ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

TEXTILE BASED SENSING SYSTEM FOR LEG MOTION MONITORING

M.Sc. THESIS

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Computer Engineering Programme

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To my family,

FOREWORD

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ABBREVIATIONS

ARSLO	: Always Read Send Last One
DIP	: Dual In-line Package
E-textile	: Electronic Textile
IMU	: Inertial Measurement Unit
I/0	: Input/Output
I2C	: Inter Integrated Circuit
MISO	: Master In-Slave Out
MOSI	: Master Out-Slave In
MC	: Microcontroller
NPM	: Node Package Manager
PSNR	: Peak Signal-to-Noise Ratio
RAS	: Read And Send
RX	: Receiver
SBPN	: Send Before Prepare Next
SCLK	: Serial Clock
SCL	: Serial Clock Line
SDA	: Serial Data Line
SPI	: Serial Peripheral Interface
SS, SS_n	: Slave Select
SMD	: Surface-Mounted Device
3D	: Three-Dimensional
TX	: Transmitter
2D	: Two-Dimensional
UART	: Universal Asynchronous Receiver-Transmitter
Wi-Fi	: Wireless Fidelity

SYMBOLS

R	**:** Resistance
C	**:** Capacitance
θ	**:** Angle
k	**:** Dielectric constant
ε	**:** Permittivity
A	**:** Area
d	**:** Seperation

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TEXTILE BASED SENSING SYSTEM FOR LEG MOTION MONITORING

SUMMARY

In recent years, electronic products have become integrated with textile products with the production of chips having small size, being cheap and needing low energy need. Thanks to research in the field of textile, e-textile was born from the electrical response of textile product to the physical environments. With the multidisciplinary studies carried out in the fields of electronics, computers, control, and textiles, these electronic textiles are now being transformed into products used by consumers. It is possible to see electronic textiles in different fields such as sports training, robotics, health imaging, body motion analysis, etc.

The textile based sensors have four different types: resistive, capacitive, optical and solar. Capacitive and resistive sensors can be used in motion capture systems. Resistive sensors have disadvantages such as low linearity, drift problem and high response time, whereas capacitive sensors have good features such as high linearity, low response time and high resolution. Although capacitive sensors have many advantages, noise is generated in the measurement due to the distance between the sensor and the measuring device.

Motion capture systems, rely on three different techniques: optical, magnetic and mechanical. Optical motion detection systems operate according to the principle of extracting the skeletal structure of humans by using image processing methods. However, this system has many disadvantages such as the ability to measure in a specific area and require high processing cost in the calculation units. Magnetic motion capture systems are based on the principle of finding joint angles by magnetic sensors placed on the body. Unlike optical motion capture systems, these systems do not require a specific area of operation and high processing cost. However, these systems are affected by objects such as metals and circuits that will create an electromagnetic effect since these systems use magnetic sensors. In mechanical systems, joint angles are determined by sensors placed on the joints. These systems are not affected by the magnetic field and are not required to be used in a specific area. Since the sensor data is equal to the joint data, there is no calculation load. However, special clothing equipped with sensors should be used in such motion capture systems. The cost of this special clothing is the biggest drawback of such motion capture systems.

This thesis deals with increasing the measurement quality by reducing the noise due to distance in the measurement of textile based capacitive sensors, creating a prototype with integration to textiles, and developing a motion monitoring system that will receive and store data from the prototype. This thesis focuses on the problem of noise in the measurement results due to the distance which is the biggest problem of capacitive sensors. This makes it possible to make use of the advantage of the capacitive sensors.

The electrical system consists of textile based capacitive sensors, microcontrollers, bus, a transmitter, a mobile phone, and a battery. Microcontrollers are placed closest to the sensor. Thus, the noise caused by the distance is minimized. The microcontrollers are connected to the transmitter via bus. The transmitter transmits both requests and power to microcontrollers via the bus. The microcontroller measures and transmits them to the transmitter via the same line. Since the I2C connection is used in the system, the four-wire bus is created for the power and data line. The transmitter transmits the received data to the mobile phone via a Bluetooth connection. The entire system is fed with the battery connected to the transmitter.

An Android application has been developed to receive data over a mobile device. The application shows the data to the user and sends them to the server. The server saves the data to the database and also sends it to other web clients instantly. With the prepared web front end, the measurement results are displayed instantaneously. In addition, historical measurement data is displayed on the web front end. Data communication between the web service, phone and web clients is made by socket programming to be fast and instantaneous.

The sensor used in the system is a textile based flexible capacitive sensor. This sensor consists of two conductive fabrics and the dielectric material. The sensor acts as a parallel plate capacitor. The increase in the length of the sensor increases the electrode area of the sensor. This change also increases the capacitance of the sensor.

In the textile integration of the design, the sensor is placed on the knee using the knee bracket. The microcontrollers are also located near the sensor and connected to the sensor. The bus to be established between the transmitters and the microcontrollers is made of conductive yarns. These conductive yarns are sewn on the fabric strip. In this way, the prototype will be tested under similar conditions to the commercial product to be prepared in the future.

In the experiments with the prototype, the test object walks first, then stops, and finally makes a squatting motion. During walking, all characteristics of phases of gait can be extracted from the measurement data. The theoretical and practical results are similar when compared. At the same time, when the signals from both knees are compared, there is a phase difference between the signals parallel to the walking. In the motionless phase, there is no change in the signals. During the squatting motion, both signals move simultaneously, and there is no phase difference between them. When all stages are examined, it is verified the system successfully performs the lower limb motion capturing.

The contribution of thesis is that we minimized the noise generated in the measurement results due to the distance which is the biggest problem of capacitive sensors. In addition, a system was prepared to collect data from users and send end-to-end data. Since the system is designed with low-priced materials, it will be suitable to be commercialized. In following studies, a follow-up system for patients in the health care domain, physiotherapy applications, and sports applications etc. can be developed. This thesis will also contribute to science as it opens new fields of study.

BACAK HAREKETİ İZLEME İÇİN
TEKSTİL TABANLI ALGILAMA SİSTEMİ

ÖZET

Günümüz teknolojisinde, ufak boyutlu, ucuz ve düşük enerji ihtiyacı olan çiplerin üretilmesi ile elektronik ürünler tekstil ürünleri ile entegre olmaya başlamıştır. Tekstil alanında yapılan çalışmalar ile tekstil ürünlerinin dış ortamlara karşı vermiş olduğu elektriksel tepkilerden e-tekstiller ortaya çıkmıştır. Elektronik, bilgisayar, kontrol ve tekstil alanlarında yapılan multidisipliner çalışmalar ile de artık bu elektronik tekstiller kullanıcıların kullanabileceği sistemlere dönüşmeye başlamıştır. Elektronik tekstilleri spor eğitimi, robotik, sağlık görüntülemesi, vücut hareket analizi gibi farklı alanlardaki uygulamalarda görmek mümkündür.

Tekstil yapılı sensörlerin rezistif, kapasitif, optik ve solar olarak dört farklı çeşidi bulunmaktadır. Hareket yakalama sistemlerinde kapasitif ve rezistif sensörler kullanılabilmektedir. rezistif sensörlerin düşük lineerlik, drift problemi ve yüksek tepki süresi gibi dezavantajları bulunmaktadır, buna karşılık kapasitif sensörler ise yüksek lineerlik, düşük tepki süresi ve yüksek çözünürlük gibi iyi özelliklere sahiptir. Kapasitif sensörlerin birçok avantajı bulunmasına rağmen, sensör ve ölçüm cihazı arasındaki mesafeden kaynaklı, ölçümde gürültü oluşmaktadır.

Hareket yakalama sistemleri ise optik, manyetik ve mekanik olmak üzere üç farklı tekniğe dayanmaktadır. Optik hareket sistemleri görüntü işleme yöntemleri kullanılarak kişilerin iskelet yapısının çıkartılması prensibine göre çalışmaktadır. Fakat bu sistemin belirli bir alanda ölçümleme yapabilmesi ve hesaplama birimlerinde de yüksek işlem gücü gerektirmesi gibi birçok dezavantajı bulunmaktadır. Manyetik hareket yakalama sistemleri ise vücuda yerleştirilen manyetik sensörler aracılığı ile eklem açılarının bulunması prensibine dayanmaktadır. Bu sistemde optik sistemlerin aksine, belirli bir alanda çalışma ve yüksek işlem gücü gerektirmemektedir. Fakat bu sistemler manyetik sensörler kullandığı için metal, elektronik devreler vb. elektromanyetik etki yaratacak nesnelerden etkilenmektedir. Mekanik sistemlerde ise eklemlerin üzerine yerleştirilen sensörler aracılığı ile eklem açıları belirlenmektedir. Bu sistemler, manyetik alandan etkilenmezler ve belirli bir alanda kullanılma zorunluluğu yoktur. Sensör verileri ise eklem verisine eşit olduğu için hesaplama yükü bulunmamaktadır. Buna rağmen, bu tarz hareket yakalama sistemlerinde sensörleri içeren özel kıyafetler kullanılmalıdır. Bu özel kıyafetlerin maliyeti bu tarz hareket yakalama sistemlerinin en büyük dezavantajıdır.

Bu tezde, tekstil tabanlı kapasitif sensörlerin ölçümünde mesafeye bağlı oluşan gürültünün azaltılarak ölçüm kalitesinin arttırılması, tekstile entegrasyonu olan bir prototip oluşturulması, donanım prototipinden verileri alacak, kullanıcıya gösterecek ve depolayacak hareket yakalama sisteminin oluşturulması konularını ele almaktadır. Bu tez kapasitif sensörlerin büyük problemi olan mesafeye bağlı olarak ölçümlerde oluşan gürültü problemine odaklanmaktadır. Bu sayede kapasitif sensörlerin avantajlarından yararlanmak mümkün olmaktadır.

Sistemin elektriksel tasarımı mikrodenetleyiciler, verici, iletim yolu, sensör, cep telefonu ve bataryadan oluşmaktadır. Mikrodenetleyiciler sensöre en yakın noktaya yerleştirilmiştir. Böylece mesafeye bağlı olarak oluşan gürültü en aza indirilmiştir. Mikrodenetleyiciler vericiye iletim yolu ile bağlıdır. Verici mikrodenetleyiciye bu yoldan hem isteklerini hem de güç aktarımı yapmaktadır. Mikrodenetleyici de vericiden gelen veri isteği için ölçüm yapar ve aynı hat üzerinden aktarır. Sistemde I2C bağlantısı kullanıldığı için de güç ve veri hattı için toplamda dört kablo iletim hattı oluşturulmuştur. Verici de aldığı verileri Bluetooth bağlantısı üzerinden mobil cihaza aktarmaktadır. Tasarlanan tüm sistem vericiye bağlanan batarya ile beslenmektedir.

Mikrodenetleyici ile kapasitans ölçümünde genellikle doldur-boşalt yöntemi kullanılmaktadır. Fakat sensörün kapasitans değeri düşük olduğu için, kapasitans dolma ve boşalma süreleri çok kısadır. Bu sürede zaman sabitini bulabilmek için yüzlerce megahertzlerlik bir mikrodenetleyiciye ihtiyaç duyulmaktaydı. Bu sebeple, kapasitans ölçümünde sistemde gerilim bölücü yöntemi kullanılmıştır. Sensörün kapasitans verisi mikro işlemcinin iç kapasitans değerinden yararlanarak bulunmaktadır.

Verici cihazı da bir mikro denetleyici olduğu için veri transferi için mikrodenetleyiciler arası haberleşme yöntemleri kullanılması gerekmektedir. Verici ve mikrodenetleyicilerimizin desteklediği haberleşme protokolleri UART, SPI ve I2C'dir. UART ile birebir iletişim yapıldığı için ve her yeni mikrodenetleyici eklemek için ek iki adet hat gerekli olduğu için bu protokol sistem için çok uygun değildir. SPI birçok iyi özelliği olmasına rağmen, her çip için ayrı çip seçim portuna ihtiyaç duyduğu için bu protokolde sistem için çok uygun değildir. İki adet kablo ile onlarca cihazı konuşturabilmesi ve kolay kurum gibi özellikleri nedeniyle I2C'nin sistemde kullanılması uygun görülmüştür.

Mobil cihaz üzerinden veri alınabilmesi için bir Android uygulaması geliştirilmiştir. Uygulama cihazdan aldığı veriyi hem kullanıcıya göstermekte hem de sunucuya aktarmaktadır. Server ise aldığı veriyi hem veritabanına kaydetmekte hem de anlık olarak diğer web istemcilere göndermektedir. Hazırlanan web önyüzü ile de ölçüm sonuçları anlık olarak görüntülenebilmektedir. Ek olarak geçmişe yönelik ölçüm verileri de web önyüzde görüntülenebilmektedir. Veri iletişiminin hızlı ve anlık olması adına web servis, telefon ve web istemcileri arasındaki yazılım soket programlama ile yapılmıştır.

Sistemde kullanılan sensör tekstil tabanlı esnek kapasitif sensördür. Bu sensör, iki adet iletken kumaş ve bir adet dielektrik malzemeden oluşmaktadır. Sensör paralel levhalı kapasitör gibi davranmaktadır. Sensörün boyundaki değişim, sensörün elektrod alanını arttırmaktadır. Bu artışda sensörün kapasitansını arttırmaktadır.

