Luleå University of Technology

Dept. of Computer Science, Electrical and Space Engineering

Master Thesis Engineering Physics and Electrical Engineering *VHF-Unit*

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Abstract

Surveillance and control has come a long way the last years. Every new mobile phone, most cars and smart watches have a Global Positioning System (GPS) tracing device built in to it. Today it is hard to go anywhere without there beeing some sort of way of finding you. The art of finding has been around for a long time and one company that have taken the tracking aspect to the next step is Followit. For over 40 years they have built different types of sattelite and radio transmitters to keep track of everything from small animals like hares and dogs to big elephants. They also got tracking solutions for vehicles like trucks and excavators.

Preface

I would like to thank the personal at Followit to taking me in and helping me through the project time. A special thanks to Bengt for his supervision and help.
A big thanks goes to my supervisor Jonny Johansson at LTU for his support and guidance in the project.

Josef Lundberg
Lindesberg, May 22, 2018

Contents

0.1 Acronyms

1. **ADC** Analog-to-digital converter *Glossary:* ADC
2. **CAD** Computer-aided design *Glossary:* CAD
3. **DRC** Design Rule Check *Glossary:* DRC
4. **ERC** Electronic Rule Check *Glossary:* ERC
5. **GPIO** General Purpose Input Output *Glossary:* GPIO
6. **GPS** Global Positioning System 1, *Glossary:* GPS
7. **I^{2}C** Inter-Integrated Circuit *Glossary:* I^{2}C
8. **IC** Integrated Circuit 2, 9, *Glossary:* IC
9. **IMU** Inertial Measurement Unit 11, *Glossary:* IMU
10. **IPC** Institute for Printed Circuits *Glossary:* IPC
11. **JTAG** Joint Test Action Group 16, *Glossary:* JTAG
12. **LDO** Low-dropout regulator 11, 19, *Glossary:* LDO
13. **LED** Light-emitting diode *Glossary:* LED
14. **LGA** Land Grid Array *Glossary:* LGA
15. **LIB** Battery Management System *Glossary:* LIB
16. **MCU** Microcontroller Unit 9, 11–13, 16, 20, *Glossary:* MCU
17. **NAME** Personal Computer 20, *Glossary:* PC
18. **NMEA** National Marine Electronics Association standard *Glossary:* NMEA
19. **PCB** Printed Circuit Board 4, 16, 21, 26, *Glossary:* PCB
20. **PNG** Portable Network Graphics *Glossary:* PNG
21. **PTC** Positive Temperature Coefficient *Glossary:* PTC
22. **PWB** Printed Wire Board *Glossary:* PWB
23. **RTC** Real time clock 11, *Glossary:* RTC
24. **SEK** Swedish Krona *Glossary:* SEK
25. **SMD** Surface Mount Device *Glossary:* SMD

26. **SPI** Serial Peripheral Interface 9, 20, *Glossary:* SPI
27. **ST** STMicroelectronics *Glossary:* ST
28. **SWD** Serial Wire Debug *Glossary:* SWD
29. **TI** Texas Instruments Inc. *Glossary:* TI
30. **UART** Universal asynchronous receiver-transmitter 19, 20, *Glossary:* UART
31. **USB** Universal Serial Bus *Glossary:* USB
32. **via** vertical interconnect access *Glossary:* VIA

0.2 Glossary

33. **GPS** The Global Positioning System (GPS) is a radionavigation system owned by the United States government and operated by the United States Air Force. It uses sattelites for geolocation and time. 1
34. **IC** Integrated Circuit (IC) is a set of electronic circuits on one small flat chip. 2
35. **IMU** Inertial Measurement Units (IMUs) are integrated circuits that can measure acceleration, rotational velocity and magnetic field strength. 11
36. **IPC** Institute for Printed Circuits (IPC), Institute for Interconnecting and Packaging Electronic Circuits 10
37. **JTAG** JTAG is an industry standard for verifying designs and testing printed circuit boards after manufacture. 16
38. **LDO** A low-dropout regulator is a DC linear voltage regulator that can regulate the output voltage even when the supply voltage is very close to the output voltage. 11
39. **MCU** A Microcontroller Unit (MCU) is a single computer chip designed for embedded applications. 9
40. **PC** Personal Computer (PC) is a multi-purpose computer whose size, capabilities, and price make it feasible for individual use. 20
41. **RTC** A Real time clock is an IC that is used to mesure time even when the main device is off. 11
42. **SPI** Serial Peripheral Interface Bus (SPI), is a synchronous serial communication interface specification used for short distance communication, primarily in embedded systems. 9

43. **UART** Universal asynchronous receiver-transmitter (UART) is a computer hardware device for asynchronous serial communication. 19

1

Introduction

This chapter describes the idea behind and the background to this project. A rough sketch of how the work is divided and the goals for this project is provided.

