WIRELESS KNEE JOINT ANGLE MEASUREMENT SYSTEM USING GYROSCOPE

SUKHAIRI BIN SUDIN

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DEDICATION

To my late father Sudin Bahari, my mother Kalsom Kadir and all my family's member, thank you so much for the support and attention to me. Your son and brother are so proud to have you. This is not going to be my last steps.

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ABSTRACT

Sensors are the eyes of control enabling one to see what is going on. Joint movement measurement system is a type of sensor to give the feedback measurement such angular displacement, angular velocity and angular acceleration. The measurements should be accurate and repeatability in order to get good controller's performance. This project is concerned on the design and development of wireless joint movement measurement system specifically for Spinal Cord Injury (SCI) patient by using Functional Electrical Stimulation (FES) assisted activities such as cycling. FES is used to activate the paralyzed muscle by giving appropriate electrical signal through electrodes. Aims of this project are to create portable, wearable and wireless knee joint angle measurement system. To meet the desired aim if this project, practical and compact design technique are emphasized in order to create a wearable and usable product. The design of knee guard should be portable, flexible and at the same time comfortable while still giving a reasonably good grip to avoid misalignment of sensor after a few set of movement occur. Two gyroscope sensors are installed on the knee guard which covers thigh and shank part. Gyroscope provides the orientation of two axes and this orientation will determine the elevated position of thigh and shank. Technique of comparison of the position between thigh and shank, provided by both gyroscopes will generate angles at knee joint. This wireless based system will be helped to reduce the complexity of wired sensor as well as user-friendly and portable measuring system. Wireless communication using ZigBee protocol with two Xbee devices will be used to transfer data from the sensory unit to the computer controlled system. In sum, with using wireless based system, the movement limitation barrier is no longer an issue to the user. This device will be developed as a new measuring technique of joint angle and will be one of the contributing factors in Rehabilitation Engineering for patients with SCI.

ABSTRAK

Sensor adalah mata kepada sistem kawalan yang membolehkan ia mengetahui apa yang sedang berlaku. Sistem pengukuran pergerakan sendi ialah sejenis sensor untuk mengukur sesaran sudut, halaju sudut dan pecutan sudut. Pengukuran haruslah menpunyai ketepatan dan kejituan yang tinggi untuk mendapatkan prestasi pengawalan yang baik. Projek ini berkisarkan merekabentuk sistem pengukuran pergerakan sendi tanpa wayar khusus untuk pesakit yang mengalami kecederaan saraf tunjang (SCI) yang Stimulasi Berfungsi Elektrik (FES) sebagai bantuan untuk menjalankan aktiviti seperti berbasikal. FES digunakan untuk mengaktifkan otot yang lumpuh dengan memberi isyarat elektrik yang sesuai melalui elektrod. Matlamat projek ini adalah untuk mewujudkan sistem pengukuran sudut lutut tanpa wayar. Untuk menjayakan matlamat projek ini, reka bentuk praktikal ditekankan untuk mencipta produk yang sesuai dan boleh digunakan. Reka bentuk sistem pengukur sudut lutut tanpa wayar seharusnya mudah alih, fleksibel, selesa dan pada masa yang sama memberikan cengkaman yang agak baik untuk mengelakkan salah jajaran sensor selepas beberapa set pergerakan berlaku. Dua sensor giroskop telah dipasang di pengawal lutut yang meliputi bahagian paha dan betis. Giroskop menyediakan orientasi dua paksi dan orientasi ini akan menentukan kedudukan paha dan betis. Sudut pada lutut ditentukan dengan melakukan pembandingan sudut pergerakan antara giroskop pada paha dan betis. Sistem ini berasaskan tanpa wayar dimana ia mengurangkan kerumitan pendawaian. Komunikasi tanpa wayar menggunakan protokol ZigBee dengan dua peranti Xbee akan digunakan untuk memindahkan data dari unit deria untuk sistem kawalan. Kesimpulannya, dengan menggunakan sistem berasaskan tanpa wayar, halangan pergerakan bukan lagi satu isu kepada pengguna. Peranti ini akan dibangunkan sebagai satu teknik pengukur sudut menjadi salah satu faktor yang menyumbang dalam bidang Kejuruteraan Pemulihan untuk pesakit dengan SCI.

