Master's Thesis
MA667

Design and Implementation of a Signal Analysis and Processing System for a Low Power Sensor System used to Monitor Physiological Data

Gerhard Zancolo

Institute of Electronics
Graz University of Technology
Head: Univ.-Prof. Dipl.-Ing. Dr. techn. Wolfgang Pribyl

Graz University of Technology

Assessor: Ass.Prof. Dipl.-Ing. Dr. techn. Peter Söser

Advisor: Dipl.-Ing. Dr. techn. Stefan Rosenkranz

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Kurzfassung

Ziel dieser Masterarbeit ist die Entwicklung eines drahtlosen Messsystems zur Aufnahme der Herzrate bzw. der Herzratenvariabilität. Dieses System wird in der Landwirtschaft im Speziellen bei Nutztieren angewandt. Die gemessenen Daten werden an eine Basisstation übertragen und in einem Datenbankserver abgespeichert. Die Ergebnisse werden mit Hilfe einer Software evaluiert bzw. interpretiert. Mit diesem Gerät kann bei Nutztieren, in ihrer natürlichen Umgebung oder beispielsweise bei Tiertransporten, die Herzrate bzw. Herzratenvariabilität bestimmt werden. Diese Werte können verwendet werden um Rückschlüsse auf das autonome Nervensystem zu ziehen. Somit ist es möglich physiologische Reaktionen auf verschiedene Stressoren zu analysieren und einen Beitrag zur Tiergesundheit zu leisten.

Schlüsselwörter: Senorsystem, Signalprozessor, Veterinärtelematik, Herzrate, Herzratenvariabilität, Stress

Abstract

The goal of this Master's Thesis is the development of a wireless heart rate/heart rate variability measurement system for use in agriculture in particular for farm animals. The acquired data are sent to a base station and are put on a database server. The data can then be interpreted with an evaluation software. With this device it is possible to measure and analyse heart rate variability on cattles in their natural environment or for example during animal transports. The results can be used to determine parameters to draw conclusions from the autonomic nervous system. Therefore it is possible to analyse physiological reactions on different stressors and has a great potential to contribute much to the understanding of stress in farm animal's welfare.

Keywords: sensor system, signal processing, wireless, veterinary telematics, heart rate, heart rate variability, stress

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Acknowledgement

First of all I would like to thank Dr. Stefan Rosenkranz and Mario Fallast who enabled the establishment of this thesis at their company smaXtec product developement GmbH and supported me in every problem as well as to my colleagues for their help.

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Thanks to all of you,

Graz, June 2010 Gerhard Zancolo

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Chapter 1

Introduction

The usage of electronic devices in the field of intensive agriculture is getting more important. More and more crucial data is collected automatically. For example dairy farms are increasing in size, so the farmers need more electronic devices to help them with the daily work. Due to the permanent growth of the farms, it is not possible to check the state of health only with keeping an eye on the animals. Hence symptomes of disease may not be recognised in time.

Nowadays it is not possible to imagine intensive agriculture without automatic systems, e.g. automatic feeder or automatic milking machines. More electronic devices can be found in the area of reproduction, e.g. to determine the progesteron rate in milk or the detection of rut. Furthermore there are pedometers in use. Sensors are converting the activities of the animals into electrical signals to have additional information about the estrous cycle. The pedometers can be fixed with a strap on the neck (like a collar) or above the ankle.

To check the conductivity during the milking, to prevent an inflamation of the mammary gland, there are electronic devices existing. In dairy farms, special quantity measurement instruments as well as systems to identify the animals are used every day [1].

For the developement of animal husbandry systems it is very important to consider aspects concerning appropriate animal husbandry, that is to avoid animal suffering or even to increase the well-being of the animals [2] [3]. Such situations are subjective feelings, which can not be measured directly. Therefore it is necessary to find objective criteria which can evaluate well-being and suffering of animals [4]. One way is to measure physiological parameters to classify stress.

Animals react on changes in their environment, whereas their autonomic nervous system plays a key role. Alteration in the sympathetic and parasympathetic balance of the autonomic nervous system have an influence on the activity of the heart [5].

To classify stress on animals it is usual to measure heart rate, because of its easy handling. Data acquisition of heart rate is useful to recognise short-term problems, but can not be applied to give statements about long-term effects. Furthermore there can only be done a few statements about the characteristic of the sympathetic/parasympathetic interaction [6]. A higher heart rate can be measured due to decrease of parasympathetic activity as well as an increase of sympathetic activity, or as in most cases because of both influences. Activities of these antagonists of the autonomic nervous system determine the stress situation of the organism. A high activity of the sympathetic nerve refers to a physical or mental pressure while a high parasympathetic nerve activity is typical for a relaxed/resting organism [5] [7].

The control system of the heart by the sympathetic and parasympathetic nerve results in a not constant heart rate. This phenomenon indicates a healthy heart and is called heart rate variability. The heart rate variability is a generic term for many parameters, which are determined by different analysing methods. Especially the vagal tone (parasympathetic nerve) can be specified with several parameters [8].

The goal of this thesis is the development of a wireless heart rate measurement system to determine heart rate variability. With this device it should be possible to measure and analyse heart rate variability on cattles in their natural environment or during animal transports.

1.1 Motivation

The need of economic optimisation does not stop for animals as well. Especially in producing milk the need or wish to more performance leads to problems with the health of animals. An animal cannot be compared to a machine and problems with health may not be recognised soon enough [1]. smaXtec product developement GmbH developed a measurement system for health monitoring of farm animals, which is used in agricultural research and is currently further developed to be placed on the market. With modern sensors the measured values are collected in situ and the conditioned values are sent directly to the user. To extend the field of application, especially in the area of human medicine, it is necessary to analyse and process the measured physiological signal. The existing system with an analog signal processing should be extended by a digital signal processing unit.

1.2 Disposition

In **chapter 2** the physiological basics of the heart are discussed. The focus is on heart rate, heart rate variability and stress, respectively how it may be correlated.

The **chapter 3** deals with the practical implementation of the electronic system. First the complete system is described followed by the signal processing hardware. The hardware is divided into the communication to the WearLink strap, the control unit and the communication to the base station. Then the Firmware respectively the application flow is discussed.

Chapter 4 contains the evaluation of the system. Therefore a heart rate measurement has been accomplished and a signal analysis of the measured values has been realised.

Finally, in **chapter 5**, an outlook of further capabilities of this signal analysis system is shown.

Chapter 2

Medical Background

This chapter deals with the structure, functioning and parameters of the heart. To keep it simple and due to the fact that it is very similar to the humans, the heart of humans is described. Afterwards the heart rate variability is explained, which can be measured with the heart rate measurement system developed in this thesis. Then some conclusions, which can be drawn from the heart rate variability, are given. The content of the following chapters is based on [9] [10] [11] [12] [13].

2.1 Anatomy and Physiology of the Heart

The heart is a hollow organ which pumps blood via rhythmic contractions into the body. Thus oxygen (O_2) and nutrients are provided for the whole body. Metabolic waste products and carbon dioxide (CO_2) are removed. The next picture (figure 2.1) illustrates the anatomy of the heart. The cardiac septum seperates the heart into two parts, which pulsate at the same time. By the right half of the heart the "poor of oxygen" blood is sucked in and pumped into the pulmonary circulation, where it gets enriched by oxygen. Out of the lung the blood flows into the left half of the heart and gets back into the systemic circulation. This cardiovascular system can be seen in figure 2.2. The right and left side are also divided into two further compartments. The two atria (left and right) and the two ventricles (left and right). The two atria "collect" the blood from the systemic and pulmonary circulation. The blood from the two atria is sucked by the two ventricles and pumped back into the system and pulmonary circulation [12] [13].

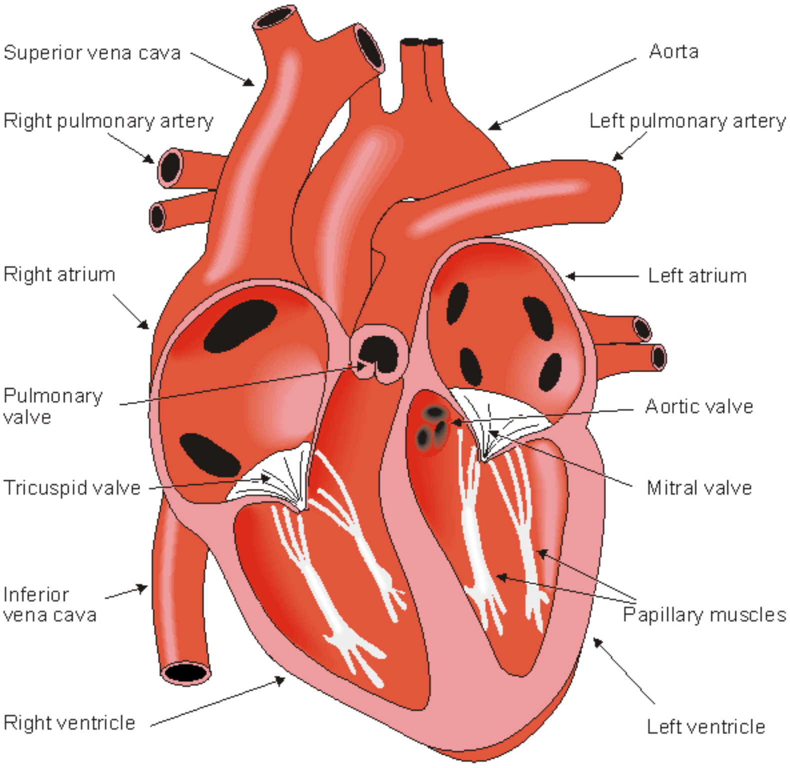

Figure 2.1: Anatomy of the Heart [10]

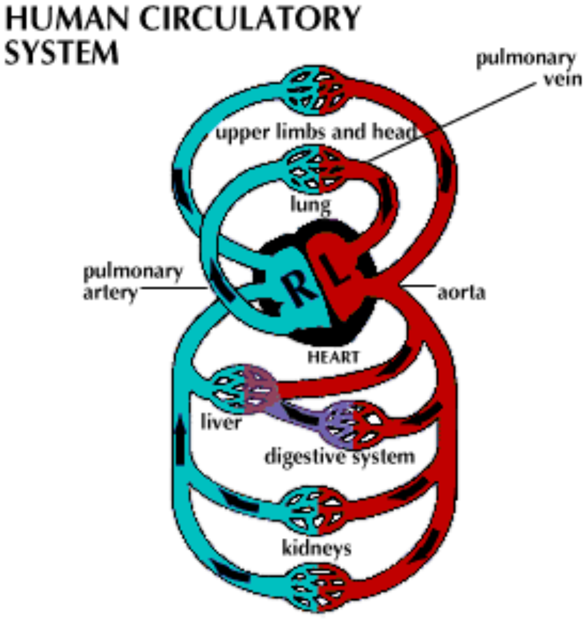

Figure 2.2: Cardiovascular System [13]

2.1.1 Electrical Conduction System

The actuation of the heart is in its nature: The heart runs autonomously. Every muscle needs an electric impulse for contracting. While skeletal muscles are controlled by the central nervous system, the heart is regulated by special cardiac muscle cells. These are called pacemaker cells. The central nervous system (CNS) can effect the heart rate and the strength of the heart beat but the heart will work without the CNS as well. This is because the cardiac muscle cells are interconnected by gap junctions, which are low resistance pathways. The system of these special muscle cells is called electrical conduction system (ECS). An excitation leads to a full contraction of the heart [12] [13].

Figure 2.3 shows a schematical illustration of the electrical conduction system.

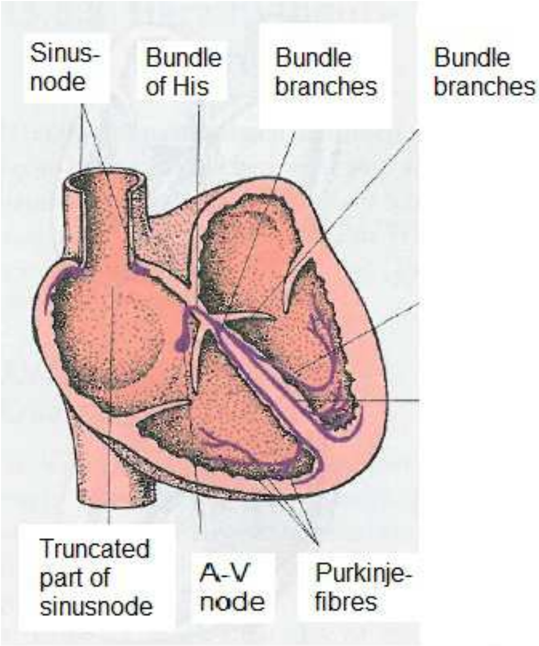

Figure 2.3: Schematic Illustration of the ECS [12]

The physiological conduction activity starts with the most important structure - the sinus node (SA node). The sinus node generates every excitation for the rhythmic contractions (approximately 40 - 55 pulses/min) of the heart. The sinus node is also called the pacemaker. The secondary excitation is done by the atrioventricular node (AV node) followed by the tertiary excitation done by bundle branches and Purkinje fibres [13].

2.1.2 Electrocardiography

The electrical excitation of the sinus node propagates along a given way in the heart. Thereby a small current flow is generated which propagates along the complete surface of the body. With electrodes, a recording of the electric potentials across the body is possible. This is called an electrocardiogram (ECG) [12] [13]. A typical ECG signal is illustrated in figure 2.4.

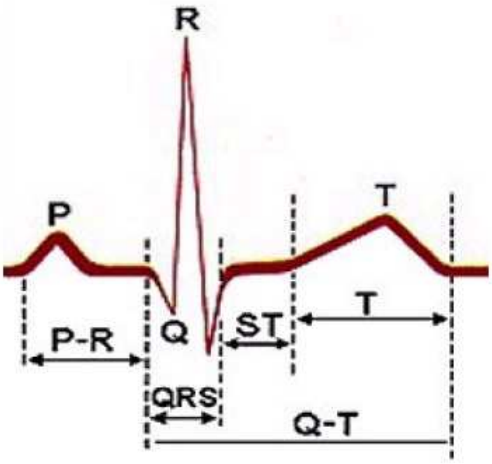

Figure 2.4: Typical ECG signal [13]

The next points explain the different points visible in an ECG [13].

- P wave: The sequential activation of the right to the left atrium (from SA node to AV node).
- QRS complex: the depolarisation of the two ventricles.
- ST/T wave: repolarisation of the two ventricles.
- P-R interval: time between start of depolarisation of the atrias and the begin of depolarisation of the ventricles.
- QRS interval: duration of depolarisation of the ventricles.
- QT interval: time between depolarisation and repolarisation of the ventricles.

- RR interval: duration of ventricular cardiac cycle (reciprocal of the heart rate).
- PP interval: time between atrial depolarisation.

2.2 Heart Rate

The heart rate (HR) is defined as the inverse of the RR interval and is the number of heartbeats per time respectively heartbeats per minute (bpm). The heart rate depends on the physiological stress, age and fitness of the individual (human or animal). The resting heart rate at humans is about 60 - 100 bpm. With animals it depends on the size. The bigger the animal the lower the heart rate. Cows have a heart rate about 50 bpm. The heart rate, the conduction velocity and the contractility of the heart is regulated by the autonomic nervous system (ANS; the sympathetic and the parasympathetic fibres). If there is a need for more blood, during metabolic activity, the blood flow must increase. Thus the sympathetic and parasympathetic nervous systems change the activity of the pacemaker cells to regulate the heart rate. The nervus vagus (the biggest nerve of the parasympathetic nervous system) plays an important role. The sinus node (SA node) is mainly affected by the right vagus. The left vagus controlles the atrioventricular node (AV node). Both nodes are innervated by the sympathetic nervous system as well. Figure 2.5 illustrates the innervation of the heart.

Stimulation of the right vagus slows the conduction system between SA and AV node, hence the heart rate reduces speed. Stimulation of the left vagus decreases the conduction speed through the AV node. A simultaneous balanced influence of the parasympathetic and sympathetic nervous system is essential to regulate the heart rate. An increase in heart rate is caused by stimulation at the SA node (sympathetic) and stimulation on the left vagus effects a faster conduction through the AV node. In addition to a faster heart rate, sympathetic stimulation forces the cardiac muscle to contract more powerful [13].

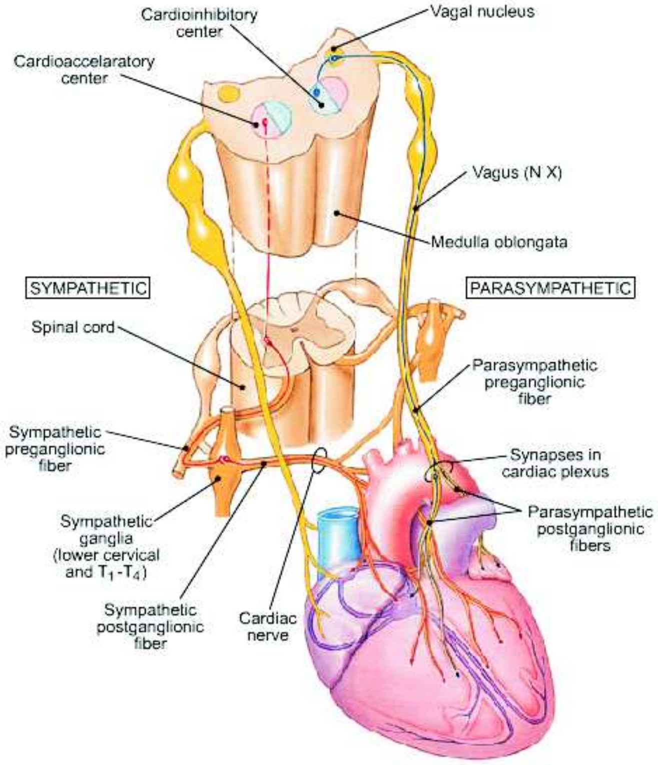

Figure 2.5: Innervation of the Heart [13]

To sum up, fast changes in HR are caused by parasympathetic actions [14] [15] [5] [16]. The SA node reacts on stimulation of the vagus within one to two heart beats. After stimulation the HR achieves his previous value in less than five seconds. On the other hand on sympathetic stimulation the HR reacts considerably slower. Thereby a delay up to five seconds may occur with a maximum reaction by progressive increase up to 20 to 30 seconds [5] [17]. In healthy organisms the HR represents the interaction of sympathetic and parasympathetic actions. Sympathetic activities increases the heart rate, parasympathetic ones decreases it. In the state of resting heart rate the influence of the vagus dominates. With increased physical activity the influence of the vagus diminishes, while the influence of the sympathetic system grows and therefore the heart rate increases [5] [18].

