

# **Sensor Based Dairy Cow Estrus Detection**

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## Prologue

I would like to thank you everyone. [28] [7]

Otaniemi, 16.1.2017

Miika S. Ihonen

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# Symbols and Abbreviations

## Symbols

$g$	acceleration unit $\approx 9.81[\text{m/s}^2]$
$\mathbf{B}$	magneettivuon tiheys
$c$	valon nopeus tyhjössä $\approx 3 \times 10^8[\text{m/s}]$
$\omega_D$	Debye-taajuus
$\omega_{\text{latt}}$	hilan keskimääriinen fononitaajuus
$\uparrow$	elektronin spinin suunta ylöspäin
$\downarrow$	elektronin spinin suunta alaspäin

## Operators

$\nabla \times \mathbf{A}$	vektorin $\mathbf{A}$ roottori
$\frac{d}{dt}$	derivaatta muuttujan $t$ suhteen
$\frac{\partial}{\partial t}$	osittaisderivaatta muuttujan $t$ suhteen
$\sum_i$	summa indeksin $i$ yli
$\mathbf{A} \cdot \mathbf{B}$	vektorien $\mathbf{A}$ ja $\mathbf{B}$ pistetulo

## Abbreviations

MCU	Micro-Controller Unit (or micro-controller)
SD	Secure Digital
SDHC	High Capacity Secure Digital
SDXC	Extended Capacity Secure Digital
SPI	Serial Peripheral Interface bus
I <sup>2</sup> C	Inter-Integrated Circuit bus (also IIC)
EEPROM	Erasable Programmable Read-Only Memory
SRAM	Static Random-Access Memory
FIR	Finite Impulse Response
IIR	Infinite Impulse Response
FIFO	First In, First Out
IDE	Integrated Development Environment
FFT	Fast Fourier Transform
RISC	Reduced Instruction Set Computer
CISC	Complex Instruction Set Computer
USB	Universal Serial Bus
ISR	Interrupt Service Routine
I/O	Input/Output

# 1 Introduction

In master's thesis the introduction section should cover from 2–4 pages. No subsections required. The introduction should explain the following:

Background of the research. Read books and interview persons for this.

Research problem might be difficult to define. However, it comes clear repeating question “why” instead of questions “what” or “how”. Why am I doing this work? Why it is so important? Why is it interesting? Because continuous-time observing without using technology is expensive. It is impossible to observe tens or hundreds of cows without technological equipment. This functionality can be integrated with others in same device.

Research objective? The objective of this research is to provide alternative methods for observing health of cows. This new method should overcome older methods in cost, usability and so forth.

Restrictions of the research. What is included and why? What is excluded and why? This research focuses only on cows of milk farms. Other cows and animals are excluded in spite of the possibilities of using same technologies but other algorithms. Also the device and hardware are limited. The power consumption and battery saving sets limits for the possible algorithms. The usability sets restrictions for the maximum size of the device.

## 2 Background

Originally, humans were hunter-gatherers who obtained food by collecting plants and pursuing wild animals. The methods for obtaining food have changed substantially since the beginning of agriculture. Plants and animals are grown centralized by farmers. Moreover, it has been estimated that the animal husbandry has started more than 10,000 years ago in western Asia. Accordingly, goats were among the first domesticated animals in history [27]. Thereafter, people have been domesticating other species e.g. cows, sheep and pigs for food, milk and other animal products. In addition to the number of species, the head count has been growing with human population (lähde?). Furthermore, the industrial revolution has started a trend of increasing farm sizes and a loss of small farms. Considering only cow farming, alone in the United States of America, there were nearly 90 million cows and calves in 2014 [2]. Respectively, the head count world wide has been estimated almost up to 1,000 million heads in 2016 [3]. Nowadays, the cattle rearing is divided into two trends of beef and dairy farming. Moreover, the breeds for beef cattle and dairy cattle are different. The scope of beef breeding is in rapid brawn growth, whereas it is high milk yield with dairy breeding. In despite of the scope of this study in dairy farming, some of the results of this study could be adoptable and beneficial also in beef farming. Eventually, it is very likely for both of the breeds to end up in food or animal feed.

According to the title, the scope of this study is in dairy farming and specially in estrus detection. Thus, it is mandatory to explain the principles of dairy farming and study dairy cow in general. Furthermore, it is necessary to be acquainted with milk yield related lactation and estrus cycles. Otherwise, the comprehension of the reason for the estrus detection will not be unambiguous. Therefore, we start with the basics present-day of dairy farming. Even today the technological progress in dairy farming is dispersed. Thus, we need to discuss of both, conventional and modern dairy farming. Next, we take a look on a generalized dairy cow. Moreover, we discuss of its natural and farm environments. Furthermore, we discuss in detail of the lactation and the estrus cycles and how they affects on milk yield. Milk yield affects directly to farm profitability. Consequently, it is the fundamental motive for this study. Second lastly, we study currently utilized health monitoring and estrus detection methods and technical aids. Furthermore, we discuss of their assets and disadvantages. Lastly in this section, we discuss of most resent research and development on health monitoring and estrus detection devices.

### 2.1 Dairy Farming

As discussed in previous subsection, the origins of animal husbandry are over 10,000 years old, whereas, the drinking of milk started 8,000 years ago in Turkey area. Thousand years later, dairy farming started to spread to Europe and next to Africa 6,000 years ago [27]. Thereafter, dairy farming has spread all over the world and the variety of dairy products has exploded simultaneously. In result, there are numerous different milk, cheese and yogurt products as well as other dairy refinements (lähde). Nowadays, dairy products have an essential part in human nutrition. Milk and dairy products are produced more than never

before. The farm sizes have been increasing meanwhile the number of farms has started to decrease. In 2015 in Finland there were total of 909,000 cows of which 282,000 milking cows[16]. In comparison in 2014 in the United States of America, there were more than 89 million cows and calves of which more than 9 million were milking cows[2]. In the end of the year 2015 in Finland, 7890 farms delivered milk to milk processing plants. The average yield of the farms was 279 thousand liters and the average yield of a cow was 8300 liters. In summary the total yield in Finland was 2365 million liters. [16] In the USA the total farm income in cash in the year 2014 was over 49,349 million dollars [2].

Originally, cows were wild pasture animals domesticated by humans. Moreover, people were migrating nomads. Thus, in the beginning of animal husbandry the cattle traveled with people. Finally, people started to settle in constant regions with the animals. First, animals were held in yards but people started to build structures for keeping and protecting the animals. Next, people started to keep cows in buildings. In linear pottery culture, people and animals lived together inside longhouses. Finally, people started to build separate building called cowshed for keeping cattle. Currently, the cowsheds are divided in two types of tie-stall and loose-house cowsheds [12]. In general, tie-stall cowsheds are smaller and tighter than loose-housed cowsheds. Furthermore, cows are not allowed to move freely in tie-stall. Conversely, In loose-housed cowshed cows are allowed to move freely. Additionally, they may have free access to pasture. Recently, the tie-stall cowsheds have been under critique. That is, the cows are not able to behave as social animals. Moreover, monitoring and keeping health is more difficult in tie-stalls. Therefore, new-builds are rather loose-housed than tie-stall cowsheds. In addition, it is easier to monitor the health and estrus behavior of freely moving animals. Thus, cows living in a loose-housed cowshed are in the scope of this study.

### **2.1.1 Dairy Cow**

Tähän alkuun vielä jotakin lehmän perustietoja, kuten arvio rotujen määristä. Lehmän keskimääräinen paino, koskeus, pituus jne. Ehkä myös maininta siitä, kuinka paljon lehmä tarvitsee tilaa mm. laskeutumiseen ja ylösnuosuun.

Previously, we surveyed through the history of animal husbandry and discussed of the beginning milk producing. Additionally, we introduced such cowsheds as tie-stall and loose-housed cowsheds. Correspondingly, this subsection will debate on the dairy cow itself in general level. Whereas, the subsequent subsections will focus on such milk yield related cycles as estrus and lactation cycles. Inherently, cows are plain and herd animals. Moreover, they live in hierarchy [9]. In large herds they form smaller groups where they do their daily activities such as eat and rest together [9, 12].

Typically, cows lay down approximately from 11 h to 12 h every day. Meanwhile, they stand up and change their pose several times [30]. Additionally, they may move their location between haunts and watering places. Thus, in loose-housed cowshed a cow may walk from 400 m to 800 m per day [21]. On pasture, their daily walking range may extend to several kilometers [21, 9]. However, cows are very cautious animals. Thus,



Figure 1: Cows in a tie-stall-cowshed [11]. Cows are tied in stall and they are not able to move freely. They also have less space than in a loose-housed cowshed.



