Enhancing Ultrasonic Robot Positioning Accuracy with Parallel Codes Acquisition of Composite Pseudo-noise Sequences

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Abstract—**Ultrasonic robot positioning with composite codes acquisition is investigated in this paper. The indoor robot positioning system was previously examined with single Pseudo-noise (PN) signal sequence. In views of correlation acquisition, the longer the code acquisition time, the longer the path estimation distance, and the worse the robot positioning accuracy. Under comparable period lengths, acquisition time for composite PN codes can be shorter than that of pure PN codes, thus can largely enhance the robot positioning accuracy. In the devised system configuration, three transmitters continuously send out their ultrasonic coding signals to the robot receiver. The robot evaluates its current position by measuring time difference of arrival (TDOA) among the three paths. Optimization algorithms can then be undertaken over the measured TDOAs to obtain more accurate robot location. Based on correlation characteristics of the proposed composite PN codes, we finally make a general analysis on codes acquisition time to the robot positioning accuracy.**

Keywords -- Indoor positioning system; Composite M-sequences; Parallel codes acquisition; Time difference of arrival (TDOA).

I. INTRODUCTION

With the mature technology, the functionality of robots is more and more pluralism. For example, the navigation robot, the cleaning robot, and other service type of robots, when robots execute their task, they need to move around. Therefore, the accuracy of positioning is very important, and the error of measurements between robot and sensor must be solved. For example, the multipath propagation is caused by the interference, because the ultrasonic wave is transmitted at all direction. As a result, multipath propagation will occur when the ultrasonic wave collide obstacles. Transmitting signals may be cut by obstacles so that a longer distance and a large time delay are produced. Time of Arrival (TOA) [1][2] and Time Difference of Arrival (TDOA) [3][4] positioning are easily influenced by errors so that the positioning accuracy is reduced.

In order to improve indoor ultrasonic positioning accuracy, so the robot object can be more precise positioning, and capture ultrasonic signals in the process. How to confirm the capture of ultrasound echo signals to the correct sources and reduce errors is the most important issue to study.

Several previous works that have used the coding techniques of the ultrasonic signal to determine the robot position, using PN sequences [5][6], Gold sequences [7], Loosely Synchronous (LS) sequences [8], Golay codes [9] and Barker codes [10]. These works represent the development of a Local Positioning System (LPS), based on the transmission of ultrasonic signals.

Pérez et al. [8] explored characteristics of LS sequences which exhibit an Interference-Free Window (IFW) within correlation functions to construct an ultrasonic beacon-based LPS, as well as to reduce the multipath effect. Hernández et al [9] developed system which used Golay codes in the ultrasonic signal processing and obtained features of arbitrary long pseudo-orthogonal sequences with no cross-interference. Hossain et al. [10] found pairs of Barker code with low cross-correlation so that they can be used in multi-user environment.

Huang et al [11] proposed a coding scheme of composite PN code sequences to encode the transmission signals. Such composite codes possess characteristics of mutual codes orthogonality and can asynchronously cancel the mutual interference among transceivers. With sophisticated balanced correlation detections, matched codes with high correlation magnitude can get unique code identification and unmatched codes will be rejected in the receiver end. De Angelis et al. [12] investigated an acquisition system to solve the problem of having more than one BS in the same PN code acquisition system to make it necessary to discriminate between correct detection and false alarm events.

In this paper, we simulate an indoor ultrasonic robot positioning scheme based on Direct Sequence Spread Spectrum (DSSS) system. Through DSSS system architecture, we make our higher power and narrow band of the original signal into a low power and broadband signals. Each transmitter is controlled by central controller. The central controller will select the assigned composite code sequences for the corresponding transmitter's unique code identification. The robot calculates the number of frame peak between local code replica and received summed sequence. The number of frame peak offers estimates of the robot distance to the corner transmitters. With such estimates of transceiver distance, the robot executes TDOA calculation and optimization to obtain its absolute location.