Tasarımın tekstil entegrasyonunda, sensör dizlik kullanılarak diz üzerine yerleştirilmiştir. Mikrodenetleyiciler de sensöre en yakın noktaya yerleştirilmiş ve sensör bağlantısı yapılmıştır. Verici ve mikrodenetleyiciler arasında kurulacak olan iletim hattı iletken ipliklerden oluşturulmuştur. Bu iletken iplikler, kumaş şerit üzerine dikilmiştir. Bu sayede prototip ile gerçek üründe kullanılacak olan iletken ipliklerin testi de yapılmıştır.

Prototip ile yapılan ölçümde test objesi, önce yürümekte, daha sonra durmakta ve son olarak da çömelme hareketi yapmaktadır. Yürüme esnasında, ölçüm verisinden yürüyüş aşamalarının tüm özellikleri çıkartılabilmektedir. Teorik ve pratik sonuçlar karşılaştırıldığında benzerdir. Aynı zamanda her iki dizden toplanan sinyaller karşılaştırıldığında, yürüyüş hareketine paralel olarak, sinyaller arasında faz farkı bulunmaktadır. İkinci aşama olan durma anında da sinyallerde değişim olmamaktır. Son aşama olan çömelme hareketinde, her iki sinyal birbiri ile paralel şekilde hareket etmekte ve aralarında faz farkı olmamaktadır. Tüm aşamalar incelendiğinde sistem başarılı bir şekilde dizdeki hareket yakalama yapabildiği doğrulanmıştır.

Bu tez kapasitif sensörlerin büyük problemi olan mesafeye bağlı olarak ölçüm sonuçlarında oluşan gürültü problemini en az seviyeye indirmiştir. Ek olarak, kullanıcılardan veri toplayacak ve uçtan uca veri gönderebilecek bir sistem hazırlanmıştır. Sistem en uygun fiyatlı malzemeler kullanılarak tasarlandığı için ticarileşmeye de uygun olacaktır. Sonraki çalışmalarda bu yapılan çalışmalar kullanılarak, sağlık domaininde hastalar için takip sistemi, fizyoterapi uygulamaları, sporcu uygulamaları vb. geliştirilebilir. Bu tez aynı zamanda yeni çalışma alanları açtığı için bilime de önemli katkısı olacaktır.

1. INTRODUCTION

Nowadays, wearable technology products are developing rapidly through collaborations in textile, computer, electrical and electronics engineering. During this development, studies on getting the perception function of textile products continue intensively. With the textile-based sensing elements, the physiological parameters of the human body such as respiration rate [1], body temperature [2], heart rhythm [3] can be measured. In addition, joint movements of human body can also be observed with electronic textiles [4, 5].

Soft and stretchable sensors are preferred for joint motion sensing. In literature, resistive and capacitive sensors are the most preferred structures. Although it is easy to collect data with microcontrollers using resistive sensors, they have some disadvantages such as low linearity, drift problem, and high response time [6]. High response time is a convenient feature in real applications. Capacitive sensors have high linearity, low response time and high resolution [7]. Although capacitive sensors have many good characteristics the noise increases depending on the distance in measured values. For this reason, a coaxial cable must be used for measurements at far distances [8]. Textile integration of coaxial cables is more difficult than with conductive yarns, thus coaxial cable is avoided to be used on the textile.

In motion capture systems, it is possible to find many studies in the field of robotics [9], health [10], and games [11]. However, such systems can only be used by companies such as movie and gaming because of reasons such as installation difficulty, the necessity of wearing special clothes, cost and so on.

In this thesis, a system which is low cost, requires low energy consumption and in which data can be taken from the sensors independently of the distance, is investigated. Different algorithms and methods developed for system design will be mentioned and it will be explained which methods are preferred in the next stages of the system.

This thesis consists of five chapters. Detailed information is given in the next paragraphs.

In Chapter 2, the studies in the literature about the textile based sensors, motion detection systems, and gait analysis are examined. Next, information about the properties, types, and applications of these sensors are given. Later on, information is given about the motion capture systems and different types of sample applications. Afterwards, information about phases of gait is given.

In Chapter 3, information about textile based sensing system is given. This chapter consists of electrical system design, measuring sensor data, data transfer. In electrical system design, information about the designed system and its work is provided. In Section 3.2, information about capacitance measurement methods with microcontrollers and the methods used in the system is given. In Section 3.3, communication protocols between the transmitter and the microprocessor, and between the mobile device and the transmitter, and data flow methods to be used with the selected communication protocol are described.

In Chapter 4, the system implementation and textile integration are explained. In Section 4.1, the developed mobile application and the data flow from the electrical circuit to users are described. In Section 4.2, the web service is examined. In Section 4.3, the capacitive stretch sensor and the prototype are explained.

In Chapter 5, measurement results and theoretical information are described. This chapter contains software and hardware, experimental framework and results. In Section 5.1, the software and hardware used in experiments are explained. In Section 5.2 experimental frameworks for linearity of sensors and leg motion monitoring performance are examined. In Section 5.3 results on the effect of external capacitance, the linearity of system, the effect of number of samples for averaging, the effect of transmission method, and the leg motion monitoring performance are explained, and theoretical and measurement results are compared.

In Chapter 6, the studies, the experiments and results in the thesis are concluded, and information about future studies is given.

2. LITERATURE REVIEW

In this chapter, the related literature review for textile based sensors, motion capture systems, and gait analysis is present.

2.1 Textile Based Sensors

Thanks to technological developments, electronic circuits and batteries can be produced small enough to be placed in clothing. Thus, electronic circuits for different purposes have begun to be integrated into clothing. For wearable technologies, there are many different fields of research such as commercial [12], medicine [13], military [14], and aerospace [15] and the number of studies in these fields is increasing day by day. In parallel with the development of the electronic domain, there have been many developments in the field of textiles and electronic textiles (e-textiles) were born from the electrical response of different textile products given to the physical environment. E-textile is an effective way of adding sensing properties to the fabric. Fabrics can be used to detect different physical environment properties such as capacitive, resistive, optical and solar [16]. This section will give information about textile based resistive and capacitive sensors.

Textile based resistive sensors are frequently encountered in e-textile studies. Piezoresistive, thermoresistive, magnetoresistive, chemiresistive, and photoresistive based sensors are types of textile-based resistors and these sensors can detect different physical changes [17]. Piezoresistive sensors, one of the most widely used resistive sensors, operate on the principle of changing the resistance of the sensor material according to the changes in pressure or the length of the sensor [18]. Piezoresistive sensors can be used in many different applications such as motion monitoring [19], respiratory rate monitoring [20], pressure sensing [21]. Pan [21] developed the application of the recognition of different weight chess pieces using piezoresistive material. The chess pieces are weighed out and mapped according to their weights in this application. Although resistive sensors find solutions to many problems, there are some disadvantages such as low linearity, drift problem, and high response time [6].

Textile based capacitive sensors have high linearity, low response time and high-resolution properties [7]. Textile based capacitive sensors consist of dielectric material such as foam [22] and silicone elastomer [8] placed between two conductive fabric electrodes. Textile based capacitive sensors operate as parallel plate capacitor according to their structure. Recognition of sports activities, muscle activity measurements, and motion capture systems can be developed by using the principle of changing capacitance values due to the change in the size [8] and pressure [22, 23] of capacitive sensors.

As an example of the production stages of capacitive sensors, we can present the Silicone-Textile Composite Capacitive Strain Sensor used as a sensor in this thesis. Figure 2.1 shows the step by step production of the textile based capacitive sensor.

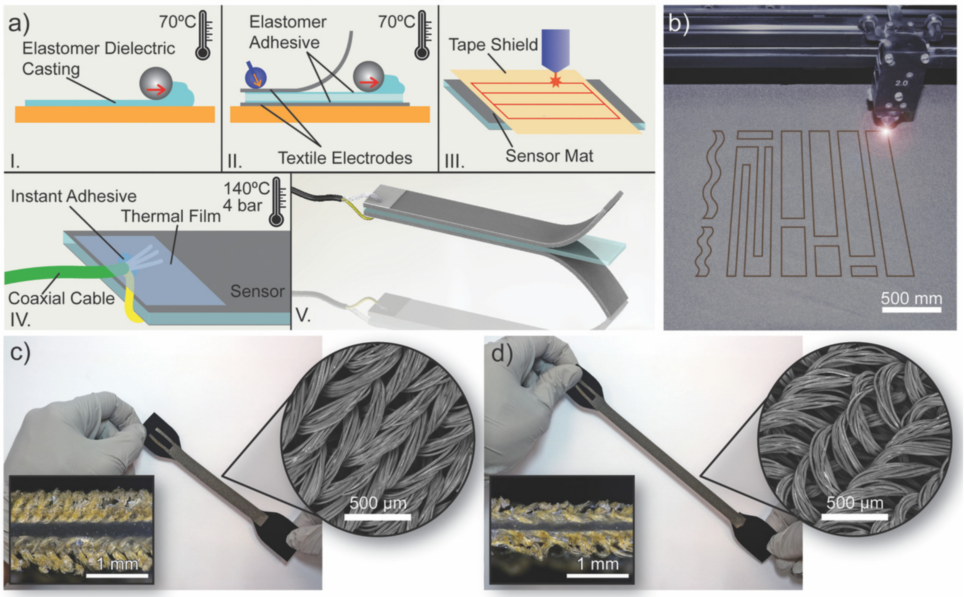


Figure 2.1 : Production of silicone-textile composite capacitive strain sensor. a) Schematic diagram of the fabrication process of the composite textile-silicone sensor: I. Dielectric silicone casting. II. Bonding of fabric electrodes via silicone elastomer casting. III. Placement of tape shield and laser cutting of sensor. IV. Creation of permanent electrical connection between coaxial cable and fabric electrode using instant adhesive and thermal film. V. 3D illustration of the sensor and material layers. b) Schematic diagram of arbitrary shaping of sensors via laser cutting. c,d) Photos of the sensor illustrating application of stretching at 0% and 100% strain; insets: cross-section views; popouts: surface views [8].

Figure 2.1 a) shows dielectric silicone casting, combining the fabric electrode with silicone material, laser cutting of the sensor, the connection of the conductive cables using thermal film and the 3D figure of the layers of the sensor. Figure 2.1 b) shows the laser cutting of sensor in different size and shape. Figure 2.1 c) and Figure 2.1 d) show the sensor changes in the 0% and 100% elongation conditions. Popouts have a surface view of sensor and insets have cross-section views. Since the capacitive sensor can be produced in any desired size and shape, sensors for different needs can be easily designed and manufactured [8].

2.2 Motion Capture Systems

Measurement of human body kinematic provides significant information in areas such as physiotherapy, virtual reality, sports performance monitoring. Therefore, motion capture systems appear in many areas such as robotics [9], health [10], and games [11]. In general, motion capture systems can be grouped under three headings: magnetic motion capture systems, mechanic motion capture systems, and optical motion capture systems [24].

Magnetic motion capture systems use electromagnetic sensors. Electromagnetic sensors give position and rotational information instantaneously. The data obtained from these sensors can be used to create the skeletal structure of people in real time. All these operations require low processing costs [24]. Figure 2.2 is an example of a magnetic motion capture system.

Figure 2.2 : Measuring system (Physilog) [25].

This system performs lower limb motion monitoring with 4 miniature gyroscopes. In this study, two gyroscopes were placed on both legs. Since the position of sensors on legs is constant, angle values can be calculated mathematically using the distance between sensors [25].

Mechanical motion capture systems require the use of special clothes. There are mechanical sensors that can capture motion data on these special clothes. This sensor data can be converted directly into the movement of the human body without the need of high processing cost [24]. Figure 2.3 shows special clothes for a motion capture system. This system uses mechanical sensors which are textile based resistive stretchable sensors. This system also used IMUs for position determination [26].

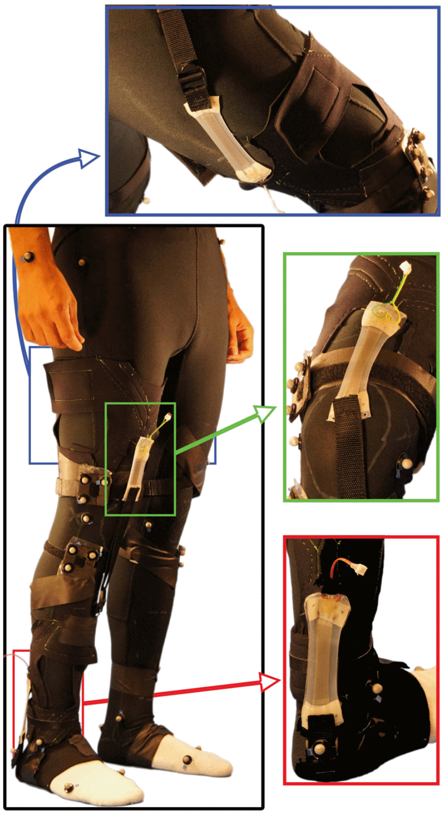


Figure 2.3 : Motion capture clothes [26].

