Improvement of Measurement Range via Chaotic Binary Frequency Shift Keying Excitation Sequences for Multichannel Ultrasonic Ranging System

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Abstract
The important indicators of multichannel ultrasonic ranging system are correlation characteristics and energy efficiency. The excitation sequences with good correlation characteristics can help avoid crosstalk among multichannel ultrasonic sensors. High energy efficiency can enhance measurement range. This paper proposes a crosstalk elimination method by using the optimal binary excitation sequences modulated with chaotic codes, which include chaotic binary amplitude shift keying (c-BASK), chaotic binary phase shift keying (c-BPSK) and chaotic binary frequency shift keying (c-BFSK). To obtain the both best correlation characteristics and energy efficiency, the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is applied to optimize the chaotic binary excitation sequences. Real experiments have been conducted using an ultrasonic ranging system that consists of eight-channel SensComp 600 series instrument-grade electrostatic sensors excited with chaotic binary modulation sequences. The experimental results show that the c-BFSK outperforms the c-BASK and c-BPSK in terms of the correlation characteristics and energy efficiency. With 2 ms c-BFSK excitation sequences, the longest measurable distance was 720 cm (i.e., increased 11% and 27% with c-BPSK and c-BASK, respectively) with maximal relative error 2.4%.

Keywords: Ultrasonic crosstalk, Chaotic series, Energy efficiency, Correlation characteristic

1. Introduction
Ultrasonic sensors have been extensively applied on ranging system, thanks to their hardware construction simple and price is low. In order to obtain all directional distance information, a sensor ring with multiple ultrasonic transducers is required in a ranging system [1]. The ultrasonic crosstalk problem is occurred, when these sensors in a ring are working simultaneously [2]. Generally, ultrasonic receiver cannot distinguish whether the received echo from its own transmission or not, so the incorrect time-of-flight (TOF) measurements often occur.

The effective crosstalk elimination method is to give each ultrasonic sensor a unique excitation signature in the transmission and then identify the signature using a correlation technique in the receiver. Jörg and Berg [3] were the first to give a recognizable signature of each sensor in the transmission using pseudorandom code and frequency modulation. And then in the receiving circuit, the identification of the transmitted source sensor was by a matched filter. Subsequently, some researchers have applied different codes and modulation schemes to construct excitation sequences as a transmission signature to solve the ultrasonic crosstalk problem. Barker codes [4] were used to avoid crosstalk in ultrasonic system, although the available Barker codes limit their application. In ultrasonic distance measurement system, Golay codes [5–7] were applied to restrain...
crosstalk and increase the signal-to-noise ratio. But the realization complexity of Golay
codes restricts their application. The BFSK and BPSK signals [8] were applied to drive
multiple piezoelectric ultrasonic sensors with narrow bandwidth. In ref. [9] and [10],
BPSK modulation was used to construct the transmission signals of ultrasonic system. But
they adopted different codes to modulate, i.e., Alvarez et al. [9] used complementary
sequences codes and Iwasawa et al. [10] applied M sequence. The chaotic codes [11-14]
with good correlation characteristic were exploited to construct the ultrasonic emission
signals. Fortuna et al. [11] adopted chaotic pulse position modulation (CPPM) to excite
the ultrasonic transducer to restrain crosstalk and improve the efficiency of ultrasonic
distance measurement system. And to minimize the correlation functions of CPPM
signals, Meng et al. [12] optimized the chaotic initial value by genetic algorithm. Chaotic
pulse position–width modulation (CPPWM) signals triggered the ultrasonic transducer
were proposed to suppress crosstalk [13].

The measurement range in ultrasonic ranging system can be enhanced with high energy
efficiency excitation sequence. Meng et al. [14] adopted spectrum optimization of a
CPPM excitation signal to improve energy efficiency. In order to both obtain the best
echo energy and correlation characteristics, Yao et al. [13] used nondominated sorting
genetic algorithm II to optimize the CPPWM sequences in ultrasonic ranging system.

This paper aims to exploit the novel crosstalk elimination method by applying chaotic
binary modulation excitation sequences which includes chaotic binary amplitude shift
keying (c-BASK), chaotic binary phase shift keying (c-BPSK), and chaotic binary
frequency shift keying (c-BFSK). To both improve energy efficiency and correlation
characteristics, the NSGA-II is used to optimize the proposed excitation sequences. The
ultrasonic distance measurement system consisting of eight-channel SensComp 600 series
ultrasonic transducers was designed and recommended the best chaotic binary modulation
approach for ultrasonic sensor via experiments.

