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# A Novel Implementation of Knee Joint Monitoring Device using Step Index Optical Fibre and Linear Array Photodiode Sensor

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# A Novel Implementation of Knee Joint Monitoring Device using Step Index Optical Fibre and Linear Array Photodiode Sensor

**G M Salim[1], M A Zawawi[1]**

[1]Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

ghassan.m.a@ieee.org , mohdanwar@ump.edu.my

**Abstract**. Knee monitoring is one of the common injuries suffered by people who are active in extreme sports. Traditional ways to identify these problems are based on background study of the patient, physical examination, and sometimes with the use of x-rays and MRIs. The use of x-rays and MRIs for repetitive use is not preferably suggested by physicians due to the high cost and other associated side-effect related to exposure to radiation. Due to these factors, an alternative device based on optical fibre sensor is proposed in this study. The proposed knee monitoring sensor is based on the use on step index type plastic optical fibre and linear array photodiode sensor. Based on the mathematical estimation and initial sensor measurement, this sensor is able to perform full range of motion between 0 to 155 degrees. The accuracy and resolution of this sensor is 1.0 degree and 0.5 degree, respectively. The aim of this study is to determine the current performance of the device before further improvement could be proposed.

## 1.  Introduction

There have been many methods developed and used to measure different body joints rotary angles to determine the physical condition of the joint or to assess the joint recovery during rehabilitation process. This work is focused on knee joint angle measurement, as the knee is the most commonly injured joint due to its exposed location and the fact that it carries the entire burden of our body practically our whole life [1]. Currently, the two most commonly used methods to assess knee conditions are pain measurements and gait symmetricity [2]. If pain is detected at the knee, then obviously the joint is already damaged. The damage related to knee, most of the times is curable but there are cases where it is beyond repair [3]. Gait symmetricity on the other hand measures the knee angle during continuous movement. Any asymmetricity in the knee angle measurement during continuous movement even as low as 3 degrees requires attention and rehabilitation to maintain the condition of the knee and to prevent further damage [4]. This method can detect potential knee damage long before they become serious injuries or permanent scar tissue.

The problem with measuring gait symmetricity is that current technology uses estimation algorithms similar to GPS, commonly known as electrogoniometer. Its measuring method is based on determining the acceleration of the moving person, before the velocity is derived from the acceleration, and then determine the distance travelled by the person respectively. Based on distance travelled by the patient, angle variation is estimated and analysed [5]. Whereas in this application, the proposed method is by using linear array photodiode sensor. In this sensor, the joint rotary movement of the knee is directly translated into actual data using light beam as the input signal. Significant advantages of the proposed

method are fast interfacing response, accurate measurements and high sensitivity to angle movement of the knee, due to the light modulation method of the sensor.

## 2. Sensing Mechanism and Working Flow

The process of how the proposed knee monitoring sensor is working as explained in Figure 1 below.
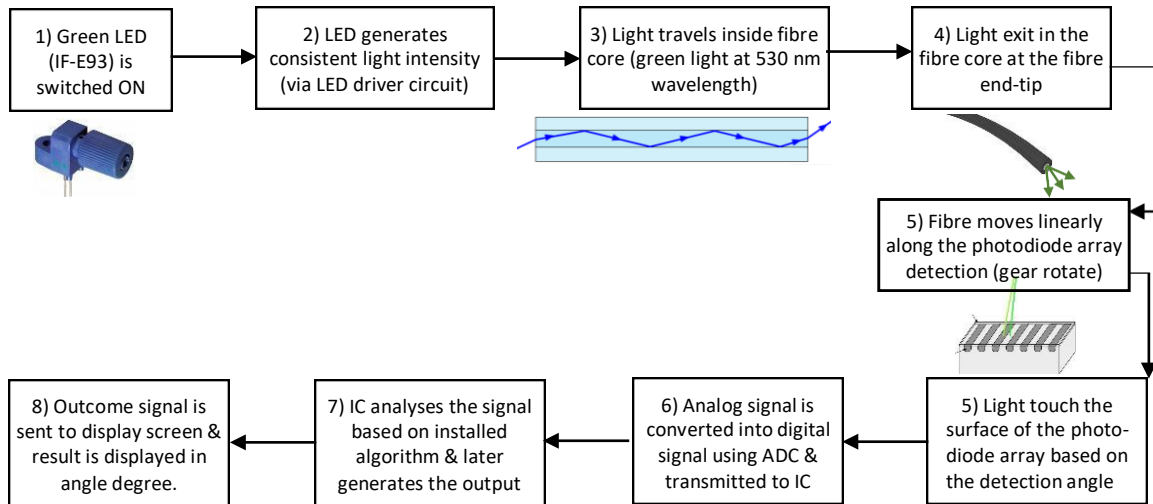