Optical motion monitoring systems can be divided into marker-based motion monitoring systems and markerless motion monitoring systems. The images taken in the cameras are converted into the skeletal structure of the human with image processing processes. Movements can be captured from changes in the skeletal structure obtained from sequential images. All these processes require a high computational cost [24]. In Figure 2.4, the skeletal structure of the 2D image is converted to 3D figure. Herein, using the image processing, the joints of the people were determined, and the 3D human figure was extracted from the determined joints [27].

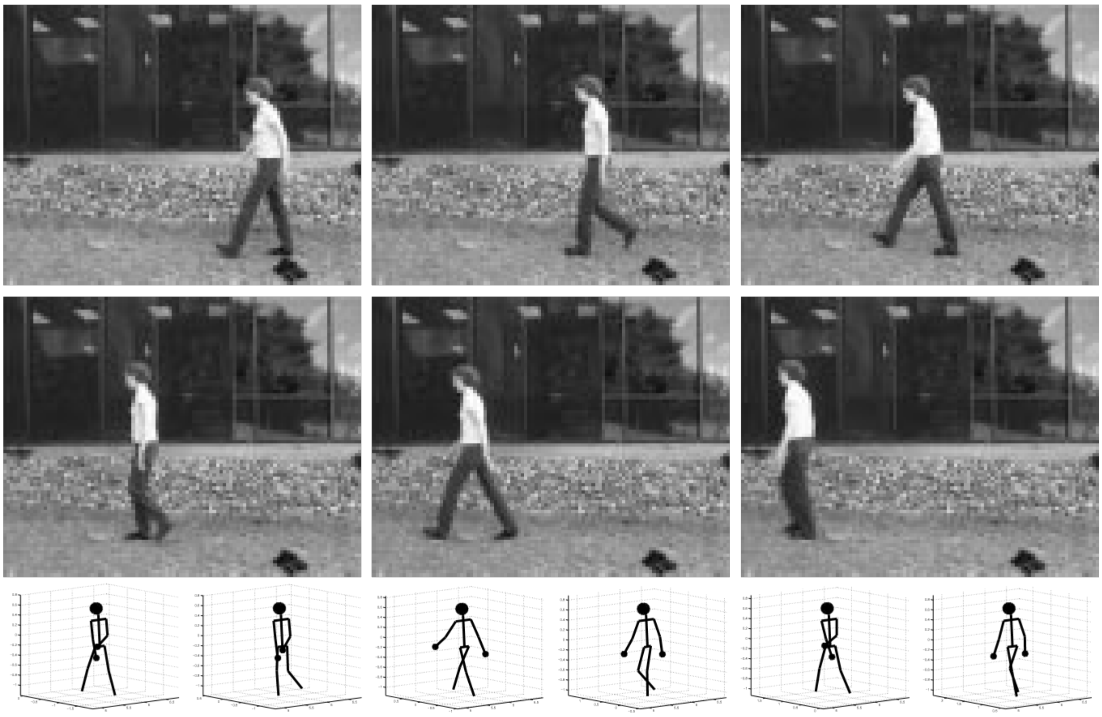
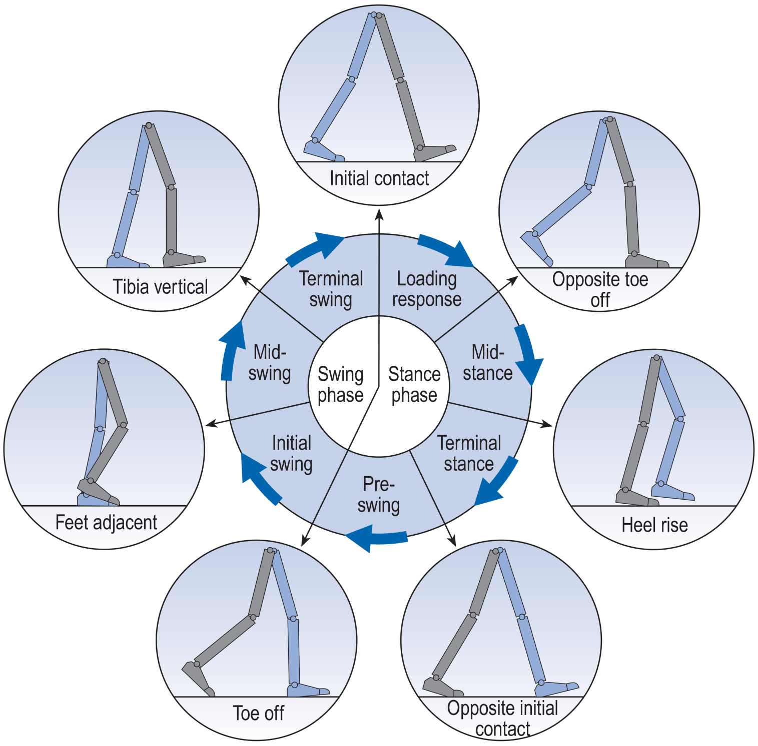


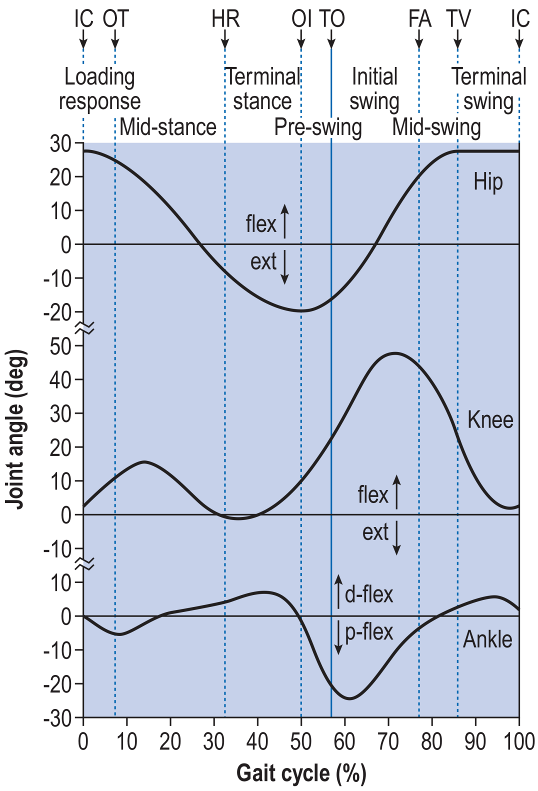
Figure 2.4 : Tracking of 3D human figures using 2D image motion [27].

2.3 Gait Analysis

Gait cycle consists of two main phases as stance and swing. Figure 2.5(a) shows the phase of gait and 2D simulation corresponding to these phases. The stance phase includes loading response, mid-stance, terminal stance, and pre-swing phases. The swing phase contains the initial swing phase, the mid-swing phase, and the terminal swing phases. In walking, these phases continue in sequence. From the loading response phase to the terminal swing phase, the entire motion is called gait cycle. Figure 2.5(b) shows a period of hip, knee and ankle angles from loading response to terminal swing. In the terminal stance and terminal swing phases, the leg is straight. Therefore, the angle is assumed as 0 degrees. The angle signal has a global maximum of 50 degrees in the initial swing phase and a local maximum of 20 degrees in the mid-stance phase [28]. Since the angle values and capacitance values are expected to be parallel, the measurement results and the chart of the angle values will be compared.



(a)



(b)

Figure 2.5 : Phases of gait. (a) Gait cycle. (b) Hip, knee and ankle angles on phases of gait [28].

3. TEXTILE BASED SENSING SYSTEM

In this chapter, electrical system design, measuring sensor data, and data transfer are explained.

3.1 Electrical System Design

The noise, which is one of the problems of capacitive sensors, is caused by the distance between the sensor and the measurement device and the noise signal disrupts the measurement quality. In this design, conductive yarns are used to facilitate textile integration between sensors and measuring devices. These conductive yarns produce additional capacitance with respect to their length and the distance between each other. When measuring in stationary systems, additional capacitance increases the sensor value by a constant. For example, 10 cm conductive yarns can produce an additional capacitance of 15 pF. However, in moving systems, the distance between the conductive yarns and the yarn lengths vary depending on the movement. The variable capacitance value in the conductive yarns between the sensor and the measuring device causes noise in the sensor measurements. Therefore, it is necessary to reduce the noise value by minimizing the distance between the measuring device and the sensor. Although this process is easy on single sensor systems, additional equipment is needed in systems with more than one sensor away from each other. In such systems, measurement devices can be added to the nearest possible location to the sensors to avoid noise.

This thesis presents a system which includes sensors with long distances, can measure the sensor values with the least impact from the noise, collect all data in a single point and collect in the data center via a mobile device. As shown in Figure 3.1, the system consists of textile based capacitive sensors, MicroControllers (MC), bus, transceiver, mobile phone, and battery.

Since the system would be on textile, it is necessary to reduce the battery capacity by minimizing the energy consumption. As the capacity of the batteries increases, their

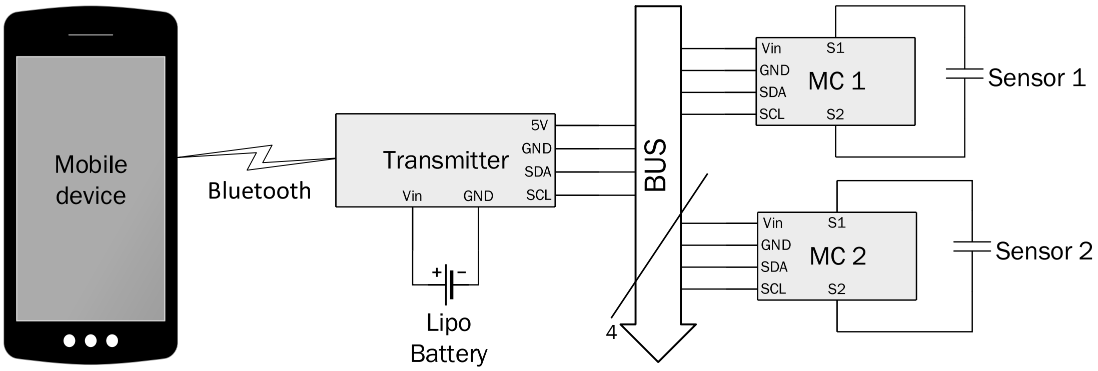


Figure 3.1 : Transmission and measurement design of capacitive sensors.

weight increases. The weight increase in the batteries also brings additional weight to the clothing. This weight reduces the comfort of clothing and disturbs users. For this reason, all the elements in the system are selected to meet the system requirements and consume minimum power at the same time. The electrical system is fed with a 3.7-Volt Lipo battery as in Figure 3.2. The lipo battery is connected to the transmitter, and the transmitter transmits energy to the microcontroller via the bus.

Figure 3.2 : 3.7 V Lipo battery [29].

Textile based capacitive strain sensors are used in this system. An example of a sensor is shown in Figure 3.3. The length and capacitance values of the capacitive strain sensors change linearly. Thus, capacitive change of the sensors due to movement in the joints represents joint movements. Two capacitive sensors are used in the system to get the values of motion data regarding both knees. In this way, the data from both knees can be received through these sensors.

Microcontrollers are located at the closest points to the sensors to reduce noise. Microcontrollers are used to measure and transmit sensor data to the transmitter. The microcontrollers convert the analog sensor data to digital so that the signal is less affected by the noise in the transmission line. At the point of measurement and

Figure 3.3 : Textile based capacitive strain sensor [8].

data transmission, the ATtiny85 microcontroller [30] is selected which has the lowest price, size, and energy consumption to meet the system requirements. Figure 3.4 shows the ATtiny85 microcontroller used in the system. In the selection of the microcontroller, attention is paid that the product has both Dual In-line Package (DIP) and Surface-Mounted Device (SMD) versions. Tests on the prototype are carried out with the DIP version of microcontrollers for easy removal and insertion. In the case of real product integration, SMD versions of microcontrollers are used to minimize material dimensions.

Figure 3.4 : ATtiny microcontroller [30].

The transmitter in the system serves as the main center of transmission of power. The transmitter also controls the data communication in the electrical system. The transmitter requests data from microprocessors in 20 ms period. After the data from the microprocessors are buffered in the transmitter, the transmitter sends these data to the mobile phone via Bluetooth. For this reason, the Bluno Beetle Arduino Controller is selected as a transmitter, because it is a small control card that can be integrated into textiles, has Bluetooth and wired data transfer capability. In addition, microcontrollers and transmitter can be programmed using common programming language because they have the same architecture. Thus, it will be able to produce faster results by focusing on a single programming language. Figure 3.5 shows the Bluno Beetle Arduino Controller.

