

# Development of a Dynamic Goniometer with an Incremental Encoder

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**Abstract**— Angle dynamic measurements of body joints have become an important parameter to know for sportsmen, physicians and analysts of rehabilitation processes. The development of devices that allows those measurements turns out to be a hard work for biomedical engineers because during the acquisition process the mechanical system usually affects the natural joints movements. Digital goniometers have been constructed using different electronic principles, especially using resistance variations in potentiometers. In this paper we propose the construction of a dynamic goniometer with an incremental encoder using a mechanical transmission between a hinge and a pulley connected to an optical disk. The rotation is detected with an infrared led and a phototransistor. Calculations are done through a microcontroller and finally shown in real time using a liquid crystal display (LCD).

**Keywords**—Encoder, Goniometer, Orthosis, Phototransistor, Hinge.

**Resumen**— La medición dinámica de los ángulos articulares se ha convertido en un parámetro fundamental para deportistas, médicos y analistas de los procesos de rehabilitación. El desarrollo de dispositivos para estas aplicaciones ha presentado retos importantes debido a la imposibilidad de implementar los sistemas mecánicos requeridos para la medición, sin afectar el movimiento natural de las articulaciones. Los goniómetros digitales se han construido a partir de diferentes principios electrónicos, particularmente basados en las variaciones resistivas de potenciómetros. Este trabajo muestra el desarrollo e implementación de un goniómetro dinámico basado en un encoder incremental con un sistema de transmisión mecánico entre una articulación de tipo bisagra y una polea conectada a un disco óptico. La rotación se detecta con un LED infrarrojo y un fototransistor. El cálculo del movimiento angular en la articulación se realiza con un microcontrolador. Finalmente los datos se muestran en tiempo real en una pantalla de cristal líquido (LCD).

**Palabras Clave**—Encoder, Goniómetro, Ortesis, Fototransistor, Articulación tipo bisagra.

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## I. INTRODUCTION

Measurement of flexion and extension angles of the principal body joints, mainly knee and elbow, turns out to be of great interest in many areas of medicine and biomedical engineering, such as sports medicine, physiotherapy, biomechanics, and rehabilitation process as well as the control of the movement angles in post operative recuperation [1, 2]. Sportsmen and sport physicians need to know whether a physical activity is being done in the right way, and joints angles measurements are good parameters

than can be used for this purpose [3]. It is also important for rehabilitation processes of joint displacements when there is an atrophy or movement difficulty, because it is necessary to have information about the evolution reached with physiotherapy [4].

In postoperative recuperation from some surgeries as anterior cruciate and medial collateral ligament reconstruction, it is fundamental to have control of joints movements, because there is a high probability of injury or damage of the results already obtained after surgery. A partial control

is gained with immobilization systems such as braces or orthosis. However, those methods do not provide accurate information about the angle of movement because there are many factors with no control, such as soft tissue. The construction of a dynamic goniometer can be very useful for physicians, because it may provide accurate information about the angle of joints movements [5].

## II. MATERIALS AND METHODS

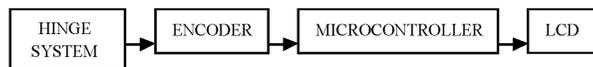
### A. Materials

Electronics: Optical sensor (GP1A71R, Sharp), microcontroller (PIC16F873A, Microchip), LCD display.

Mechanical: aluminum braces (for the hinge system), straps, Velcro, neoprene, rotary disk, band, hinge system.

### B. Methods

In the first stage (Fig. 1), an assembly is built to adapt the encoder to the joint movement where information about the angle is needed [6], which consists of a hinge system adapted to the joint of interest. The use of an encoder as a sensor, instead of other devices such as potentiometers or other optical sensors that use lasers (in the visible wavelength) is due to the high precision and resolution of these devices when determining the rotation of the encoder rotary disk.



**Fig. 1.** Block diagram of the dynamic goniometer developed. The joint movements are translated through a hinge system and detected with an encoder. A microcontroller interprets the encoder signal as an angle and it is shown in an LCD.