1.1 Background

This is not a new area of pruducts for Followit, different types of radio sending units have been made for over four decades now. With new and improved technology arriving each and every year new pruducts ought to be made to have the latest most efficient and effective systems. Every generation of a component will most likley have a smaller physical size, have more advanced features and draw less power then the previous one. Followit wants to make a new unit which implement all the new and improved technologies into a small, advanced product with low power consumption. Customers have been asking for a simple, small and cheap radio unit from the company to complement their more advanced and powerful products. With this type of product they could produce them in a larger number and gain new sale territories. By having such a small product it can be used in new areas that they never could before. The smaller the animal you want to track, the smaller equipment you could strap to them. This is one of the reasons that this product is so sought for in the buisness.
Most of the Integrated Circuit (IC)'s are already chosen by the company, but there are no acctual implementations. The final version is supposed to work in different areas, both as a tracker for animals and also as a product for theft protection in cars a vehicles. This means that the design of the product needs versitality to work in all these different areas. Much consideration is taken to get the product both small and inexpencive. The cost of the PCB depends on the size, manufacturing and the numbers of layers. The rest of the cost comes down to the components, batteries and casing.

1.2 Project goals

Followit wants to produce a VHF radio unit which have a powerful MCU for advanced programs and with some extra feautures that makes it possible to use the finished product in different areas and with different types of characteristics. The project involves a first test prototype and also a final version which is presented to the company as a finalised product ready for marketing and sales. To ensure proper functionallity of the prototype a test program is written to the system to test the connection and functionallity of all the components and acessebilities.
Both the cost of the bare board and the components needs to be kept down. This require some special attention to the board design, the manufacturing and component selection. There will be a study of the ways of making the product both small and cheap at the same time. The problem formulation will be considering between making a prototype wich is tiny but have a high manufacturing cost and a inexpencive that have a bigger physical size. The procedure of finding a good balance between the two is explained later in further detail.

1.3 Scope

Main focus of this thesis is to create a PCB prototype that is tested and well designed and works as intended. Some of the coponents in the product are predefined but their implementation have to be done. Extended test code is written to the product which includes tests for all the components in the circuit. The final PCB design will be delevered to the company for further programming and implemetation. If case of time a casing for the product aswell as battery considerations wil be made.

1.4 Approach

The idea that was presented to me was a half finished principle that i needed to understand and also expand with all the neccesary components that is not mentioned in this design. The initial work prior to this project can be seen in ??

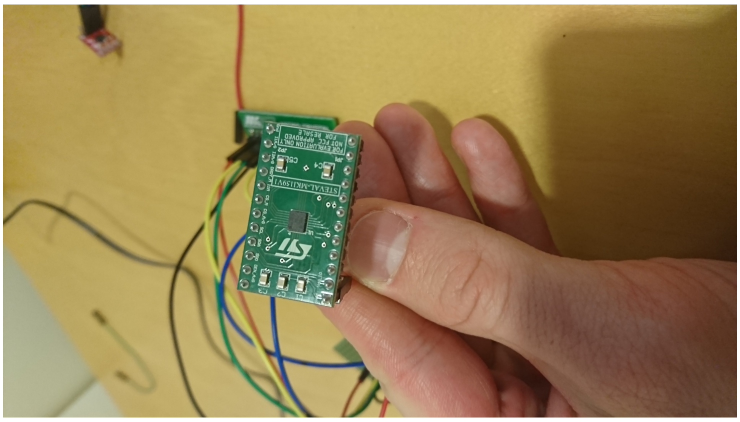

Figure 1.1: The initial schematics made by Followit
Source: Aurthor

To get an understanding of all the parts and what there function are a list is constructed for a simple overview of the system.