**Figure 1**. Mechanism of angle detection using optical sensor

Figure 2 shows the system's algorithm flowchart on how the system's logical gates handles the inputs/outputs.
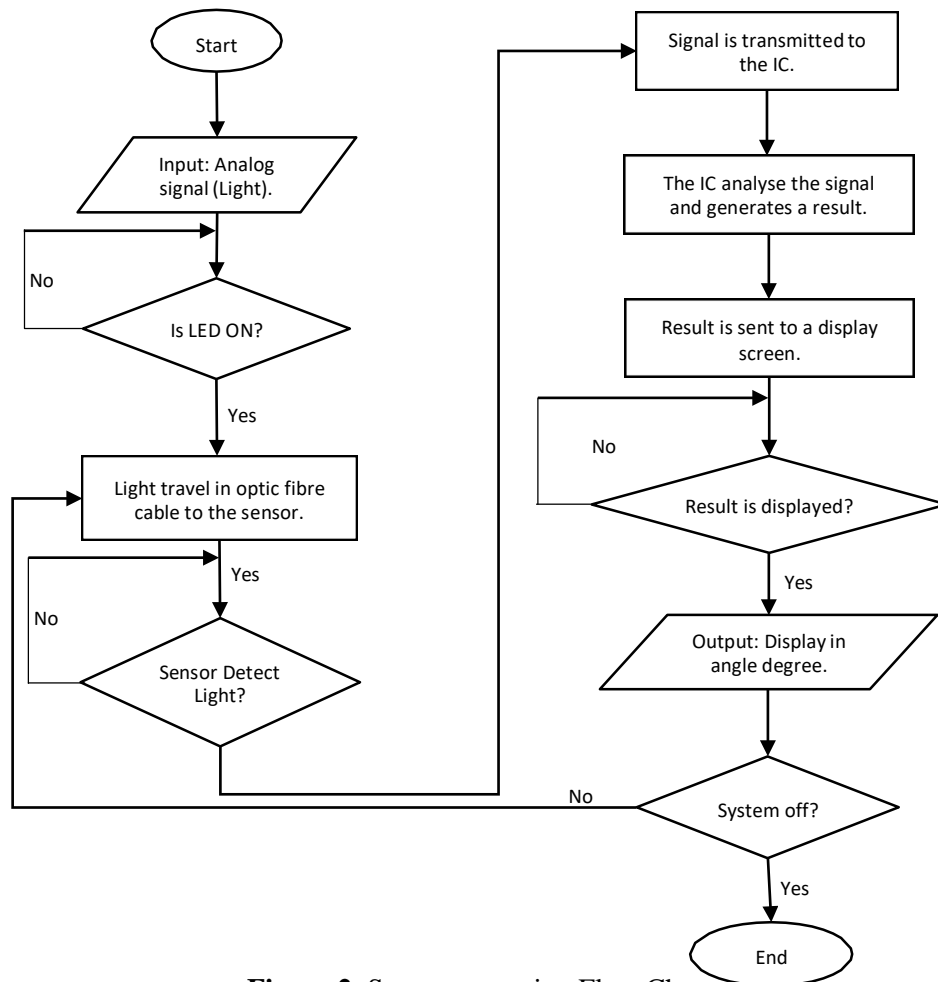
**Figure 2**. System operation Flow Chart