2.2.1 Heart Rate Variability

Due to the permanent interaction of the parasympathetic and sympathetic nervous system for heart rate regulation, the heart rate is never constant but varies from beat to beat even in the absence of physical or psychological stress. Hence the heart rate variability (HRV) is an indicator for the prevailing balance of the parasympathetic and sympathetic nervous system. HRV measurements have been done in cardiology and psychophysiology since 1960 and enable accurate interpretation of cardiac activity in terms of the autonomic nervous system [19] [20].
Between three methods of HRV analysis is differentiated:

- Time Domain
- Frequency Domain
- Nonlinear Domain

Studies from human medicine have shown that the time course of HRV contains nonlinear chaotic components. Therefore more and more approaches with nonlinear analysing tools are done. With these different domain analyses it is possible to focus on different aspects of the HRV [19]:

- quantity of variance (time domain).
- periodic processes due to autonomic regulation (frequency domain).
- chaotic phenomena in the regulation of cardiac activity (noninear domain).

These parameters often correlate, but also complement each other. Table 2.1 shows some parameters which have been used in previous analyses.

Method	**Parameter**	**Declaration**
Time domain	HR [bpm]	Mean heart rate
	RMSSD [ms]	Root Mean Square of successive differences of RR intervals
	SDNN [ms]	Standard deviation of all RR intervals
Frequency domain	HF_{norm}	Normalised power of the high frequency band
	LF_{norm}	Normalised power of the low frequency band
	LF/HF ratio	Quotient of LF to HF component
Nonlinear domain	Recurrence [%]	percentage of recurrent points in the recurrence plot
	Determinism [%]	percentage of recurrent points forming upward diagonal lines
	Entropy	computed as the Shannon entropy of the deterministic line segment length distributed in a histogram
	Maxline	Longest diagonal line segment

Table 2.1: Analysis Methods and Parameters out of it [19] [20]

A recognised certain variation of HRV is characteristical for a healthy organism. A certain reduction of the duration of the RR interval has been associated with diseases [19] and with emotional or psychological stress in farm animals and humans [21] [22] [23].

2.3 Heart Rate/Heart Rate Variability and Stress in Context

Especial susceptibility towards pressure during breeding, transportation and slaughter is defined as stress sensitivity on farm animals [24]. In particular bad husbandry conditions leads to strong exposure on animals [25] [26]. Biophysical measurements (like the heart rate) are used to evaluate stressful situations [25]. In particular for big farm animals there are telemetric measurement tools existing to measure the heart rate. Providing that the animals are used to the measurement devices, it is almost possible to have a stress free data acquisition. That is a big advantage towards invasive measurements, e.g. blood physiological parameter [27]. The heart rate is one of the first physiological parameters which is used in the research of farm animals [28] [29]. The reason might be found in the easy measurement approach (e.g. with a stethoscope) [27]. Nowadays electrocardiography measurements, or simply heart rate belts are used.

The HR applies to a reliable indicator for the internal physiological state of animals, respectively mammals [30] [31] [32]. Actually it might be a better indicator than the behaviour of animals [33]. It is also suited for measuring psychological and physiological stress effects [27].

The physical environment of an individual has a big impact on the HR. The HR adapts on climatic facts like temperature, air moisture or air pressure [34]. Also the animal husbandry has an effect on the HR [35]. For example there has been found a higher heart rate on heifers who have been living on slatted floors under tied housing conditions than on heifers who have been living in a deep litter house.

Hunger slows the HR down due to reduced metabolic activity because of insufficient energy [36]. 48 hours fasting of cows has reduced the resting HR. Also a manual emptying of bull's rumen decreased the heart rate about 22 % [37].

The measurement of heart rate variability enables a more exact approach to characterise the autonomic nervous system than the HR does. With HRV measurements it is possible to quantify the state of the autonomic nervous system especially in reaction to psychological influences [27]. Parasympathetic influences can be seen in most analysing methods (see table 2.1 - chapter 2.2.1 Heart Rate Variability) due to the fact that all fast changes in HR are parasympathetic [14] [15] [5] [16]. The power of the HF component in the frequency domain is almost only influenced by vagal activity [38]. In time domain the RMSSD parameter reflects the parasympathetic activity as well and correlates with the HF component of the frequency domain [39] [40] [18] [41].

The sympathetic influence on the HRV is harder to quantify. Many researchers believe that the LF component of the frequency domain corresponds to the sympathetic activity [7] [17] [42]. Other researchers think that there is an influence of the vagus tone as well, which is seen in the LF component, thus the sympathetic influence cannot be quantified by the LF component [8] [27]. Hence a quantification of the sympathetic activity with the LF component is problematic.

At first sight it might be a disadvantage that the sympathetic activity can not be quantified cleary, because it is a central point in stress studies [43]. Physical as well as physiological stress leads to an increase of the sympathetic activity [7] [44]. On the other hand there exist indices, that the vagus tone (parasympathetic activity) for the evaluation of stress respectively stress sensitivity is better suited [22]. In this concept stress is defined as an autonomic state, which reduces its parasympathetic activity by a disturbance of the homeostasis. Thereby it is possible to quantify stress on a physiological level. It can be said that a low parasympathetic tone is identified by a high stress sensitivity [27].

Chapter 3

Practical Implementation

In this chapter the hardware and firmware is described. First of all, the complete system is discussed followed by the signal processing unit (SPU). The SPU is divided into three subsections which describe the communication to the WearLink strap, the control unit and the communication to the base station. The complete schematic and layout can be seen in the appendices A.1 and A.2. Then the firmware respectively the application flow and the communication protocol with the base station is discussed.

3.1 Complete System

The complete system consists of the following subsystems:

- Signal Processing Unit
- Base Station
- Evaluation Unit (Database Server and embedded Linux PC)

The signal processing unit is attached on the cattles chest. To measure the heart rate a *Polar Equine WearLink* strap is used. The strap is fixed around the cattles chest. In section 3.2 a detailled description of the SPU is given. The measured values are transmitted with a wireless transceiver which is working at 433 MHz. The frequency of 433 MHz is a part of the ISM (Industrial, Scientific and Medical) radio band, which fits very well for this application. If the cattle is in operating range of the antennas, the base station receives the data and puts it on the database server or directly to an evaluation software.

In figure 3.1 the complete system is shown.

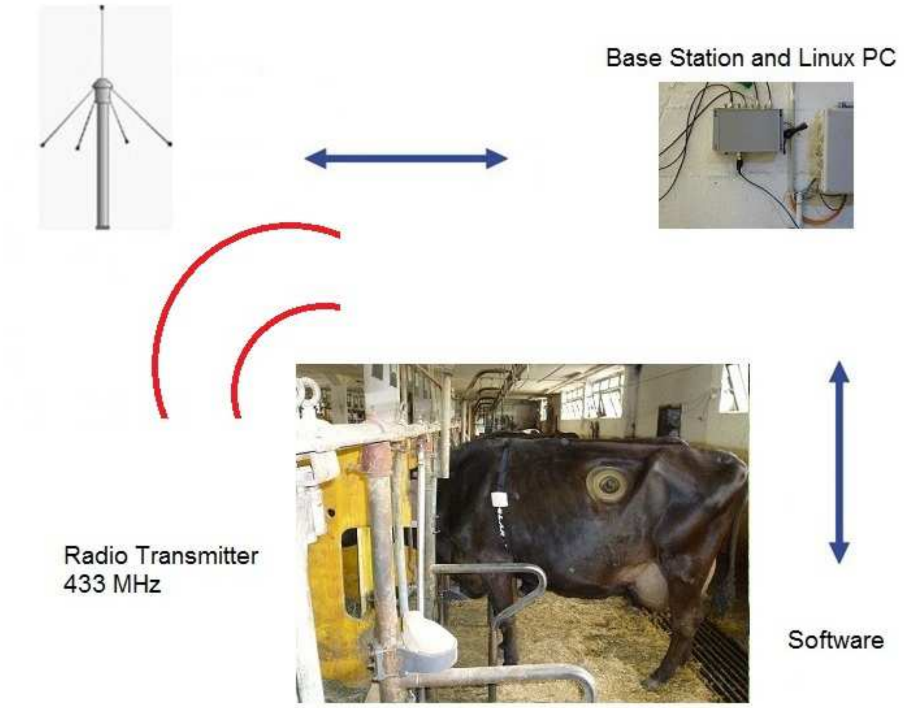

Figure 3.1: Complete System

The base station with the Linux PC is shown in figure 3.2.

The base station consists of the following hardware components:

- A microcontroller (μC) MSP430F167 from Texas Instruments to control all integrated devices on board.
- RF Transceiver CC1101 from Texas Instruments to transmit data between base station and signal processing unit.
- Low Dropout Regulator (LDO) MIC5209 from Micrel to provide constant voltage on board (3.3 V).
- USB Controller FT232RL from FTDI (Future Technology Devices International) for communication to the Linux PC.

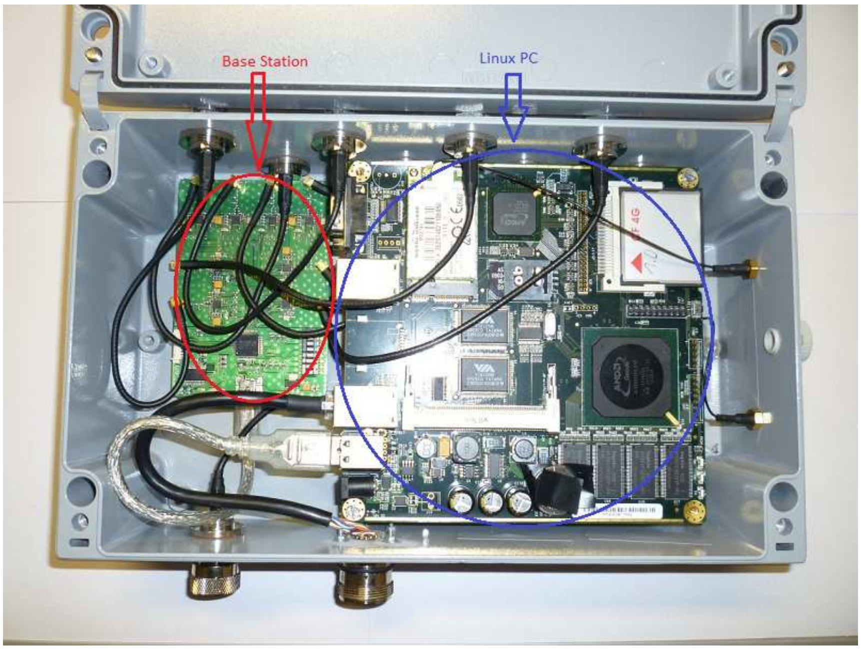

Figure 3.2: Base Station with Linux PC

The Linux PC (Alix6E1) from PC Engines GmbH has a clock rate of 500 MHz and a primary storage of 256 MB DDR DRAM. On this PC a daemon (a program which runs in the background) is responsible for an automatic readout of the measured data from the signal processing unit. After startup a script starts the daemon. Data is first stored in the primary storage and then put into a MySQL database. If an internet connection exists data are transmitted to a Server and are then available for further analyses. For more information about the base station see [1].

3.2 Signal Processing Unit

3.2.1 Block Diagram

The block diagram of the signal processing unit is shown in figure 3.3.

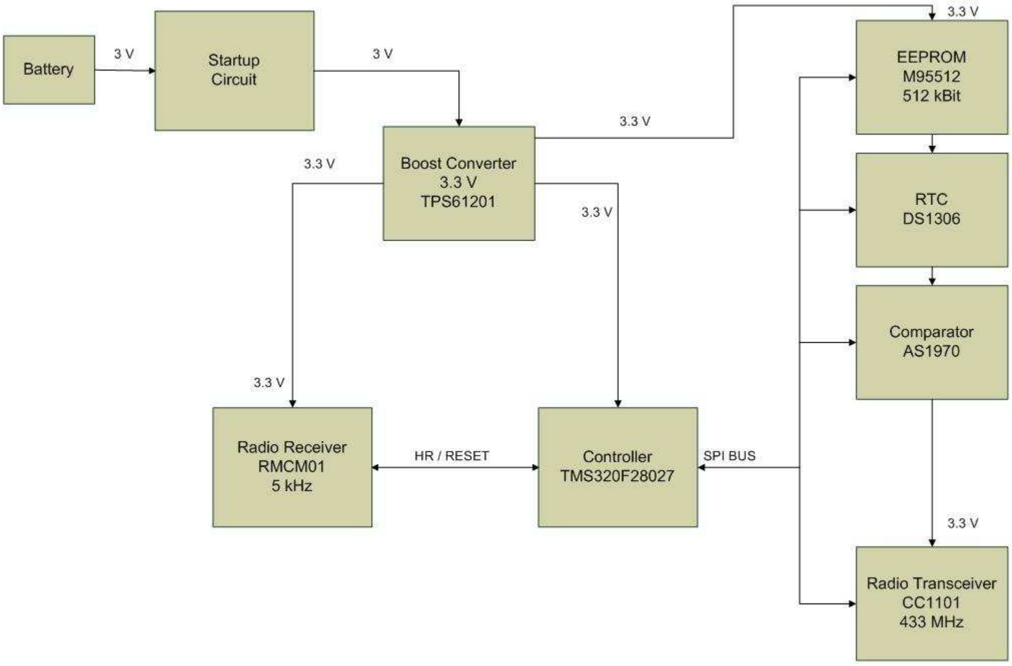

Figure 3.3: Block Diagram of the SPU Hardware

The following electronic components are used:

- Two AAA lithium batteries for power supply (3 V)
- A startup circuit to activate the application respectively to power the boost converter
- Boost Converter TPS61201 to provide 3.3 V constant voltage on board
- RMCM01 5 kHz Polar WearLink OEM module to receive pulses corresponding to the heart beat
- TMS320F28027 to control all integrated devices on board and to measure heart rate data

- EEPROM M95512 512 kBit from STMicroelectronics to save measured/processed data
- RTC (Real Time Clock) DS1306 from Maxim Integrated Products for time controlled application
- Comparator AS1970 from austriamicrosystems AG to reverse a dedicated signal

Because of the constant discharge curve, lithium batteries fits best for a mobile application. The used batteries have an electric charge of 1250 mAh.
The following table 3.1 shows the current consumption of the complete system in different modes.

Mode	Device	Max. Current Consumption	Unit
Sleep	TMS320F28027	60	μA
	TPS61201	55	μA
	RMCM01	50	μA
	DS1306	0.6	μA
	M95512-R	3	μA
	AS1970	8.5	μA
	CC1101	100	μA
Total		**277**	**μA**
Operational	TMS320F28027	100	mA
	CC1101	20 (average)	mA
Total		**120**	**mA**
Typical	Complete Unit	40	mA
Total		**40**	**mA**

Table 3.1: Current Consumption of the Signal Processing Unit

The current consumption of the "Typical Mode" follows an application where the Signal Processing Unit is put in sleep mode for 10 minutes then wakes up and is in operational mode for 5 minutes. This results in an average current consumption of approximately 40 mA. Operational mode means continuous measurement, calculation and communication with the base station.

To turn the signal processing unit on a startup circuit is used. Pin AGND and Batt_GND must be short cut (for a few seconds) then the battery voltage is passed through to the TPS61201. In figure 3.4 the startup circuit is shown.

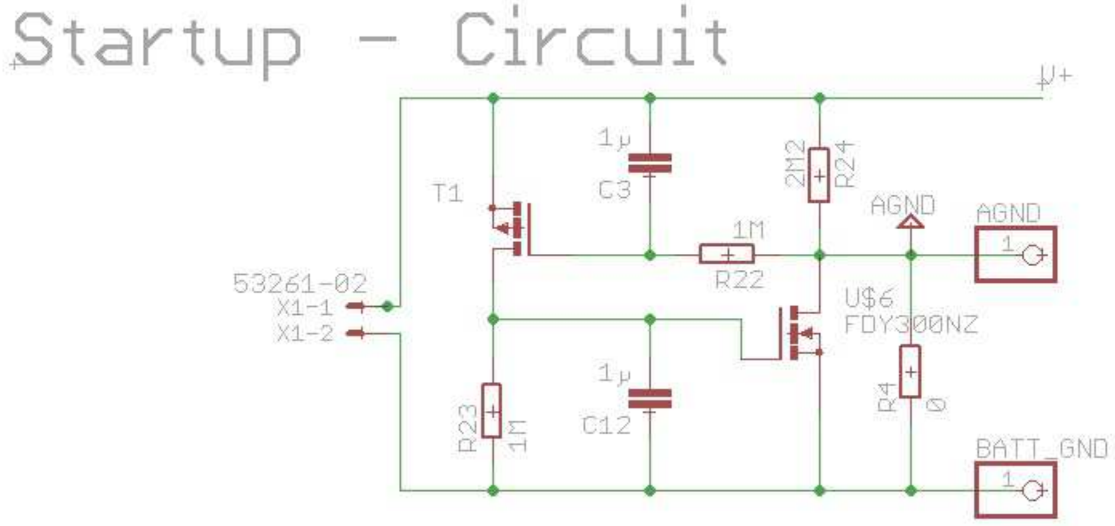

Figure 3.4: Startup - Circuit

To provide a constant voltage of 3.3 V at the signal processing unit the TPS61201 of Texas Instruments is used. The big advantage for this mobile application is that the TPS61201 only needs a quiescent current of about 55 μA and has a very high efficiency (approximately 90 % at 300 mA and 3.3 V output voltage) with low output ripple. The output voltage can be programmed with the voltage divider (R1, R2) or it is fixed inside the integrated circuit [45]. In this application the output voltage is fixed and is 3.3 V. In figure 3.5 the circuit of the TPS61201 in this application is pictured out.

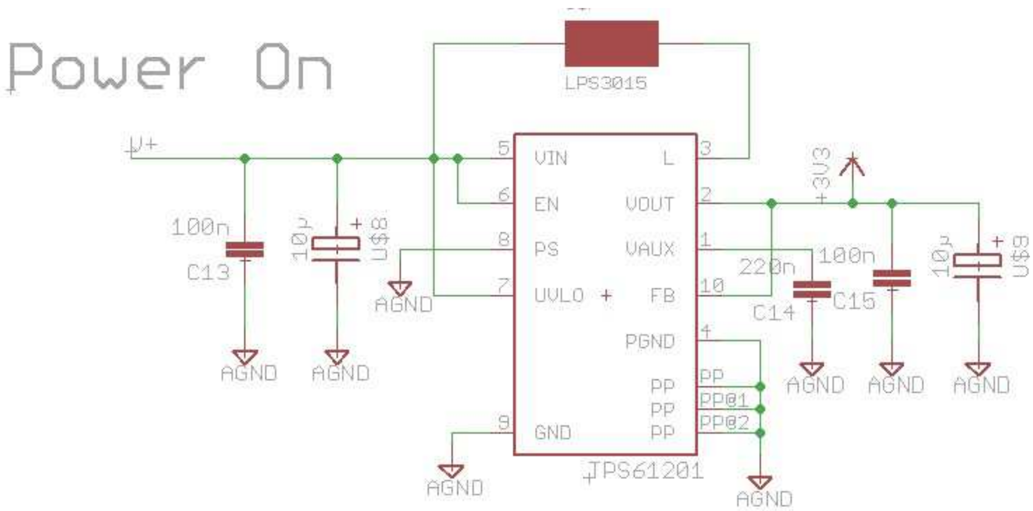

Figure 3.5: Circuit of the TPS61201

3.2.2 Communication with WearLink Strap

Figure 3.6 illustrates the block diagram of the communication with the WearLink Strap.