The rest of this paper is structured as follows. Section 2 presents the principle of
chaotic binary modulation excitation sequence. The correlation characteristics and energy
efficiency are explained in section 3. Section 4 introduces the optimization algorithm of
the proposed excitation sequences. The experiments and discussion are shown in section
5, followed by the conclusions in section 6.

2. The Principle of Chaotic Binary Modulation Excitation Sequence

2.1. Chaotic Codes

Chaotic codes had been used to construct excitation sequence because of their good
correlation characteristics. In this paper, the Ulam–von Neumann transformation [15] was
used to produce chaotic codes as follows,

\[ y_i = 1 - 2y_{i+1}^2, y_i \in [-1,1], \quad i = 1,2,\ldots \]  \hspace{1cm} (1)

Binary chaotic codes were generated by the following formula,

\[ \text{sgn}(y_i) = \begin{cases} 0 & y_i < 0 \\ 1 & y_i \geq 0 \end{cases}, \quad i = 1,2,\ldots \]  \hspace{1cm} (2)

2.2. Chaotic Binary Modulation Scheme

The binary modulation techniques include BASK, BFSK and BPSK, which have two
states of amplitude, frequency and phase, respectively. In the proposed chaotic binary
modulation approach, the variation of amplitude, frequency and phase are on the basis of
chaotic codes. Since the hardware implementation of a square wave is much easier than a
sinusoidal wave, the square wave is adopted as the carrier signal of chaotic binary
modulation sequences.
2.2.1. c-BASK:

In c-BASK, the amplitude of a fixed-frequency carrier wave is changed with each symbol of base-band signal using binary chaotic codes. Mathematically, the form for c-BASK sequence can be written as,

\[ X_{\text{c-BASK}}(t) = c(t) \left[ \frac{1}{2} + \sum_{k=0}^{\infty} \frac{2}{\pi(2k+1)} \sin \left( \frac{2\pi(2k+1)}{T_c} t \right) \right], \]

where \( c(t) \) generated by formula (2) is binary chaotic codes used to change the amplitude of carrier signal.

2.2.2. c-BPSK:

With c-BPSK, the chaotic information is contained in the phase of the modulated carrier signal. The c-BPSK is given by the following formula,

\[ X_{\text{c-BPSK}}(t) = \frac{1}{2} + \sum_{k=0}^{\infty} \frac{2}{\pi(2k+1)} \sin \left( \frac{2\pi(2k+1)}{T_s} t \right) c(t), \]

where \( T_s \) is the symbol width of base-band signal. In c-BPSK, the base-band signal is the binary chaotic codes.

2.2.3. c-BFSK:

C-BFSK transmits the chaotic information using two carrier frequencies \( f_1 \) and \( f_2 \) to represent symbol states. Mathematically this is written by the following,

\[ X_{\text{c-BFSK}}(t) = \begin{cases} \frac{1}{2} \sum_{k=0}^{\infty} \frac{2}{\pi(2k+1)} \sin \left( \frac{2\pi(2k+1)}{T_s} f_1 t \right) c(t) = 1, \\ \left[ \frac{1}{2} + \sum_{k=0}^{\infty} \frac{2}{\pi(2k+1)} \sin \left( \frac{2\pi(2k+1)}{T_s} f_2 t \right) c(t) = 0 \right. \end{cases} \]

3. The Correlation Characteristics and Energy Efficiency

3.1. Correlation Characteristics

Correlation characteristics [14] include the autocorrelation function and cross-correlation function. In the ultrasonic distance measurement system, the autocorrelation function signal is defined as follows,

\[ R_{x_{\text{echo}}}(m) = \begin{cases} \sum_{n=0}^{N-1} x_{\text{echo}}^n \cdot x_{\text{echo}}^{n+m} & m \geq 0, i = 1, \ldots, M, \\ R_{x_{\text{echo}}}(-m) & m < 0 \end{cases} \]

where \( M \) is the channel number of ultrasonic distance measurement system, \( x_{\text{echo}}^n \) and \( x_{\text{echo}}^n \) are the \((n+m)\)th and \(n\)th sampling site of the \(i\)th echo signal, respectively, \( N \) is the sample number in the echo sequence.

