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REDUCED MEASUREMENT TIME IN ABSOLUTE PSEUDORANDOM OPTICAL ENCODERS

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Abstract. *Optical rotary pseudorandom encoders are an excellent solution for reliable and precise angular position measurement in various industrial motion systems. The paper describes an improved optical rotary pseudorandom encoder solution that has a reduced angular position measurement time. The presented encoder uses two heads to read the pseudorandom code and to form the main and control code words. The encoder algorithm has been improved so that code conversion is not performed after each new code word. In presented solution, after each new code word, a code reading error checking is performed, and the position is determined based on the previous measured value if no code reading error is detected. The functionality of the proposed encoder solution in the LabVIEW environment is tested.*

Key words: *Pseudorandom binary sequence, digital position measurement, optical position encoder, measurement time.*

1. INTRODUCTION

Modern motion systems are constantly raising demands regarding the performance of angular position measurement, with optical encoders being most commonly used for these purposes. This primarily relates to resolution, accuracy, measurement time, and reliability of angular position measurement [1, 2, 3, 4, 5]. According to the principle of operation, optical position encoders can be of absolute and incremental type. Pseudorandom optical encoders, as

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a special type of absolute encoders, have a single code track on the disk that is encoded with a pseudorandom binary code, [3, 4, 5]. The serial (cyclic) nature of the pseudorandom binary code has enabled serial reading of the code, but parallel reading can also be implemented [6, 7]. Since adjacent code words differ in only one bit, to form a new code word it is necessary to read one new bit from the code track. The read bit, together with the previous n-1 bits, located in the buffer, forms a unique code word that is used to determine the angular position. If an n-bit pseudorandom binary code is applied to the code track of the encoder, then a total of 2^n-1 different code words are distributed on the code track. Because a pseudorandom encoder has a single code track, a smaller diameter disk can be used, compared to a classic absolute encoder of the same resolution.

Serial reading of a pseudorandom code can be implemented with one or two reading heads [6]. For parallel reading of a pseudorandom code, individual photodetectors or a linear array of photodetectors [7] can be used. Serial reading enabled the use of a smaller number of photodetectors compared to classic absolute encoders. The moment of reading the pseudorandom code is defined using a signal from a synchronization track located next to the pseudorandom code track. Synchronization of pseudorandom code reading can be achieved without an additional synchronization track, but by applying additional encoding of pseudorandom code bits [8]. In addition to synchronizing code reading, signals from the synchronization track are used to determine the direction of rotation of the encoder disk, and can also be used for hybrid operation of the encoder in order to increase its resolution. Unlike classic absolute encoders, pseudorandom encoders can use advanced algorithms to automate the definition of the zero position when mounting the encoder [9]. In the process of determining the angular position in pseudorandom encoders, it is necessary to convert the pseudorandom code into a natural code after forming the code word, [10, 11]. Serial converters are simpler in hardware but the conversion time is longer compared to parallel converters. Serial converters use a Fibonacci pseudorandom sequence generator, while parallel converters use fast memory during code conversion. Serial-to-parallel converters are a compromise solution suitable for use with very high resolution pseudorandom encoders. Pseudorandom encoders can also use various methods to check code reading errors, with the aim of increasing reliability in work, [12, 13, 14]. Research on pseudorandom optical encoders is mainly focused on increasing the resolution, accuracy, and reliability of angular position measurements, as well as reducing the position measurement time. Reducing the angular position measurement time can allow for faster rotation of the encoder disk. It is also always a goal to reduce the diameter of the encoder disk, which leads to a reduction in the size of the encoder, also a reduction in power consumption and in the price of the hardware used to implement the encoder.

The first part of the paper describes the operating principle of a pseudorandom encoder and the process of determining the angular position, while considering the components that contribute most to increasing the measurement time. Then, an improved pseudorandom encoder algorithm is described, which allows for shorter measurement time. The proposed algorithm was analyzed and tested by implementation in the LabVIEW environment. The operation of the encoder under ideal conditions without the presence of code reading errors was analyzed, as well as operation in various scenarios of the occurrence of code reading errors.