## 3.  Sensor Components

This circuit is designed specifically for the implementation of linear array photodiode sensor on a compact board. The sensor is applied to detect the light (analog signal) and to convert the measured signal into voltage form. Using the pre-programmed algorithm, the input reading is then represented in its respective angle before being displayed on a screen. Among the advantageous of this device is that, it is made out of lightweight components (fibre optic, LED, photodiode array, etc.) and low overall cost. Despite these, the device still carries the inherited benefits of optical fibre which are being immune to hazardous environmental conditions and electromagnetic waves [6]. In addition, the application of light signal (light-wave) as the sensing mechanism could provide less signal delay due to the fast signal transmission of the light from the light source to the photodetector. Whereas, the use of linear array photodiode sensor which consists of 2048 diodes (represented in pixels) [7] provides a very accurate and consistent angle measurement as presented in our mathematical estimation [8]. The components arrangement of the proposed optical sensor, which consists of a linear array photodiode, a green LED and a standard optical fibre cable (Mitsubishi Rayon Eska *GH-4001* step index plastic fibre) is able to provide larger range of detection (angle in degree) than our previously developed method using two separated fibre, an LED and a standard photodiode [9].

### 3.1  Linear Array Photodiode Sensor

Linear array photodiode used in this application is S11639-01 sensor as shown in Figure 3. It consists of a long range of photosensitive area with a long vertical pixel connected together to form a continuous

measuring interface that detects the light. The number of photo sensitive pixels of this sensor is 2048 pixels which allow the user to have a wide measuring range with high accuracy and reliability [7].

Applications of photodiode array sensor can vary in many fields of uses such as security sensing devices, spectrometry, imaging, medical instruments, and even military implementations. At the time of publication, no other knee angle monitoring device has been developed using this photodiode array. There are still many potential use of the linear photodiode array for human health applications.



**Figure 3**. The S11639-01 sensor.

### 3.2 Electronics Circuits Assembly

This sensor circuit assembly consists of two parts, firstly is the system control circuit which has the programmed microcontroller that is responsible for system interface to receive input signals, then to process them, and finally to generate the sensor output. To serve this complex task, a Texas Instruments Tiva-C board was used due to its compact size, low cost, sufficient memory and RAM to perform the required processes [10]. Second part is the sensor driver circuit which is connected to the CMOS linear image photodiode to control, filter, and manipulate analog/digital inputs/outputs of the sensor. This circuit design is obtained from the S11639-01 sensor's datasheet and then prepared manually. Both first and second part of the circuits are then assembled together in the plastic casing as shown in Figure 4 below.



**Figure 4**. Encased Electronic System

### 3.3 Sensor Mechanical Design

Mechanical design of the sensor is consisted of gear and rack shaft assembly as shown in Figure 5. As the knee is rotated in flexion direction, the attached shaft is allowed to move in the same rotational direction, rendering the fibre to move in lateral direction (e.g. linear displacement) along the linear array photodiode. The light detection of different pixel position on the linear array photodiode is analysed based on the pre-installed algorithm to demonstrate the sensor output in angle (degree). The mechanical design of the sensor is printed using a 3D printer.
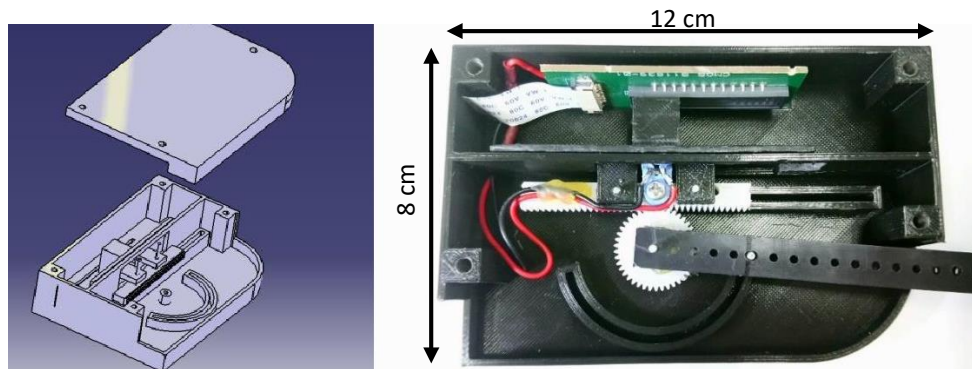
**Figure 5**. Mechanical design in CATIA software and 3D printed hardware respectively.