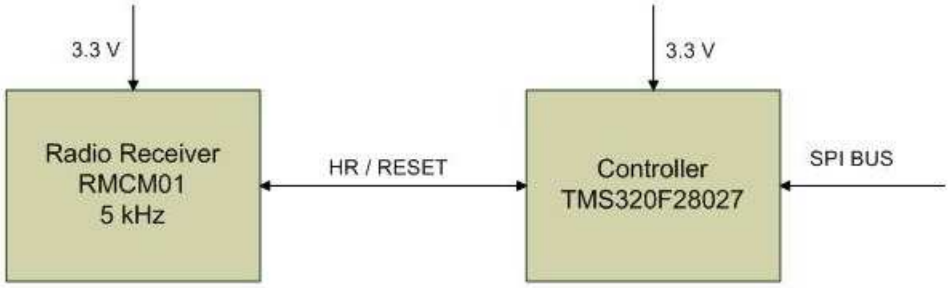

Figure 3.6: Communication with WearLink Strap

To communicate with the Polar WearLink Heart Rate Transmitter, which is connected to the strap and worn around the chest, the Polar RMCM01 OEM Wireless Receiver Module is needed. The WearLink Transmitter transmits a pulse corresponding to the heart beat and the RMCM01 module receives the signal and generates a digital pulse with an amplitude of 3 V and 1 ms width. If a coded transmitter is locked by the RMCM01 (that means only data from the coded transmitter is received), the generated pulse is output on the HR pin of the RMCM01 [46].

Figure 3.7 shows the measurement setup of the RMCM01 receiver module and in figure 3.8 a picture of the RMCM01 is illustrated.

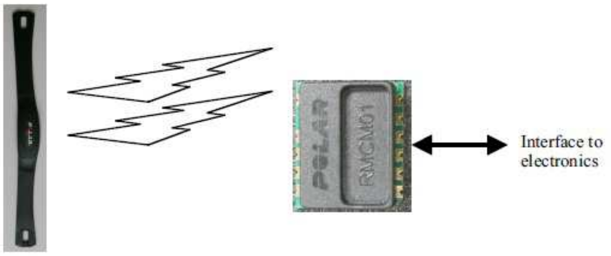

Figure 3.7: RMCM01 Measurement Setup [46]

Figure 3.8: RMCM01 Receiver Module [47]

The RMCM01 Receiver Module needs an operating current of approximately 50 μA, which suits very well for this mobile application [46].
The circuit of the RMCM01 module in this application is shown in figure 3.9.

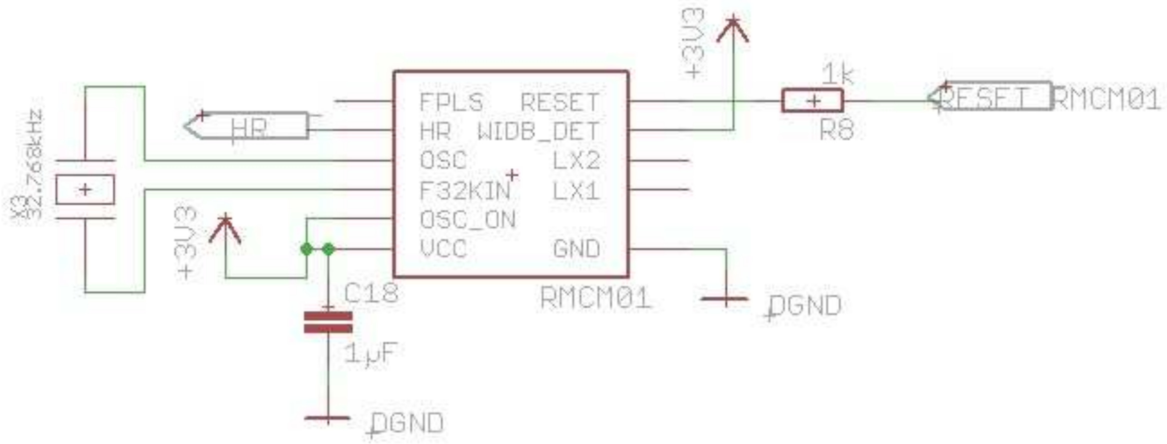

Figure 3.9: Circuit of RMCM01

3.2.3 Control Unit

The block diagram of the control unit section is pictured in figure 3.10.

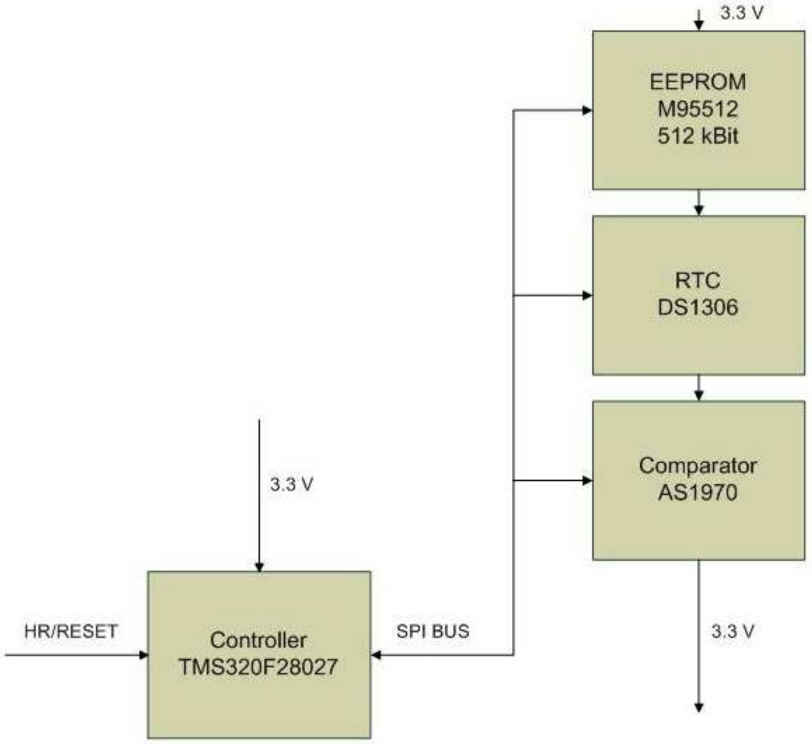

Figure 3.10: Block Diagram of Control Unit

To control all peripherals of the signal processing unit the μC (in the past this kind of microcontroller was counted among the digital signal processors) Piccolo TMS320F28027 from Texas Instruments is used. This μC is specially optimised for signal processing operations. It is a 32-bit CPU based on the C2000 processor, works with a clock frequency of 60 MHz and needs a supply voltage of 3.3 V. The storage capacity is 32K (16-bit-word) in FLASH and 6K (16-bit-word) in SARAM [48].

In operational mode the current consumption of the TMS320F28027 is approximately 100 mA, which is not very useful in a battery supplied application. But the TMS320F28027 provides three power down modes, which makes it suitable for a mobile application if an intelligent firmware operates on the controller. In the lowest power down mode, the so called HALT mode, the controller only needs approximately 60 μA supply current [48].

Figure 3.11 shows the functional overview of the TMS320F28027.

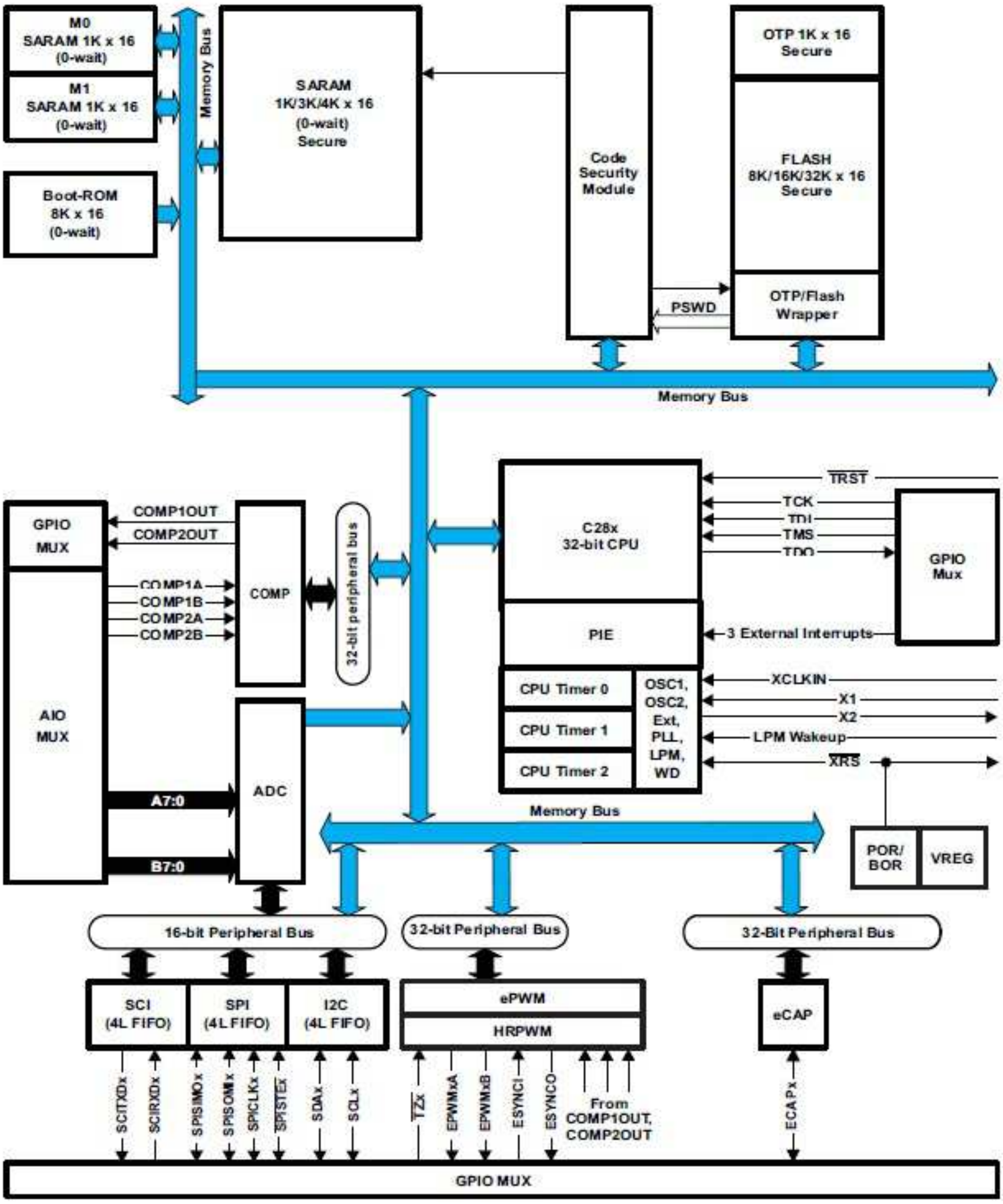

Figure 3.11: Functional Overview TMS320F28027 [48]

The following peripheral components of the TMS320F28027 are used

- Central Processing Unit (CPU) Timer 0
- Serial Peripheral Interface (SPI) Bus
- Enhanced Capture Module (eCAP)
- General Purpose Input/Output (GPIO) Pins

In figure 3.12 the circuit of the TMS320F28027 in this application is illustrated.

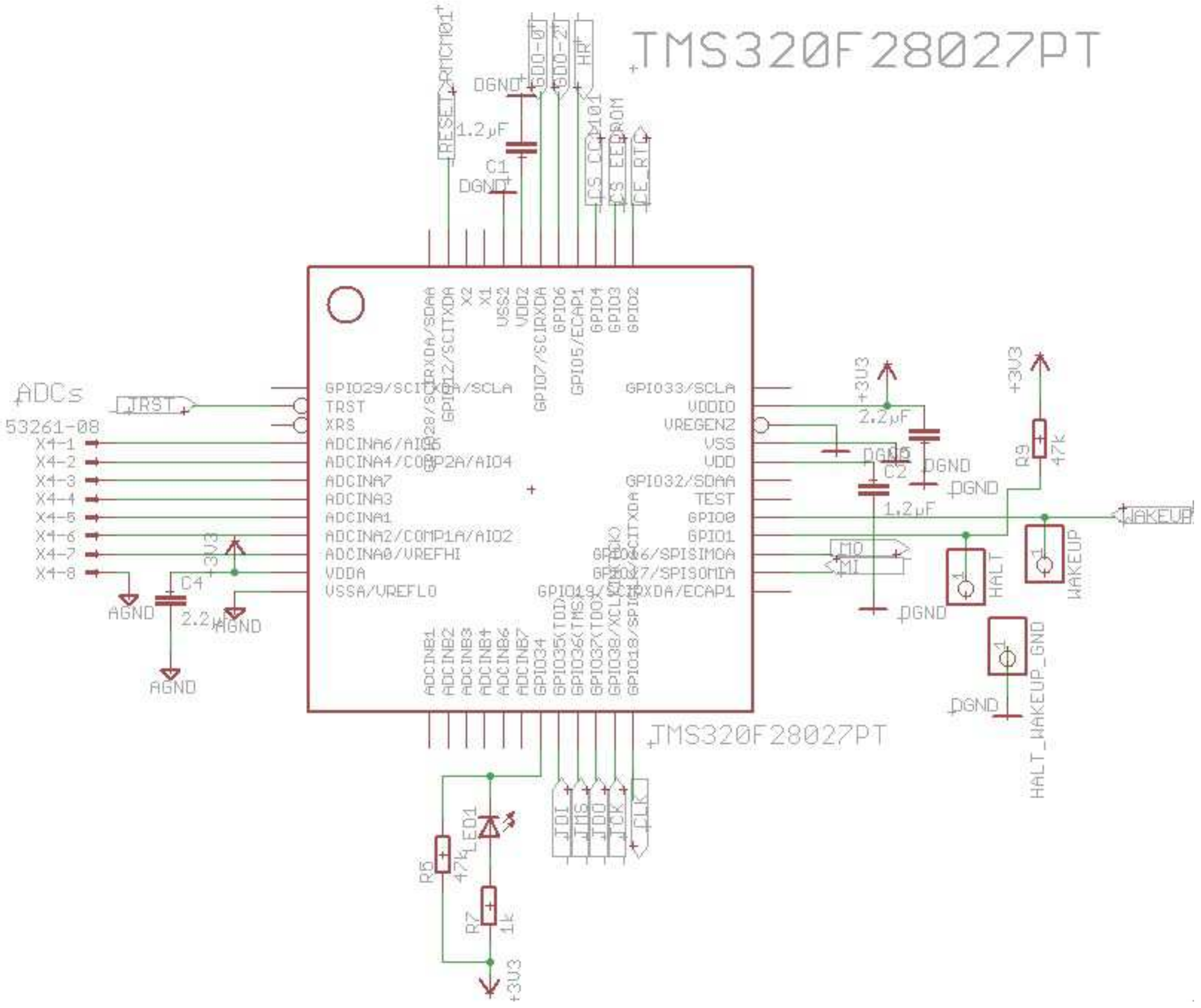

Figure 3.12: Circuit of TMS320F28027

To save the processed data a data storage is needed. In this application an EEPROM (Electrically Erasable Programmable Read Only Memory) from STMicroelectronics is used. In the following itemisation some properties of the M95512-R are listed [49].

- 64 kByte * 8 Bit → 512 kBit
- 2.5 - 5.5 V supply voltage
- Compatible with SPI bus serial interface
- Clock rate up to 20 MHz
- Byte and Page Write possible (up to 128 bytes)

In figure 3.13 the block diagram respectively the memory organisation of the M95512-R is shown.

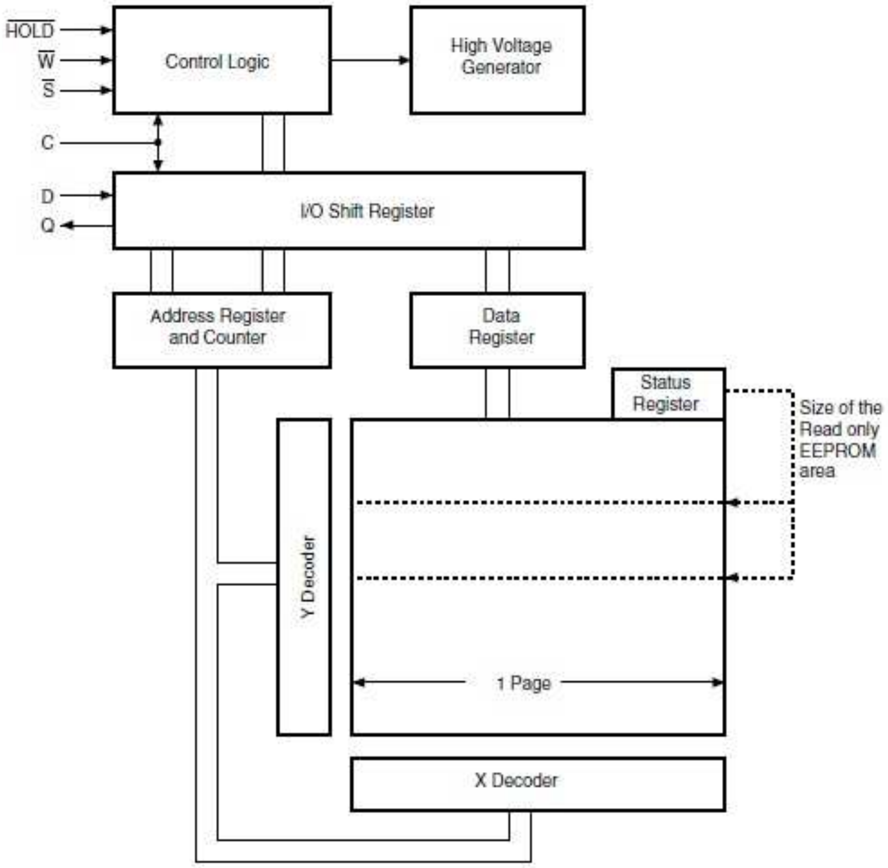

Figure 3.13: Block Diagram of the M95512-R [49]

Assuming that an average heart rate of 100 beats per minute is measured by the Signal Processing Unit. To save the RR interval between each beat, in this case 600 ms, a datatype of an integer is needed. So the number of possible saved values in the EEPROM is 32768 (64 kByte / 2 Bytes per integer). In that case (100 beats per minute) it is possible to measure approximately five hours until the data storage is full. It can be expected that at least once a day the storage is readout by the base station and it will not be required to measure more than five hours per day, so the data storage capacity of 512 kBit should be enough. In figure 3.14 the circuit of the EEPROM in this application is shown.