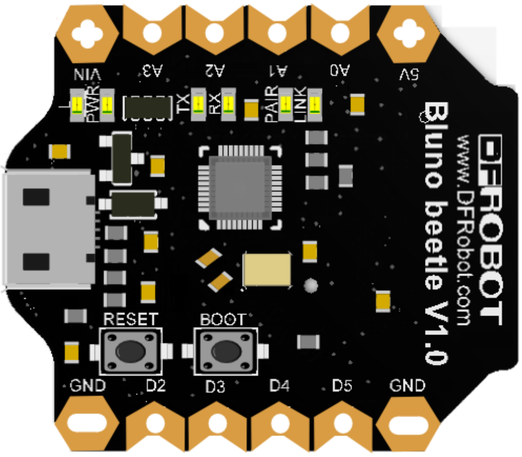


Figure 3.5 : Bluno Beetle Arduino Controller [31].

In the system, both communication and power transmissions are made through the bus structure. I2C protocol is preferred for data communication. A more detailed explanation will be given in Section 3.3. Since the I2C communication protocol is used on the system, the bus consists of two data lines and two power lines. Power lines transmit power to microcontrollers. With four parallel cables, power transmission and data communication are provided to all microcontrollers. Since data transmission will be digital, data will be less affected by noise. In the prototype, the bus will be formed using conductive yarns. In this way, the textile integration of the system is also tested. Figure 3.6 shows the bus created with conductive yarns.

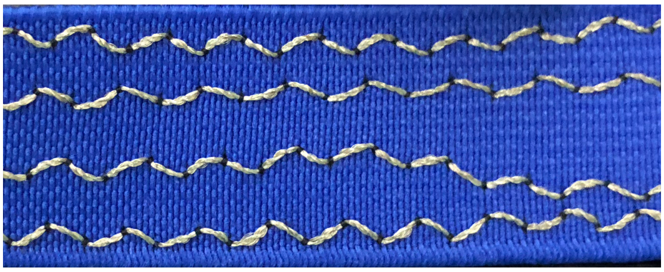


Figure 3.6 : Bus structure with conductive yarns.

In this system, the sensor data is measured at the nearest point and converted to digital data and the data transmission is done digitally in the remaining system. Digital communication techniques have features such as low error rate, less interference, high fidelity, error correction [32]. Therefore, in the transmission of sensor data, digital transmission is preferred to analog transmission. In this way, the sensor data is transmitted more safely.

3.2 Measuring Sensor Data

Methods such as AC Bridge method [33], charge/discharge method [34], and oscillation method [35] etc. are used for capacitance measurement. This section consists of charge/discharge method and voltage divider methods.

3.2.1 Charge/discharge method

According to the examination of all these techniques, the most proper method for integration with textiles and measurement with microcontrollers is charge/discharge method. As shown in Figure 3.7, the measuring system can be installed with the sensor and two resistors with a fixed value according to the working principle of this method. While charging, the charging pin is in the output mode, and the discharge pin is in the input mode. In contrast, while discharging, the charging pin is in the input mode, and the discharge pin is in the output mode. Calculations based on the charging time are made using the charging resistance. In the same way, discharging resistance is used in calculations made with respect to the discharge time. The method is based on the presence of charging or discharging time of the capacitance which is required to be measured with the help of resistance. The time value found is also equal to the time constant of the system generated by the resistance and the capacitance. The formula of the time constant is R_xC_x where R_x is the charge or discharge resistor and C_x is the capacitor to be measured. As the resistance value is constant, the capacitance value can be calculated by using the time constant measured over the system. However, although this system has a simple structure, it is not suitable for textile based capacitive sensors. The sensors in the system produce capacitance between 30 and 100 pF. To measure such low-valued capacitive sensors, the operating frequency of the system must be around several MHz [35]. The operating frequency is also the charging/discharging frequency. To determine the time constant, the operating frequency of the microcontrollers would have to be approximately several hundred MHz. However, there is no microcontroller in the system with low energy, low price, and small dimensions. Therefore, this method is not suitable to be used in this system.

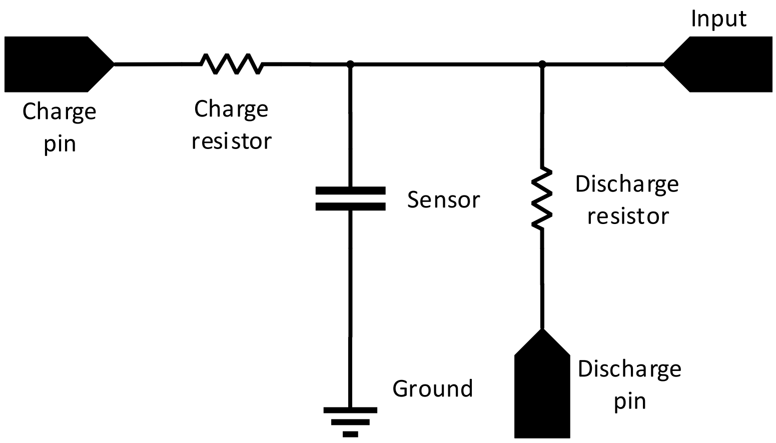


Figure 3.7 : Electrical model of the charge/discharge method.

3.2.2 Voltage divider method

Instead of the charge/discharge method, voltage divider method is preferred because of its simple structure, cost, and performance. Although the capacitance value of stray negatively affects the measurement results in many capacitance measurement methods [35], it has a significant role in this method together with external capacitance as reference capacitance value. As shown in Figure 3.8, two capacitance and output and input pins are required for measurement. The external capacitance value is used to increase the measurement resolution of the sensors in different capacitance ranges and can be added optionally.

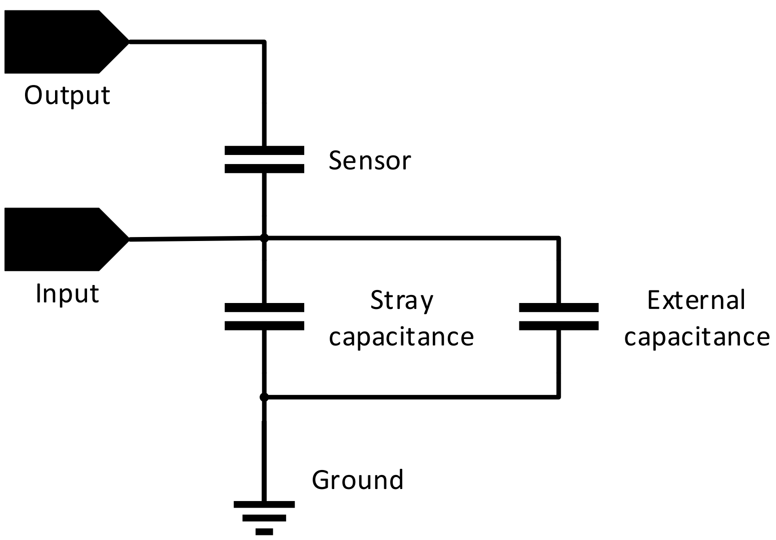


Figure 3.8 : Electrical model of the voltage divider method.

During system operation, the output pin charges the capacitances and the input pin measures the voltage of reference capacitance. After the measurement data is taken, the capacitances are discharged for the next measurement. Since there is no additional resistance on the system except the internal resistors, the charging and discharging times are very short, and no system waiting is required. The measured voltage value is defined as:

$$V_{in} = \frac{V_{out}C_x}{C_x + C_{stray} + C_{ext}}, \tag{3.1}$$

where V_{in} is the input voltage, V_{out} is the output voltage that charges the capacitances, C_x is the sensor capacitance value, C_{stray} is the stray capacitance value of the input pin, and C_{ext} is the external capacitance value. In this system, C_{stray} and C_{ext} are parallel to each other. Therefore, V_{ref} is defined as:

$$C_{ref} = C_{stray} + C_{ext}. \tag{3.2}$$

This equation can be used to simplify the Equation in (3.1) as follows:

$$V_{in} = \frac{V_{out}C_x}{C_x + C_{ref}}. \tag{3.3}$$

Using this equation, the formula of C_x is defined as:

$$C_x = \frac{V_{in}C_{ref}}{V_{out} - V_{in}}. \tag{3.4}$$

Because V_{ref}, V_{out}, and V_{in} are known, the sensor data can be calculated using this equation. When the system is examined, the values of C_{ref} and V_{out} are constant and the same in the whole system. As a result of the calculation, the value of C_x is a floating number, although the input value is an integer number. Due to the lack of floating point on the microcontrollers and floating point numbers take up more space during data transfer, this calculation will be done on the mobile device. In this way, the V_{in} value, which is an integer number, will be transmitted in the electrical system. Because C_{ref} and V_{out} values are known, the calculation can be made easily on the mobile device.

A filtering method, which uses the integer average of 32 data collected, is used to reduce the noise caused by the measurement of the V_{in}. The signal is smoother because of filtering. In determining the number of measurements to be used on average, two and its power are preferred, because the microprocessors operate in the 2-fold base, this process can be performed more quickly using the shift operator instead of the division operator. As the number of measurements used in the filter increases, the signal becomes smoother but the operation time of the microprocessor increases. Therefore, 32 measurement values lasting 4.6 microseconds are used in the system, and the process is completed in less than 20 millisecond sampling period.

3.3 Data Transfer

This section consists of communication protocols and data flow methods. In the Section 3.3.1, communication protocols that can be used between microprocessors and transmitter are examined. At the same time, the communication protocols between the transmitter and the mobile device will be compared. In the next subsection, the transmission methods developed for the selected communication protocol are inspected.

3.3.1 Communication protocols

For the data line to be established between the transmitter and microcontrollers, there is a need for a protocol that can communicate more than one device simultaneously and uses less cable to provide ease of textile integration. Since the transmitter device is a microcontroller system, we will examine the communication protocols that can be used between microcontrollers. The communication protocols supported by our microcontrollers and the transmitter are Universal Asynchronous Receiver-Transmitter (UART), Serial Peripheral Interface (SPI) and I2C [30, 31].

3.3.1.1 UART

The UART communication protocol provides asynchronous, one to one, and bidirectional data transfer. It is the fundamental communication protocol used by many asynchronous communication protocols. The device needs a transmitter and a receiver port for this protocol. Data inputs and outputs are made via these ports. There is no master-slave relationship between devices [36]. As shown in Figure 3.9, when connecting UART between microprocessors, the transmitter port of a microprocessor is connected to the receiver port of the other, and its receiver port is connected to the transmitter port of the other. However, since this protocol has one to one structure, it needs two additional ports and wires on the transmitter for each new microcontroller. Because the transmitter has a limited number of UART ports, this protocol is not suitable for structures with multiple sensors. At the same time, the increase in the number of lines may cause problems in integration.

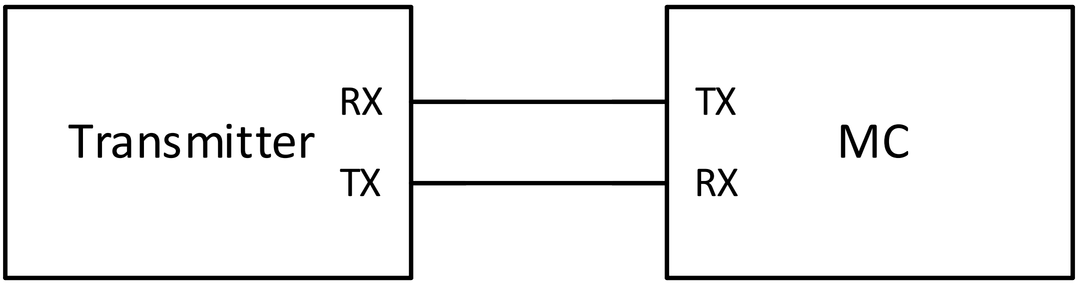


Figure 3.9 : UART circuit diagram.

3.3.1.2 SPI

The SPI protocol is a synchronous protocol in which multiple devices can communicate bidirectionally. The SPI protocol is a synchronous-structure communication protocol in which multiple devices can communicate bidirectionally. The SPI protocol has a master-slave relationship. As shown in Figure 3.10, the protocol uses the Master Out-Slave In (MOSI), the Master In-Slave Out (MISO), the clock signal (SCLK) and the Slave Select signal (SS_n) ports where n is the index of the slave device. The MOSI port is used to transfer data from the master device to the slave device. The MISO port is used to transfer data from the slave device to the master device. With the SLCK port, the clock signal is sent from the master device to the slave devices. The MOSI and MISO signals are synchronized with the clock signal. The SS_n port is used to determine the slave device to communicate with the master. All ports except SS_n port are connected in parallel in master and slave devices. In the SS_n port, each slave must be connected to the corresponding port of the master device. For each new slave device, a new SS port and SS cable are required in the master device [37]. In the system, the transmitter will act as a master device, and the microcontrollers will act as slave devices. As the number of slaves increases, the number of ports in the transmitter will be insufficient, and this system will not be suitable for the designed system.

