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Estimation of the energy expenditure of a person by means of an acceleration sensor platform

Diploma/Master thesis

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Graz, September 2011

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Words of thanks

At this point, I would like to express my gratitude to everybody who helped and supported me during my years of study.

My particular thanks go firstly to the Institute of Medical Engineering of the University of Technology Graz and especially to my tutor Dr. techn. Scharfetter Hermann who enabled me to write this master thesis. In addition, I have to thank Dr. techn. Merwa Robert who established the connection between the University of Technology Graz and the University of Applied Sciences Linz and who always supported me energetically.

I am also much obliged to Dr. techn. Schrempf Andreas and the whole team of the University of Applied Sciences Linz.

A big thank-you also goes to my partner in life, my family and my friends whose patience and heartening words were a big support during the last months.

Kurzfassung

Körperliche Inaktivität wird zunehmend zu einem Thema in unserer Gesellschaft. Durch die Modernisierung im Alltag ist es in vielen Bereichen nicht mehr notwendig, sich körperlich zu betätigen. Dies führt dazu, dass die Gesellschaft anfälliger für Krankheiten wird, vor allem das Herz-Kreislaufsystem ist davon betroffen. Der Schaden schlägt sich nicht nur gesellschaftlich, sondern auch volkswirtschaftlich nieder und belastet die Krankenkassen zunehmend.

Die in dieser Arbeit präsentierte Methode zur Bestimmung der körperlichen Aktivität beruht auf der Messung der Körperbeschleunigung mithilfe einer Beschleunigungseinheit. Mittels mathematischer Ansätze wird daraus die Bewegungsgeschwindigkeit des Probanden errechnet. Anschließend wird mit der modifizierten Goldman Gleichung die verbrauchte Energie des Probanden bestimmt. Es wurde ein System entwickelt, mit welchem diese Berechnung durchgeführt werden kann. Dieses System besteht aus einer Sensorplattform mit integrierter Beschleunigungseinheit und einem externen GPS-Modul. Die Implementation eines geeigneten Auswertealgorithmus, die reibungslose Kommunikation der einzelnen Komponenten und erste Tests waren die Ziele dieser Arbeit.

In einer ersten Laufband-Testphase kann gezeigt werden, dass durch individuelle Kalibration der Berechnungskoeffizienten die Bewegungsgeschwindigkeit genau ermittelt werden kann. Die Bestimmung der aktuellen Höhe mithilfe des GPS-Modules funktioniert nur unzureichend genau und führt bei geringen Höhenänderungen zu starken Schwankungen.

Für weitere Entwicklungsschritte muss der Empfang des GPS-Modules verbessert werden. Weiters soll ein Drucksensor an das vorhandene System angebunden werden, um die aktuelle Höhe bestimmen zu können. Die Höheninformation - basierend auf den GPS- und den Drucksensordaten - könnten gewichtet, je nach Signalqualität in die Berechnung eingehen. Um die Akzeptanz der AnwenderInnen zu erhöhen und den apparativen Aufwand zu minimieren, sollten weitere Ansätze wie zum Beispiel eine LAN bridge verwirklicht werden. Desweiteren sollte der Wirkungsgrad, der bei der Berechnung der verbrauchten Energie basierend auf der Goldman Gleichung benötigt wird, an die individuelle Herzleistung angepasst werden.

<u>Schlüsselwörter:</u> Beschleunigungseinheit, GPS-Modul, Energieberechnung, Goldman Gleichung, Auswertealgorithmus

Abstract

Physical inactivity becomes increasingly an issue in our society. Because of modernizations in everyday life, physical activity becomes unnecessary in many stituations. As a consequence, the society is liable to illnesses, especially the cardiovascular system is involved. This loss does not only reflect socially but also economically and in addition it burdens the public health insurance companies.

In this thesis, a method for determining the physical activity is presented. This approach is based on the measurement of the body acceleration with the aid of an acceleration unit. By use of mathematic approaches the speed of movements of the proband is calculated. Subsequently, the consumed energy of the test person is determined with the modified Goldman equation. For these calculation steps, a new system has been developed. This system consists of a sensor platform with an integrated acceleration unit and an external GPS-module. The implementation of an adequate evaluation algorithm, the frictionless communication of each component and initial tests were aims of this master thesis.

In a first treadmill testing phase could be shown, that the speed of movement can be calculated precisely with individual calibration of the calculation coefficients. The determination of the current altitude with the aid of the GPS-module works only insufficient accurately and leads at slight altitude changes to wild fluctuations.

For further development steps, the reception of the GPS-module has to be improved. In order to determine the current altitude, a pressure sensor should be tied to the existing system. The altitude information, resting upon the GPS- and pressure sensor data, could be – weighted on the signal quality – included in the calculation. For the purpose of increasing the acceptance of the system and to reduce the complexity of the equiptional effort, further approaches, e. g. a LAN bridge, should be realized. In addition, the efficiency factor, which is used for the calculation of the consumed energy basing on the Goldman equation, should be adjusted to the individual cardiac output.

Key words: acceleration unit, GPS-module, energy calculation, Goldman equation, evaluation algorithm

Contents

Nomenclature

ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
ANT	Wireless network protocol
ATP	Adenosine triphosphate
BMI	Body mass index
BMR	Basal metabolic rate
DLW	Double-labeled water
GPS	Global Positioning System
IUNS	International Union of Nutritional Sciences
MCU	Micro controller unit
MET	Metabolic equivalent of tasks
NEON	Sensor platform
NMEA	National Marine Electronics Association
PA	Physical activity
PAL	Physical activity level
PC	Personal Computer
SI	International System of Units

SPI Serial peripheral interface

TEE Total energy expenditure

TEF Thermogenetic effect of food

UART Universal asynchronous receiver/transmitter

1 Indroduction

1.1 Motivation

Within living memory the physical activity is a basic of our life. The characteristics of our human motion apparatus will be mainly influenced by the physical activity. As a result, the human musculature and the bones grow and manage the equilibrium of the human body. Furthermore, the activity influences the inner harmony and leads to violence prevention.

A report of the World Health organization from 2002 belongs physical inactivity to the most common health risks in industrialised countries. The physical inactivity is valuated as risky as overweight or smooking. According to this report the body inactivity is responsible for 1.9 million of premature deaths worldwide. They estimate alone in Western Europe that 8 % to 10 % of premature deaths occur because of physical inactivity. Furthermore 16 % of the intestinal- and breast-cancer and 22 % of the ischemic heart diseases were attributed directly to physical inactivity.[1]

Most deaths do not happen because of the physical inactivity directly, rather this fact supports other diseases such as coronary heart diseases, breast cancer, typ two of Diabetes mellitus, colorectal- and prostate-cancer.[2]

Reducing the prevalence for physical inactivity must be the main goal. The prevalence depends on the geographical location and varies significantly. A study conducted in 2008 in the American Journal of Preventive Medicine occupied with the worldwide variability in physical inactivity. In the scope of this study data collection was carried out by International Physical Activity Questionnaire (IPAQ) in 51 countrys. It could be shown that the age-standardized country prevalence of physical inactivity ranged from 1.6 % (Comoros) to 51.7 % (Mauritania) for men and from 3.8 % (Comoros) to 71.2 % (Mauritania) for women. Physical inactivity was generally high for older age groups and lower in rural as compared to urban areas. About 15 % of men and 20 % of women from the 51 countries which were analyzed in this study are at risk for chronic diseases due to physical inactivity.[3]

For that reason, the minimization of the prevalence for physical inactivity has to be an aim of health insurances and the country as well as an aim of the today's society: The not irrelevant economic damage – which emerges through physical inactivity – charges the national budget and the health insurances. An easy, non-invasive possibility for the determination of the physical activity is the accelerometre. At this, the body acceleration is recorded for a specific period of time. Out of the acceleration data one may recognize special patterns and the activity of the subject can be calculated. The accelerometre is applicable versatilely.

A possible outcome of early detection of physical inactivity is the prophylaxis and prevention. At this, affected risk groups can be supervised and the physical activity of these people can be controlled. If required, the activity of the patients can be increased with specific exercises. To be sure, that the patients do their exercises at home, surveillance has to take place, e.g. with the aid of an acceleration unit. The system can be used as evaluation unit but only if it is validated adequately.

Also the therapy in the context of rehabilitation could be improved with a measuring instrument which measures the acceleration of the body. On the one hand, the implementation of the exercises could be controlled. On the other hand, the instrument is applicable versatilely and could also be used for increasing one's own motivation. This motivation could be in the form of a visual feedback via a monitoring system, for example this system shows the patient the daily activity reference value and the already completed percentage of it. The system is also expandable for a group for encouraging the competitiveness and gaining credence for this system. At the end of a therapy, the system could also be applied for therapy evaluation. Thereby, the connection between the achieved activity and the physical health could be compared. Consequently, there are a lot of important conclusions concerning type, duration, intensity and progress of a therapy.

1.2 Procedure and arrangement of this master thesis

In order to receive an accurate determination of the energy expenditure of a person during various physical activities, an energy-efficient sensor platform should be combined with a GPS-compliant sport watch and a chest strap. The sport watch calculates the energy conversion with the company-side implemented algorithm by means of the heart rate, which is defined by the chest strap. Independent of this calculation the sensor platform should estimate the energy expenditure with the aid of the 3D acceleration unit, which is arranged on the platform. In addition an external GPS module should deliver the latitude and longitude of the subject to calculate the speed of travel. For that purpose, an algorithm has to be implemented on the available µController. On the basis of this algorithm, one can estimate the energy expenditure of a person. The network technology ANT allows, that the sensor platform NEON substitutes and stores data from the GPS sport watch and the chest strap. In order to enable this communication, the interfaces have to be defined and the products have to be choosen, so that a frictionless communication among them is possible. By means of the sensor platform, stored data is read out as txt-file and can be processed individually. In the next step, this system should be compared and validated by means of measurements on a treatmill and outdoor with the help of reference systems.

1.3 Aims

The aims of this work can be formulated as follows:

- Adaptation of an algorithm to evaluate the energy expenditure of a subject at walking and running with a MCU
- Determination and conformation of the device interfaces
- Data transfer between the sensor platform and the chest strap with the aid of the ANT protocol
- Read-out the stored data of the sensor platform by means of an USB access
- Test of the established system by means of measurements in- and outdoor and with reference systems

2 Basic principles of the physical activity measurements

This chapter gives an overview about the basic definitions of the energy expenditure and the current measurement systems for the physical activity.

2.1 Conceptual definitions

2.1.1 Gravity of Earth

The gravity of earth refers to the acceleration, that the earth imparts to objects on or near the earth surface. Every object, independent of the mass of the object, experiences an acceleration to the geocenter. The value of the "acceleration of gravity", denoted g, depends on the latitude, longitude and on the height over geoide.

The average value, known as standard gravity, is a derived unit from the International System of Units (SI) and is, by definition:

$$1g = 980.665\,\frac{cm}{s^2} \approx 9.81\,\frac{m}{s^2} \tag{2.1}$$

The unit of the standard gravity (2.1) is always written uncapitalized and in italic to preclude a confusion with the constant of gravity and the unit of the mass, gram.[4]

2.1.2 Work and Energy

By definition, mechanical work is the dot product of force $\vec{F}$ and the corresponding displacement $\vec{s}$. Work can be done by a constant force and by a varying force. If the force is constant and in the same direction as the motion, the work done W is equal to the magnitude of the force vector times the displacement. If the displacement is not in the same direction, the work done by the force is equal to the magnitude of the force component in the direction of motion times the displacement itself.[5]

$$dW = \vec{F} * d\vec{s} = |\vec{F}| * |d\vec{s}| * \cos\theta = F * s * \cos\theta \tag{2.2}$$

Force and displacement are both vector quantities and they are combined using the dot product to evaluate the mechanical work, a scalar quantity. If an applied force is a function of displacement, then the work done can be calculated by the integral of the force over the trajectory along which it is applied [5]:

$$W = \int dW = \int \vec{F} * d\vec{s} \tag{2.3}$$

The unit of the mechanical work is by definition Joule (J).[4] Each ability to execute work, is identified as energy. Among this, one has to differentiate between potential and kinetic energy.

Potential energy

The potential energy of a system is associated with its position or elevation. The energy depends on the height h and the mass m of an object and the gravity constant g (2.4). This means, that the same object has a greater potential energy in higher reaches.

$$E_{pot} = W * h = m * g * h \tag{2.4}$$

Kinetic energy

The kinetic energy is associated with the motion of an object. The product of one half of the mass m and the square of the speed v of the object is equal to the kinetic energy of the object itself (2.5).[5]

$$E_{kin} = \frac{1}{2} * m * v^2 \tag{2.5}$$

2.1.3 Power

The power is the work W over time t and therfore the unit of the power is Watt ($\frac{J}{s} = W$). This means, the shorter the time - which is needed for a specific work - the higher the power.

$$P(t) = \frac{dW(t)}{dt} \tag{2.6}$$

The sum of the potential and kinetic power is the mechanical power $P_{mechanical}$ or the power of non-conservative forces P_{nc}, e.g. the muscle forces. In order to accelerate and decelerate a body and for overcoming the force of gravity, we need the potential energy. With (2.6) we can constitute the power of non-conservative forces as a quotient between the mechanical energy and the time [6]:

$$P_{mechanical}(t) = P_{pot}(t) + P_{kin}(t) = \frac{dW_{pot}(t)}{dt} + \frac{dW_{kin}(t)}{dt} = P_{nc}(t) \tag{2.7}$$

2.1.4 Efficiency

In general, the efficiency is the ratio between the useful output of a device and the input, in energy terms. The input consists of an useful ouput part and a mostly unuseful part, the heat production. A high efficiency is mostly the major goal at the development of a new system or device. The efficiency of the human skeletal muscles comes up in vivo to 30 % under ideal conditions like running, cycling or climbing.[7]

$$\eta = \frac{useful\,output}{input} \tag{2.8}$$

2.2 Physical activity

There are a lot of different definitions in the literature for a similar phenomenon: *sports*, *sporty activities*, *physical activity*, *athletic and physical training*, *life style activities* and so on. In the rehabilitation, also the expression *therapeutic exercise* is used. The term *physical activity* is the preamble and comprises the terms *sports*, *life style activities* and *exercise*.

We talk about sport, if the competitive sport is involved and the record concept is in the first place. This kind of sport is practised in specific sports facilities and one has to train hard to be successful. Another type of sport are the risk and life style sports. The main emphasis lays on the competitive sport itself. All these sports come under the term *sporty activities* and one has to perfect your techniques to be effective.

If sport is not explicitly for competitive sports, but health-oriented, we are talking about *exercise*.

We could increase the physical activity with *sporty activities*, but also with *life style activities*. Life style activities are operations like gardening, houseworking, taking a walk, cycling and occupational work.[2]

The unit of the energy, which is needed for every type of action in the human body, like the contraction of a muscle, the alimentary thermogenesis or the metabolism, are denoted in Joule (J) which is a derived unit of the International System of Units (SI) [4]. Joule is also the unit of the energy and of the heat quantity.

$$1\,J = 1\,N * m = 1\left(\frac{kg * m}{s^2}\right) * m = 1\left(\frac{kg * m^2}{s^2}\right) = 1\,W * s \tag{2.9}$$

2.2.1 Calorie

The calorie is the oldest unit of the energy. It is already common in Europe and denoted on food. There are different ways of definitions for the calorie and this results in some confusion. For this reason, the *Committee on Nomenclature of the International Union of Nutritional Sciences* decided, that a calor is the "energy", which is needed to increase the temperature of one litre of water from 14.5°C to 15.5°C. The conversion factor between calorie and joule is given in equation (2.10) and is used for the calculations in this work.[8]

$$\begin{aligned} 1\,Joule &= 0.239\,Calorie \\ 1\,Calorie &= 4.182\,Joule \end{aligned} \tag{2.10}$$

The calorie consumption of the human body depends on the type of physical activity (see table (2.1)). The mean daily total energy expenditure depends on age, sex and the conditions of living of the person. The arithmetic average for a physical inactive men is 2 300 kcal per day and for women 2 000 kcal per day. [9]

Worldwide, particularly in America, also the definitions MET and PAL are in common use.

activity	body mass in kg				
	55 - 60	65 - 70	80	90	110-115
sitting	10	12	14	16	20
housework	34	41	47	53	68
climbing stairs					
- downstairs	56	67	78	88	111
- upstairs	146	175	202	229	288
walking					
- 3 km/h	29	35	40	46	58
- 6 km/h	52	62	72	81	102
jogging (10 km/h)	118	141	164	187	232
cycling					
- 10 km/h	42	50	58	67	83
- 21 km/h	89	107	124	142	178
to mow the lawn					
- with the lawnmower	34	41	47	53	67
- by hand	38	45	52	58	74
to chop wood	60	73	84	96	121
to bowl	56	67	78	90	111
golfing	33	40	48	55	68
cross-country skiing	98	117	138	158	194
swimming (crawl, slow)	40	48	56	63	80

Table 2.1: Calorie consumption per ten minutes plots against the body mass for different physical activities, modified from [10]. Particularly for sports, where the technique of motion plays a big role, the given values are only approximate values.

