FACTA UNIVERSITATIS (NIŠ)
SERIES: ELECTRONICS AND ENERGETICS VOL. 6 (1993), 13–23

POSITION MEASUREMENTS BASED UPON THE APPLICATION OF PSEUDORANDOM ENCODING

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Abstract: This paper discusses one-dimensional position measurement using pseudorandom encoding. An application in the navigation of automated guided vehicles is described. Special attention is paid to the problem of Pseudorandom/Natural code conversion and the solution how to reduce maximum time needed for conversion is proposed. A new method for serial reading of the pseudorandom code using two reading heads is also developed. This method eliminates systematic errors and makes the system resistant to oscillations in the movement course. A position transducer with 12 bit output resolution has been designed.

Key words: Measurement, pseudorandom encoding, code conversion, position transducer.

1. Introduction

Automated guided vehicles (AGV's) are driverless carriers used on the factory floor as mobile production platforms or for material transportation. The ability to measure their absolute position is an asset for the AGV's which are frequently interacting with other manufacturing units (robots, machine tools, loading/unloading devices, etc.). Long moving path of the AGV's implies a great number of the quantization steps regardless of the absolute resolution value. Therefore, usage of the classical absolute position transducers is unacceptable for economical reasons because of great number of the coding tracks. Today, most of the systems rely on incremental methods for position measurement, which have the well-known defect of the errors accumulation. Some attempts have been made to compensate for this drawback by using either optical calibration methods, or code labeling of

Manuscript received April 12, 1993.
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specially designed locations. For economical reasons, the applicability of these solutions is restricted to a limited number of reference points.

In order to find out a good solution, for positioning of the transporting devices, the alternative to the "transverse" absolute encoding procedure is developed. This alternative method, let us call it "longitudinal", is based on the peculiar property of the pseudorandom codes that the first n-1 bits of such a code word are identical with the last n-1 bits of the previous code word. To draw a distinction from the transversal coding technique which requires a recording of determined digital code for each sector of the code device on a transversal course, the longitudinal method of coding enables an absolute determination of the position by using only a single code track. This is based on a "window property", described in [1], of the pseudorandom binary sequences (PRBS)

$$\{S(p)/p = 0, 1, \ldots, 2^n - 2\} \tag{1}$$

According to this, any n-bit word

$$\{S(p + n - k)/k = n, \ldots, 1\} \tag{2}$$

provided by scanning the pseudo-random binary sequence (PRBS) by the window width n, $x(k)/k = n, \ldots, 1$, is unique and it can completely identify the window's absolute position p with regard to the start of a sequence.

A pseudorandom/natural code conversion may be executed by using a memory which contains a translation table or corresponding combinational nets. However, such methods are not of practical use for the pseudo-random binary sequences of a relatively great length. Therefore, a development of the code conversion method, which enables a simple code conversion into a natural code for such sequences, is of a particular importance. In this paper, the code conversion problem is just considered from that aspect.

2. Pseudorandom/natural code conversion

The pseudorandom binary sequence (1) of the length $2^n - 1$, generated by n-bit shift register is being discussed. As it is written with one bit per sector, a code track (i.e. disc in case of the rotational encoder) is divided to $2^n - 1$ sectors. The S(p) terms represent the content of the n-th stage of the shift register after p shifts to the left. Knowing the fact that the pseudorandom sequences are periodical, it is all the same which n-bit word is adopted as initial,

$$\{S(n - k)/k = n, \ldots, 1\} \tag{3}$$

Further on, it can be considered that a pseudorandom binary sequence (1) is generated by a shift register with feedback function, according to the following algorithm

$$X(0) = X(n) \oplus c(n-1)X(n-1) \oplus \ldots \oplus c(1)X(1)$$

$$X(i) = X(i-1), \quad \text{where} \quad i = n, \ldots, 1,$$

and the feedback coefficients $c(n-1), ..., c(1)$ are defined in advance. Table 1 shows this. The Table is formed on a basis of the primitive polynomials table as it is described in [1]. Primitive polynomials of higher degree have been found in [2].

Table 1.

