 bytes) and forward error rate. The actual data coded at the error rate is contained in the payload.

Hardware Design

The RFM95 Transceiver module is a 65mm x120mm x1.8mm component which weighs 2 grams.The component has a built-in low battery indicator and temperature sensor. It also has a completely integrated synthesizer. Moreover, it contains a bit synchronizer. The component has absolute maximum temperature ratings of -55 and +115 degrees Celsius. Also, maximum supply voltage ratings of -0.5V and 3.9V.

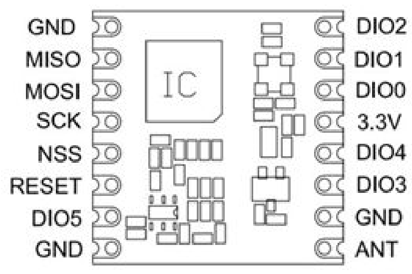


Figure 2. Pin Diagrams

Figure 11: Pin Configure

The component has 3 ground(GND) pins and 1 3.3V supply pin. It has a MISO and MOSI pin for SPI Data input and output. It also has an SPI clock and SPI chip select.

These pins are connected to the microcontroller as shown below.

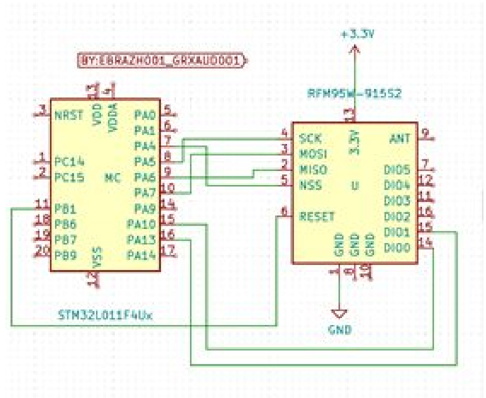


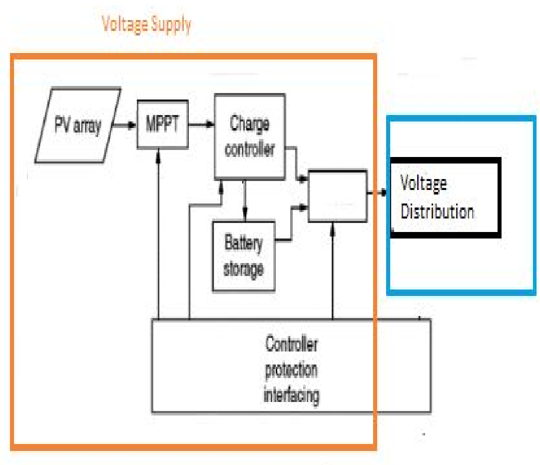
Fig 12: Connection between the RFM95 and STM32LO11 microcontroller

The component also has an ANT pin which is used for direct connection to an external antenna.Lastly, the component has a reset pin as well as many Digital I/O pins.

Power Supply System

Off-grid PV-Battery power supply system

For this system usage, an off-grid PV-battery system was chosen. It complements the lower power, durability requirements of the system by providing a 12V solar panel. This draws solar energy and supplies current to the power supply subsystem. The voltage is transferred and regulated to then supply a 6V 2500 mAh battery. The battery voltage is then distributed amongst the peripheral subsystem. Figure 13 below illustrates how the overall system works, the system is divided into a voltage supply system and voltage distribution system. Figure 14 illustrates the details on the power supply system



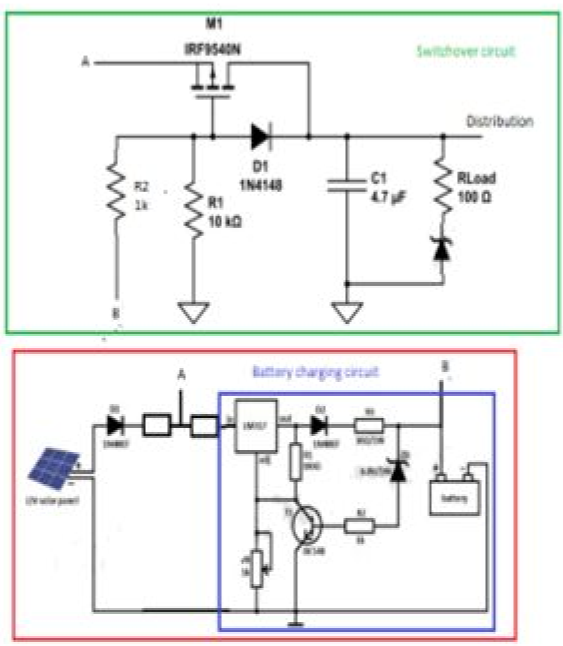


Figure 13: Voltage supply circuit block diagram

Figure 14: Power supply Circuit

Supply System

Battery charger circuit

The circuit uses a 12V solar panel and a variable voltage regulator Integrated Circuit, model LM 317.

