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An FPGA-based design for optical encoder fault detection and correction

Diseño basado en FPGA para detección de fallas y corrección en encoders ópticos

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Abstract

High-accuracy industrial machines such as robotic manipulators and CNC machinery are highly dependent on optical encoders for achieving precise movements. These devices generate streams of pulses as feedback to the main controller for accurate electrical motor speed or position control. Due to high electrical disturbances caused by industrial machines, these digital pulses may get lost and cause significant current spikes and therefore damage on the controller's power circuitry. Several solutions have been proposed although these have been mainly restricted to fault detection at certain motor speeds. In this work, the authors propose a simple reconfigurable solution based on finite state machines which not only detects missing encoder pulses but can also regenerate them regardless of motor speed. Results were validated on computer simulations, as well as experimental implementation. The proposed architecture will be useful for researchers seeking a simple and precise method for optical encoder fault detection and pulse correction.

Quadrature encoder, Faulty pulse sensor, Electrical motor control

Resumen

Máquinas industriales de alta precisión, tales como manipuladores robóticos y maquinaria CNC son altamente dependientes de los encoders ópticos para lograr movimientos precisos. Estos dispositivos generan trenes de pulsos como retroalimentación al controlador principal para lograr un control exacto de la velocidad o posición de motores eléctricos. Debido a disturbios eléctricos en máquinas industriales, estos pulsos pueden perderse y con esto, causar transitorios de corriente que dañan la circuitería de potencia del controlador. Diversas soluciones han sido propuestas, aunque se limitan a simplemente detectar la falla en ciertos rangos de velocidad del motor. En este trabajo, los autores proponen una solución reconfigurable simple, con base en el uso de máquinas de estado finito, la cual no solo detecta la pérdida de pulsos en el encoder, sino que también puede regenerarlos independientemente de la velocidad del motor. Los resultados fueron validados en simulaciones de computadora y también en implementaciones experimentales. La arquitectura propuesta será útil para investigadores en busca de un método simple y preciso para detección de fallas en encoders y corrección de pulsos.

Encoder de cuadratura, Fallas sensor de pulsos, Control de motores eléctricos

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1. Introduction

Both robotic manipulators and CNC numerical control machines are an essential part of the automotive industrial machinery because they achieve highly repetitive and precise movements (Li-Ding y Jin, 2017). To execute the latter, these devices depend to a large extent on the use of optical encoders, which are mounted on each of the electric motors in order to quickly control their speed or position (Liu, 2002), (Belanger, Dobrovolny, Helmy y Zhang, 1998).

An optical decoder, more commonly called encoder (of its name in English), is an electromechanical device that generates one or more electric pulse trains based on any rotational movement of a motor; this allows the electronic controller to quickly determine its current speed or position of the arrow. The encoders are used in a wide variety of machines and can generate a wide range of pulses per revolution (ppr), starting from 100 ppr in printing equipment and reaching up to 10,000 ppr in industrial robots (Merry, Van de Molengraft y Steinbuch 2008).

Even though the encoders are extremely accurate and reliable, the train of pulses that they generate can be affected by external electromagnetic interference or disturbances in the electrical network, very common events in an industrial environment (Rothenhagen y Fuchs, 2008). When there is a loss of pulses in the line to the motor controller, a current transient occurs, which can cause damage to the electronic devices of the equipment. (Boggarpu y Kavanagh, 2010), (Alejandre y Artés, 2004), (Wang, Sun y Ooi, 2010). Even a high degree of vibration in the electric motor can create the same effect on the encoder pulses (López, Artés y Alejandre, 2011).

Various solutions have been proposed for the problem of loss of pulses in the encoders of industrial equipment, however, they have drawbacks of implementation or are simply limited to the detection of the fault. In the investigation of López and Artés (2012), a solution for the compensation of loss of pulses due to vibration is presented; this is based on Lissajous figures that was only validated by simulations and no experimental results are reported. In addition, the method is effective only in a certain range of engine speed.

Bourogaoui et. al (2015) presents a solution based on the application of the discrete wavelet transform, however, the system requires a high processing capacity in a personal computer and is limited only to detect the failure, without the possibility of compensating the loss of pulses, no matter how small.

