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# Device for 3D Analysis of Basic Movements of the Lower Extremity

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***Abstract*****—**This document details the process of developing a wireless device that captures the basic movements of the foot (plantar flexion, dorsal flexion, abduction, adduction.), and the knee movement (flexion). It implements a motion capture system by using a hardware based on optical fiber sensors, due to the advantages in terms of scope, noise immunity and speed of data transmission and reception. The operating principle used by this system is the detection and transmission of joint movement by mechanical elements and their respective measurement by optical ones (in this case infrared). Likewise, Visual Basic software is used for reception, analysis and signal processing of data acquired by the device, generating a 3D graphical representation in real time of each movement. The result is a boot in charge of capturing the movement, a transmission module (Implementing Xbee Technology) and a receiver module for receiving information and sending it to the PC for their respective processing.

The main idea with this device is to help on topics such as bioengineering and medicine, by helping to improve the quality of life and movement analysis.

***Keywords*****—**abduction, adduction, A / D converter, Autodesk 3D Max, Infrared Diode, Driver, extension, flexion, Infrared LEDs, Interface, Modeling OPENGL, Optical Fiber, USB CDC (Communications Device Class), Virtual Reality.



## I. Introduction

DAY by day are becoming more evident the human needs to create technologies in different subject of daily life, to achieve this purpose, it is wanted to take advantage of each knowledge acquired about new scientific areas. In this continuous process, bioengineering is looking for contribute to society. The computer analysis of human movement is a field that is increasingly taking a higher interest stimulated by the specter of possible applications. For example, by performing a segmentation of human body parts in an image or by tracking the movement of joints over an image sequence and recover the underlying body structure, it is particularly useful to analyze the athletes performance or for medical diagnoses [1].

In Latin America and other countries around the world have been conducting researches for biomedical area due to the boom in these technologies. For this reason, a sensing device-able to detect the movements of plantar flexion (bending the foot down), dorsal flexion (bending the foot upward), abduction (Movement of the foot to outside.), adduction (Movement of the foot to inside.) [2] and the flexion movement of the knee (Movement of the leg which the back of the calf is moved to the back of the thigh.) [3], is implemented in order to measure the angles which are generated by the joints. For the motion capture, a optical fiber sensor is built since it allows to carry light and data in a directional form, besides it has the following advantages: small size and low weight, noise immunity (Electromagnetic interference.), electrical insulation, it can work on hazardous environments, provide a wide bandwidth [4], easy connection of output optical signals with electronic instruments, minimum response times and high data transference rate. Additionally, infrared transmitter and receiver diodes are used (Depending on the intensity of the beam light it is possible to measure a voltage variation which is generated from a specific angle or distance.) but equally a virtual environment is designed to enable real-time display of each movement, for that purpose, OPEN GL libraries (Open Graphics Library. It is a software interface to graphics 3D scenes), were used to facilitate the coupling of the graphical interface to the modeling phase of the joints in 3D max studio (Software for 3D modeling, animation, which has a toolset for graphic design.).

## II. Device Design

One of the main characteristics that must be taken into account when using optical fiber as transmission medium, is the wavelength which it works so an specific type of transmitter and receiver can be determined and used according with the compatibility of this parameter.

The wavelength of light in optical fiber is 850 nm, 1310 nm or 1550nm [5], therefore the led (Light-Emitting Diode) used as transmitter for this purpose should have a wavelength equal to or similar to that of the fiber to facilitate the signal path in this way. Finally, the different types of existing diodes were compared and it is decided that the infrared diode has a wavelength close (greater than 750nm [6]) to the optical fiber

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so a better stable and suitable behavior is expected from this diode at the time of transmission data.

Single-mode optical fiber is used to send the data due to its special design. Minimum dispersion (It can guide and transmit a single beam light, a mode of propagation.) and has the distinction of having a high bandwidth [5]. Infrared diodes are designed especially for detection and positioning of objects, detection of shapes, colors and surface differences, even under extreme environmental conditions. Its emitted light is not perceptible to the human eye just by electronic devices [7].