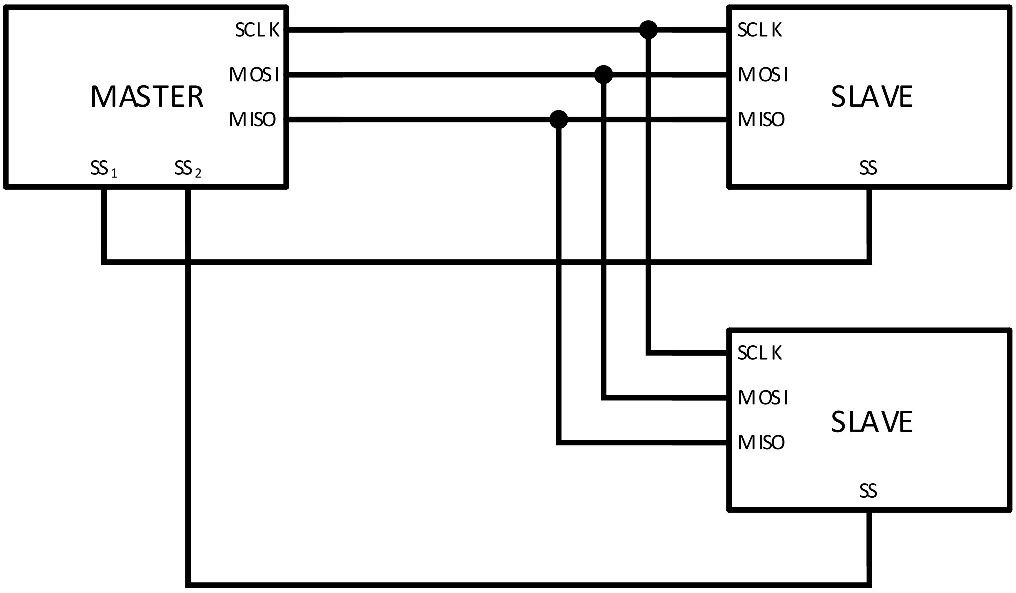


Figure 3.10 : SPI circuit diagram.

3.3.1.3 I2C

In the I2C protocol, multiple devices can communicate over two lines. As seen in Figure 3.11, there are SCL and SDA ports in the system. In this protocol, there is no need for the slave select port. Each device has a unique 7-bit slave address and is connected to the master via this address. The SCL goes from the master to the slaves, such as the SCLK signal in the SPI, and is synchronized with the SDA. The address and data are sent to the slave chips using the SDA. Data is transferred to the slave with the corresponding address. Other devices ignore data that their addresses do not contain. The SCL and SDA ports are connected in parallel to the master and all slave devices. All chips can communicate using only two wires [37].

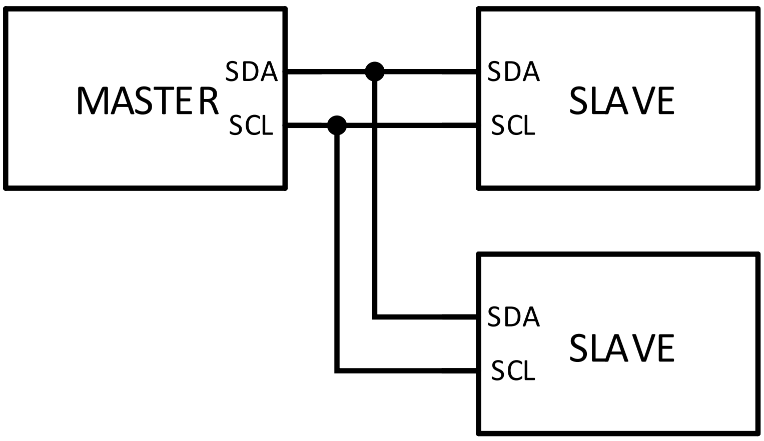


Figure 3.11 : I2C circuit diagram.

Compared to all methods, the I2C protocol is preferred because dozens of devices can communicate with this protocol using two wires. Since the system can be used in outdoor sports, the Bluetooth connection is preferred between the mobile device and the transmitter, because connection problem may occur due to coverage problem in the Wi-Fi. As the transmitter has a built-in Bluetooth feature, it will provide extra convenience in the integration of the system.

3.3.2 Transmission methods

Even if the electrical design of the system is effective, performance will not be optimum unless the suitable method for microcontrollers is specified algorithmically. Three methods have been developed to work in the system. These methods are 1) Read and Send (RAS), 2) Always Read Send Last One (ARSLO) and 3) Send Before Prepare Next (SBPN).

3.3.2.1 RAS

In the Read and Send method, after the transmitter makes a request to the microcontroller, the microcontroller measures the data from the sensor. Then it sends its measurement to the transmitter. This method provides the most up-to-date data as it makes measurements and sends data after taking a request. However, as the average number of measurements in the system increases, the delay increases. In systems where more than one microcontroller is to be used, the measurement period from all microcontrollers will exceed the sampling period and the system frequency will decrease.

3.3.2.2 ARSLO

In the Always Read Send method, microcontrollers collect data continuously. When the transmitter requests data from the microcontroller, the last measurement is sent to the transmitter. In this method, data collection time is shorter than RAS, since there is no measurement and calculation after the data request. With this method, more devices will be able to communicate at the desired sampling frequency. This method has two disadvantages. Firstly, the value sent is not actually the most up-to-date data since it was the last completed measurement and measured just a few milliseconds ago. However, this disadvantage is not important to us, as delays that do not exceed the sampling period are acceptable in our system. Secondly, the microcontroller makes continuous measurements, whether this measurement is used or not. In short, the microcontroller makes several measurements in a sampling period and sends only one of them. Other measurements are made unnecessarily because they are not used, so the sensor and microcontroller serve more jobs.

3.3.2.3 SBPN

In the Send Before Prepare Next method, when the microcontroller request arrives, it sends the previous value and then measures the next value. After the measurement is completed, the microcontroller starts to wait for a new request. This method is similar to RAS in that it takes a single block of measurement for each sample and performs less computation in the sensor and microcontroller. At the same time, it is similar to ARSLO in that the speed of data retrieval is high by sending the last data prepared. The only disadvantage of this method is that the data received by the transmitter, is prepared approximately before the period time.

Compared to the three methods, the SBPN method is chosen as the most suitable method for reasons such as performance and low computational load. The microcontrollers to be integrated with the project function using with this method.

4. SYSTEM IMPLEMENTATION AND TEXTILE INTEGRATION

In this chapter, information will be given about a mobile application, a web service application, sensor structure, and textile integration. Mobile and web service are used to collect data from the designed electrical system. The data flow of the end-to-end system will be completed by letting these three applications communicate with each other and the electrical circuit. Thus, the system is tested in a laboratory environment and then work on the prototype can be started.

4.1 Mobile Application

All data in the electrical system is collected in the transmitter. The transmitter sends the collected data to the mobile device via Bluetooth. Therefore, a mobile device application would be needed to communicate with the transmitter. For this reason, an Android-based mobile application is developed. As shown in Figure 4.1, the Android application act as a bridge between the user, the electrical system and the server. Users can instantly view the measured data from the sensors, while the measured data can be transmitted to the server via the Internet.

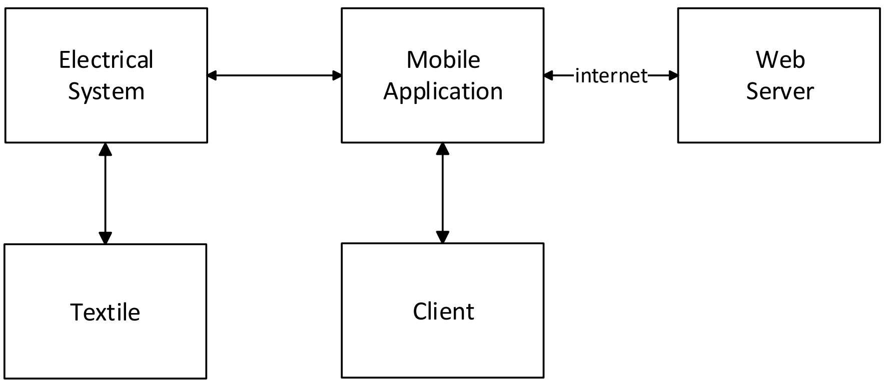


Figure 4.1 : Mobile device communication diagram.

The mobile application has a home screen as shown in Figure 4.2 on the first launch. Settings, measurement and system information screens can be accessed via this screen. In the Settings screen, the information of the server to be connected can be accessed and modified. System information screens include system developer information and test pages during development. The home screen only acts as a bridge for other screens. The most functional screen of the Android application is the measurement screen.

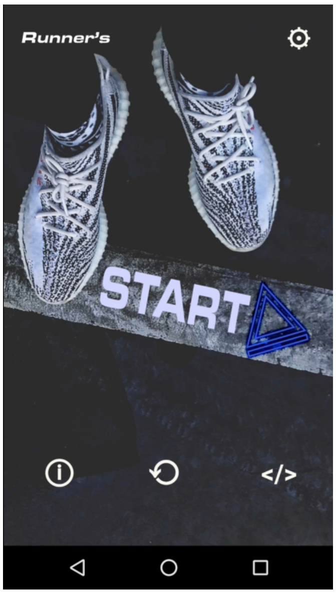


Figure 4.2 : Home screen of mobile application.

This screen connects to the active prototype devices. After connection is established, the mobile device starts receiving data from the transmitter as shown in Figure 4.3. Because the input values C_{ref} and V_{out} are known, they are converted to capacitance values by using Equation (3.4) and printed on the screen. The blue line on the chart shows the angle data of the left knee and the pink line shows the angle data of the right knee, where the x-axis represents measurement id and the y-axis represents capacitance value.

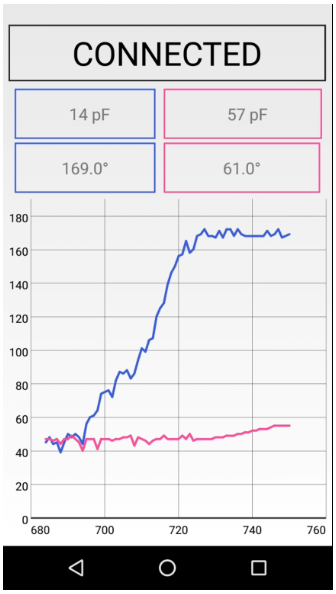


Figure 4.3 : Measurement screen of mobile application.

A simple mathematical equation is established for the calculation of angle values. The maximum angle of the knee is set as 180°degrees, and the sensor would have the lowest capacitance value at this angle. The lowest angle value is selected as 45°, and this angle value will cause the sensor to generate the maximum capacitance value due to knee movement. The user is given a 5 sec calibration time and is asked to continuously move his legs with an angle between 45°and 180°. Maximum and minimum capacitance values are determined during calibration. There is inverse proportion between the capacitance and angle values. With the measured values, the instantaneous angle value can be defined as:

$$\theta_{ins} = \theta max - \frac{135^{\circ}(C_{ins} - C_{min})}{C_{max} - C_{min}}, \tag{4.1}$$

where θ_{ins} is the instantaneous angle of knee, θ_{max} is the maximum angle of knee, θ_{min} is the minimum angle of knee, C_{max} is the maximum capacitance measured on the sensor, and C_{min} is the minimum capacitance measured on the sensor. With $\theta_{max} = 180^{\circ}$ and $\theta_{min} = 45^{\circ}$, the equation can be defined as:

$$\theta_{ins} = 180^{\circ} - \frac{135^{\circ}(C_{ins} - C_{min})}{C_{max} - C_{min}}. \tag{4.2}$$

Using this formula, angle values are calculated separately for both knees.

The measured capacitance values and the calculated angle values are transferred to the server via socket communication, and the data is stored on the server. The developed Android application helps to display and store both data instantaneously.

4.2 Web Service Application

One of the significant parts of the system is the web service because it is responsible for both data storage and communication between devices. As seen in Figure 4.4, the web service serves as a bridge between the mobile phone, the database, and the web browser. Web service can be examined in four parts such as the back-end, database, socket programming, and front-end.

For the web service application, there is a need for a platform that is efficient and fast in real-time applications as well as asynchronous programming. NodeJS meets the needs of the system with its event-driven and non-blocking I/O structure, rich Node Package Manager (NPM) repository, and ability to run on different platforms [38]. The web

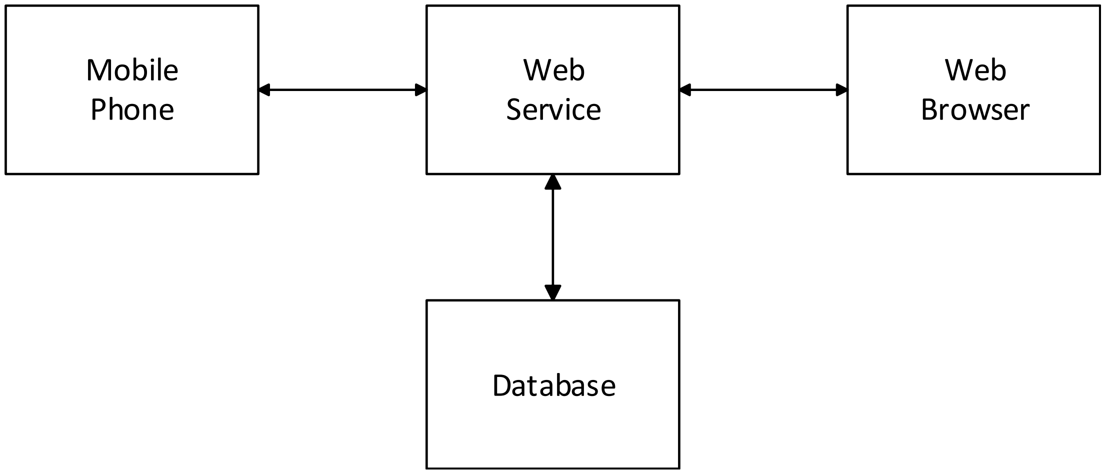


Figure 4.4 : Web Service communication diagram.

service application has been implemented with NodeJS Express Web Framework, and it performs database operations such as user login and historical data display.