In this work, the authors present a solution to the loss of pulses from a high resolution encoder, which is based on the use of finite state machines (FSM) in a low complexity digital architecture. Through this proposal, it is possible to quickly detect the loss of pulses, and also to generate them again, regardless of the speed at which the motor is working at that moment. In this way, user intervention is not required unless the failure is continuous or repetitive.

The proposal was implemented in an electronic card with low processing resources, which uses a field-reconfigurable gate array (FPGA, from the English Field Programmable Gate Array) Intel-Altera Cyclone V. The results were validated by computer simulations, as well as in experimental implementation using a 500 ppr encoder, in a DC motor working at a wide range of speeds; from 10 to 2500 revolutions per minute (rpm). The pulses were intentionally eliminated at different intervals and with different duration, without the controller registering on occasion, an increase in motor current.

2. Operation and construction of an optical encoder

An optical encoder is a specialized sensor, which is linked externally to the arrow of an electric motor. Its main function is to generate electrical pulses as the motor rotates and thus determine its speed, position and direction of rotation (Soloman, 2010).

Encoders can be classified, generally, as incremental and absolute; Incrementals generate one or more pulse trains with motor rotation. To determine the information of speed or position of its axis, a starting point is necessary and, from this, an electronic device keeps track of the number of pulses that were generated. In contrast, the absolute encoder, delivers a unique digital data for each position of the motor. In this way, it is not necessary to count the pulses since you have information of your radial location at any time.

Due to its simplicity of construction and low cost compared to the absolute encoder, the incremental is more used in high precision industrial machinery (Drury, 2009), which is why it is the central theme of this work.

The main operation of the optical encoder is based on the use of the light-emitting diode (LED). The encoder can have one or more LEDs, depending on how many pulse trains are required. There are single channel encoders; they are the simplest and most economical case, however, they apply only when the engine rotation is always in the same direction. When the direction of rotation is in both directions, two pulse channels are required (Figure 1), which are offset 90 °; this type of encoder is called incremental quadrature. In addition to the quadrature channels, it is possible that the encoder has a third output signal, called index (Z), which contains an electrical pulse for each complete revolution of the motor shaft. These signs can be seen in Figure 1.

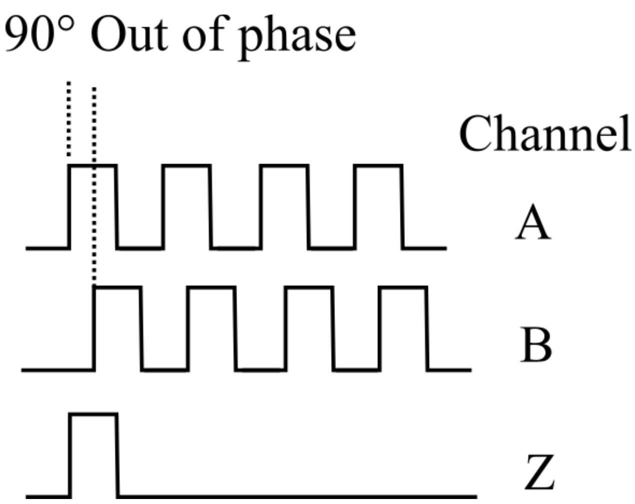

Figure 1 Output signals of an incremental quadrature encoder
Source: Self Made

Internally, the incremental encoder contains a transparent disk, which has a series of thin dark stripes along its circumference. This disk is fixed to the internal arrow of the encoder, which in turn is fixed to the arrow of the electric motor. The LEDs are placed on one side of the disk so that the beam of light emitted crosses the transparent disk and hits light receptors placed on the opposite side (Figure 2). When there is movement in the motor, each dark band of the disc momentarily blocks the beam of the LEDs, thus generating the pulses of each of the channels.