- MCU - For processing data and connecting all the periferals together to a complete system.
- Accelerometer - Used for measuring movements. Important for knowing how much the device is moving or if lying still.
- Radio - All the communication to the outside world is done using radio transmissions.
- RF switch - To switch between two low pass filter antennas from a single output.
- Real time Clock - The best way to keep an exact time, used for the system to keep track of the time even after one year of constant operation.
- Hall switch - To turn on and off the device, a solution that is already used by the company.
- Programmable buck converter - To alternate the supply voltage for the system.
- Logical inverter - To invert the signal for the programmable buck converter.
- LDO - Supply the radio oscillator.
- Other components - Two LED's, two oscillators, one for the processor and one for the radio module.

To get to the point of making the actual PCB a thorough analyse of the components and their connections needs to be made. Firstly the datasheets are considered for an understanding of the component itself and the required connections for this particular implementation. Both power and data is crucial

for operation and there might also be some peripherals connections and chip selection that needs to be considerd.
By writing a program the functions of each individual component can be tested. The processor used in this project comes from the PIC18 family of 8-bit processors produced by Microchip Technologies. This processor is a failry simpel unit, which makes it a bit more challanging to program. It doesen't have a buch of advanced libraries for example communication through SPI or I2C like some other commonly used processors. The process will therefore involve some close to hardware programming. A more thurough description of the processor will be described later in this report. The code language used for this project is C.

2

Theory

This chapter will introduce the reader to the problem formulation and the underlaying principles taken into account. The priciple of radio communication and the important steps involved in developing a new product prototype will be presented. Basic information of the communication and programming will also be presented.

2.1 Prototyping

Much considerations is taken in orderto construct the final product. In this case the final prototype shoud be as small and inexpensive as possible. Some of the design elements of this prototype is directly related to this. Some basic criteriums for manufacturing is taken from the PCB suppliers website. These parameters is some industry standards and also from the manufacturers side the limitations for their equipment. Whitout going up in cost but keeping the cost down with no extra price these are the.

2.2 PCB

To get good characteristics of the circuit the system will be produced on a four-layer PCB. This have a lot of advatages over a standard two layer board. The four layer design will have a top layer where all the components will be placed, a bottom layer with extra room for tracing tracks and having another ground pylogon. The two inner layers consist of a power plane and a ground layer. Both for easier connecability and also as a good way of making the circuit more resistant to high frequency noise between the traces on the top and bottom layer.

2.3 Radio Frequency

Radio frequenzy are a set frequencies that is used for trancieving and receiving data wirelessly. Radio frequencies begins with at one end of the spectrum where the frequencies is about 100Hz. It contains all the frequencies up to 300Ghz. Here the acctual wavelength is 1mm long.

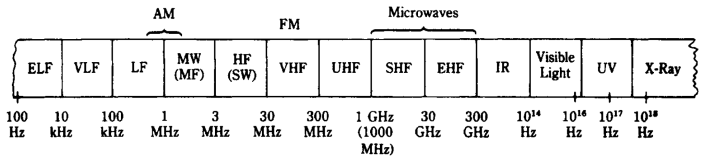

Figure 2.1: Electromagnitical frequencies
Source: Aurthor

Frequency Band Range Wavelengths VLF 3 to 30kHz 100 to 10 km LF 30 to 300 kHz 10 to 1 km MF 0.3 to 3 MHz 1 to 0.1 km HF 3 to 30MHz 100 to 10m VHF 30 to 300 MHz 10 to 1m UHF 300 to 3000 MHz 100 to 10 cm SHF 3 to 30GHz 10 to 1 cm EHF 30 to 300 GHz 10 to 1mm
(RF Circuit design) Appendix
The very low frequency (VLF) region extends from just above the ELF region, although most authorities peg it to frequencies of 10 to 100 kilohertz (kHz). The lowfrequency (LF) region runs from 100 to 1000 kHz—or 1 megahertz (MHz). The medium-wave (MW) or medium-frequency (MF) region runs from 1 to 3 MHz. The amplitude-modulated (AM) broadcast band (540 to 1630 kHz) spans portions of the LF and MF bands. The high-frequency
Designing a circuit for radio transmission is a advanced and complex procediur. The high frequencies introduces a lot of intresting phenomenons that need to be considered when construction a circuit in these frequincies. When designing a circuit for RF the components and traces on the PCB behaives in a different way and takes on different characteristics than a equal system at lower frequencies. Some of the challenges that arises are described in "Secrets of RF Circuit Design". Stray capacitance is one of the phenomenon that arises when handlig RF. Between conductors, conductors to ground and between components a small capacitance occures when dealing with RF. To ensure a good radio signal some criterias need to be fulfilled. The output signal from the radio tranciever is matched at 50 ohms and this has to be matched with the output stage components. These components commonly is a network of inductors and capacitors .This matching network is described later in this section. From different types of radio signal trancievers the type used in this case is determined by the radio ICs manufacturer.
Another phenomena thats intruduces is the so called skin effect, where the "skin" part comes from the fysical phenomenal thats hapening. When the frequencies rises the resistance in conductors increases with it. The explanation to for this is that current choses the path of least resistance
Radio frequincies does many things to a board, these problems and apperances most be evaluated and considered.
"Secrets of RF Circuit Design"