The paper is organized as follows. In Section II, we introduce composite code architecture in detail. Important correlation characteristics are investigated for parallel codes acquisition to estimate robot distance to transceivers. In Section III, composite PN codes are assigned to indoor corner transceivers to determine the absolute position of robot object by hyperbolic triangulation of the distance obtained from the measurement of the difference in TDOA among a transceiver and the others. In Section IV, with parallel codes acquisition scheme, we analyze the accuracy of the positioning and expect to improve the accuracy of the indoor positioning systems. Finally, in Section V, we present our discussions and conclusions. With parallel PN codes acquisition, robot positioning error is found much reduced to provide more precise movement behaviors.

II. COMPOSITE CODE SEQUENCES

Composite code sequences constructed with M-sequence codes are a particular set of PN sequences. This family of composite sequence codes possesses high magnitude of auto-correlation and low value of cross-correlation characteristics. We assigned different composite codes to transceiver in a DSSS system and controlled by central controller, and signals can be sent simultaneously and be separated at the receiver.

In this paper, we propose a coding method for DSSS indoor robot positioning system. The assigned transceiver composite codes are made up of M-sequence component codes. There are many groups of composite codes that the ultrasonic transceiver can be assigned with. Now, we select two M-sequence codes to illustrate a composite code set of them. Let $\boldsymbol{C}_1$ be an (n_1, k_1) binary M-sequence code and $\boldsymbol{C}_2$ be an (n_2, k_2) binary M-sequence code, where code periods n_1 and n_2 are relatively prime. Let $\boldsymbol{C}_1(X) \in \boldsymbol{C}_1$ and $\boldsymbol{C}_2(X) \in \boldsymbol{C}_2$ denote the basis code words or code vectors in code space $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$. Let $T^i\boldsymbol{C}_1(X)$ denote the i-chips cyclic right-shift of $\boldsymbol{C}_1(X)$, $0 \le i \le n_1-1$, and $T^j\boldsymbol{C}_2(X)$ the j-chips cyclic right-shift of $\boldsymbol{C}_2(X)$, $0 \le j \le n_2-1$. With $n=n_1n_2$, let code vector $T^i\boldsymbol{C}_1(X) \in \boldsymbol{C}_1$ repeat itself $n/n_1=n_2$ times and $T^j\boldsymbol{C}_2(X) \in \boldsymbol{C}_2$ repeat itself $n/n_2=n_1$ times, we obtain the repeated binary M-sequences of common period $n=n_1n_2$:

$$\left(T^i\boldsymbol{C}_1(\mathrm{X})\right)^n = (T^i\boldsymbol{C}_1(\mathrm{X}), T^i\boldsymbol{C}_1(\mathrm{X}), \cdots, (n_2 \text{ times})) \tag{1}$$

$$\left(T^j\boldsymbol{C}_2(\mathrm{X})\right)^n = (T^j\boldsymbol{C}_2(\mathrm{X}), T^j\boldsymbol{C}_2(\mathrm{X}), \cdots, (n_1 \text{ times})) \tag{2}$$

By combining (1) and (2) in a chip-by-chip modulo-2 addition, we get a composite code vector defined with the above component M-sequences

$$\left(C^{(i,j)}(\mathrm{X})\right)^n = \left(T^i\boldsymbol{C}_1(\mathrm{X})\right)^n \oplus \left(T^j\boldsymbol{C}_2(\mathrm{X})\right)^n \tag{3}$$

The notation "$\oplus$" represents a modulo-2 summation. The composite code vector of (3) are non-maximal length codes though their constituent component codes are maximal-length ones. In the above equations, we have defined $(T^i\boldsymbol{C}_1(X))^n$ and $(T^j\boldsymbol{C}_2(X))^n$ the repeated component M-sequence codes while $(\boldsymbol{C}^{(i,j)}(X))^n$ the composite codes made up from the above repeated M-sequences codes. Figure 1 depicts a schematic shift register circuit for composite M-sequence codes $\boldsymbol{C}^{(i,j)}(X) = T^i\boldsymbol{C}_1(X) \oplus T^j\boldsymbol{C}_2(X)$, where $T^i\boldsymbol{C}_1(X)$ codes are generated in the upper branch with recursion connection $h_1(X) = 1+X+X^2$ while $T^j\boldsymbol{C}_2(X)$ codes be generated in the lower branch with feedback connection $h_2(X) = 1+X+X^3$.