*A. Sensor of Plantar and Dorsal Flexion*

For plantar flexion movement (Standard angle of 45º.) and dorsal flexion movement (Standard angle of 20º.) [8], the sensor developed is formed by:

1. Coupling system: Optical fiber 8 centimeters in length is used to develop this sensor. It is placed inside a black hose with the same length due to optical fiber is an element which has high sensitive and response to light environments. At one end of the hose is located the transmitter infrared diode and at the other end the receiver one, in this way optical fiber acts as conductive medium of light into the hose. The elements must be fully joined and isolated.

The sensor implemented is an optical type; in consequence it is necessary to minimize the noise sources for this kind of system. Otherwise, the influence of the colors that were chosen for the design of the sensor coating affects its sensitivity. In this case, a black color for hose and the box is selected because of the physical property it has for absorbing all kinds of different colors [3], greatly decreasing the leakage of light, in this way the correct environment is created the for functioning of the sensor.

2. System that enables movement of the hose: At one end of a black hollow box is fixed the infrared receiver diode. Inside the box, the distance from the diode to the other end of it, is used to displace the hose that belongs to the coupling system as shown in Fig.1.

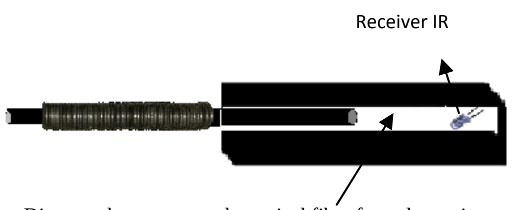


Fig. 1 Internal Structure of the sensor

3. Spring system: Once all materials have been arranged in the correct form it is required a component that will produce the displacement of the hose. For this reason, chose a spring connected end to end with the outside of the opposite end which has been placed the receiver diode. On the other hand, the other side of the spring is secured to the hose, so when the hose is pulled away by the movement of the join, the spring elongates getting away the beam transmitted through the optical fiber from the infrared receiver. In the opposite case, when the hose is directed inwards box the elements are completely at odds. How the elements were placed on the spring system is shown in Figure 1 in Fig.2.

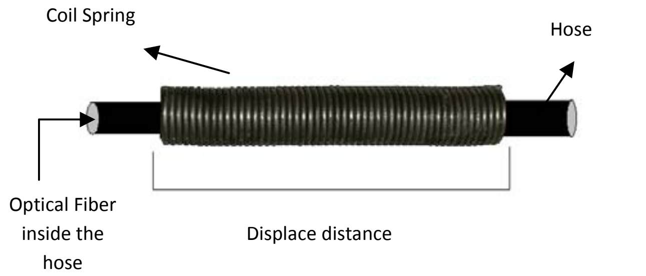


Fig. 2 System to generate displacement of the hose emulating the movement.

The change in voltage produced by the distance between optical fiber and the beam light of the receiver diode is measure through the sensor. It generates the displacement of the hose between the space into the box according to the angle of inclination of the foot.

Sensor Specifications:

1. Box Length: 7,5 centimeters
2. Box width: 2,4 centimeters.
3. Hose 8 centimeters in length and 6 millimeters in diameter.
4. Spring length: 3,3centimeters
5. Infrared diodes 3 millimeters in diameter.

*B. Sensor of Abduction and Adduction*

The same principle of the sensor of plantar and dorsal flexion is used for abduction (Rotation angle of 10 °.) and adduction (Rotation angle 20 °.) [8] sensor. The specifications are:

1. Box length: 10centimeters
2. Box Width: 2centimeters
3. Hose 12 centimeters in length and 6 millimeters in diameter
4. Spring Length: 3.7 centimeters
6. Infrared diodes 3 millimeters in diameter.