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CHAPTER 1

INTRODUCTION

1.1 Preamble

Sensor is the most important device in closed-loop system that functioned to measure and produce a feedback to complete a cycle of closed-loop system. Mostly, sensors operate and produce analog signal as it output. The big issue that related to all sensors is it accuracy in real time application including lost in communication between sensors and control system. There are many types of sensors with different function and measuring variable and one of them is sensor to measure angle. In Body Sensor Network (BSN) field for medical purpose, body joint angle measurement system is quite important and useful for continuous monitoring in rehabilitation activities especially for Spinal Cord Injury (SCI) patients[1].

Body joint angle measurement system is sensory type systems that provide information about angle movement of body joint. It is usually used at knee and arm joint to monitor the movement while patients do some exercises. This very important and helpful to the therapists and physicians in order to see the effectiveness of rehabilitations training[1-3].

Rehabilitations training and exercise is important for SCI patients in order to keep them healthy while avoiding suffers from other diseases like obesity and diabetes[4]. In order to do rehabilitations training, patients need to keep their lower limb abdomen functioned and for SCI patients, they cannot keep their function without help from artificial device such as Functional Electrical Stimulator (FES)[5].

Gait and cycling were the most popular rehabilitations training for SCI patients. In cycling, FES is used to generate a suitable stimulation pattern as contraction to muscle to keep cycling rhythm to make it continuous[6]. The important of joint angle measurement system here is to give a feedback to FES module for further action to make it continuous cycling.

1.2 Spinal Cord Injury (SCI)

Human is the creature with vertebrate that build from the structure of spine that including spinal column and spinal cord. Spine is a block of bone that sits on top of others that link each other by ligament. These links of spine have hole in the centre that call as spinal canal that makes the tube of nervous tissue that known as spinal cord completely surrounded. Spinal cord carries signal and massage from brain to whole body like muscle to make them work[7].

Spinal cord injuries (SCI) are the damage to the cord either it totally or partially damage that affected the nerves ability to carry impulses from brain to muscle or vice versa. Total damage to cord will cause no nerve transmissions can past the site of the injury and this will shut all the sensation and movement capacity below the level of the injury cord. In most cases, damage to the spinal cord are partial and there still have a part of nerve transmission remain that leave patients some sensation or movement capacity below the level of the cord injury[8].

Normally the injuries to the spinal cord result from trauma that can be caused by vehicles accident, interpersonal violence, falls and sport injuries. Vehicles accident is the largest factors that drive to the traumatic SCI with 46% from all causes[9]. Some injuries to the spinal cord are non-traumatic which it result from tumor, cancer, arthritis, blood vessel problems or spinal infection. Non-traumatic cause is slow and cumulative act to damage but by the end it will come to the same SCI result[8].

Structurally spinal cord composed from 31 parts of spinal column that can be divided into 5 different parts: 8 part of Cervical or neck (C1-C8), 12 part of Thoracic or dorsal (T1-T12), 5 part of Lumbar or lower back (L1-L5), 5 part of Sacral or buttock (S1-S5) and 1 Coccyx or tail bone which very small at the bottom end. These structured are illustrated in Figure 1.1, which each level of spinal column have its own nerves function. If the spinal cord injury occurs at certain level from this part it will affect all the nerves below that damage point[7].

