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Measurement of horses gaits using geo-sensors

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Preface

This project was mainly related to the Signal Processing in terms of me, although it had some overlaps with the animal science. I found this project from the Prof. Niclas Björnell, he is my supervisor, so first I would like to thank him, he gave me many useful suggestions on the project plan, methods for analysis, and the report. The project was actually conducted by Mr. Bengt Julin from the Future Position X (FPX) in Teknik Parken of Gävle, he made great efforts on this project, coordinated the time of different people and arranged the measurements, also thanks for his hard work. Prof. Lars Roepstorff from the Swedish University of Agricultural Sciences in Uppsala is the expert of horses, he attended the measurement, and gave many professional recommendations on the measurement set-up and photographed the horse with his camera. Miss. Camilla Alsen and her colleagues from the Gävletravet gave great support to this project, and they provided the horse and the track. I am very appreciating for the support and understanding from all of them.

There is one thing I should mention, since this project contains some secrets, so no appendices will be put in the end.

Abstract

The aim of this thesis is to determine the horse's gait types using the acceleration values measured from the horse. A measurement was taken in Gävletravet, a total of five Nanotrak sensors were used, four on the different parts of the horse, and one on the hand of the horse's driver, a car was driven parallel to the horse and the motions of the horse was recorded by a camera in order to synchronize with the data measured by the sensors, a total of four videos were recorded. The software to process the data was Matlab R2010b, and the methods to analyze them were Fast Fourier Transform (FFT), Short Time Fourier Transform (STFT), and Least Squares (LS). Different window functions were tried when applying the STFT, and the Hanning window was the best to smooth the curves, different window sizes (or data length) were also tried, the data length of 512 was found to be the most proper value. The methods for classification of horse's gaits included amplitude, ratio, and LS. The method of amplitude worked well for the first three videos except for the last one, and performed better than the other two. The method of ratio was more reliable, but the results were not satisfactory. The method of LS gave bad results, so it was not trustworthy. More measurements and more analysis needed to be done in the future to find a proper way to automatic determine the horse's gaits, and the use of modern technology will be very popular in other fields like animal science.

Key words: Horse's gaits, Acceleration, Measurement, Sensors, Short Time Fourier Transform, Window functions, Least Squares, Classification.

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1 Introduction

Horse trotting match is very famous in Sweden, and the total turnover is 13.5 billion every year. Similar to other competitions, the Swedish horse trotting has its own regulations, according to the Swedish Competition Regulations, No.60 – Unauthorized gait and unclean trot. It means that the horses can only trot during the matches, and other gait types like gallop and amble are not allowed. However, the judgment of the gait types can only be observed by eyes or with the help of TV cameras currently, i.e. there is no system to automatic determine whether a horse is trotting or galloping during the match.

The gait types of horses can generally be categorized as four types: walk, trot, canter and gallop, but this thesis only studies two of them, i.e. trot and canter. Trot is a two-beat gait when the horse uses its diagonal limb pairs, left fore limb and right hind limb (left diagonal) or right fore limb and left hind limb (right diagonal) to touch the ground alternatively. Canter is a three-beat gait when the horse uses its left (or right) hind limb to solely touch the ground first, and then left (or right) diagonal, finally, the right (or left) fore limb push it forward. The gallop is actually a four-beat gait, but the canter can be regarded as three-beat gallop as well, and in this paper, the canter is also treated and called as gallop, it means that the ‘gallop’ mentioned below actually means canter.

Recently, a system that could automatic position the trotting horses and automatic determine the horses’ gait types was developed by the New Century Information (NCI), a company which was founded in June 2013, and a combination of sensors like GNSS (i.e. GPS + GLONASS + GALILEO + COMPASS + DGNSS), accelerometer, gyroscope and magnetometer are adopted to perform such research, and these sensors are now called geo-sensors. This system had been tested for 6 months in Gävle, and some initial measurements had been done, but the data processing had not started.

From the previous equine studies, the majority of the subjects were focused on the horse movement using kinematic or kinetic analysis, tools like treadmill, force shoes, force plate etc. , methods like photographic system, optoelectronic system etc. and parameters such as Ground Reaction Force (GRF), stride length, displacements etc. were often used in the

kinematic or kinetic analysis [1]. More interests were put in the fields like accuracy or precision of certain algorithms or determination of whether a horse had lameness using kinematic or kinetic data when the horses moved with certain gait types (e.g. walking, trotting, and galloping). Although sensors like accelerometers were used by some researchers during their studies, nearly none of them applied accelerometers to the gaits determination. For example, Barrey *et al.* [1][2] used two accelerometers mounted beneath the horse's sternum to measure longitudinal and dorsoventral accelerations of the trunk. Keegan *et al.* [1][3] combined the accelerometer with gyroscopic transducers to indicate the timing and the stance phase, so the location of the lameness could be determined. M. H. Thomsen *et al.* [4] from the University of Copenhagen developed three symmetry indices (i.e. W, S and A) based on the accelerometric data in trotting horses to judge whether the horses had lameness. H. Uchiyama *et al.* [5] from Japan compared the walking types among different kinds of horses and human using acceleration values both in time domain and frequency domain. However, a paper published early this year seemed to change the picture, J. B. Burla *et al.* [6] from ETH Zurich, Switzerland used absolute acceleration values from horses of different breeds to distinguish among four different gaits (i.e. standing, walking, trotting, and galloping), and found very good intervals of acceleration amplitudes of different gait types without any overlaps, so it would be easy to judge the gait types by simply observing the absolute acceleration values.

1.1 Aim of the thesis

The aim of this thesis is to take advantage of the acceleration values from the data measured by geo-sensors mounted on a horse, and then process and analyze them to find an algorithm to determine whether the horse has pure trot or not. Different methods in signal processing are tried, and comparisons are made so as to choose the best one. Moreover, time coded and synchronized videos are provided to help identify the results.

1.2 Outline of the thesis

The outline of the thesis is organized as follows. The theory that is related to this project will be explained in Chapter 2. In Chapter 3, the process of the measurements, and the methods that were used to process the acceleration data and to determine the horse's gaits will be

illustrated, the main results will be shown with some explanations. The results will be discussed in the Discussion with the strong and weak points of the work. Finally, the Conclusions will be drawn.