2. WORKING PRINCIPLE OF THE PSEUDORANDOM OPTICAL ABSOLUTE ENCODER

The pseudorandom encoder disk, whose operating algorithm will be improved in terms of reducing position measurement time, contains one synchronization and a pseudorandom code track next to it, Fig. 1. Reading the pseudorandom code is done serially using two reading heads $x(0)$ and $x(n)$, which are at a distance of nq, where q is the quantization step of the code track, and n is the resolution of the pseudorandom code [6]. Using two heads to read the pseudorandom code enables continuity in the formation of code words when changing the direction of rotation of the encoder disk, as well as the application of a reliable method of checking the code reading error [13]. The bits read from one head are used to fill the buffer when forming a code word in one direction of rotation, while the bits from the other head are used in the opposite direction of rotation. A reliable method of checking code reading errors, described in the reference [13], uses the fact that the main code word formed by one code reading head and the control code word formed by the other head are at a fixed distance from each other. The checking of the fixed distance between the main and control code words is done using a Fibonacci pseudorandom binary sequence generator. In addition to the two heads for reading the pseudorandom code track, two more heads, AUT and VER, at a distance $q/2$ are used to read the synchronization track. The signals from these heads are used to define the moment of reading the pseudorandom code, as well as to determine the direction of rotation of the encoder disk (CCW or CW), Fig. 1.

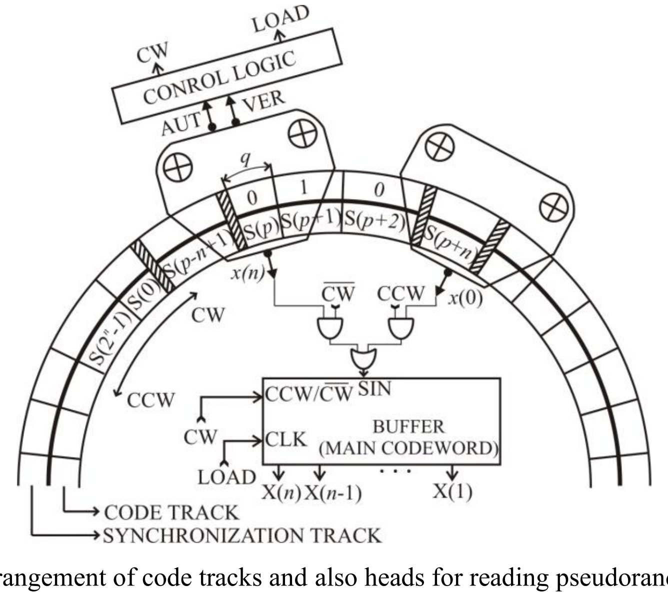

Fig. 1 Arrangement of code tracks and also heads for reading pseudorandom code

The small distance between the code reading heads in Fig. 1 must be fixed, but during long-term operation of the encoder in industry it may change under the influence of temperature, vibration, shock. In extended research, the possibility of introducing another phase-shifted pseudorandom code track, so that the reading heads can be in line, one below the other, has been considered in order to minimize the problem.

3. Error Checking and Pseudorandom Code Conversion Using Fibonacci Generator with Inverse Feedback

According to the usual algorithm of operation of a pseudorandom encoder, after the formation of the main and control code words, a check for code reading errors is performed. If no error is detected, the main code word is converted from pseudorandom to natural code and the angular position is determined, Fig. 2. The paper uses an example of a 6-bit resolution pseudorandom encoder to describe its operation. Pseudorandom to natural code converter based on a Fibonacci pseudorandom binary sequence generator with inverse feedback is used, Fig. 2. For the case of pseudorandom to natural code conversion, this code converter is used to calculate the distance of the read code word from the reference code word, which corresponds to the zero position. The number of clock periods required to complete the code conversion depends on the position of the read code word relative to the reference code word. Thus, $1 \div (2^6\text{-}1) = 1 \div 63$ clock periods may be spent on the code conversion in case of 6-bit pseudorandom code. The angular position measurement time is calculated for the case where the code converter needs the most clock periods to complete the code conversion. A code converter with the same structure as in Fig. 2 is used to check for code reading errors, whereby the read code word (main) is loaded into the Fibonacci generator and its distance from the control code word is calculated, whereby the same value should always be obtained for the case when there are no code reading errors.