The solar panel consists of solar cells each rated at 1.2 volts.

12 volt DC is available from the panel to charge the battery. Charging current passes through D1 to the voltage regulator IC LM 317. By varying the Adjust pin, output voltage and current can be regulated.

VR is placed between the adjust pin and ground to provide the battery with an output voltage of 6V. Resistor R3 Restrict the charging current and diode D2 prevents the discharge of current from the battery.

Transistor T1 and Zener diode ZD act as a cut-off switch when the battery is fully charged. Normally T1 is off and the battery gets charging current. When the terminal voltage of the battery rises above 6.8 volts, Zener conducts and provides base current to T1. It then turns on grounding the output of LM317 to stop charging.

Changeover circuit:

The purpose of this circuit is to create a switchover in voltage between the battery and a voltage point. In this case, it will provide an easy way to switch between the battery voltage and that of the peripheral subsystem connected to it. It switches between power source and battery. When the power source is absent, then the battery will act as the power source for the load. Figure 13 shows a diagram of the circuit. In this context, the pMOSFET device acts as a switch; while the PV panel is receiving sunlight(when V1is on), the pMOSFET is off, the battery is being charged and the load receives power directly from V1. When V1 is off, the pMOSFET switches on and the load receives power from the battery. This circuit allows a switch between the battery and PV panel providing power to the system.

Battery selection

9V 650mAh lithium-ion rechargeable battery. High-grade cells guarantee long storage lifespan. Provides very long use time per charge with high capacity. Convenient operation without memory effect, can be charged anytime. Protect circuit board inside. Enhanced performance designed for high drain applications, such as R/C controller, smoke alarms, detector, transmitter, professional audio, medical devices etc. The circuit requires about 10mA supply current, the battery will last for about 65 hours(2 and a half days) with this current, this will be able to compensate the 6 hours that it will take to charge the battery daily. The circuit design will also automatically control how the battery charges and will not overcharge the battery when it is full, thus leading to a longer life span of the battery.

Power Management design and Device selection

Power supply budget/summary table

Systems	Voltage range	Typical/chosen voltage	Current range	Typical/chosen current
Microcontroller	1.8 - 3.6 V regulated	2 V regulated	any	3mA
Low-Power wireless sys	0 - 3.9 V	3.7 V	any	3mA
Gyro(magnetometer)	2.2 - 3.6 V	2.5 V	any	3mA
Temperature Sensor	3 - 5.5V	3.2 V	0.7 - 1.5mA	0.7mA
Accelerometer	1.2 -3.6v	2.4 V	1 -130 microA\	0.05mA
Total	8.2 - 20.2 V	appr. 13.8V External voltage		9.75mA

Table 3: Power Supply Budget

Simplification due to similarities and external circuit supply

Subsystems	Voltage
Microcontroller	2V regulated
Magnetometer and accelerometer	2.4V regulated parallel voltage supply
Temperature sensor and Low -Power wireless system	3.5V regulated parallel voltage
Total	7.9V

Table 4: Simplification due to similarities and external circuit supply

The 9V battery supply power supply a 12V solar supply will compensate for this

Distribution system

The distribution circuit will get power from the power supply circuit then distribute the power to the different subsystems using voltage regulators. R1, R2 and R3 are voltage dividers resistors to distribute power to voltage regulators