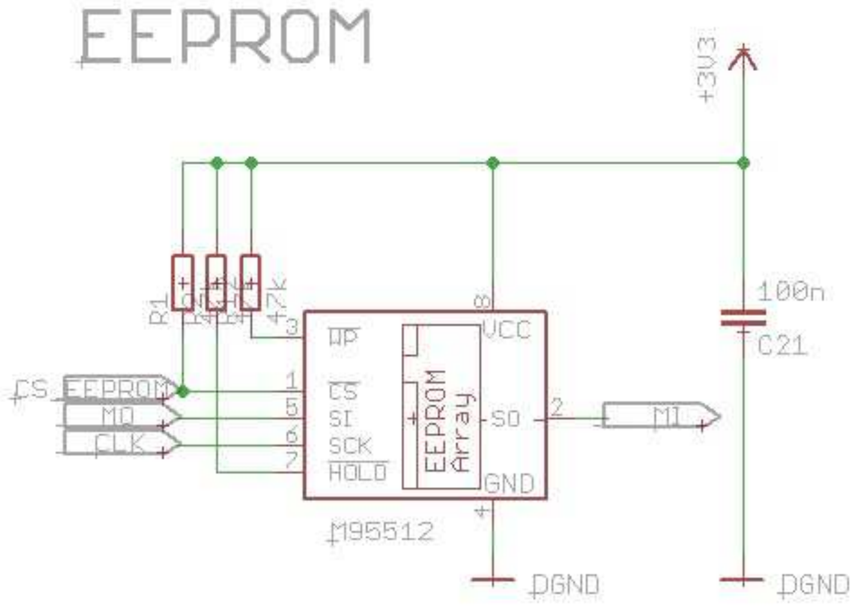

Figure 3.14: Circuit of EEPROM

To add a time stamp to each dataset an RTC (Real Time Clock) is needed. In this application the DS1306 from Maxim Integrated Products is used because of its special functionality. The DS1306 owns an alarm function which generates an 62.5 ms wide active-high pulse (low to high and high to low transition) [50]. A similar pulse is required to bring the TMS320F28027 out of the HALT mode. Only the generated positive pulse has to be inverted. To invert the pulse the comparator AS1970 by austriamicrosystems AG is used. So the RTC also has a kind of "controlling" functionality in this application.

In figure 3.15 the block diagram of the DS1306 is pictured.

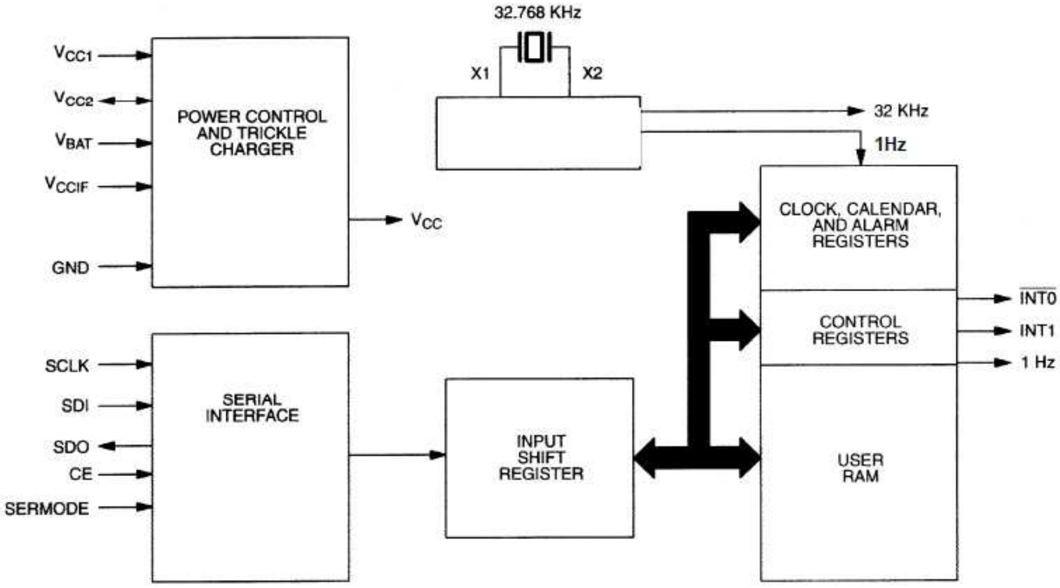

Figure 3.15: Block Diagram of the DS1306 [50]

The next itemisation shows some facts of the DS1306 [50].

- 2.0 - 5.5 V supply voltage range
- Supports SPI functionality
- Two Time-of-Day Alarms
- 62.5 ms wide interrupt pulse
- 600 nA quiescent current

Below one finds some properties of the AS1970: [51]

- 2.0 - 5.5 V supply voltage range
- Approximately 10 μA quiescent current

The next figure 3.16 illustrates the circuit of the DS1306 with the AS1970.

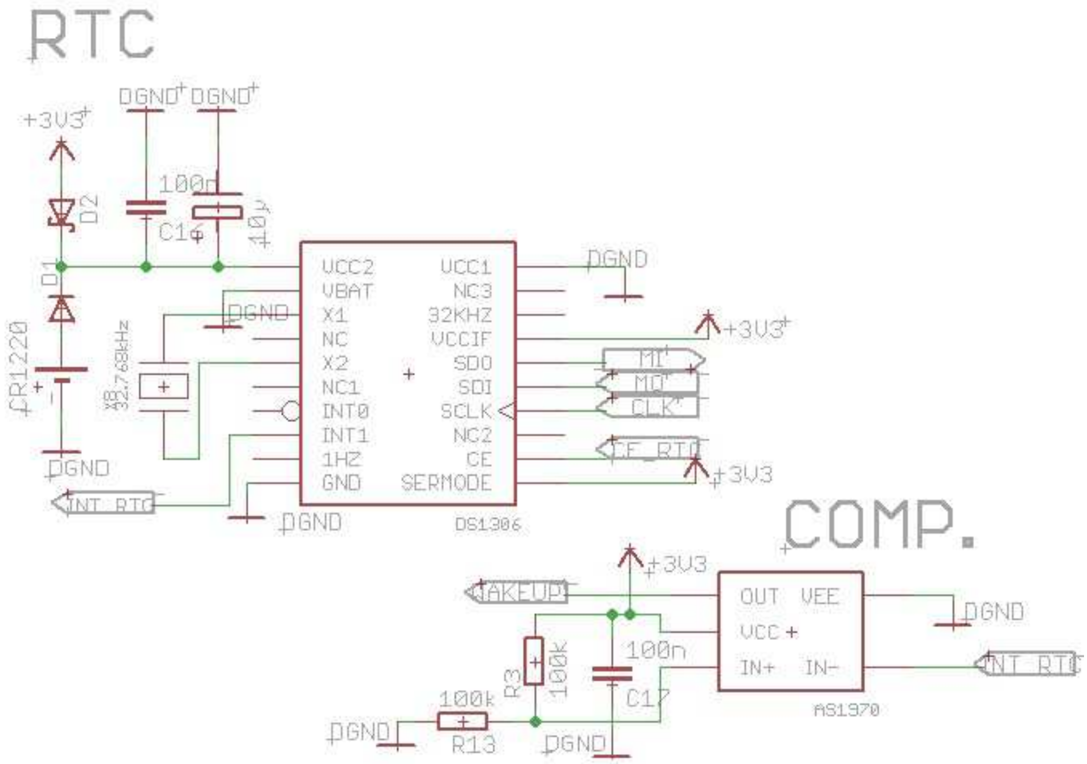

Figure 3.16: Circuit of DS1306 with AS1970

Maxim Integrated Products suggests three power configurations for the DS1306. In configuration 1 (figure 3.17) the DS1306 is backed up by a non - rechargeable energy source, e.g. a lithium battery. The system power supply must be connected to VCC1 and VCC2 must be grounded. Configuration 2 (figure 3.18) shows the DS1360 being backed up by a rechargeable energy source. Thereby VCC1 has to be connected to the primary power supply and VCC2 must be connected to the rechargeable energy source. In configuration 3 (figure 3.19) the DS1306 is in battery - operate mode. In this case VCC2 is connected to the battery, VCC1 and VBAT is grounded [50]. In this configuration the RTC is not being backed up, e.g. if the battery is changed or goes empty.

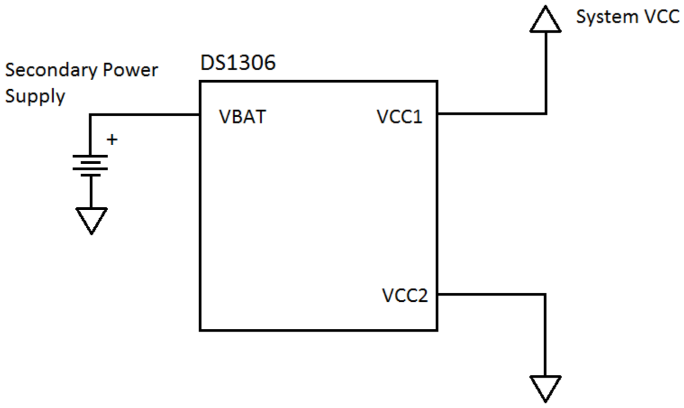

Figure 3.17: Supply Configuration 1 [50]

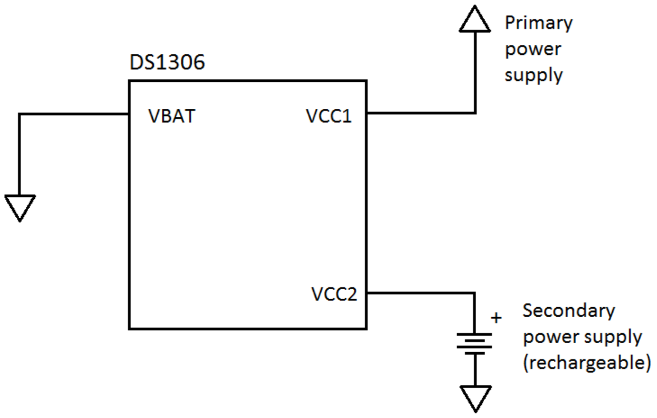

Figure 3.18: Supply Configuration 2 [50]

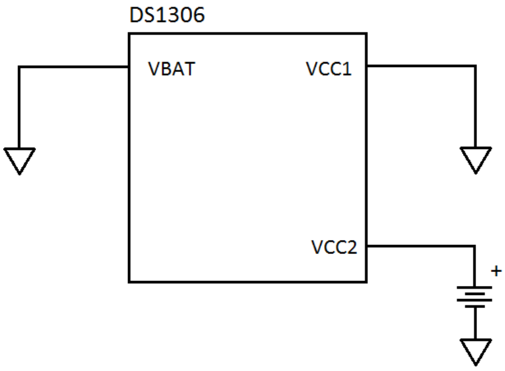

Figure 3.19: Supply Configuration 3 [50]

In this application (figure 3.16) the power is not applied as it is recommended by the data sheet of Maxim Integrated Products. The reason is, that the DS1306 must be powered by VCC2 or VBAT to throw the 62.5 ms interrupt pulse. So configurations 1 and 2 are not feasible for this application. In order to have a backed up RTC and to have the possibility to throw an interrupt pulse, the power configuration in figure 3.16 is used. Thereby the RTC is powered via the schottky diode D2 and if the battery has to be changed or is empty, the RTC will be powered by the backup battery CR1220 via the diode D1. The reason for D2 is that the backup battery should not supply the complete system if the primary supply is empty or missing.

3.2.4 Communication with Base Station

The communication with the base station is achieved by the CC1101 radio transceiver as illustrated in figure 3.20.

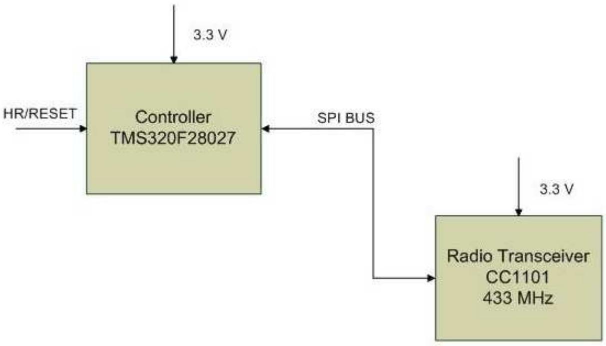

Figure 3.20: Communication with Base Station

Because of the high sensitivity (-112 dBm with 1.2 kBaud @ 433 MHz, 1% packet error rate), the low current consumption (approximately 15 mA receive mode, 200 nA sleep mode) and the programmable respectively adjustable ISM frequencies, the CC1101 from Texas Instruments is used. The CC1101 is designed for the ISM frequencies 315, 433, 868 and 915 MHz. In Europe the frequency band of 433 MHz is used [52].

In the next two pictures (figure 3.21 and figure 3.22) the pinout and the block diagram of the CC1101 are figured out.

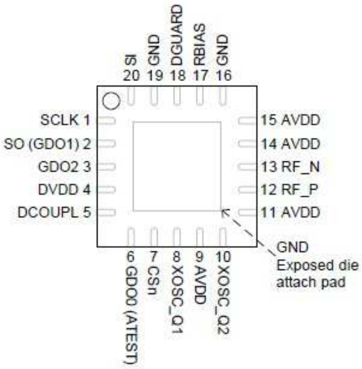

Figure 3.21: Pinout CC1101 [52]

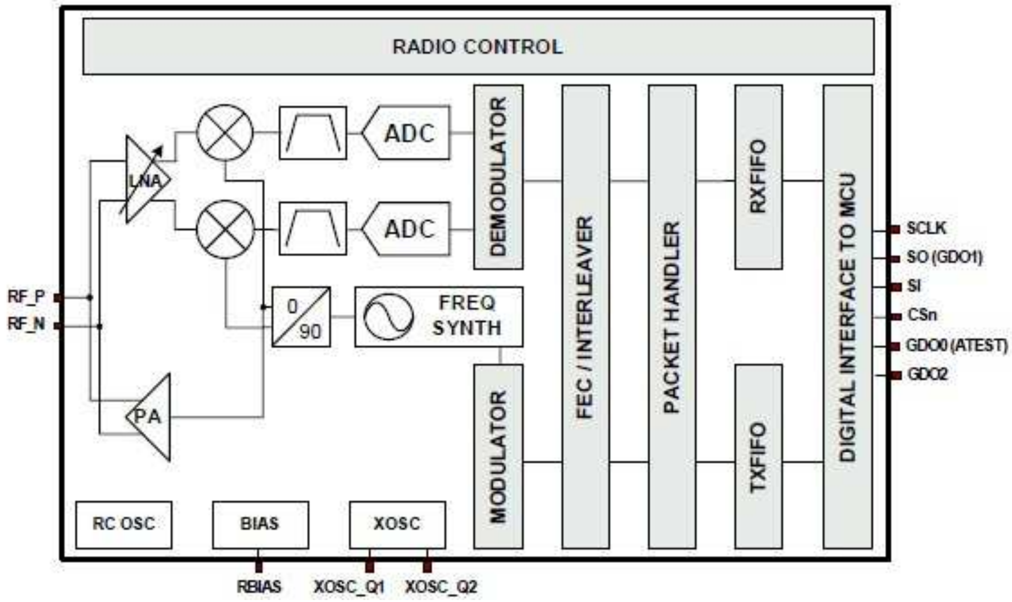

Figure 3.22: Block Diagram CC1101 [52]

In the following the CC1101 is described. The LNA (Low Noise Amplifier) receives the RF signal and amplifies it. Then the signal is down - converted to an I/Q signal and is digitised by the ADC (Analog to Digital Converter). Filtering, demodulation and AGC (automatic gain control) are processed digitally. The frequency synthesizer generates the transmitted signal by an on - chip VCO (Voltage Controlled Oscillator), 90 degree phase shifter and a modulator. At pin XOSC_Q1 and XOSC_Q2 a crystal has to be connected. This oscillator generates the reference frequency for the synthesizer, the ADC and the digital part [52]. The circuit of the CC1101 for this application is shown in Figure 3.23.

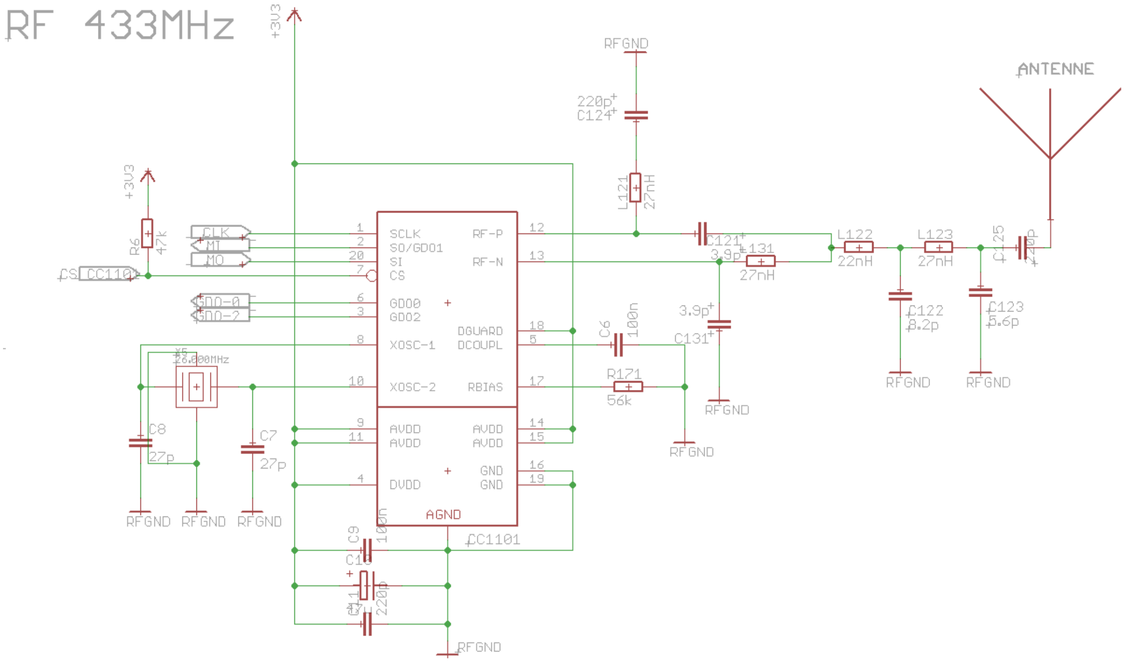

Figure 3.23: Typical Application CC1101

The RF input and output is represented by the two common pins RF_N and RF_P. The switching between receive and transmit is controlled by a special on-chip function. Only a few external passive components have to be attached to ensure a match in receive and transmit mode. The components C131, L131, L121 and C121 form a balun which is responsible for converting the differential RF signal to a single-ended RF signal. C124 and C125 provide DC blocking. The LC network L122, C122, L123, C123 transform the impedance to a 50 Ω load. For optimal performance it is important to follow the reference design of Texas Instruments [52].