The definition of the cross-correlation function is given as follows,

\[ R_{x_{\text{echo}}}(m) = \begin{cases} \sum_{n=0}^{N-1} x_{\text{echo}}^n \cdot x_{\text{echo}}^{n+j} & m \geq 0, i = 1, \ldots, M, j = 1, \ldots, M, i \neq j, \\ R_{x_{\text{echo}}}(-m) & m < 0 \end{cases} \]

where \( x_{\text{echo}}^n \) is the \(n\)th sampling site of the \(j\)th echo signal.
3.2. Energy Efficiency

Because the ultrasonic sensor has a band-pass spectrum, the excitation energy can be transmitted by the ultrasonic ranging system when spectrum of the excitation sequence matches with that of the ultrasonic sensor. The energy efficiency is to measure the spectrum matching degree.

The energy efficiency \( \eta \) is defined as follows,

\[
\eta = \frac{E_x}{E_t},
\]

(8)

\[
E_x = \frac{1}{R_e} \sum_{i=1}^{N} X_i^2,
\]

(9)

\[
E_t = \frac{1}{R_r} \sum_{i=1}^{N} Y_i^2,
\]

(10)

Where for the excitation signal, \( X_i \) is its \( i \)th sampling site, \( E_x \) is its energy; For the echo signal, \( Y_i \) is its \( i \)th sampling site, \( E_t \) is its energy; \( R_e \) and \( R_r \) are the equivalent resistance of the transmitting and receiving circuits, respectively.

4. The NSGA-II based Optimization of the Proposed Excitation Sequence

To both get the best correlation characteristics and energy efficiency, a NSGA-II is used to optimize the chaotic initial values, the carrier frequency \( c_f \) of c-BASK and c-BPSK, the symbol width \( s_T \) of c-BASK and c-BPSK, the carrier frequency \( c_f_1, c_f_2 \) of c-BFSK, the symbol widths \( s_T_1, s_T_2 \) of c-BFSK. The optimized procedure is given in the following steps.

Step 1: The initial parent population \( Q_{PA} \) is produced randomly, where \( P \) is the population size. Let \( P = 100, M = A + 2 \) (corresponding to \( M \) chaotic initial values for \( M \) channel ultrasonic ranging system, \( A \) is set to second for c-BASK and c-BPSK, and \( A \) is set to four for c-BFSK), and the maximum generation number is set to 100.

Step 2: The two objective-functions values of individuals are ordered. Then a column vector of fitness values is returned. The objective functions \( ObjV1 \) and \( ObjV2 \) are defined as follows:

\[
ObjV1 = \max (R_{c_{\text{max}}}, R_{a_{\text{max}}})
\]

(11)

\[
R_{a_{\text{max}}} := \max (R_a(m)), i = 1, \ldots, M, m = 0, \ldots, N - 1 - \delta
\]

(12)

\[
R_{c_{\text{max}}} := \max (R_c(m)), m = 0, 1, 2, \ldots, 2N - 1, i = 1, \ldots, M, j = 1, \ldots, M, i \neq j
\]

(13)

\[
ObjV2 = \max (\eta)
\]

(14)

where for autocorrelation functions, \( R_{a_{\text{max}}} \) is the maximal side-lobe; For cross-correlation functions, \( R_{c_{\text{max}}} \) is the maximal peak; \( \eta \) is the energy efficiency of the \( i \)-channel ultrasonic ranging system. To both obtain the best correlation characteristics and energy efficiency, the objective function \( ObjV1 \) should take the minimal value and \( ObjV2 \) should take the maximal value.

Step 3: The selection probability of individuals is set to 0.9, and the selected individuals are returned to the new population.
Step 4: The crossover and mutation operators are used to generate the new children population.
Step 5: The offspring population is combined with the current generation population and selection is performed to set the individuals for the next generation.
Step 6: Repeat Step 2 to Step 5 until the maximum generation algebra is reached.