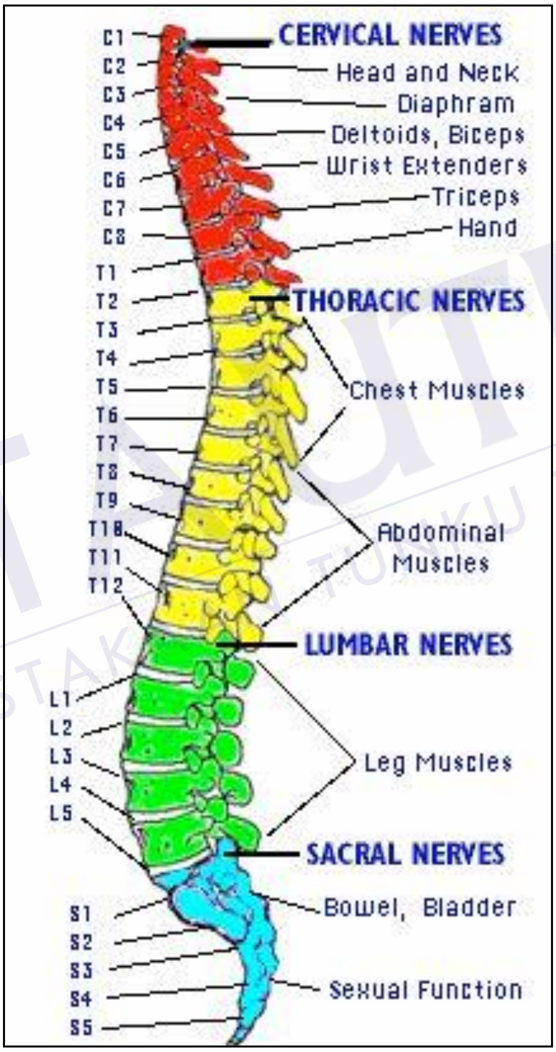

Figure 1.1: Spinal cord structure and its damage area[7].

Basically the damage of the spinal cord will cause the patients experience quadriplegia or paraplegia. Quadriplegia is lost of sensation and movement ability of all legs and hands and this happened due to damage at T1 and above. For spinal cord damage from T1 and below, it will drive to paraplegia which means patients will lost their sensation and movement ability for both their left and right legs. America Spinal Injury Association (ASIA) classified that 49.2% from SCI patients experienced paraplegia with 27.9% of complete paraplegia and 21.3% incomplete paraplegia. Most common level of damage for paraplegia occurs at T12[10]. Due to damage of spinal cord not only legs and arms involved, Table 1.1 will explain the nerve at each part of spinal column that will be affected due to damage at that level.

Table 1.1: Nerves served to each spinals part.

Spinal part	Nerves served
CL-C6	Neck flexors
CL-TL	Neck extensors
C3,C4,C5	Suply diaphragm (mostly C4)
C5,C6	Shoulder movement raise arm (deltoid); flexion of elbow (biceps)
C6	externally rotates the arm
C6,C7	Extends elbow and wrist (triceps and wrist extensors); pronates wrist
C7,T1	Flaxes wrist, Supply small muscle of the hand
T1-T6	Intercostals and trunk above the waist
T7-L1	Abdominal muscles
L1,L2,L3,L4	Thigh flexion
L2-S1	Thigh abduction
L5,S1,S2	Extension of leg at the hip (gluteus maximus)
L2,L3,L4	Extension of leg at knee (quadriceps femoris)
L4,L5,S1,S2	Flexion of leg at the knee (hamstrings)
L4,L5,S1	Dorsiflexion of foot (tibialis anterior); Extension of toes L5
S1,S2	Plantar flexion of foot
L5,S1,S2	Flexion of toes

1.3 Functional Electrical Stimulator(FES)

Damage that produce by SCI, mostly occurs above the level of the motoneurons to the lower limb that remains the function of the lower limb muscle and their motoneurons. Functional electrical stimulator (FES) that was developed about 30 years ago as a technique to restore the motor function for the SCI patients[11, 12].

This technique that developed by Moe before Kralj improved it by using low levels of electrical pulse to stimulate the peripheral nervous in skeletal muscle[12].

Stimulator electrode was patch directly on the human skin above the target muscle. In order to make shank extend, FES will apply to quadriceps muscle that located on upper thigh while for opposite direction FES will apply at lower part of thigh to interact with hamstring muscle. It was necessary to scrub skin before electrode patched to the skin to minimize the skin-electrode impedance. Electrical pulse that contraction to muscle will cause quadriceps and hamstring muscle fatigue and this will reduce the FES effectiveness[13]. Figure 1.2 illustrated the stimulator patched on the thigh for contraction with quadriceps muscle.