2 Theories

The devices that were used to measure the horse's movements in this project included accelerometers, gyroscopes and magnetometers, which were widely and typically used in the motion measurements, navigation or positioning system, and they could also roughly called sensors. Since acceleration was the parameter used in this thesis, so accelerometers would be explained more in detail with its usages, types, structures and basic principles, while the gyroscopes and the magnetometers would be explained concisely.

The main mathematical method for analyzing the data that were measured by the sensors was Fourier transform. There are many forms of Fourier transform, and in this thesis, Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) would be used and explained. Since the window functions were applied in the STFT, so there were explanations for some of the window functions as well. Another method regarding the concept of Least Squares would be used, actually the typical frequency spectrums of trot and gallop were created with the same and limited length in frequency domain first. Then generated the same length of spectrums for the whole process from trot to gallop using STFT, and compared these spectrums with the typical ones to see if they were more like trot or more like gallop. When creating the typical spectrums of trot and gallop, the Welch's method was used to average the amplitudes, so Least Squares and the Welch's method would be briefly introduced after the STFT.

2.1 Sensors

In this section, the accelerometer, the gyroscope and the magnetometer will be introduced. The accelerometer is more in detail, while the gyroscope and the magnetometer are just briefly stated.

2.1.1 Accelerometer

Acceleration is an important parameter to be considered in general-purpose absolute motion measurements, vibration, and shock sensing. The accelerometers have been used for many

years and are widely used in many fields like automobile, ships, sports, robotics, machine control and so on [7]. In the modern studies of equine locomotion, the accelerometers have also been used by many researchers. There are many types of accelerometers, and the most traditional accelerometers are of mechanic types using analog electronics, which make them a little big and heavy. However, the modern ones are manufactured as integrated chips using semiconductor materials, so they become smaller and lighter [7]. Although there are various kinds of accelerometers, the basic structures are almost the same, which can be summarized as a seismic mass that is free to move along a sensitive axis contained in housing or a frame [7]. Some of them are listed below.

Inertial accelerometers

Inertial accelerometers are mechanical types that use a spring or a lever to suspend a seismic mass within a rigid frame, and a transducer is connected to the mass to sense displacement. When the system vibrates, the relative displacement between the mass and the frame can be converted to electrical variables like resistance, capacitance, inductance etc. by the transducer in order to process further [7]. As is known, the acceleration is the second derivative of the displacement, so the acceleration value can be calculated according to this basic principle.

For the inertial accelerometers, different kinds of transducers can be used to sense the relative displacement between the mass and the frame. One way is to use a voltage divider potentiometer, and the measured acceleration ranges from $\pm 1g$ ($g \approx 9.8 \text{ m/s}^2$, is the gravitational acceleration) to $\pm 50g$, the size of this device is about 50 mm^3 , and weighs about $1/2 \text{ kg}$. Another way is to use devices called Linear Variable Differential Transformers (LVDTs), and cover the range from $\pm 2g$ to $\pm 700g$, the size is about 50 mm^3 as well, but the mass reduces to about 120 g [7].

Piezoelectric accelerometers

Piezoelectric accelerometers are usually used for measuring general-purpose acceleration. The Piezoelectric material is made of ceramic or quartz crystals that can sense the force from the mass when acceleration is applied to this system and electric charge will appear. The electric charge q is proportional to the force F , and they have the relationship of [7]

$$q = d_{ij}F = d_{ij}ma \quad (1)$$

Where d_{ij} is the piezoelectric coefficient of the material, m is the mass, and a is the acceleration.

This kind of device can be just 3×3 mm in size, and have a mass of only about 0.5 g.

Strain-Gauge accelerometers

The Strain Gauge is made of a material called piezoresistance, when the system is vibrating (i.e. an acceleration is applied to the system), it will cause the Strain Gauge to stretch or compress, the resistance of the Strain Gauge will change according to the formula [7]

$$\frac{dR/R}{dL/L} = l + 2\nu + \frac{d\rho/\rho}{dL/L} \quad (2)$$

Where l indicates the resistance change due to length, and ν indicates the change due to surface, and $(d\rho/\rho)/(dL/L)$ indicates the change due to piezoresistivity. The change of the resistance is thus related to the acceleration of the system.

The typical measured range of these accelerometers varies from $\pm 5g$ to $\pm 200g$, and the mass is usually less than 25 g [7].

Micro and Nanoaccelerometers

These accelerometers use the principles of some of the previous types explained earlier, but are smaller and lighter than them, because these accelerometers are manufactured in integrated chips. In addition, multiple accelerometers can be mounted in a single chip in order to measure the acceleration in x, y and z directions. The micro-accelerometers used in military conditions can have a measured range up to $\pm 1200g$, and with a size of only about 6 mm in diameter and 4.3 mm in length, and weigh only about 9 g [7].

2.1.2 Gyroscope

Gyroscope is another kind of sensor that is widely used in modern life, it can measure angles or angular velocity, and has a variety of applications, including Inertial Navigation System (INS), which is widely used on the planes and the rockets; Anti-Roll Devices, which can stop things from falling over; Global Positioning System (GPS) etc [8].

The most basic structure of it is a spinning wheel, and can resist attempts to change its rotating direction due to the angular momentum, and this is a very important property of gyroscope. When adding a set of gimbals outside the spinning wheel, it becomes the basic gyroscope called spinning mass gyro, when a force is applied to tilt it, the gyroscope will not move toward the direction of the force, it will actually rotate in the direction perpendicular to the direction of the force, and this is another crucial property of gyroscope called precession. The usages of gyroscope actually largely depend on these two properties.

2.1.3 Magnetometer

Magnetometer is used to measure the magnetization or direction of a magnetic field. The magnetometer has many applications in the field like archaeology, geography, military, and telecommunications (many smartphones contain it as compass) etc. There are many types of magnetometers, such as fluxgate magnetometer, proton precession magnetometer, and optical pumped magnetometer etc according to the applications.

2.2 Fourier transform

Fourier transform is widely used in the Signal Processing, the essence of the Fourier transform is that it decomposes a waveform into a sum of sinusoids of different frequencies, and the pictorial presentation of the Fourier Transform is a diagram that shows the amplitude and frequency of each sinusoid [10]. These sinusoids can also be summed to form the original waveform in the inverse process. The Fourier transform contains the same information as in the original waveform, the difference is that the Fourier transform contains information in frequency-domain.