*3.4 System Assembly*

Upon completing the mechanical parts and electronic circuits, they are then assembled together and an interfacing is achieved by uploading C language coding algorithm to allow interfacing in the overall system. Hence, by achieving a combined system of mechanical, electronic, and software control system, a mechatronic system is produced. Based on the current design, the overall dimension of the sensor case to be attached on the knee is 12 x 8 x 3 cm (L x W x D). The sensor's overall weight (with all components) is 150 grams. The device is as shown in Figure 6.
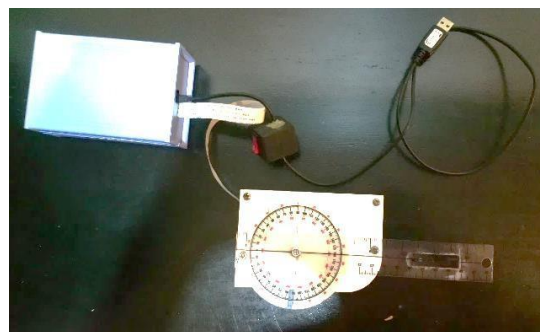


**Figure 6**. Knee range of angle assessment device.

## 4.  Angular Test Rig for Sensor Attachment

In order to obtain initial results for the newly developed knee monitoring device, a wooden test rig was built in-house which is divided into two sections. A fixed part which has the device fixed to it, and a moving part that is able to rotate that assemble a similar motion of the knee as shown in Figure 7 below.
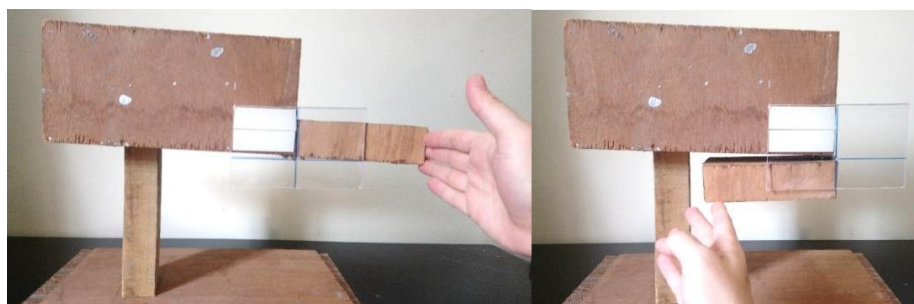


**Figure 7**. Wooden setup to assemble knee angular motion.

After the sensor system is ready, the plastic case that contains the photodiode, gear, shaft and other

components is placed on the wooden rig setup, where a serial data cable is connected to the laptop for output data transfer. The sensor's output is displayed using a Processing software (a flexible software sketchbook where the code is developed within the context of the visual arts) and Java language was used to build the result display page. This software receives the results data from the device via serial port interface and display the results in a continuous graphical form, as shown in Figure 8 below.
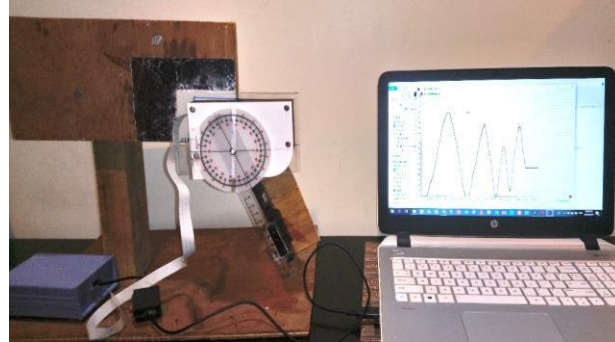