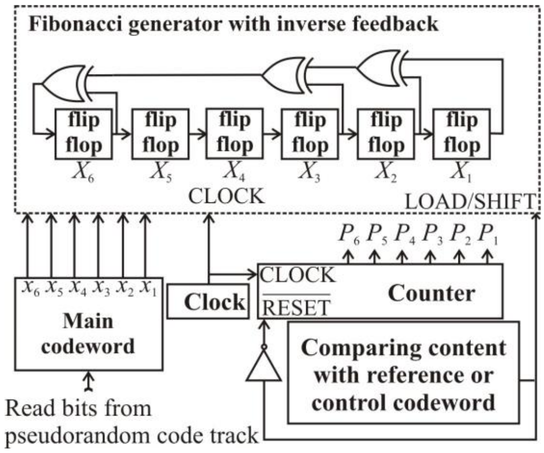

Fig. 2 Serial pseudorandom to natural code converter

The basic principle of operation of the proposed improved pseudorandom encoder with reduced angular position measurement time is described using the algorithm in Fig. 3. As a consequence of the serial reading of the pseudorandom code, when starting the encoder, an initial movement is required to read *n* bits and form the first valid code word and angular position after code conversion. After that, by reading new bits from the pseudorandom code track using the $x(0)$ and $x(n)$ reading heads, the main code word as well as the control code word are formed. A code reading error check is performed and if there are no errors, the code is not converted, as in the case of normal pseudorandom encoder operation, but the position is obtained by incrementing or decrementing the previous position value depending on the direction of rotation of the encoder disk. In the event of a code reading error being detected, the encoder switches to incremental mode using signals from the synchronization track. During incremental mode, a constant check is made for code reading errors from the pseudorandom code track, so that the encoder can return to normal operation. Incremental mode can only be present in one part of the code track where code reading errors occur. In paper [13], it was shown that the applied method of checking code reading errors is reliable, i.e. every code reading error is detected. For the case of the code word with the longest conversion time, the read main codeword is $2^n - 1$ clock periods away from the reference code word. Whereas in the proposed solution, for each read code word, n clock periods are always required to perform a code reading error check. By applying the previously described mode of operation of the encoder, in which the code conversion is performed once, and a reliable method of checking the code reading error is applied in the further operation of the encoder, the position measurement time would be significantly shortened.