The most basic form of Fourier transform is Continuous Fourier Transform (CFT), but in order to be applied on the digital computer, the Discrete Fourier Transform (DFT), which uses discrete values, is developed. However, the computation time will be very long if DFT was applied to large data records, thus the Fast Fourier Transform (FFT) is developed based on DFT, and the FFT will be briefly introduced in 2.3.1. Another form called Short Time Fourier Transform (STFT), contains the information both in time and frequency domain, will be introduced in 2.3.2, and the window functions used in STFT will be explained as well.

2.2.1 Fast Fourier Transform

FFT is a very widely used tool in signal processing and analysis. The application areas of FFT are not only limited in the traditional electrical and electronic fields like conventional radar, communications, sonar etc. but also extend into the fields like biomedical engineering, imaging, analysis of stock market data etc [10].

The FFT is based on the discrete Fourier transform (DFT), but is much faster than DFT. Assume a finite data sequence $x(n)$ in time domain consists of N elements, and is equal to zero outside the interval $[0, N-1]$, so the N -point DFT can be expressed as [11]

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi kn/N}, k = 0, 1, \dots, N-1 \quad (3)$$

And the results are in frequency domain, for each frequency point $X(k)$, it needs N complex multiplications and $N-1$ complex additions to obtain, so for the N -point DFT, there will be N^2 complex multiplications and $N*(N-1)$ complex additions in total, if N becomes very big, the total number of calculations will be extremely large. Although the modern computers have very high operational speed, it still seems not efficient to use DFT. Fortunately, FFT solves this problem to a large extent, if $N = 2^\mu$ (μ is a positive integer), the number of complex multiplications and complex additions can be reduced to $\frac{N}{2} \log_2 N$ and $N \log_2 N$ respectively [11].

2.2.2 Short Time Fourier Transform

STFT is special case of Fourier transform, but instead of taking the Fourier transform for the whole interval, it uses a window function to limit the signal in a shorter time interval, and then take the Fourier transform of it. The STFT is thus called windowed Fourier transform as well. Assume a continuous function $f(t)$, recall the continuous Fourier transform

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \quad (4)$$

Which is the most basic form, and the STFT is [12]

$$F(\omega, b) = \int_{-\infty}^{\infty} f(t) h(t-b) e^{-j\omega t} dt \quad (5)$$

Where $h(t-b)$ is the window function which confines the complex sinusoid $e^{j\omega t}$ [12], and b is the time duration of the window or window size, b can be different values, but it can not

exceed the length of $f(t)$. The window function will first be applied to the first time section of the original function $f(t)$, and then shift along the time axis by a fixed step until it covers the whole interval of $f(t)$, so there may be overlaps among several neighboring time sections, the length of the step can be adjusted, but it can not exceed the width of the window. The results $F(\omega, b)$ contains information both in time and frequency domain, and the resolution in frequency domain will increase while the resolution in time domain will decrease when the window size increases, so there is a tradeoff between the resolutions in time and frequency domain. There are many types of window functions, such as Hamming, Hanning, cosine, Kaiser, and Gaussian. Some of the window functions will be explained further as follows.

Rectangular window

Assume that the time interval of the window is T , and the window function of this kind is [13]

$$h(t) = \begin{cases} 1 & \text{for } -T/2 \leq t \leq T/2 \\ 0 & \text{else} \end{cases} \quad (6)$$

And the power presentation of the Fourier transform is [13]

$$|H(\omega)|^2 = T^2 \left(\frac{\sin(\omega T / 2)}{\omega T / 2} \right)^2 \quad (7)$$

The power presentation of the rectangular window using Fourier transform is shown in the Fig. 1. The suppression of the first sidelobe is only about -13.2 dB. In fact, since the window function of the Rectangular window is 1 within the time interval, it does not have any effects to the original function that will be transformed, so it is equivalent to taking the Fourier transform in that interval without any windows.

Fig. 1. The power presentation of the Rectangular window

Hanning window

Hanning window, also called the $\cos^2$ -window, and the window function is given by [13]

$$h(t) = \begin{cases} \cos^2 \frac{\pi t}{T} & \text{for } -T/2 \leq t \leq T/2 \\ 0 & \text{else} \end{cases} \quad (8)$$

The corresponding Fourier transform is [13]

$$H(\omega) = \frac{T}{4} \sin \frac{\omega T}{2} \times \left(\frac{1}{\pi - \omega T/2} + \frac{2}{\omega T/2} - \frac{1}{\pi + \omega T/2} \right) \quad (9)$$

Fig. 2. The power presentation of the Hanning window

The power presentation $|H(\omega)|^2$ of the Hanning window is shown in the Fig. 2. The suppression of the first sidelobe is decreases to about -32 dB this time, and the sidelobe's asymptotic decay is -18 dB/octave [13], which indicates that the amplitudes of the sidelobes attenuate very fast when the frequency increases, so the energy is mainly concentrated in the main lobe.

Hamming window

The window function of the Hamming window is given by [13]

$$h(t) = \begin{cases} a + (1-a) \cos^2 \frac{\pi t}{T} & \text{for } -T/2 \leq t \leq T/2 \\ 0 & \text{else} \end{cases} \quad (10)$$

The Fourier transform is [13]

$$H(\omega) = \frac{T}{4} \sin \frac{\omega T}{2} \left(\frac{1-a}{\pi - \omega T/2} + \frac{2(1+a)}{\omega T/2} - \frac{1-a}{\pi + \omega T/2} \right) \quad (11)$$

Where $0 < a < 1$, when $a = 0.15$, $|H(\omega)|^2$ is shown in the Fig. 3. The shape of the window function of the Hamming window is similar to the Hanning window, but with a “Pedestal”. However, there is a slightly change in the shape of the $|H(\omega)|^2$, the suppression of the first sidelobe decreases to nearly -40 dB, but the asymptotic decay is only -6 dB/octave [13], the sidelobes will have more side effects to the results at higher frequencies.