2.3.1 Chebychev Filter

The chebychev type of filter is special in the fact that it have a steep fall rate and a high "Q". The Q factor is commonly used in filter design as a function

of the length of the stopband through the whole passband. This makes it very suited for radio designs..
[7] Class E - A New Class of High-Efficiency Tuned Single-Ended Switching Power Amplifiers
The class E (CLE) type used here uses switching type of The most intresting part of the class E is the fact that up to ideal power eficcianty can be acceived by constructed by this type. Class E makes use f
Stating in the datasheet to the radio IC the rough design aspects are defined. From

2.4 Radio component

The radio module used in this project is from the company Silabs. The chosen radio IC have the characteristics that are wanted in this type of product. The radio trasmission used is the earlier explained class E. With this pice the class E is already implemented in the radio as this is widley used today and a very effective radio signal. The type of filter used for sending radio signals at VHF frequencies is defined in the defined

2.5 MicroControllerUnit

Every advanced system needs a central processing unit to make all the calculations needed. Why a lot of systems needs some powerful processor this system wich is a bit easier with The power consumption is higly dependent on the speed of which the processor is runnig, the faster the more power it consumes and also the slower the less current it will draw. And by the MCU beeing the component with the single higest power consumption the speed is set to a speed as low as possible. This low speed is not a concern in this particular system when the operations required is not time or speed sensitive. The voltage supplied to the MCU is another parameter that will alter the power consumption. The comonent is a low power model which can handle a lower source voltage. A voltage between 1.7 to 3.6 is required, anything lower will not start the device and anything higer will damage the the part. To get the right speed of a crystal we need to get the right product for this particular case. As a crystal Many different types of oscillators exists, both internal and external types.

2.6 IMU

The motions of the system is measured with an IMU system. This system can be used in a lot of different cases, both to detect if the unit is stationary or moving or if there is very hard and fast movements in the product. One of the simplest IMU's is the 3-axis accelerometer, it

2.7 SPI

Serial Peripheral Interface (SPI) communication is used to communicate between the Microcontroller Unit (MCU) and other IC's on a circuit board. The SPI is It uses four wires to communicate and additional one wire for each extra IC that is connected. The transmisson works in a synchronous serial maner where each bit is sent one at the time syncronous to a supplied clock signal. Different types of SPI exists but with the most common beeing the four-wire serial bus. SCL, SDO, SDI and SS is used

- SCL - Serial CLock, a clock is supplied to synchronise the data transmissions.
- SDO - Serial Data Out, Data is sent from this port.
- SDI - Serial Data In, Data is transmitted in to this port.
- SS - Slave Select, Selects a device for communication.

The interface uses one master device and multiple slaves. The master device handles the communication and supplies the selection of slaves. To enable a connection and choose which slave is used an induvidual slave select must be present. When set, only the choosen slave device is able to communicate. From the MCU's datasheet the following diagram show in Figure 2.2 how the connection works when connection several slave devices.