Figure 2: Cows in a loose-housed-cowshed [22]. Cows are able to move freely and act as social animals.

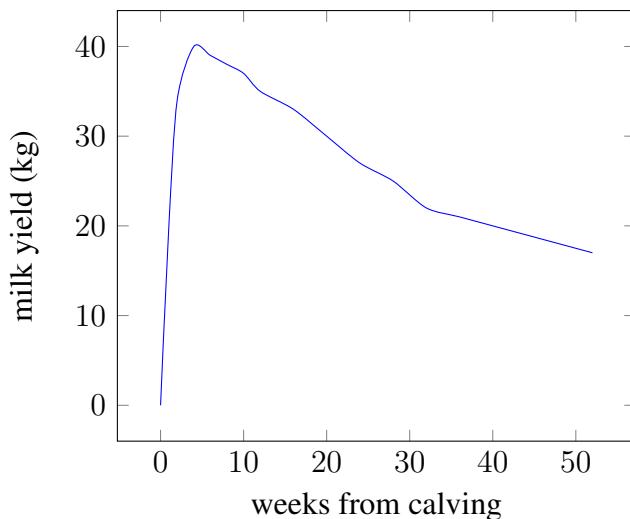


Figure 3: the lactation curve [17]

insecure circumstances such as slippery ground or high steps can reduce their daily range. Furthermore, cows can be easily injured in challenging places. Naturally, injuries affects to their health and consequently to profitability [12]. Nevertheless, Walking enforces their health, increases hormonal activity and metabolism [21].

In addition to their normal activity, cows may have exceptional states. Typically, these states become apparent in their behavior. That is, sicknesses and injuries reduces their activity level, whereas, proestrus increases it. Phases of estrus are covered in detail in section ??.

Tämme vähän lisää tietoa lehmien terveysongelmista, kuten ontumisesta, sorkkahomista ja ruoansulatusvaivoista.

Cow can lick all of its body excluding neck and head. Cows doze standing and sleep lying. The estrus period is approximately 21 days and the estrus lasts from 12 to 16 hours. A bull may detect estrus 2 days before the main estrus. [9]

Access to fresh and clean water is vital. [21]

### 2.1.2 Lactation Cycle

In previous section we discussed of dairy farming and dairy cow in very general level. Conversely, this section is in the core of the scope of this study. That is, lactation cycle is strictly related to the milk yield and, thus to profitability. Furthermore,

Lehmien tuotos kasvaa jokaisella poikimiskerralla [1].

Laktaatio kierrosta, perusasiat, kesto, merkitys maidontuotannolle yms.

### 2.1.3 Estrus Cycle

Kiimakierrosta, kesto, vaiheet, mikä merkitys jne.

The estrus period is approximately 21 days and the estrus lasts from 12 to 16 hours. A bull may detect estrus 2 days before the main estrus. [9]

Estrus a.k.a standing heat.

## 2.2 Health Monitoring and Estrus Detection

The previous subsection 2.1 discussed of the fundamentals of dairy farming. The discussion started form the history of animal husbandry and ended to study of dairy cow itself. The study of dairy cow included basic knowledge of the cow and its environments. Moreover, we discussed of lactation and estrus cycles and their affect on the milk yield and profitability. Additionally, we briefly surveyed through the most common health issues with dairy cow. In continuation to previous discussions, this subsection discusses of different methods for detecting estrus and health issues. First of the following subsection 2.2.1 surveys through currently used methods and technologies. Correspondingly, the second subsection 2.2.2 discusses of studies of existing technology as well as recent development projects for future solutions.

### 2.2.1 Current Solutions

In this subsection we will discuss of currently used methods for observing the cattle. The discussion starts from conventional and non-technical methods and ends to current commercial technical products.

Traditionally, health monitoring and estrus detection have been based on purely visual observations. However, this method is not considered efficient. In the USA, the rate of successfully detected estruses has been estimated below 50 % in large farms. Additionally, this inefficiency leads to annual loss of 800 million dollars for the milk industry. [8]

Moreover, the only method for monitoring and detection has been observing the cows sight-wise [12]. Naturally, the reliability of the observations depends on several such factors as the experience of the cattle tender, availability of time and the amount of cattle. That is, the larger the cattle, the more work and, thus, the less time available. Consequently, the available time per cow decreases exponentially when the amount of cattle increases. In addition to the experience level of the tender, it is fundamental to know the cattle.

In despite of the challenges, observations of cattle tender are still common monitoring method in small farms and in developing countries. [8]

Therefore, the cattle tender must know his cattle well in order to receive satisfying results. The larger the cattle

## 2.2.2 Research and Development

Former subsection discussed of currently used farming technologies. In contrast, this subsection reveals technologies under research and development and discusses future options.

This subsection reviews the wearable sensor devices used in dairy farming. The review includes currently used technologies as well as technologies that have been under research but have not been commercialized yet.

### **behavior pattern recognition using three-dimensional accelerometer and support vector machines**

Used three-axis accelerometer and support vector machines for detecting the following behavior of cows:

- Standing
- Lying
- Ruminating
- Feeding
- Normal walking
- Lame walking
- Lying down
- Standing up

The sampling frequency was 10 Hz and the data was sent to a PC computer via 2.45 GHz radio band. Measurement range of  $\pm 3$  g. The sensor was ADXL330, Analog Devices Inc., USA and it was attached to the neck. They used 30 Ayrshire and Holstein-Friesian cows. The cows were loose-housed and the barn used automatic milking system. Most of the days the cows had a free access to a pasture. The data was recorded during 30 days. The video, stopwatches and accelerometers were synchronized manually. Cows had different gait scores ... Used multi-class support vector machines. 70 % of the data was used as training set and 30 % was used as a test data set. Lying head erect does not differ much from standing posture considering the accelerometer data. This causes misclassifications. The interest was predicting the behaviour that occurred instead of the behaviour that did not occur. Fixed parameters (e.g. time window) are not suitable for all different behaviours. [18]

Six dairy cows monitored continuously for 36 h. They used a decision-tree algorithm for detecting if the cow was either standing, feeding or lying. The algorithm matches the performance of computationally more intensive algorithms such as hidden Markov model and support vector machines. It is suggested that the decision-tree algorithm could be

a part of a real-time behavioural monitoring system. The performance of the algorithm varies in function of the time window which was from 1 to 10 minutes. In the algorithm comparison table the decision-tree algorithm was better in 1 minute window than in 10 minute window. The support vector machine, however, was equally good or even better algorithm. Holstein dairy cattle located in Essex, UK. The cows were loose-housed in a cubicle shed. The herd was milked three times a day. The cows selected for the study did not show signs of lameness or other diseases. Drinking, brushing and walking activities were excluded in this study. [29]

Combines step count and leg tilt data. Data was extracted from 44 dairy cows over an 8 month period. The results show sensitivity 88.9 % and error rate 5.9 %. The sensor was IceTag3D ®which is a three-axis accelerometer. The sample period was chosen to be 1 minute and is the time resolution through the study. The sensor provides four variables: the percentage spent in three of the stages and step count. The stages are lying, standing and motion. The lying and standing are detected by the tilt of the sensor. The variables lying and standing gives the percentage of the sampling period spent in each of the two states; the motion index is a measure of how much the cow has moved in the sampling period and step count is the number of steps in each sampling period. The measurements were available for a total of 88 cows over varying periods. The data transfer from the IceTag was done manually holding a reader close to the IceTag device. Data sequence for estrus detection were selected around 18 and 23 days between two estruses. 62 cows did not get pregnant, 18 cows were inseminated wearing an IceTag and 44 were not inseminated at all wearing an IceTag. Total of 26 cows became pregnant. The conclusion says, this method could only improve other estrus detecting methods but not alone reliably detect estruses. [13]

They used pedometers. The data set consists of data gathered from 98 cows successfully inseminated by visual estrus detection. The pregnancy was considered as a confirmation for the detection. In the data gathering period of six months a total of 335 estrus cases occurred. 237 cases were discarded since the cows either did not become pregnant or did not wear pedometers. They could improve the visual estrus detection up to 84.2 % accuracy. [8]