**Figure 8**. Complete lab setup to obtain preliminary results.

## 5.  Measurement Result and Analysis

In order to identify the stability of the sensor outcome, it is important to determine the repeatability of the produced output results. Hence, the device setup was put to test, where the sensor was fixed on 100 degrees angle and the result is presented in Figure 9 below. A consistent output angle is observed from the straight line in graph below where the measurement was taken for a few minutes during this test.
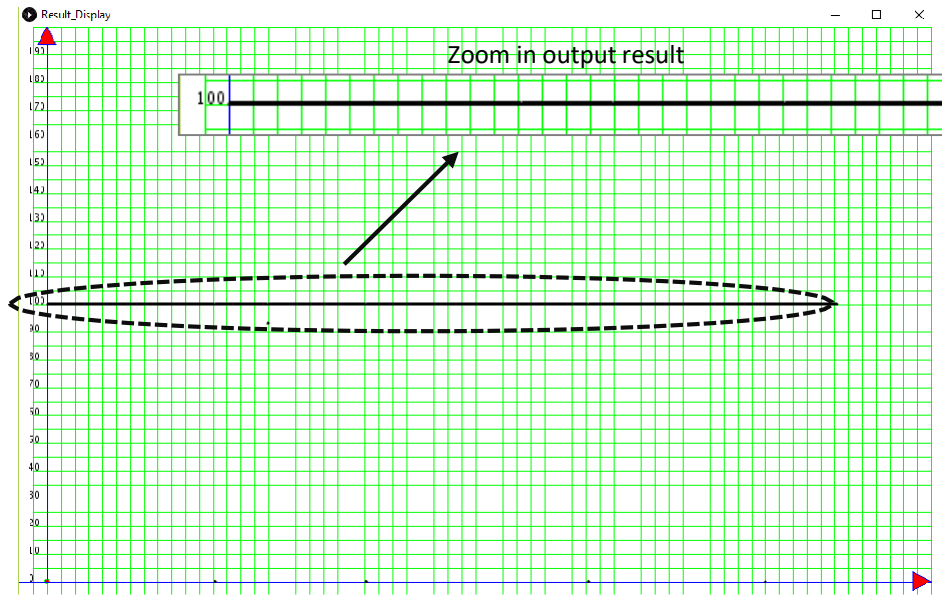


**Figure 9**. Consistent result display against time.

### 5.1 Output Test for Gait Knee Movement

Wooden rig with the device setup fixed on it was then used to obtain a result similar to a gait movement. Hence, the wooden rig was moved within an estimated angle of 40 to 110 degrees. Due to this movement, continuous and repeatable waveform graph was generated which shows the angle variation as illustrated in Figure 10. These kinds of results can be used to assist physiotherapist to identify the condition of the knee, or to decide if further rehabilitation is needed to allow the knee to recover based on angular symmetricity of different knee angle movement during the gait test.
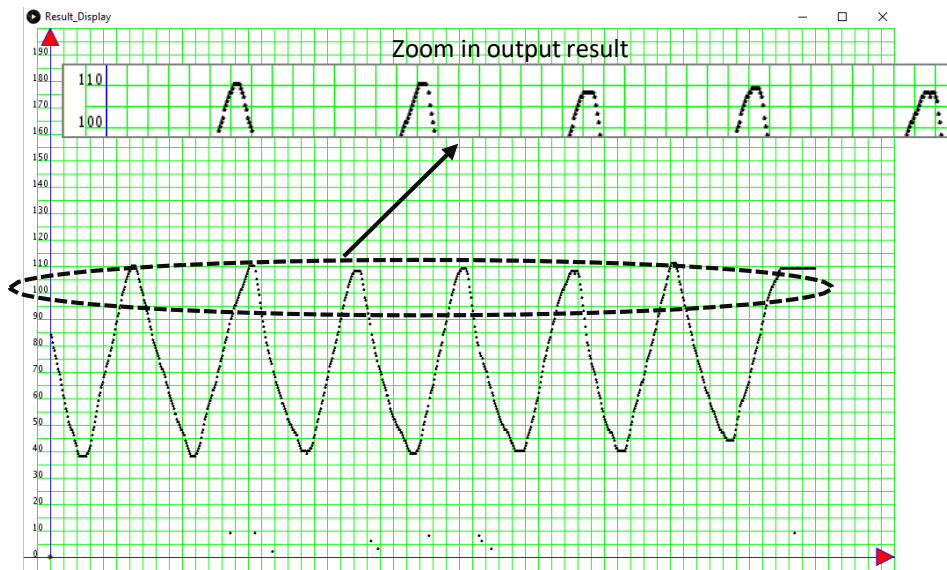
**Figure 10**. Gait waveform result resemblance