SHIFT REGIS. LENGTH n	*FEEDBACK FOR DIRECT P. R. B. S.* $X(0) = X(n) \oplus c(n-1)X(n-1) \oplus \ldots \oplus c(1)X(1)$	*FEEDBACK FOR REVERSE P. R. B. S.* $X(n+1) = X(1) \oplus b(2)X(2) \oplus \ldots \oplus b(n)X(n)$
4	$X(0) = X(4) \oplus X(1)$	$X(5) = X(1) \oplus X(2)$
5	$X(0) = X(5) \oplus X(2)$	$X(6) = X(1) \oplus X(3)$
6	$X(0) = X(6) \oplus X(1)$	$X(7) = X(1) \oplus X(2)$
7	$X(0) = X(7) \oplus X(3)$	$X(8) = X(1) \oplus X(4)$
8	$X(0) = X(8) \oplus X(4)$ $\oplus X(3) \oplus X(2)$	$X(9) = X(1) \oplus X(3)$ $\oplus X(4) \oplus X(5)$
9	$X(0) = X(9) \oplus X(4)$	$X(10) = X(1) \oplus X(5)$
10	$X(0) = X(10) \oplus X(3)$	$X(11) = X(1) \oplus X(4)$

For given position p, a reading system with n heads

$$x(k)/k = n, \ldots, 1,$$

provides n-bit word (2), for each $p = 0, 1, \ldots, 2^n - 2$. Transition of this n bits into a natural code is executed on a basis of the following considerations. The generation nature itself of PRBS points out a possibility of obtaining the initial code word by using the feedback function relation used for generating either "direct" or "reverse" pseudo-random binary sequences, although PRBS is generated by using "direct PRBS" generating law. In another words, if a current position refers to the pseudorandom code word

$$\{X(k) = S(p-n+k)/k = n, \ldots, 1\},$$

the natural value of the position can be obtained in two ways, as follows:

- by counting steps required by a shift register with an reverse feedback function in order to come to an initial state (3) by successive shift to the right, or
- by counting steps required by a shifting register with a "direct" feedback function in order to come to an initial state (3) by a successive shifting to the left, and then by subtracting that number from $2^n - 1$.

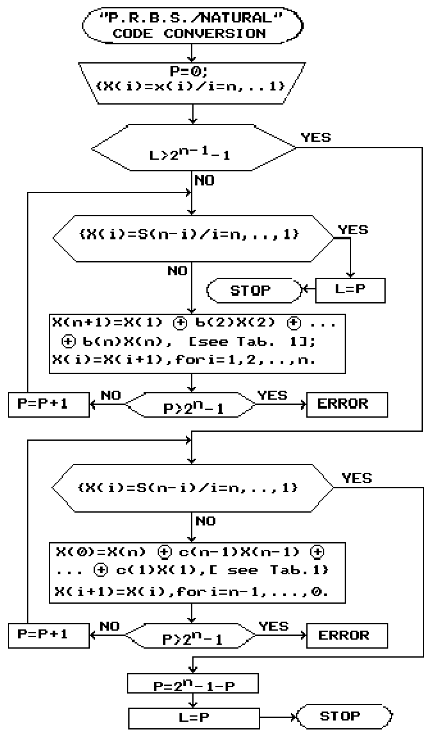

Fig. 1 A pseudorandom/natural code conversion algorithm.

On the basis of a preceding position it will be decided which of these two ways are to be used at the current pseudorandom/natural code conversion. Consequently, a new algorithm of code conversion (Fig.1) starts by placing a n-bit variable "X" on a current value which is obtained by the reading heads. After that, depending on a preceding position, "X" is cyclically modified according to an "reverse" or "direct" generation law given in Table 1. The algorithm will cycle in this way until "X" reaches the predefined "initial state" (3). When this state is finally reached, the algorithm stops cycling, and the current value of the index "p" represents the n-bit natural code of a current position. Referring to an information about a preceding position has not a big significance, as its eventual not existence (for example, at a system start) does not influence on the accuracy of code conversion. Time incrementation of such current code conversion may only occur. A new algorithm, compared with the existing solutions which used a reversibility property of the PRBS, decreases a maximal time of the code conversion approximately twice.