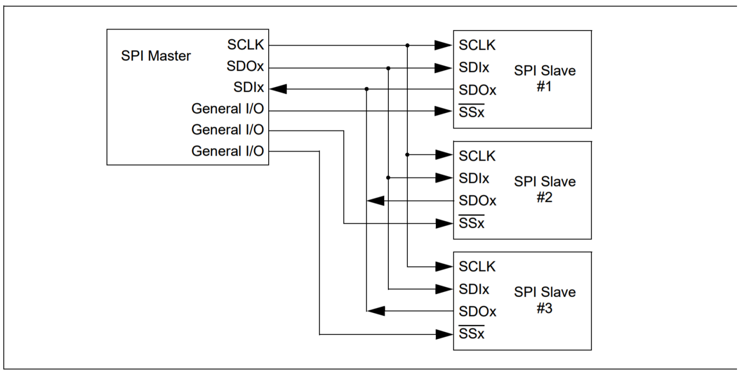

Figure 2.2: SPI master and multiple slave connections
Source:
http://ww1.microchip.com/downloads/en/DeviceDoc/40001412G.pdf

2.8 I^{2}C

3

Hardware

A deeper look into each component with some information of their functionality and implementation will be presented in this chapter. Why some specific components are chosen is also aswered here.

3.1 Layout parameters

When starting the layour some inintial rules needs to be setup. These parameters are set by the board manufactuer. The design can be produced at different places but when ordering from this manufacturer the constrains that is used is the same parameters that the supplier uses as their standard. These rules and constrains may differ from one supplier to another but as the company already this supplier the same will be used for this project. Naturally for this project the minimum spaces and distances that does not make for a supplement charge are chosen as the design rules. A list of these parameters can be seen below.

- Trace width: minimum of 6 mils (0,1524mm)
- Via diameter: 10 mils
- Maximium thickness of board

3.1.1 Landgrid

The industry standard is always good to aim for, in this case the basic designs are taken from IPC's design guidline[**?**]. Whilest these are made for optimal manufacturability the footprints used on the testboard are modified to enable for easier solderability, production and rework if needed. The land grids are made slightly bigger and longer to acheive this. The downside of making the pads larger is that the final board size increases and therefore the size of the land grids requires to be reduced.

3.1.2 Easy prototyping

The components that are going to be used in high frequency often comes in tiny packages. This gives the protypability problems with easy ability to solder and use, but the problem is that the best components used in this area of work will be small to fit in small advanced systems. To make a

3.2 Structure

The product is constructed with a number of components, which all have a central role of the final product. They can all be seen in Figure 3.1. A list of the major components and their function can be seen below:

- MCU: The central part of any integrated system, handles all the calculations and the program code.
- Radio: All the communications with the rest of the world will be handled by the radio, sending on the VHF and UHF band.
- Inertial Measurement Unit (IMU): Movement detection is measured with a accelerometer, this to determine if the unit is in motion or laying still.
- Low-dropout regulator (LDO): A Low-dropout regulator can supply the system with a smoother voltage because no switching is taking place.
- Hall sensor: The hall sensor is used as a switch for the system by sensing if a magnet is nearby and then turning off the circuit.
- Real time clock (RTC): A real time clock is important to aquire data at a specific set time. It is important that the clock is exact over the whole life of the pruduct.

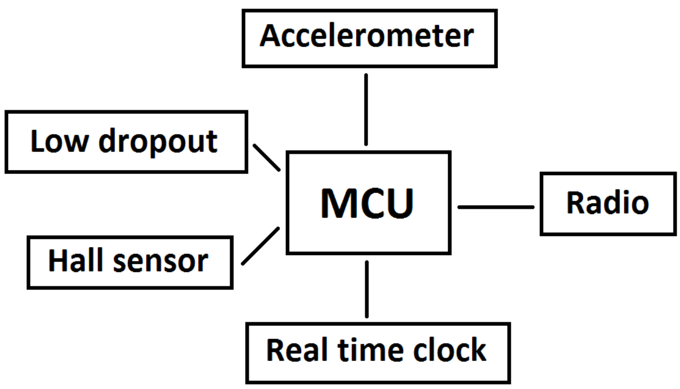

Figure 3.1: The prototype connection
Source: Aurthor

Each of the components in this project is carfully chosen to get the functionallity and effect that the company is after. To ensure the system works as intended the company have aquired development boards to each of the components. Every components needs to be tested to ensure their induvidial functionallity. Each development board is connected to the micro controllers board. First off the MCU have to be set up in a correct way with all it parameters and then the other components could be connected and initilized one after another. The whole connection can be seen.