The box and hose length depend on the force needed to produce an effective elongation of the spring and consequently a considerable range of variation of data. In this case, the necessary force was achieved by lengthening the hose to the bottom of the ankle.

*C. Sensor of Flexion of the knee*

Following the same principle of making sensors, the sensor designed captures the variation of the angle of rotation of the knee for the flexion movement (It was measured up to a standard angle of 90º.). The sensor has the following specifications:

1. Box Length: 11,5centimeters.
2. Box width: 2 centimeters
3. Hose 30 centimeters in length and 6 millimeters in diameter.
4. Spring Length: 10 centimeters.
5. Infrared diodes 3millimeters in diameter.

## III. SENSORS LOCATION

A kind of boot was designed to support all sensors. It is divided into two parts: The top one supports sensor of the knee and the bottom one contains sensors of foot movements. The sensors are distributed as follows:

A. The sensor of plantar and dorsal flexion is located on the top of the tibia and tarsus, metatarsus and phalanges of the foot.

B. The abduction and adduction sensor is located on the fibula and at the outer edge of tarsus metatarsus and phalanges of the foot.

C. The sensor of the knee is along the femur and patella.

At the time a bracelet (Located on the ankle.) was made to allow a better stability of the device. This bracelet has a slot in the front to fit the sensor box of dorsal and plantar flexion movements. The other slot was located on the side to fit the sensor box of abduction and adduction movements. The final appearance can be seen in Fig. 3

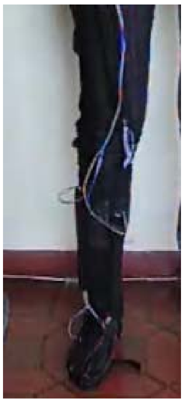

Fig. 3Final appearance of the device

## IV. DATA ANALYSIS

The following comparison tables are made by measuring the voltage variation caused by the proximity between the light transferred through optical fiber and the diode receiver.

The maximum value of voltage is the same of the power supply (5V) when these two elements are completely at odds. If the separation distance is greater, this value will decrease to reach 0V.

Sensed data are compared with established reference angles in medical studies of the joints for foot and knee. For analysis, the movements are measured from a reference to 0 º (Normal position), obtaining a voltage measurement as a function of angle.

Tolerance of the device refers to the margin of error of each sensor after the tests of repeatability. In most cases is stable with a tolerance less than 5%.

TABLE I
VOLTAGE VARIATIÓN Vs. ÁNGLE OF THE DORSAL FLEXIÓN MOVEMENT

| VOLTAGE (V) | ANGLE (º) | AVERAGE VALUE MAXIMUN ANGLE | RANGE OF TOLERANCE |
|---|---|---|---|
| 0,590 | 0 | | |
| 0,900 | 5 | | |
| 1,350 | 10 | 3,416 | 4% |
| 1,920 | 15 | | |
| 2,310 | 20 | | |
| 3,440 | 25 | | |

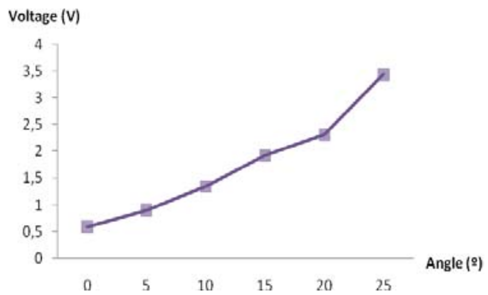


Fig. 4 Graphic for comparison between voltage and the angle of dorsal flexion movement

TABLE II
VOLTAGE VARIATIÓN Vs ÁNGLE OF THE PLANTAR FLEXIÓN MOVEMENT

| VOLTAGE (V) | ANGLE (º) | AVERAGE VALUE MAXIMUM ANGLE | RANGE OF TOLERANCE |
|---|---|---|---|
| 0,590 | 0 | | |
| 0,400 | 5 | | |
| 0,350 | 10 | | |
| 0,280 | 15 | 0,141 | 4% |
| 0,200 | 20 | | |
| 0,168 | 25 | | |
| 0,132 | 30 | | |