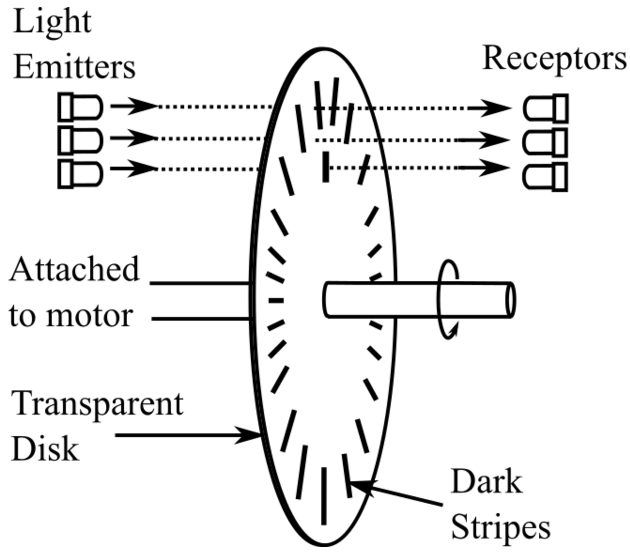

Figure 2 Internal construction of optical encoder
Source: Self Made

The number of slots per channel varies according to the resolution required in the encoder. There are low resolution encoders that can have 100 fringes in each quadrature channel; These devices are normally used in equipment whose mobile parts do not require high precision. An example is in printing equipment, in which the print head must move to a specific position to print the correct data. On the other hand, there is industrial machinery whose movements can be of the order of microns, as it is in CNC machining centers.

In this case, the optical encoders used can have up to 10,000 slots per channel, thus being able to generate a signal of pulses of very high frequency in each rotation. For this reason, the high resolution encoders are perfectly sealed to avoid the intrusion of dust, metal filings or liquids normally present in an industrial environment. In addition, the arrow of the device must be very well aligned and balanced, with bearings sealed so that, when the arrow is rotated, there is no minimum vibration between the components or even friction between the encoded disk and the emitters / receivers of the beam light.

3. Failures in optical encoders

The optical encoder is a highly reliable and long-lasting device, however, there are faults of different types that may occur. When this happens, there is an increase in the current of the power stage of the motor motion controller (Rothenhagen y Fuchs, 2008).

This is because, when the controller stops receiving pulses, it interprets it as an engine stop due to lack of power. Therefore, it increases the current to increase the torque in order to keep it moving. If there is still no movement, the current will be able to grow very quickly, damaging your electronic circuitry. In this way, it is important that the pulse train is not interrupted when there is a movement command from the controller.

One of the first faults in encoders may be due to vibration (López, Artés and Alejandre, 2011) or due to electrical disturbances in the power supply network. (Bourogaoui et. al, 2015). Whether due to defects in manufacturing or use, if there is a high degree of vibration in the device or if there are transients in the power supply, it is possible that there are losses of pulses or a deformation of them. This is because you can lose the square between the channels or if the emitters / receivers of light present friction against the encoded disc.

Another cause of failure is due to mechanical sensor problems (Bourogaoui et. al, 2015). Due to the high resolution of precision encoders, these are perfectly sealed to prevent the entry of external contaminants. However, due to the use and high speed of the shaft, over time the seals of the device suffer wear, which can allow the entry of oils, dust or even moisture. When deposited on the coded disk or on the light receivers, this causes intermittent losses of pulses in the quadrature channels.

4. Proposed solution

This paper presents a digital system implemented in an FPGA, which continuously monitors each of the pulse channels of the incremental encoder. The crucial information for the system is the duration of the sensor pulses and the quadrature between the channels. In this way, when one or several of them are lost, the pulse is reconstructed at the precise moment, so that the controller does not record it. Only in the case of a total loss of sensor pulses, the system sends an alarm signal and stops the process.

The design of the architecture is based on the use of FSM, because they allow the operation of synchronous circuits at high speed and with great efficiency, in systems with limited digital processing resources (Pedroni, 2013), (Tiwari y Tomko, 2005).

The proposed digital architecture is divided into two main modules, identified as the measurement module (MED) and the regeneration module (REG), and are shown in Figure 3.

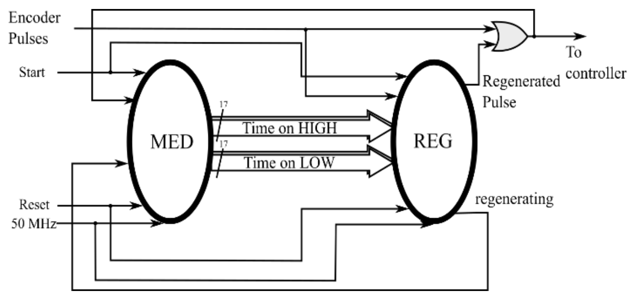

Figure 3 Block diagram of the proposed system
Source: Self Made

The MED function consists of constantly measuring the duration of time in high and low pulses of the encoder. These times are stored at each signal transition, in 17-bit registers. The function of the REG module is to regenerate one or several lost pulses, with the same time and square. Because the system uses a 50 MHz clock, it is possible to check the pulse signal every 60 ns, regardless of whether the motor works at different speed ranges or with high or low resolution encoders.