This research aims to provide a cheap sensor for estrus detection which is an alternative for current commercial products based on accelerometers and odometers. The provided sensor is a wireless intravaginal probe measuring temperature and conductivity. The benefit of this probe against accelerometers is that the cow is not required to move for estrus detection. In the study a video camera was used for detecting the action of the cow, since, moving, standing, eating and stress increases the body temperature. It is suggested that an accelerometer could be used instead of videocamera for automated motion detection. The conductivity measurements were not satisfying since, the contact between the animal and the tissue were not constant and caused noisy measurements. Yet, some correlation were detected with the cow activity. [5]

in the further study the probe measured vaginal temperature, acceleration and vaginal tissue resistance. They had two kinds of probes, a 160 mm 160 mm probe and a 1 120 mm probe. The longer one caused bleeding during the trials. The shorter one worked out fine but started to rotate during the estrus and it even ejected. Therefore, no sufficient probe design was found. The 3-axis accelerometer provided different spaces for datapoints when

the cow was either standing up, resting wide or resting narrow. [4]

Four wireless accelerometers were used per cow, one on each limb. In the research the wavelets were analyzed and mismatch in symmetry of variances observed for lameness detection. Sampling frequency was 25 Hz 25 Hz. [20]

### 3 Research

In previous section 2, the backgrounds of this study were in discussion. The discussions covered the dairy farming in general level and the dairy cow more in detail. Moreover, the section focused in milk yield related estrus and lactation cycles. Additionally, we discussed of current and future solutions for dairy cow health monitoring and estrus detection. In conclusion of the first section, there is a certain need for efficient and cost-effective solutions for dairy cow monitoring. Accordingly, wearable wireless sensor devices are currently promising due their overall performance and availability. Respectively, in this section the target is to develop convenient estrus detection algorithm for a wearable wireless sensor device. Furthermore, the development initiates from a scratch. That is, no assumptions are made based on previous studies.

In this study, the research section has been divided in three subsections. The first subsections 3.1 discusses of data recording. The discussion includes the description of the hardware as well as the software implementation. The hardware description covers the main hardware components in reasonable detail. Additionally, we discuss of the communication between the main components. Respectively, the software implementation description discusses of the work flow of the data recording software.

The second subsection 3.2 introduces a set of methods applied on the recorded data. The set consists of basic statistics as well as various digital signal processing methods. The basic statistics contains only the most fundamental measures of statistical analysis. Nevertheless, they are discussed only briefly in this section. Conversely, the digital signal processing methods contains more advantageous calculus. Thus, they are discussed more in detail.

Lastly in this section 3.3, we develop three different algorithms for dairy cow estrus detection. All these algorithms have their basis in data processing methods introduced in previous subsection 3.2. However, each of them have slightly different approach to detect the estrus. Nevertheless, all the algorithms detects rather the pro-estrus than the actual estrus 2.1.3. All these differences are covered in the discussions. Furthermore, we discuss of the background and describe the evolving of each algorithm in detail.

Tähän ehkä jotain hypoteesia tutkimuksesta ja jotain mahdollisia ennakkooletuksia?

#### 3.1 Data Recording

Formerly, we described the research of this study in general whereas, the topic of this subsection is in the data recording. Altogether, the data recording is divided in three more sections. The first describes the data recording hardware. The hardware was a prototype of a sensor device for dairy cow monitoring. Furthermore, the hardware was modified for data recording purposes. Nevertheless, any hardware design is not included in this study. Next, we discuss of two different software implementations for data recording hardware. The starting point for the first implementation is making of no assumptions whereas, the

second implementation is based on the results of the results of first recorded set of data. Lastly in this subsection, we discuss of the data recording process itself.

### 3.1.1 Hardware

As discussed previously, the hardware for the data recording was a prototype of a dairy cow sensor device. Originally, the hardware consisted of micro-controller unit (MCU), accelerometer and thermometer. However, it lacked of storage memory for storing the recorded data. Thus, the hardware was customized and a Secure Digital (SD) memory card slot was added. Otherwise, the hardware remained the same during the entire study. In despite of the customization, the hardware design is not in scope of this study. Therefore, the following is rather description of the hardware than comprehensive discussion of the design itself. In addition to hardware components, we briefly discuss the communications between the components. In general, the main hardware components brief descriptions are as follows:

- *Atmel ATmega32u4* is a high performance low power 8-bit micro-controller. It is designed for optimizing power consumption versus processing speed. It contains 135 powerful Reduced Instruction Set Computer (RISC) architecture instructions of which most executable in single clock cycle. [6]
- *Bosch Sensortec BMA222E* is an accelerometer with on-chip motion triggered interrupt controller. Thus, it enables motion-based applications even without use of micro-controller. It is capable of measuring acceleration in three perpendicular axes. BMA222E is designed for various consumer products from game controllers to pedometers. It is small sized and low power consuming. Therefore, it is suitable for mobile solutions. [7]
- *Texas Instruments TMP112* is a high-accuracy, low-power, digital temperature sensor. It is designed for various applications from portable and battery-powered solutions to general temperature measurements in industrial controls. [28]
- *Secure Digital (SD)* memory card is specially designed to meet the security, capacity and performance requirements in newly emerging consumer electronic devices. The standard capacity of SD memory card is up to 2 GB. However, High Capacity SD (SDHC) extends the maximum capacity to 32 GB and Extended Capacity SD (SDXC) up to 2 TB. [24].

Naturally, all of these hardware components are assigned to specific tasks with respect to their functional description. Their special assignments are discussed in detail in the following descriptive sections.

#### **Micro-controller**

The micro-controller unit (MCU) is the fundamental component of the sensors device in this study. It is responsible of execution of the software flow whenever the device

is powered. The software flow starts from the boot, that is, after switching the power on or resetting the micro-controller. During the boot, it initializes itself as well as the connected sensors according to the prior set configurations in the software. After the boot, the micro-controller begins the execution of the repetitive software loop including various tasks and events. The initialization configurations and the tasks and events are discussed more the software section [3.1.2](#).

As stated earlier, the micro-controller unit of the sensor device in this study is Atmel ATmega32u4. The following describes the main features of the MCU considering this study.

- 32 kB of *In-System Self-Programmable Flash memory* is the memory space for the actual program storage. Furthermore, the memory space is divided into two sections, Boot Program Section and Application Program section.
- *USB 2.0 Full-Speed/Low-speed Device Module* provides interface to write on the In-System Self-Programmable Flash of the controller. Thus, it enables uploading the application software without external USB module. Additionally, Interface contributes serial communication between computer and the device.
- *General I/O* consists of 26 programmable I/O lines. These lines can be set as input or output separately. Furthermore,
- *Interrupts* are occasions that usually sets an interrupt flag. The Interrupt Service Routines (ISR) corresponding the interrupt flags are executed with respect to their priority. There are internal and external interrupts. The interrupt can be enabled individually. Interrupts are beneficial in generating events into software flow instead of executing tasks periodically.
- *On-chip Temperature sensor* of the controller provides accuracy of 0.5 °C. The accuracy of the BMA222E is relatively low in comparison to the TMP112 temperature sensor. However, it can be used as reference or verification value with the temperature sensor.
- *Watchdog Timer (WDT)* of ATmega32U4 counts time on separate on-chip 128 kHz oscillator. The WDT is capable of interrupting and/or resetting the system. Additionally, it is enabled in most of the power modes.
- *Power Management and Sleep Modes* allows the user to tailor the power consumption to the application's requirements. This es beneficial specially with battery-powered solutions where regular re-charging is not effortless.
- *SPI and I<sup>2</sup>C* serial bus interfaces are used for internal communication the micro-controller and the sensors as well as the SD memory card.
- 32 KB of in-system self programmable flash
- 2.5 KB internal SRAM
- 1 KB internal EEPROM

## Accelerometer

is a triple-axial accelerometer used for measuring change in motion as well as position recognition. The axis of the accelerometer are in right angle to they each other. Thus, it can measure in all direction. Additionally, it contains several on-chip functions for prior and post filtering as well as detecting different conditions. The filters and the detectable conditions are configurable and they are discussed in detail later in this section.

This subsection surveys through the most likely worthwhile features of the accelerometer used in this study. However, all of the features discussed features may not be used in this study but may become sensible in future studies. The overview of the hardware of this study was discussed previously. The specific configurations of the sensor are discussed in subsections 3.1.2 and 3.1.2. The accelerometer used in this study is Bosch Sensortec BMA222e digital, triaxial acceleration sensor. Its key features are

- on-chip interrupt controller
- on-chip FIFO register
- acceleration ranges  $\pm 2$  g,  $\pm 4$  g,  $\pm 8$  g and  $\pm 16$  g
- high pass filter from 7.81 Hz to 1000 Hz
- offset compensation
- SPI and I<sup>2</sup>C digital interfaces
- 8-bit resolution
- low power consumption
- temperature sensor. [7]

These features are discussed more in detail in this subsection.

Limited capacities of power sources are significant issue with wireless devices. Therefore, the low power consumption all together with other on-chip features of the accelerometer become useful. That is to say, it is reasonable to maximize the usage of the low power sensor and meanwhile minimize the use of more power consuming micro-controller.