3.3 MicroController Unit

The MCU used for this project is a processor type that is used by this company many times before and has been chosen to this project for its small size, low power draw, sufficient connections and feautures. The particular processor used is the PIC18LF46K22[1]. The version used is one with 40 pins. All the connections avalible are shown in Figure 3.2.

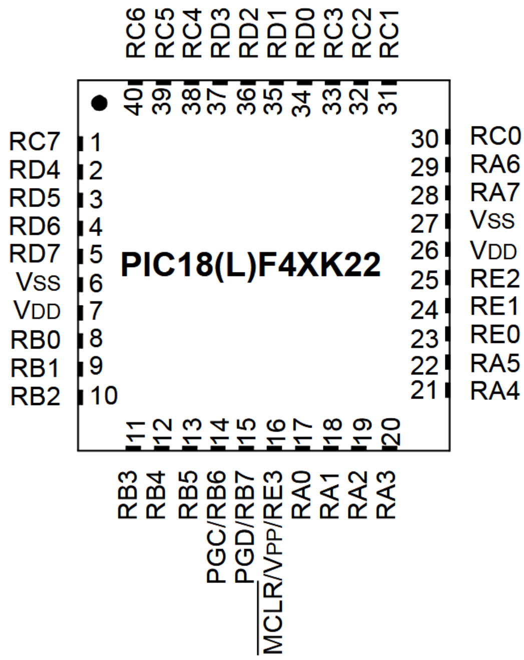

Figure 3.2: PIC18LF46K22 pinout
Source:
http://ww1.microchip.com/downloads/en/DeviceDoc/40001412G.pdf

3.3.1 Connections

3.3.2 Power

Powering it is done by connnecting the VDD pins to the power net. Connected to ground is the Vss pins on the processor. To ensure the current fed is as smooth as possible capacitors are connected between these two pins. The value of these capacitors are choosen to 100nF.

3.3.3 Oscillator

To operate the MCU a clock signal is mandatory, this can be implemented in different ways. Either with the internal High, Medium and Low frequency oscillator or a external one. Where the external rely on a specific circuitry to provide the clock source. Examples of external oscillators are: clock modules, quarts crystal resonators or ceramic resonators and resistor-capacitor circuits. When a circuit is specified to be power efficient the speed of the clock plays a central role. As this product is specified to run on a small battery the speed of the system is kept low to increase the lifetime of the battery. The clock signal is generated from a external temperature compensated Crystal Oscillator (TCXO).

3.4 Accelerometer

The component used is a 3-axis, ultra-low-power and high performance accelerometer from ST[2]. The component is the simplest of IMU's that this manufactorer have and this simplicity makes for a product that is only incorparite one sigle function. 3-axis accelerometer means that it can measure

3.5 Power

Two voltage connections is apperent on this device, one which is called VDD and the other is called VDD-IO.

3.5.1 Connenctions

3.5.2 Software implementation

3.6 Radio

3.6.1 Power

3.6.2 Connenctions

In the registers

3.6.3 Solidworks PCB

Followit uses the PCB board design software Solidworks PCB from DASSAULT SYSTÈMES. It utilizes the industry-proven Altium design engine for layout and routing of printed circuit boards and combined with a close connection with the mechanical CAD of classical Solidworks. With this program the PCB layout and design can be transfered seamlessly over to the mechanical enviroment to create a exact case or enclosure for the circuit board. The version used in this theisis is (Update 2.0).

3.7 Power consumption

The total power consumption is calculated by adding the current draw from each induvudual component together. Different test is conducted to try different modes of the system. One describing the power cunsumption of only the processor. This is done by running it in a infinite loop with all the other components at the circuit powered down or in power down mode. Since the system is not supposed to be active just a small time with a longer power down mode in between the power consumption on the system has to account for a longer time span. The tests is made with a standard scheme used already by the company. The scheme consist of a small radio pulse every second and the system beeing inactive in between these radio pulses. All the systems

4

Software

What is the step after the PCB is produced? Yes it is time to test the system, and this is done with the help of a test program. This chapter will guide the reader through this process of setting up the processor to run program code. How all the components are programmed and tested will be explained in this chapter.