Fig. 3. The power presentation of the Hamming window

Gauss window

The window function of Gauss window is given by [13]

$$h(t) = \begin{cases} \exp\left(-\frac{1}{2} \frac{t^2}{\sigma^2}\right) & \text{for } -T/2 \leq t \leq T/2 \\ 0 & \text{else} \end{cases} \quad (12)$$

And the Fourier transform is [13]

$$H(\omega) = \sigma \sqrt{\frac{\pi}{2}} e^{-\frac{\sigma^2 \omega^2}{4}} \left(\operatorname{erfc}\left(-\frac{i\sigma^2 \omega^2}{\sqrt{2}} + \frac{T^2}{8\sigma^2}\right) + \operatorname{erfc}\left(\frac{i\sigma^2 \omega^2}{\sqrt{2}} + \frac{T^2}{8\sigma^2}\right) \right) \quad (13)$$

Where erfc stands for the complementary error function, when $\sigma = 2$, $|H(\omega)|^2$ is shown in the Fig. 4. The suppression of the first sidelobe is only about -60 dB, but asymptotic behavior is not very good [13].

Fig. 4. The power presentation of the Gauss window

The most ideal window is to have both high attenuation in the first sidelobe and fast attenuation at high frequencies, but the windows described above can not meet both requirements simultaneously, it is very hard to determine which one performs the best by just seeing the power presentation, so they will be tried separately when using the STFT to analyze the data.

2.3 Least Squares

The Least Squares (LS) approach is to minimize the squared difference between the given data set $x[n]$ and the assumed signal $s[n]$, where $n = 0, 1, \dots, N-1$. If LS is applied to the parameter estimation, and assume the unknown parameter to be θ , and $s[n]$ depends on the parameter θ , then the Least Squares Estimator (LSE) of θ is to find the value that makes $s[n]$ closest to the given data $x[n]$, and in general the relationship can be given by the LS error criterion [14]

$$J(\theta) = \sum_{n=0}^{N-1} (x[n] - s[n])^2 \quad (14)$$

since $s[n]$ has a dependence on θ , so the value of θ that makes $J(\theta)$ the minimum will be the LSE.

The characteristics of the LSE are that no probabilistic assumptions are made to the data as in the method of Maximum Likelihood Estimation (MLE), the signal model is unknown and must be assumed according to the given data samples $x[n]$, so the performance of this method

will largely be effected by the choice of the model. However, this method is easy to implement due to its simple calculation of the LS error. The LSEs are usually applied in the situations where a precise statistical characterization of the data is unknown or where optimal estimator cannot be found [14]. The LSE finds an important application in curve fitting, which is very similar to the case in this thesis. In this situation, assuming the curve is given by [15]

$$y = a_0 + a_1x + a_2x^2 + \cdots + a_kx^k \neq 0 \quad (15)$$

and has the observation data of coordinates (x_i, y_i) ($i = 0, 1, 2, \dots, n; n \geq k+1$), the aim is to find the unknown coefficients a_j ($j = 0, 1, 2, \dots, k$) that minimizes the sum of the squared error given by [15]

$$S = \sum_{i=1}^n (y_i - a_0 - a_1x_i - a_2x_i^2 - \cdots - a_kx_i^k)^2 \quad (16)$$

so that the curve given by equation (15) will best fit the curve given by the observation data. As explained in 2.1, the method adopted in this thesis is to compare each section of spectrums with the typical trot and typical gallop. It is actually done by calculating the sum of the squared errors between the typical values and the values that are to be estimated, and then make comparisons to see whether the estimated values are better fit to trot or better fit to gallop, so it is the similar concept as the LSE in curve fitting. The difference is that in curve fitting, the coefficients a_j that describe the curve are unknown, while in the thesis, the curves are already known, the aim is just to calculate the errors to see which one is smaller.

2.4 Welch's Method

Welch's Method is used to average modified periodograms. The periodogram is obtained by normalizing the squared magnitudes of Discrete Fourier Transform (DFT) for a given data set $x[n]$ ($n = 0, 1, 2, \dots, N-1$). If $x[n]$ was divided into many sections of the same length, the periodogram of each section may not be completely the same, so there is a need to average the periodograms for all the sections. There are several ways to average the periodograms, Bartlett's Method, Welch's Method and Blackman-Tukey Method. In Bartlett's Method, the data set is divided equally without overlaps, while in Welch's method, two modifications are

made, the first is to allow overlaps between each section of data, and the amount of overlap is either 50% or 75%, the second is to allow a data window to be applied to each section, thus result in modified periodograms. Assuming $x[n]$ is divided into K sections and each section has a length of L , and has 50% overlap, then the following relationship can be derived [11]

$$K = 2 \frac{N}{L} - 1 \quad (17)$$

and the Variability, which is the normalized variance, and resolution of the periodograms are given by [11]

$$V = \frac{9}{8} \frac{1}{K} \quad (18)$$

$$\Delta\omega = 1.28 \frac{2\pi}{L} \quad (19)$$

the most ideal situation is to have both small V and $\Delta\omega$, so it will have small variance and high resolution, hence K and L have to both be big, but according to the equation (17), increasing L will result in a reduction of K , so K and L can not be big simultaneously, there is a tradeoff between these two parameters.

3 Process and Results

The way to obtain the acceleration data is to implement real measurements of the horse using sensors. The sensors used in the thesis, which are called Nanotrak sensors, will be introduced first. Before taking the measurements, the positions to mount the sensors have to be decided, so the selection and the results of the displacements of the sensors will be given then, followed by the outline of the measurements set-up. The next step is the pre-processing by using software Matlab, the method used in pre-processing is FFT, and the results using FFT will be shown there. The major mathematical method for analyzing the data is STFT, and window functions will be applied, the lengths of the windows are quite important, so the window size will be discussed, and the results using different windows and window sizes will be plotted. After taking STFT, some classification methods which are going to be used to determine the horse's gait types must be found, and they will be in the last section. The flow chart for the whole procedure is shown in the Fig. 5.

Fig. 5. Flow chart of the procedure

3.1 Sensors used in the project

The sensors used in this project are called Nanotrak, they are developed by the Catapult Sports from Australia, a company which applies the GPS technology into sports. The Nanotrak contains tri-axial accelerometers, gyroscopes and magnetometers, and provides movement quantification for in-depth analysis. The Nanotrak measures the data at a frequency of 100 Hz. The data from the Nanotrak is not real-time, it can only be seen using a software called Catapult Sprint developed by the same company when the sensor is connected to the computer via a docking station and a USB, the data can be exported as a comma-separated value (.csv) file from the software for further use [9].