5. Experiments and Discussions

5.1. Experimental Setup

The eight-channel ultrasonic distance measurement system was used in our experiments. Each channel of the ultrasonic distance measurement system has the same hardware realization. Figure 1 illustrates the hardware realization schematic diagram for one channel ultrasonic distance measurement system. The chaotic binary modulation sequence was sent from the field programming gate array (FPGA). After power amplifying, the ultrasonic sensor was triggered to transmit ultrasound. In our experiments, a SensComp 600 series instrument-grade electrostatic sensor was used as both transmitter and receiver. After band-pass filter, automatic gain control amplification and shaping, the polarity correlation [16] between the binary echo signal and a reference echo signal was carried out. The reference echo signal was recorded from an acrylic board placed 40 cm in front of the ultrasonic sensor. Here it should be noted that the emitted pulse sequence and its echo sequence are different owing to the filtering effect of the ultrasonic sensor, so the correlation characteristics between the excitation sequence and its own echo is poor. That is why we did not use the emission sequence as the reference to calculate the correlation characteristics. Actually, similar correlation processing method was also adopted by Jörg et al. [3], where the echo instead of the emitted pulse sequence was used as the reference. Lastly, the distance calculation was implemented if the echo sequence was recognized to be from its own sensor transmission.

![Figure 1. The Hardware Realization Schematic Diagram For One Channel Ultrasonic Ranging System](image)

5.2. Experimental Results of Chaotic Binary Modulation Signals and Discussions

5.2.1. The Correlation Characteristic Analysis of Chaotic Binary Modulation Sequences:

For each chaotic binary modulation excitation sequence, eight chaotic code series were used to construct eight excitation sequences, respectively. The length of the chaotic binary modulation excitation sequence is set to 2 ms. Using the NSGA-II optimization algorithm, the optimized correlation characteristic results for the c-BASK, c-BPSK and c-BFSK sequences were $ObjV_{cBASK} = 0.4735$, $ObjV_{cBPSK} = 0.3666$ and $ObjV_{cBFSK} = 0.3379$, respectively.

Comparison with the optimized c-BASK and c-BPSK sequences, the echo correlation characteristics of the optimized c-BFSK sequence is better than that of c-BASK and c-BPSK sequences.

Figures 2-3 show the correlation characteristic of c-BASK without optimization and after optimization, i.e., correlation characteristic includes the autocorrelation functions of two echo sequences and the cross-correlation function. As shown in figures 2-3, the
optimized c-BASK sequences have lower side-lobe of echo autocorrelation functions than that of the unoptimized c-BASK ones, i.e., 0.33 vs 0.58. Moreover, the c-BASK sequence after optimization also has lower peak of echo cross-correlation function than that of the c-BASK sequence without optimization, i.e., 0.39 vs 0.51. The comparison results between the optimized c-BPSK sequences and the unoptimized c-BPSK sequences are presented in figures 4-5. From these figures, we can find that the side-lobe of echo autocorrelation functions of the optimized c-BPSK sequences is about 0.1 lower than that of the unoptimized c-BPSK sequences. And the peak of echo cross-correlation function of the optimized c-BPSK sequences is about 0.08 lower than that of the unoptimized c-BPSK sequences. Figures 6-7 demonstrate the correlation characteristic of c-BFSK without optimization and after optimization. As indicated in figures 6-7, the side-lobe of echo autocorrelation functions of the optimized c-BFSK sequences is about 0.14 lower than that of the unoptimized c-BFSK sequences. And the peak of echo cross-correlation function of the optimized c-BFSK sequences is about 0.1 lower than that of the unoptimized c-BFSK sequences.

Comparison with the optimized c-BASK and c-BPSK sequences, the correlation characteristic of the optimized c-BFSK sequence is lower than that of c-BASK and c-BPSK, i.e., the optimized c-BFSK sequence has the lowest side-lobe of echo autocorrelation functions and the lowest peak of echo cross-correlation function. In other words, the optimized c-BFSK sequence has the best echo correlation characteristics among the chaotic binary modulation sequences.

![Figure 2. The Correlation Characteristic Of C-BASK Without Optimization: The Normalized Autocorrelation Of Echo Sequence 1 (Left), The Normalized Autocorrelation Of Echo Sequence 2 (Middle), And The Normalized Cross-Correlation Of Echo Sequence 1 And 2 (Right).](image1)

![Figure 3. The Correlation Characteristic Of C-BASK After Optimization: The Normalized Autocorrelation Of Echo Sequence 1(Left), The Normalized Autocorrelation Of Echo Sequence 2(Middle), The Normalized Cross-Correlation Of Echo Sequence 1 And 2(Right).](image2)
5.2.2. The Spectrum and Echo Analysis of Chaotic Binary Modulation Sequences:

Using the NSGA-II optimization algorithm, the optimized energy efficiency results of chaotic binary modulation sequences were shown in Table 1. From Table 1, we can see that both the echo and excitation energies of the c-BASK sequences are the smallest. And
the energy efficiency of the c-BFSK excitation sequence is better than that of the c-BPSK and c-BASK sequences.