## Temperature Sensor

is a high-accuracy temperature sensor for various applications from portable devices to industrial controls. In this study the temperature sensor is used for monitoring the skin temperature of the cow. The target of the monitoring is to find correlation between arisen skin temperature and ongoing estrus. Thus, in the case of positive correlation the temperature sensor can confirm the detected estrus.

The temperature sensor used in this study is Texas Instruments TMP112 high-accuracy, low-power, digital sensor. It is designed for replacing NTC/PTC thermistors in high accuracy applications. Its main features are

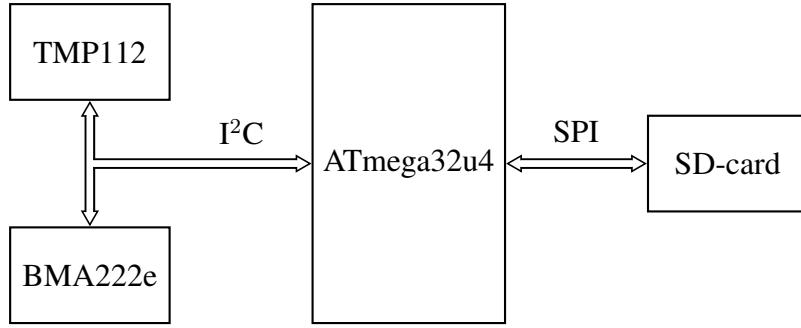


Figure 4: Block diagram of the device. The temperature sensor and acceleration sensor are connected to the micro-controller via I<sup>2</sup>C-bus, whereas, SD-card is connected via SPI-bus.

- high accuracy without calibration
  - 0.5 °C in range from 0 °C to 65 °C
  - 1.0 °C in range from –40 °C to 125 °C
- resolution of 0.0625 °C in 12-bit and 13-bit mode
- low power consumption
  - 10 µA in active mode
  - 1 µA in shutdown mode
- SMBus<sup>TM</sup>, Tow-Wire and I<sup>2</sup>C digital interfaces
- supply voltage range from 1.4 V to 3.6 V

### Secure Digital Memory Card

This hardware configuration uses a secure digital (SD) memory card as a memory storage for data recording.

#### 3.1.2 Software

This subsection discusses of the data recording software. In contrast to the hardware, the software improved during this study. Thus, the first software implementation differs significantly from the latter. As a matter of fact, the first software implementation based on previous researches and intuition, whereas the latter based on the results received from the first recorded set of data. That is to say, the results of the first set of data formed a general view on typical behavior of a cow, while the purpose of the following data sets were used for the actual estrus detection. *Tähän vielä jokin tärnsitiofraasi, ehkä?*

The software were implemented in Arduino IDE (*Integrated Development Environment*). The use of Arduino IDE offers effective environment for implementing embedded software without expert-level knowledge on micro-controllers. The Arduino provides extensive libraries... However, the driver interfaces for accelerometer and temperature sensors as well as the entire flow of the software were self-implemented.

## First Software Implementation

The starting point for implementing the first software included only a cursory conception of the behavior of a diary cow. Therefore, the properties of the accelerometer described in section 3.1.1 are treated with care in order to avoid loss of relevant data. In conclusion, a high data rate was prioritized over other features. Furthermore, it was decided not to use offset compensation since, it could cause unawareness of the pose of the device.

The accelerometer sets a hard restriction of 2000 Hz for the maximum data rate. However, the usage of secure digital (SD) memory card as a data storage limits the data rate even more as discussed in section 4. That is, the duration of the SD file operations exceeds the disposable time at high data rate and, thus, causes loss of data. In contrast, a low data rate could cause a loss of possibly relevant features on higher frequencies. Therefore, the selection of the data rate is more or less a trade off between data losses and data bandwidth.

The flow of the software consists of tasks and conditions. Each task contains a single function or a sequence of functions the micro-controller must execute before proceeding to the next task or condition in the flow. In this flow, the conditions are used to decide whether a task is being executed or not. Alternatively, a condition may be followed by an entire branch of tasks instead a single task. The conditions of the software flow and their explanations are:

- *Interrupt* is true if an interrupt flag is set by an interrupt from the accelerometer which in this case is a certain FIFO buffer level.
- *Timer* condition is used for reading temperature data from both of the sensors periodically.
- *Timeout* is a backup feature if an interrupt is being missed and, therefore, no more interrupts received.
- *Errors* is true if any of the predefined errors have occurred during the execution of the main loop.
- *Buffer empty* condition checks the buffer level of the micro-controller. If the buffer level is non-zero the contents of the buffer will be written to the SD card.
- *Save data*

and following tasks:

- *Initialize* task (which is analogous for *setup* function in Arduino IDE) is executed only once right after the device is powered up. This task initializes the desired configurations for the accelerometer and the temperature sensor. It
- *Read acceleration data* task reads the data from the FIFO buffer of the accelerometer and stores the acceleration data into the FIFO buffer of the micro-controller.

- *Save Data to SD-card* task saves the data written on the SD card. That is, the file where data is being written must be closed in order to ensure the written data is being saved. Once the file is closed for saving the data it has to be re-opened for continuing the writing process. Alternatively, if the size of the current file exceeds a preset limit, a new file is opened. Furthermore, the duration of the open and close file operations could exceed the time required to fill up the FIFO buffer of the accelerometer. Thus, the FIFO buffer is being read empty before and after closing the current file and once more after opening a file.
- *Read temperatures* task reads the temperature data of both sensors and stores the value to the memory of the micro-controller. No temperature data are buffered. Thus, only the latest values are written to log file on SD card.
- *Set Interrupt flag* sets the interrupt flag without an interrupt if a timeout condition is met. Once the interrupt flag is set, the micro-controller will read the acceleration data from the FIFO buffer of the accelerometer.
- *Handle errors* task handles predefined errors if one or more of them have occurred. In practice, this task writes the name of the occurred to the text file and resets the error flag.
- *Write buffer to SD-card* writes a single line of acceleration data from the FIFO buffer of the micro-controller into a text-file on the SD card.

## Second Software Implementation

The approach for recording the second data set differs significantly from the first one. The first software implementation attempted to maximize the data rate, whereas the second focused on power saving.

The work flow consists of the following conditions:

- *FIFO-level > 0* condition is true if the FIFO buffer level of the accelerometer is non-zero.
- *WDT flag* condition is true if the watchdog timer has set a watchdog timer (WDT) flag.

and the following tasks:

- *Initialize*
- *Read acceleration* task reads all the data from the FIFO buffer of the accelerometer and stores the data into a FIFO buffer of the micro-controller.
- *Read temperature* task reads the temperature of both of the sensors, accelerometer and temperature sensor.