R4 = 667 Ohm , R5 = 800 Ohms , R6 = 48000 Ohms ,R7 = 200 Ohms , R8 = 1166 Ohms

R_A = 2k , R_B = 4k , R_C = 3k , R_D = 3k

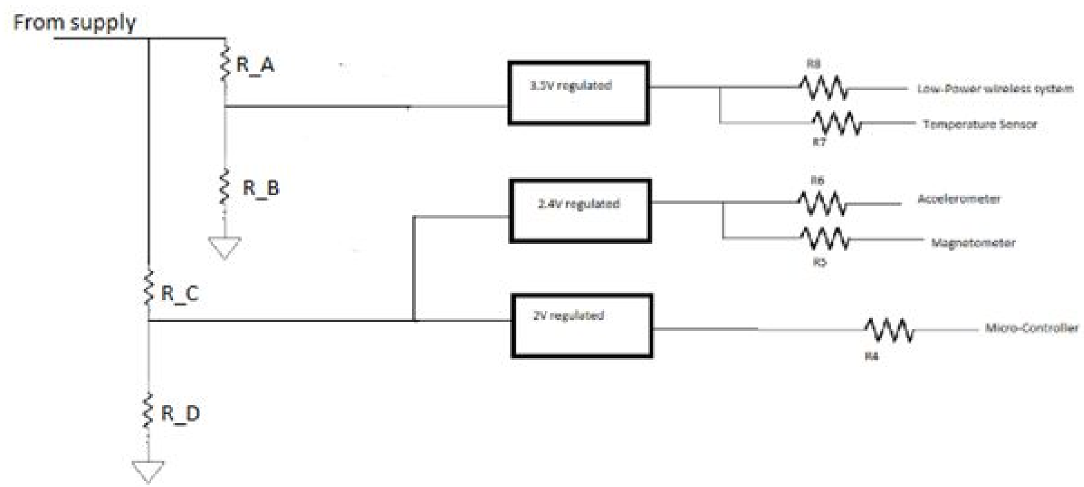


Figure 15: Distribution System

Operating conditions of the Supply System

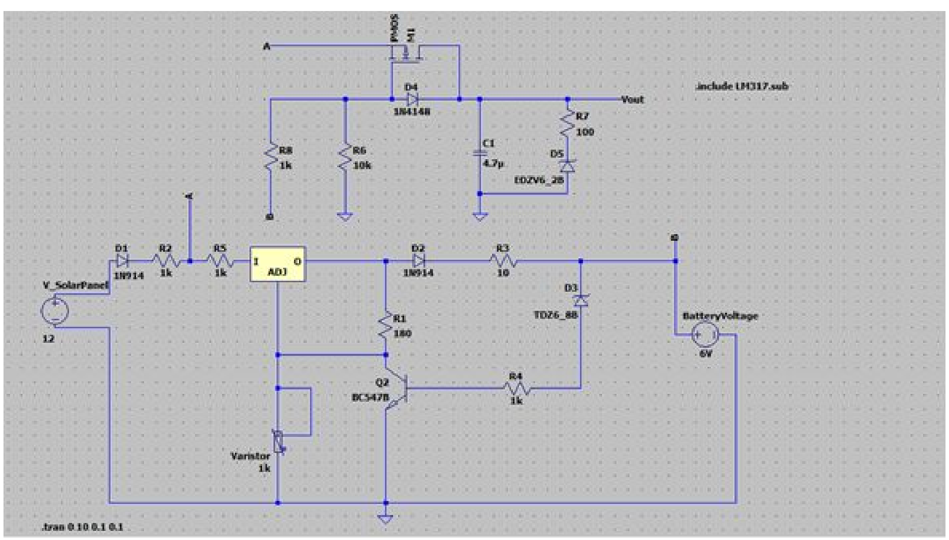