The tri-axial accelerometer contains accelerometers in three directions. The vertical acceleration is measured by the 'Up' accelerometer, the mediolateral acceleration will be measured by the 'Sideways' accelerometer, the anterior/posterior acceleration will be measured by the 'Forward' accelerometer.

3.2 Selection for placements of the sensors

The positions to mount the sensors and the orientation of the sensors are quite important. In equine studies, the accelerometers had most often been put on the hoof wall to detect initial ground contact [1]. For example, accelerometers were placed on all four hoofs of horses to study the hoof impact of different stride types and functional limb types by E. Hernlund *et al.* [16]. S. D. Starke *et al.* [17] used a combination of devices to evaluate the accuracy and precision of foot contact timings of horses, including a hoof-mounted accelerometer. L. H. Douilly *et al.* [18] studied the hoof slip distance by placing piezoelectric accelerometer at the right front hoof of the horse. Other parts on the horse had also been tried, sensors attached to the poll (head) and withers [19], [20]; accelerometer placed on the sternum (the bone of the chest) [21]; accelerometer attached to the saddle had been used to measure the acceleration of different gaits [1][22]. However, the purpose was different in this study, the aim was to find which part on the horse had the most stable acceleration, so in order to decide which part on the horse was the best place to mount the sensor, four sensors were put on the head, the back, the left side and the right side of the trunk of the horse respectively, and the results are shown in the Fig. 6. The selection for these positions was just a try, and covered the main parts on

the horse, because no papers were found to discuss the best position of the placements of the sensors on the horses. There was also a sensor held by the driver of the horse on the hand, and this sensor would be treated as a reference for the other sensors. Hence, there were five sensors in total.

Fig. 6. The placements of the sensors on the horse: (a) Head (b) Back (c) Left side of the trunk (d) Right side of the trunk

3.3 Measurement set-up

The measurement was held in the Gävletravet. Five Nanotrak sensors were used in the measurement, four of them were mounted on different parts of the horse, one on the head, one on the back, and the other two were on the left and the right side of the trunk. The last one was held by the driver of the horse, the reason to choose the positions of these placements would be explained in the next subsection. The five sensors were started simultaneously in order to be time-synchronized, and then mounted on the horse. The horse was driven by the driver to run around the track, and the motions of the horse were captured using a camera on

a car which was driven parallel to the horse, the camera recorded the motions at a speed of 30 frames per second (fps), a total of four sections of videos were taken. The videos taken by the camera would be used to synchronize with the data recorded by the sensors. The photographer on the car would give the driver of the horse a start command, and the driver would hit the sensor which was held on her hand for several times, so there should be some peaks in the data from this sensor, these peaks would be treated as time-starting points for the analysis, and it would be easy to find the starting points for the other sensors regarding this sensor. The horse was driven to trot first, and then gallop, in order to find the differences between these two gaits in further analysis.

3.4 Pre-processing

The tool for analyzing the data is Matlab R2010b. Matlab is very widely used in the signal processing, it contains a lot of useful functions, including FFT and window functions. The obtained csv files that contain the data are inserted into the Matlab and are converted to Matlab data files. The way to do pre-processing here is to generate the frequency spectrums using FFT.

First, the frequency spectrums of acceleration of different directions when the horse was trotting were obtained by using the data sequences the same period as in the first video from the horse's back using FFT, and they are plotted in the Fig. 7. As can be seen from the Fig. 7, the frequency spectrums of the forward and mediolateral acceleration are quite irregular, no useful information can be picked from them, while for the vertical acceleration, there is a peak around 5 Hz, and two harmonics can be clearly seen as well. As a result, the acceleration from the forward and mediolateral directions can not be used to analyze any more, only the vertical acceleration is useful.

Then the frequency spectrums of the vertical acceleration of horse's back when the horse was trotting and galloping are shown in the Fig. 8, the acceleration in the galloping distributes more in other frequency components, it's hard to find the regularity from it. The corresponding frequency spectrums of the other parts of the horse were analyzed, the best ones were from the data of the head, and they are plotted in the Fig. 9, the common point between the Fig. 8 and the Fig. 9 is that the acceleration values in some frequency (e.g.

between 5 Hz and 10 Hz) components are higher in galloping than in trotting, this may be the case. Besides, the ratio between the peak and the harmonics may also change from trot to gallop, which is also worth to have a deep view.

Fig. 7. The frequency spectrums of the acceleration of the horse's back in different directions:

(a) Forward (b) Mediolateral (c) Vertical

Fig. 8. The frequency spectrums of the vertical acceleration of the horse's back in (a) trot (b) gallop

Fig. 9. The frequency spectrums of the vertical acceleration of the horse's head in (a) trot (b) gallop

3.5 Selection for window size

When choosing the window size, a tradeoff between time and frequency resolutions is taken into account. Using a small window will result in good time resolution but poor frequency resolution, and vice versa. To analyze slowly varying components, such as low-frequency components, a large window should be used, while a small window is better for analyzing short-duration transient components [23]. In this thesis, the center frequency of vertical acceleration of the horse is relatively low, typically around 5 Hz, so a large window is preferred. However, the time delay will increase as the window size increases, and in this thesis, will cause long-delayed determination of the gait, so the time delay shall be as small as possible, and the window size shall not be too large. Hence, the tradeoff between the window size and the time delay shall also be considered. Assume the window size to be N , and in the thesis, $N = 2^x$ (x is a positive integer from 4 to 10) were selected.

3.6 Short Time Fourier Transform

In order to see what happens to the frequency components explained in the end of the section 3.4, taking the whole process from trotting to galloping of the head into account, of which part performs the best in its spectrums both in trotting and galloping. The 3-D plot of the corresponding acceleration data using the method of STFT is shown in the Fig. 10, no window function was applied, time points for each STFT was 64, and the step was 1. The first

Fig. 10. The 3-D plot of the vertical acceleration of the horse's head using STFT

(a)

(b)

(c)

(d)

Fig. 11. STFT of the vertical acceleration of the horse's head in time domain using different windows: (a) Rectangular (b) Gauss (c) Hanning (d) Hamming

video lasts about 215 s, and the time in the Fig. 10 has been adjusted according to the first video, the acceleration values have been transferred into decibel (dB). The magnitudes

of the frequency components within the deep blue sign increase with the time, although the increase is not that obvious, it is still worth for processing further.