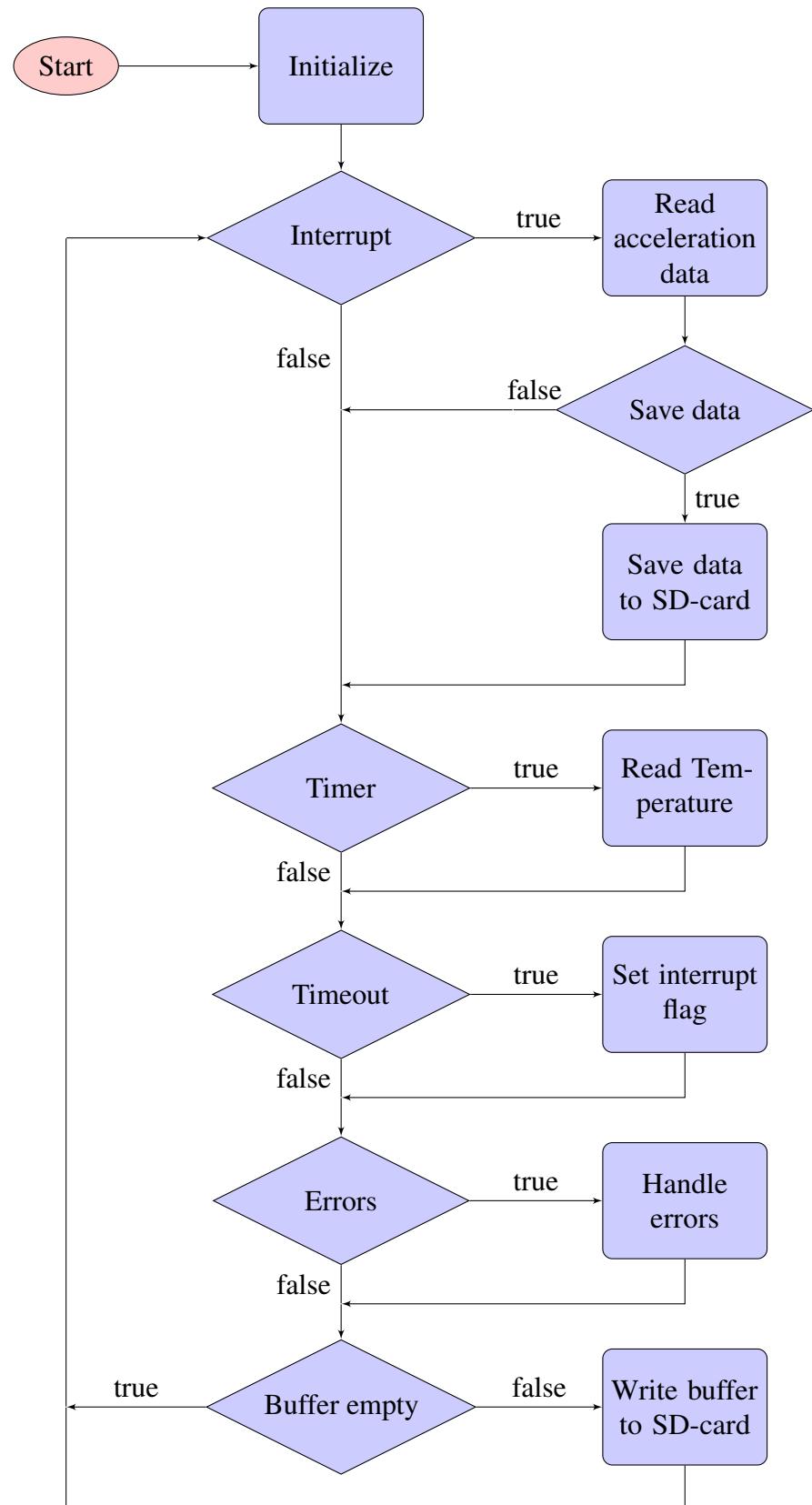


Figure 5: The flow of data logging program

- *Open file* task opens a file for writing the data. The task opens a new file if the size of the current file exceeds a preset limit for maximum file size.
- *Write data to file* writes all the buffered acceleration data into the opened file on the SD card. In addition, the task writes the temperatures of both of the sensors, the number of occurred watchdog timer interrupts and the up-time of the micro-controller into the text file.
- *Close file* task closes the opened file in order to ensure the written data is being saved.
- *Sleep* task puts the micro-controller in a power saving mode. That is, all the other functionalities but watchdog timer and interrupts are disabled in order to minimize the power consumption. The micro-controller remains in the sleep until the watchdog timer or an interrupt from the accelerometer wakes up the micro-controller. After waking up, the

## First Data Set

All the data used in this study were recorded on a dairy farm in coordinates N63°6'3.6" E23°10'35.5". The breed of the farm consists of Ayrshire and Holstein cows, which were also used for data recording.

The data was recorded in two separate occasions. Furthermore, the software implementation for these occasions differed significantly as discussed in sections 3.1.2. The sets of data were recorded in a farm at The breeds on the farm are

The primary objective for the first recorded data set was achieving an overview on the behavior of a dairy cow. Thus, the sensor device was attached to the neck of a cow with a trail camera. In the beginning of the recording of the first data set, only one sensor device and one trail camera were available. Therefore, only one cow could have been chosen for recording simultaneously. In spite of the primary objective of observing the behavior, it was desired to obtain estrus data as well. Thus, the cattle tender assisted choosing a cow that was estimated having an estrus during the recording process. The maximum recording period was approximated up to 16 days, hence the capacity of the SD card was 8 GB and the recording required approximately 500 MB per a day.

The recording of the first data set was started on Friday September the 9<sup>th</sup> at the farm. The sensor device was attached to the neck of a selected cow with a trail camera. The recording lasted till Sunday September the 18<sup>th</sup>. After the sensor and the camera were detached from the neck of the cow, the recorded data from both, the sensor device and the trail camera were copied on a computer for analysis.

## Second Data Set

The second data set was recorded in two phases. First phase was recorded from December the 14<sup>th</sup> to 15<sup>th</sup>. The second phase was recorded instantly after the first and lasted until January the 20<sup>th</sup>. The cows selected for the data recording were such that they were estimated to have an estrus during this period.

MAINITSE että lehmillä oli heatime!!!



Figure 6: Cow wearing a sensor device. The axis directions are illustrated as red arrows in the figure. The sensor is in parallel with a commercial Heatime device shown in this figure.

### 3.2 Data Processing

This subsection discusses about the methods used in data analysis. The used methods consists of pure visual observations as well as statistical analysis and more advanced digital signal processing. However, the visual observations remain the primary tool before and after applying any statistical os signal processing method.

#### 3.2.1 Statistics

In this study, statistical methods are included in the estrus detection algorithms discussed in section ???. Furthermore, statistics are used in analysis of duration of SD file operations in section ??.

The statistical methods used in this study are defined as follows [25]:

- *Mean* is used for describing the most common value of the data set. It is defined as the sum of all values divided the number of values:

$$\bar{x} = \frac{\sum_{i=1}^n x(i)}{n} \quad (1)$$

- *Median* is another number for describing the most common value of the data. In contrast to the mean, it is not that sensitive to exceptionally large or small values. It is defined as the middlemost value of sorted data. If the number of values in the data is even, the median is the sum of two middlemost values divided by two.

*Median* is the middlemost number of the data set sorted from smallest to largest numbers. If the number of elements in array is even, the median is the mean value of the two middlemost values.

- *Variance* describes the expectation of the squared deviation of a random variable from its mean, and it informally measures how far a set of (random) numbers are spread out from their mean:

$$s^2 = \frac{\sum_{i=1}^n (x(i) - \bar{x})^2}{n} \quad (2)$$

- *Standard deviation* describes the amount of variation in the data set. A low standard deviation means the values tend to be close to the mean value, whereas a high value means the values tend to be far from the mean. In contrast to the variance, the standard deviation describes the “typical” distance between the values and the mean. The standard deviation is actually the square root of variance:

$$s = \sqrt{\frac{\sum_{i=1}^n (x(i) - \bar{x})^2}{n}} \quad (3)$$

- *Minimum value* is the smallest value in the data set.
- *Maximum value* is the largest value in the data set.
- *Range* is the difference of the minimum and maximum values.

### 3.2.2 Fourier Transform

Discrete Fourier transform (DFT) is linear mapping of a signal from time domain to frequency domain [23]. That is, a time variant sample can be transformed into frequency domain for providing the frequency spectrum of the data. In this study, the frequency spectrum of cow behavior is valuable information in deciding the the bandwidth of the accelerometer.

### 3.2.3 Digital Filters

The Bosch Sensortec BMA222e accelerometer provides two on chip filters: one 2nd order low-pass filter and another 1st order high-pass filter for offset compensation [7]. Digital filters can be divided into two categories, filters with finite impulse response (FIR) and filters with infinite impulse response (IIR). The main difference between these filters is that the output of a FIR filter is dependent only on the input, whereas, the output of an IIR filter is dependent also on the previous outputs of the filter. Therefore, [10] [15].

The digital signal processing methods consists of applying filter and other mathematical methods. In these methods, any features of the sensors could be simulated afterwards instead of using the features of the sensor. E.g., offset compensation using the low pass filter causes the loss in information of orientation of the device.