MET is the short cut for *metabolic equivalent of tasks* and PAL stands for *physical activity level*. The precise description is given in the following subchapter.

2.2.2 Metabolic equivalent of tasks (MET)

Metabolic equivalent of tasks stands for the metabolic unit and was introduced 1993 from a working group of the Canadian physiologist Barbara E. Ainsworth (Ainsworth, Haskell et al. 1993). This unit designates the absolute but not the individual intensity of stress and represents the relative metabolism equivalent of the activity. The central reference value is the energy expenditure that an adult person must have at rest: This energy complies 1 MET. For this effort, an oxygen consumption of 3.5 ml oxygen per kg body weight per minute or an energy expenditure of 1 kcal per kg body weight per hour is calculated. Measuring actual

nutrient	energy content in kcal/100g
chicken meat	200
milk	65
apples	59
beer	45
chocolate	500
noodle	362

Table 2.2: Energy content of different types of nutrient in kcal per 100g (kcal/100g), modified by [9].

METs requires, that the person being tested, wears a mask in order to measure his or her oxygen consumption and the exhaled carbon dioxide.[2]

$$1\,MET = 3.5\,\frac{mlVO_2}{kg * min} = 1\,\frac{kcal}{kg * h} \tag{2.11}$$

The calculation from the oxygen consumption is justified, because a physically trained person can consume an huger amount of oxygen per time than an untrained person. The maximum oxygen uptake is increased by systematic sporty training. With the help of the volume measurer MET, the total energy expenditure of the physical activity can be estimated in kilocalories. Barbara E. Ainsworth reports the activity as a multiple of metabolic equivalent of tasks.[2]

In recent years, the working group around Ainsworth published a lot of new listings for the MET-data for different activities. Every activity up to three METs is considered to be easy or low intensive. Between three and six METs, the activity rate is moderate and above six METs classified as highly intensive stress. Furthermore, the lists are seperated in professional, housework and leisure activities.[2]

Table 2.3 gives an overview about different activities and the corresponding MET values. The main advantage of MET is the comparability of different activities.

2.2.3 Physical activity level (PAL)

The mean daily energy expenditure depends on the equal activities of sex, body mass and age. In consequence of this fact, a standardisation is conducted, which relates the total energy expenditure to the basal metabolic rate.

activity	MET
sleeping	0.9
meditating	1.0
sitting - knitting	1.5
making bed	2.0
feeding animals	2.5
walk/run, playing with animals, light	2.8
walk/run, playing with animals, moderate	4.0
hunting, general	5.0
roofing	6.0
carrying groceries upstairs	7.5
carrying heavy loads	8.0
fire fighter, general	12.0
forestry, ax chopping, fast	17.0

Table 2.3: MET-table, modified from [11].

Due to this standardisation the influence of age, sex and body mass is already considered in relation to the amount of the energy expenditure. The result of this standardisation is the so-called *physical activity level*, which is the quotient of the energy expenditure and the basal metabolic rate, see equation 2.12. This value was established by the world health organization.[12]

$$PAL = \frac{total\,energy\,expenditure}{basal\,metabolic\,rate} \tag{2.12}$$

Basically, the level of this value is defined with the physical acitivity. It comprises not only the activities of work and leisure time, but also those of repose and sleep. In the case of illnesses, additional correction factors are applied to adjust the total energy expenditure.[12]

2.2.4 Body mass index (BMI)

Body mass index is a simple index of weight-for-height, that is commonly used in classifying overweight and obesity in adult populations and individuals. It is defined as the weight in kilograms divided by the square of the height in meters ($\frac{kg}{m^2}$).[13]

$$BMI = \frac{Bodyweight}{Bodyheight^2} \tag{2.13}$$

working stress and leisure behaviour	PAL	example
exclusively of sedentary or reclining job	1.2	old, invalid person
exclusively of sedentary occupation with less or no hard leisure activity	1.4 - 1.5	office worker, precision mechanic
sedentary occupation, sometimes additional energy expenditure	1.6 - 1.7	laboratory technician, driver, student, assembly line worker
mainly going and standing works	1.8 - 1.9	housewive, seller, waiter, mechanic, craftsmen
physical sustained professional work	2.0 - 2.4	construction worker, farmer, lumbermen, miner, competitive athlete

Table 2.4: PAL (physical activity level) = average daily energy expenditure for the physical activity as multiple of the basal metabolic rate, modified from [12].

This index can be compared with tabular values. There are four main categories: underweight, normal weight, overweight and obesity. A BMI value of 25 or more means, that the person is overweight and a factor of 30 or more stands for obesity.

At first, the calculation seems very easy but the correlation of the BMI isn't very significant because the body fat ratio is not considered in this calculation. The following example brings out the importance of this problem: There are two subjects with a BMI of 27. The first subject is an unfit person with a body fat ratio of 27 % and therefore overweight. The second person is a bodybuilder with a body fat ratio of 8 % and in accordance with the table overweight too, but extremely skinny.

Furthermore, for children and teenagers the BMI equation (2.13) is not applicable and must be modified.

Classification	BMI ($\frac{kg}{m^2}$)
	Principal cut-off points
Underweight	<18.50
- Severe thinness	<16.00
- Moderate thinness	16.00 - 16.99
- Mild thinness	17.00 - 18.49
Normal range	18.50 - 24.99
Overweight	≥25.00
- Pre-obese	25.00 - 29.99
Obese	≥30.00
- Obese class I	30.00 - 34.99
- Obese class II	35.00 - 39.99
- Obese class III	≥40.00

Table 2.5: BMI classification for the four main categories and the subcategories.[14]

2.3 Energy expenditure

2.3.1 Total energy expenditure

The *total energy expenditure* (TEE) is made up of the *basal metabolic rate* (BMR) and the *physical activity* (PA), the so-called *work metabolic rate*. The *thermogenetic effect of food* (TEF) is a part of the basal metabolic rate. The total energy expenditure is an important reference value for the nutritional medicine and reflects the daily energy turnover. Under normal conditions, the total energy expenditure must be the same as the daily ingestion of food. If this is not the case, it comes to a gain or loss in weight.[10]

$$TEE = BMR + PA \tag{2.14}$$

2.3.2 Basal metabolic rate (BMR)

For the maintenance of the body functions, like the beat of the heart or the function of the liver, a minimum of energy is needed. This energy is called *basal metabolic rate* and is under normal conditions about 70 % of the total energy expenditure. The calculation is comparatively easy, but must be enforced under the following standard conditions [10]:

- soonest twelve hours after the last ingestion of food
- free of pain
- constant room temperature
- free of psychological stress
- in the morning after satisfactory sleep
- lying without physical activity, but awake

If the person would sleep during the measurement, the value would be 10 % less, because the energy expenditure decreases. For a large number of subjects, the determination of the *basal metabolic rate* is not easy. In practice, there are some formulas based on basic approaches to calculate the BMR. The most common used formula was published by Harris and Benedict (2.15)(2.16). The calculated basal metabolic rate depends on the age a in years, the sex, the body mass wt in kilogram and the bodyheight ht in centimeter of the person. The unit of the calculated basal metabolic rate is kilocalorie per day ($\frac{kcal}{day}$).

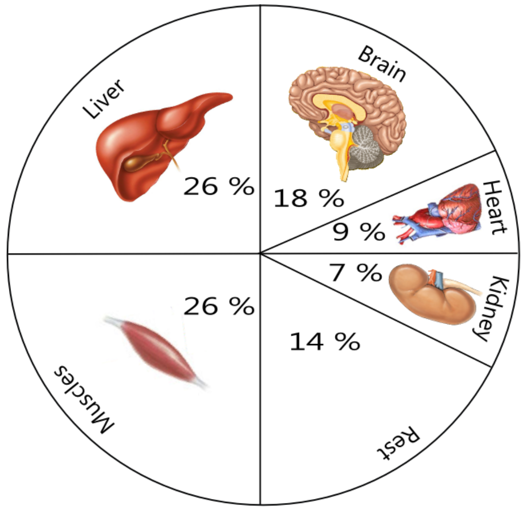

Figure 2.1: Shares of the organs on the basal metabolic rate, modified from [9].

$$EE_{BMR_{man}}\left(\frac{kcal}{day}\right) = 66.5 + (13.75 * wt) + (5.003 * ht) - (6.775 * a) \tag{2.15}$$

$$EE_{BMR_{woman}}\left(\frac{kcal}{day}\right) = 655.1 + (9.563 * wt) + (1.850 * ht) - (4.676 * a) \tag{2.16}$$

In accordance with the study of Frankenfield D.C., et. al. [15] the absolute mean percental difference between calculated and measured BMR depends significantly on the body mass index (BMI) and the gender of the subject. In 67 % of the cases, the calculations with the Harris-Benedict equation was failing for men with a BMI over 50. With regard to women with a BMI over 50, the error rate of the calculations was only 13 %. Therefore, the equation should not be used for men with a body mass index over 50. For the whole test group (obese, nonobese, men and women together) of the study of Frankenfield, the accuracy of the prediction of the BMR was 67 % (p = .05).[15]

2.3.3 Physical activity (PA)

Physical activity is the energy which is additionally generated above the basal metabolic rate. It includes every form of activity like swimming, walking, skiing, mowing the lawn and also job related energy consumption. The upper limits for continous work are for men 20 100 kJ and for women 15 500 kJ per day. During the peak performance at work it is possible to arrive at an upper limit of 50 000 kJ and more per day. In competetive sports, where the peak performance only lasts a few seconds or minutes, the value can be much higher.[9] The reason for this huge value is the long recovery time between the physical stress. The target values for the daily activity energy expenditure (AEE) should be between 2927 - 12 546 kJ/day.[16]

$$PA = \frac{1}{\eta} * P_{nc} \tag{2.17}$$

P_{nc}... power of non-conservative forces, e.g. the muscle forces in W
η... efficiency of the human skeletal muscles

2.3.4 Thermogenetic effect of food

The ingestion of food raises the metabolic rate 10 to 20 % due to the energy costs of digesting, absorbing and storing nutrients. This effect, food-induced thermogenesis, is highest after eating a high protein meal and less after eating carbohydrates and lipids.[17] It is a part of the basal metabolic rate and is named in the English literature as *thermogentic effect of food* (TEF). The thermogenetic effect of food depends only on the type of food but not on the sex and age of the subject.[10]

2.3.5 Calculation of the TEE by the Goldman equation

The total energy expenditure can be defined with a lot of methods. One of many is the so-called „Goldman equation“ which is also applied in the following chapter. The total energy expenditure is composed of four terms and consists of the metabolic power which corresponds to the oxygen absorption VO_2 of the organism.

$$TEE = BMR + PA = BMR + \frac{1}{\eta} * P_{nc} \tag{2.18}$$

$$TEE = EE_{bmr} + EE_{el} + EE_{kin} + EE_{pot} \tag{2.19}$$

The first addend corresponds to the basal metabolic rate. The BMR is only an easy estimate in the Goldman equation based on the body mass of the subject, see equation (2.20). This estimate can be enhanced with a more precise statement, e. g. by means of the often used Benedict and Harris equation (see equation 2.15 and 2.16) or the Miffin equation.

Furthermore, these equations incorporate body height, body mass, age and gender which lead to an accurate determination.

$$EE_{bmr}(t) = \int (1.5 * wt)\, dt \tag{2.20}$$

wt ... body mass in kg

If the person carries an external load, he/she has to spend more energy, because a major mass has to be accelerated and moved. Certainly, also during standing, the musculature has to carry a major load. This fact asks for external energy [18], this constituting the second addend of the Goldman equation (see equation 2.21). Goldman et al. [19] showed, that a linear relationship exists between the metabolic power and the body mass – without external mass. Furthermore, external loads up to 30 kg can come across as increase of the own body weight. In the case of major loads the existing correlation of equation 2.21 persists.

$$EE_{el}(t) = \int \left(2 * (wt + el) * (\frac{el}{wt})^2\right) dt \tag{2.21}$$

el ... external load in kg

According to Goldman, the power required for locomotion represents the main part of the metabolic power. The third addend in the Goldman equation stands for this energy. As per equation 2.22, for the determination the speed of travel v, the body mass, the external weight, the efficiency η, the factor k_{loc} and the so-called terrain factor T are required. The terrain factor reflects the underground and is – depending on the condition of the soil – a particular numerical value which can be taken from the table 2.6. Example: A person runs on a sandy beach. In this case, according to table 2.6, the terrain factor is defined with 2.4 to calculate the locomotion energy.

$$EE_{loc}(t) = \int \left(T * (wt + el) * \frac{k_{loc}}{\eta} * v(t)^2\right) dt \tag{2.22}$$

v ... speed of movement in $\frac{m}{s}$
T... terrain factor

k_{loc}... factor represents the mechanical efficiency of locomotion
η... efficiency

underground	terrain factor
asphalt	1
compressed snow	1.3
fields and meadows	1.35
soft underground	1.8
loose sand	2.1
snow with 15 cm sinking depth	2.5
snow with 25 cm sinking depth	3.3

Table 2.6: Terrain factors for different underground, will be needed for the calculation of the kinetic and potential energy.[20]

The fourth addend reflects the power required to change the energy of the position. According to equation 2.23, the energy is determined with the aid of body mass, external load, terrain factor, efficiency, the differential height alteration $\frac{dh}{dt}$ and the factor k_{pos}. The differential height alteration can be zero in the plane, positive at an upward movement and negative at a downward movement.

$$EE_{pos}(t) = \int \left(T * (wt + el) * \frac{k_{pos}}{\eta} * \frac{dh(t)}{dt} \right) dt \tag{2.23}$$

$\frac{dh}{dt}$... differential height alteration in $\frac{m}{s}$
k_{pos}... correction factor

As you can see in equation 2.19, all four addends are summed up to get the whole metabolic power.[20]

2.4 Methods to determine the energy expenditure

According to the principle of conservation of energy, no energy can be destroyed or lost. There are plenty of methods to measure the energy expenditure of the human body. A couple of these methods are explained on the following pages.

The units of the invested energy are represented with the units which were described in chapter 2.2. To estimate the energy expenditure with the factorial method, like the estimation with the physical activity level (PAL) or with the metabolic equivalent (MET), is one of the easiest way.

However, there are some problems with these factorial methods, which leads to an inaccuray of the evaluation. The first problem is, that there is a wide range of activities and physical efforts performed during normal life and it is not possible to measure the energy costs of each. Although generalisations are essential in trying to account for the energy costs of daily activities, substantial errors may be introduced. In addition, energy expenditure during sleep, once considered to be equivalent to the basal metabolic rate (BMR), is generally somewhat lower (-5 to -10 %) than the BMR .

The most important fact of the factorical method is, that it takes into account only those activities which can be specifically accounted for (e.g.: household work, running, fishing, hunting, swimming, and so on). 24-hour room caliometer studies showed, that a signficant amount of energy is expended in spontaneous physical activities like fidgeting, flicking with one's fingers and other things. This not respected part of energy was on average about 350 kcal/day, ranging from 140 to 700 kcal/day. That means, that the factorial method is predefined to underestimate usual energy needs. Most comparisons of the factorial approach with double-labeled water method determinations of TEE showed significantly higher measured values for the total energy expenditure, than predicted by the factorial method.[21]

To determine the total energy expenditure accurately, other methods are needed. Therefore, a couple of methods are in common use like the *double-labeled water method*, the *calorimetry*, the *acceleration sensors* or the *heart rate monitoring systems*.

2.4.1 Double-labeled water (DLW)

The double-labeled water method is a technique, that measures the total energy expenditure in free-living individuals. The method was invented in the 1950s and was originally proposed and developed for use at small animals. Since the 1980s, the method has been adapted for human subjects.

Two stable isotopic forms of water ($H_2{}^{18}O$ and ^2H_2O) are administered and their disappearance rates from a body fluid (e. g. urine or blood) are monitored for a period of time, optimally 7 to 21 days in most human subjects.

The disappearance rate of ^2H_2O relates to water flux, while that of $H_2{}^{18}O$ reflects water flux plus carbon dioxide (CO_2) production rate, because of the rapid equilibration of the body water and bicarbonate pools by carbonic anhydrase. The difference between the two disappearance rates can therefore be used to calculate the CO_2 production rate and with knowledge of the composition of nutrition, total energy expenditure can be calculated.

To predict TEE from a measurement of CO_2 production, it is necessary to have an estimate of the mean respiratory quotient of the subject during the period of measurement. The respiratory quotient is the ratio of VCO_2 produced to the VO_2 consumed:

$$RQ = \frac{VCO_2}{VO_2} \tag{2.24}$$

Therefore the oxygen production rate can be calculated and consequently also the energy expenditure of the subject.

Short-term measurements of RQ by indirect calorimetry are not useful for the double-labeled water technique, because RQ varies markedly during the day, particularly after meals. Several validation studies of the double-labeled water method were conducted in which DLW-derived estimates of total energy expenditure were compared with measurements of total energy expenditure in whole-body calorimeters.