Figure 16: Power Supply Citcuit

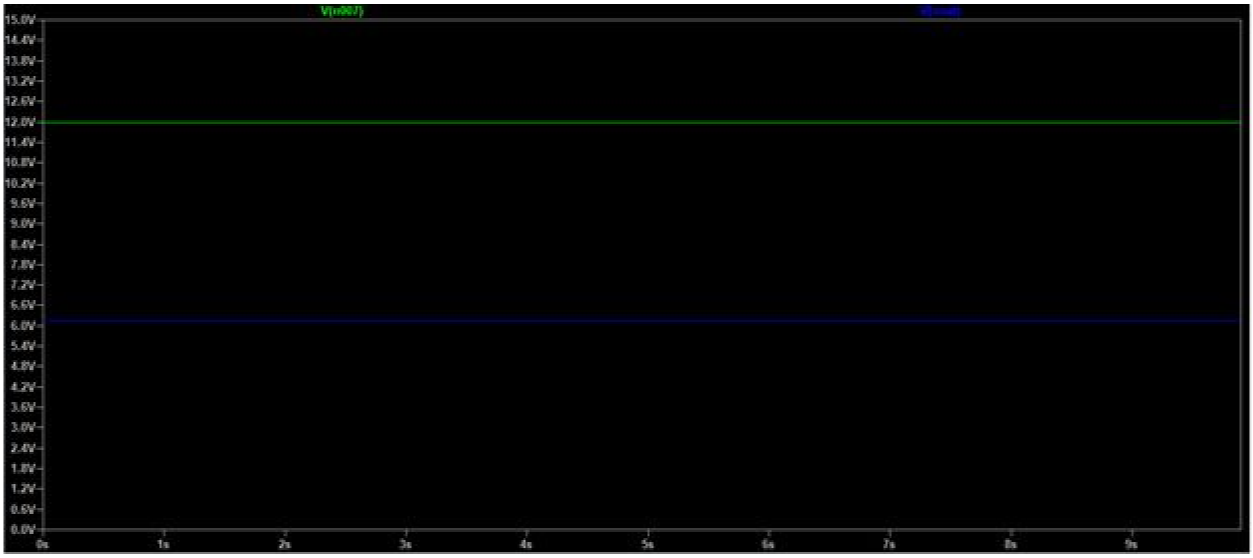
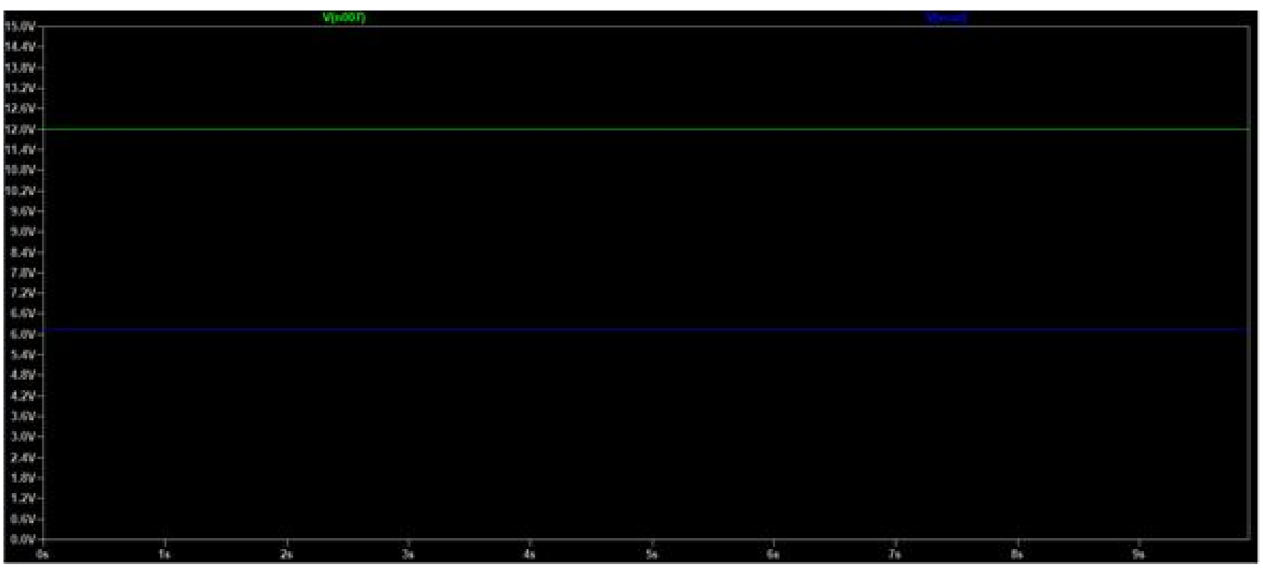


Figure 17: Vout Simulation when Both PV and Battery are on

Test cases

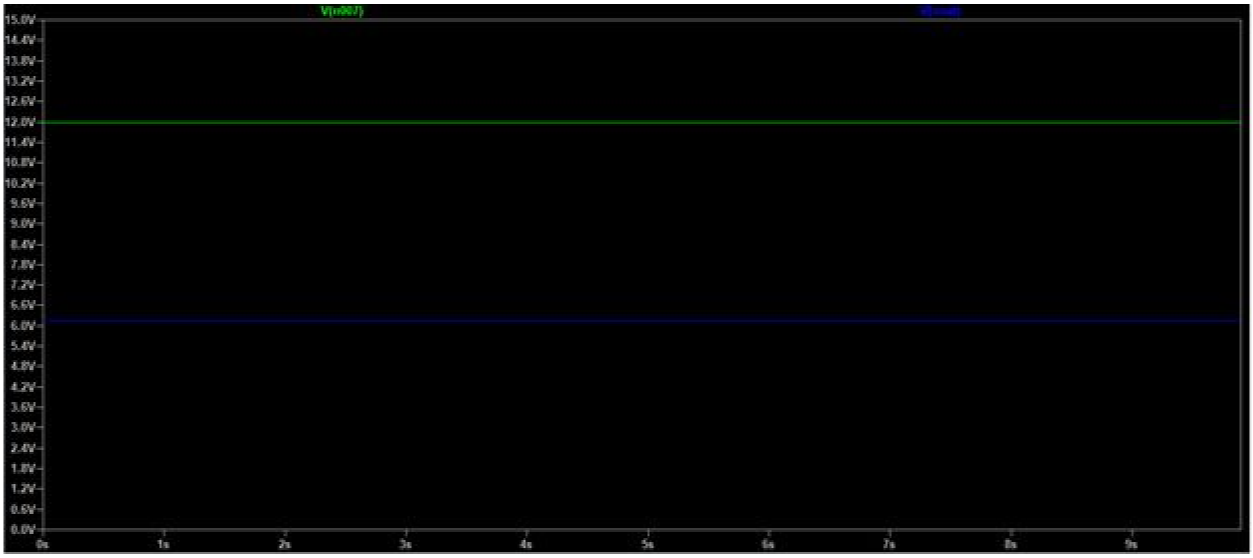
*1) **Supply from PV simulation (No load simulation)***