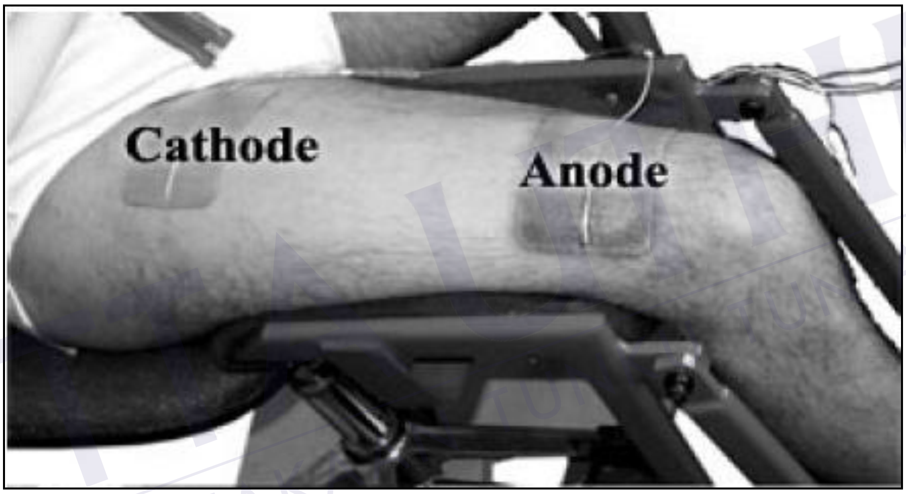

Figure 1.2: Stimulator electrode on thigh[5].

FES used to send bursts of charge pulse to skeletal muscle in order to activate the motoneurons synchronously. Minimum frequency that needed to create a contraction to skeletal muscle like quadriceps and hamstring is around 20Hz to 25Hz. This minimum frequency will only give a smooth contraction. In order to move the leg, a higher frequency must apply to get the strong contraction. In many cases, FES frequency has been used between 35Hz to 50Hz of range. However, using high FES frequency will contribute to muscle fatigue more rapidly from normal contraction[5].

1.4 Body angle measurement

Angle is one of the important parts in geometry which commonly measured in degrees or radians unit. Measurement of angle in geometry subjected to trigonometric function. Degrees are an artificial unit that easily to interpret and shows to other but it's not related to trigonometric function like radians that more convenience and always used in calculation.

Body angle measurements always refer to an angle at one of human body joint that affected by movement of two body abdomen linked by that joint. In medical field, human body angle measurement normally done by physiotherapist and one the measuring device used is goniometer[14].

Mostly existing joint angle measurement system is suitable to use in laboratory and require time to setup while it's a bit expensive[2]. This will create a gap for consumer to use it by their own at home with self exercise. It's also come along with such amount of cable connected within reader and controller and it will create a barrier in user movement. Currently system will make user less comfort since it not portable with heavy and large size.

1.5 Aims and objective of the project

The aim of this project is to develop a wireless joint angle movement measurement system for human body joint especially for paraplegic patients due to SCI. In order to achieve this aim, the objectives are formulated as follows:-

i. To investigate on the existing measurement system of joint angle.
ii. To develop a portable measuring system that can be used as feedback.
iii. To develop a wireless based measurement system to minimize the wiring complexity.

1.6 Thesis outline

Thesis organization has shown the sequence and step to development of wireless knee joint angle measurement system. This thesis classified into five chapters with follows outline:

First chapter describes on the research induction. The introduction is describing what this project is all about. Aside from that, there are also definition of proposed objectives and scopes for this project, deciding the methods to conduct the study and developing the plan of the project.

Chapter II deals with the literature review of the project. It describes the definition, concepts, principles and tool used in this project. Literature review provides a background of this project and also gives guidelines and direction in this research.

Chapter III deals with a research methodology. This chapter will describe the detailed method that has been used to conduct this research. There are also some explanations on how knee angle has been measured and calculated.