Table 1. The Energy Efficiency Of Chaotic Binary Modulation Excitation Sequences.

<table>
<thead>
<tr>
<th>Excitation Sequences</th>
<th>Energy (μsV²)</th>
<th>c-BASK</th>
<th>c-BPSK</th>
<th>c-BFSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation Sequences Energy</td>
<td>498.0000</td>
<td>1003.000</td>
<td>1022.000</td>
<td></td>
</tr>
<tr>
<td>Echo Energy (μsV²)</td>
<td>167.5800</td>
<td>328.8600</td>
<td>358.4800</td>
<td></td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>0.3365ς</td>
<td>0.3279ς</td>
<td>0.3508ς</td>
<td></td>
</tr>
</tbody>
</table>

Figures 8, 9 and 10 show the optimized c-BASK, c-BPSK and c-BFSK sequences and its spectrum, and the corresponding echo sequences reflected from a wooden board placed 40 cm in front of the ultrasonic sensor, respectively. Here it annotated that the echo sequences were sampled before automatic gain control module to see the real echo energy. The echo signals were sampled using a Tektronix oscilloscope (TDS2012B) with a bandwidth and maximum sampling rate of 100 MHz and 1.0 GS/s, respectively. And the sample period was 1 μs.

As shown in Figure 8, there is significant amount of spectral distributes in the frequency band [1, 40] kHz as well as in the frequency band [40, 70] kHz, which is the pass-band of the ultrasonic ranging system. In other words, the spectrum of c-BASK excitation sequence mismatches with that of the ultrasonic ranging system. Compared
to the c-BASK, c-BPSK in Figure 9 presents that there is more spectral distributes in the frequency band (i.e., [40, 70] kHz) of the ultrasonic ranging system, but some excitation energy is still distributed out of that band. As shown in Figure 10, there is more energy of c-BFSK sequence distributes in the frequency band of the ultrasonic ranging system than that of c-BASK and c-BPSK sequences. At the same time, there is less energy of c-BFSK sequence distributes out of that band. Therefore, in the three chaotic binary modulation excitation sequences, the c-BFSK excitation sequence most spectrally matches with the ultrasonic ranging system.

Figures 8-10 also illustrate the corresponding echo sequences of c-BASK, c-BPSK and c-BFSK excitation sequences, respectively. The c-BFSK method in Figure 10 produces the highest echo amplitude of 0.9 V at some sampling time and most echo amplitude of [0.6, 0.8] V because of the matched spectrum between the excitation sequence and ultrasonic ranging system. As indicated in Figure 8 and 9, the echo amplitude in c-BASK and c-BPSK are less than that of the c-BFSK in Figure 10.

5.2.3. The Characteristics Of Chaotic Binary Modulation Signal At Different Distances:

To compare the characteristics of the chaotic binary modulation excitation sequences at different distances, the eight-channel ultrasonic ranging system were triggered using c-BASK, c-BPSK and c-BFSK sequences, respectively. The acrylic board was placed from 40 to 800 cm with intervals of 40 cm in front of the ultrasonic transducer. At these different distances, the echo signals were sampled, polarized and correlated calculation.

Table 2 shows the echo energies of chaotic binary modulation excitation sequences to different distances. It can be found that the echo energy of the c-BFSK sequence is greatest in the three chaotic binary modulation sequences for all distances measured. And the c-BASK sequence is least in the three chaotic binary modulation sequences.