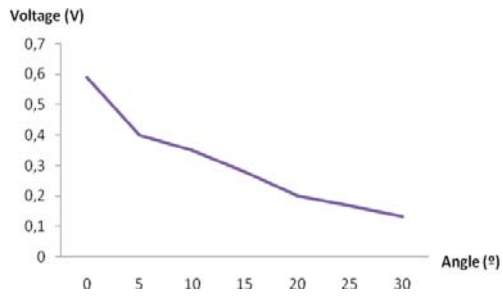

Fig. 5 Graphic for comparison between voltage and the angle of Plantar Flexion

TABLE III
VOLTAGE VARIATIÓN DE Vs ÁNGLE OF ABDUCTIÓN MOVEMENT

| VOLTAGE (V) | ANGLE (º) | AVERAGE VALUE MAXIMUM ANGLE | RANGE OF TOLERANCE |
|---|---|---|---|
| 4,860 | 0 | 4,932 | 2.24% |
| 4,890 | 5 | | |
| 4,940 | 10 | | |
| 4,950 | 15 | | |

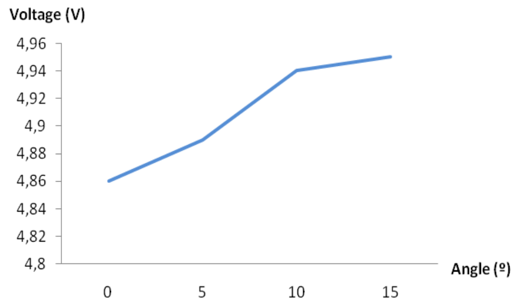


Fig. 6 Graphic for comparison between voltage and the angle of the abduction movement

TABLE IV
VOLTAGE VARIATIÓN DE Vs ÁNGLE OF THE ADDUCTION MOVEMENT

| VOLTAGE (V) | ANGLE (º) | AVERAGE VALUE MAXIMUM ANGLE | RANGE OF TOLERANCE |
|---|---|---|---|
| 4,820 | 0 | 2,866 | 5.12% |
| 4,280 | 5 | | |
| 3,800 | 10 | | |
| 3,200 | 15 | | |
| 2,850 | 20 | | |

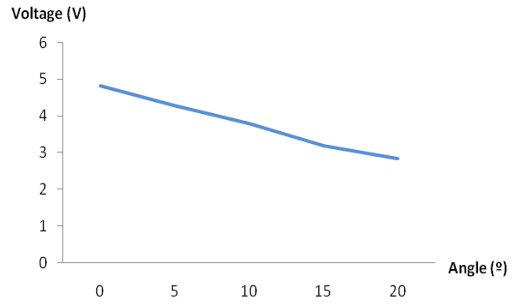


Fig. 7 Graphic for comparison between voltage and the angle of the adduction movement

TABLE V
VOLTAGE VARIATIÓN Vs ÁNGLE OF THE FLEXIÓN MOVEMENT OF THE KNEE

| VOLTAGE (V) | ANGLE (º) | AVERAGE VALUE MAXIMUM ANGLE | RANGE OF TOLERANCE |
|---|---|---|---|
| 4,300 | 0 | 0,506 | 3.12% |
| 3,970 | 10 | | |
| 3,450 | 20 | | |
| 3,050 | 30 | | |
| 2,620 | 40 | | |
| 2,100 | 50 | | |
| 1,550 | 60 | | |
| 1,300 | 70 | | |
| 0,730 | 80 | | |
| 0,520 | 90 | | |