Chapter IV is for the result and discussion. This chapter will highlight the overall of the research outcomes with the results of the neural network. The results consist of graph of angle data from some kind of experiment with different condition. It's also displayed analysis about the angle error after comparison.

Chapter V consists of conclusion for this study. It also describe the problem arises and recommendations for the future research.

1.7 List of publication

Technical paper that produced from this research, which it has been accepted or submitted is listed as follows:-

1.7.1 Conference paper

1. S. Sudin and B.S.K.K. Ibrahim, *Design and development of wireless joint movement measurement system, in National Conference on Electrical and Electronic Engineering (NCEEE 2012).* 2012, pp.136-138: Johor, Malaysia. (published)
2. S. Sudin, B.S.K.K. Ibrahim, D. Hanafi and M.M.A. Jamil, *Knee joint angle measurement system using gyroscope, in IEEE EMBS Conference on Biomedical Engineering & Science (IECBES 2012), 2012. Langkawi, Malaysia.* (submitted)

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are few types of system that have been developed by other researchers. Each system has its own device and method which contains advantages and disadvantages. The purpose of the system is to produce a system that can be used to measure at human body and can use this measurement output as feedback to other control system. There are also many sensors that can use for angle measurement purpose and one of them is gyroscopes which provide data about angular rate. Type of communication between sensors and controller also a main issue that will affect the effectiveness of the system.

2.2 Body angle measurement

According to Previdi and Carpanzano (2003), the most important problem in FES control is the development of neuroprostheses to SCI patients like paraplegic which means to control the electrical pulse that provide to muscle to make it work. Joint angle is important that can use as feedback to the closed-loop system for scheduling the FES control. For example to control the leg swinging, feedback about knee joint angle is required to schedule the time need to contraction muscle with pulse or not[15].

Watanabe and Saito (2011) used body joint angle measurement compared to 3D motion measurement to show the characteristic of human gait. Sensors were placed at various body parts like feet, shank, thigh and back to measure hip, knee and ankle joint angle in short distance while subject walk[2].

Dejnabadi. et al. (2005) provided kinematic data from gait analysis to evaluate and qualifying the effect of surgical intervention from body joint angle and focused to knee joint angle. Based this information, it make clinicians easily choose a suitable treatments to patient. Accelerometer and gyroscope have been chosen as measuring sensors that mount on body like illustrated by figure 2.1. These will provide data about angular acceleration and angular velocity[14].

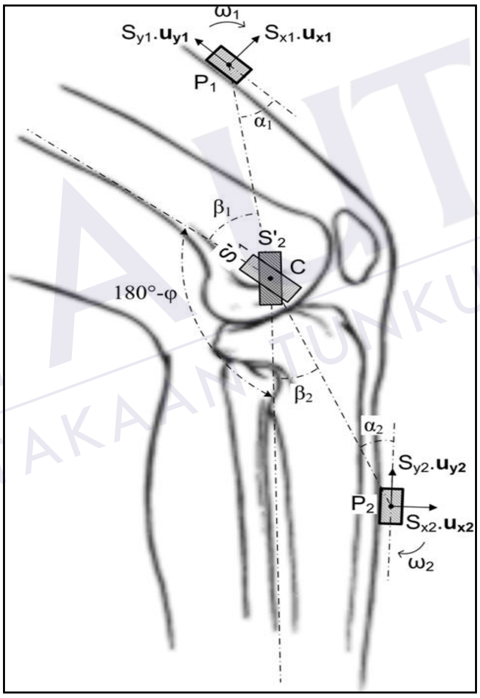

Figure 2.1: Sensor placed on thigh and shank with virtual sensor as center of rotation[14].

Bakshi, S. et al. (2011) compared between various techniques that previously used in human body joint angle movement measurement that state in table 2.1 before come out to use Inertial Measurement Unit (IMU) which consists gyroscope and accelerometer. This used to measure knee angle by placed IMU at thigh and shank to get different between this two units of sensors in order to calculate knee angle.