Although studies in whole-body calorimeters do not take off normal life conditions, they allow an exact comparison of the double-labeled water method with classic calorimetry, which is considered the most reliable measurement of energy expenditure. The difference of double-labeled water measurements to calorimetry range from -2.5 to 5.9 % in different studies. These validation studies show, that the double-labeld water method can provide an accurate assessment of the CO_2 production rate and hence total energy expenditure in a wide range of human subjects.

One particular advantage of the double-labeled water method is, that it provides an index of total energy expenditure over a period of several days. Because one to three half-lives of isotope disappearance are needed for changes in isotopic abundance to be measured accurately by mass spectrometry, optimal time periods for double labeled water measurements of total energy expenditure range from one to three weeks in most groups of individuals. Thus, in contrast to other techniques, double labeled water can provide total energy expenditure estimates over biologically meaningful periods of time that can reduce the impact of spontaneous daily variations in physical activity. Moreover, measurements can be made at probands while leading their normal daily lives.[22][21]

2.4.2 Calorimetry

The calorimetry is a very old technique to measure the heat of a chemical reaction or physical change. The founder of the field of calorimetry was the Scottish physician and scientist Joseph Black (1728 - 1799). He was the first, who realized the differentiation between heat and temperature.[23] The energy source of the human body is the adenosine triphosphate (ATP), which is produced in the mitochondria of the human body. By the hydrolytic cleavage, the adenosine triphosphate changes to adenosine diphosphate (ADP) or to the adenosine monophosphate (AMP) and to phosphate. The energy released by this process is about 32.3 kJ/mol for a cleavage of one bond. This energy maintains the performance of the cell which directly correlates with the heat quantity released of the organism.[9]

From the first law of thermodynamics we know the relationship:

$$\Delta U = q + w \tag{2.25}$$

ΔU is the change of the internal energy of a system, e. g. the human body. q represents the heat and w is the work done on the system. For infinitesimal quantities the equation 2.25 can be expressed as [23]:

$$dU = dq + dw \tag{2.26}$$

But this equation is only valid for stationary systems. If this is not the case and the system is in motion, an external energy componet E_{ext} of the system (kinetic and potential energy) has to be added, see equation 2.27 [23].

$$dU + dE_{ext} = dq + dw \tag{2.27}$$

The heat production of the system can be calculated from the mass m, the specific heat c

and the change of the temperature ΔT as follows [23]:

$$\Delta q = m * c * \Delta T \tag{2.28}$$

Direct calorimetry

The heat quantity is calculated by a calorimeter. The person resides in a measuring chamber with a constant volume. Figure 2.2 shows the basic principal. At a constant temperature, the person is subjected to a defined load, e. g. by the treadmill. The waste heat of the person is picked up by the cooling water of the heat exchanger. In the next step, the change in temperature and the flow rate of the cooling water are measured. The heat quantity is now determinable by the change in temperature of the cooling water.

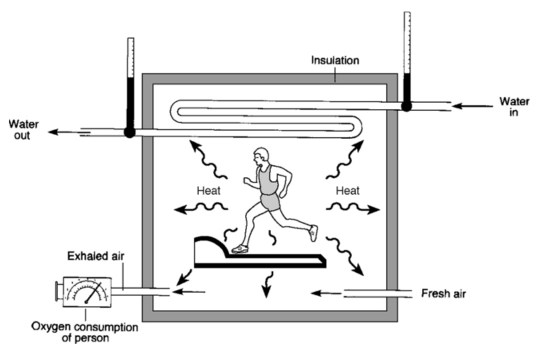

Figure 2.2: Measuring chamber to calculate the heat quantity of a person by direct calorimetry.

The apparative effort for the calculation is very high and expensive too and therefore things are often calculated by the indirect caliometry.

Indirect calorimetry

The heat quantity is calculated indirectly by the oxygen consumption and the carbon dioxid production of the person. This method is cheaper and faster than the direct approach and is used in many research centers and clinical situations. Measurements over short periods can be achieved with any available apparatus. The most common methods are the full face maske, see figure 2.3, mouthpieces or ventilated hoods. These methods are both for children and adults in health and in disease.[22]

Figure 2.3: Adult Full Face Mask for the indirect calometry from the company Susquehanna Micro Inc.

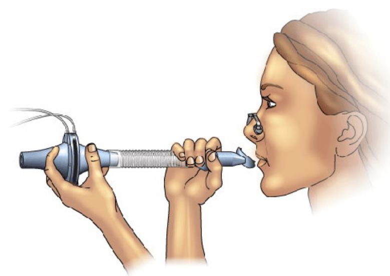

Figure 2.4: The figure shows a mouthpiece which is used for the caliometry measurement.

2.4.3 Accelerator

The determination of the energy expenditure by means of an accelerator becomes more and more important. The energy expenditure, which is consumed at walking and running, is measured through an acceleration sensor. This sensor is fixed on the human body and measures the acceleration of the subject. Furthermore it could be demonstrated, that here is a linear relationship between the integral of the absolute body acceleration and the oxygen consumption or the energy expenditure.

The acceleration is defined as the time rate of change in velocity and is represented with the symbol a. The unit of the acceleration is $\frac{m}{s^2}$, it is a derived unit from the *International System of Units* (SI).

$$\vec{a} = \frac{d\vec{v}}{dt} \tag{2.29}$$

The acceleration sensors are basically force sensors with an attached constant mass m, usally called “seismic mass”. The mechanical force is proportional to the acceleration. This relationship is a generally accepted code of practice, according to the second law of Newton. If there is an acceleration, a force is generated.[24]

$$\vec{F} = m * \vec{a} \tag{2.30}$$

There are different types of acceleration sensors for uniaxial and triaxial measurment. The transducer element can be designed to work under compression, flexion or shear. Furthermore, the material of the seismic mass is very important for the sensitivity and the resonant frequency.

Typical sensor element materials are quartz or ceramic. The highest resonant frequencies achieved with ceramic elements are around 250 kHz, while the quarz sensor manages 125 kHz. For a given sensitivity, the mass of a sensor with ceramic element can be up to 100 times smaller than that of a quartz sensor element. The lightest mass of a ceramic sensor is 0.2 g and for a quartz sensor 0.7 g. This means, that the user must know the field of application to choose the right sensor.[24]

Concerning the uniaxial acceleration sensor, the acceleration can only be measured in one direction. The measured acceleration-direction depends on the position of the sensor in the space. The frequency, the intensity and the duration of the acceleration are measured. The determination of the energy expenditure with an uniaxial acceleration sensor is very inaccurate because the device does not realise the increase or the decrease of the energy expenditure on up and downhill. That implies, that the potential energy is not included in the calculation of the energy expenditure.

A triaxial acceleration sensor has two additional dimensions in space, it is a three-dimensional (3D) sensor, see figure 2.5. The three acceleration values, which are the amplitudes of the vector components, are summed up geometrically to the sum-vector acc_{sum}.

$$acc_{sum} = \sqrt{acc_x^2 + acc_y^2 + acc_z^2} \tag{2.31}$$

acc_x, acc_y, acc_z ... acceleration in x, y and z direction

The measurement devices are mounted on a belt, so the wearing comfort is better than the heart-rate-monitoring system. The energy expenditure can be calculated more accurately than with an uniaxial sensor.

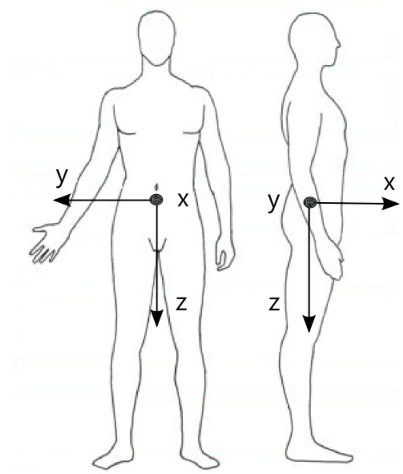

Figure 2.5: Coordinate system for a triaxial acceleration sensor.

Bouten and his colleagues investigated the assessment of energy expenditure using a triaxial acceleration sensor. They were able to show, that there is a linear relationship between the integral average of the acceleration (IAA) and the energy expenditure of a subject. The strength of this characteristic depends mainly on the activity itself. For different activities they could show, that the sum of the integrals of the absolute value of accelerometer and the energy expenditure due to physical activity correlates ($r = 0.82$, $P < 0.001$). During *walking,* the energy expenditure due to physical activity was highly correlating with the integral of the absolute accelerometer output in antero-posterior direction (IAAx; $r = 0.96$, $P < 0.001$). General can be said, that the energy expenditure at walking can be calculated with an accuracy of about 15 %.[25]

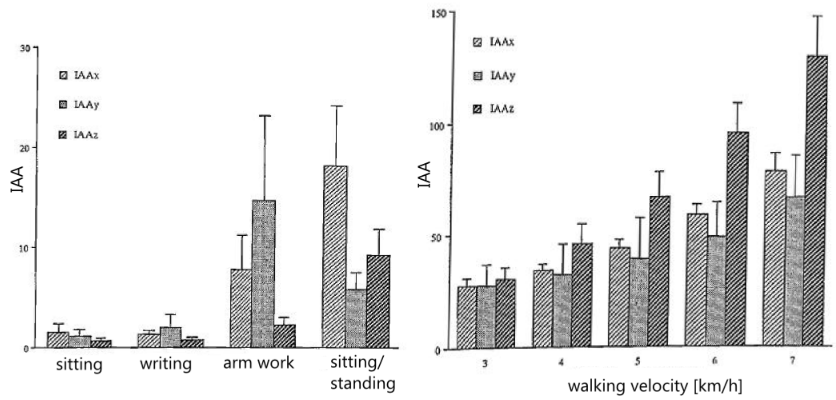

Figure 2.6: The figure shows the integral average of the acceleration (IAA) of the human body in x-, y- and z- direction. In the left diagram for "different activities" and in the right diagram for "walking" at varying speeds.[25]

2.4.4 Heart rate monitoring

Heart rate monitoring is an already common method to predict the energy expenditure. The energy expenditure is derived from the regression of oxygen production versus heart rate. This interrelation must be calculated for every person individually because the relationship between the heart rate and the oxygen production varies from person to person. One of the advantages is the low apparative effort, compared with e.g. the double-labeled water method.[22]

There are a lot of companies that provide such apparatuses. In this indicated statement, respiratory gas parameters are needed to calculate the energy expenditure. A lot of available commercial sport watches - including the one of Garmin – also display the energy expenditure without taking into account the oxygen consumption of the body. The company Garmin has a great collection of heart rate measuring units like the Forerunner 305 chest strap. The chest strap derives the heart rate and sends it wirelessly to the sport watch. Then the energy expenditure is calculated and can be read off on the sport watch.

The method is independent of respiratory gas parameters and take place with a propietary mathematical model, the details of which are not disclosed. The calculation requires some subject specific parameters. In the majority of cases, body mass, sex, size and age have to be entered. Among other things, in this thesis both the correlation of the chest strap data and the data of the acceleration unit are analysed and compared.

At the University of Applied Sciences in Linz, within the framework of a master thesis, a model for the calculation of the energy expenditure was introduced.

The model is based on linear regression between the energy expenditure and the heart rate of a person. The mathematical coherence between the energy expenditure and the heart rate is defined separately for *walking* and *running* with the aid of the regression line. The regression line is based on ergospirometry measurements, which were conducted in the context of the diploma thesis of Watzinger C.G. at the general hospital Linz, Austria [16]. By means of the available equation (2.32), (2.33), (2.34) and with the assistance of sex, body mass wt and the heart rate HR, the total energy expenditure of the test person can be specified very easily. Because of the small number of subjects, who were available for the derivation of the equations, the results must be interpreted with care. Furthermore – due to the minor number of female subjects – only the coherence for the domain *walking* was determined. Unfortunately, no correlation factors for the equations were mentioned in the literature.

$$EE_{walk\,man}\left(\frac{kcal}{min}\right) = \left(0.0012 * HR\left(\frac{beats}{min}\right) - 0.0564\right) * wt(kg) \tag{2.32}$$

$$EE_{run\,man}\left(\frac{kcal}{min}\right) = \left(0.0025 * HR\left(\frac{beats}{min}\right) - 0.2123\right) * wt(kg) \tag{2.33}$$

$$EE_{walk\,woman}\left(\frac{kcal}{min}\right) = \left(0.0016 * HR\left(\frac{beats}{min}\right) - 0.1311\right) * wt(kg) \tag{2.34}$$

3 Methods

This chapter gives an overview of the system components, the interaction of the components and the measurement itself. At first, the particular system components are explained in detail. Subsequently the individual steps of the measurement algorithm and the implementation of the algorithm on the MCU are explained too. In further succession, the communication and the data transfer between the different devices are shown. The evaluation of the data with the software tool Matlab (The MathWorks, Inc., Massachusetts USA) finalizes this chapter.

3.1 Sensorplatform NEON V 1.3.1

NEON is an energy efficient sensor platform from the company Spantec (Spantec GmbH, Vienna Austria). The platform is equipped with different hardware components, in particular:

- two buttons for control
- one reset button
- four LEDs (red, green, blue and yellow) for the status display
- ANT AP2 radio module
- 256kBit external RAM
- micro SD-card socket
- 3D-acceleration sensor
- temperature sensor
- interface for external sensors
- USB-mini AB plug with USB to serial converter
- 3.3V and 5Vpower supply for the external supply
- port for lithium-polymer-accu (LiPo)

- charging regulator for the LiPo
- external real time clock (RTC)
- sampling frequency up to 1kHz
- battery for the external RTC
- MCU (PIC24FJ256GA108)

Figure 3.1: Top view of the sensorplaform NEON V1.3.1.

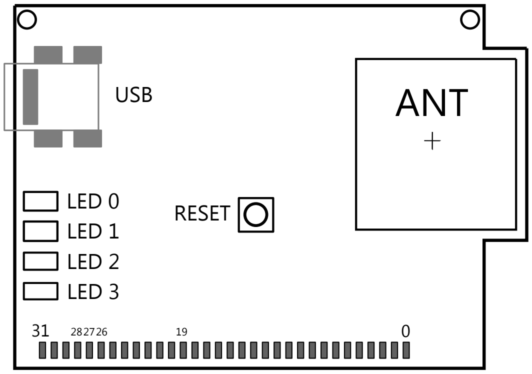

Figure 3.2: Top layout of the sensorplaform NEON V1.3.1.

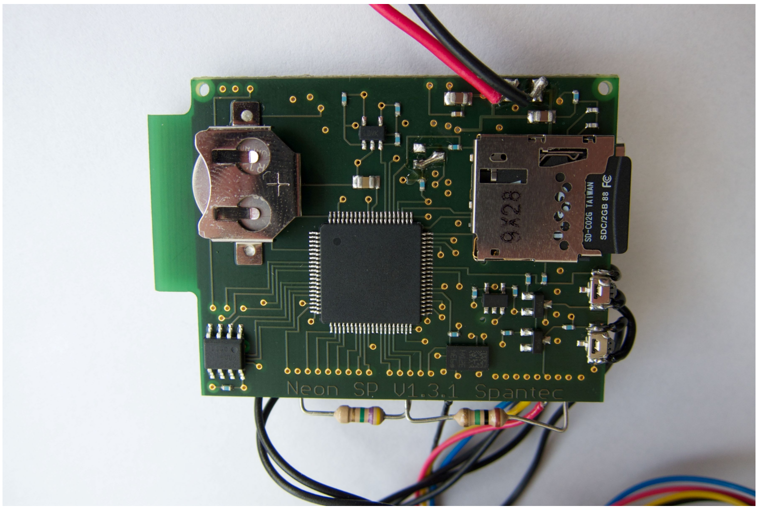

Figure 3.3: Bottom view of the sensorplaform NEON V1.3.1.

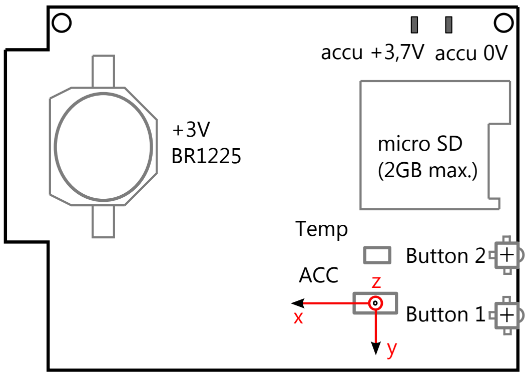

Figure 3.4: Bottom layout of the sensorplatform NEON V1.3.1.

3.1.1 MCU

A microcontroller unit from Microchip (Microchip Technology Inc., Aricona USA) is obstructed on the platform. The unique type reference of the MCU is PIC 24FJ256GA108.

Pins	80
Programm Memory	256 kbytes
SRAM	16 kbytes
UART	4
SPI	3
I^2C	3
Timers 16-Bit	5

Table 3.1: Features of the PIC24FJ256GA108.