This is when the battery is discharged and power is coming directly from the PV panel. Essentially there is a short across the battery “BatteryVoltage”:



2) *Supply from the battery (Load simulation)*

This is when the battery is fully charged and power is coming directly from it. Essentially there is a short across the PV panel "V_SolarPanel":



Vout is kept at 6V even after the solar panel stops providing power (when there is no solar energy)

Cost analysis

Component	***Price***
Resistors: 10 1001805x 1k, 10k	*R0.38 x 9 = R3.42*
LM317 Voltage Regulator Circuit	*R42.26*
2 x 1N914, 1N4148, EDZV6, TDZ6 diodes	*R0.43 x 5 = R2.15*
PV solar panel	*R73.55*
Battery	*R50.00*
Total	*R171.38*

Table 3: Cost Breakdown For Power supply

Micro-controller

Device Selection:

Based on the user requirements the following key specifications have been identified:

Power Supply:

For this particular use case, we would want a low power device that can run at voltages of around 1.8V

Operating Temperature:

The controller should be able to function at high enough temperatures to still be able to send a signal at high ambient temperatures (e.g. in the event that a fire is detected).

Low-Power Mode:

The device needs to be able to enter an ultra low power mode when sensor data is not being read, processed, or sent to the transmitter

Efficient On-Board Communication:

The choice to make use of SPI was made from the following:

A faster protocol would mean that the data retrieval time can be reduced thus we can minimise the active time of the system. Furthermore, a bus type communication protocol would be preferable since we can interact with multiple sensors almost simultaneously.

SPI was chosen, since even though it requires more pins, it has a higher speed when compared to protocols such as UART or I2C and also allows for a full-duplex configuration[Basics, C., 2020]. In addition, SPI will be preferable for the user requirements since the current is only drawn when data is being transferred so the power consumption is less than in I2C for example [McCreary, 2020].

Clock Speed:

The clock speed does not need to be particularly high for the required application. Furthermore having a lower clock speed can further reduce power consumption. Ideally, this would be around 32MHz at most, but controllers that can efficiently work with slower clock speeds can still be suitable for the application.

Available Memory:

Large flash memory is not required since the only data that is physically stored on the device would be the software for operation. All generated sensor data is immediately transmitted to the substation. In terms of RAM, there is not a particularly high requirement for this as we do not expect to work with large amounts of data at a time.

Interfaces with other systems:

Where devices return analogue signals we could need an ADC to obtain a digital signal to work with.

From all the above specifications and requirements, the **STM32L011F4** was chosen. Key features include:

1. Cost: USD1.79 {STM32L011F4P6 STMicroelectronics | Mouser, 2020}
2. Power Supply: 1.65 - 3.6V
3. Operating Temperature: -40 to 125 ℃
4. Low-Power run: current drawn is down to 7μA
5. On-Board Communication: SPI Is available
6. Supports external clock speed of 0 - 32MHz
7. Memory: 16KB Flash, 2KB RAM
8. 12-Bit ADC

The above was taken from page 1 of the datasheet

Operating Modes

The STM32L011F4 has eight operation modes in total [datasheet page 14], however for the current application two of them are to be considered:

1. Run/Active Mode
2. Low-Power Run

Run/Active Mode:

Here the controller is operating at its full capacity. It is drawing the maximum current and all peripherals are enabled. The system is only expected to operate in this mode when an interrupt is received from the transceiver. This mode will be utilised to minimise the time spent handling the interrupt so as not to cause too much of a drift in the timing of normal run events.