In order to illustrate a code conversion, an example of the transportation system is given (Fig.2). 15 bits PRBS, generated by using 4-bit shift register with direct feedback function $X(0) = X(4) \oplus X(1)$, is employed for a code track encoding. With the aim to realize all 15 positions, the first three bits are added at the end of code track. A register current content for temporary data storage which corresponds to a transportation system current position is given by

$$\{X(4), X(3), X(2), X(1)\} = \{1, 0, 0, 1\} \tag{4}$$

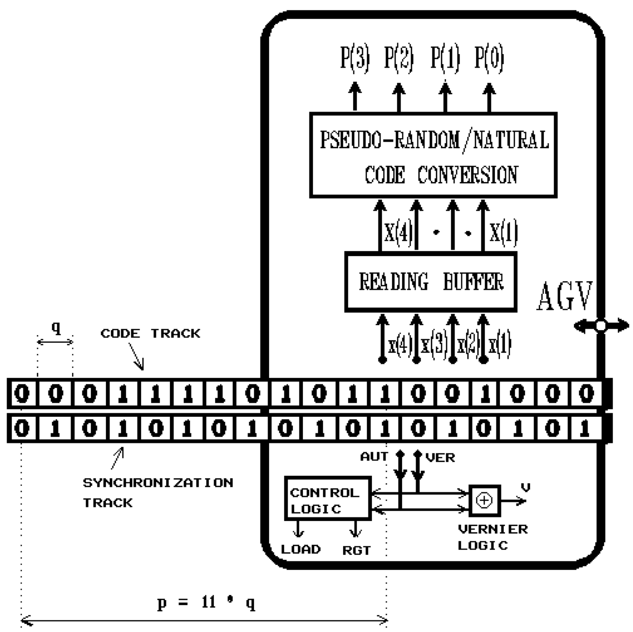

Fig. 2 Example of encoding technique.

According to a solution which only uses a reversibility property of the PRBS generation, a pseudorandom/natural code conversion is executed exclusively by the shift register with an reverse feedback function $X(5) = X(1) \oplus X(2)$. Concrete in this case, a register would pass through the following states $1,1,0,0$, $0,1,1,0$, $1,0,1,1$, $0,1,0,1$, $1,0,1,0$, $1,1,0,1$, $1,1,1,0$, $1,1,1,1$, $0,1,1,1$, $0,0,1,1$ and $0,0,0,1$, when it would stop. During that time, the number of register shifting would be counted until the initial state (3) appears, by using the counter, which was initially reset. In this case, there is eleven shifts of a shift register, and therefore the counter state would be p = 11, at the end of the conversion, which is just the current position value of the AGV. At the output 4-bit binary number would be attained

$$\{P(3), P(2), P(1), P(0)\} = \{1,0,1,1\} \tag{5}$$

According to a new algorithm, as the preceding position was certainly greater than $2^3 - 1$, the code conversion of 4-bit word (4) is executed by the shift register with direct feedback function $X(0) = X(4) \oplus X(1)$. The register, now, passes through the following states $0,0,1,0$, $0,1,0,0$, $1,0,0,0$ and $0,0,0,1$, when it is stopped. At the same time, the number of shift register shiftings is counted, by the counter which was initially reset, until initial state is reached. Now $p = 4$, i.e. at the counter output it is obtained

$$Q(3), Q(2), Q(1), Q(0) = 0,1,0,0 \tag{6}$$

Finally, for the position of the AGV we obtain $(2^4 - 1) - 4 = 11$, i.e. the natural code output is attained (5). It can be noticed that (5) is obtained by complementing (6), which will be used at a hardware realization of a new algorithm. As it is shown in the lower part of the Fig. 2, within the concrete realizations it is necessarily to introduce a synchronization track, two additional heads for determination of movement direction and a corresponding control logic [4], with the aim to solve the problems of the reading uncertainty and because of the necessity for acquiring the system movement direction.

3. Number of heads reduction for the code reading and experimental results

At the system which require a high resolution of the position determination, a technical problem may appear like placement of two code reading heads on distance q, where q is quantization step. The compromise solution for this problem is based on the idea that n bits are serially linked into bidirectional n-bit shift register, where n bits represent position code, by using only one reading code head, instead of their parallel readings. The application price of this solution is such that position information is lost at every change of the movement direction and it is established again after the system makes n-quantization steps in a new direction.