4.1 Programming

In start of every embedded system the processor have to be programmed. Here the most common implementation is the Joint Test Action Group (JTAG), where the all the programming and debugging is done through a standardized interface. The approach is different on this MCU, here three pins are used to program the device. The first one is the "PGC", which is the clock signal for the In-Circuit Debugger and "PGD", In-Circuit Serial Programming. The third pin needed from the processor is the MCLR. These pins on the processor have to be accessible to program the microcontroller.

4.2 Software implementation

The processor do not start up on it own, much consideration needs in making right initzilation and configure it right. A source voltage is supplied to the processor to get it to operate. There are some initial registers that needs to be set in order to inintialize and start the processor. This varies between different processors and models and is different for applications and systems. These registers contain information about the speed of the processor.

4.3 Radio implementation

Radio Chip Waking Up First, the radio is in the off state. After the SDN pin is pulled low, the radio wakes up and performs a Power on. Reset which takes a maximum of 6 ms (900 μ s typical at room temperature) until the chip is ready to receive commands on the SPI bus. The GPIO1 pin goes high when the radio is ready for receiving SPI commands. During the reset period, the radio cannot accept any SPI commands.

4.4 Software

The fundation for every developmet is a good development enviroment, both as the circuit boards are createt and the software inplementations needed later in the process.
(In the early days of computing, programming in Assembler was used to program almost any type of computer. These days, however, it is pretty much the preserve of embedded designers, particularly when using smaller 8-bit devices) (PICDESIGN)

4.4.1 MPLAB

Microship which is the producer of the MCU used in this project have their own development enviroement with holds a lot of handy features when making a program for their products.

4.4.2 Assembly

The acctual code that runs on this processor is assembly, the most common hardware code which is used in almost all types of MicroController units. Assembly is a harware type language which means that is describes the acctual process for the

4.4.3 C18

The C program is compiled with the compiler C18. This is the compiler which have been the official compiler for this particular processor. This compiler is used for all the processors in the family PIC18. This complier is some years old and lacks some modern features. The vesion used in this project is (3.47)?

5

Results

This chapter will guid the reader through the whole process of developing a system prototype. Designing the PCB, soldering the components, troubleshooting the board and writing the neccesary code are some of the steps involved and they will all be described in detail here.

5.1 Schematics

The schematics over the circuit is created by placing all the components discussed earlier, every IC have a small amont of components that is placed in a way so that it is easy to understand which components is belongs to which. A title is added to every part in the design for a good overwiev over the system. Since the section which included the radio is large it is placed on a separate page. When additional components are added in additional pages can be inserded. These schematics can be found in "aoutoref appendix schematics".

5.2 Layout

5.2.1 First design

The first of two boards is 3.5 times 3.5 mm in size. The different parts of the circuit is layed out in a way that it is easy to inspect and resolder if neccesary. The main components of the board is placed close to each other at one side to get an idea of the design for the final product. This board is equipped with some testpoints for easy connections with test probes and oscillioscope. The silcskreen print on the top of the board was vague at some places and made destinguish them between eachother hard. The pin one location at one part could not been spottet. A view of the board can be seen in **??**.