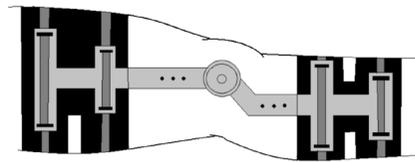
The outgoing signal of these devices has been widely studied, and its post processing is minimal because it is already digital [7]. Calibration of the outgoing voltage is easier and more trustful than in other logarithmic devices such as potentiometers. In fact, the only requirement for an accurate determination of the joint angle is to know the radius ratio of the disk in the hinge system and the rotary disk (toothed) that interacts with the optical sensor, and the number of slits (holes or black marks) in the toothed disk.

In the second stage, the outgoing signal of the encoder is taken to the microcontroller. It is decoded by translating the square signal of the sensor into exact values of the rotation angle of the rotary disk, and therefore the rotation angle of the joint that is being studied (this two can be equal or equivalent depending of the assembly built). The microcontroller could also be programmed to estimate the minimum and maximum angles, which could give more information for studying the joint movement dynamic.

Finally, the outgoing signal of the microcontroller is taken to a device that allows the visualization of the current angle, minimum angle and maximum angle during the movement. A good option in this stage would be using a LCD, which can be easily adapted to the microcontroller output.

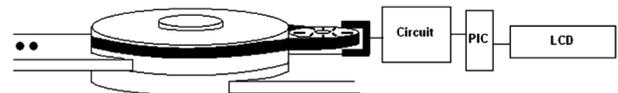
- *Principles of operation*

The first step to determine the joints angle with the goniometer with encoder is to adapt the rotation of the joint with the rotation of the rotary disk. A mechanical system, such as a hinge (Fig. 2) is attached to the joint of interest, allowing its movement, and its rotation can transmit angular movement to the detection system of the goniometer.



**Fig. 2.** Drawing of the mechanical system where the goniometer would be adapted. It was an original design of the authors.

The measurement system should not interfere with the natural movement of the joint, so special attention must be paid to the dimension and the attachment of the goniometer. Commercial encoders are very expensive and could also limit the attachment system because it would be necessary to adapt the design to the axis dimensions of these devices. The objective is to design an encoder for this special application, so the system fits perfectly to the required conditions, such as comfort and free movement.



**Fig. 3.** Schematic of the mechanical system for the activation of the encoder rotary disk. Block diagram for the post processing of the sensor output signal.

The encoder that is going to be implemented is shown in Fig. 3. It has two basic elements: a rotary disk and a pair diode-phototransistor, which are used to detect the disk movement. The connection between the rotary disk and the hinge system is done by a band transmission system.

To determine the measured angle, there has to be a relationship of proportionality between the number of revolutions of the hinge system and the number of revolutions of the goniometer rotary disk. This relationship is expressed by the radius ratio of the disks (hinge and goniometer), because of the equal displacement between them. It is supposed there is no sliding of the band along the disks.

$$2\pi R = 2r\theta\pi$$

$$\theta = \frac{R}{r} \quad (1)$$

From (1),  $\theta$  is equivalent to the number of degrees that the hinge system rotates for every degree of rotation of the goniometer disk. Because  $r < R$ , there is an increase in the resolution of the goniometer when using this mechanical system for angular movement transmission. For example, if the system was designed with  $r=R/2$  and the resolution of the encoder were  $\pm 1^\circ$ , so the resolution of the goniometer would be  $\pm 0.5^\circ$ .

According to the number of slits in the rotary disk, each pulse generated by the encoder will be equivalent to a defined angular displacement. The angle that the mechanical system displaces to produce a complete pulse in the outgoing signal is defined as  $360^\circ$  electrical degrees [8].

$$360^\circ \text{ electric} = \frac{360^\circ \text{ mechanical}}{N^\circ \text{ pulses / turn}} \quad (2)$$

The number of slits is always greater than one (each slit generates a pulse), so every mechanical degree is equal to a greater number of electrical degrees. As a result, there is an increase in the resolution in the measurement of the hinge angle, and therefore of the joint where it is placed. Each pulse of the outgoing signal indicates a variation in the angle of the joint which is given by a constant of proportionality  $Q$ .

$$Q = \frac{\theta}{N^\circ \text{ pulses / turn}} \quad (3)$$

Knowing the constant of proportionality  $Q$ , and multiplying by the number of pulses registered, it is possible to determine the number of degrees of displacement.