Low-Power Run:

Here, the number of enabled peripherals is limited and so is the clock speed. Data will be captured from the sensors and checked. If reading is beyond a specified threshold, the run mode is switched to active to speed up generating the error signal. If everything is fine, then the controller sends a signal to the next one every 10 minutes indicating its status. We expect to check each sensor every 10 seconds. This will allow us to observe any alarming changes within a short time

Current Consumption

Run/Active Mode:

Current consumption is around 128μA/MHz. With the clock running at 16MHz, active current consumption is at 2.048mA[datasheet page 18].

Low-Power Run:

Current consumption down to 7μA[datasheet page 18].

Real-Time Design

Normal operation:

In its normal operation the controller will :

- Obtain the temperature data from the sensor
- Obtain accelerometer/gyroscopic data in all 3 axes
- Obtain magnetometer data in all 3 axes
- Check values against expected thresholds
- If any reading exceeds a threshold value, generate an error message
- Transmit the data to the next pole
- Send a status message every 10 minutes just to determine if everything is operational

Interrupt Handling:

The interrupts will be obtained from the transceiver whenever a signal has been received. On interrupt the following will happen:

- The controller will switch to active mode so as to minimise the disruption of the normal operation.
- The received signal will be taken from the transceiver
- The data will be re-transmitted to the next pole
- The controller will switch back to low-power run

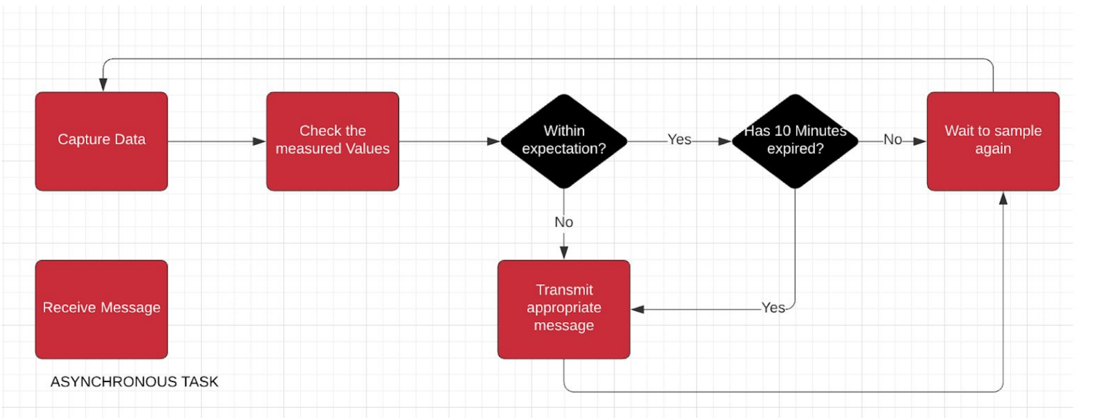


Figure : Real time design layout

Schematic

See Appendices, Microcontroller Appendix 3

Pseudo Code Design

Looking at the role of the microcontroller in the system four functions were identified, namely:

1. Device setup, i.e. initialising all the ports on the controller and establishing on-board communication.
2. Switching between operation modes to reduce power consumption.
3. Retrieving and Processing Sensor Data
4. Receive and transmit data to the next pole

The general processes for each function are defined below.

Device Set-Up

```
Function toInitialize_GPIOPins(void){
        //make PA7 an input
        //make PA6 an output
        // enable clock for press buttons
        // enable internal pull-up resistors
        // enable the SPI pins on the controller

}
```

Switching Between Operation Modes

The system is expected to operate in low power mode for the majority of the time so that power consumption can be reduced. Functions defined below.

```
Function toActive(){
        //Trigger wake up
}

Function toLow(){
        //this will be called at the end of the interrupt handling of the interrupt
        //activate low-power run
}
```

Retrieving and processing sensor data

```
Function void loop()
//Runs over and over again and processes sensor data each time
delay(10)//data is obtained from the sensors at 10 second intervals
{
Function to Retrieve_Temp_data()
{
 //gets data from the temperature sensor and stores it in an integer variable.

If (temperature <=300C)
        //check to see how much the temperature increase from the previous reading
        If that increase was smaller than 5  degrees we don't proceed to generate an error , this will help detect fires
        Otherwise
        Output = OK
Else
        Output = error message
Function to Retrieve Magneticdata()
{
 //gets data from the magnetometer and stores it in an array
//checks if the x,y and z values are within the expected magnetic field range
```

```
If (true)
        Output = OK
else
        Output = error message

}}
Function to Retrieve Acceleration_data()
{
 //gets data from the accelerometer and stores it in an array
//compare the new values to the new ones and check if there was a difference greater than 1G acceleration
If (withinRange)
        Output = OK
else
        Output = error message

}}
```