3.1.2 3D acceleration sensor

The available acceleration sensor on the platform is the LIS302DLH from STMicroelectronics (STMicroelectronics N.V., Geneva). It is an ultra low-power high performance 3-axes “piccolo” accelerometer and a digital output motion sensor. Some important features of the acceleration sensor are:

- low thickness 0.8 mm
- ultra low-power mode consumption, down to 10 µA
- dynamically selectable fullscale (±2g/±4g/±8g)
- I^2C/SPI digital output interface
- 16 bit data output
- 10000 g high shock survivability

3.1.3 ANT communication module

ANT is a wireless sensor network protocol. It is running in the 2,4 GHz ISM band and is designed for ultra low-power applications. The major advantage of the ANT protocol is the network key. Devices from various manufacturers are able to communicate and exchange data by means of the ANT module. The manufacturers ensure compatibility and make sure, that the data transfer of their units will be done as it is defined in the ANT protocol.

Furthermore, the ANT protocol stack is very compact and requires minimal microcontroller resources. This project is based on ANT compatible devices from Garmin, namely the chest strap and the sport watch. The ANT module is located directly on the sensor platform Neon.

3.2 GPS receiver module

The GPS-320FW is a compact all in one GPS module from RF Solutions (RF SolutionsLtd., Lewes Uinited Kingtown). The standard of the GPS data transmission is the NMEA 0183, which is defined by the National Marine Electronics Association (NMEA). This data format is a well-defined structure. The standard configuration for the universal asynchronous receiver/transmitter for the GPS module is:

- 4800 baud rate
- no parity
- 8 byte data
- 1 stopbit

In table 3.2 and 3.3 the structure of two of the important GPS data sets will be explained in detail:

$GPGGA,191410,4735.5634,N,00739.3538,E,1,04,4.4,351.5,M,48.0,M,,*45	
$GPGGA	data set type
191410	Time (UTC time)
4735.5634,N	Latitude
00739.3538,E	Longitude
1	Quality of the measurement:
	0 = illegal
	1 = gps
	2 = dgps
	6 = estimate only NMEA-0183 2.3
04	Number of the captured satellites
4.4	HDOP (horizontal dilution of precision) accuracy
351.5,M	Height over geoide (sea) in meters
48.0,M	Geoid height minus ellipsoid height on meters
*45	

Table 3.2: The table displays the structure of the GPGGA-data set.

$GPRMC,191410,A,4735.5634,N,00739.3538,E,0.0,0.0,180311,0.4,E,A*19	
$GPRMC	data set type
191410	Time (UTC time)
A	Status of the appointment: A=Active; V=void
4735.5634, N	Latitude with (algebraic sign) direction (N=North, S=South) : 47° 35.5634' North
00739.3538,E	Longitude with (algebraic sign) direction (E=East, W=West): 007° 39.3538' East
0.0	Speed over ground (in bend)
0.0	Direction of Motion degree (true)
180311	Date: 18.03.2011
0.4,E	Deviation (with direction)
A*19	New in NMEA 2.3: Kind of the appointment
	A=autonomous
	D=differential
	E=estimated
	N=not valid
	S=simulator

Table 3.3: The table displays the structure of the GPRMC-data set.

This GPS module is an external unit, which is integrated on the sensor platform NEON above the pin slat. The pin allocation of the NEON is as follows:

Pin Number	Pin Allocation
19	Ground
26	IO_15
27	IO_16
28	Power

Table 3.4: Pin allocation of the sensorplatform NEON for the GPS module.

According to the technical specifications of the manufacturer, the uncertainty of the location determination is in the range of 5 meters. The speed can be calculated with an uncertainty of 0.1 $\frac{m}{sec}$. The GPGGA-data set is used in this work.

3.3 Garmin Forerunner 305 sport watch and chest strap

The sport watch calculates the total energy expenditure of the subject with the aid of the heart rate tracked by chest strap. The data are sent from the chest strap to the sport watch wirelessly according to the ANT protocol. The intern algorithm of the sport watch for calculation of the total energy expenditure is protected by copyright and unpublished.

In this project, the ordained heart rate of the chest strap from the subject is used to calculate the total energy expenditure with a model based on a linear regression, already described in 2.4.4.

With the Garmin Forerunner 305 sport watch, the position of the subject can be determined with an uncertainty of <10 meters. The running speed can be read out with an uncertainty of 0.05 $\frac{m}{sec}$.

3.4 Device configuration of the complete measurement system

The above mentioned units together constitute the whole measurement system of this project. The assembly is depicted in figure 3.10. For testing, the sensor platform and the GPS module were inserted into a black case with the dimensions 80 x 55 x 40 mm, see figure 3.9. This case

Figure 3.5: Garmin Forerunner 305 sport watch

was equipped with a belt to fix the device to the human body close to its center of gravity. On the backside of this case, a stainless steel clip for fixing the case at the waistband was attached. Furthermore, the case contains three buttons for: configuration, measurement and reset mode. The visible USB cable in figure 3.9 is for programming the Neon and for the data transfer after the measurement.

Figure 3.6: Garmin chest strap to determine the heart rate of the subject.

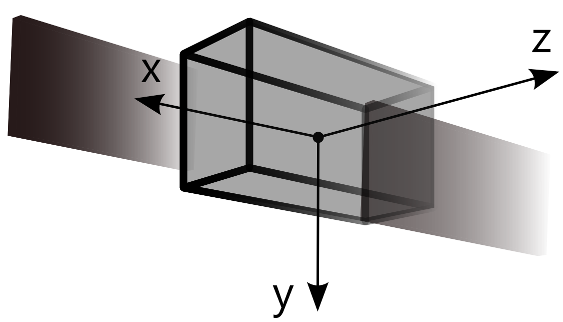

Figure 3.7: Coordinate system of the test case which includes the acceleration sensor unit.

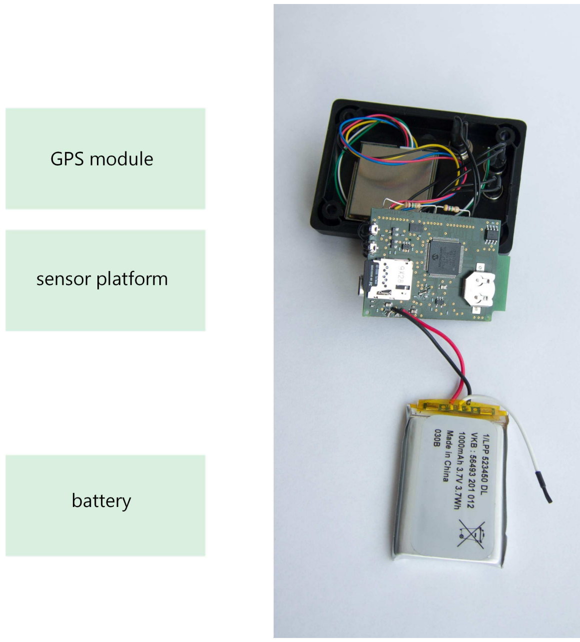

Figure 3.8: The individual parts of the black case without the belt.

Figure 3.9: The figure shows the black case which includes the sensorplatform Neon, the GPS module and the battery. The three buttons are for the three possible modes configuration, measurement and reset.

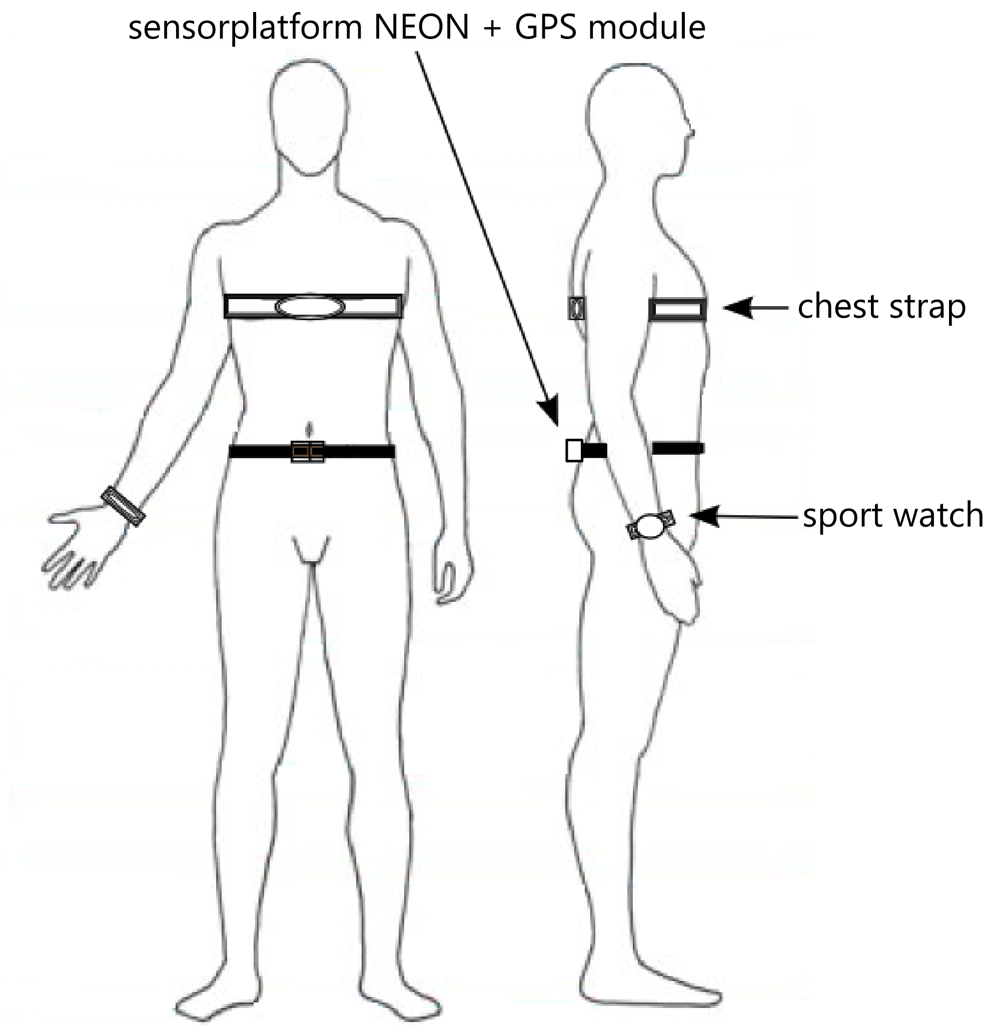

Figure 3.10: Schmeatic device configuration for the measurement. The sensor platform is worn on the belt on the back near the center of gravity. It provides the acceleration signals. The chest strap is placed, as the name implies, on the chest and provides the heart rate signal for the sport watch. The appropriate sport watch can be worn on the left or right hand.

3.5 Reference values for the calculation

To check the energy expenditure calculated with the sensor platform, reference values are required. Two methods for determining these reference values were realised and applied for the evaluation in the scope of this thesis.

3.5.1 Energy calculation with heart rate from the chest strap $EE_{kcal_{HR}}$

The formulas of chapter 2.4.4 were used for the energy calculation based on the heart rate. The heart rate of the proband and the activity state were recorded during the measurement and saved on the integrated SD-card of the sensor platform. After the measurement, the heart rate was read out and the energy expenditure of the subject was determined mathematically.

3.5.2 Energy calculation with the treadmill equation $EE_{kcal_{treadmill}}$

During the treadmill test, the energy expenditure of the test person was also calculated with the aid of the adjusted treadmill speed. The treadmill is a product of the company Woodway, Germany (type PPS 55ortho, serial number 9622E06).

The first step of determining the energy expenditure is the calculation of the power during *running* and *walking*. The approach for estimating the power is based on a linear regression for the state *running* and on a squared regression for the state *walking*, see 3.1 and 3.2.[26]

The individual activity state of the proband was saved on the SD card and used for the following calculations.

$$P_{walk}\,(W) = \left[4.81 + \left(0.42 + 0.033 * n\,(\%) + 0.0021 * n^2\right) * v^2\right] * \frac{wt(kg)}{3.6} \tag{3.1}$$

$$P_{run}\,(W) = \left[1.75 + \left(1.065 + 0.0511 * n\,(\%) + 9.322 * 10^{-4} * n^2\right) * v\left(\frac{km}{h}\right)\right] * wt(kg) \tag{3.2}$$

wt ... body weight in kg
v ... adjusted treadmill speed in $\frac{km}{h}$
n... slope in %

The energy expenditure in $\frac{kcal}{min}$ then results from the measured power as follows [16]:

$$EE\left(\frac{kcal}{min}\right) = \frac{P\,(W) * 60\,(s) * 0.239(cal)}{1000} \tag{3.3}$$

3.5.3 Energy calculation with the sport watch $EE_{kcal_{Garmin}}$

The internal mathematical algorithm of the sport watch for calculation of the total energy expenditure is protected by copyright and unpublished. The algorithm for calculating the energy expenditure of the proband with the heart rate of the chest strap and individual subject parameters (weight, sex and age).

3.5.4 Speed calculation with longitude and latitude from the GPS-module

The accuracy of estimating energy expenditure is based on the precise determination of the speed which is obtained from the acceleration data. For that reason, a sufficiently accurate reference value has to be determined for the speed. This value is received from the GPS data string. For every time step of the measurement – in this case every two seconds – the current latitude and longitude are saved on the SD card of the sensor platform. The x and y values of the relative motion are calculated with the aid of a Matlab script. Based on the mathematical relationship in equation 3.4, the speed $\vec{v}_{gps}$ can be calculated from the covered distance $\vec{d}$ per time step t.

$$\vec{v}_{gps} = \frac{d\vec{d}}{dt} = \begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \end{bmatrix} \tag{3.4}$$

3.6 Experimental protocol

3.6.1 Treadmill measurements (indoor)

The measurement was conducted at the University of Applied Sciences Linz, Austria on the treadmill of the company Woodway, Germany (type PPS 55ortho, serial number 9622E06). A standardized running programme was set up for these measurements (see table 3.6 and figure 3.11). The testing phase lasted for 40 minutes and consists of seven different speed levels. Table (3.5) indicates the mean error of the adjusted treadmill speed levels.

nominal speed ($\frac{km}{h}$)	real speed ($\frac{km}{h}$)	error (%)
2	1,962	-1,90
3	2,977	-0,73
4	4,021	0,53
5	4,984	-0,32
6	6,001	0,00
8	7,954	-0,58
10	10,022	0,22

Table 3.5: Error of the adjusted treadmill speed provided by the Woodway service team.

time (min)	activity	treadmill-speed $\left(\frac{km}{h}\right)$
2	walk	2
4	walk	3
6	walk	4
8	walk	5
10	walk	6
14	run	6
18	run	8
22	run	10
26	run	8
30	run	6
32	walk	6
34	walk	5
36	walk	4
38	walk	3
40	walk	2

Table 3.6: Running programme for the indoor testing phase.

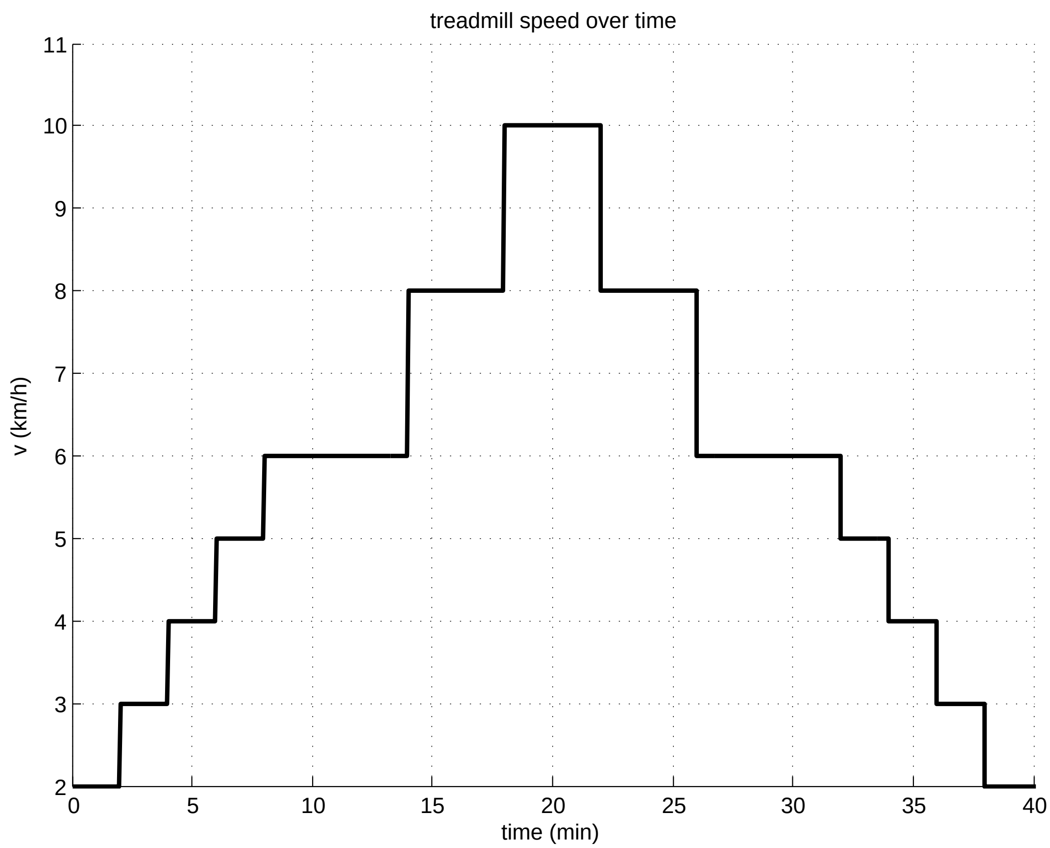

Figure 3.11: Chart of the indoor testing phase.