In this paper, a new solution is proposed. It eliminates the above mentioned technological problem of a displacement of reading code heads, as well as the problem of losing the positional information when a movement direction is changed. Therefore, a system does not lose the positional information even in the case of an oscillation in a movement course, which was not the case according to the solution described by Petriu, [4]. This is based on the idea of the use of two reading heads for code reading, instead of one, where the distance between these two heads equals to $n \cdot q$. According to the example in Fig. 2, two heads would be $x(n)$ (respectively $x(4)$) and $x(0)$, where $x(0)$ designates that the second head is placed to the right for q with regard to the position of the head $x(1)$. By that, depending on a movement direction, and along with a help of logic shown in the lower part of Fig. 3, an information arrives only from one reading head into a bidirectional shift register. So, if system moves to the left the bits read out by the head $x(n)$ will be accepted, and by system moving to the right the bits read out by the head $x(0)$. Now, a position information is invalid only after the switching on of the system, before the system makes first n quantization steps in any direction. So, a protection mechanism from invalid information can be realized simply by a software, unlike the previously solutions. A correction logic with parallel adder is needed no more as well. Namely, preceding solution required necessarily a correction for q i.e. $9 \cdot q$ respectively, at the system moving in a direction from initial state, whether for the system with n reading code heads or for the system with one head. By the above proposed arrangements of the reading code heads, the systematic errors are eliminated which simplifies the system realization.

When $n = 9$, by using identical principles of a programming, a software realization of the pseudorandom/natural code conversion is executed for previously algorithm proposed in [3] and for new algorithm shown in this paper. The software executions of two programs in a machine language, by using microprocessor Intel 8051, which operates at 12 MHz. Respectively, for the first algorithm maximal time of the code conversion is T=5.62 ms=5.6 ms. This time is obtained for the transition of pseudo-random code word $0, 1, 0, 0, 0, 0, 0, 0, 0$ which corresponds to the position 510 ($2^9 - 1$), with regard to the adopted initial n-bit word $1, 0, 0, 0, 0, 0, 0, 0, 0$. For a new algorithm, maximal time of the code conversion is T=2.83 ms=2.8 ms, and that time is obtained by the transition of 9-bit code word $0, 0, 0, 0, 1, 0, 1, 0, 1$ which corresponds to the position 256 $(2^9 - 1)$. In the case of an adopted coding step $q = 1$ cm, maximal speeds allowed of the system moving would be respectively, $V = 6.4$ km/h and $V = 12.7$

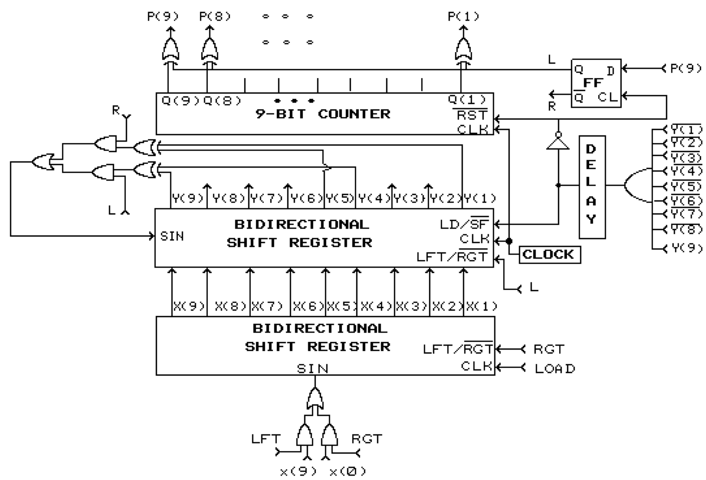

Fig. 3 A hardver realisation of the code conversion algorithm

Therefore, a hardware realization of the new algorithm, shown in Fig. 3, will result in equivalent improvement. It includes also previously described solution which eliminates the problem of losing the information at a change of movement direction. Another bidirectional shift register, depending on MS bit of the output binary information from preceding position, makes a shifting to the left or to the right to the initial state (3). A counter counts those shiftings and in the case of shifting to the right its output is just natural value of the position. When shifting is the left a value which corresponds to an actual position is obtained by complementing of the counter output. This problem, that the output should be complemented or not depending on a shifting direction, is solved simply by using EXOR circuits, Fig. 3.

4. Position transducer with 12 bit output resolution

A position transducer with 12 bit output in the natural code, using improved pseudorandom coding techniques, implying the application of vernier method, has been designed. Previously described method using two heads for serial code reading ($X(10)$ and $X(1)$), as shown in Fig. 4, to read 10 bit pseudorandom code, is applied. At the same time, this method enabled development of one reliable method for permanent checking of correctness of code reading. Depending on the direction of the system movement, one head is used to form a pseudorandom code word, while the other head bits are taken to the auxiliary shift register to form code word for checking. Code track bits are read off when the head AUT detects the hole on the synchronization track.