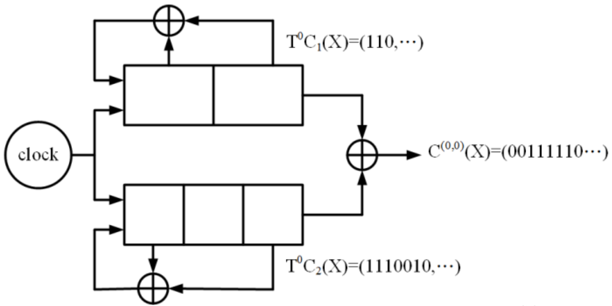


Figure 1. Shift register generator for composite codes $\boldsymbol{C}^{(i,j)}(X) = T^i\boldsymbol{C}_1(X) \oplus T^j\boldsymbol{C}_2(X)$.

On the receiver side, the goal is to capture the matched code signal to estimate position distance while reject interference from other unmatched signal codes. As depicted in Figure 2, we devise a parallel codes acquisition circuit for the robot receiver. Balanced correlators detection/subtraction scheme is adopted. In the upper circuit, the received signals will perform correlation operation with local code signal $\boldsymbol{C}_1 = (1, 1, 0)$ and $\overline{\boldsymbol{C}}_1 = (0, 0, 1)$ to capture acquisition peaks with every 3 bits cycle shift. In the lower circuit, the received signals will perform correlation operation with local signal code $\boldsymbol{C}_2 = (1, 1, 1, 0, 0, 1, 0)$ and $\overline{\boldsymbol{C}}_2 = (0, 0, 0, 1, 1, 0, 1)$ to capture acquisition peaks with every 7 bits cycle shift. The acquisition peaks combined from the upper and the lower correlators will appear at the common periodicity of 21 bits cycle shift. By using this method, the receiver can remove interference of other signals and capture the relative signal $\boldsymbol{C}_1 \oplus \boldsymbol{C}_2 = (1,1,0, \ldots) \oplus (1,1,1,0,0,1,0, \ldots)$.

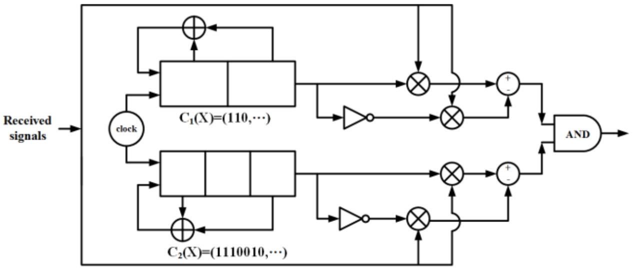
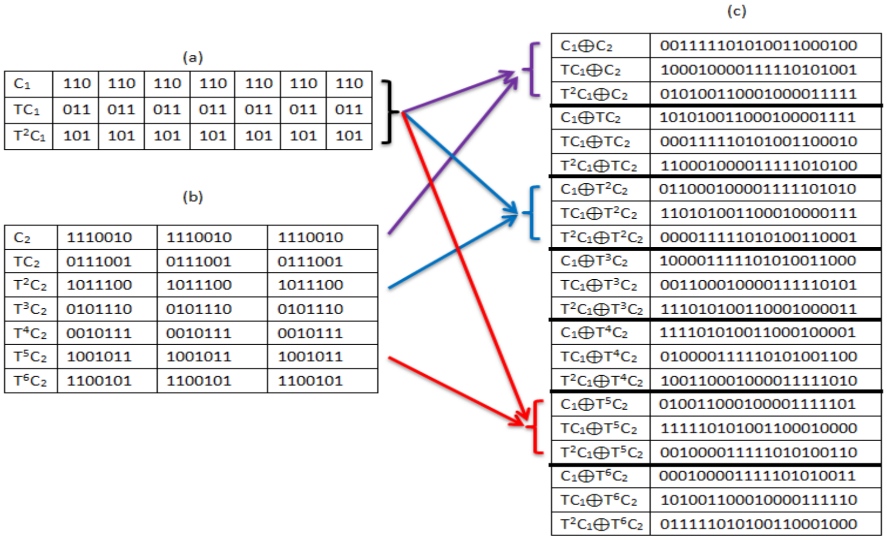