Transmit and receive data from to and from other poles

```
Function encrypt(){

//this function is to encrypt the message using a key common to all the devices in the chain

//returns the encrypted string

}
Function handleReceive_IRQ(){
toActive();
//get the data from the necessary registers in the transceiver module
Data = fetchedData;
//push the fetched data for transmission
pushToTransmit(Data)
}
Function pushToTransmit(string message){
        Takes the data and writes it to the transceiver for transmission
        // this function is automatically called every 10 minutes as a status check
        // also called whenever the sensors data has been evaluated as beyond threshold

}

Function generateMessage(bool type){
//Function to be called whenever there is a message that needs to be sent to the next pole
        if type is true{
                //this means everything is okay and this is meant to be sent every 10 minutes
                pushToTransmit(encrypt("Status: OK"));
        }else{
                //fault was detected
```

```
            pushToTransmit(encrypt("Status: Fault Detected!"));
        }

}
```

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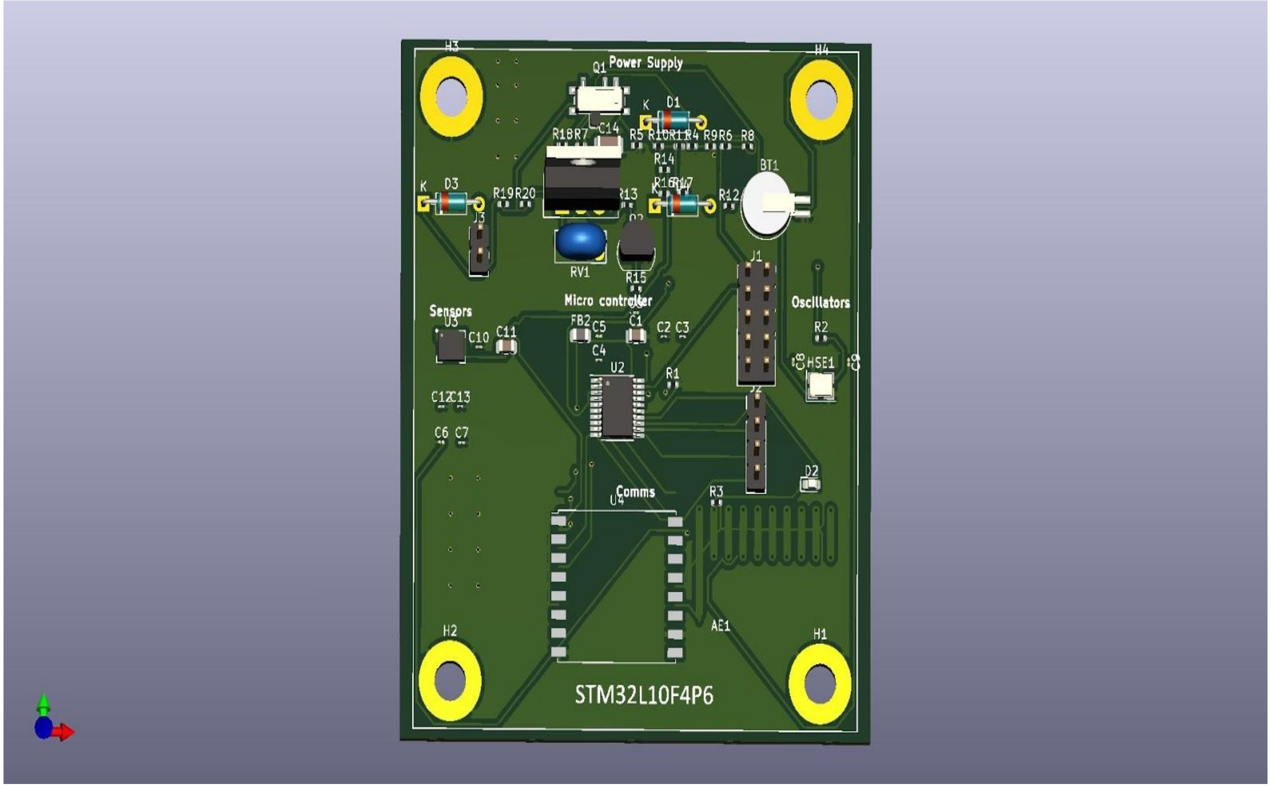
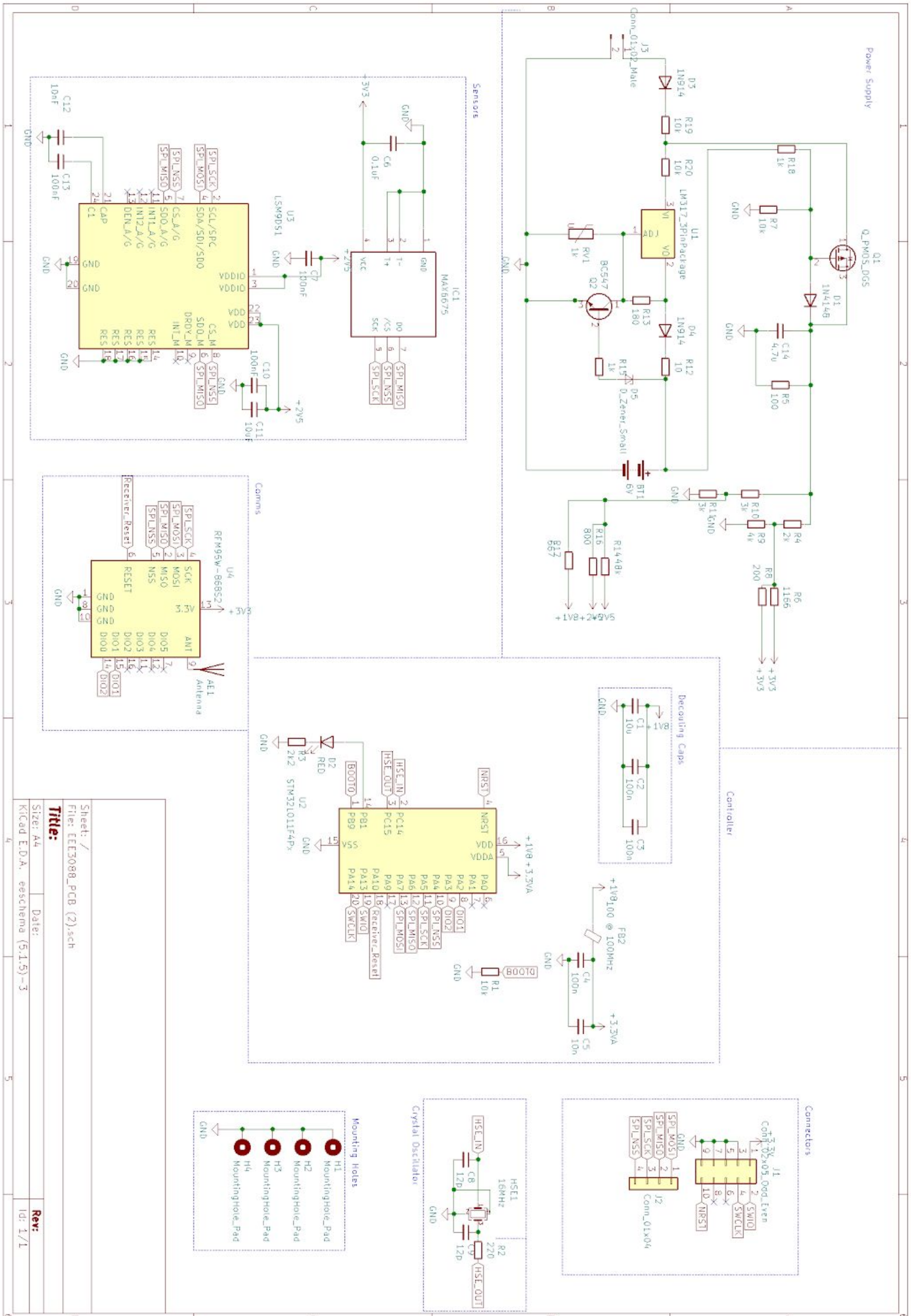
Appendices

Microcontroller



Appendix 1: PCB Connections



Appendix 2: Schematic

Sensing

Code for the simulations

```
using XLSX

using PyPlot

using FFTW

using Statistics

xf = XLSX.readxlsx("Pole measuremnet data EEE3088.xlsx")

XLSX.sheetnames(xf)

sheet = xf["Sheet1"]

time = sheet["A2:A4097"]

x1 = sheet["B2:B4097"]

x = convert(Array{Int64}, x1);

X = fft(x);

abx = abs.(X)

angx = angle.(X)

figure()

grid()

title("Measured Acceleration values on the x-axis")

xlabel("Time (ms)")

ylabel("Acceleration")

plot(time,x,".-");
```

```
figure()

grid()

title("FFT of the x-axis acceleration values")

plot(X[100:4000]);

figure()

grid()

title("Absolute valvue of of the FFT of X")

plot(abx[100:4000]);
```