Taking the STFT of the acceleration values from the four parts of the horse using four different windows (Rectangular, Hamming, Hanning, and Gauss) and with time points (window size) N equals to 16, 32, 64, 128, 256, 512, and 1024 respectively, the step is 2. The results contain the information both in time and frequency domain, choosing the frequency components between 5 Hz and 10 Hz whose amplitudes increase with time, and plot them just in time domain. Since the results are very bad when $N < 256$, so they are ignored, and the STFT of the acceleration of the head when $N = 256$ using different windows are shown in the Fig. 11, the Hanning window performs the best to smooth the signal, while the rectangular window is the worst. The STFT of the acceleration of the head using Hanning window when $N = 512$ and 1024 are shown in the Fig. 12, the curve is better when N is bigger.

Fig. 12. STFT of the vertical acceleration of the horse's head using Hanning window with data length of (a) 512 (b) 1024

3.7 Methods for classification

The method of the classification for determining the horse's gait types includes amplitude, ratio, and the LS errors.

The method of analyzing the amplitude is to use the absolute acceleration values, because the acceleration of the horse may change when it goes from trot to gallop, so there will be a

threshold when the horse changes its gaits, but the disadvantage of this kind of method is that the threshold may vary for different horses.

Another kind of method is to find ratio, e.g. the ratio between the peak and the harmonics, and the ratio may also change when the horse changes its gaits, so there will be a threshold in the middle as well. The method of finding ratio is more trustworthy, because the ratio may keep constant for different horses.

The method regarding the LS will be done in two parts: frequency spectrums and histograms. The first part has been explained at the start of the chapter 2 and in 2.3. For the second part, the procedure is similar, but the typical histograms of trot and gallop with the same length are constructed instead. The histograms are constructed using the absolute acceleration values. Then the histograms for the whole process, say estimated histograms, are generated. Then calculate the sum of the squared errors between the estimated histograms and the typical histogram of trot (ε_1), and between the estimated histograms and the typical histogram of gallop (ε_2). If $\varepsilon_1 < \varepsilon_2$, it will be regarded as trot, otherwise it will be regarded as gallop.

3.7.1 Amplitude

After plotting the results, there must be a method to judge whether the horse is trotting or galloping, since the acceleration is increasing with time at these frequency components, the proper way here is to choose thresholds in the middle to distinguish between these two gait types. The horse changed the gait types from trot to gallop at about 169 s according to the first video, and the thresholds were chosen based on this fact. Here, another parameter called misclassification was also applied, in this situation, assume certain thresholds were already chosen, if the amplitude of the time point before 169 s was above the thresholds, it would be classified as one misclassification, and those amplitudes which were after 169 s would be vice versa. The percentage of the misclassification would be the total number of misclassification divided by the total time points. The thresholds and the percentages of the misclassification are shown in the Table. 1, Table 2, Table 3 and Table 4, the percentages which are above 10% have already been ignored, the numbers in the round brackets represent the locations of the frequency points.

Table 1. The thresholds and the percentages of misclassification using the acceleration data of horse's back in the first video. (T = Threshold, P = Percentage, N_0 is the location of the frequency component)

	Window function			
	Rectangular		Hamming	
N	T (m/s ²)	P (%)	T (m/s ²)	P (%)
256	0.1 ($N_0 = 26$)	5.49	0.034 ($N_0 = 26$)	5.13
512	0.1 ($N_0 = 49$)	1.69	0.04 ($N_0 = 49$)	2.39
1024	0.044 ($N_0 = 97$)	5.07	0.008 ($N_0 = 98$)	4.19
	Hanning		Gauss	
N	T (m/s ²)	P (%)	T (m/s ²)	P (%)
256	0.032 ($N_0 = 27$)	2.86	0.039 ($N_0 = 26$)	5.37
512	0.045 ($N_0 = 49$)	3.24	0.038 ($N_0 = 49$)	2.39
1024	0.008 ($N_0 = 98$)	7.71	0.017 ($N_0 = 100$)	6.83

The Table 1 shows the worst results compared with the other three tables, even when N is as big as 1024, so the data from the back should be ignored. The Table 4 seems to give the lowest percentages when using Hamming and Gauss windows, when $N = 512$, the frequency point is located at about $f = fs * (N_0/N) = 100 * (94/512) \approx 18.35$ Hz, but when looking at the frequency spectrums shown in the Fig. 13, the acceleration when frequency is about 18.35 Hz behaves like noise, so the data from the right side is not trustworthy. The Table 2 and the Table 3 both have very low percentages when $N = 1024$, but the time delay under this condition, which is given by $N * (1/fs) = 1024 * (1/100) = 10.24$ s, is very long, so N must be smaller. When $N = 512$, the percentages in the Table 2 give lower values than in the Table 3,

although the delay is still 5.12 s, a solution can be applied to achieve better results, that is to increase the sampling frequency of the sensors, e.g. $fs = 400$ Hz, so the delay will be just $5.12/4 = 1.28$ s, which can be an acceptable value.

Since the data from the head give the best results, so further applying the window functions to the data sequences which have the same periods as in the other three videos, let $N = 512$, the thresholds and percentages of misclassification are shown in the Table 5. The percentages are quite low in the 2nd and the 3rd video using Hamming, Hanning and Gauss windows, but for the 4th video, it was unable to determine the thresholds because the curves had very large variations.

Table 2. The thresholds and the percentages of misclassification using the acceleration data of horse's head in the first video.

	Window function			
	Rectangular		Hamming	
N	T (m/s ²)	P (%)	T (m/s ²)	P (%)
256	0.13 ($N_0 = 24$)	6.68	0.067 ($N_0 = 24$)	2.51
512	0.109 ($N_0 = 47$)	0.42	0.057 ($N_0 = 47$)	0.28
1024	0.039 ($N_0 = 93$)	0.66	0.018 ($N_0 = 93$)	0.44
	Hanning		Gauss	
N	T (m/s ²)	P (%)	T (m/s ²)	P (%)
256	0.064 ($N_0 = 24$)	3.1	0.063 ($N_0 = 24$)	3.46
512	0.053 ($N_0 = 47$)	0.99	0.052 ($N_0 = 47$)	1.13
1024	0.016 ($N_0 = 93$)	0.22	0.016 ($N_0 = 93$)	0.22

Table 3. The thresholds and the percentages of misclassification using the acceleration data of horse's left side of the trunk in the first video.