Figure 2. Parallel acquisition circuit for composite codes $T^i\boldsymbol{C}_1(X) \oplus T^j\boldsymbol{C}_2(X)$.

The composite codes $\boldsymbol{C}^{(i,j)}(X) = T^i\boldsymbol{C}_1(X) \oplus T^j\boldsymbol{C}_2(X)$ can be partitioned into proper subsets for assignment to ultrasonic transceiver sets. For example, on referring Table I, with $0 \le i \le n_1-1$ and $0 \le j \le n_2-1$, we see the possible code vectors $T^i\boldsymbol{C}_1(X)$ and $T^j\boldsymbol{C}_2(X)$ in Tables I(a) and I(b), and the modulo-2 combined composite M-sequence codes in Table I(c). With respect to Table I(c), transceiver #1 can be allocated with composite codes $(T^i\boldsymbol{C}_1 \oplus T^0\boldsymbol{C}_2)$, transceiver #2 with composite codes $(T^i\boldsymbol{C}_1 \oplus T^2\boldsymbol{C}_2)$, and transceiver #3 with composite codes $(T^i\boldsymbol{C}_1 \oplus T^5\boldsymbol{C}_2)$. Alternative transceiver codes assignment can also be adopted.

TABLE I. (a). $T^iC_1(X)$ CODE SEQUENCES; (b). $T^jC_2(X)$ CODE SEQUENCES; (c). COMPOSITE CODE SEQUENCES $C^{(i,j)}(X) = T^iC_1(X) \oplus T^jC_2(X)$.



(a)

C_1	110	110	110	110	110	110	110
TC_1	011	011	011	011	011	011	011
T^2C_1	101	101	101	101	101	101	101

(b)

C_2	1110010	1110010	1110010
TC_2	0111001	0111001	0111001
T^2C_2	1011100	1011100	1011100
T^3C_2	0101110	0101110	0101110
T^4C_2	0010111	0010111	0010111
T^5C_2	1001011	1001011	1001011
T^6C_2	1100101	1100101	1100101

(c)

$C_1 \oplus C_2$	001111101010011000100
$TC_1 \oplus C_2$	100010000111110101001
$T^2C_1 \oplus C_2$	010100110001000011111
$C_1 \oplus TC_2$	101010011000100001111
$TC_1 \oplus TC_2$	000111110101001100010
$T^2C_1 \oplus TC_2$	110001000011111010100
$C_1 \oplus T^2C_2$	011000100001111101010
$TC_1 \oplus T^2C_2$	110101001100010000111
$T^2C_1 \oplus T^2C_2$	000011111010100110001
$C_1 \oplus T^3C_2$	100001111101010011000
$TC_1 \oplus T^3C_2$	001100010000111110101
$T^2C_1 \oplus T^3C_2$	111010100110001000011
$C_1 \oplus T^4C_2$	111101010011000100001
$TC_1 \oplus T^4C_2$	010000111110101001100
$T^2C_1 \oplus T^4C_2$	100110001000011111010
$C_1 \oplus T^5C_2$	010011000100001111101
$TC_1 \oplus T^5C_2$	111110101001100010000
$T^2C_1 \oplus T^5C_2$	001000011111010100110
$C_1 \oplus T^6C_2$	000100001111101010011
$TC_1 \oplus T^6C_2$	101001100010000111110
$T^2C_1 \oplus T^6C_2$	011111010100110001000