The following figure 3.24 shows the symmetry of the balun and the LC network (illustrated in the yellow label). The balun is used to convert differential into single-ended signals. That symmetry is highly recommended in the reference design.

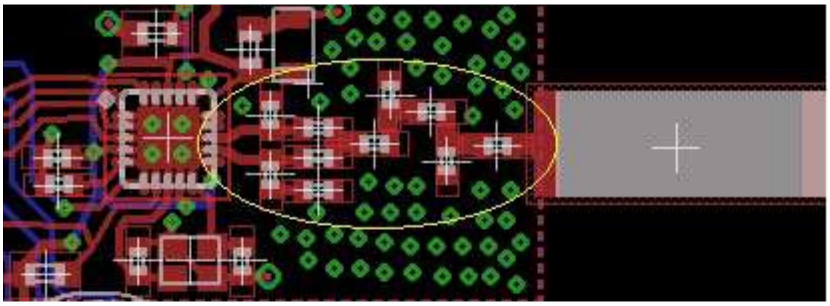

Figure 3.24: Layout respectively arrangement of the balun/LC network

To ensure having best signal strength, measurable with the RSSI (Received Signal Strength Indicator), it is very important to have a dedicated RF ground plane around the CC1101. The top and bottom layer should have the same ground and should be separated from other grounds. Figure 3.25 RF - GND, figure 3.26 Analog GND and figure 3.27 Digital GND are illustrating the separation of the different grounds on the PCB (printed circuit board).

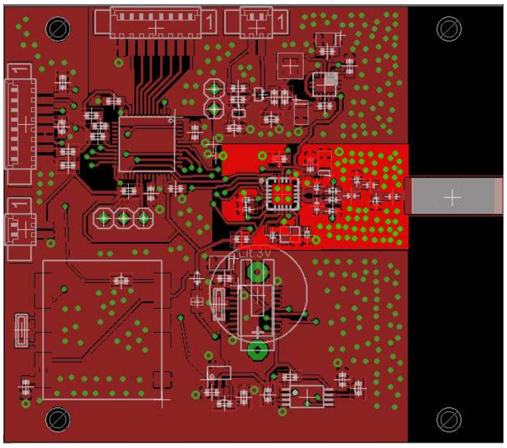

Figure 3.25: Layout RF - GND

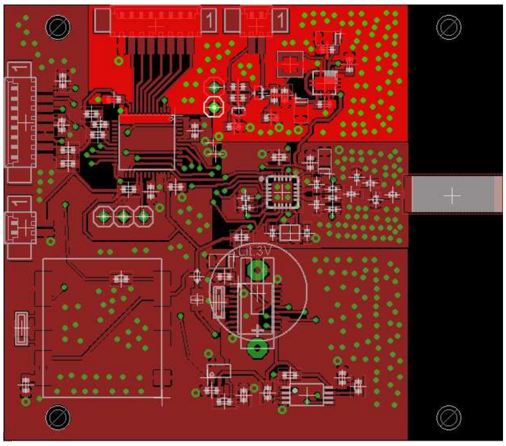

Figure 3.26: Layout A - GND

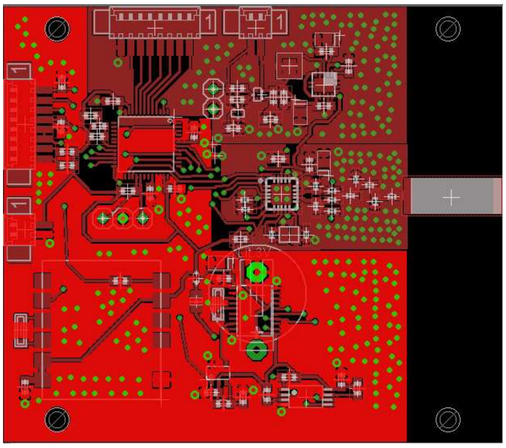

Figure 3.27: Layout D - GND

3.3 Firmware

This section deals with the flow of the program running on the Signal Processing Unit. Then the communication protocol with the base station is described. For more information about the communication protocol to the base station see [1].

3.3.1 Application Flow

The next points show the general functionality of the Signal Processing Unit:

- If there is no communication with the base station or measurement of the heart rate the Signal Processing Unit is in sleep mode to save power.
- Wake up every $T_{communication-interval}$ seconds and wait for inventory command.
- When there is no communication for $T_{communication-timeout}$ seconds switch back to sleep mode.
- The same applies if the communication is interrupted.
- If a dedicated number of communication intervals has been reached the Signal Processing Unit starts measuring and saves data.

For better understanding the firmware flow is illustrated with the help of a state diagram (figure 3.28).

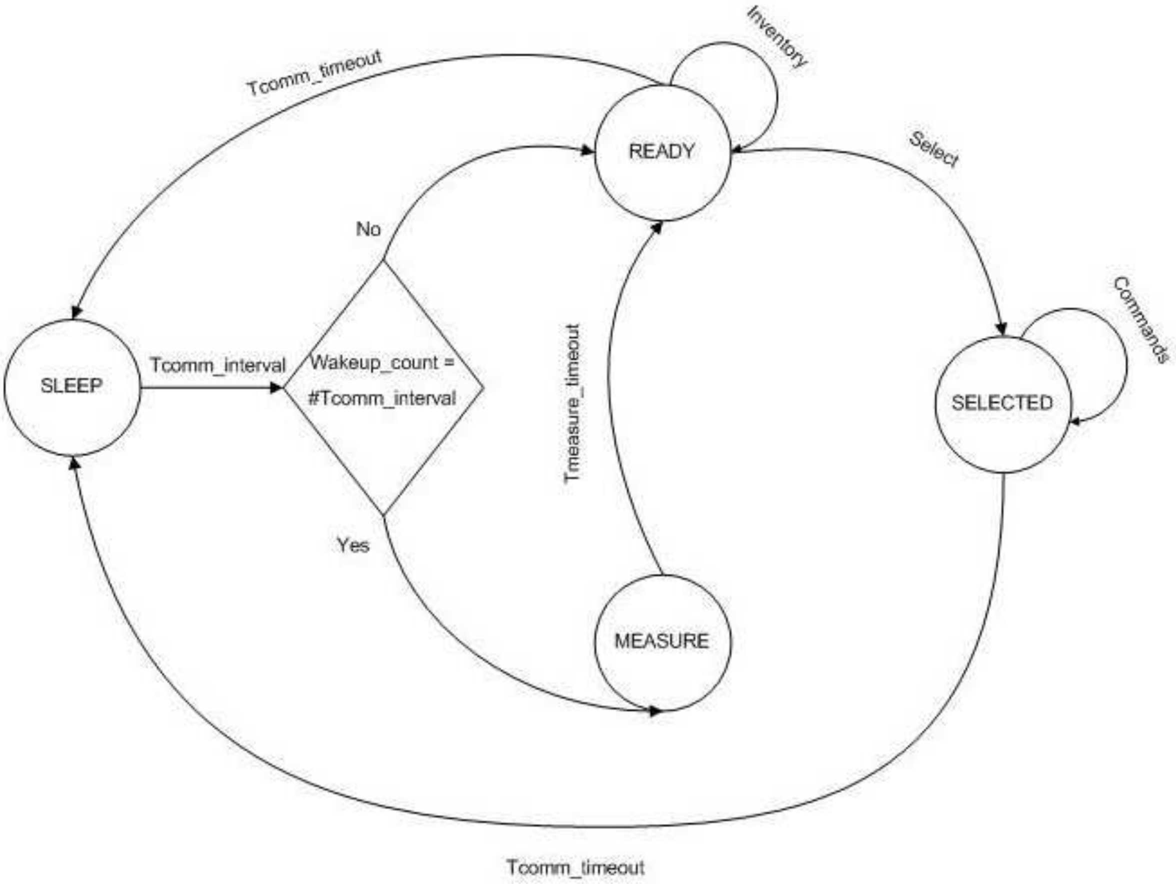

Figure 3.28: State Diagram of the SPU

To save power the Signal Processing Unit (SPU) is generally in "SLEEP" mode. In this state the current consumption is 277 μA (compare table 3.1).
Every "$T_{communication-interval}$" [seconds] the SPU switches into "READY" state where it stays for "$T_{communication-timeout}$" [seconds]. If a dedicated command is received, the "$T_{communication-timeout}$" is refreshed and changes into the "SELECTED" state. Now the SPU may receive different commands from the base station. These commands are described below. In the "SELECTED" state the SPU can be configured, data can be read out and so on. To avoid collisions between several SPUs within the operating range of the base station, only one SPU may be set in this mode. If no commands are received within "$T_{communication-timeout}$" [seconds], the SPU reverts to "SLEEP" mode. After a dedicated amount of "$T_{communication-interval}$" (Wakeup-count) is reached, "MEASUREMENT" state is selected. Once $T_{measurement-timout}$ expires the SPU reverts to "READY" state.

The default timeouts are defined as follows:

$T_{communication-interval}$	60 s
$T_{communication-timeout}$	2 s
$T_{measurement-timout}$	5 min

The data packets which are used for the communication between the Signal Processing Unit and the base station are defined as follows:

SOF	Length	Payload	EOF

Every packet starts with a SOF (Start of Frame) character, followed by the packet length and the payload. An EOF (End of Frame) character completes the packet.

SOF	0x7b "{"
EOF	0x7d "}"
Length	1 - 125

3.3.2 Signal Processing Unit Instruction Set

This section describes the commands of the Signal Processing Unit (SPU).

Inventory with Anti Collision ("I")

An Inventory Command with round number is used to avoid collisions when multiple Signal Processing Units (SPUs) are in operating range. In combination with the "Quiet" Command every SPU in operating range is detected.
The approach is as follows:

- A round number is generated $\neq$ 0x00.
- Inventory and round number is sent by the base station respectively the host computer.
- Signal Processing Units reply after a random delay (0...300ms).

- Host sends quiet command to detected Signal Processing Units → affected SPUs do not reply for inventory commands in this round anymore.
- After $2 \cdot T_{communication-interval}$ one inventory round will be finished.

Inventory with Anti Collision Data Packet:

Command	"I" (0x49)
Parameter	Current Round (1 Byte $\neq$ 0x00)
SPU Response	Serial Number (8 Byte)

Quiet ("-")

Located SPUs are approved by the Quiet Command. The affected SPU answers with its Serial Number and ignores further Inventory Commands in this Inventory Round.

Quiet Data Packet:

Command	"-" (0x2d)
Parameter	Serial Number (8 Byte)
SPU Response	Serial Number (8 Byte)

Select ("S")

This command selects the SPU. Typically only one SPU is in Selected Mode.

Select Data Packet:

Command	"S" (0x53)
Parameter	Serial Number (8 Byte)
SPU Response	Serial Number (8 Byte)

The next commands can only be executed if the SPU has been in Selected State before.

Unselect ("U")

This Command forces the SPU in Ready State.

Unselect Data Packet:

Command	"U" (0x55)
Parameter	
SPU Response	Serial Number (8 Byte)

Erase Data ("E")

This command deletes the content of the EEPROM.

Erase Data Data Packet:

Command	"E" (0x45)
Parameter	
SPU Response	Acknowledge (1 Byte)

Get Measurement Count ("A")

This command delivers the number of measurements saved in the EEPROM.

Get Measurement Count Data Packet:

Command	"A" (0x41)
Parameter	
SPU Response	Number of Measurements (2 Byte)

Get Measurement Info (”G”)

This Command delivers the number of data, date and time of the selected measurement.

Get Measurement Info Data Packet:

Command	”G” (0x47)
Parameter	Measurement Number (2 Byte)
SPU Response	Number of data in this measurement (2 Byte) Date: Day, Month, Year (3 Byte) Time: Hour, Minute, Second (3 Byte)

Read Data (”R”)

This command sends all data of the selected measurement to the host.

Read Data Data Packet:

Command	”R” (0x52)
Parameter	Measurement Number (2 Byte)
SPU Response	Data (2 Byte)

Set Time (”T”)

This command sets the date and time for the Real Time Clock.

Set Time Data Packet:

Command	”T” (0x54)
Parameter	Date: Day, Month, Year (3 Byte) Time: Hour, Minute (2 Byte)
SPU Response	Acknowledge (1 Byte)

Get Time ("B") This command delivers the actual date and time of the Real Time Clock.

Get Time Data Packet:

Command	"T" (0x42)
Parameter	
SPU Response	Date: Day, Month, Year (3 Byte) Time: Hour, Minute,Second (3 Byte)

For programming the TMS320F28027 the Code Composer Studio Version 4.1.1 as Integrated Developement Environment has been used. The CCS (Code Composer Studio) consists of the following parts:

- Editor
- C2000 Compiler
- Linker
- Debugger

For emulation respectively programming the XDS100V2 USB JTAG Emulator from Spectrum Digital Inc. has been used. Figure 3.29 illustrates the emulator.

Figure 3.29: JTAG Emulator XDS100V2

Chapter 4

Evaluation and Results

This chapter deals with the evaluation of the signal processing hardware developed in this thesis. Therefore a heart rate measurement on a cow has been realised and the measured data have been interpreted respectively analysed. The measuring has been accomplished in cooperation with the Institute for Animal Husbandry and Animal Health at the Agricultural Research and Education Centre in Raumperg Gumpenstein Austria. The represantatives of this institute enabled the evaluation by ”providing” a cow to carry out a heart rate measurement.

4.1 Heart Rate Measurement on Cows

To measure the heart rate of a cow, a Polar Equine WearLink Strap has been used. This strap is normally used by horses to measure the state of fitness. Due to the similar size of these animals it is possible to use the Polar Equine WearLink Strap on cows as well. It must be attached around the chest, with one electrode near to the heart. In figure 4.1 the strap with the electrodes is illustrated.

Figure 4.1: Polar Equine WearLink Strap

To transmit the RR values from the Strap to the Signal Processing Unit, a Polar WearLink Transmitter has to be applied on the strap. Therefore a coded 5 kHz transmitter is used, because the RMCM01 receiver module works at this frequency as well. Figure 4.2 shows the transmitter and figure 4.3 illustrates how the transmitter is mounted on the strap.

Figure 4.2: Polar WearLink Coded Transmitter

Figure 4.3: Mounted WearLink Transmitter

The Signal Processing Unit is attached next to the transmitter, because the operating range of the transmitter is only about 90 cm [46] [47]. Figure 4.4 shows the complete system attached to the cow.
The Signal Processing PCB (Printed Circuit Board) is fixed in a case from OKW GmbH. The accurate labeling of the case is Ergo - Case S, flat and has dimensions of:

- Length: 80 mm
- Width: 96 mm
- Height: 32mm

The biggest possible size of the PCB which fits into the case may have dimensions of:

- Length: 65 mm
- Width: 56 mm

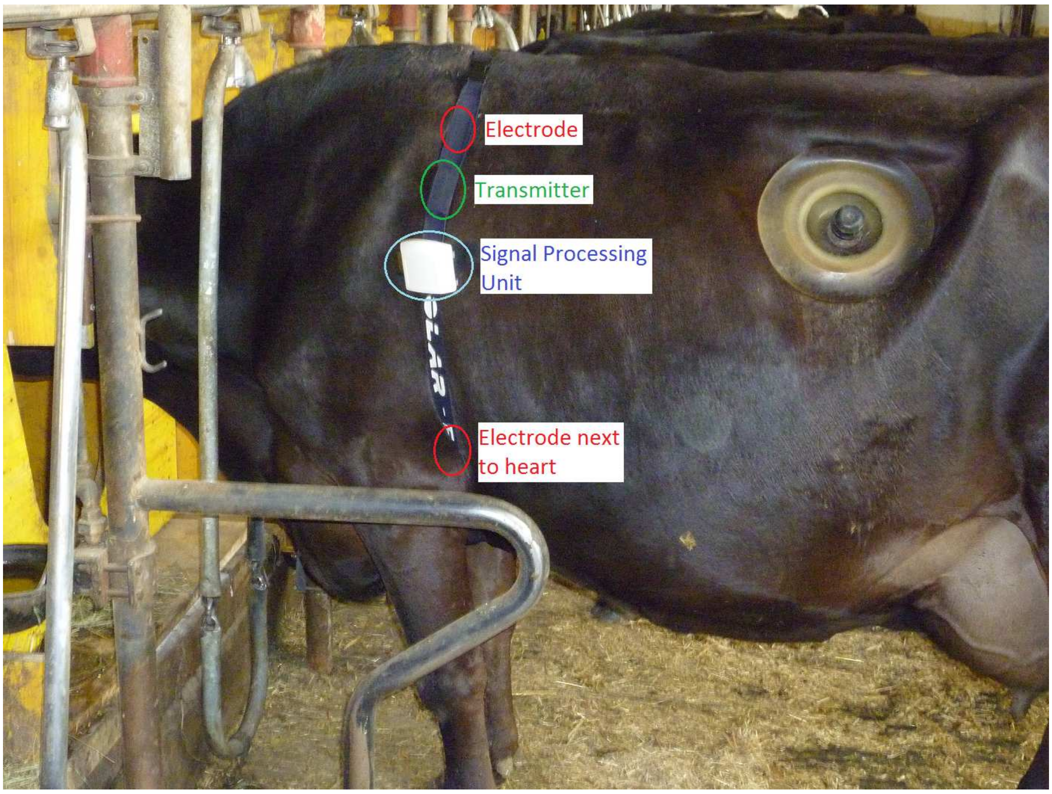

Figure 4.4: Complete System mounted on cow

With this specifications the dimensions of the Signal Processing PCB are determined. The next two pictures (figure 4.5, figure 4.6) illustrate the case.

Figure 4.5: OKW case front

Figure 4.6: OKW case back with strap fixation

This case has its own battery compartment, with space for two AAA batteries. In figure 4.7 the battery compartment is shown.