Since different sensor data could be added in different part of the project, dynamic structured data is needed to collect data in a single database infrastructure. Since fifty data per second would come from a single device, the database must also have the ability to insert data quickly. MongoDB was preferred because of its fast data insertion and selection operation, dynamic structure, and NodeJS compatible features [39]. The database design consisted of three collections named users, measurement_info and measurement_data.

The socket programming is used in the system to provide instant communication between the mobile phone, server and web clients. In this way, the data is transferred to the web service instantaneously, and the web service sends data to web clients. Socket.io which is a library of NodeJS, used for socket programming. Socket.io is an easy-to-use library with real-time, bi-directional, secure data transmission [40].

On the front-end of the web service application, it enables to display the data from the server via socket.io in the web browser. The front-end of the web service application is used to instantly display data from the server via Socket.io in the web browser. the received data is displayed on the chart instantly. The data sent from the web service is received by the JavaScript library of Socket.io. Then JavaScript adds this data to the chart.

With the web service application, the components project can now communicate end-to-end and provide key features of user interfaces. The data is stored in the database for future analysis. Thus, all backward measurements can be accessed from a single point. All these processes are carried out in effective methods with the appropriate platforms.

4.3 Sensor Structure and Textile Integration

In previous studies [8], the method of production and operation of the sensor is explained. At this point, as seen in Figure 4.5, soft capacitive sensors consist of two conductive knit fabrics and a silicone elastomer. Conductive knit fabrics act as a parallel plate electrode. The silicone elastomer acts as a dielectric layer. As a result, the soft capacitive sensor acts as a parallel plate capacitor.

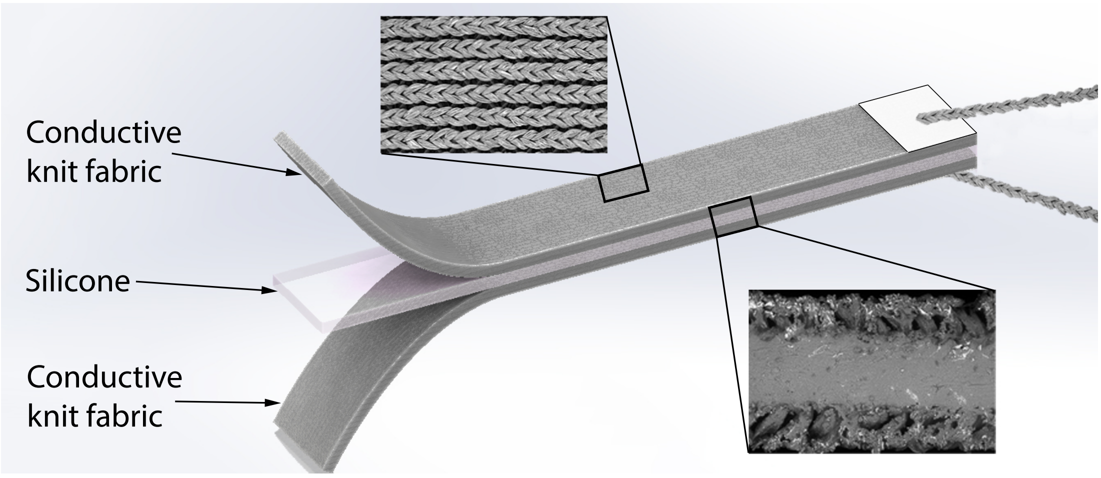


Figure 4.5 : Soft sensor architecture [41].

As the sensor operates as a parallel plate capacitor, we can define the capacitance formula of the sensor as a parallel plate capacitor formula. The parallel plate capacitor formula is described as:

$$C = k\varepsilon_0 \frac{A}{d}, \tag{4.3}$$

where C is the capacitance, k is the dielectric constant, ε_0 is the permittivity of free space, A is the area of the plates, and d is the plate separation [42]. As the principle of sensor operation, the length of the sensor changes in response to the load applied on it. However, the elongation in the length of the sensor increases the area of plates in parallel, while in the case of plate separation there is no significant change. The elongation in the length of the sensor also increases the area of plates in parallel. In contrast, there is no significant change in plate separation. Therefore, increasing the length of the sensor increases the capacitance value.

A zigzag stitch is variant geometry of the lockstitch. It is a back-and-forth stitch used where a straight stitch will not suffice, such as in reinforcing buttonholes, in stitching stretchable fabrics, and in temporarily joining two work pieces edge-to-edge [43]. For this study, we selected to use zigzag stitch that enables us to sew conductive yarn on stretchy base fabric. Moreover,stitch length and width were adjusted as maximum through the machine setting in order to make sewing process relatively easy on stretchy base fabric. Table 4.1 shows the properties of the conductive yarn used in the study.

Table 4.1 : The properties of the conductive yarn [44].

Property	Value
Name	Shieldex® Conductive Twisted Yarn Silver Plated Nylon 66 Yarn 235/34 dtex 2-ply HC +B
Purpose	Anti-microbial applications for garments, smart textiles, and sewing thread
Description	99% pure Silver plated Nylon yarn 560/68 dtex with anti-tarnish coating
Liner resistance	<100 Ω/M
Yield	17,500 M/Kg
Tenacity	Average 46 cN/tex
Elongation	Abt. 15.5%
Denier	520/68f (S 500 400 tpm Z)
Melt point [F]	492

Textile integration consists of three stages. In the first stage, the proper position of the sensors on the knee brace is determined, and the sensors are placed at this point. Since the product is a prototype, the sensors are mounted in a removable fashion so that the sensor position can be changed. In the second stage, the bus structure is created. The bus structure consists of two data lines used by I2C and two power lines to transmit the energy to the microcontrollers. In the prototype, a total of four conductive yarns are used for power and data lines, and these conductive yarns are sewn on the fabric strip. In this way, the prototype is brought closer to the real textile product, and most of the integration is made with textile products. In the last step, the microcontroller and transmitter devices are located on the bus. All the bus connections in the system are made in parallel, so there is no need to use extra cables and pins. The prototype is prepared by establishing sensor connection with microcontrollers.

The prototype in Figure 4.6 is used in the experiments. The close-up photo on the left shows the connection of the microcontroller with the bus and the sensor. The close-up photo on the right shows the bus sewn on fabric strip with conductive yarns [41].

Figure 4.6 : Prototype of the system formed by conductive yarns [41].

5. EXPERIMENTS AND RESULTS

This chapter consists of software and hardware, experimental frameworks, and results.

5.1 Software and Hardware

Software and hardware preferences cause a slight change in experimental results. In this section, hardware and software preferences are given in order to reconstruct experimental environments.

The electrical design is equipped with microcontrollers and transmitter. ATtiny 85 is preferred for microcontrollers and the clock frequency of microcontrollers is set to 1 Mhz. In the stretch meter ve comparison of the transmission method, Arduino Uno is preferred. Bluno Beetle Arduino Controller is preferred on the prototype. The serial port is used between computer and transmitter with 115000 bits per second. The C ++ language is used in the programming of electrical components.

In the experiments on the prototype, Samsung Galaxy Note 2014 Edition is used as a mobile device. This device has Octa-core (4x1.9 GHz Cortex-A15 & 4x1.3 GHz Cortex-A7) CPU, 16 GB internal storage, 3 GB ram and Android 4.4 operating system. The mobile application used in the communication between the transmitter device and the mobile device is developed with the sdk version 18. This application works on Android 4.3 and above.

The computer is used as the server in the data collection stage. This computer has Intel Core i7-2670 CPU, 16 GB DDR3 Ram, 480 GB SSD and Windows 10 Pro operating system. A NodeJS-based server application is developed for the system to collect data from the prototype. A data collection application with C# based and the graphical interface is developed for data collected from the serial port.

5.2 Experimental Framework

This section consists of information about experimental frameworks for linearity of sensor, and leg motion monitoring performance.

5.2.1 Experimental framework for the linearity of sensors

The most important reason for using a capacitive sensor in a prototype is the high linearity of the capacitive sensors. In order to test this feature of the prepared sensors, a stretch meter with stepper motor and data communication with the computer is developed. The stretch meter is shown in Figure 5.1. The microcontroller in the circuit board is programmed using two different methods. The first method measures and sends a single capacitance value of the sensor. The second method takes N consecutive measurements and sends the integer average of these measurements. Two experiments were conducted for both methods under the same conditions.

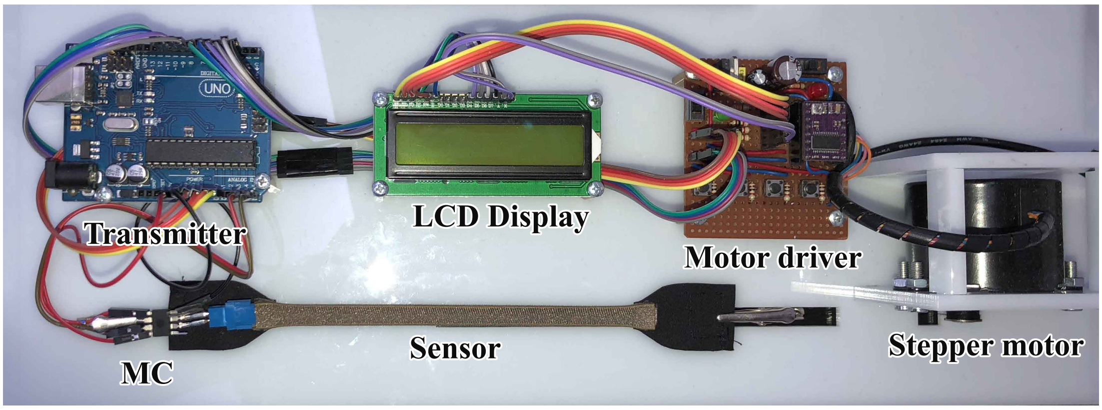


Figure 5.1 : Stretch Meter.

5.2.2 Experimental framework for the leg motion monitoring performance

In order for walking tests to be carried out successfully, there must be a suitable environment. For this reason, the facilities of the gym in ITU campus were used to test the performance of the prototype. The walking test is carried out on the treadmill, and the effects of the test are minimized due to the external effects. In order to prevent the difference in tension measurements between two sensors, the data collected is linearly scaled between 25 pF and 40 pF using min-max normalization for each sensor. The sensor data was collected on the mobile phone and transferred to the computer.

5.3 Results

In this section, results on the effect of external capacitance, the linearity of sensors, the effects of number of samples for averaging, the effect of transmission methods, and the leg motion monitoring performance are examined.

5.3.1 Results on the effect of external capacitance

In the system, the capacitance is measured by using the internal capacitance of the microcontroller as a reference. In the measurement of sensors with different capacitance ranges, the internal capacitance value of the microcontroller did not show the same performance. For this reason, external capacitance is added to the system in order to obtain the desired value of the reference value.

The change of the measurement resolution in terms of different external capacitance value is shown in Figure 5.2. The horizontal axis shows the input voltages to the microcontroller, which are between 0 and 5 V. The vertical axis shows the capacitance values corresponding to the input voltages.

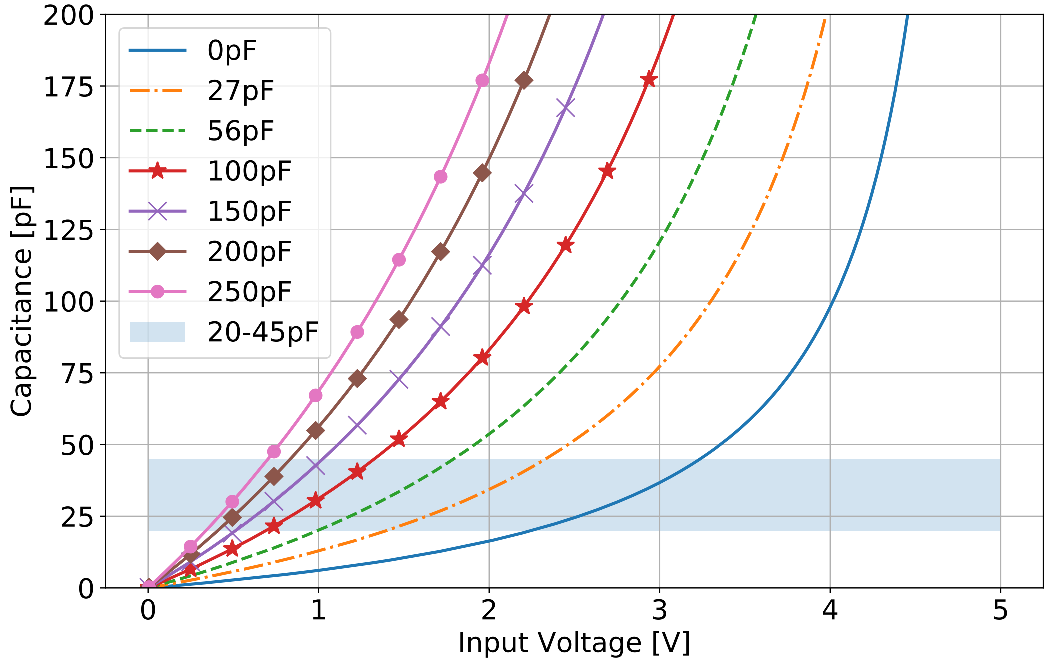


Figure 5.2 : External capacitance curves in relation to the input voltage.