III. ROBOT POSITIONING SYSTEM ARCHITECTURE

In views of correlation acquisition, the longer the code acquisition time, the longer the path estimation distance, and the worse the robot positioning accuracy. According to the proposed composite coding scheme, we devise a parallel composite codes acquisition scheme to implement the indoor robot positioning system; the position of a target can be captured from the distances between the ultrasonic transceivers and a receiver of a target.

Figure 3 depicts a conceptual schematic of the proposed indoor robot positioning system. In the transmitter, the ultrasonic transceivers are installed at the corners and connected to central controller. Three composite PN codes structured from relatively prime-length M-sequence codes are assigned to different transceivers. These composite codes are modulated with ultrasonic carrier wave to generate transmission signals.

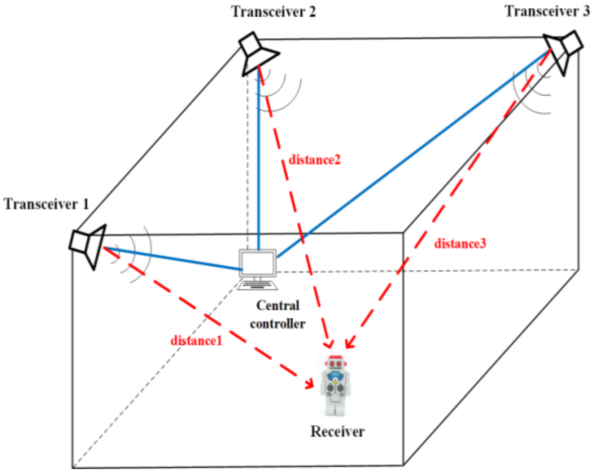


Figure 3. Overview of the indoor positioning system.

The reason we use ultrasound instead of higher frequency modulation signals is for easy visualizing robot codes acquisition under our limited PN code lengths in the transceivers. Take as comparative numerical figures for the high and low modulation rates. With 21-chip lengths per code frame and suppose 5-frames time is needed to confirm code acquisition. On using RF chips rate of 2000-kHz (2x10^6 chips/sec), the estimated object distance will be 21x5/2x10^6 = 5x10^{-5}m. This figure is hardly distinguishable on the robot distance to the transceiver. But on using ultrasonic chips rate of 20-Hz (20 chips/sec), the same code length and acquisition frame will yield an estimated object distance of 21x5/20 = 5m. This figure is something acceptable. In practice, acquisition chips period length in mobile positioning can reach up to 2^{13}-1 = 8191 chips per frame to yield a distinguishable object distance.

In the robot receiver, in order to calculate the distance from each transceiver, the robot needs to separate the incoming signals from different transceivers. The robot bears the same ultrasonic carrier wave and composite PN codes as those of the transceiver signals, which are called the replica signals. On correlating received code signals with local replica signals, the robot can separate correlation peaks for the matched transceiver code from correlation nulls for the unmatched ones. This procedure for correlation detection of code signals is called code acquisition.

The robot positioning block chart for acquiring signal codes and estimating their flight time is as shown in Figure 4. In coding/modulating part of Figure 4(a), every transceiver performs ultrasonic signal modulation with assigned signature code, and emits this ultrasonic signal continuously. Once the signal is received by the robot, the receiver turns the signal from analog to digital, and demodulates it into a corresponding code sequence. Since the receiver needs to identify the intended sequence code among all received signals, the demodulated code sequence is connected to three parallel correlators to calculate with each assigned code. Figure 4(b) depicts conceptual block chart on correlation decoding processes in the robot side. The output correlation passes through a peak detector to estimate the time of flight from transceiver to the robot. The robot then evaluates its current position by measuring time difference of arrival (TDOA) among the three transceiver paths.