### 5.2 Output Test for Neutral to Maximum Knee Flexion Range

Another test was carried out to show the sensor output response to repetitive movements from neutral position (zero degree) to maximum range of flexion (at least 160 degrees). It can be observed in the graphical output of Figure 11 that the result plot begins at zero degree and then it increases consistently depending on the motion's velocity. As can be seen, upon the start of every waveform there is an error that can be detected which displays a result of 11 degrees while the actual angle is at zero degrees and then the graphical plot starts at zero degree again and re-correct its outcome. After thorough investigation on the issue, it is found out that the gear of the dynamic mechanism part requires slight alignment, the minimal misalignment has caused the light beam to differ from its correct direction and causes an error of 11 degrees at point zero degree. Other than that, the expected highest amplitude of the waveform is 160 degrees, whereas the actual device result shows a maximum amplitude of 155 degrees. The device was unable to provide any result at an angle of higher than 155 degrees. After investigating the error, this undetected 5 degrees is due to the width of the beam, as this sensor consist of 2048 pixels and each pixel width is 14um, hence, the 1mm width light beam needs to be further concentrated by using optical lens to concentrate the light into smaller beam diameter or by using smaller optic fibre cable to transmit smaller amount of light intensity to the pixels of the sensor.
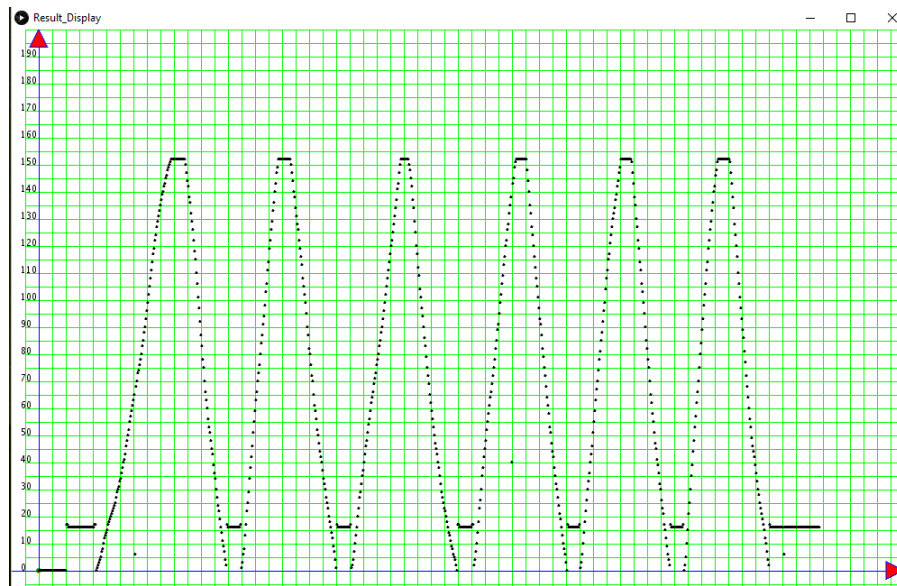
**Figure 11**. Neutral to maximum range of angle result display.

## 6.  Conclusion

A novel implementation of knee monitoring device using linear array photodiode is presented in this paper. The device working principle is basically based on the detection of light from an LED source on different pixel of light-sensitive area of the photodiode array sensor. The respective pixel of photodiode array that detects the light beam is directly used to represent the angle of the shaft of the device. The shaft movement in this case is the expression of knee joint angle in degree. The proposed device is able to continuously detect an angle of typical range of motion of the knee which is between 0 to 155 degrees. The results of the sensor output are good in terms of its accuracy (minimum 1 deg. angle), consistency (less than 1 deg. fluctuation/min) and with sufficient output resolution for the desired knee joint monitoring application. Although at current preliminary study, the device has shown some limitations especially when the shaft is repeatedly returned to its initial neutral position from maximum flexion, this concern will be solved in the near future before the sensor is applied for actual human test in laboratory setting. The advantage of this knee monitoring device is that it could measure a wide angle range of motion (up to 155 degree) as compared to other intensity modulation-based optical sensor for human monitoring application. Other improvement on the device performance will be carried out based on the initial results obtained from this study.

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