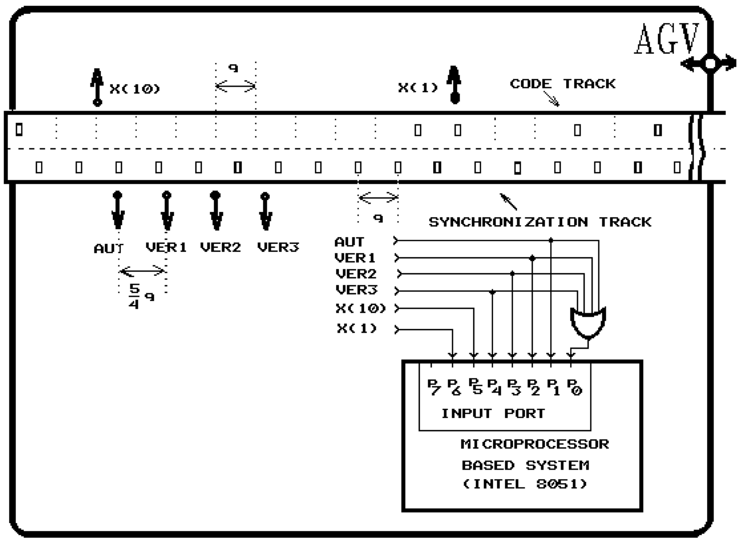

Fig. 4 Position transducer with 12 bit output resolution

The head AUT and three additional heads VER are placed at distance S according to the vernier law,

$$S = (1 + \frac{1}{m+1})q = (1 + \frac{1}{4})q = \frac{5}{4}q,$$

where m is a number of heads VER. The total resolution is now $q/(m+1) = q/4$. Since the time needed to get an information at the output is critically dependent on the time required for conversion of pseudorandom/natural code, the upper maximal movement speed is 16 times increased with regard to classical pseudorandom 12 bit encoding.

The basic functions achieved by the realized algorithm are: providing of the information on relative position with regard to the starting position, up to the moment of pseudorandom code word formation (10 quantization steps q in the same direction), when the absolute position is determined and an information on system readiness is given; detection of the movement direction; ensuring of the stability of information on the position for the case of system oscillation in the movement direction; permanent check of the code reading correctness; pseudorandom code conversion; for the case of a detected error, continuation of the operation according to incremental method with regard to the last correct information on absolute position, up to the moment of an automatic restoration of the system; detection and alarm in the case of code or synchronization track contamination.

For the case $q = 10$ cm software realization of the entire algorithm, performed by using 12 MHz Intel microprocessor 8051, enables the system movement up to 42 km/h.

5. Conclusions

An application of absolute position transducers with a pseudorandom coding has the well-known advantage of decreasing the complexity of realization and number of code tracks. However, significant time required for pseudorandom/natural code conversion restricts maximal speed allowed of a realized system moving. In this paper, it is suggested a code conversion algorithm, the application of which would enable greater speed of moving for approximately two times compared with a solution proposed by Petriu, [3]. Except of that, a reading method of the pseudorandom code is proposed by using two reading heads, placed on a distance $n \cdot q$, where n is length of pseudorandom code word, and q is a quantization step. Beside a decrease of the number of heads for $n - 2$, eventual technical problems of the heads arrangements are eliminated in a case of high resolution. Compared to the solution with one reading code head [4], the loss of position problem after the change in direction of system's movement is eliminated. Thus system becomes resistant to an eventual oscillation in movement course. The arrangement suggested for the reading code heads eliminates the systematic errors when reading a code, unlike the solutions with one or n heads. So, there is no need for the use of parallel adder as a correction element, which further simplifies a system realization.

A software realization of the new algorithm is executed, and a hardware realization is proposed. These realizations comprise all improvements mentioned above. Also, the characteristics of the realized position transducer with 12 bit output resolution are shown. Along with the above mentioned improvements, suitability of the combination of the pseudorandom encoding technique with incremental method is utilized, enabling realization of measurement transducer with good performances and low cost. For the case q=10 cm, moving speeds of the automated guided vehicle is limited to 42 km/h, which is satisfactory for many applications.

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