Table 2.1: Previous technique used before to measure body joint angle

Previous technique	Comment
Measuring joint flexion based on resistive flex-sensor along with extended Kalman filter (Bakhshi and Mahoor, 2011)	This method produce about 6.92˚ error rate for knee joint angle measurement
Using conductive fiber that placed at wearable and comfortable garment to monitor long term body movement. (Gibbs and Harry, 2004)	Fiber tensions and resistance alterations produce inconsistence sensor output
Measuring hand joint angle using 20 Hall Effect sensor that mount an the glove (Dipietro, et al. 2003)	This method comes out with 6.17˚ of error rate while measuring an angle.
Monitoring knee joint angle using MARG sensor that include magnetic, angular rate and gravity. (Kobashi et al. 2008)	This gives a high accuracy but it not suitable to use as home application because it need high cost and large size.

2.3 Gyroscope

The idea of Gyroscope was discovered by Johann Bohnenberger in early 1800s. Jean Bernard Leon Foucault (1826-64), the scientist from French was the first person who used the name of gyroscope. It combination two Greek words “gyros” means rotation and “skopeein” means to see. At the beginning, gyroscopes were modeled only to measure the rate of the rotation of an object. Earliest model of gyroscope have been illustrated in figure 2.2[16].

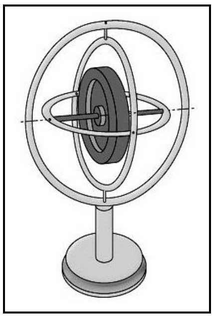

Figure 2.2: Earliest model of Gyroscope

Due to large size and high cost of conventional gyroscopes, Micro-Electro-Mechanical System (MEMS) Gyroscope was invented using conventional gyroscopes work concept which produced much cheaper and very small size. MEMS-Gyroscope basically does a measurement for angular rate. Chien-Yu et al. state that Friedland and Hutton proposed equation for the direct angle measurements for vibratory gyroscope in 1978. However, the applicability of these equations was limited only to gyroscope with “ideal” dynamics[17]. Piyabongkarn, et al. (2005) was design and developed a different way of an absolute angle measurement by using MEMS vibratory gyroscope[18].

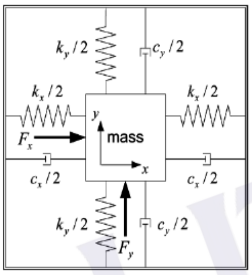

Figure 2.3 : Schematic diagram of vibratory gyroscope[18].

The basic vibrating gyroscope design like illustrated in figure 2.3 allowed mass to move both in y and x direction by elastic members. Originally function of gyroscope is to measure angular rate and the motion of the system represented by equation (1) and (2):

$$\ddot{x} = -\omega_x^2 x - \frac{c_x}{m}\dot{x} + x\dot{\theta}^2 + y\ddot{\theta} + 2\dot{\theta}\dot{y} + \frac{\dot{F}_x}{m} \qquad (2.1)$$

$$\ddot{y} = -\omega_y^2 y - \frac{c_y}{m}\dot{y} + y\dot{\theta}^2 - x\ddot{\theta} - 2\dot{\theta}\dot{x} + \frac{\dot{F}_y}{m} \qquad (2.2)$$

where θ represent gyroscope rotation around the z axis while F_x and F_y represent total force that applied to mass in x and y direction with $\omega_x^2 = k_x/m$, $\omega_y^2 = k_y/m$, $c_x = 2m\xi_x\omega_x$, $c_x = 2m\xi_x\omega_x$ and external angular velocity $\dot{\theta} = \Omega$ [18].

MEMS gyroscope have many advantages from conventional gyroscope from size, weight and cost, but it usually produce some large drift. Xun Sheng, J., et. al (2006) used combination of median filtering, wavelet decomposition and Adaptive Kalman filter in order to reduce drift in MEMS gyroscope. This combination method reduced gyroscope drift from originally 80.42 deg/h to 18.31 deg/h.[19].