3.6.2 Running distance (outdoor)

The outdoor testing phase was conducted close to Wels, Upper Austria. The route has a total length of 2.63 km, a height difference of 33.6 meters, a maximum slope of 5.9 % and an average slope of 2.3 %. The course of the route and the altitude profile are shown graphically with the aid of GoogleEarth (figure 3.12 and 3.13).

Figure 3.12: Outdoor running course plottet in GoogleEarth (Google Inc., Kalifornien, USA). The running direction was clockwise.

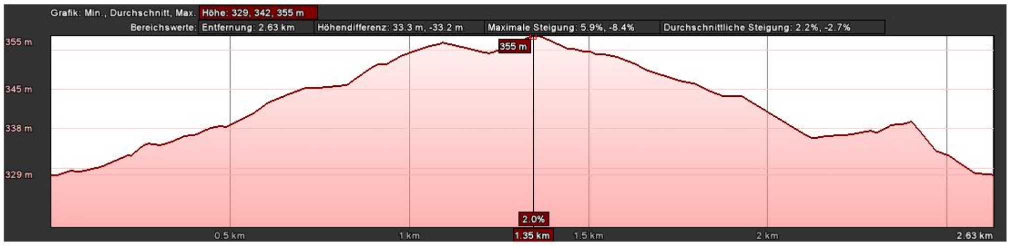

Figure 3.13: Altitude profile of the outdoor running distance, taken from GoogleEarth.

3.7 Algorithm for the MCU

The evaluation algorithm should yield the estimated daily energy expenditure of a person. Starting from the raw values of the acceleration sensor, the mean absolute acceleration is calculated. Independent of the acceleration value, the differential height alteration is taken into account. With the aid of these value, the activity level and furthermore the speed of the subject can be determined. Based on the speed and the differential height alteration, the consumed energy can be calculated. The implemented algorithm for calculating the energy expenditure is based on the Goldman equation which has been already described in chapter 2.3.5.

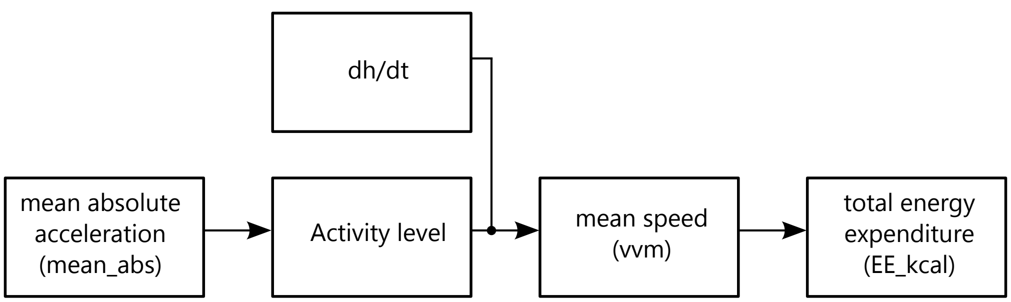

Figure 3.14: The main stages of the algoritm are represented in this figure. The first stage is the calculation of the mean absolute value of the acceleration.

3.7.1 Calculation of the mean absolute acceleration

The calculation of the mean absolute acceleration of the body is one of the most important steps. The successful estimation of the energy requires the correct calculation of the mean absolute acceleration. If this value is not determined precisely, the produced error influences the whole calculation algorithm.

The sample rate of the NEON was set to 100 Hz, that means that the acceleration sensor delivers new raw values every 0.01 seconds. These values, acc_x for the x-direction, acc_y for the y-direction and acc_z for the z-direction, were offset corrected. For this purpose a 3^{rd} order highpass filter was used. The filter coefficients were determined with Matlab for a sample frequenz f_s of 100 Hz and a cutoff frequenz f_{cut} of 0.5 Hz. The general IIR filter transfer function is depicted in equation 3.5.

$$H(z) = \frac{B(z)}{A(z)} = \frac{Y(z)}{X(z)} = \frac{b_0 + b_1 * z^{-1} + b_2 * z^{-2} + ... + b_M * z^{-M}}{a_0 + a_1 * z^{-1} + a_2 * z^{-2} + ... + a_M * z^{-M}} \tag{3.5}$$

Because of the finite word length and the fnite MCU memory, only a finite set of quantized sequences is possible. This fact leads to internal roundoff errors and instability of the filter. The roundoff error involves a distortion of the signal and leads to a loss of information. Therefore a 3^{rd} order highpass with only one transfer function can not be realised in C.

To avoid filter instability, the 3^{rd} order highpass is realised with two series-connected lower order highpasses, see figure 3.15. The two highpasses, 2^{nd} and 1^{st} order, are equivalent a 3^{rd} order highpass.

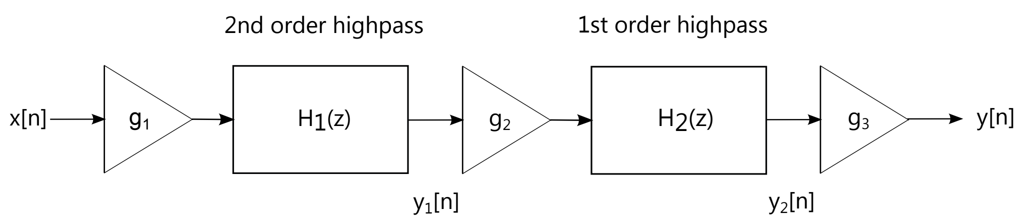

Figure 3.15: Implemenation of the 3^{rd} order highpass by two series-connected lower order higpasses. The gain factors are marked with a g.

The available function *sosMatrix* from the software program Matlab (version R2008a) generates the necessary coefficients and gain factors for the implementation. The coefficients are stored in a (m x 6)-matrix, in this case in the sosHP-matrix. Every column of the matrix represents one 2^{nd} order highpass and the lines include the numerator and denumerator coffecients of the specific filter. Between the highpasses, the signal is amplified with the calculated gain factors of the sosMatrix, see figure 3.15. The calculated sosMatrix coefficients and the gain factors for the IIR filter are listed in equation 3.6 and 3.7.

$$sosHP = \begin{bmatrix} b_{10} & b_{11} & b_{12} & a_{10} & a_{11} & a_{12} \\ b_{20} & b_{21} & b_{22} & a_{20} & a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} 1.0 & -2.0 & 1.0 & 1.0 & -1.96810 & 0.96907 \\ 1.0 & -1.0 & 0.0 & 1.0 & -0.96907 & 0.0 \end{bmatrix} \tag{3.6}$$

$$gainHP = \begin{bmatrix} g_1 & g_2 & g_3 \end{bmatrix} = \begin{bmatrix} 0.00084 & 1.0 & 1151.81319 \end{bmatrix} \tag{3.7}$$

Next, the offset corrected signal is multiplied with a conversion factor to get the acceleration signals $\mathrm{acc_x}$, $\mathrm{acc_y}$ and $\mathrm{acc_z}$ in the unit $\frac{m}{s^2}$.

$$acc_{(i)}\left(\frac{m}{s^2}\right) = acc_{highpass\,(i)} * \left(\frac{g * fullscale * 2}{2^{16}}\right) \qquad for\, i = 1:3 \tag{3.8}$$

g is the earth gravity and the variable *fullscale* is the dynamic range in bits of the Neon. It is predefined to 8. In the next step, the absolute value of the acceleration is calculated from the three components $\mathrm{acc_x}$, $\mathrm{acc_y}$ and $\mathrm{acc_z}$ as follows in equation 3.9.

$$abs\left(\frac{m}{s^2}\right) = \sqrt{acc_x^2 + acc_y^2 + acc_z^2} \tag{3.9}$$

Next, the absolute value of the acceleration is smoothed with a 2^{nd} order FIR lowpass filter. The lowpass filter coefficients are calculated for a sampling frequency $\mathrm{f_s}$ of 100 Hz and a cutoff frequency $\mathrm{f_{cut}}$ of 0.15 Hz. The coefficients calculated with Matlab are shown in equation 3.10.

$$coeff_{lowpass} = \begin{bmatrix} b_0 & b_1 & b_2 \end{bmatrix} = \begin{bmatrix} 0.06896 & 0.86207 & 0.06896 \end{bmatrix} \tag{3.10}$$

Subsequently, the absolute lowpass filtered acceleration signal is averaged over a defined time interval. The selected time interval is 2 seconds, that means that every 200 measurement steps one mean absolute acceleration value is stored. The new sampling frequency is 0.5 Hz.

In figure 3.16, the whole calculation routine is depicted. The raw values and the highpass filter plot are only added for the acceleration in z-direction.

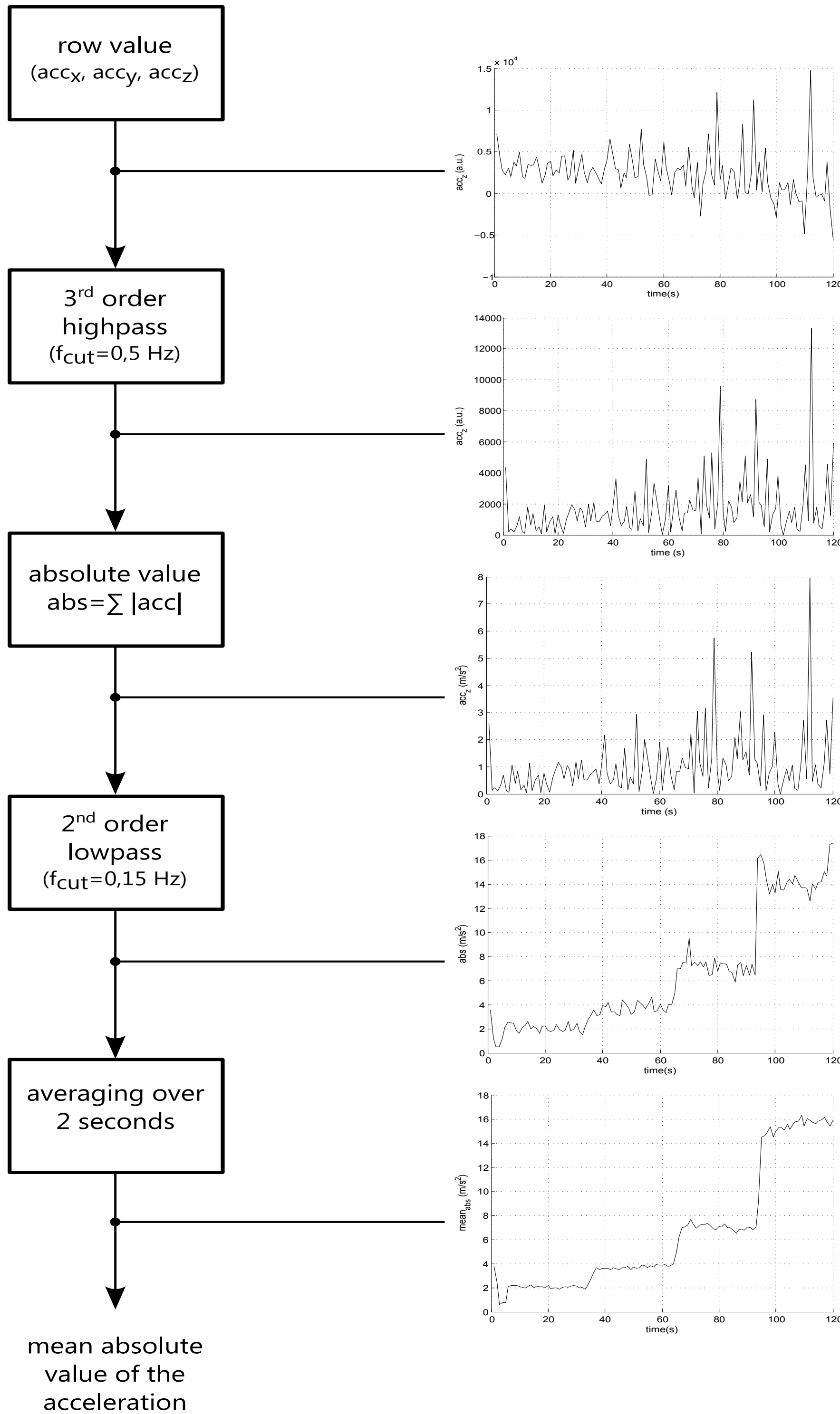

Figure 3.16: Calculation of the mean absolute acceleration value.

3.7.2 Calculation of the activity state

The calculation of the activity state depends mainly on the mean accleration value. The value of the mean acceleration determines the activity states *no activity*, *run* and *walk* (see table 3.7). If the value is below 1.5 $\frac{m}{s^2}$, *no activity* is present. Is the value between 1.5 $\frac{m}{s^2}$ and 7.5 $\frac{m}{s^2}$, the activity state is *walk*. For a value above 7.5 $\frac{m}{s^2}$, the activity state is *run*.

activity state	activity	mean absolute acceleration $\left(\frac{m}{s^2}\right)$
0	no activity	< 1.5
1	walk	$1.5 < \text{mean}_{\text{abs}} < 7.5$
2	run	> 7.5

Table 3.7: Activity states for the mean absolute acceleration values.

The activity state is evaluated and stored for every calculated mean acceleration value.

3.7.3 Calculation of the differential height alteration

The GPS module receives every second a new gps data string. Among other things, the data string implies the current height over geoide in meters. That means, that the current differential height alteration for a defined time interval can be calculated from the current and the last height value, as follows:

$$\frac{dh}{dt}_i \left(\frac{m}{s}\right) = \frac{\left(h_i - h_{(i-1)}\right)}{t} \tag{3.11}$$

$\frac{dh}{dt}$... differential height alteration
h_i... current height
$h_{(i-1)}$... height one time step before the current height

3.7.4 Calculation of the mean speed

In this work a model, which is developed by Kreutzer [27], is used to calculate the speed of the subject with the aid of the previously evaluated variables. The mathematical model is based on a linear regression between the squared speed vv and the mean absolute acceleration

$mean_{abs}$ of the subject. Additionally, the approach considers the slope $\frac{dh}{dt}$ and is formulated as follows:

$$vv\left(\left(\frac{m}{s}\right)^2\right) = coeff_v\left[a_{state}\right][0] + coeff_v\left[a_{state}\right][1] * mean_{abs} + coeff_v\left[a_{state}\right][2] * \frac{dh}{dt} + coeff_v\left[a_{state}\right][3] * mean_{abs} * \frac{dh}{dt} \quad (3.12)$$

The coefficients of the linear equation system were determined by [27] from probands data. A GPS reference system was used to get the speed and the altitude of the test probands. The acceleration data were provided by a separate triaxial acceleration sensor. Following, the coefficients (3.13) from the linear equation system were calculated for the different activity states. Each row of the coefficients matrix $coeff_v$ represents an activity state. The first row contains the coefficients for *no activity*, the second row represents the state *walk* and the third row represents the state *run*. The slope is only considered in this approach for the activitvy state *run*.

According to the activity state of the subject, the coefficients vary (see equation 3.13). If the activity state is *no activity* , there is no mean absolute acceleration and no squared speed. For the activity state *walk,* the first two elements of the coefficients matrix are not zero. All four elements are not zero, when the person is running and the activity state is *run*. In this case, the differential height alteration influences the result.

$$coeff_v = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.63301 & 0.59182 & 0 & 0 \\ -0.68350 & 0.42569 & -2.69730 & -0.0678 \end{bmatrix} \quad (3.13)$$

3.7.5 Calculation of the energy expenditure

The main task of this algorithm is the calculation of the physical activity. Within the scope of this study, the modified Goldman equation is applied to calculate the total energy expenditure. As shown in figure 3.17, the energy expenditure is formed by the four terms *basal metabolic rate*, *energy for additional load*, *position energy* and *locomotion energy*. A detailed description of these four terms was already given in chapter 2.3.5. The four components of the equation were immediately calculated in the unit Watt. Therefore, the power terms are related to the timestep t to get the energy terms in the unit Joule.