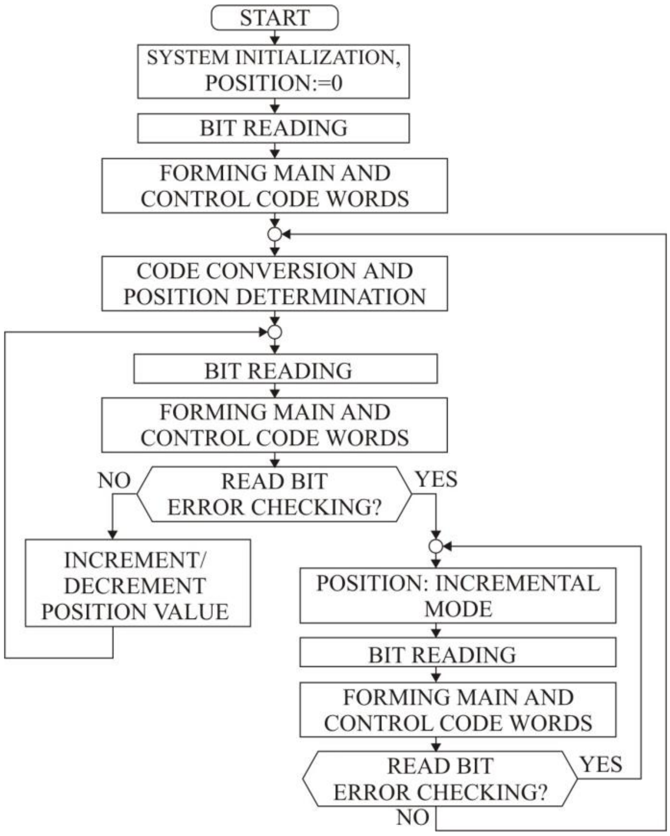

Fig. 3 Improved algorithm of operation of pseudorandom position encoder

There are numerous causes of code reading errors, some of which are: disk eccentricity, slits print quality, poor centering of the fixed slit and read heads, contamination of the code track, vibrations, shocks, the influence of temperature, humidity, etc. Also, various external influences such as temperature or vibration can change the distance between the code reading heads in Fig. 1, and this leads to code reading errors in high-resolution encoders.

4. Encoder Operation Simulation in LabVIEW

For the purpose of testing and analyzing the functionality of the proposed pseudorandom encoder solution, the encoder algorithm was implemented in the LabVIEW environment, Fig. 4 and 5. The reading of bits from a pseudorandom code track with a resolution of 6 bits was simulated, but the same principles and conclusions can be applied to any resolution encoder. The pseudorandom binary sequence used for code track on disk is generated by a Fibonacci generator having a [6,5,4,1] feedback configuration for the direct generation law. All bits of the code track in the form of one-dimensional array were inserted into the block diagram of the virtual instrument and serial reading of the bits with two heads for both directions of disk rotation was simulated, Fig. 5. Bits from the simulated code track are used to form the main and control code words in two separate buffers. The codeword 111111 is chosen for the reference code word, which corresponds to the zero position. Reading bits from the code track was simulated for both directions of rotation of the encoder disk. When starting the encoder, it operates in initialization mode until the first valid code word is formed.

The front panel of the virtual instrument allows the user to change the starting position from which the code track reading begins. Also, the contents of the buffers for the main and control code words can be viewed on the front panel, and the measured position value can be monitored on a chart in the form of a graph or as the position of the pointer on the gauge. On the right side of the front panel, the measured position value is paired with an indicator that signals whether the position was determined in the normal or incremental encoder operating mode. Serial code converter based on the Fibonacci generator uses a [6,5,2,1] feedback configuration for the inverse generation law is implemented in block diagram, Fig. 2. To implement the code conversion process, the content of the flip-flops of the Fibonacci generator in code converter is compared with the reference codeword 111111. The same code converter is used to check for code reading errors after each new bit read, when the content of the flip-flops of the Fibonacci generator is compared with the control code word obtained by the second head for reading the code.

After each new bit is read and the main and control code words are formed, a check is made for the code reading error. If there is no code reading error, the position is determined by decrementing or incrementing the previous position value, depending on the direction of rotation, which significantly reduces the time for determining the position. The decrement or increment operation of the position takes one clock period, while the code conversion can take from one to 63 clock periods in this specific example of a 6-bit pseudorandom binary sequence. In this way, the angular position measurement time was significantly reduced. This significantly increased the speed of position measurement using the proposed encoder, i.e. the encoder disk can rotate faster.