	Window function			
	Rectangular		Hamming	
N	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$
512	0.147 ($N_0 = 47$)	7.18	0.093 ($N_0 = 47$)	5.07
1024	0.081 ($N_0 = 93$)	1.32	0.04 ($N_0 = 93$)	0.44
	Hanning		Gauss	
N	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$
512	0.088 ($N_0 = 47$)	7.18	0.086 ($N_0 = 47$)	2.96
1024	0.036 ($N_0 = 93$)	0.22	0.036 ($N_0 = 93$)	0.22

Table 4. The thresholds and the percentages of misclassification using the acceleration data of horse's right side of the trunk in the first video.

	Window function			
	Rectangular		Hamming	
N	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$
512	0.13 ($N_0 = 94$)	1.69	0.066 ($N_0 = 94$)	0
1024	0.084 ($N_0 = 187$)	1.76	0.035 ($N_0 = 187$)	0
	Hanning		Gauss	
N	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$	$T \text{ (m/s}^2\text{)}$	$P \text{ (%)}$
512	0.059 ($N_0 = 94$)	0.28	0.059 ($N_0 = 94$)	0
1024	0.03 ($N_0 = 187$)	0.22	0.031 ($N_0 = 187$)	0

Table 5. The thresholds and the percentages of misclassification using the acceleration data of horse's head in the other three videos. (\ = can not be determined)

	Window function			
	Rectangular		Hamming	
	T (m/s ²)	P (%)	T (m/s ²)	P (%)
2nd video	0.019 ($N_0 = 48$)	8.46	0.011 ($N_0 = 48$)	0.19
3rd video	0.025 ($N_0 = 46$)	8.78	0.009 ($N_0 = 46$)	0.49
4th video	\	\	\	\
	Hanning		Gauss	
	T (m/s ²)	P (%)	T (m/s ²)	P (%)
2nd video	0.011 ($N_0 = 48$)	0.19	0.011 ($N_0 = 48$)	0.77
3rd video	0.009 ($N_0 = 46$)	0.49	0.009 ($N_0 = 46$)	0.49
4th video	\	\	\	\

(a)

(b)

Fig. 13. The frequency spectrums of the acceleration of the right side of the trunk in (a) trot (b) gallop

When comparing the misclassification using the data from the back, head, left side and right side for the first three videos, and using Hanning window with a data length of 512, the results are shown in the Table 6. In the first video, all of the four positions show percentages

less than 10%, especially for the right side. However, for the second video, only the head of the horse shows a very low percentage, and for the third video, all of the positions give very low percentages. Overall, the misclassifications of the back, left side and right side have large variations in different conditions, only the misclassification of the head has very low percentages and very stable performance in different conditions.

Table 6. Misclassification using the data from head, back, left side and right side of the horse in the first three videos

	Misclassification (%)			
	Head	Back	Left side	Right side
1st video	0.99	3.24	7.18	0.28
2nd video	0.19	15.19	18.46	19.04
3rd video	0.49	0	0	0.49

3.7.2 Ratio

An alternative method based on the STFT can also be applied, that is to find proper ratios to distinguish between trotting and galloping. As shown before, the data from the head performs the best, so looking back at the frequency spectrums of the acceleration of the head shown in the Fig. 9, the ratio between the amplitudes of the peak and its harmonics can be considered, the ratio in the galloping may have some differences from that in the trotting. Taking the STFT of the acceleration of the head using Hanning window when $N = 512$ into account, regarding the information in frequency domain at each time point, instead of just regarding the peak, some of the neighboring values at both sides of the peak were added together with the peak, so it would be more accurate, the sum can be denoted as P_{tot} . Similarly for the harmonics, the same number of neighboring values of the harmonics was also added together with the harmonics, the sum of all the harmonics can be denoted as H_{tot} . Using the 2nd and the 3rd harmonics, let the number of neighboring values be four (two at each side), and calculated the ratio between P_{tot} and H_{tot} , the ratio was given a name Total Harmonic

Distortion (THD) here for convenience. Repeated the calculation for all the time points, the THD was in time domain and is shown in the Fig. 14, the time had been synchronized according to the video, as explained before, the horse changed its gait at about 169 s, but it was very difficult to determine a threshold at that point to distinguish between trotting and galloping. Different numbers of harmonics and neighboring values were tried, but no results were found to be good.

Fig. 14. THD of the vertical acceleration of the horse's head using Hanning window when $N = 512$

3.7.3 Least Squares

The results of Least Squares will include two parts. In the first part, the typical frequency spectrums of trot and gallop are constructed, and then the spectrums of each section from trot to gallop, the estimated spectrums, are compared with the typical values. The sum of the squared errors between the estimated spectrums and the typical trot, and between the estimated spectrums and the typical gallop are calculated separately to see which one is smaller, on the other hand, to see whether the estimated spectrums are closer to typical trot or typical gallop. For the second part, the procedure are similar to the first part, but instead of using frequency spectrums, the typical histograms of trot and gallop are constructed, and compare with the histograms of each section from trot to gallop. The data from the back, head, left side and right side of the horse, which have the same periods as the first three videos are used, and for each part, the percentages of misclassification are also calculated.

Frequency spectrums

The typical frequency spectrums of trot and gallop are constructed using the data as in the first video, the spectrums are averaged by using the Welch's Method with 50% overlap, and are plotted in the Fig. 15.

Fig. 15. Typical frequency spectrums of (a) trot and (b) gallop

Then generating the frequency spectrums of each section for the whole process from trot to gallop in the first video using STFT, and calculate the sum of the squared errors between these spectrums and the typical spectrums, if the error between the estimated spectrums and the typical trot is smaller than the error between the estimated spectrums and the typical gallop, then the estimated spectrums are said to be more fitted to the typical trot, and the determination of trot will be set to 1, refer as “True”. For the contrary condition, it will be set to 0, refer as “False”, the determination of the trot is shown in the Fig. 16.