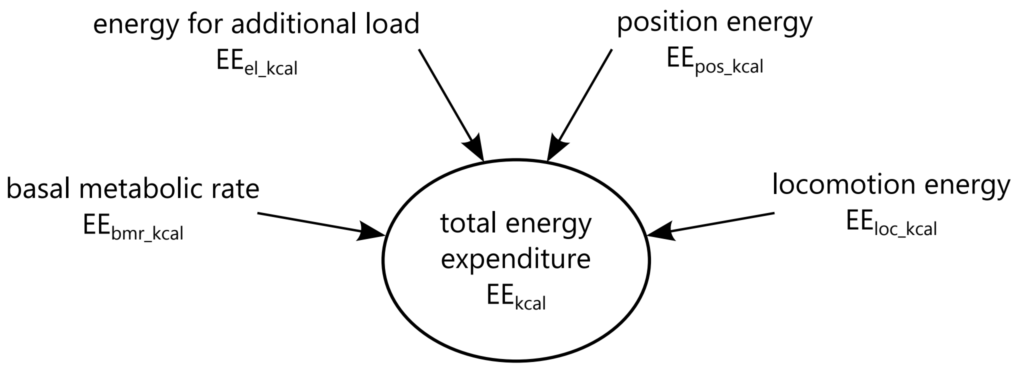

Figure 3.17: Calculation of the total energy expenditure of a person, formed by the four terms *basal metabolic rate*, *energy for additional load*, *position energy* and *locomotion energy*.

3.7.5.1 Basal metabolic rate EE_{bmr}

The basal metabolic rate is the energy expenditure during physical inactivity and at rest. In contrast to the Goldman equation [19], the Harris and Benedict approach is applied to extract the basal metabolic rate more precisely. The value depends mainly on the age in years, body mass wt in kg, bodyheigt bh in cm, gender of the subject and the time t in s. The equation is displayed in 3.14 and the unit is Joule (J).

$$EE_{bmr}(t) = \int (1.2 * (coeff_{bmr}[gender][0] + coeff_{bmr}[gender][1] * wt + coeff_{bmr}[gender][2] * bh - coeff_{bmr}[gender][3] * age))dt \tag{3.14}$$

The coefficients are located in the $\mathrm{coeff_{bmr}}$-matrix. The first line contains the coefficients for men and the second line for women.

$$coeff_{bmr} = \begin{bmatrix} 3.22148 & 0.66609 & 0.24236 & 0.32820 \\ 31.7352 & 0.46326 & 0.08962 & 0.22652 \end{bmatrix} \tag{3.15}$$

3.7.5.2 External load EE_{el}

The additional energy for carrying loads was modeled, as described in the Goldman equation (see equation 3.16). The external load is given by el and wt represents the body mass of the person. The unit of both values are kg.

$$EE_{el}(t) = \int \left(2 * (wt + el) * \left(\frac{el}{wt}\right)^2\right) dt \tag{3.16}$$

3.7.5.3 Locomotion energy EE_{loc}

The motion energy, also known as kinetic energy, represents the main part of the four components. The above calculated current squared speed vv in $\left(\frac{m}{s}\right)^2$ of the subject and the values body mass wt in kg, external load el in kg, terrain factor T and the time t in seconds are needed to evaluate the locomotion energy (see equation 3.17). Toward to Goldman, the correction factor k_{loc} was modified from 1.5 to 1.2, according to [27].

$$EE_{loc}(t) = \int \left(T * (wt + el) * \left(\frac{k_{loc}}{\eta}\right) * vv(t)\right) dt \tag{3.17}$$

3.7.5.4 Position energy EE_{pos}

The position energy describes the needed energy component to overcome a differential height alteration. The energy depends mainly on the current differential height alteration $\frac{dh}{dt}$ in $\frac{m}{s}$, the body mass wt, the external load el, the efficiency of the body η, the terrain factor T and the time t. Also a correction factor $k_{pos} = 0.5$, which was determined in the Bachelor thesis of Kreutzer, plays a rule for the calculation [27]. According to Speck, who said, that the efficiency of the human skeletal muscles come up in vivo to 30 percent under ideal conditions like running, cycling or climbing, η was assumed with 28 percent.[7]

$$EE_{pos}(t) = \int \left(T * (wt + el) * \left(\frac{k_{pos}}{\eta}\right) * \frac{dh(t)}{dt}\right) dt \tag{3.18}$$

3.8 Implementation on the MCU

3.8.1 Programmer and bootloader

The sensor platform Neon from the company Spantec contain a microcontroller unit from Microchip (Microchip Technology Inc., Arizona USA) on the platform (PIC 24FJ256GA108). For further details, please refer to the chapter 3.1.1. This program code was programmed with the MPLAB Integrated Development Environment (IDE) version 8.46. MPLAB IDE is a free integrated toolset for the development of embedded applications employing Microchip's PIC and dsPIC.

After successful coding, the file can be built with the compiler from HiTec dspic16/24. Then, the generated file must be transferred to the MCU. This is done with the bootloader. Post successful *programming* of the sensor platform, the measurement can be started. The data is stored on the SD card of the sensor platform. At the end of the measurement, the data can be read out with the Windows program HyperTerminal (Microsoft, Redmond USA) or with other software tools like HTerm (Tobias Hammer).

3.8.2 Software modules

The algorithm was implemented on the MCU as described in section 3.7. The program was splitted in several major modules:

- main.c (main.h)
- mess.c (mess.h)
- calcEnergy.c (calcEnergy.h)
- calcSpeed.c (calcSpeed.h)

Following, the integration of the algorithm into the modules is shown by means of one measurement step. Figure 3.18 gives an overview about the integration of the algorithm into the modules.

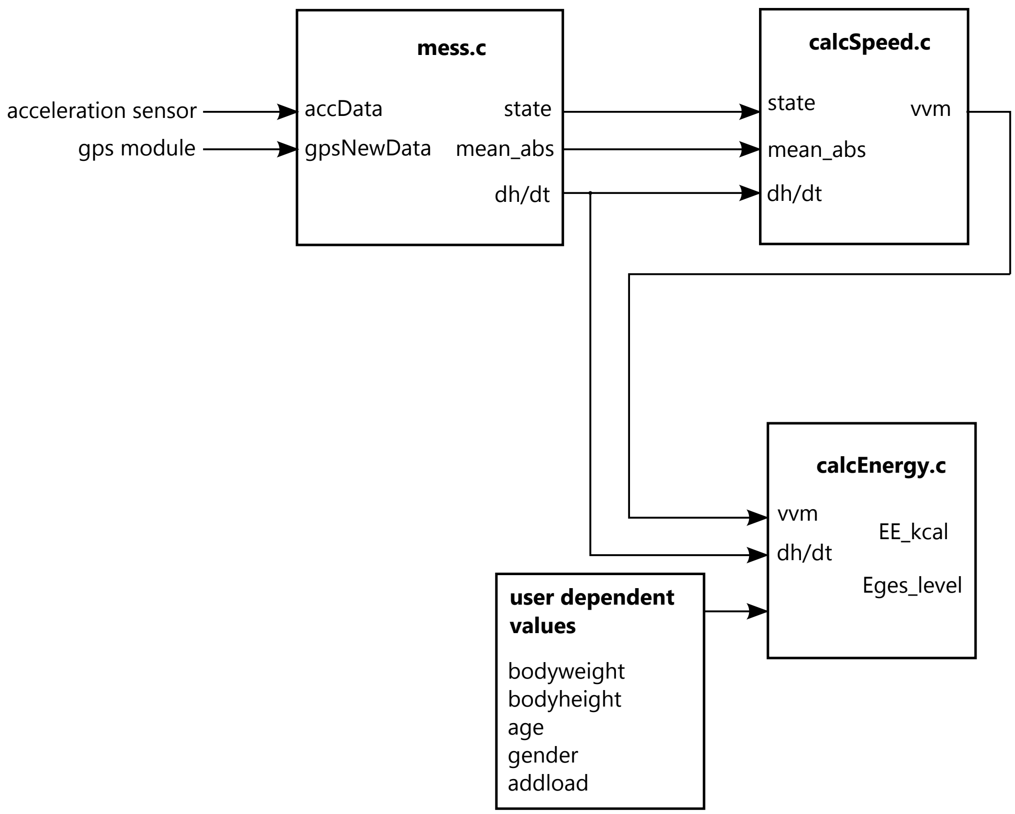

Figure 3.18: Integration of the calculation algorithm into several modules of the MCU.

main.c

By pressing the configuration button for at least five seconds, the sensor platform is started in the main.c module. This module contains the basic definitions for the communication and the initialisation of the whole system. The system is in the configuration mode, when this procedure is done and the orange LED is set. The sampling frequency of 100 Hz was defined in the main module.

mess.c

The measurement is started by pressing the measurement button, the green LED is set and the orange LED is cancelled. The program is now in the mess.c module. Inside the mess.c module, the calculation is done in a while-loop. In this module, the raw values are picked up and the mean absolute acceleration value are calculated.

The value accData(i) contains the raw values from the acceleration sensor. The whole measurement periode runs in a for-loop, where the index value i stands for the three acceleration directions x, y and z. The 3rd order highpass is therby realised as follows:

$$\begin{aligned}
x(k) =& accData(i) \\
x_1(k) =& x(k) * gainHP[0] \\
y_1(k) =& b_{10} * x_1(k) + b_{11} * x_1(k-1) + b_{12} * x_1(k-2) - a_{11} * y_1(k-1) - a_{12} * y_1(k-2) \\
x_2(k) =& y_1(k) * gainHP[1] \\
y_2(k) =& b_{20} * x_2(k) + b_{21} * x_2(k-1) + b_{22} * x_2(k-2) - a_{21} * y_2(k-1) - a_{22} * y_2(k-2) \\
y(k) =& y_2(k) * gainHP[2]
\end{aligned}$$

The highpass filtered acceleration signal y_i(k) is then multiplied with a conversion factor to get the values acc_x, acc_y and acc_z in $\frac{m}{s^2}$. The absolute value is calculated by the defined makro ABS:

```
#define ABS(u) (((u)>0)?u:(-1)*u)
```

The makro is defined in the main headerfile (main.h) and the letter u stands for the input signal. Then the absolute value is processed in the 2nd order lowpass filter as follows:

$$
\begin{aligned}
y(k) &= b_0 * x(k) + b_1 * x(k-1) + b_2 * x(k-2) \\
coeff_{lowpass} &= \begin{bmatrix} b_0 & b_1 & b_2 \end{bmatrix}
\end{aligned}
$$

The input signal x(k) of the lowpass filter is the absolute value from the makro. The lowpass filtered signal is then summed up for a defined measurement time with a counter. By means of a for-loop, the counter variable is compared with a given time interval. If this time interval is reached, the for-loop is executed. The counter value is then 200, that means, that 200 measurement steps have been executed. The new created sampling frequency in the for-loop is now 0.5 Hz. At the beginning of the loop, the mean absolute acceleration value is calculated by dividing the summed lowpass filtered signals through the counter value. In the next step, the activity state is calculated as described in 3.7.2.

The differential height alteration is calculated in the following way: The GPS modul delivers every second a new GPGGA-data string. At first, the quality of the measurement must be valid and a minimum of three captured satellites must be available to consider the height information as trustworthy. If this is the case, the stored old value for the height is deducted from the current height value. It is defined that the absolute value of the differential height alteration must be less than 5 $\frac{m}{s}$ otherwise the change is regarded as wrong and the value $\frac{dh}{dt}$ is set to zero. A proband can reach under normal conditions a maximum differential height alteration, at walking and running, of 5 $\frac{m}{s}$. Examples therefore are the first valid height value: It would lead to significant greater change in height as 5 $\frac{m}{s}$ because the stored old height value is still zero. The error propagation would be significant.

```
//every two seconds one calculation
if((ABS((acthighValue-oldacthigh)))<10){
        dhdt=acthighValue-oldacthigh;
}else{dhdt=0;}
oldacthigh=acthighValue;
```

Also the longitude, latitude, number of captured satellites and the UTC time is stored for every mean absolute acceleration value step. Furthermore, the module mess.c invokes the functions *calcSpeed(ActivityState,mean_abs,dhdt)* and *calcEnergy(ABS(vvm),dhdt).* The variables activity state, mean absolute acceleration and $\frac{dh}{dt}$ are transferred to the function *calcSpeed*. The return value of this function is the calculated squared speed vvm in $\left(\frac{m}{s}\right)^2$.With this squared speed and the variable $\frac{dh}{dt}$, the total energy expenditure and the energy level of the person can be calculated from the function calcEnergy.

In the mess.c module, the current heart rate is also received. It is delivered from the ANT module, to be exact from the chest strap. The received heart rate values are summed up over the counter period. By dividing the summed heart rate signal through the counter value, the mean heart rate over the period is calculated and stored. The following data are stored on the SD card at the end of the while-loop:

- acc_{x}... raw value of acceleration in x direction
- acc_{y}... raw value of acceleration in y direction
- acc_{z}... raw value of acceleration in z direction
- abs... absolute value of the acceleration
- $mean_{\mathrm{abs}}$... average absolute value of the acceleration over the averCount period
- vvm... average squared speed value
- EE_{kcal} ... total energy expenditure
- $EE_{ges_{level}}$... daily energy level
- $averCount$... counter for the captured measurement steps
- $ActivityState$... activity state of the subject
- $acthighValue$... actual height over geoide
- $numberSat$... number of captured satellites
- $\frac{dh}{dt}$... differential height
- $latitudeD$... latitude degree
- $latitudeM$... latitude minutes
- $longitudeD$... longitude degree
- $longitudeM$... longitude minutes
- UTC... UTC time
- HR... heart rate from chest strap

After the successful storage of the data, the counter value is set to zero. This routine is called in every sampling step of the MCU.

calcSpeed.c
The function calculates the squared speed, as described above. A moving average filter over four values is included to get the mean value of the square speed.

calcEnergy.c
The modified Goldman equation was introduced to get the daily total energy expenditure of a person. The four components of the equation were immediately calculated in the unit W. Therefore, the energy terms are related to the above mentioned timestep of two seconds and then multiplied with $0.239*10^{-3}$ to get the unit kcal.

$$
\begin{aligned}
1\,W * s &= 1\,J = 0.239\,cal \\
1\,J &= 0.239 * 10^{-3}\,kcal
\end{aligned}
$$

$$
P_i(kcal) = (P_i(W) * timestep) * 0.239 * 10^{-3} \qquad (3.19)
$$

Furthermore, the energy level in percent (%) is calculated with the aid of the total energy expenditure and a defined total energy nominal value $E_{nominal}$. The value $E_{nominal}$ is made up of two components: The basal metabolic rate P_{bmr} for 8 hours and the activity energy expenditure AEE (700 kcal-3000 kcal). In average, under urban conditions the value $E_{nominal}$ can be set to 1300 kcal.[27]

3.8.3 Floating-point versus fixed-point evaluation of the mean absolute acceleration

At the first evolutionary step, the investigation of the mean absolute acceleration was realised by floating point calculation. As shown in chapter 3.7.1, the signal is averaged in the last calculation step of mean_abs over 200 measured values. Based on the averaging of this signal, the sampling frequency is modified to 0.5 Hz. At the following testing phase it could be seen, that the requested sampling frequency of the raw data is not reached. The floating point calculation of mean_abs requires too much time and therefore the sampling frequency cannot be attained. In order to coerrect this error, the calculation of the mean absolute acceleration was changed to fixed point arithmetic. Due to this conversion, the calculation can be accomplished quicker and the requested sampling frequency of 100 Hz could be realised.

3.8.4 Communication

The communication between the different devices is an important point to ensure the smooth operation of the measurement. For this purpose, the sensor platform equipped with an ANT module, an Universal Asynchronous Receiver Transmitter (UART) interface module, a Serial Peripheral Interface (SPI) module and an I2C module.

The data transfer between the GPS module and the MCU is realized with the UART 2 interface. For this reason, the input- and output-line must be defined in the headerfile config.h.
Furthermore a baudrate of 4800 Bd, parity bit "No Parity" and the initialisation must be set in the main.c module in order to work.
Also for the communication of the PC and the sensor platform an UART interface is used (UART 1). It operates with a baudrate of 460800 Bd and a parity bit of one.
To get the heart rate from the chest strap, a wireless communication with the ANT module and the SPI interface is in use. The network protocol for the ANT communication is included in the mess.c module. Only the initialisation of the SPI is in the main.c module.
For further details please refer to the helpful and very comprehensive software descriptions [28] and [29] from Spantec. Finally, the figure 3.19 shows schematically the communication of the system components in a schematic way.