| Table 2. Echo Energies Corresponding To Different Distances. |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
|               | 40cm          | 80cm          | 120cm         | 160cm         | 200cm         | 240cm         | 280cm         |
| c-BASK echo   | 0.224         | 22.793        | 6.467         | 2.539         | 1.272         | 0.767         | 0.515         |
| c-BPSK echo   | 327.780       | 68.975        | 19.543        | 7.602         | 3.832         | 2.275         | 1.473         |
| c-BFSK echo   | 354.211       | 74.650        | 21.090        | 8.254         | 4.165         | 2.477         | 1.601         |
|               | 320cm         | 360cm         | 400cm         | 440cm         | 480cm         | 520cm         | 560cm         |
| c-BASK echo   | 0.348         | 0.244         | 0.155         | 0.116         | 0.075         | 0.058         | 0.044         |
| c-BPSK echo   | 0.992         | 0.699         | 0.473         | 0.331         | 0.229         | 0.167         | 0.117         |
| c-BFSK echo   | 1.078         | 0.749         | 0.511         | 0.381         | 0.257         | 0.185         | 0.130         |
|               | 600cm         | 640cm         | 680cm         | 720cm         | 760cm         | 800cm         |               |
| c-BASK echo   | 0.034         | 0.027         | 0.015         | 0.013         | 0.012         | 0.004         |               |
| c-BPSK echo   | 0.085         | 0.056         | 0.039         | 0.020         | 0.016         | 0.013         |               |
| c-BFSK echo   | 0.085         | 0.060         | 0.046         | 0.029         | 0.021         | 0.014         |               |

The correlation characteristics results corresponding to different distances are illustrated in Figure 11, where the horizontal axis is the distance in centimeter and the vertical axis is the normalized correlation characteristics value. The peak value of normalized autocorrelation to each distance in Figure 11 (left) is the minimal autocorrelation result among the eight channel ultrasonic sensors. The each value of ObjV in Figure 11 (right) is the maximal crosscorrelation results. Figure 11 presents that the autocorrelation peaks of c-BASK are smaller than that of c-BFSK and c-BPSK, while the ObjV values of c-BASK are bigger than that of c-BFSK and c-BPSK. It can be also found that the ObjV values corresponding to c-BFSK are smaller than the c-BPSK ones, while the autocorrelation peaks corresponding to c-BFSK are equal to or bigger than the c-BPSK ones.
If the peak of polarity correlation between the sampled echo and reference echo signal is bigger than the threshold, the sampled echo signal is confirmed to be from its own transmission. The TOF is acquired, and then the distance information is calculated. The threshold is set to the maximal value of $ObjV$ among the measured distances. From Figure 11, we can conclude that the longest measurable distance is 800 cm with c-BFSK excitation signal, the maximum distance is 760 cm with c-BPSK and the furthest distance is 520 cm with c-BASK. In order to ensure measurement reliability, the threshold is set to 0.50. The longest measurable distances with c-BASK, c-BPSK and c-BFSK are 520 cm, 640 cm and 720 cm, respectively. It is clear that among the chaotic binary modulation excitation sequences, the longest measurable distance with c-BFSK is biggest.

Figure 11. The Correlation Characteristics Results Corresponding To Different Distance: The Peak of Normalized Autocorrelation Results (Left), the Values of ObjV (Right)

5.2.4. Distance Measurement of Multichannel Ultrasonic Ranging System:

The distance measurement experiments of multichannel ultrasonic ranging system were implemented in October 2015 with the temperature of 17°C. The ultrasound propagation speed in air can be calculated as follows:

$$v = v_0 \sqrt{\frac{T}{T_0}}.$$ \hspace{1cm} (15)

where $v_0 = 341.45$ m/s, and $T_0 = 273.16$ K. In our distance measurement experiments, the ultrasound speed was about 341.61 m/s at 17°C temperature.

The threshold of normalized autocorrelation peak is set to 0.5. The distance measurement results based on the c-BFSK excitation sequences are illustrated in Figure 12. Figure 12(left) shows the measured distances comparison with the real distances, where the abscissa axis is the real distances in centimeter and the vertical ordinate is the measured distances in centimeter. The measurement absolute and relative errors are expressed in Figure 12 (middle) and (right), respectively. It can be found that the maximal absolute error is 6.2 cm and the maximal relative error is 2.4%.
6. Conclusions

In this paper, a crosstalk elimination method based on the optimal binary excitation sequences modulated with chaotic codes is presented in this paper. The optimized chaotic binary modulation sequence based NSGA-II both has the best echo correlation characteristics and energy efficiency. Real experiments using an ultrasonic ranging system, which consists of eight-channel SensComp 600 series instrument-grade electrostatic sensors excited with binary sequences, showed that the c-BFSK outperforms the c-BASK and c-BPSK in terms of the energy efficiency and correlation characteristics among the chaotic binary modulation sequences. The maximum measurable distance was 720 cm with 2 ms c-BFSK sequences. The maximal absolute error is 6.2 cm and the maximal relative error is 2.4%.

The results of this paper can also be used in robots which install multiple ultrasonic sensors simultaneous working.

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