In the sensor range to be used, the capacitance value which has the most uniformly spread input voltages, is more suitable. In other words, the curve with the lowest slope in the desired range shows the optimum capacitance value. The sensors used on the prototype varied in value from 20 to 45 pF. Therefore, the external capacitance is not used in the prototype for capacitance measurement since the highest resolution is obtained without external capacitance as seen in Figure 5.2 for these range of capacitance values.

5.3.2 Results on the linearity of sensors

As shown in Figure 5.3, both experimental results have linearity. However, in the single measurement method, fluctuations in the signal are more severe. This fluctuation is due to the measurement noise of the microcontroller. In the average measurement values method, the measurements have a smoother trend.

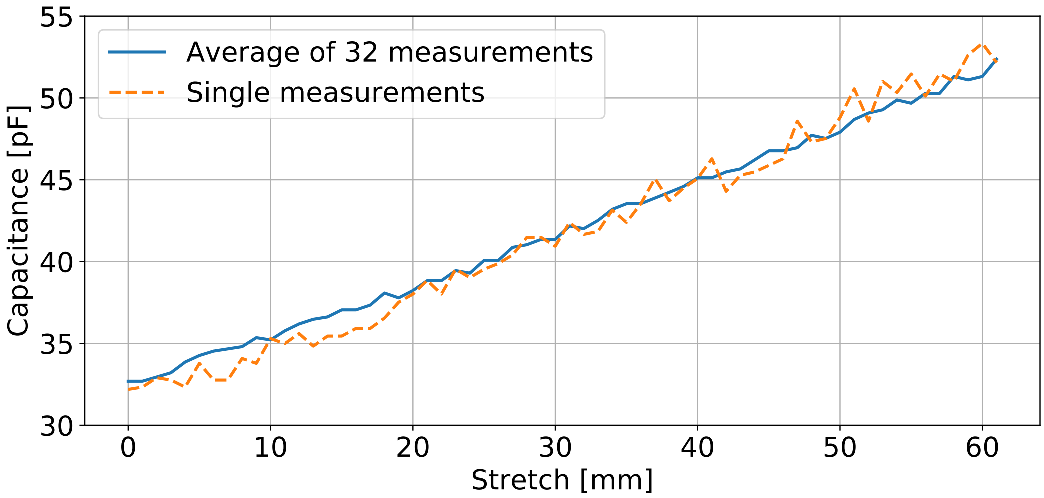


Figure 5.3 : Linearity of capacitive sensors.

For the comparison of the noise values of both methods, 1000 measured values are collected for each stretch value. Then the peak signal-to-noise ratio (PSNR) values are calculated to show the quality of the signal for both methods. If the noise increases, the quality of the signal decreases. In the single measurement values method, PSNR is 48.24 dB. On the other hand, PSNR is 54.15 dB in the average measurement values method. The signal quality of the average measurement values method is better than the single measurement method. For this reason, microcontrollers working with this method will be used on the prototype.

5.3.3 Results on the effect of number of samples for averaging

In this experiment, the effect of the number of samples for averaging is examined. The shift operation is used to make the integer division operation fast for numbers that are the power of two. Therefore, six different numbers are the power of two are selected to make division operation fast. Data is collected from the microcontroller at 50 hertz for 10 minutes and the average measurement time is calculated using this data for each number. As shown in Figure 5.4, when the measurement is made in the microcontroller, as the number of measurements to be used in the calculation of the average value increases, the working time of the system is increasing. For example, in a system with 32 measurements, this time is 4.8 ms. This value is acceptable because it is shorter than the system period. Therefore, if more than 32 measurements are used for the average value, the working time will be folded and the sampling period will be exceeded. For this reason, 32 measurement values have been determined heuristically as the main averaging sample value in the system.

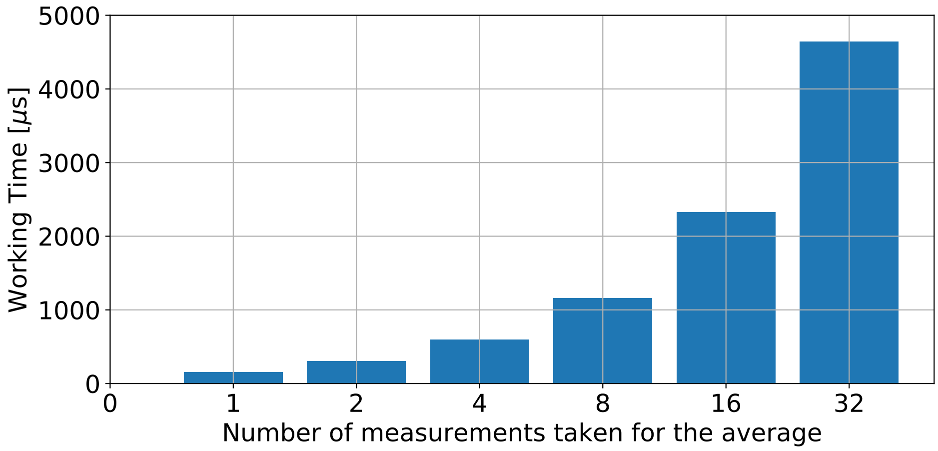


Figure 5.4 : Measurement time of the microcontroller.

5.3.4 Results on the effect of transmission method

In Figure 5.5, response times are shown according to different measurement numbers in the Read and Send (RAS) method and in the Always Read Send Last One (ARSLO) method according to 32 measurement numbers. The data collected from transmitter at 50 hertz for 10 minutes and the average response time is calculated using this data for each experiment. Since the measurement is made after a request in the RAS method, the duration of the response also affects the measurement time. As the number of measurements for the average increases, the response time also increases. For 32 measurements this time is close to 5ms. With this method, data can be taken from a maximum of 4 sensors at a sampling frequency of 50 Hz. Although the ARSLO method works with 32 measurement numbers, its response time is shorter than RSO's minimum response time.

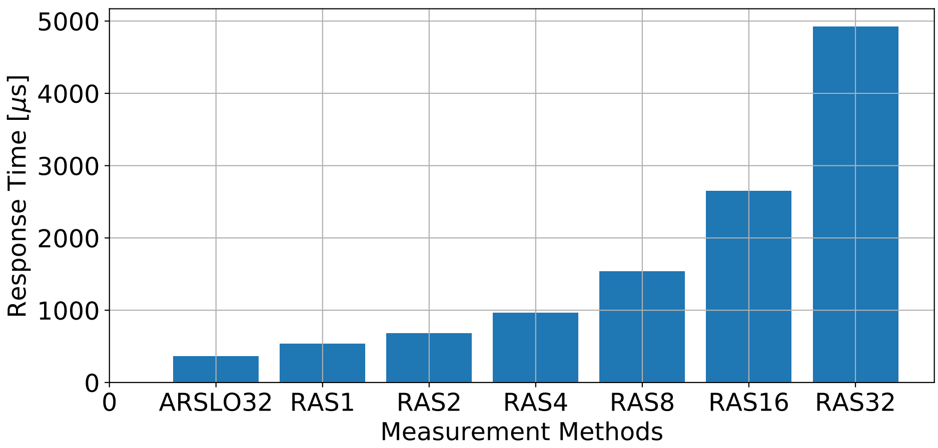


Figure 5.5 : The response time of the microcontroller.

Although the ARSLO 32 method is the most appropriate method for the system because of the smoothness of the measured values and the low response time, at the sampling frequency of 50 Hz, there is some unused calculation in each period because this method only sends the last measurement value and other values are deleted. Therefore, Send Before Prepare Next (SBPN) 32 method, which is modified form of the ARSLO 32 method, forms a single measurement value within a single sampling period and does not unnecessarily overload the microcontroller and its sensors, has been found suitable for use in subsequent studies.

5.3.5 Results on the leg motion monitoring performance

Figure 5.6 shows the measurement results. The test object is moving at a static velocity on the treadmill between 0-11 secs. If the results are examined within this period, each signal contains repetitive local and global maximum points. In the mid-stance phase of gait, the capacitance value increases and reaches the local maximum point. Afterwards, the walking movement continues, the capacitance value decreases to the minimum point in the terminal stance phase. In the initial swing of gait, the capacitance value reaches a global maximum value such as an angle value. Then, the cycle continues, and the capacitance value decreases to the minimum point in the terminal swing phase. The terminal swing phase is the last phase of the gait cycle. When these signals are examined separately for both legs, theoretical data and measurement values have a similar pattern. If both leg signals are compared, there is a phase difference between these two signals as both legs move sequentially.

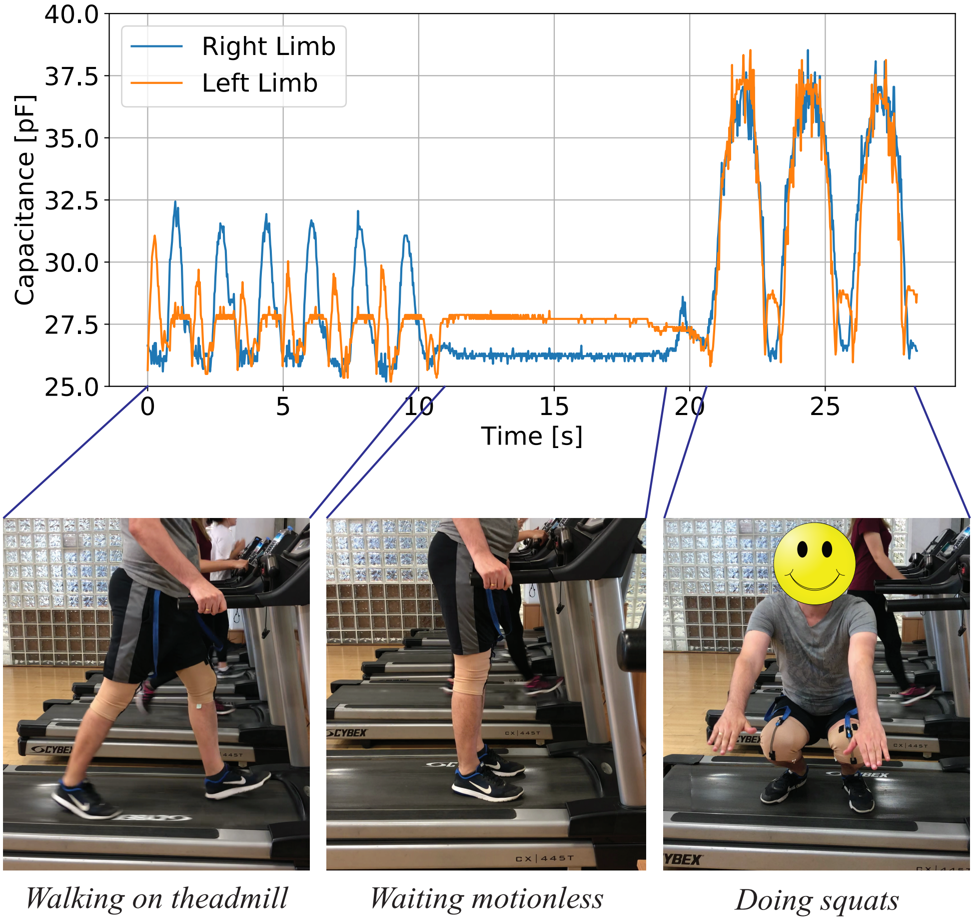


Figure 5.6 : Motion monitoring results of the proposed prototype.

The person waits motionless between 11-18 seconds. During the wait, as the person keeps the left leg in a more tensioned position than the right leg, the capacitance value is slightly higher for the left leg.

Between 21-30 seconds, the person makes a squatting motion 3 times. During this motion, phase difference does not occur and the signals are similar to each other.

If it is desired to examine the measurement results in a different way, the motion data can be converted into velocity data. The velocity data is expressed by taking the numerical derivative of the motion data. Figure 5.7 shows the conversion of motion data to velocity data. The horizontal axis shows time. The vertical axis shows the velocity of capacitance change. As the motion data has increasing and decreasing capacitance values, the velocity data includes both positive and negative region data. Since the test object is moving at a constant speed between 0-11 sec, the phase is different in both signal data. Since the test object waits motionless between 11-18 seconds, the speed is almost zero. Since the test object makes a squatting motion between 21-30 seconds, the signals are similar to each other.