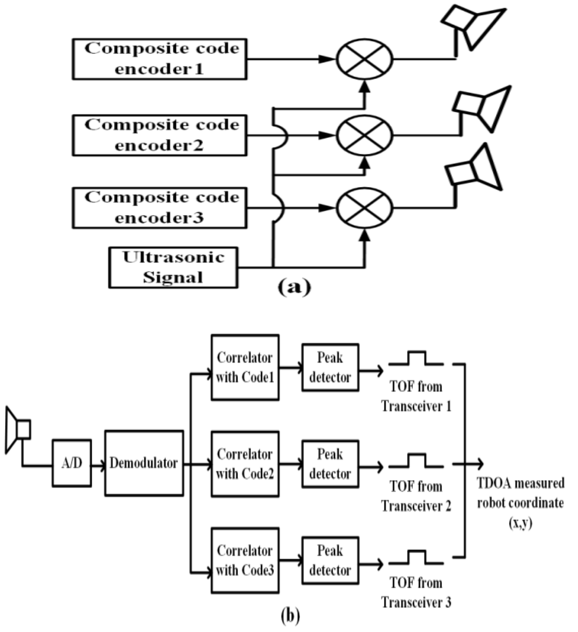


Figure 4. Block chart for robot positioning system; (a). Signals coding in transceivers; (b). Correlation acquisitions in the robot.

With regard to the block diagram of Figure 4 for robot positioning system, we will give detailed descriptions on codes correlation acquisition/detection, acquisition time difference and time error, and relative distance/locations determination of robot object in the following subsections.

A. *Code acquisition with correlation detection*

After the transmission signals transmit to the receiver, the received signals have a transmission time delay so that the received signals are not synchronous with the replica signal. Therefore, how to capture the relative signal and ignore the interference is the main course. We provide solutions to overcome the interference and improve the accuracy in the following sections.

For code acquisition, we note that the correlation characterizations of the assigned composite codes are related with their code weights. If code vectors $T^iC_1(X)$ and $T^jC_2(X)$ have the respective code weights w_1 and w_2, then composite code $C^{(i,j)}(X) = T^iC_1(X) \oplus T^jC_2(X)$ possesses the following code weights

$$W\left(C^{(i,j)}\right) = w_1(n_2 - w_2) + w_2(n_1 - w_1) \tag{4}$$

$$= \begin{cases} \frac{n_1(n_2+1)}{2}, & if\ w_1 = 0,\ \ w_2 = (n_2+1)/2. \\ \frac{n_2(n_1+1)}{2}, & if\ w_1 = (n_1+1)/2,\ \ w_2 = 0. \\ \frac{(n_1n_2-1)}{2}, & if\ w_1 = (n_1+1)/2,\ \ w_2 = (n_2+1)/2. \end{cases} \tag{5}$$

Here, we have taken advantage that a binary ($n_l = 2^{ml-1}$, $k_l = m_l$) M-sequence code has all of its n_l nonzero code vectors the same code weight of $(n_l+1)/2 = 2^{ml-1}$. Corresponding to the weight distribution of (5), the periodic correlation between composite codes $C_u^{(i_u,j_u)}$ and $C_v^{(i_v,j_v)}$ can be derived to be

$$\theta_{u,v} = \begin{cases} \left(\frac{n_1n_2-1}{2}\right), if\ u = v \\ \left(\frac{n_1n_2-n_2-2}{4}\right), \left(\frac{n_1n_2-n_1-2}{4}\right), \left(\frac{n_1n_2-1}{4}\right), if\ u \neq v \end{cases} \tag{6}$$

From the above correlations distribution of (6), we see that correlations between reference transceiver and interfering transceivers can be separated by correlation operation to track the desired transceiver sequences.