Filters with infinite impulse response (IIR):

$$y[k] = b_0x[k] + b_1x[k-1] + b_2x[k-2] + \dots + b_{n-1}x[k+1-n] + b_nx[k-n] \quad (4)$$

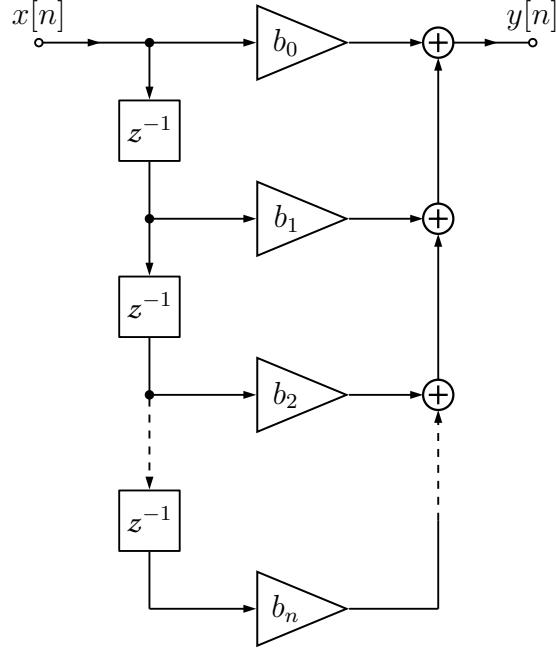


Figure 7: An example of an  $n^{\text{th}}$  order FIR filter

$$\begin{aligned} y[k] = & b_0x[k] + b_1x[k - 1] + b_2x[k - 2] + \cdots + b_nx[k - n] \\ & -a_1y[n - 1] - a_2y[n - 2] - \cdots - a_my[k - m] \end{aligned} \quad (5)$$

and filter with finite impulse responses (FIR):

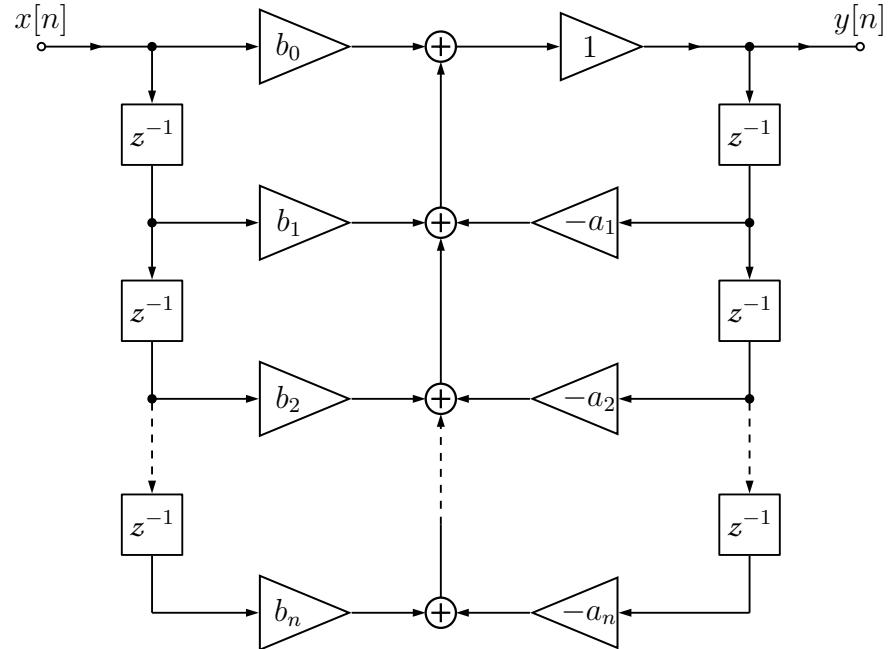


Figure 8: An example of an  $n$ -th order IIR filter in direct form I

### 3.2.4 Sliding Window

In this study, windowing is means analysis and calculus of data in segments instead of entire data set. The windowing method in this study is analogous to windowing in signal processing [26, 19] ...

## 3.3 Estrus Detection Algorithms

This section introduces a fundamental concept for the detection of a dairy cow. In general, the cow behavior changes along with the phases of estrus the cycle ???. That is, the activity level increases in proestrus

That is, the cow becomes exceptionally active in proestrus, whereas the activity normalizes in estrus. Therefore,

This subsection discusses about plausible algorithms for dairy cow estrus detection. The algorithms consists of methods of data analysis described foregoing subsections. In fact, algorithms are sequences of methods that provide answer to the question whether the cow is in estrus or not.

The principle idea of estrus detection is based on high pro-estrus activity of the cow. That is, the cow attends to move significantly more than usually. Furthermore, the time spent on rumination degrades meanwhile. Thus, it is considered to detect the pro-estrus instead of the actual estrus. Additionally, it is beneficial since, it provides wider time window for insemination. In conclusion, the basis of the algorithm is defining the amount of activity.

Considering the activity measurement in wearable devices for people, the activity is typically measured as sum of absolute values of all the axis. In studies, it has been proved it to match to the real energy consumption better than the absolute value.

Windowed mean value:

$$\bar{x}(k) = \frac{\sum_{i=k-n}^k x(i)}{n} \quad (6)$$

, where  $n$  is the size of the window.

The main features of all the following algorithms are as follows:

1. **Process data** — Data processing consists of algorithm specific data functions. These functions may include data filtering and other computations. These functions are discussed in detail in the following subsections. All the remaining phases of the algorithms follows the same pattern discussed below.
2. **Sum results** — The results of data processing are summed within time windows. The length of the time window should approximate the duration of the proestrus. Additionally, these time windows shall overlap in order to provide more continuous impression of ongoing state of estrus cycle. Furthermore, excessively long time windows without overlapping could delay the detection of the estrus. Thus, cause the failure of insemination as a consequence.

$$u(k) = \sum_{i=nk-m}^{nk} x(i) \quad , \text{where} \quad (7)$$

$k$  is the index of summed results,  $n$  is an incremental step size and  $m$  is the size of the time window.

3. **Remove offset** — The resulting data after summing may differ significantly within algorithm depending on the parameters as well as between the algorithms. Therefore, any existing offset in the data should be removed. This means adjusting the data so that the normal behavior appears around the zero. The median of the data describes the amount of the offset more reliable than mean value. Hence, median is less sensitive to proestrus peaks in the data.

$$u(k) = x(k) - \tilde{x} \quad , \text{where} \quad (8)$$

$\tilde{x}$  is the median value of  $x$ .

4. **Normalize** — After removing the offset, the data shall be normalized. In this case, the normalizing means scaling the data so that no extreme value shall exceed the range of from  $-1$  to  $1$ .

$$u(k) = \frac{x(k)}{\max |x|} \quad (9)$$

5. **Threshold** — Finally, thresholds are used for indicating the beginning and the end of the proestrus. That is, exceeding the first threshold indicates the beginning of the proestrus and next, the going below indicates the end of the proestrus. The thresholds for deciding whether the cow is in estrus or not should be separate. The end of proestrus signals to the cattle tender to prepare for insemination. The principle of the proestrus detection is presented in the following pseudo code.

```

for (i = 0 ; i < length(x) ; i++)
    if (x(i) > threshold1 && proestrus == false)
        proestrus = true;
    else if (x(i) < threshold && proestrus == true)
        proestrus = false;

```

Additionally, each change of the estrus state should trigger an alert.

### 3.3.1 Activity Measurement

The concept of the first estrus detection algorithm is analogous to an accelerometer based estimation of total energy consumption [14]. However, finding of any correlation between the activity and the energy consumption is not a focus of this study. Nevertheless, this algorithm utilizes the same method for determination of the cow activity level.

The first algorithm is based on pure analysis of full the data set. The algorithm is analogous to an estimation of energy consumption using accelerometers ...

1. **Filter** — Hence, the

$$y(k) = a_0x(k) + a_1x(k-1) + a_2x(k-2) - b_1y(k-1) - b_2y(k-2) \quad (10)$$

2. **Compute** — The actual core of this algorithm is the length of the acceleration vector and it is defined as

$$u(i) = \sqrt{x^2(i) + y^2(i) + z^2(i)} \quad (11)$$

### 3.3.2 Variance Detection

The first algorithm had a basis in continuous computation of continuous data stream. In contrast to the first algorithm, the second algorithm attempts to reduce the amount of required data. That is, using standard data samples in regular intervals instead of continuous stream. Furthermore, the calculus of the algorithms are different. The ground of the first algorithm was in summing of the lengths of the total acceleration vectors, whereas this algorithms attempts to determinate the level of variance

The first algorithm calculated the length of the total acceleration vectors. Thus, estimated the energy consumption. Alternatively, this second algorithm detects the level of variation in the acceleration data rather than the total amount of movement.

Originally, the concept of a variance based algorithm arose along with the analysis of the recorded data sets.

1. **Get a sample** — In this algorithm, the data is processed in samples instead of data stream.
2. **Compute Variance** — Compute the variance of the sample

$$u_x(k) = \frac{\sum_{i=nk-m}^{nk} (x(i) - \bar{x})^2}{m}, \text{ where} \quad (12)$$

$m$  is the size of the data sample,  $n$  is the distance between the samples and  $k$  is the index of the output data.

$$u_{tot} = u_x + u_y + u_z \quad (13)$$

### 3.3.3 Inactivity Detection

The first two algorithms were based on relatively demanding computations considering micro-controller (MCU) environments. The first algorithm required a continuous data stream and calculating powers of two and square roots. The second algorithm did not require a continuous data stream. However, the algorithm included computing of variance

which includes sum, square root and power of two as discussed in section 3.2.1. Furthermore, the available dynamic memory of micro-controllers are restricted. Therefore, it limits the maximum number of retained data points for computing the variance. In contrast, the third algorithm attempts to reduce the computation in the MCU. Therefore, it requires more advanced deployment of the features of the accelerometer. Accordingly, an interrupt driven approach becomes sensible. That is, the the MCU only counts the number of interrupt events whereas, the accelerometer performs all other computations.