5. Pulse measurement module (MED)

In order for the system to work optimally, it is first necessary to have information about the pulses coming from the encoder. This signal is a train of square pulses that go to a high level and then to a low level constantly. The time in high or low is very important because it gives us an idea of the current operation of the motor. When it starts to work, the duration of the pulses is high, since the rotation starts relatively slowly and then acquires speed, where the pulses become increasingly narrow. In addition, the engine does not always work at the same speed so the pulse width changes constantly, however, it does so gradually.

To carry out the precise measurement of time, the MED module has a high speed state machine, which detects the change of flank in the channels; in each change, it enables 17-bit counters, which work at a frequency of 50 MHz and can detect changes in pulse width in less than 60 ns.

On each flank of the pulse, the duration of the level is passed to asynchronous registers, in which the information is retained to be compared (in the REG module) with the information of the previous pulse. In this way, if the difference is greater than a tolerance programmed by the user, it means that there was a loss of pulse. The architecture of the MED module is shown in Figure 4.

To avoid entertaining the FSM in any other activity, the only function of the MED module is the measurement of high and low times. Decision making about whether a missing pulse occurred is carried out in the REG module.

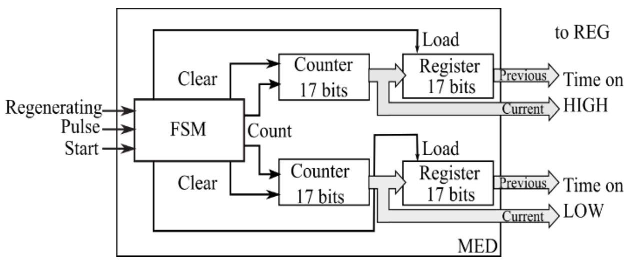

Figure 4 Architecture of the MED module
Source: Self Made

It should be noted that MED can receive two types of pulses: the first are pulses coming directly from the motor encoder. In this particular case, it continuously measures the duration of the pulses and is stored in registers. This information is also sent to the REG module, in order that the regenerated pulses are identical to the last pulse received.

Another type of pulse that can receive its input, are the pulses that were already regenerated by the REG module before the detection of a lack of pulses. In this situation, it carries out the measurement of the pulses, however, it does not save the new information in the registers, because it is a temporary pulse. Once it has been detected that the original signal of the encoder has already been restored, until then it returns to its function of measuring and saving.

6. Pulse regeneration module (REG)

To determine if there was a missing pulse, the high and low time information coming from the MED module is used. With this information and based on the tolerance time provided by the user, an FSM of 8 states determines if there was a missing pulse or the engine is only changing speed.

Even if the motor is working at the same speed, the pulses of the encoder do not always have identical times, so it is very important to provide a small tolerance. This tolerance will depend on the speed ranges at which the motor will work and the encoder resolution. The algorithmic state diagram of the FSM is shown in Figure 5 and is described below.