2.3.1 Median filter

Median filter is one of the nonlinear digital filtering techniques. This filter mostly used in image processing to remove noise in order to improve the result but it's also can be use in signal processing. Xun Sheng, J., et. al (2006) used this median filtering to reduce noise in gyroscope signal by applying equation as followed:-

$$y_{m+1} = median\left(\frac{x_1 + x_2 + \cdots + x_m}{m} + x_{m+1} + \frac{x_{m+2} + x_{m+3} + \cdots + x_{2m+1}}{m}\right) \quad (2.3)$$

where median$(*)$ is a median function. Data window 2m+1need to select carefully in order to reduce only noise and kept the useful signal for use. Usually m was selected between 3 to 5 data. Figure 2.4 illustrated the result of median filtering used to reduce drift in gyroscope by Xun Sheng, J., *et. al* (2006). This show the effectiveness of median filter which noise from original signal in figure 2.4(a) eliminated and the useful signal only pass the filter like in figure 2.4(b)[19].

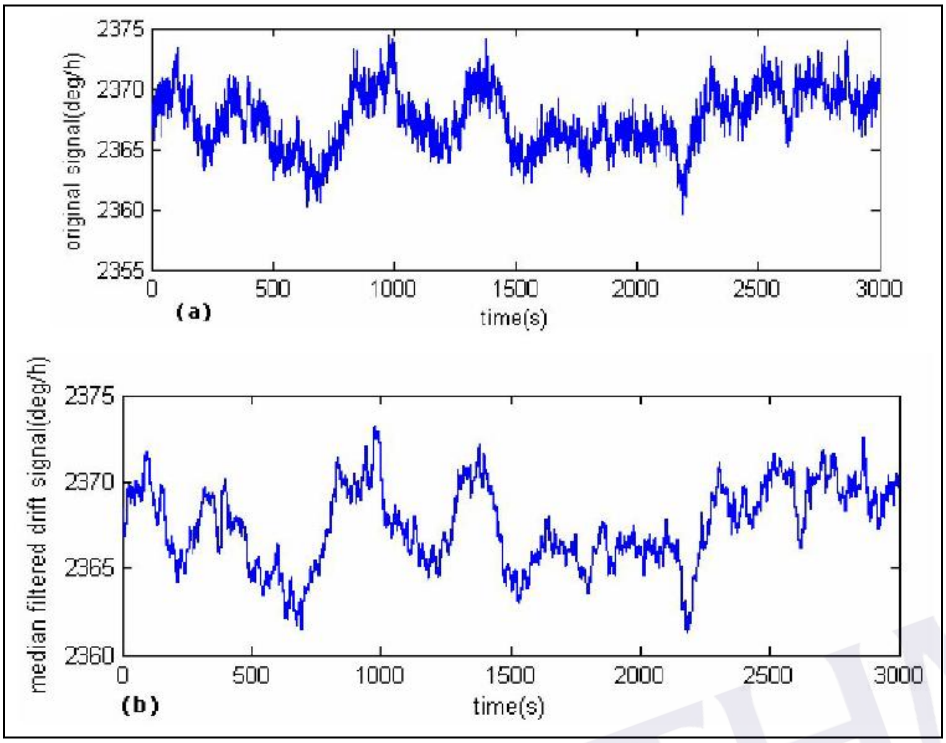

Figure 2.4: Comparison unfiltered signal and filtered signal using median filter[19].

2.3.2 Kalman filter

Linear quadratic estimation or most known as Kalman filter was named according to Rudolf E. Kalman around early 1960. This Kalman filter was firstly described and partially developed in technical papers by Swerling (1958), Kalman (1960) and Kalman and Bucy (1961). First idea about Kalman filter appeared when Kalman saw the trajectory estimation problem by the time he visit NASA Research Centre that running Apollo program.

Kalman filter work on algorithm which more precise as statistically optimal estimation algorithm that used a series of measurements observed over time and produces estimates of unknown variable to encounter noise and other inaccuracies to make more precise measurement. Kalman filter is designed to be the best linear estimator with Gaussian noise but it still can be used for non Gaussian noise system. Kalman filter is originally not suitable to use for non linear estimation state but after

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