In addition to transferring most of the calculus from MCU to accelerometer, the logic itself could be inverted. That is, monitoring inactivity instead of activity. For this perspective, the accelerometer provides the feature of *no motion detection* which was discussed in section 3.1.1. This feature suits fairly well to the aspect of transferring the computation from MCU to micro-controller and observing inactivity instead of activity. However, this study bases on recorded data instead of testing these configurations real animals. Therefore, the algorithm described below is purely a simulation of the features of the accelerometer. In consequence, the results achieved in this study might differ from those of real life.

This inactivity detection algorithm complies with the algorithm structure discussed earlier in this section. The data processing phase of this algorithm is as follows.

1. **Get Slope** — The slope is the acceleration difference. That is, the previous value subtracted from the current value:

$$u[i] = x[i] - x[i - 1] \quad (14)$$

Furthermore, the slope is offset independent. Hence, the slope is actually first order FIR filter with infinite attenuation at zero frequency, sampling frequency and its harmonics.

2. **Detect inactivity** — According to the specifications of the accelerometer, a no-motion interrupt is triggered if the absolute value of the slope remains below of a preset threshold for a preset duration of time. The following pseudo code represents the software implementation for the no-motion detection.

```
for (i = 0 ; i < length(x) ; i++)
    if (x(i) > threshold)
        prev_i = i;
    if (i - prev_i > passivity_period)
        passivity(i) = 1;
        prev_i = i;
```

In this study, the passivity array has the same length as the acceleration data array and it is initialized as zeros. During the execution, the algorithm processes through the entire data set. Meanwhile, any occurred no-motion condition yields the value of one into the passivity array. In consequence, the resulting passivity array consists mostly of zeros and few of ones within. Furthermore, the indexes of the ones are

directly related to the time of the occurrence. Thus, it enables concluding the level of inactivity in certain range of time.

Next, after these two specific phases of data processing phases the algorithm proceeds its normal sequence as discussed earlier in this section.

## 4 Results

This section surveys through the results of the data recording processes. As described in section ??, the data was recorder on two separate occasions

### 4.1 General Review

This subsection discusses about rather general results whereas the scope of subsection ?? is in the detection of estrus. In despite of the general nature of these results, they are advantageous considering research in future. Furthermore, some early stage results such as the frequency analysis discussed later in this section were used for improving the sensor device software. This subsection covers the frequency analysis of the first recorder data set as well as statistical analysis of the acceleration data and some interesting features of SD file operations.

#### 4.1.1 First Data Set

Arvoidaan ensimmäisen datasetin tuloksia, mutta myös hardwarea ja softwarea. Jotain johtopäätöksiä

#### Frequency Spectrum

The frequency spectrum of the first recorded data was analyzed using Fast Fourier Transform (FFT) as discussed in section ???. The Fourier Transform was applied on the raw data without any other signal processing methods such as offset compensation. Therefore, the frequency spectrum of each axis consists of significant components at zero frequency and nearby. These components could have been reduced using such offset compensation as a high-pass filter discussed in section 3.1.1. However, applying offset compensation to the data does not provide any additional information in frequency domain. Thus, awareness of the offset component is enough considering the usage of the results. The results of the FFT are represented in figure 9.

#### SD File Operations

In the first data recording process, it was desired to record the data in as high bandwidth as possible. The maximum bandwidth of the accelerometer were 1000 Hz. Consequently, the update time was 0.5 ms. However, the duration of SD file operations restricts the maximum recording bandwidth significantly. Finally, in the first data recording process the bandwidth was selected to be 125 Hz. Yet, the file operations exceeded the time ...

SD card file operation times were recorded after the actual data recording using the original hardware. The original software was improved with timer operations in order to enable the recording of the file operation times. The file operation times had an affect on the data recording process. The time consumed for opening a file increased among the file size. The minimum opening time was 7.26 ms and the maximum time for 1.37 GB file a was 1440 ms. The average value was 747.14 ms. The file closing times varied from 8.04 ms to 160.03 ms and seemed not to be dependent on the file size. The average file

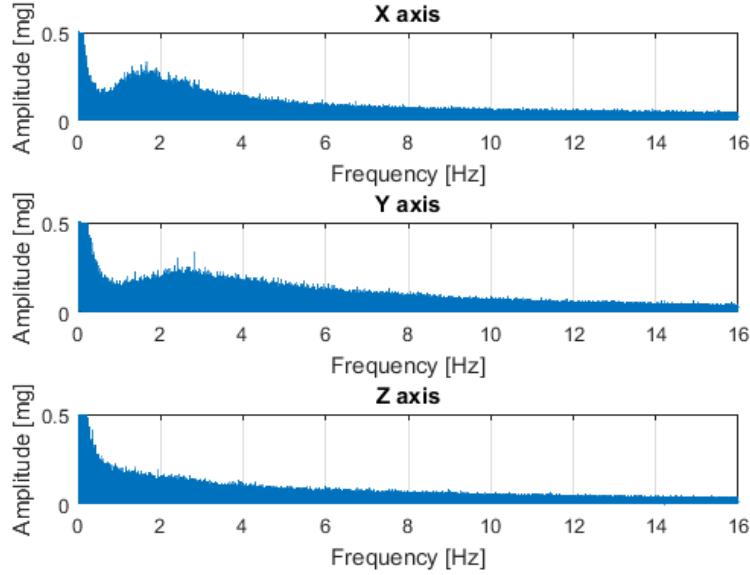


Figure 9: The results of the frequency analysis of the first data set. The frequency spectrum of each axis consists of significant components at frequencies close to zero-frequency and minor components at non-zero frequencies.

Table 1: File operation times of the first data recording hardware and software

Operation	Min [ms]	Max [ms]	Mean [ms]	Variance [ms]
Open file	2	3	4	5
Close file				
Write line				

closing time was 19.75 ms. The time spent of writing a single data line was from 56  $\mu$ s to 162.36 ms and the average was 997.76 ms.

#### 4.1.2 Second Data Set

ARvioidaan toisen (ja kolmannen) datasetin tuloksia, mutta myös laitteistoa ja ohjelmistoa. Jotain johtopäätöksiä.

This subsection concentrates in the results of estrus detection. As discussed in section ?? six cows were used in data recording process. However, two out of six data recordings failed. Thus, that data had to be discarded. The estruses were confirmed by Heatime estrus detection system.

In this study, a total of six cows were used for long period data recording.

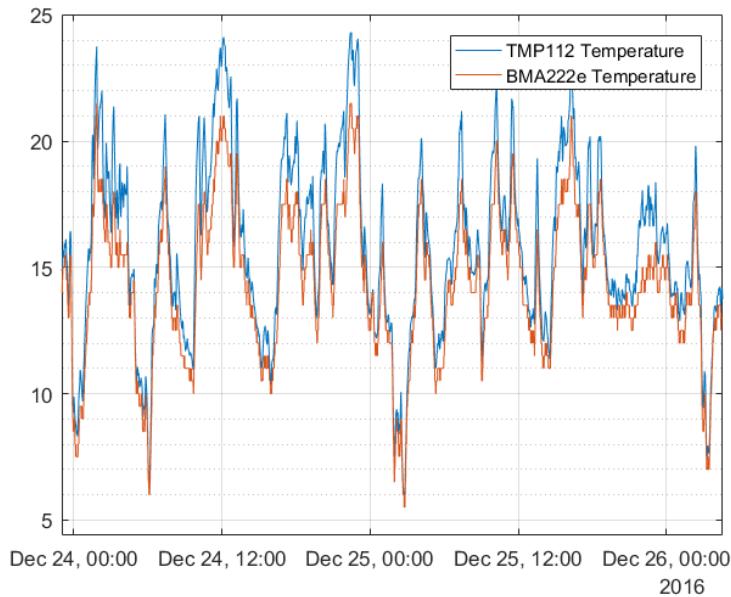


Figure 10: The temperature sensor readings do not correlate with any other results. More likely, temperature correlates with the air temperature inside cowshed.