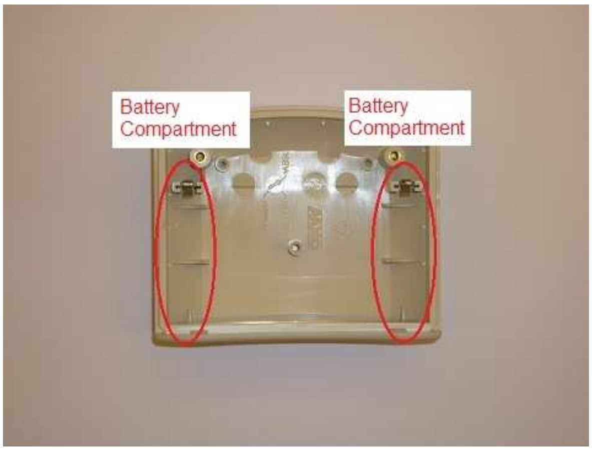

Figure 4.7: OKW Case with Battery Compartment

Picture 4.8 illustrates the PCB integrated into the case.

Figure 4.8: PCB mounted into the case

The evaluation measurement has been carried out on a tethered cow in a barn of the Institute for Animal Husbandry and Animal Health. During data acquisition the cow got fed, had lain on the floor or was simply standing and ruminating. The next two pictures shows the cow standing (figure 4.9) respectively lying (figure 4.10) on the floor during measurement.

Figure 4.9: Cow standing tethered in barn

Figure 4.10: Cow lying tethered in barn

The communication intervals were adjusted as follows:

- $T_{communication-timeout}$ = No timeout selected
- $T_{measurement-timout}$ = 30 min
- $T_{communication-interval}$ = until all data have been read out

This means that HR data was acquired for 30 minutes and then read out by the base station until all data have been read out. The total measurement duration was approximately 2.5 hours. All in all 10329 values have been measured. The quantity of the several measurments were as follows:

Time	**Quantity of Data Record**	**Activity of Cow**
13:30 - 14:00	2063	Not feeding, standing
14:00 - 14:30	2080	Not feeding, lying
14:30 - 15:00	2008	Concentrated feed, standing
15:00 - 15:30	2112	Concentrated feed, standing
15:30 - 16:00	2066	Ruminating, standing

Between 14:30 and 15:00 o'clock was the concentrated feed given in the approximately first five minutes (14:30 - 14:35 o'clock). The second concentrated feeding was at the end of the measurement, that means at approximately 15:25 - 15:30 o'clock.

In figure 4.11 all measured RR values and in picture 4.12 all measured RR values projected to the heart rate are illustrated.

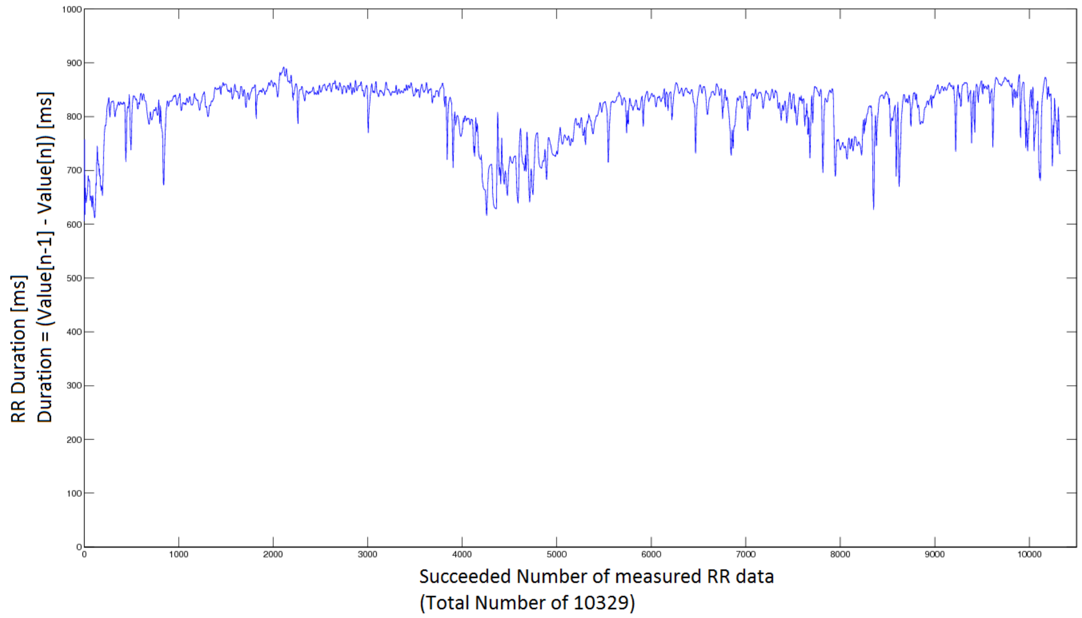

Figure 4.11: RR Data vs. actual Number of Measured Value

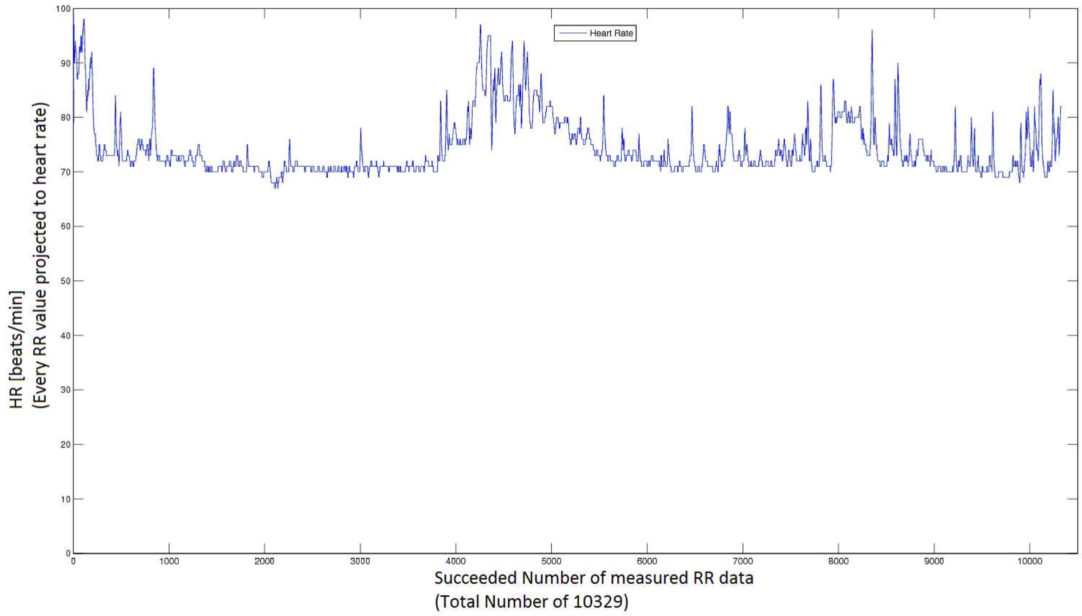

Figure 4.12: HR Data vs. actual Number of Measured Value

The next picture (figure 4.13) shows the RR values with markings to several measurements, time and activity.

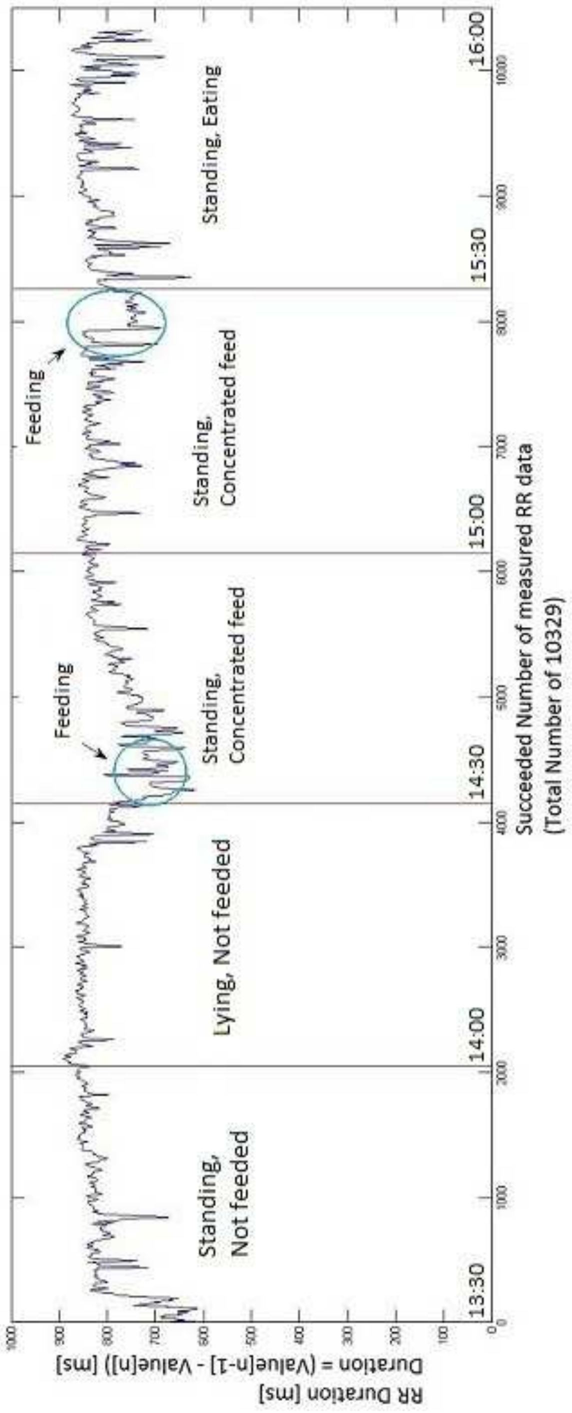

Figure 4.13: RR Data vs. actual Number of Measured Value with Marking

4.2 Signal Analysis

The interpretation of the heart rate variability curve (figure 4.13) has been done by Dr. Johann Gasteiner, head of the Institute for Animal Husbandry and Animal Health at the Agricultural Research and Education Centre in Raumperg Gumpenstein Austria:

"Heart Rate Variability in a 6 year old Holstein Frisian cow - interpretation

Heart Rate Variability (HRV) in humans and in animals, like many other physiological parameters, is influenced by a great number of different factors like species, sex (female: pregnant or not), age, diurnal rhythms, respiration, posture and fitness level. So it is very important to standardize and to control circumstances under which HRV data are recorded. In our case, a 6 year old, non pregnant and clinical healthy Holstein Frisian cow was used to conduct the measuring of HRV. The animal was kept under tied housing conditions in the barn as usual. HRV measuring was carried out while the animal was standing, lying and while the animal was fed concentrate. The cow was ruminating during the last period. It can be seen in figure 4.13, that HRV is reacting very sensitive due to the physiological stressor "feeding". At the same time the pulse rate increased, HRV decreased. Periods of standing, lying or ruminating did not show any alteration of HRV. Measurement of HRV as a non invasive technique can be used for investigating farm animals to demonstrate balance or imbalance between sympathetic and vagal activity. HRV has great potential to contribute much to our understanding of stress in farm animal's welfare."

The HRV analysis in the frequency domain has been done with a matlab based program called Kubios HRV from the Biosignal Analysis and Medical Imaging Group at the Department of Physics at the University of Kuopio Finland. This program is used for advanced heart rate variability analysis and calculates all the commonly used time-, frequency- and nonlinear- domains (compare table 2.1 in chapter 2.2.1 Heart Rate Variability). More Information about this software may be found in [53].

In this analysis the following parameters are calculated:

- VLF - Very Low Frequency [Hz]
- LF - Low Frequency [Hz]
- HF - High Frequency [Hz]

The frequency bands are commonly used and within the following limits [53]:

- VLF = 0 - 0.04 Hz
- LF = 0.04 - 0.15 Hz
- HF = 0.15 - 0.4 Hz

As described in chapter 2.3 Heart Rate/Heart Rate Variability and Stress in Context, the vagal (parasympathetic) activity can be seen in the HF component. A low parasympathetic tone (HF component) is identified with a high stress sensitivity.

For analysing the heart rate curve in figure 4.13 three parts have been taken out. First a frequency domain calculation of the whole curve is carried out. Afterwards the difference between a lying respectively resting position and a feeding one is shown.

Figure 4.14 shows the complete HRV curve (yellow background) for analysing.

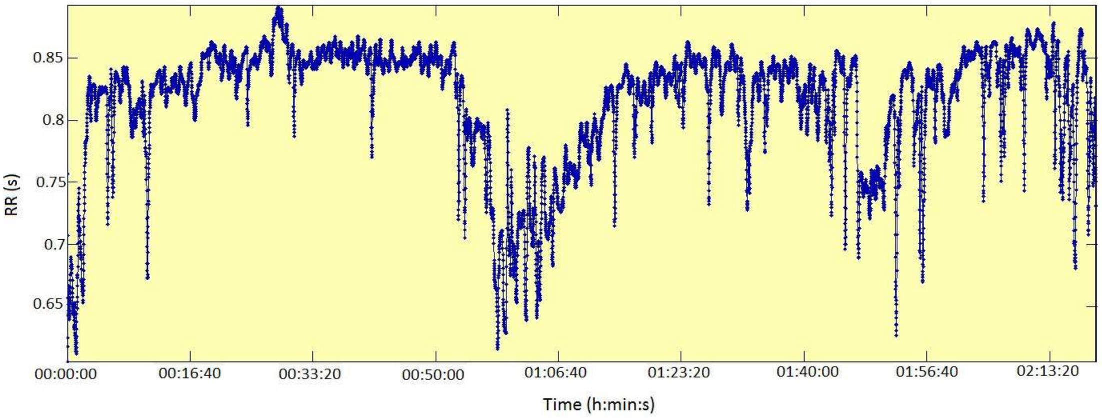

Figure 4.14: RR (s) vs. Time (h:min:s)

The results in frequency domain are pictured out in figure 4.15 and table 4.1.

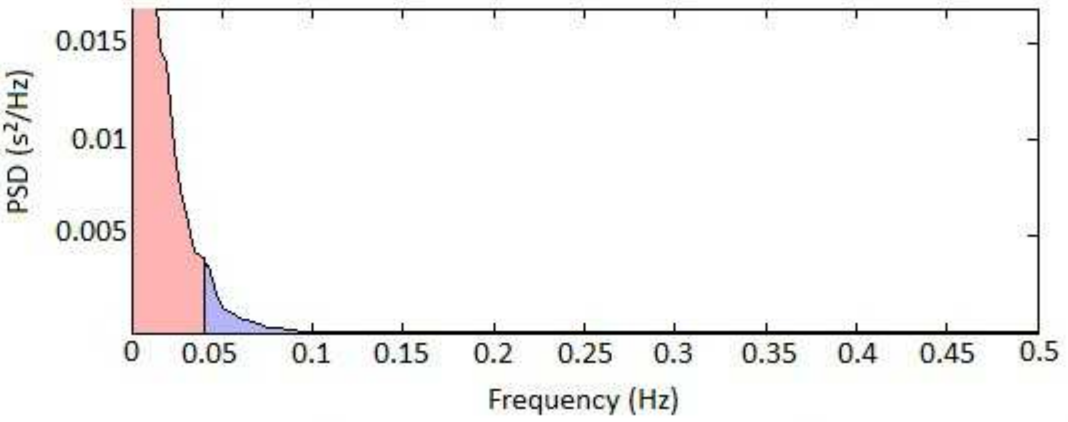

Figure 4.15: PSD (s^2/Hz) vs. Frequency (Hz)

Frequency Band	**Peak [Hz]**	**Power ms^2**	**Power %**
VLF	0.0000	1690	97.1
LF	0.0430	49	2.8
HF	0.1758	1	0.1
LF/HF			40.3

Table 4.1: Frequency Domain Results

The results in time domain are shown in figure 4.16 and table 4.2.

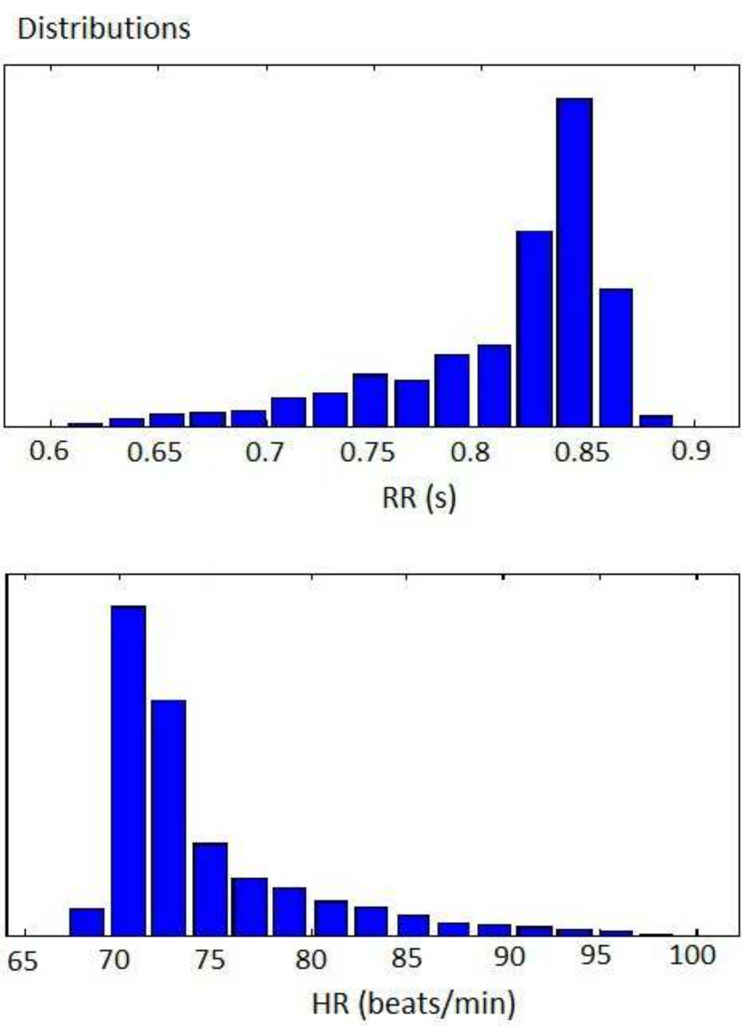

Figure 4.16: Time Domain Results

Variable	**Units**	**Value**
Mean RR	[ms]	811.5
STD RR (SDNN)	[ms]	52.1
Mean HR	[1/min]	74.27
STD HR	[1/min]	5.32
RMSSD	[ms]	3.6

Table 4.2: Time Domain Results

In the frequency domain analysis power spectrum density (PSD) of the RR values is computed and VLF, LF and HF is calculated. The FFT spectrum (power density spectrum) shows a very low HF component (only 0.1 % of the PSD), hence a low vagal activity. It might be said that this is due to a high stress sensitivity during the whole measurement. The VLF with 97.1 % is much less defined for physiological explanations [8]. The LF component is 2.8 % of the PSD and very low as well. Because of a controversial interpretation of the LF component, which is considered by some as a marker of sympathetic modulation and by others as a parameter that includes both sympathetic and vagal influences [8], it is not an important component for this analysis.
In time domain analysis the distributions of the RR - intervals and projected heart rates are illustrated. The mean heart rate is 74.27 [beats/min] which is very high for cows and it might be said this is due to a high stress sensitivity as well.