- *Circuit Schematic and programming*

The circuit used in the goniometer is shown in Fig. 4. The output signal of the optical sensor (GP1A71R) is carried to the microcontroller, which is used to determine the angles during the movement, and then data are visualized in an LCD.

The schematic is relatively simple, especially in the hardware required to take the inputs signals to the microcontroller. If a different photointerrupter sensor were used, it would be necessary to add a stabilizing stage, in which the noise derived from the light diffraction at the rotary disk slits transitions is eliminated in order to avoid any false pulse detection.

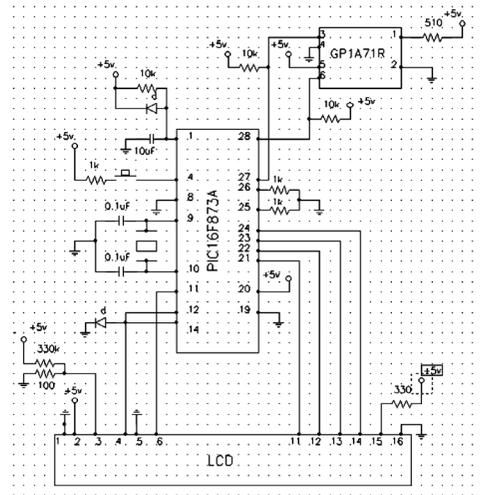


Fig. 4. Circuit built for the goniometer.

The GP1A71R photointerrupter has two output channels (named as A and B channel) where one signal is shifted  $90^\circ$  with respect to the other. This relationship between the signals A and B allows the determination of the spin direction (Fig. 5).

In Fig. 4, it is shown that the sensor output are connected to the 27 and 28 pins of the microcontroller, which correspond to the RB6 and RB7 (PORTB). The advantage of using this pins as inputs resides in the characteristics of the PIC16F87X family, because there is the possibility to use a special type of interruption that is activated when there is a change in the PORTB state (RB4:RB7). Therefore, in the schematic is shown that inputs RB5 and RB4 are connected to ground, avoiding any undesired change in the port state.

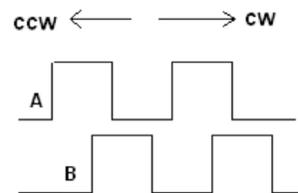
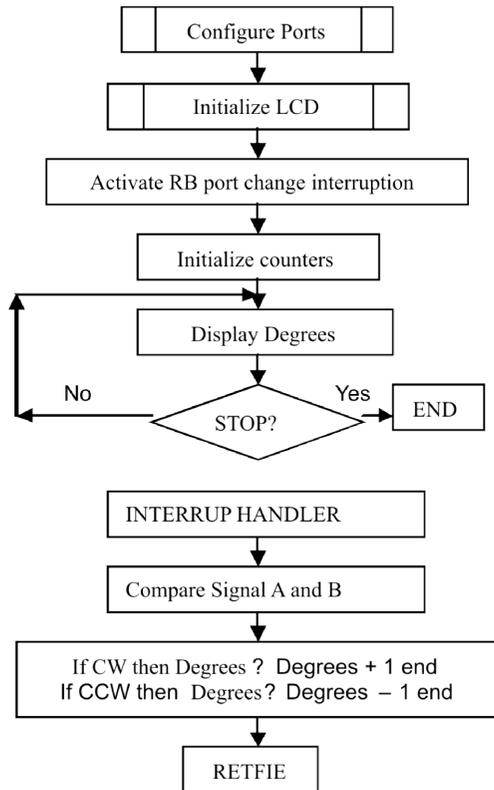


Fig. 5. Relationship between signal A and B. When rotating in counterclockwise (e.g. knee flexion) direction, signal B is the leader. CCW: counterclockwise. CW: clockwise.