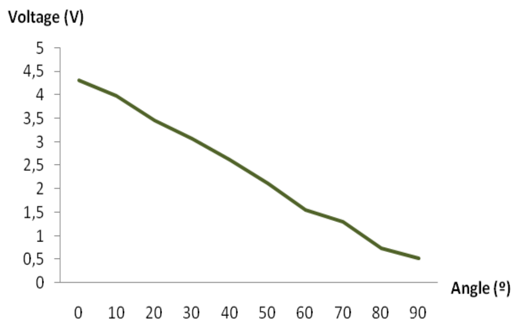


Fig. 8 Graphic for comparison between voltage and the angle of the flexion movement of the knee

As seen in the previous graphics the behavior that presents each of the sensors has a linear trend. However, there are intervals where abrupt changes are observed in some of the data captured mainly due to noise (Electrical Interference) in the system, or improper location of the sensors on a particular joint. For this reason, is important to note the proper location of the device to obtain excellent results for the analysis of the movement.

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## V. COMMUNICATION INTERFACE

A digital-analog converter (Convert an analog input of voltage into a binary value.) is used by a microchip 18f4550 microcontroller, it allows to emulate a virtual RS232 port via USB CDC communications (Communications Device Class.). One advantage of using this communication is that the circuit is smaller due to the power supply is the same that provides the computer. It makes unnecessary an external battery.

For the data transference and reception the information is decoded by using identifiers (Characters) between sensed data. This data are sent and read from the digital-analog converter (8 bits), thereby a variation of voltage was obtained from 0V to 5V depending on the deflection angle. What follows is to analyze the data in the next stage for the creation of the graphical interfaces. The information is encoded and decoded as shown in Fig 9.

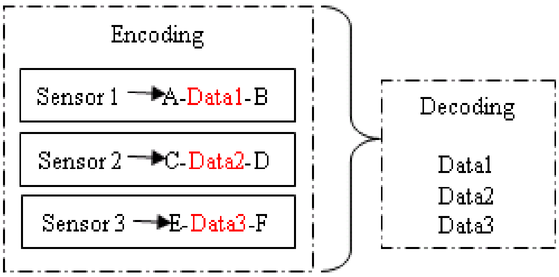


Fig. 9 Way for the data encoding and decoding

Additionally, wireless communication modules XBEE-PRO were implemented to provide comfort to users. The modules have the following features and benefits:

1. Power supply: 3.3V@ 215mA
2. Transfer rate: 250kbps Max
3. Scope: 1500 meters at external environment.
4. 6 -pin 10-bit ADC
5. Operating Frequency : 2,4 GHz
6. They can be used for RS232 and USB communication
7. Massive data transference. [9]

Figure 10 shows the arrangement of the wireless communication modules and the circuit of transmission and reception of data. It is observed that the small size of the elements makes the system portable and lightweight in order to provide greater comfort to the user.

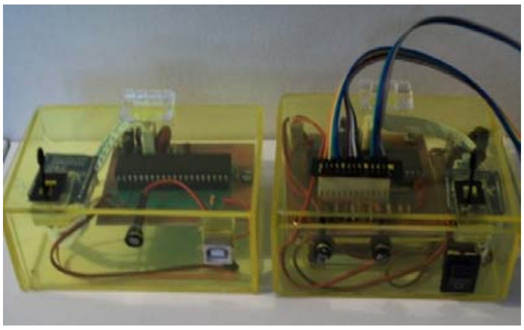

Fig.10 Circuit of transmission and reception of data by using wireless communication modules XBEE-PRO

## VI. VIRTUAL ENVIRONMENT

With Virtual reality can be played not only static scenes, but also analyzes dynamic by simulating the different objects and subjects movements in the stage. In this sector technologies for the analysis of human movement are assuming increasing importance. The applications of this methodology are numerous and range from ergonomic studies, for the human-environment and human-machine interaction, to the evaluation of the athletes performance or game development [10].

Working under the same line, a graphical interface was developed by using the Visual C + + compiler version 6.0. WINMM.LIB and wxctb-0.8.lib libraries were added to achieve a USB port communication.

The information is transferred to the computer and stored in a vector to analyze process and establish the specific data of each joint through of variables.