The next two analyses show the difference between the lying respectively resting position and feeding. For this calculation a five minute window has been taken due to duration of five minutes feeding. Figure 4.17 illustrates the analysed part (yellow background, lying position) of the complete HRV curve.

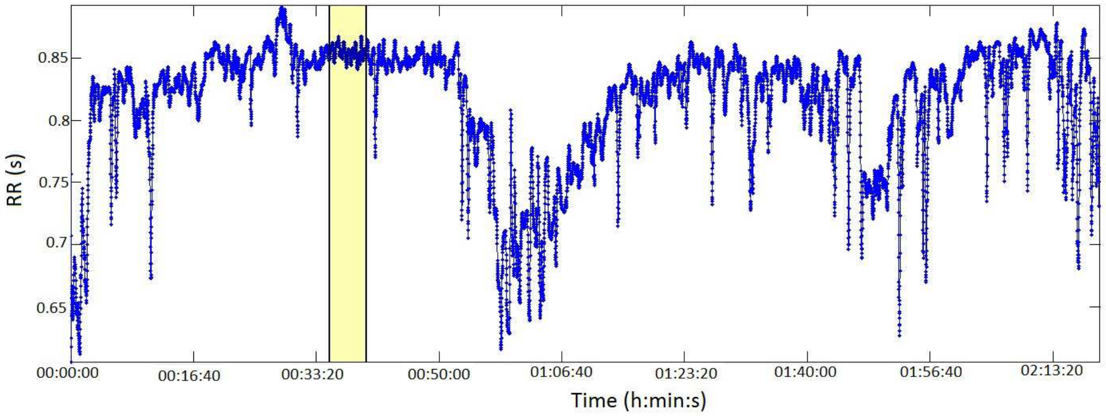

Figure 4.17: RR (s) vs. Time (h:min:s), lying position

The results in frequency domain are illustrated in figure 4.18 and table 4.3.

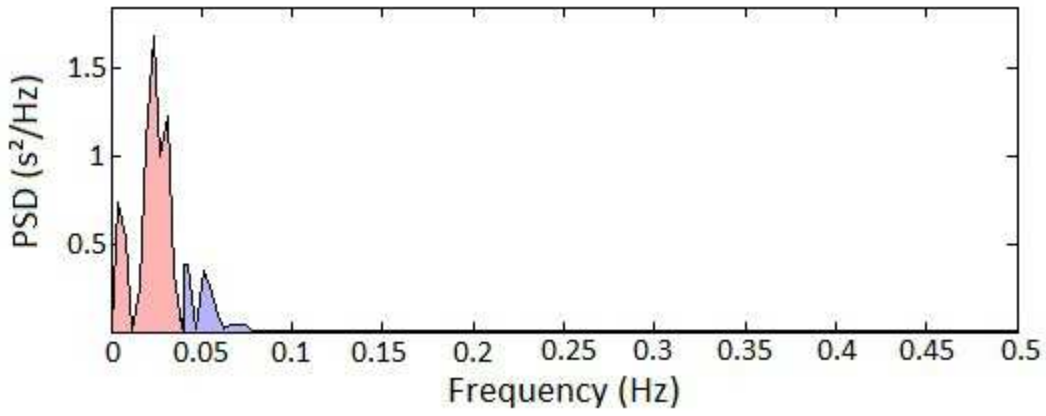

Figure 4.18: PSD (s^2/Hz) vs. Frequency (Hz), lying position

Frequency Band	**Peak [Hz]**	**Power ms^2**	**Power %**
VLF	0.0234	27	84.3
LF	0.0430	5	15.5
HF	0.1641	0	0.2
LF/HF			98.6

Table 4.3: Frequency Domain Results, lying position

The results in time domain are shown in figure 4.19 and table 4.4..

During lying the mean heart rate is 70.22 [beats/min]. The VLF component is about 84.3 % of PSD. With 15.5 % of PSD the LF component is much higher than during the whole measurement (2.8 % of PSD). Only the HF component is similar (0.1 % during whole measurement compared to 0.2 % during lying).

Variable	**Units**	**Value**
Mean RR	[ms]	854.5
STD RR (SDNN)	[ms]	5.8
Mean HR	[1/min]	70.22
STD HR	[1/min]	0.48
RMSSD	[ms]	1.1

Table 4.4: Time Domain Results, lying position

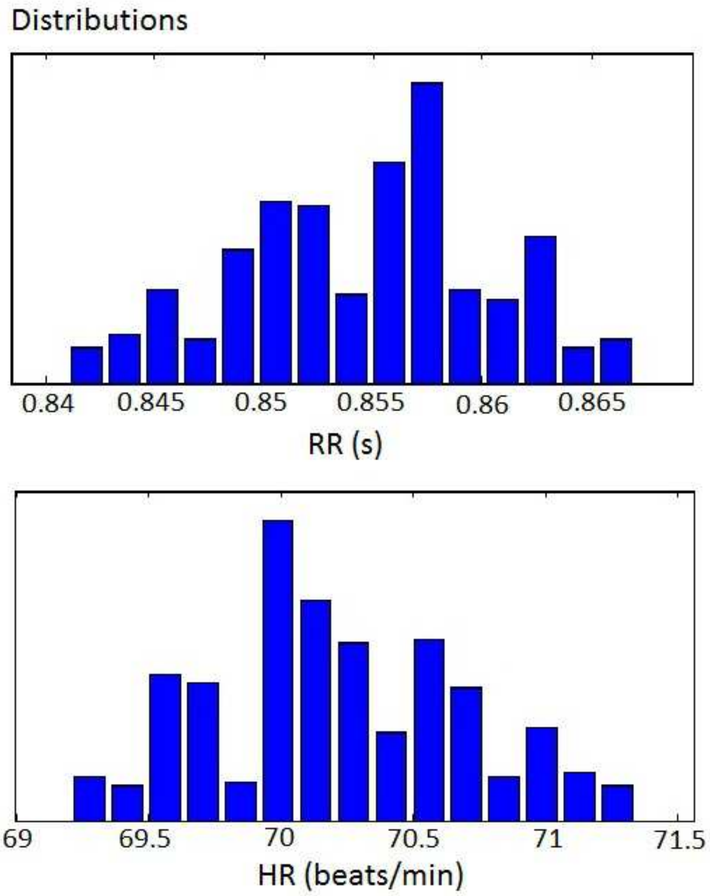

Figure 4.19: Time Domain Results, lying position

Picture 4.20 shows the analysed part (yellow background, feeding) of the complete HRV curve.
The results in frequency domain are illustrated in figure 4.21 and table 4.5.

Frequency Band	**Peak [Hz]**	**Power ms^2**	**Power %**
VLF	0.0234	1149	96.9
LF	0.0469	36	3.0
HF	0.1914	1	0.1
LF/HF			32.1

Table 4.5: Frequency Domain Results, during feeding

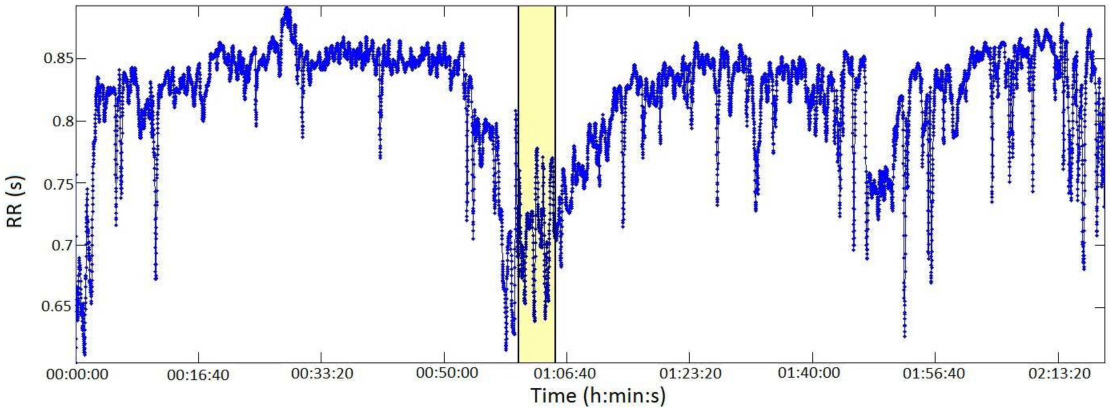

Figure 4.20: RR (s) vs. Time (h:min:s), during feeding

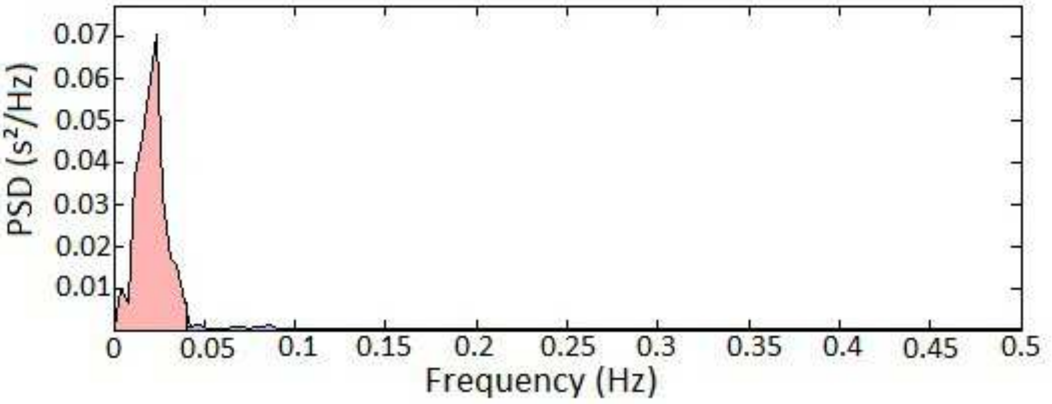

Figure 4.21: PSD (s^2/Hz) vs. Frequency (Hz), during feeding

The results in time domain are shown in figure 4.22 and table 4.6.

Variable	**Units**	**Value**
Mean RR	[ms]	709.0
STD RR (SDNN)	[ms]	33.9
Mean HR	[1/min]	84.82
STD HR	[1/min]	4.07
RMSSD	[ms]	4.1

Table 4.6: Time Domain Results, during feeding

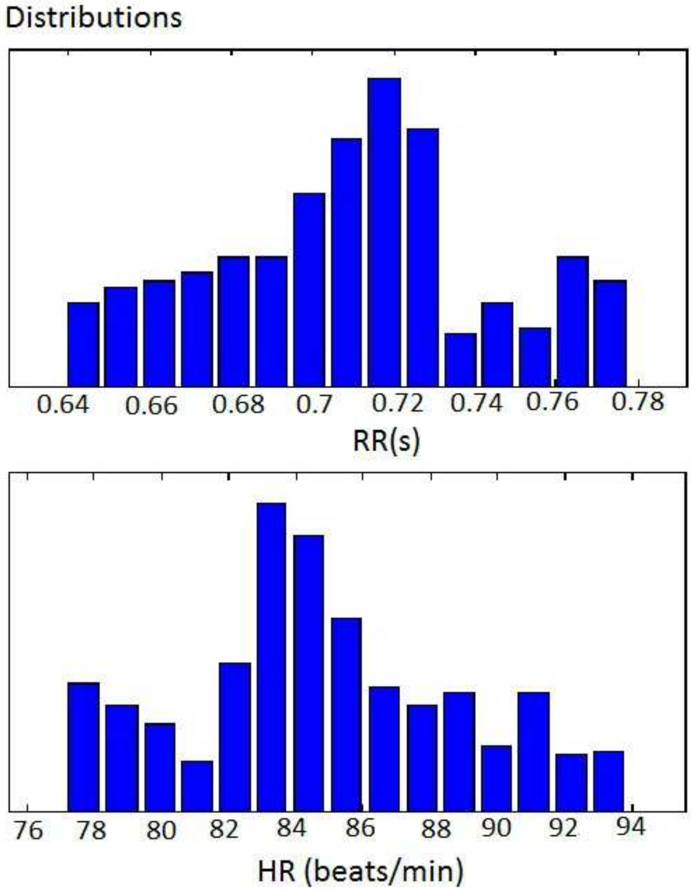

Figure 4.22: Time Domain Results, during feeding

The difference of the mean heart rates (lying position compared to feeding state) is 14.6 [beats/min] (figure 4.22 and figure 4.19, 84.82 [beats/min] during feeding and 70.22 [beats/min] during lying). Comparing the mean heart rate of lying and feeding state it can be said that the cow is reacting very sensitive due to the physiological stressor ”feeding”.

There is a big difference between both LF components as well. During feeding the LF component is much lower (3 % of PSD) than during lying (15.5 % of PSD). Unfortunately no big difference in the HF component (only 0.1 % of PSD) is seen due to high stress sensitivity during the whole measurement.

Chapter 5

Conclusion and Outlook

In the present work a wireless heart rate measurement system to determine heart rate variability has been developed. This device has been evaluated on a cow at the Institute for Animal Husbandry and Animal Health at the Agricultural Research and Education Centre in Raumperg Gumpenstein Austria.

The usage of electronic devices in the field of intensive agriculture is getting very important. More and more crucial data are collected automatically. Due to the permanent growth of the farms it is not possible to check the state of health only with keeping an eye on the animals. Hence symptoms of disease may not be recognised in time.

For the developement of animal husbandry systems or during animal transports it is very important to consider aspects concerning the avoidance of animal suffering or even to increase the well-being of animals. Such situations are subjective feelings, which can not be measured directly. Therefore it is necessary to find objective criterias which can evaluate well-being and suffering of animals. One way is to measure physiological parameters to classify stress. Measurement of heart rate variability as a non invasive technique is one possibility to classify stress sensitivity.

This wireless heart rate measurement system has a great potential to contribute much to the understanding of stress in farm animal's welfare.