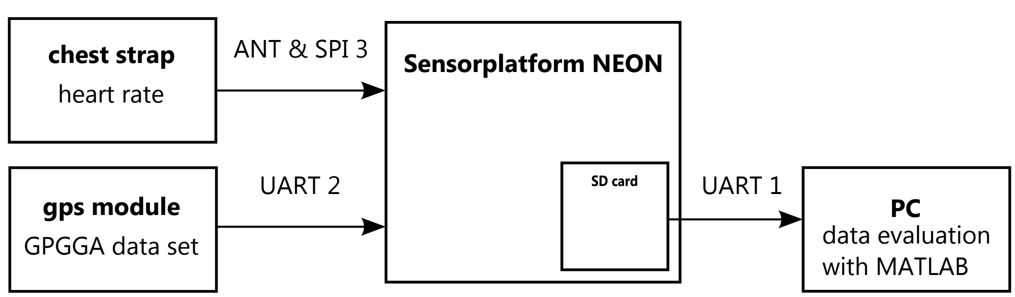

Figure 3.19: The figure shows the communication of the sensorplatform with the different devices.

3.8.5 Problems

During the development process, a couple of compiler specific failures were discovered. For further development steps, some of these will be briefly pointed out here. The different code modules occupy a predefined storage space on the MCU. Also for the functions within this modules a predefined storage space is reserved. It may come to, that the module has enough free storage space, but a specific function of this module has occupied its storage space. This function thereby causes a compiler failure, although the storage space of the specific module isn't exhausted. Another MCU specific property emerged at the handling with vectors. The utilised vectors should have an even number of vector elements. If this is not the case, a compiler error could be the result. Furthermore, the length of the USB cable, which is used for the communication and for charging the battery, should be as short as possible. If the cable is too long, the platform will not be loaded and the visual output of the sensor platform during the "charge mode" is wrong. As discussed with the development department of Spantec, this error should be removed at the newer versions of the sensor platform Neon.

3.9 Evaluation with Matlab (version R2008a)

The measured and stored data on the SD card are transmitted to the PC by the software program HyperTerminal or Hterm. The option depends on the chosen baudrate of the UART 1 interface. For a baudrate of more than 256000 Bd, the software tool HyperTerminal must be used, because Hterm is not able to handle a higher baudrate. The data are stored as a textfile, which can be imported then into the Matlab workspace.
In the focus of this work, following evaluations were realised in Matlab:

1. mean absolute acceleration $mean_{abs}$ and activity state a_{state} over the measurement time
2. correlation of mean absolute acceleration $mean_{abs}$ with the measured heart rate
3. recorded heart rate plotted over time
4. calculated total energy expenditure $EE_{kcal_{Neon}}$ from the sensor platform, $EE_{kcal_{HR}}$ from the heart rate, $EE_{kcal_{treadmill}}$ from the treadmill-equation over time for the indoor measurement
5. calculated total energy expenditure $EE_{kcal_{Neon}}$ from the sensor platform, $EE_{kcal_{HR}}$ from the heart rate, $EE_{kcal_{Garmin}}$ from the sport watch over time for the outdoor measurement
6. calculated speed v from the sensor platform over the calculated speed v_{gps} from the Matlab evaluation for the outdoor measurement

Furthermore, the stored route is visualised in GoogleEarth (Google Inc., Kalifornien, USA) by a gpx-file. This file is created with Matlab using the stored latitude and longitude data of the GPS module.

4 Results

This chapter contains the results of the two short test phases (indoor and outdoor measurements). For every test phase, specific values of the proband – which are relevant for measurement and evaluation – are listed in a table. A proband is deemed to be athletic if he/she does sport at least one day per week.

4.1 Treadmill measurements (indoor)

proband	age (year)	body weight (kg)	body height (cm)	gender	athletic	successful finished
1	25	74	184	man	yes	yes
2	29	90	186	man	yes	yes
3	29	69	181	man	yes	yes
4	25	69	175	man	yes	yes
5	25	88	184	man	no	yes
6	17	62	173	man	no	no
7	27	66	170	woman	no	yes
8	39	88	183	man	yes	yes
9	30	64	177	man	yes	yes
10	25	65	172	man	yes	yes

Table 4.1: Proband specific values for the treadmill measurement execution.

The values of the treadmill equation were chosen as reference level for all diagrams. All relevant data of the sensor platform, e.g. speed, energy expenditure and so on, were read out from the integrated SD card and imported into Matlab. In addition to the shown standard deviation, an error range for the calculated energy expenditure was established. This error range was determined individually for every proband. Therefore, for every time step, the error between the calculated energy expenditure of the test person via the sensor platform and the calculated energy expenditure (of the test person) via the treadmill equation was determined. Then, the maximum and the minimum error of all probands were defined for every time step and plotted graphically together with the average value of the calculated energy expenditure.

The following plots were generated:

- Figure 4.1: Mean absolute acceleration value mean_{abs} and activity state over the measurment time for the treadmill measurement of proband 1.
- Figure 4.2: Correlation of mean absolute acceleration mean_{abs} with the measured heart rate HR for the treadmill measurement of proband 1.
- Figure 4.3: Recorded heart rate plotted over time for the treadmill measurement of proband 1.
- Figure 4.4: Calculated speed of the sensor platform, first resting upon the linear coefficient, which was investigated in [27] (see subsection 3.7.4). Second, the coefficients were determined individually for every proband. For the state "walk" a linear regression was calculated for the velocity calculation and a quadratic approach for the state "run". The average speed value of the test person, who has successfully finished the testing phase is presented. Furthermore, the plot contains the standard deviation of the calculated average speed value and the reference value of the speed, the set treadmill speed.
- Figure 4.5: This plot contains the calculated average values of the energy expenditure. The depicted velocities of every proband in plot 4.4 were used for the calculation of the consumed energy by means of the sensor platform.
  - $EE_{kcal_{Neon}}$: mean energy expenditure determined with the sensor platform
  - $EE_{kcal_{HR}}$: mean energy expenditure determined with the heart rate
  - $EE_{kcal_{treadmill}}$: mean energy expenditure determined with the treadmill equation
- Figure 4.6: This plot contains the same variables as in figure 4.5, nevertheless, the coefficients for the activity states "walk" & "run" – which are relevant for the velocity calculation – were determined individually for every proband. For the state "walk" a linear regression was calculated for the velocity calculation and a quadratic approach for the state "run". The lower illustration of figure 4.4 show the applied velocity profile.

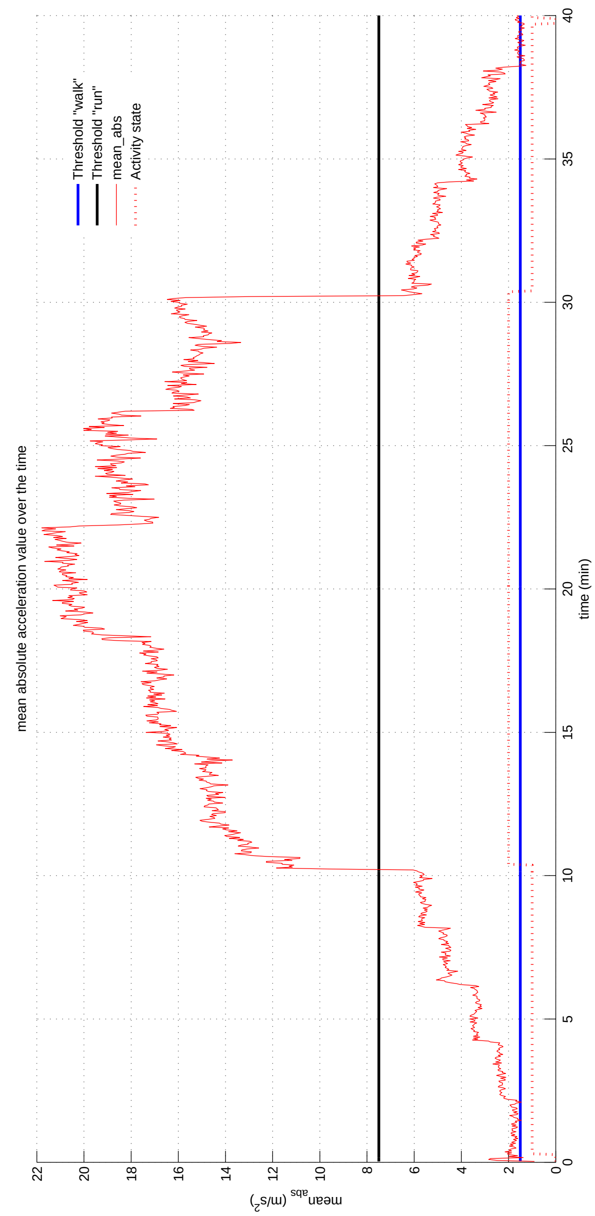

Figure 4.1: Mean absolute acceleration value mean_{abs} and activity state over the measurment time for the treadmill measurement of proband 1.

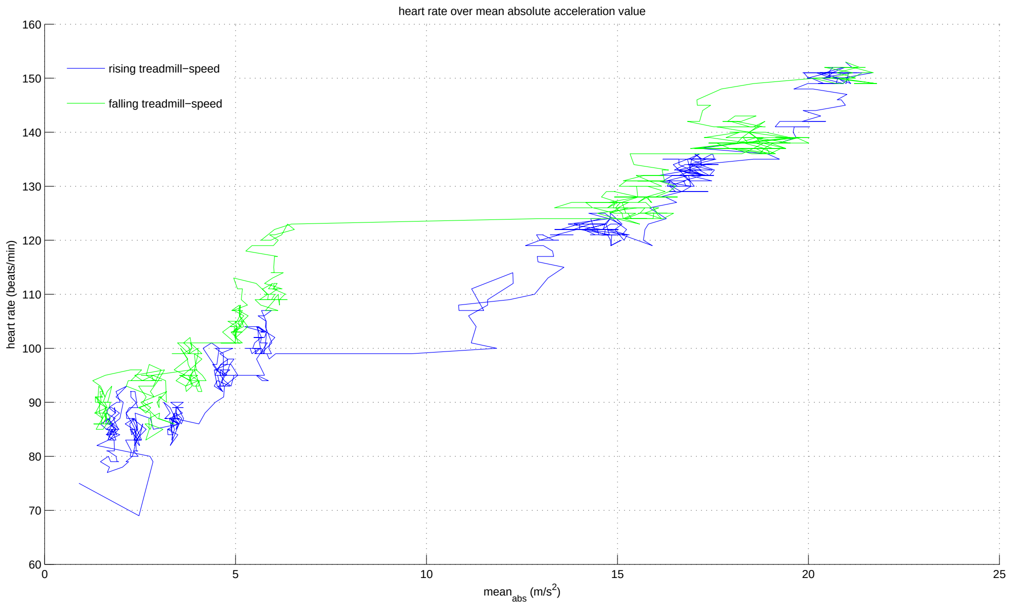

Figure 4.2: Correlation of mean absolute acceleration mean_{abs} with the measured heart rate HR for the treadmill measurement of proband 1.

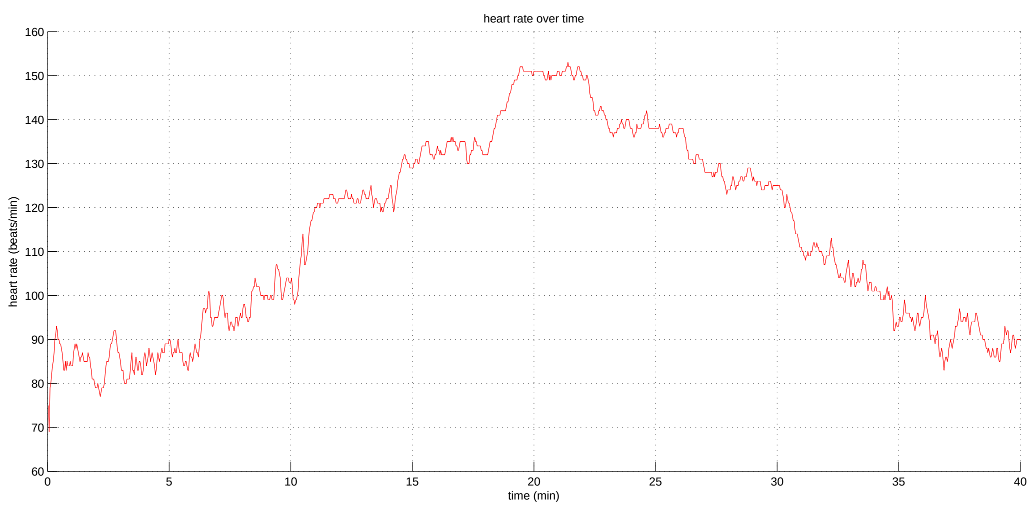

Figure 4.3: Recorded heart rate plotted over time for the treadmill measurement of proband 1.

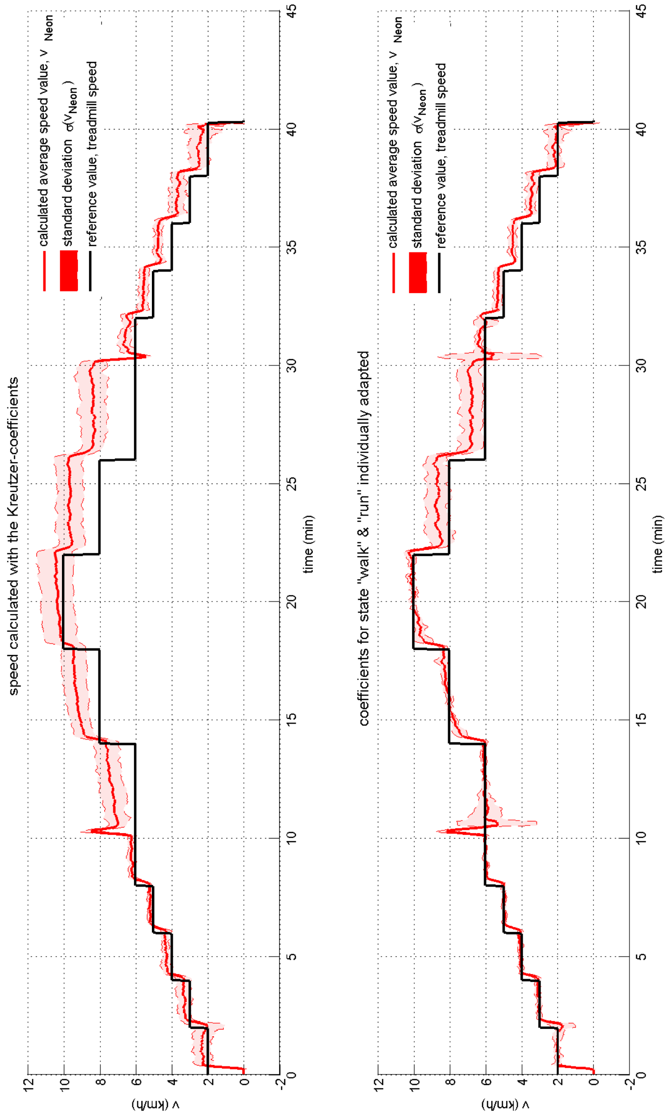

Figure 4.4: Speed calculated with the sensor platform Neon. The average speed value of the test person, who has successfully finished the testing phase, is presented in red. The black line represents the reference value, the set treadmill speed profile.

		error of the mean calculated speed of the sensor platform Neon related to the adjusted treadmill speed	
treadmill speed	activity state	Kreutzer coefficients for “walk” & “run”	coefficients individually determined
$(\frac{km}{h})$		(%)	(%)
2	walk	12,30	-0,25
3	walk	10,10	2,10
4	walk	7,48	1,63
5	walk	4,10	-0,54
6	walk	3,48	-0,38
6	run	22,33	0,45
8	run	15,50	0,65
10	run	3,20	-0,54

Table 4.2: Error in percent of the mean calculated speed of the sensor platform Neon related to the adjusted treadmill speed.

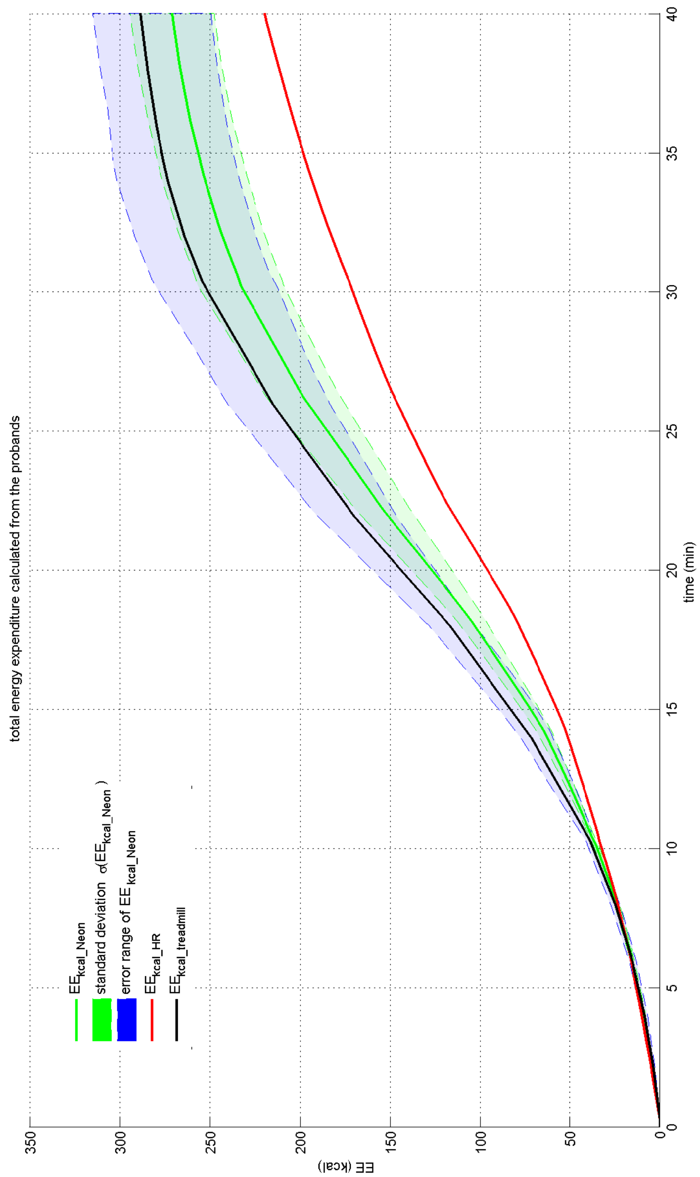

Figure 4.5: Total energy expenditure calculated from the probands who successfully accomplished the treadmill testing phase. Coefficients derived from the linear approach, which was investigated in [27].