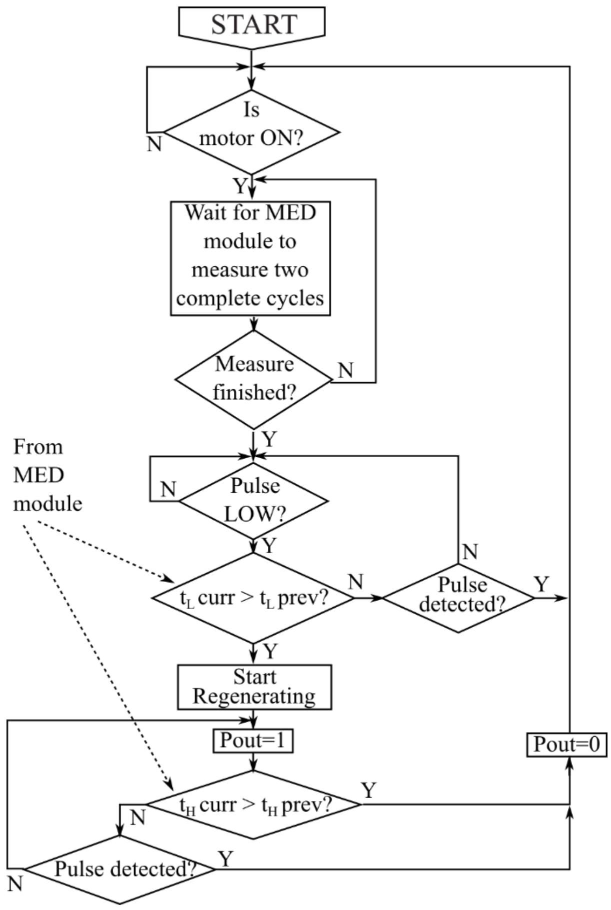

Figure 5 Algorithmic diagram of the FSM of the REG module
Source: Self Made

The process starts when a command is received to start the engine. In this case, it is necessary to first measure the width of the pulses, to have an initial reference data. In this way, it is first identified if it is a high or low pulse, and then it passes to a pair of empty states where the REG module does nothing, however, it allows the MED module to carry out the corresponding measurements of the pulses of the encoder and store them in synchronous registers. Immediately wait until a low level is present, since it is in this part of the signal that the lack of a pulse would be observed. Once the low level is identified, start comparing the time against the time of the low level in the record. If a high pulse is presented in the expected time, the next low level is expected again.

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Otherwise, it means that there is a missing pulse and goes to the regeneration stage where it sends a high level to the output, while its time is compared to the last time stored in the MED module record. Once the time has elapsed or if the pulse train of the encoder is reset, the FSM exits the state of pulse reconstruction, verifies that the start command remains active and the process is repeated indefinitely.

7. Simulation Results

The hardware encoding on the FPGA card was made using the VHDL language, using the Intel-Altera Quartus Prime Lite platform. For the electronic simulation, Modelsim Altera-Edition was used, in which multiple tests were made with two quadrature channels at different frequencies and pulse widths, to simulate different resolution encoders working at different speeds. In addition, a circuit was designed separately in the FPGA, which allows to carry out the erase of pulses at different times. In this way, when receiving an external pulse by the user, it can block any of the quadrature signals by programmable intervals ranging from microseconds to milliseconds. This in order to force the erasure of pulses and, at that moment, verify that the pulse or its square are not lost.

In the first simulation shown in Figure 6 (a), quadrature signals (PAi and PBi) are included for a 500 ppr encoder rotating at 1500 rpm. In this case, the erase time was set to 1 ms. To initiate the elimination of pulses, a signal is sent in low (BORR_A o BORR_B). A signal in high (ERASING) indicates that the period of elimination of pulses is in process. It can be seen that the quadrature signals (PA0 and PB0) of output are completely eliminated when the pulse regeneration system is disabled.

On the other hand, in Figure 6 (b) once the proposed system has been enabled, it can be observed that the quadrature signals (PA0 and PB0) of output remain identical to the input signals and have not suffered any loss or loss of squareness.

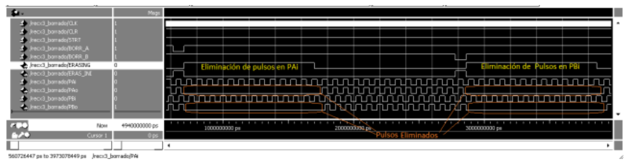
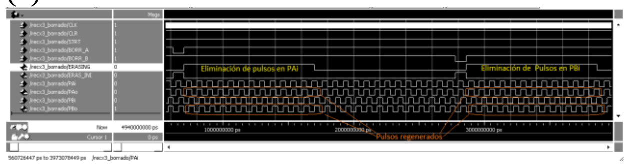

(a)

(b)

Figure 6 Computer simulation using Modelsim for an encoder of 500 ppr and a rotation speed of 1500 rpms where the pulse output (a) is shown with the proposed system deactivated, and (b) with the regeneration system enabled. Both signals had a pulse elimination time of 1 m
Source: Self Made

Simulations were carried out for different resolutions and rotation speeds, presenting all signals identical to the input ones, thus giving validity to the proposed architecture.