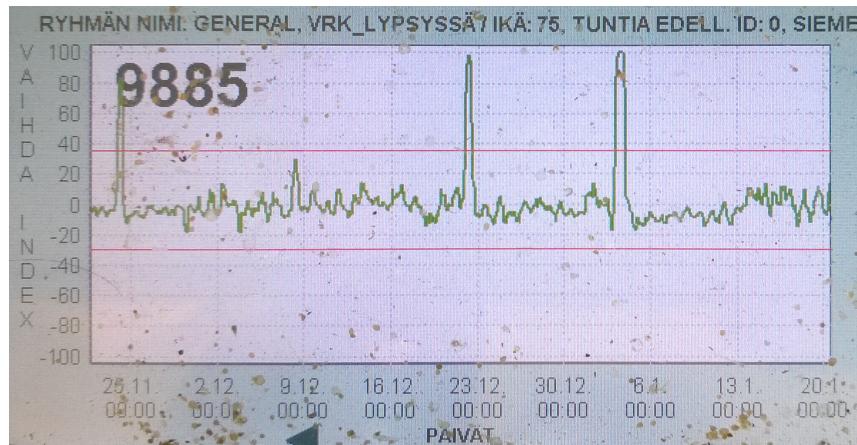


Figure 11: The estrus of the cow marked with red and green color. This cow had two estruses during the data recording period.

## 4.2 Algorithm Evaluation

### 4.2.1 Activity Measurement

### 4.2.2 Variance Detection

### 4.2.3 Inactivity Detection

The first set of data provided relatively wide frequency spectrum of data.

The sampling period provided a total of three probable estruses. One of the sensors failed during the sampling period, and therefore, no estrus could be estimated. However,

one of the cows had two estruses during the sampling period and thus, compensated the failed sensor.

Based on pure visual analysis of the acceleration data, the red cow has two highly active proestrus periods. First begins December the 22nd at 9 pm end ends December the 23rd at 9 am. The second period begins January the 4th at 2 am and ends 6 pm. Proper insemination is from 6 to 24 hours after proestrus period.

The estrus was detected using Heatime estrus detection system. The detected estruses are represented in figures...

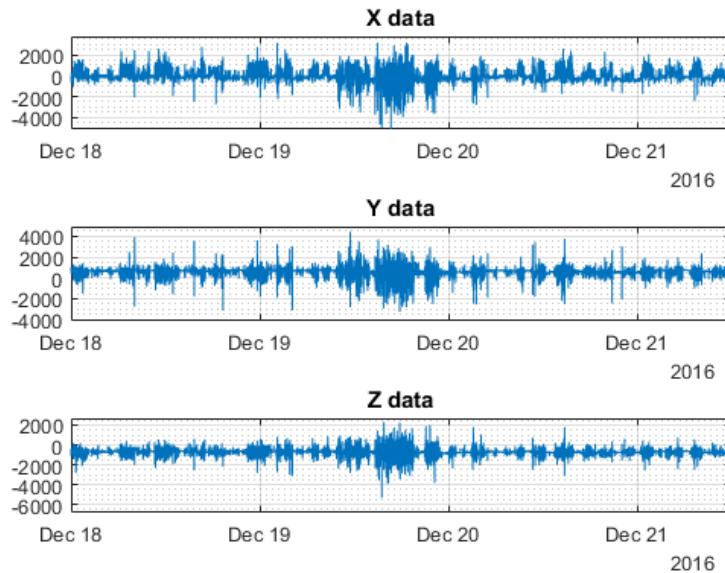


Figure 12: The estrus behaviour in recoreded data of the yellow cow.

The activity could be measured in several ways. Pedometers measures the number of steps. However, sensor worn in neck could not probably be used for step counting and therefore, no steps were estimated. Human activity bracelets and other devices could measure steps but if total energy consumption is being estimated, the values of acceleration should be taken into account. A research have shown that the sum of absolute value of the axis, instead of a absolute value is the best simple estimate for energy consumption and therefore, a good activity measure.

The cow activity was measured as a sum of absolute value acceleration vector. The activity was summed over a varying time window from 6 hours to 36 six hours. Since the resulting activity is always a sum of past activity, this method causes delay and widening of the activity peak. However, the size of the window does not affect the steepness of the rising or falling edges. Nevertheless, the size of the window widens the peaks if the window size is too high. In result, increasing the window might delay the oestrus detection, if the detection has dependencies in the falling edge. Based on the three found heat activity peaks of oestrus, an optimal window size is somewhere between 9 end 12 hours.

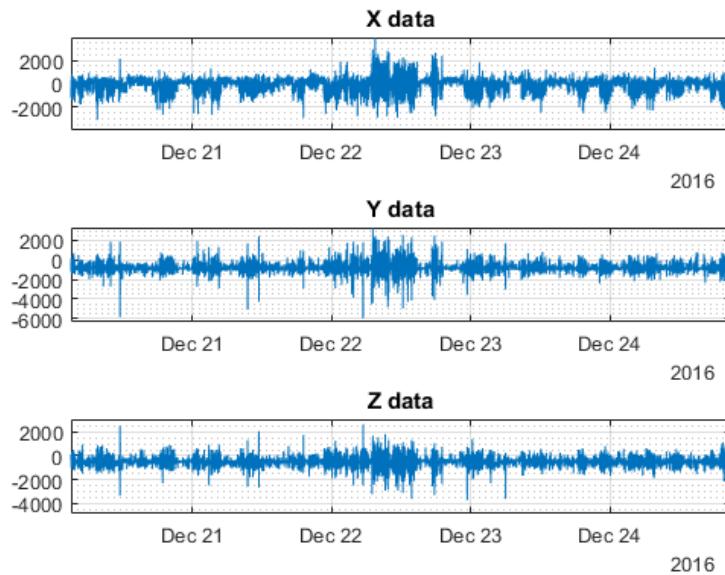


Figure 13: The first estrus activity period in the recorded data of the red cow.

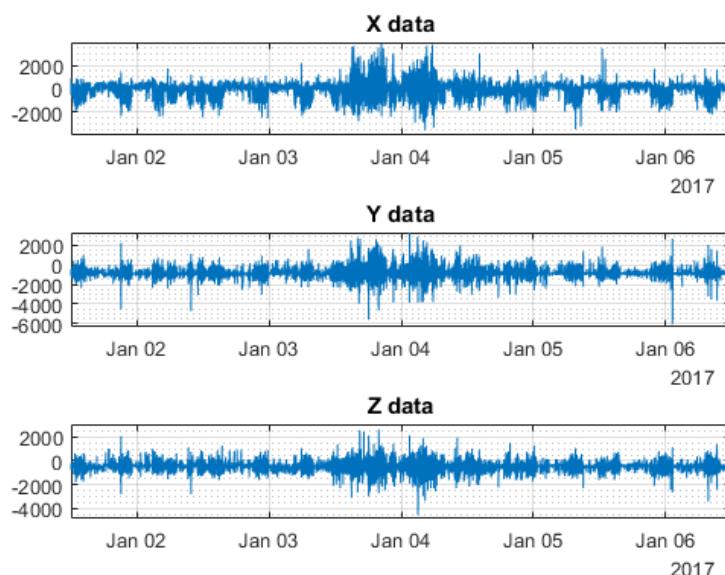


Figure 14: The second activity period of the red cow.

### 4.3 Conclusions

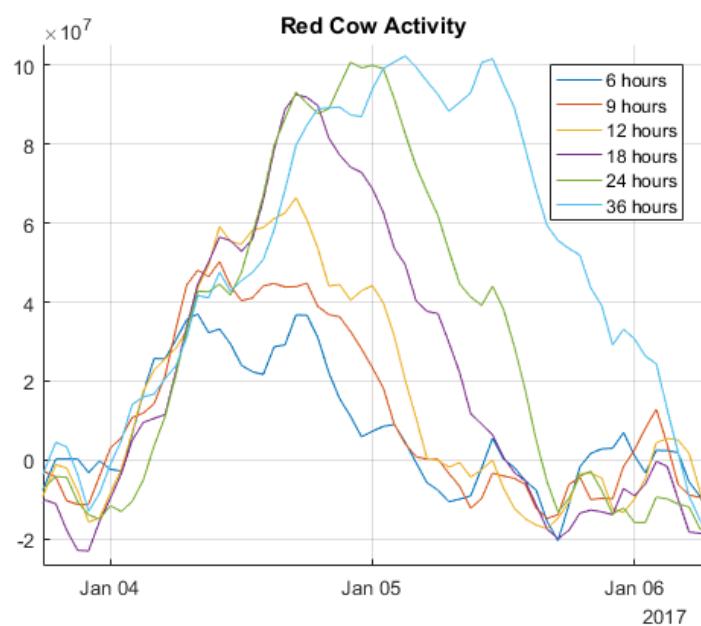


Figure 15: The activity curves of a cow in estrus. The width of the window varies. The optimal window size is approximately between form 9 to 12 hours.

## 5 Summary

Summary of all the previous. Alternatively “Discussion” or “Conclusions”...

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