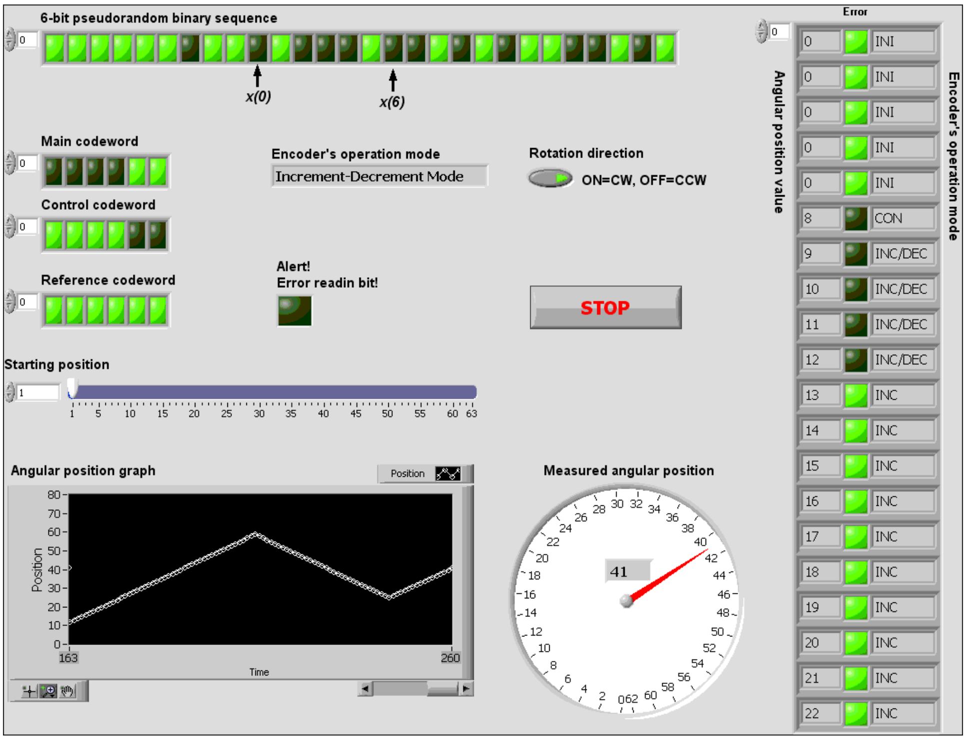

Fig. 4 Front panel of implemented pseudorandom position encoder

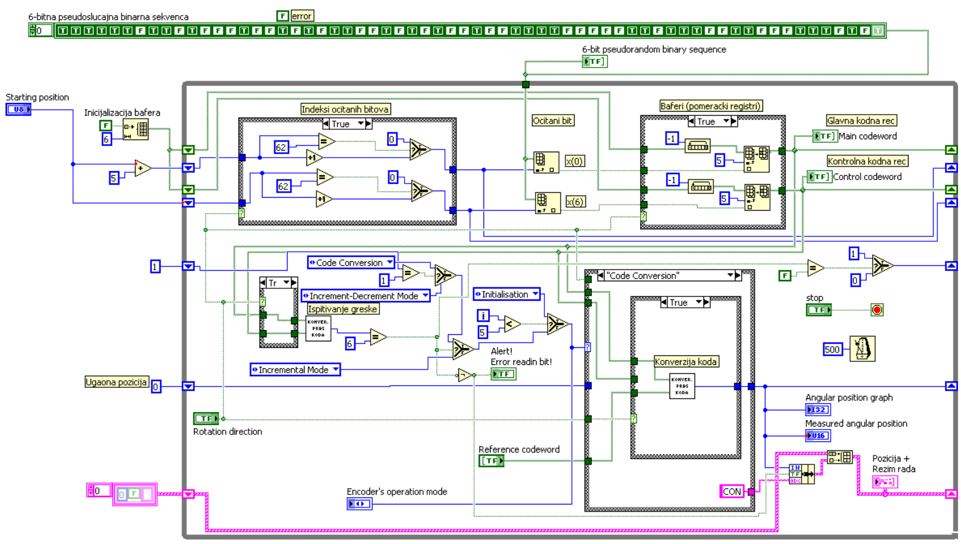

Fig. 5 Block diagram of implemented pseudorandom position encoder

The duration of the conversion process depends on the position of the read codeword relative to the reference code word, and the worst case is when the read code word is the furthest from the reference codeword. The position measurement time of the improved pseudorandom encoder consists of the sum of the time required for error checking and the duration of the clock period for incrementing the position. This time is shown in Table 1 for a clock frequency of 12 MHz and different code resolutions. Also, the position measurement time consisting of the sum of the time required for error checking and the time required for code conversion is shown in Table 1. The table also shows the percentage savings in the time required for angular position measurement. Thanks to the application of a reliable method of checking the code reading error, it is not necessary to perform code conversion for each newly formed codeword. As the encoder resolution increases, there is a greater saving in time that would be spent on code conversion when determining the angular position.