Since the horse changed its gaits from trot to gallop at 169s in the first video, so from Fig. 16, there is error determination of trot, the percentage of misclassification under this condition is about 16.6%. Repeating the same procedure of determination for the back, left side and right side in all the first three videos, the percentages of misclassification are shown in the Table. 7. The misclassification happens to drop to 1.01% using the data from the back of the horse in the first video, but the rest of the data give high percentages of misclassification, some even larger than 40%.

Fig. 16. Determination of trot (frequency spectrums)

Table 7. Percentages of misclassification of different parts of the horse in the first three videos (frequency spectrums)

	Misclassification (%)			
	Head	Back	Left side	Right side
1st video	16.60	1.01	14.87	13.67
2nd video	15.06	20.54	16.45	22.55
3rd video	40.00	27.52	45.86	21.65

Histograms

The typical histograms of trot and gallop are also constructed using the data as in the first video, and are plotted in the Fig. 17.

Fig. 17. Typical histograms of (a) trot and (b) gallop

Then doing the similar steps as in the frequency spectrums, generating the histograms of each section for the whole process from trot to gallop in the first video, and calculate the sum of the squared errors between these histograms and the typical histograms, if the error between

Fig. 18. Determination of trot (histograms)

Table 8. Percentages of misclassification of different parts of the horse in the first three videos (histograms)

	Misclassification (%)			
	Head	Back	Left side	Right side
1st video	53.25	29.97	14.75	26.03
2nd video	18.84	25.17	28.19	22.16
3rd video	25.71	35.34	38.20	44.96

the estimated histograms and the typical trot histogram is smaller than the error between the estimated histograms and the typical gallop histogram, then the determination of trot will be set to 1, and will be set to 0 for the contrary condition. The determination of trot using histograms is shown in the Fig. 18. The percentage of misclassification is 53.25%. Repeating the same procedure of determination for the back, left side and right side in all the first three videos, the percentages of misclassification are shown in the Table. 8. The misclassification using histograms are all above 10%, some even larger than 40%.

4 Discussion

The acceleration of the vertical direction of the horse's head performed the best and gave the most satisfactory results among the other directions and the other parts of the horse, but the positions of the placements of the sensors were not limited to the back, the head, the left side and the right side of the trunk, they could be mounted on the other parts of the horse to study the performance.

The use of the STFT was a very positive aspect in this thesis, different windows and window sizes were applied, and Hanning window was the best to smooth the curves, $N = 512$ was the most proper window size, although the time delay would be a little long, it could be solved if we had higher sampling frequencies. It might be doubted that the sampling rate was too high, resulted in oversampling, but in this case it was unavoidable since the resolution (or width) of the main lobe of the frequency spectrum was given by [10]

$$\Delta\omega = \frac{2\pi}{N} \quad (20)$$

where N is the number of data points that was used to take the FFT, $\Delta\omega$ should be small enough to make the main lobe narrow and high so that the power was more concentrated to the center frequency, so N should be big enough. Moreover, the data length of 512 was chosen as the best when taking STFT, so the determination would be made after taking 512 samples, and the time delay would be $\tau = 512/f_s$, where f_s is sampling frequency. The time delay should be as small as possible so a quick determination would be realized, so f_s should be high enough to make τ small. Hence, high sampling rate and large data records were preferred.

For the classification of the horse's gait types, amplitude and ratio based on the STFT were the major methods, but the results were not very satisfactory for both of them. The method regarding the amplitude seemed to perform well, but the data from the fourth video was quite bad, moreover, as explained in the section 3.7, the main drawback of this method was that the amplitude would have a great probability to change in different horses. The method of ratio was more reliable, but the results were not good, and the thresholds could not be determined. Another method similar to the Least Squares was also tried, the frequency spectrums and the

histograms were analyzed and compared with the typical values. In this case, more interests were put in the shapes of the curves to see if the spectrums or histograms are more fitted to the typical values of trot or gallop. The advantage of this method was that it was easy to implement, and was obvious to distinguish when setting the determination of trot to 1 and gallop to 0. However, the misclassification using this method was not good, although sometimes it drops to a low percentage.

More methods might be applied, but I did not have that much time to apply all of these methods to reality. Furthermore, since this project was also related to the medical science, so maybe some other methods in the medical field could be used to determine the horse's gait types as well.

In this project, due to the reasons of limited time and resources, we only implemented four measurements. We wished to take more measurements and to try more positions of placements of the sensors, but it really needed time to coordinate the time of different people and to make reservations for the track and the horse, it was very difficult to meet all these requirements.

Although the amount of measurements were not enough to give more convincing results, it was already nice to have an interesting and practical experience when taking the measurement and to look deeper into the STFT in this project. Moreover, there were many comparisons that were made during the thesis, e.g. the comparisons among different positions of placements of the sensors, the acceleration from different directions, different window functions and window sizes etc. The procedure of making tradeoff between two parameters, e.g. the window size (or data length) and the time delay, which had opposite effects on the results was another strong point. Although my major concentration was on the Signal Processing, the opportunity to gain some knowledge from other fields, like animal science, machinery, theoretical math was also quite meaningful.

5 Conclusions

The purpose of this project was to use the acceleration values measured from the horse to determine its gait types. Four major aspects were studied, the first one was the placements of the sensors, four different positions on the horse were tried, and eventually the head was found to be the best position. The second one was the windows that were used in the Fourier transform, four different windows were applied, and the Hanning window performed the best to smooth the curves. The third one is the window size (or data length), the window size from 16 up to 1024 which were the indices of 2 were tried, and 512 was the most proper length when taking the time delay into account. The last one is the classification methods, several methods were adopted: amplitude, ratio, Least Squares. The method of amplitude gives better results than the other two.

The measurement of the horse was also a very good try, a total of five Nanotrak sensors were used, and a car was driven parallel to the horse and a camera was used to capture the motions of the horse. The combination of animal science and the modern technology will be the trend for this kind of research. The work of this project should not be a show-stopper, more efforts have to be made to automatic determine the gaits and automatic position the horse. Since the horse trotting match is very famous in Sweden, any breakthrough in the equine study will bring many economical benefits to this market.

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