From the graphical analysis made for each sensor, it was showed that their behavior tends to be linear. For that reason, in order to reduce and soften the noise of information, these values were adjusted to a linear equation which has the following form:

$$y_{(x)} = m \cdot x + b \qquad (1)$$

Where **y** is the acquired angle, **x** is the input digital signal, **m** is the delta of the linear function and **b** is the offset of the signal.

Delta value is calculated with maximum and minimum values of the signal that is produced by the rotation of a joint. So it is possible to compare the maximum or minimum signal value with a maximum or minimum angle.

The first environment was designed from primitive shapes (Cubes, Spheres, Cones, and Cylinders.) and programmed in OpenGL. It has a menu that allows the user to know the interaction tools of the virtual environment as in Fig. 11 (a), and text boxes in which values of the angles of each movement are observed, as shown in Fig. 11 (b).

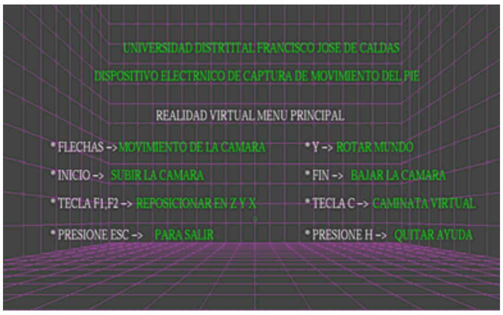


Fig. 11(a). Interface that shows a guide about how to use the commands to help users to interact in the virtual application.

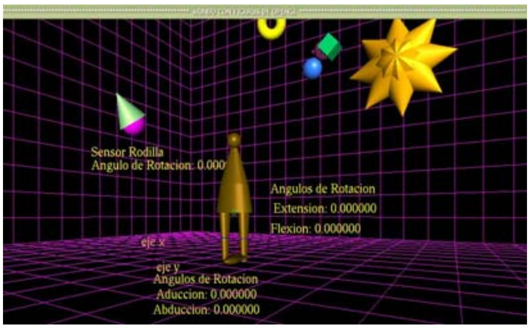


Fig. 11 (b) Virtual environment modeled on OpenGL primitive figures. Each movement can be observed and the rotation angles can be analyzed in the text boxes.

The second and third environments were modeled in Autodesk 3dmax, in addition to OPENGL libraries (Glui32, Alu and Alut.). The interface shown in Fig.11 allows window integration and sound generation, in order to obtain a more real environment. It has some buttons were a person hears about How to do a specific movement.

Fig.12 Graphical environment using sound libraries and buttons. The human body is designed by using the software 3D max Studio

The last application shown in Fig. 12 was designed in a soccer stadium. The player kicks the ball. At the moment it reaches the football arc the software specifies the type of movement done and the angle of inclination. It allows analyze athletes with excellent results on the field.

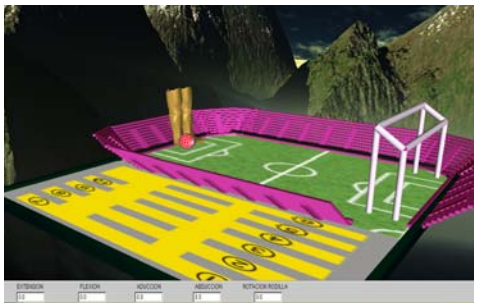

Fig.13 Interface developed to detect the angle of deflection for a soccer practice.

## VII. CONCLUSION

The device is reliable due to the tolerance it has by making the study of repeatability. The stability of the elements of the sensor, specially the optical fiber, facilitates the analysis of movements because of its wide range of variation. However, the system requires a good isolation due to the sensitivity of the sensors to light environments. The response of the system is on real time, and the technology used in the communication interface helps to reduce the electronic circuits, helping comfort. Finally, this device can serve as a basis for developing more complex virtual applications in the area of biomedicine. For example, relating the distance values from a deflection angle in order to detect any anomaly in the lower extremities.

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