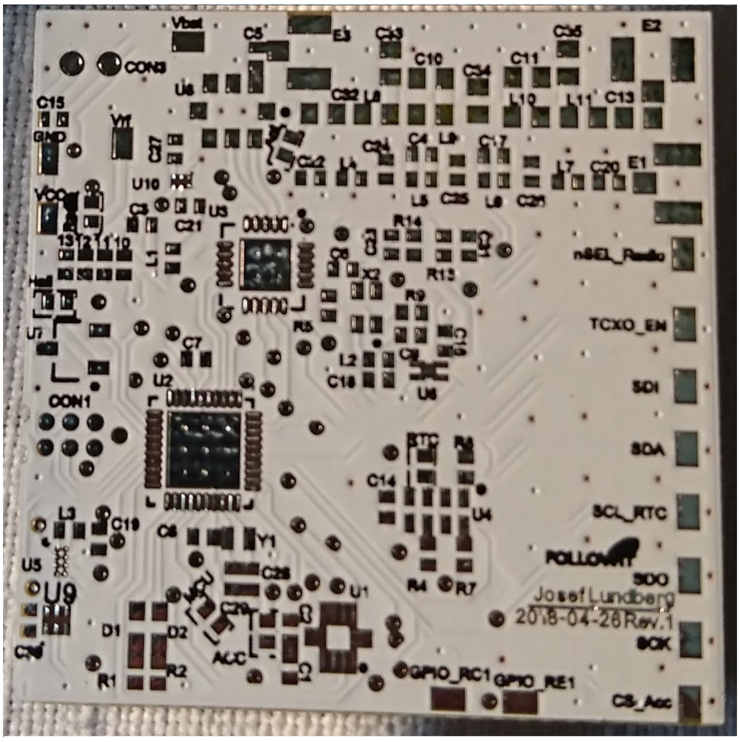

Figure 5.1: First (1) revision circuit board.
Source: Author

5.3 Communication

5.3.1 UART

The Universal asynchronous receiver-transmitter (UART) connection interfered with another connection which lead to one function not working as intended. The function that is the enabeling line to the LDO which powers the oscillator for the radio. It is fixed by connection one of the extra pins that was layed out beforehand directly to the LDO. The transmitting half of the UART connection is working as intended on this version, some of the resulting data which is sent to the computer can be seen in Figure 5.2.

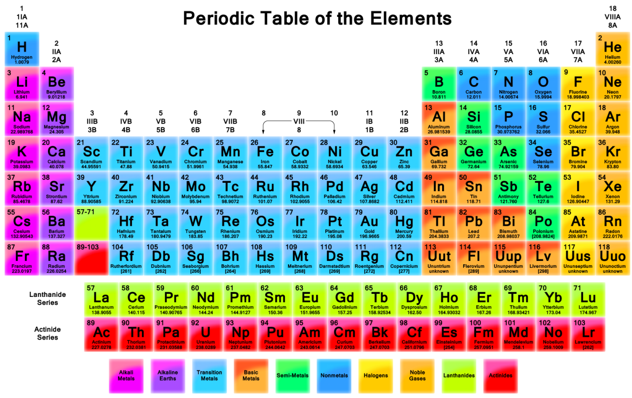

Figure 5.2: Simple UART transmission to a Personal Computer (PC)
Source: Aurthor

5.3.2 SPI

Testing started with both theMCU, radio and accelerometer soldered to the board. No communications was acheived when both of these slave devices was connected at the same time. After some troubleshooting the failing factor of this is the accelerometer having it's SPI conncetion the other way around. The data out (SDO) line was connected to the data output, and the SDI was connected to the data input line of the accelerometer.

6

Schematics

To the PCB a schematic over the complete system has to be constructed. This is built by noting all the connections that were determined in earlier chapter. The complete system is split up in to two different schematics, one describing the Radio components and the other shows the processor and all the other parts.

7

Discussion

The prototype could have been made directly using a company to place all the components, or the components should have been mounted with a pic and place machine to eliminate some initial troubleshooting and hassle regarding the SMT process. But with one of the projects goals to keep to expences down the process looked like this. This did however increase the understanding and personal expertice in the area.
The test points were a good addition, they was frequently used and eployes at the company did found them intresting for furter use in future projects. Additional test points whould be a good idea. When the board already had real estate to hold some additional points it should have been inplemented.
The hardest bit with the system were the voltage adjusting buck converter. Both the fact that it was one of the smallest pieces and also the fact that it needed some adjustments in form of
Designing a PCB with white soldermask looks great and with black silcskreen it was easy to see every marking. Problems did occur though, when visually inspecting the traces on the PCB it was hard almost inpossible to see. There is a reason that green is the most common choise. (The final design was therefore created with green soldermask)
To ease trobleshooting more a via could be placed in every single transmission line, this to be able to read the voltage levels and data at every trace. When building the first revision only some of the traces.

Bibliography

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Appendices

.1 Large Figures

.2 Lists

.2.1 Bill of Materials: Main PCB

Main Board Components	**Package**	**Quantity**
Capacitors:		
18p	0805	2
100n	0805	21
1u	0805	2
2.2u	0805	1
4.7u	0805	4
10u	Electrolytic SMD 5x5.3	6
Resistors:		
220	0805	1
1k	0805	2
1k	potentiometer	2

The project; complete with all software code, the application, hardware files and more, can be found online in the github-repo:
https://github.com/Jurriz/VHF-Unit