In the part of the code track where the bits cannot be read accurately, the encoder would work with reduced reliability in the incremental mode of operation, and in other parts of the code track it would work in the normal mode of operation. The encoder operating algorithm was first tested for different encoder disk movement scenarios in the case where there are no misread bits. When simulating the operation of the encoder in the case of a read bit error, before starting the encoder, a particular bit of a pseudorandom code was intentionally entered incorrectly in the block diagram. Different scenarios can be created with one or more error bits at different locations along the code track and the behavior of the encoder's operating algorithm can be monitored. For example, if a code reading head $x(6)$ misreads just one bit, it causes at least 6 consecutive code words to be incorrectly formed, which is detected by the error checking method. Then that same bit can also be misread by another head $x(0)$, causing at least 6 more code words to be incorrectly formed. That is, one wrong bit causes the encoder to exit normal operation mode and transition to incremental operation mode in minimum 12 consecutive position values. With a higher number of incorrectly read bits, the encoder stays in incremental mode longer time. The encoder exits incremental mode when the error detection method does not detect a code reading error.

Table 1 Position measurement time for a clock frequency of 12 MHz

Resolution of pseudorandom code	Measurement time for encoder with code conversion	Measurement time for improved encoder	Time saving in percentage
6-bit	5.75 μs (63+6 clock periods)	0.58 μs (1+6 clock periods)	89.91 %
8-bit	21.92 μs (255+8 clock periods)	0.75 μs (1+8 clock periods)	96.58 %
10-bit	86.08 μs (1023+10 clock periods)	0.92 μs (1+10 clock periods)	98.93 %
12-bit	342.25 μs (4095+12 clock periods)	1.08 μs (1+12 clock periods)	99.68 %

The use of a reliable method for checking the code reading error has allowed for a reduction in measurement time, but has also increased the reliability of the encoder. When an incorrectly read bit occurs, the encoder will not give incorrect position information, but will continue measuring the position in another operating mode. The algorithm can be upgraded so that in the event of a failure of one head for reading the pseudorandom code, the encoder can work with the other remaining head.

The implemented encoder operation algorithm can, with minor modifications, be applied to real signals read from a real encoder disk, whereby the signals can be accepted by an acquisition card. Also, this encoder operation algorithm can be implemented using modern microcontrollers or FPGA circuits, which can operate at significantly higher clock frequencies. The code from Fig. 5 requires minor modifications if it is compiled and deployed to the FPGA circuit via the LabVIEW FPGA Module.

5. Conclusion

The paper presents an improved pseudorandom optical encoder algorithm with reduced angular position measurement time. The pseudorandom code is read by two reading heads at a distance of *nq*, which enabled continuity in the formation of code words, as well as the application of reliable methods for detecting code reading errors. A Fibonacci pseudorandom binary sequence generator with inverse feedback is used to implement code conversion, as well as code reading error checking. In the normal encoder operating mode, the position is determined by incrementing-decrementing the previous position value if no code reading error is detected. Because no code conversion is performed after each formed code word, the angular position determination time is significantly reduced. The shortened position determination time enables faster rotation of the encoder disk as well as reduced encoder power consumption. In the event of a code reading error being detected, the encoder continues to operate in incremental mode, using signals from the synchronization track to determine position. The proposed encoder algorithm solution was implemented and tested in the LabVIEW environment. The operation of the encoder was analyzed for different scenarios of code reading errors and changes in the direction of rotation of the encoder disk. The plan is to further upgrade the pseudorandom encoder algorithm and implement it using an FPGA circuit or microcontroller.

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