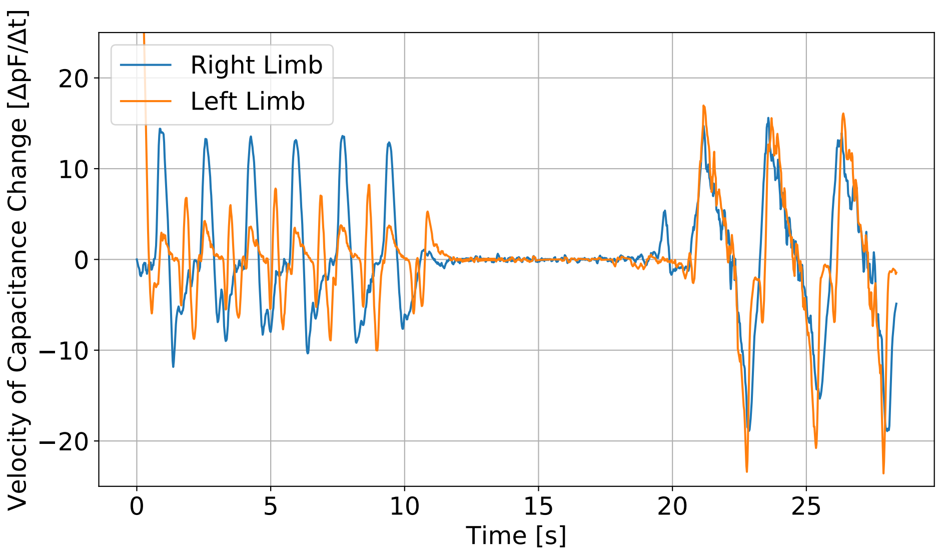


Figure 5.7 : The velocity of capacitance change of motion monitoring results.

To sum up, a similar pattern is shown when the theoretical values are compared with the measured values. All phases of gait cycle can be displayed in the measured values. Thus, the prototype performs the lower limb motion monitoring successfully. When comparing the data obtained from both knees, the results are consistent with the movements made.

6. CONCLUSION

This thesis solves the noise problem caused by the distance between the sensor and the measurement devices which is the major problems of capacitive sensors. Data can be collected from dozens of sensors simultaneously with the design, technologies used and developed methods. With the use of dynamic structures, the adaptation period of the system for new projects is minimized. In this way, new systems that work in a single central processing chip and contain more than one sensor can be developed quickly.

Since the sensor data is transmitted wirelessly via the transmitter, there are no external cables to make the prototype cumbersome, which increases the comfort level. As the system provides all the end-to-end communication, it can be easily measured anywhere, anytime. Because Bluetooth technology is used, the wearable system and the mobile device are enough for outdoor measurements. With the web application, the measured values can be displayed both instantaneously and retrospectively. In the distributed labs, multiple web clients can receive data from the same prototype and thus the measurement can be displayed at many points simultaneously. Since the whole system can be integrated with textile, and the designed system has low cost, the prototype can easily be converted into commercial product.

Using the studies in this thesis, not only in the textile field but also in medicine, robotics, industry, sports, etc. in a wide range of studies can be carried out. With end-to-end data flow, medical doctors will be able to monitor patients from sensor data. With physiotherapeutic applications to be developed, patients will be able to perform their exercises at home on their own. Sportsmen will be able to control their performance instantly using mobile application. Most importantly, it will enable new multidisciplinary studies in different fields and thus will contribute to science.

REFERENCES

[1] **Atalay, O.**, **Kennon, W.R. and Demirok, E.** (2015). Weft-Knitted Strain Sensor for Monitoring Respiratory Rate and Its Electro-Mechanical Modeling, *IEEE Sensors Journal*, *15*(1), 110–122.

[2] **Husain, M.D.**, **Naqvi, S.**, **Atalay, O.**, **Hamdani, S.T.A. and Kennon, R.** (2016). Measuring Human Body Temperature through Temperature Sensing Fabric, *AATCC Journal of Research*, *3*(4), 1–12.

[3] **Atalay, A.**, **Atalay, O.**, **Husain, M.D.**, **Fernando, A. and Potluri, P.** (2016). Piezofilm yarn sensor-integrated knitted fabric for healthcare applications, *Journal of Industrial Textiles*, *47*(4), 505–521.

[4] **Tao, W.**, **Liu, T.**, **Zheng, R. and Feng, H.** (2012). Gait Analysis Using Wearable Sensors, *Sensors*, *12*(2), 2255–2283.

[5] **Lin, F.**, **Wang, A.**, **Zhuang, Y.**, **Tomita, M.R. and Xu, W.** (2016). Smart Insole: A Wearable Sensor Device for Unobtrusive Gait Monitoring in Daily Life, *IEEE Transactions on Industrial Informatics*, *12*(6), 2281–2291.

[6] **Stoppa, M. and Chiolerio, A.** (2014). Wearable Electronics and Smart Textiles: A Critical Review, *Sensors*, *14*(7), 11957–11992.

[7] **Frutiger, A.**, **Muth, J.T.**, **Vogt, D.M.**, **Mengüç, Y.**, **Campo, A.**, **Valentine, A.D.**, **Walsh, C.J. and Lewis, J.A.** (2015). Capacitive Soft Strain Sensors via Multicore-Shell Fiber Printing, *Advanced Materials*, *27*(15), 2440–2446.

[8] **Atalay, A.**, **Sanchez, V.**, **Atalay, O.**, **Vogt, D.M.**, **Haufe, F.**, **Wood, R.J. and Walsh, C.J.** (2017). Batch Fabrication of Customizable Silicone-Textile Composite Capacitive Strain Sensors for Human Motion Tracking, *Advanced Materials Technologies*, *2*(9), 1700136.

[9] **Gobee, S.**, **Muller, M.**, **Durairajah, V. and Kassoo, R.** (2017). Humanoid robot upper limb control using microsoft kinect, *2017 International Conference on Robotics, Automation and Sciences (ICORAS)*, IEEE, pp.1–5.

[10] **Ferreira, D.**, **Oliveira, R. and Postolache, O.** (2017). Physical rehabilitation based on kinect serious games, *2017 Eleventh International Conference on Sensing Technology (ICST)*, IEEE, pp.1–6.

[11] **Szucs, V.**, **Sik-Lanyi, C. and Pan, Z.** (2015). Development of collaborative game for Kinect sensor, *2015 IEEE 16th International Conference on Communication Technology (ICCT)*, IEEE, pp.464–469.

[12] **Farringdon, J.** (2001). Wearable electronics and clothing from Philips and Levi, *Technical Textiles International*, *10*(8), 22–24.

[13] **Axisa, F., Schmitt, P.M., Gehin, C., Delhomme, G., McAdams, E. and Dittmar, A.** (2005). Flexible technologies and smart clothing for citizen medicine, home healthcare, and disease prevention, *IEEE Transactions on information technology in biomedicine*, *9*(3), 325–336.

[14] **Universal Serial Fabric Bus, U.**, `http://www.natick.army.mil/about/pao/pubs/warrior/02/janfeb/smartclo.htm`, date retrieved: 11.06.2018.

[15] **Simon, C., Potter, E., Potter, E., McCabe, M. and Baggerman, C.** (2010). Smart fabrics technology development.

[16] **Castano, L.M. and Flatau, A.B.** (2014). Smart fabric sensors and e-textile technologies: a review, *Smart Materials and Structures*, *23*(5), 053001.

[17] **Carpi, F. and De Rossi, D.** (2005). Electroactive polymer-based devices for e-textiles in biomedicine, *IEEE transactions on Information Technology in biomedicine*, *9*(3), 295–318.

[18] **Gonçalves, C., Ferreira da Silva, A., Gomes, J. and Simoes, R.** (2018). Wearable E-Textile Technologies: A Review on Sensors, Actuators and Control Elements, *Inventions*, *3*(1).

[19] **De Rossi, D., Carpi, F., Lorussi, F., Mazzoldi, A., Paradiso, R., Scilingo, E.P. and Tognetti, A.** (2003). Electroactive fabrics and wearable biomonitoring devices, *AUTEX Research Journal*, *3*(4), 180–185.

[20] **Jeong, J.W., Jang, Y.W., Lee, I., Shin, S. and Kim, S.** (2009). Wearable Respiratory Rate Monitoring using Piezo-resistive Fabric Sensor, ***O. Dössel and W.C. Schlegel**, editors, World Congress on Medical Physics and Biomedical Engineering, September 7 - 12, 2009, Munich, Germany*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp.282–284.

[21] **Pan, L., Chortos, A., Yu, G., Wang, Y., Isaacson, S., Allen, R., Shi, Y., Dauskardt, R. and Bao, Z.** (2014). An ultra-sensitive resistive pressure sensor based on hollow-sphere microstructure induced elasticity in conducting polymer film, *Nature Communications*, *5*(1).

[22] **Meyer, J., Lukowicz, P. and Troster, G.** (2006). Textile Pressure Sensor for Muscle Activity and Motion Detection, *2006 10th IEEE International Symposium on Wearable Computers*, IEEE.

[23] **Holleczek, T., Rüegg, A., Harms, H. and Tröster, G.** (2010). Textile pressure sensors for sports applications, *Sensors, 2010 IEEE*, IEEE, pp.732–737.

[24] **Guerra-Filho, G.** (2005). Optical Motion Capture: Theory and Implementation., *RITA*, *12*(2), 61–90.

[25] **Aminian, K. and Najafi, B.** (2004). Capturing human motion using body-fixed sensors: outdoor measurement and clinical applications, *Computer animation and virtual worlds*, *15*(2), 79–94.

[26] **Mengüç, Y.**, **Park, Y.L.**, **Martinez-Villalpando, E.**, **Aubin, P.**, **Zisook, M.**, **Stirling, L.**, **Wood, R.J. and Walsh, C.J.** (2013). Soft wearable motion sensing suit for lower limb biomechanics measurements, *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, IEEE, pp.5309–5316.

[27] **Sidenbladh, H.**, **Black, M.J. and Fleet, D.J.** (2000). Stochastic Tracking of 3D Human Figures Using 2D Image Motion, ***D. Vernon**, editor, Computer Vision — ECCV 2000*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp.702–718.

[28] **Whittle, M.** (2007). *An Introduction to Gait Analysis*, Butterworth-Heinemann.

[29] **Url-1**, `http://www.canadarobotix.com/battery-chargers/polymer-lithium-ion-battery-110mah`, date retrieved: 09.11.2018.

[30] **Url-2**, `https://www.microchip.com/wwwproducts/en/ATtiny85`, date retrieved: 01.11.2018.

[31] **Url-3**, `https://www.dfrobot.com/wiki/index.php/Bluno_Beetle_SKU:DFR0339`, date retrieved: 01.11.2018.

[32] **Sklar, B.** (2001). *Digital communications*, volume 2, Prentice Hall Upper Saddle River.

[33] **Hague, B. and Foord, T.R.** (1971). *Alternating current bridge methods*, Pitman.

[34] **KANNO, M.** (1980). Measurements and Applications of Small Capacitances, *OYOBUTURI*, *49*(9), 905–912.

[35] **Huang, S.M.**, **Stott, A.L.**, **Green, R.G. and Beck, M.S.** (1988). Electronic transducers for industrial measurement of low value capacitances, *Journal of Physics E: Scientific Instruments*, *21*(3), 242.

[36] **Frenzel, L.E.** (2015). *Handbook of Serial Communications Interfaces: A Comprehensive Compendium of Serial Digital Input/Output (I/O) Standards*, Newnes.

[37] **Leens, F.** (2009). An introduction to I2C and SPI protocols, *IEEE Instrumentation & Measurement Magazine*, *12*(1), 8–13.

[38] **Cantelon, M.**, **Harter, M.**, **Holowaychuk, T. and Rajlich, N.** (2014). *Node. js in Action*, Manning Greenwich.

[39] **Chodorow, K.** (2013). *MongoDB: The Definitive Guide: Powerful and Scalable Data Storage*, " O'Reilly Media, Inc.".

[40] **Rai, R.** (2013). *Socket. IO Real-time Web Application Development*, Packt Publishing Ltd.

[41] **Ozlem, K.**, **Atalay, O.**, **Atalay, A. and Ince, G.**, (2018). Textile Based Sensing System for Lower Limb Motion Monitoring, **L. Masia**, **S. Micera**, **M. Akay and J.L. Pons**, editors, Converging Clinical and Engineering Research on Neurorehabilitation III, Springer International Publishing, pp.395–399.

[42] **Grove, T.T.**, **Masters, M.F. and Miers, R.E.** (2005). Determining dielectric constants using a parallel plate capacitor, *American journal of physics*, *73*(1), 52–56.

[43] **Url-4**, `https://en.wikipedia.org/wiki/Zigzag_stitch`, date retrieved: 02.11.2018.

[44] **Url-5**, `http://www.shopvtechtextiles.com/assets/images/200121235343B.pdf`, date retrieved: 02.11.2018.

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- 2016-2018 Pinnera - Software Engineer

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Kadir Ozlem** , Ozgur Atalay, Asli Atalay, Gökhan Ince, 2018: Textile Based Sensing System for Lower Limb Motion Monitoring. *International Conference on NeuroRehabilitation*, October 16-20, 2018, pp. 395-399, Pisa, Italy.