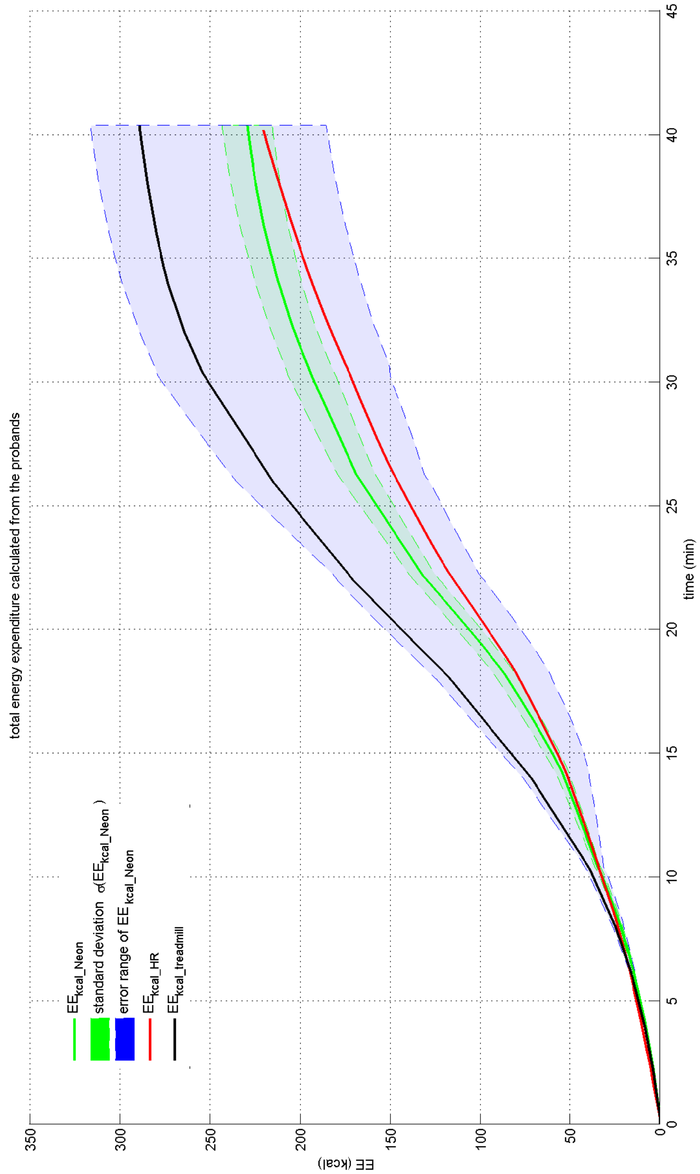

Figure 4.6: Total energy expenditure calculated from the probands who successfully accomplished the treadmill testing phase. The coefficients for activity state ”walk” and "run" were modified for the evaluation for every proband separately with a Matlab script.

4.2 Running distance (outdoor)

proband	age (year)	body weight (kg)	body height (cm)	gender	athletic	successful finished	continuous GPS signal
1	25	74	184	man	yes	yes	yes
2	25	70	174	man	no	yes	no
3	25	65	170	woman	yes	yes	no
4	50	68	170	woman	no	yes	no
5	23	73	175	man	yes	yes	no

Table 4.3: Proband specific values for the outdoor measurement .

	calculated energy expenditure			measurement difference of $EE_{kcal_{Neon}}$ related to	
proband	$EE_{kcal_{Neon}}$ (kcal)	$EE_{kcal_{HR}}$ (kcal)	$EE_{kcal_{sportWatch}}$ (kcal)	$EE_{kcal_{sportWatch}}$ (%)	$EE_{kcal_{HR}}$ (%)
1	374,54	396,52	421	-11,04	-5,54
2	460,92	502,2	310	48,68	-8,22
3	170,32	-	168	1,38	-
4	179,20	-	135	32,74	-
5	415,51	505,98	416	-0,12	-17,88

Table 4.4: Calculated energy expenditure of the probands for the outdoor test. The energy expenditure, based on the indivdual heart rate, can't be calculated for the female probands three and four. The model for the calculation of the energy expenditure, based on the heart rate, is only validated for men, see chapter 2.4.4.

			calculated energy expenditure			heart rate	
proband	round (#)	lap time (min)	$EE_{kcal_{Neon}}$ (kcal)	$EE_{kcal_{HR}}$ (kcal)	$EE_{kcal_{sportWatch}}$ (kcal)	max. (beats/min)	mean (beats/min)
1	1	16 : 43	193,50	193,23	211	159	144
	2	16 : 04	181,04	203,29	210	167	149
2	1	21:07	217,90	223,03	164	163	144
	2	22:30	243,02	279,47	146	171	157
3	1	19 : 57	170,32	-	168	167	152
4	1	22 : 43	179,20	-	135	150	133
5	1	16 : 16	200,50	237,64	204	180	166
	2	16 : 54	210,33	268,34	212	189	172

Table 4.5: Measurement data from the outdoor test of the probands for every lap. Also the maximum and the average heart rate for every proband are listed in this table. The energy expenditure, based on the indivdual heart rate, can't be calculated for the female probands three and four.

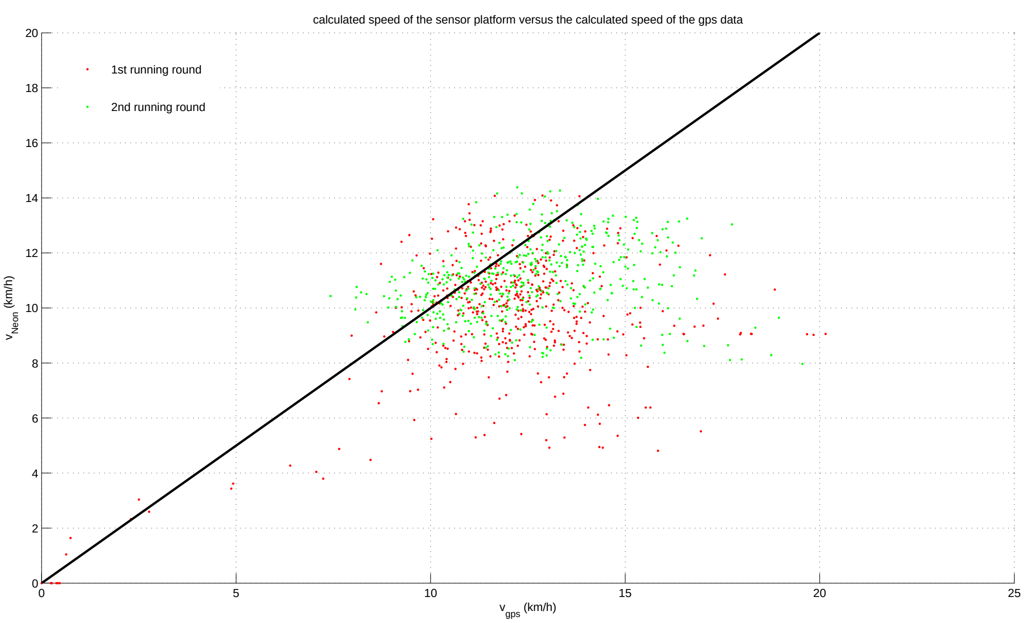

Figure 4.7: Calculated speed of the sensor platform Neon versus the calculated speed of the GPS data of proband 1. The black line represents the line of identity.

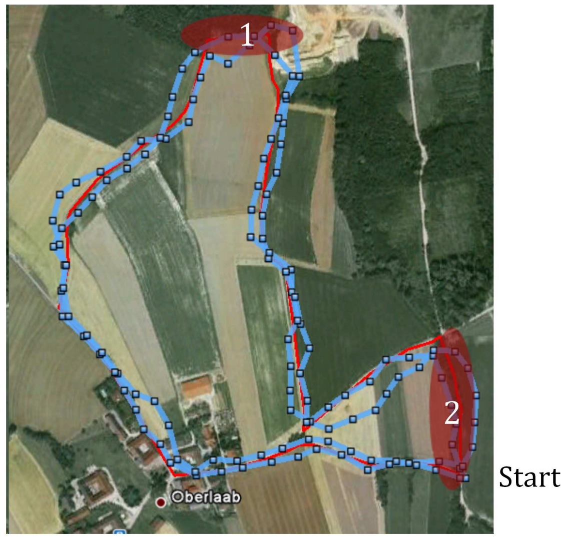

Figure 4.8: Outdoor route visualised in GoogleEarth created with the stored latitude and longitude data of the gps module for proband 1. The red hatched areas show the forest sectors. The running direction was clockwise.

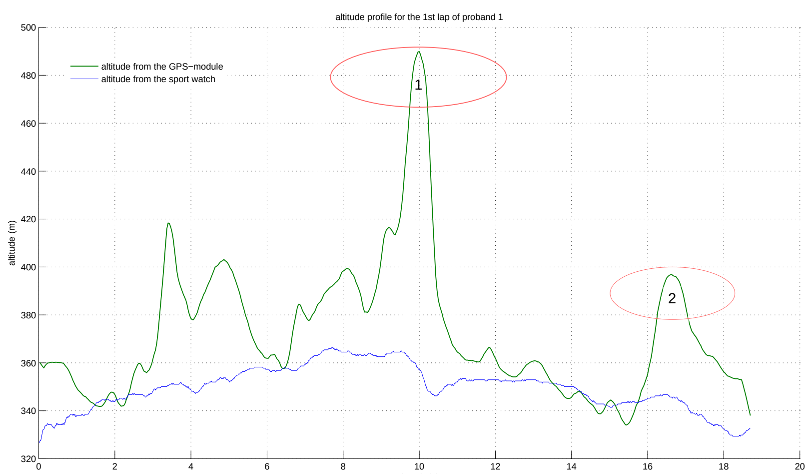

Figure 4.9: Altitude profile of the outdoor test for the 1st lap of proband 1. The red circled areas mark the forest sectors of the route, see figure 3.12.

5 Discussion

Due to the conversion of the calculation of the mean absolute acceleration $mean_{abs}$ (from floating point to fixed point arithmetic), the requested sampling frequency could be realized. The correct sampling frequency is very important, especially for the filters, which are the main part of this calculation step. The coefficients were calculated for this sampling frequency. An alteration leads directly to an erroneous of the signal.

Figure 4.1 shows the time course of the mean absolute acceleration for proband 1 during the indoor treadmill test. The graph indicates very clearly that the differentiation between 'walking' and 'running' – based on the two thresholds – works quite reliably. The relationship between activity and mean absolute acceleration was also published by the working group of Bouten [25].The resulting variable activity state is presented red punctured. An activity state has to be maintained at least 10 seconds to be recognized. Spontaneous fluctuations of the mean absolute acceleration, e. g. caused by temporary stops, are disregarded, provided that they last less than 10 seconds.

The hysteresis in figure 4.2, which becomes visible when plotting the heart rate over the mean absolute acceleration at increasing and then decreasing load, is very significant. The area, which includes the hysteresis, is depending on the training conditions of the proband; the smaller the area the quicker the heart of the test person regenerates . The heart is a physiological system, which only reacts with a finite time delay to changes of the load condition. The acceleration unit can react faster to a variation of the load condition and is only limited by the temporal resolution of the sensor platform.

The determination of the speed, based on the coefficients of Kreutzer [27], is possible for the state walk with a mean maximum deviation of 12.3 %. For the state run, the coefficients have to be determined individually, because the approach – relying on Kreutzer's coefficients – leads to an overestimation of the speed. The mean maximum deviation is reached at 6 $\frac{km}{h}$ with a percentage of 22.33 %. On the one hand, this is due to the different acceleration sensor type and on the other hand, it has to do with the design of the test case. The design and the fixing of the case leads at higher speed to more powerful movements of the

measurement case, what could explain the deviation. The coefficients for the state run were determined individually with a square regression. The resulting speed is presented in figure 4.4. Furthermore, in this figure a linear regression was presented for the state walk. It can be shown, that the speed can be determined, for this one test phase, very precisely by the individual calibration of the coefficients. For the application in the state walk, the approach based on Kreutzer's coefficients can be used with adequate accuracy. If the system should be applied at higher speed, an individual calibration must take place necessarily.
Because of the individual adaptation of the coefficients and the associated more precise calculation of the speed, the energy expenditure can be determined more exactly. The process of the mean energy expenditure of the probands converges to the mean energy expenditure of the probands based on the heart rate (see figure 4.6).
The outdoor testing phase must be seen as an exemplary trial. In the context of this trial, the GPS-module – which provides the required altitude information – was tested. Figure 4.8 shows the running route and the two laps of proband 1, blue marked, in GoogleEarth. For every lap, the altitude profile was determined with the help of a GPS-unit and for the first lap superimposed with the altitude profile of the sport watch in Matlab, see figure 4.9. One can recognize very clearly, that the determination of the current altitude from the GPS-signal works only with insufficient accurately. This is due to the limited local resolution of the GPS-module, 5 – 10 meters, the limited number of available satellite and the geographical conditions (forestal areas). The GPS reception must be improved on the hardware and software side.
The calculated speed depends on – as before described – the current altitude variation. Because of the inaccurate determination of the altitude, the speed and consequently the energy calculation are erroneous. As a result, these facts explain the huge deviations of the outdoor measurements.

5.1 Conclusion

The outdoor testing phase has shown that – independent of the small number of probands – the determination of the current altitude from the GPS-signal works only insufficiently accurately. Causes for this unsatisfactory determination is on one hand the GPS-signal loss, e. g. due to weather (clouds), the geographical conditions and of course indoor measurements (climbing stairs). On the other hand, a correct altitude calculation is obtained only at a satellite number ≥ 4. On average, there were four satellites for the calculation of the current

altitude at the outdoor measurements.
In order to avoid this problem, an additional pressure sensor, which calculates – independent of the GPS-signal – the current altitude from the atmospheric pressure, would be advantageous. According to the software, one could chose between the altitude, which was determined from the pressure sensor data and the altitude from the GPS-signal. This would mean, that the altitude of the GPS sender is used at a valid GPS-signal. On the contrary, at a measurement, where no GPS-signal is existing, the altitude of the pressure sensor could be used. Of course, both signals – weight to their quality – could be included in the altitude calculation. Additionally, the reception of GPS-signals should be improved. This would not only be advantageous concerning the altitude determination. The reception would permit a more precise determination of the current speed, depending on the GPS data. During a measurement, the GPS signal could be used in real-time for adjusting the calculation coefficients.
In order to organise the transfer of the data more easily, a LAN bridge should be used in further development steps. The patient has to position the system only near the active LAN bridge and this LAN bridge could transmit the data directly to the doctor in charge. The doctor can give feedback, e.g. by phone very quickly and the patient doesn't have to visit the doctor. This would minimize the effort of the patient or client and increase the acceptance.
Unfortunately, in the context of this thesis only simplified approaches were used for the comparison of the calculated energy values. The number of the probands was limited too and therefore the results have to be regarded critically. In order to make a more precise statement, further measurements with a major number of probands – well mixed – should be undertaken. In addition, an adequate Goldstandard has to be found as a reference for the real energy expenditure.
In further development steps, the efficiency of the test person should be determined individually by means of the heart rate. This could coincide within a smaller error band. It could be realized, that the acceleration data of two probands, as long as body mass, body height, sex and the running dynamic is comparable approximately, are similar. This leads to a very similar energy expenditure, although it is possible, that one of the probands is untrained and has to spend much more energy for the same acceleration.
Finally, one can say, that the main focus of the further development is the validation of the system against an adequate Goldstandard, the correct altitude evaluation and the better usability. Because of the above mentioned results, with regards to the precision of the speed estimaion for lower speeds, the field of application of this system should be in the range of rehabilitation and therapy.

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List of Figures

List of Tables