The importance of using this kind of interruption is related with the resolution of the goniometer. For instance, if an event counter in the microcontroller were to be used for detecting the pulses, with a 36 slits rotary disk the total resolution would be  $\pm 10$  degrees, but if it were possible to detect both the high to low and low to high transitions the resolution would increment to  $\pm 5$  degrees. So, the interruptions provide information of both transitions, allowing a further increase in the resolution of the dynamic goniometer.



**Fig. 6.** Simplified flow diagram of the algorithm implemented. The detection of CW and CCW is based on the comparison between the interruptions  $I_i-1$ ,  $I_i$  and the  $I_i+1$ . So the direction detection is based on the state of the PORTB in three different states of the input signal (three transitions).

The implementation of the signal decoding using an appropriate interrupt handler eliminates the need for polling RB6 and RB7 state. The decoding process increases the algorithm efficiency and ensures the detection of all the transitions (i.e., information coded in A and B sensor channels) if the frequency of operation of the device is high enough. Although with a 4 MHz external oscillator the instruction cycle is approximately  $1\mu s$  and the angular speed of the joint movement is relative low, the amplified movement in the rotary disk and the need to detect every single interrupt derived from changes in both channels forced the implementation of a different oscillator with a 10 MHz frequency.

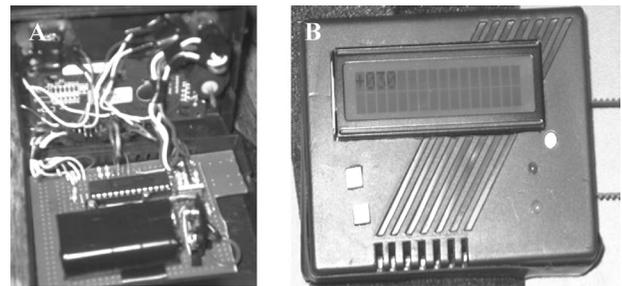
In the Fig. 6 a simplified flow diagram of the algorithm implemented is shown. The angle measurement is based on PORTB register value rather than RB6 and RB7 state (decoding process), including the changes due to the communication with the LCD through RB0-RB4. However, the angle information is contained in the last bits of the register, so an appropriate mask is required prior to deciding the spin direction.

Finally, the whole circuit is powered using a 9VDC battery which is taken to a 5V regulator. Eliminating the

need for an external power supply permits a great flexibility for the transport, adaptability (measuring in different conditions) and integrity of the device.

### III. RESULTS

In the final stage of the development of the dynamic goniometer with incremental encoder, a prototype was constructed (Fig. 7). The mechanical system of the incremental encoder gave a constant  $\theta$  equal to 5, with a hinge system of 5cm (disk diameter) and a pulley of 1cm (diameter) to transmit the movement to the rotary disk coupled with the photointerrupter. The band used was of 6mm width, and 25cm length. Besides, the number of slits in the rotary disk was 36. In this case, the resolution obtained is  $\pm 1^\circ$ .



**Fig. 7.** Prototype Photograph. A. Internally. B. Externally.

The resolution obtained is acceptable, especially when the available systems in the local market are considered. The linear and incremental aspects of the developed goniometer are interesting, bearing in mind that it is possible to measure any angle (from any start up position) and without the need of a complex process of calibration. The former characteristic is one of the main differences in respect to potentiometer based goniometers, which must be calibrated to a single start up position, so the reference is always the same. In contrast, in the encoder based goniometer, the incremental mode allows to register any angle between the initial position and any posterior joint movement, which can be positive or negative respect to the reference angle (start up position).

### IV. CONCLUSION

The performance of the encoder based goniometer was optimal, especially considering that the transmission system used was adapted from other devices (exclusively the pulley, rotary disk and transmission band). So, it would be a better choice to design the pieces specifically for this application.

Although the goniometer resolution is acceptable, this characteristic is one of the weak aspects of the device performance. Besides, there are several options to increase this resolution, and with no changes on the design, simply but re-calculating the constant of proportionality  $Q$  (e.g. reducing the pulley diameter, increasing the diameter of the hinge disk, and software processing). The future implementation of other goniometers with incremental encoder using the proposed design must consider the modification of the construction parameters, in order to reach a greater resolution of the device and to increase the advantages and interest for using (practical application) the goniometer developed.

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