Appendix A

Appendix

A.1 Schematic

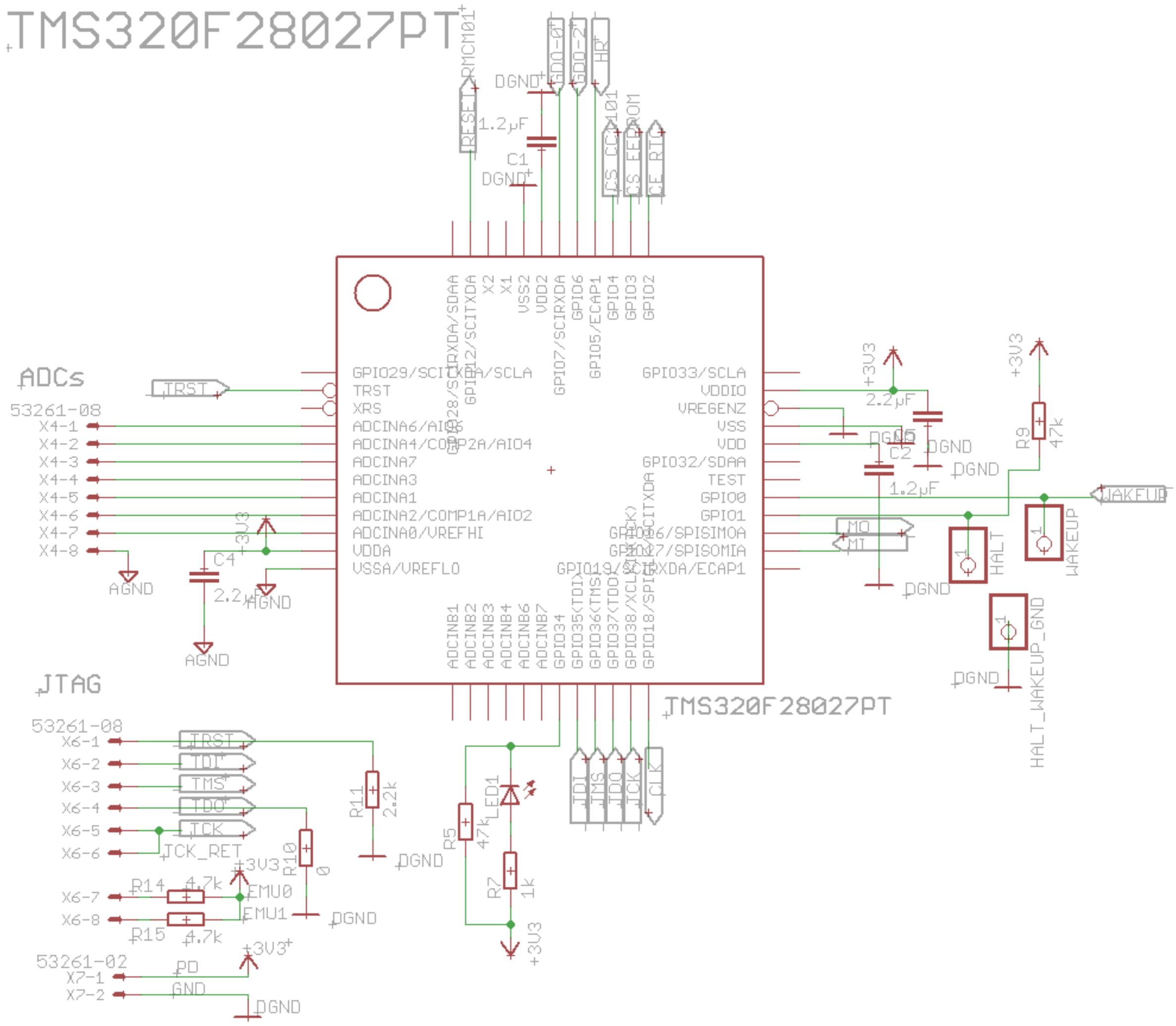

Figure A.1: Schematic Part 1

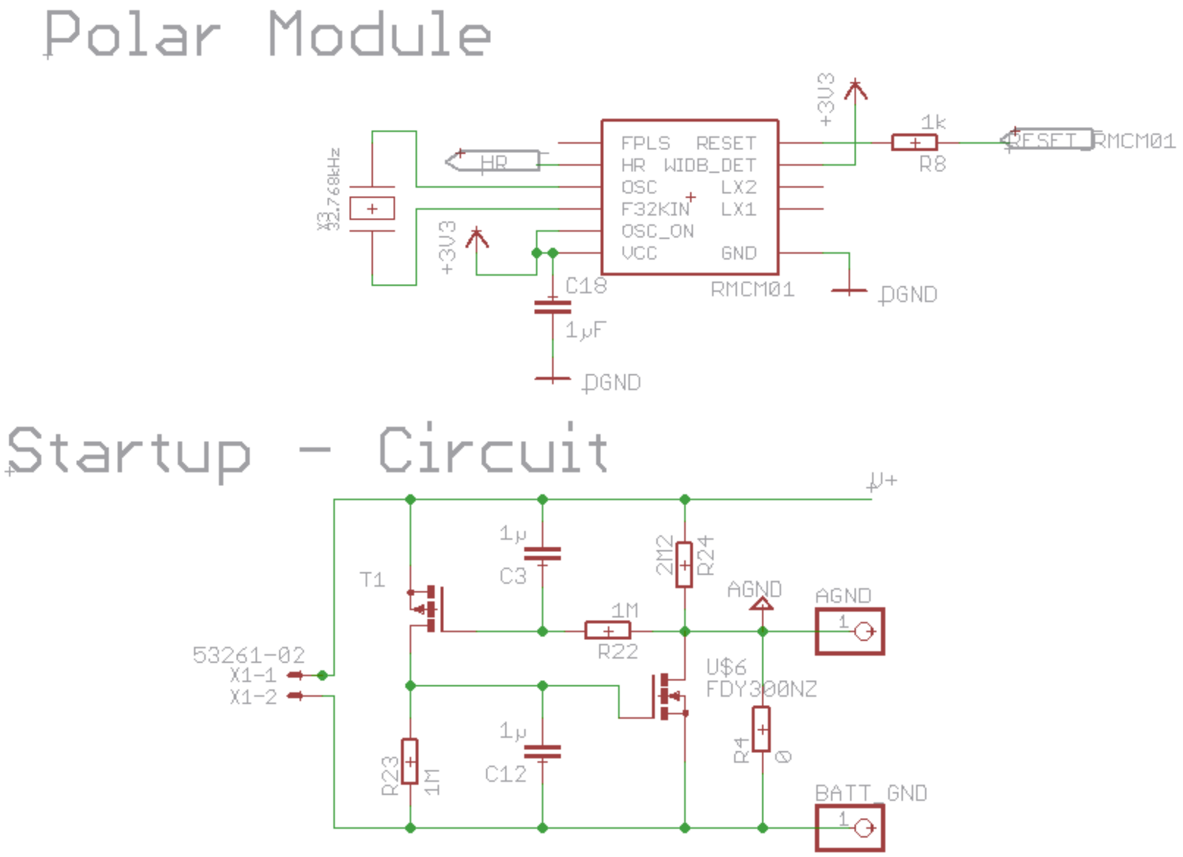

Figure A.2: Schematic Part 2

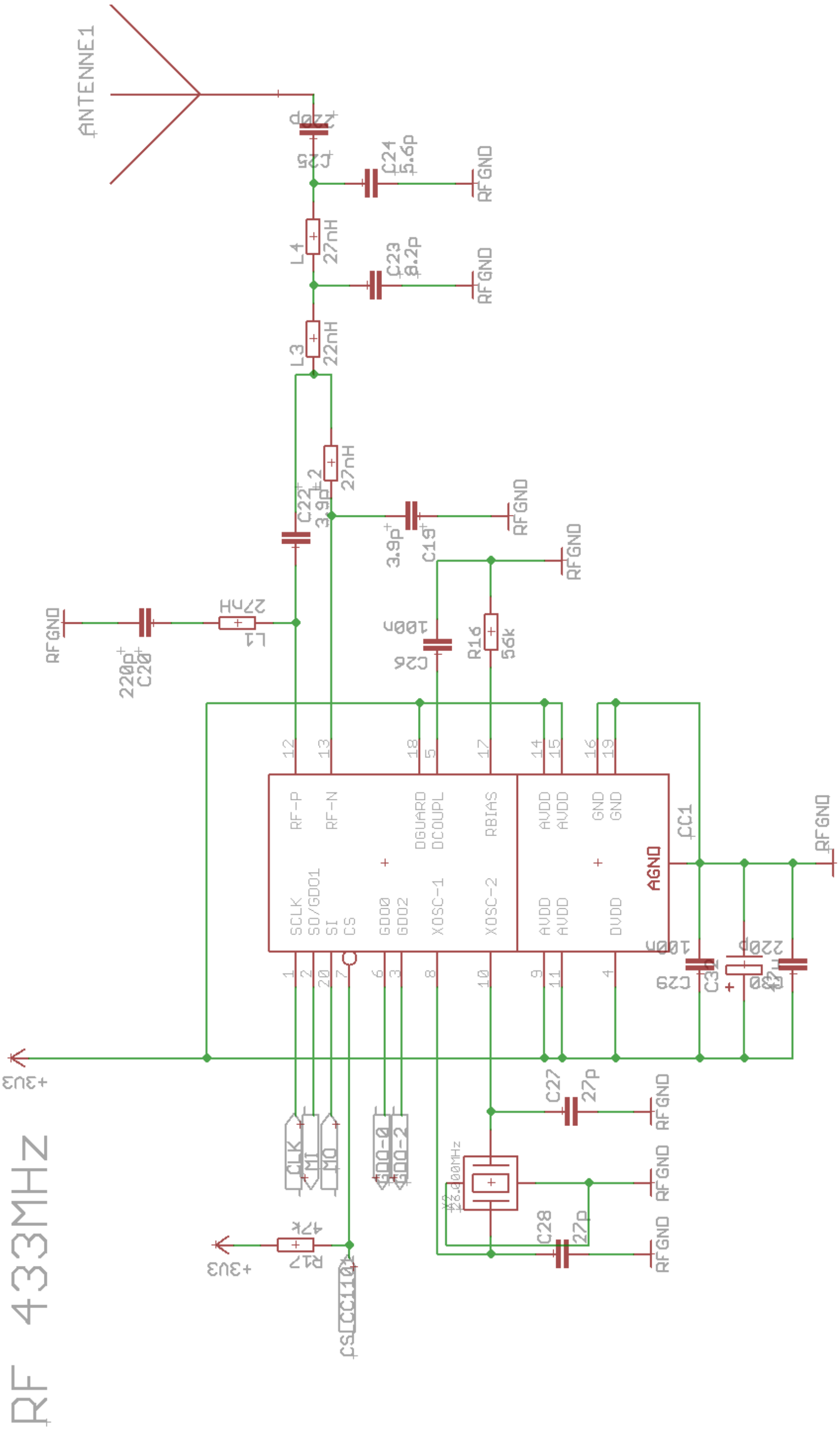

Figure A.3: Schematic Part 3

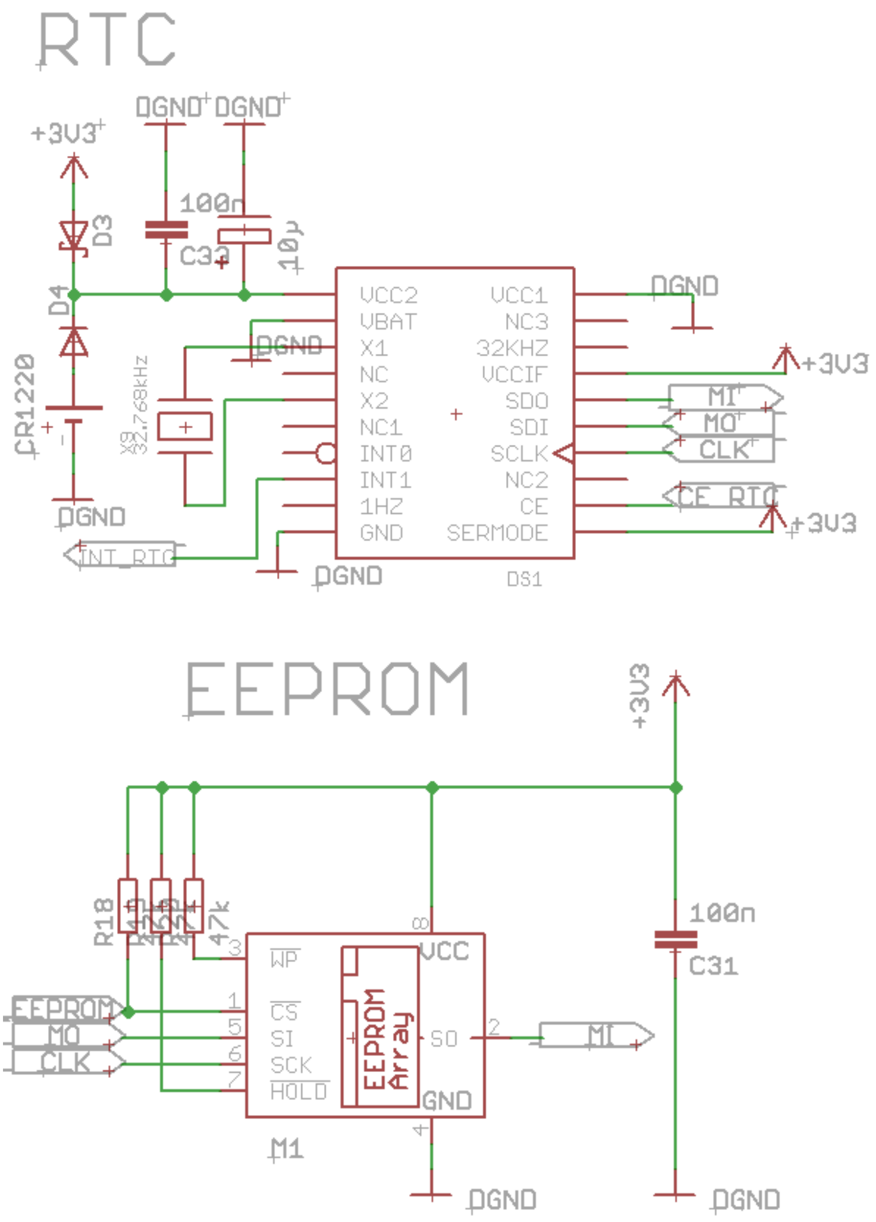

Figure A.4: Schematic Part 4

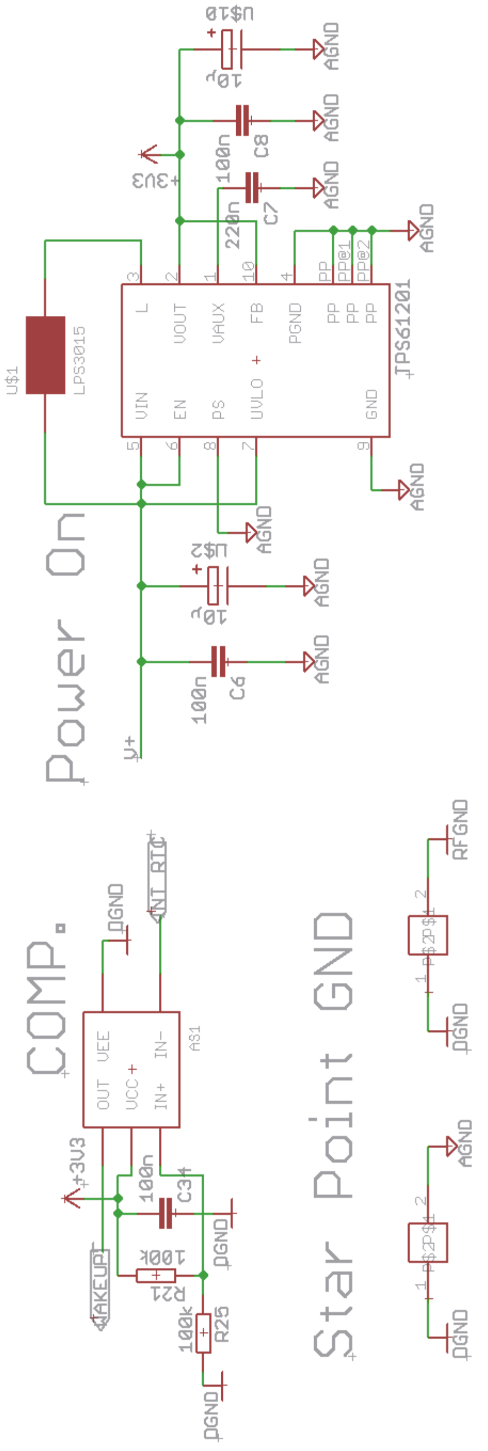

Figure A.5: Schematic Part 5

A.2 Layout

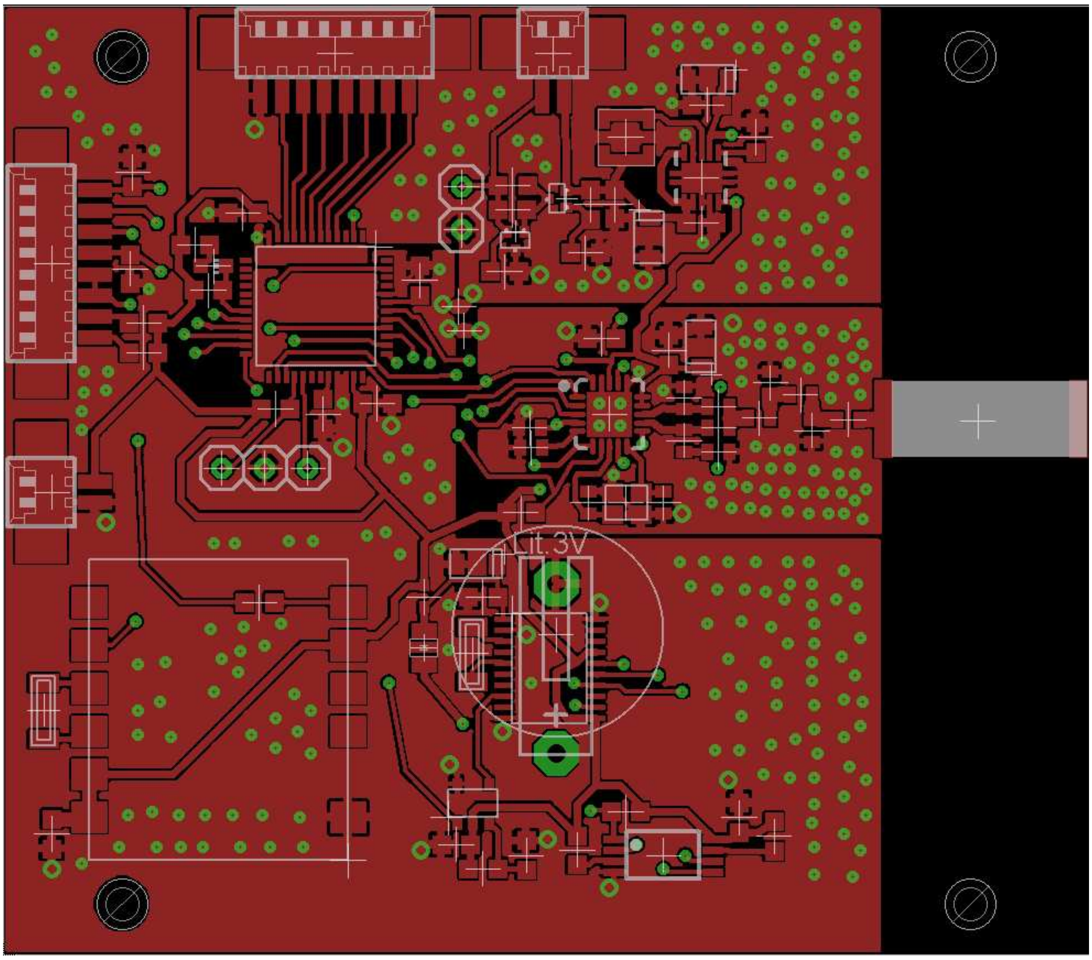

Figure A.6: PCB Top Layer

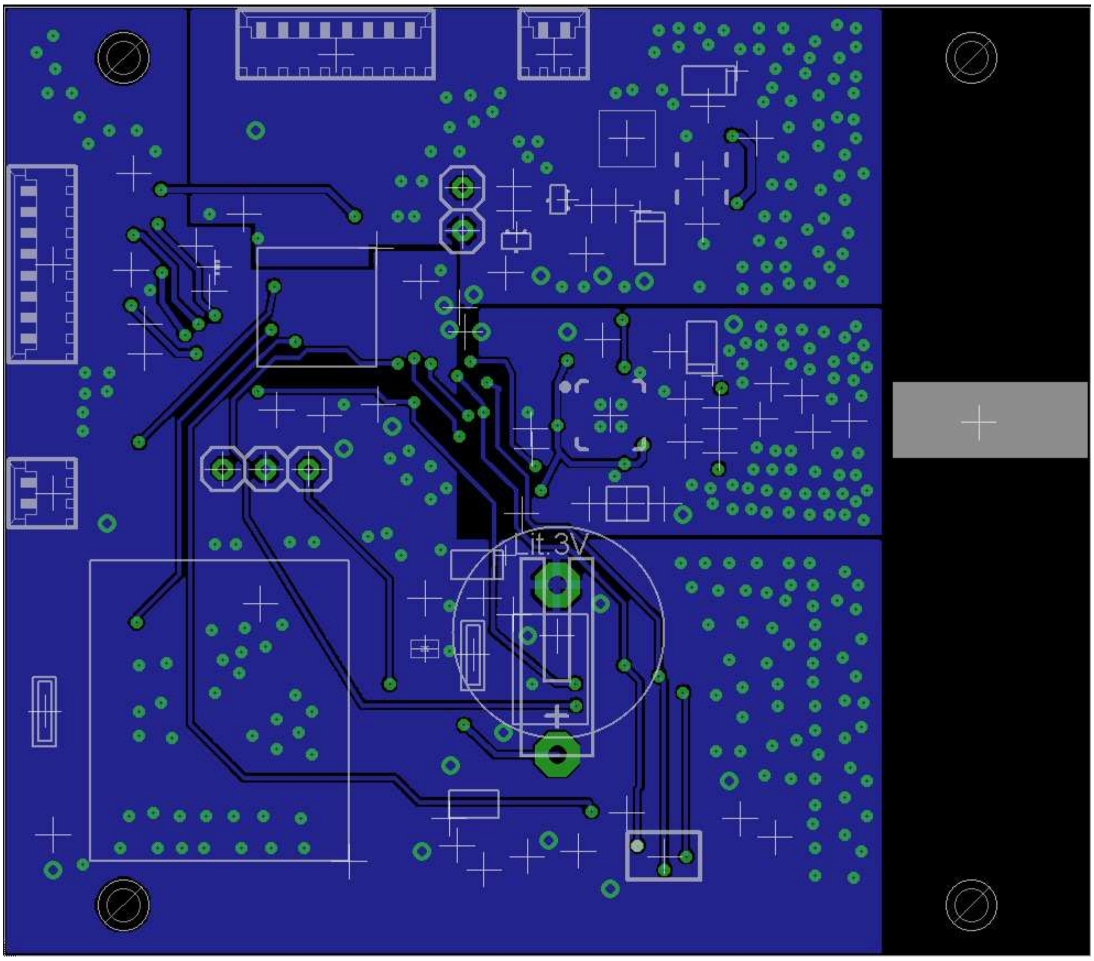

Figure A.7: PCB Bottom Layer

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