8. Experimental results

For the experimental validation, a direct current motor with brushes and a quadrature encoder of 500 ppr were used. The engine has a Pololu VNH5019 sensor, which allows monitoring the behavior of its current. Both the pulse signals of the encoder and the current signal are displayed in the LabVIEW © software through the use of a myRIO-1900 module from National Instruments.

The digital architecture of the proposed system was implemented in the Intel-Altera DE1-SoC development card, which uses the FPGA Cyclone V 5CSEMA5F31C6. The complete system is shown in Figure 7.

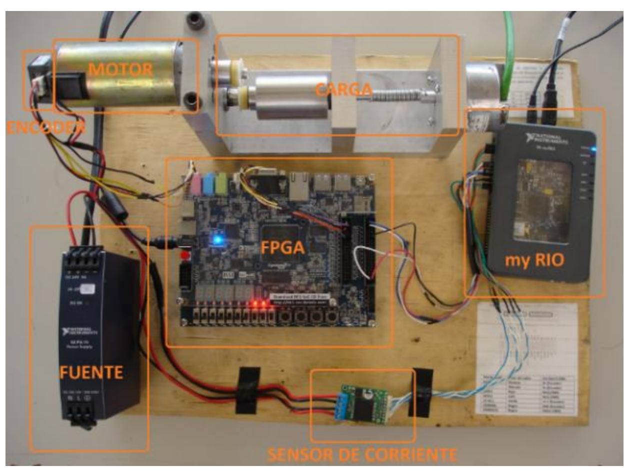
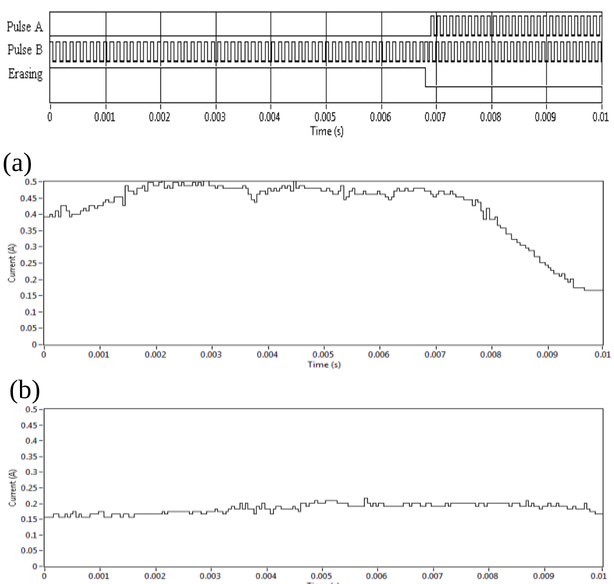


Figure 7 Complete implementation of the proposed system on the DE1-SoC card
Source: Self Made

As was done in the validation by simulation, tests were carried out at different engine speeds, with ranges from 100 to 2500 rpm. The pulse channels of the encoder pass through the FPGA card and then continue to the myRIO module; this in order to be able to eliminate the pulses with different periods, which ranged from 100 μs to 100 ms, depending on the speed of the motor.

In Figure 8 (a), the signals for a test at 1000 rpm can be observed using periods of 7 ms pulses. In principle the engine is made to work and a pulse is sent manually to initiate the elimination of pulses of channel A for the aforementioned time. During this period, the ERASING signal remains high to indicate that the system is blocking the pulses of channel A, while the REG module is regenerating them and sending them to the motor controller.

Figure 8 (b) shows the behavior of the current when the pulses are eliminated and the regeneration system is disabled. In this case, the motor current rose to more than double its nominal value because no encoder pulses were recorded. Once the system is enabled, it is observed in Figure 8 (c) how the current stays within its normal range during the erase time.



(c)

Figure 8 Experimental results observed in National Instruments LabVIEW © software, (a) when encoder pulses from channel A are eliminated, the behavior of the motor current (b) with the regeneration system disabled is observed, and then (c) with the system enabled
Source: Self Made

9. Conclusion

In this work, the authors have presented a reconfigurable system for detection and regeneration of lost pulses in incremental quadrature encoders. This digital architecture in FPGA based on finite state machines, allows a quick compensation of this type of failure regardless of the working range of the electric motor or the resolution of this type of transducer. Through computer simulations and experimental results, it was possible to verify that the system allows detecting and correcting the pulse problem in time, without the characteristic increase in motor current.

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