When the robot receives the incoming ultrasonic signals the receiver demodulates the received signals and performs correlation operations between the demodulated PN sequences and the replica signals stored in the correlators. The correlation computation will offer codes acquisition information on the periodic correlation peaks, and the receiver calculates the delay time and the codes acquisition error accordingly. Figure 5 illustrates the possible correlation spectra for composite signal sequence been acquired with M-sequence component codes $\boldsymbol{C}_1(X)=\boldsymbol{U}(X)$ and $\boldsymbol{C}_2(X)=\boldsymbol{V}(X)$. Here we take as example the composite signal sequence of period length $n_1.n_2=21$ and component M-sequences $\boldsymbol{C}_1(X)$ and $\boldsymbol{C}_2(X)$ of period lengths $n_1=3$ and $n_2=7$. These code sequences will respectively be assigned to the corner transceivers and the central robot.

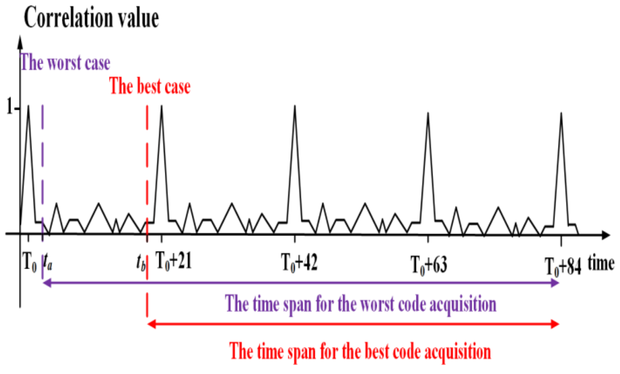


Figure 5. Correlation spectra to illustrate time span for the worst and

the best code acquisitions.

The robot receiver carries out correlation operations between received PN sequence and local M-sequence $\boldsymbol{C}_1(X)$; and in parallel, the robot receiver carries out correlations between received PN sequence and local M-sequence $\boldsymbol{C}_2(X)$. If no correlation peak occurred in either operation, the corresponding local code will advance one chip to another code pattern to continue its correlation computation. On the other hand, if an individual low-level correlation peak occurred, the local code will advance one period cycle of the current code pattern to continue its correlation computation. This process will continue until a high-level common correlation peak is obtained. The local codes in the robot will keep continuing their code sequences advancement for upto three to five common period lengths (3~5 frames) to confirm the final code acquisition status.

B. Code acquisition time difference and time error

In the indoor positioning environment, transmission signals interfere with each other. Every transceiver has different code sequence. In order to capture the relative code sequence to confirm the received signal which the transceiver transmitted. We determine the time between two adjacent peaks interval whether the corresponding transmission signal. If the time interval satisfies the correlation characteristic of the relative signal, we use this signal to calculate the time of flight and the time error of code acquisition.

On advancing code chips for correlation peaks, instant time t_a in Figure 5 depicts the worst case of code acquisition in which twenty-chip advancement is needed to reach an initial common correlation peak. Apparently, the common correlation peak is not captured very soon by the peak detector so that the time span of code acquisition takes much longer. On the other hand, instant time t_b in Figure 5 depicts the best case of code acquisition in which only one-chip advancement will reach the initial common correlation peak. In this case, the common correlation peak can be quickly captured by the peak detector so that the span time of code acquisition is significantly shortened.

A flow chart for the above correlation acquisition processes is as shown in Figure 6. Received summed sequence of period 21 is parallelly correlated with local PN sequences of period lengths 3 and 7. If not getting a correlation peak in either correlator, implies unmatched local and received sequence codes, one-chip relative shift is advanced and correlation magnitude is again calculated. But if a correlation peak is obtained in either correlator, matched local and received sequence codes is assumed, 3- or 7-chips relative shift is advanced and correlation magnitude is again calculated. The processes continue until a highest correlation peak occurs at the common code frame length of 21 chips. From then on, further confirmation of high peak correlation over 3~5 code frames will assure a complete code acquisition.

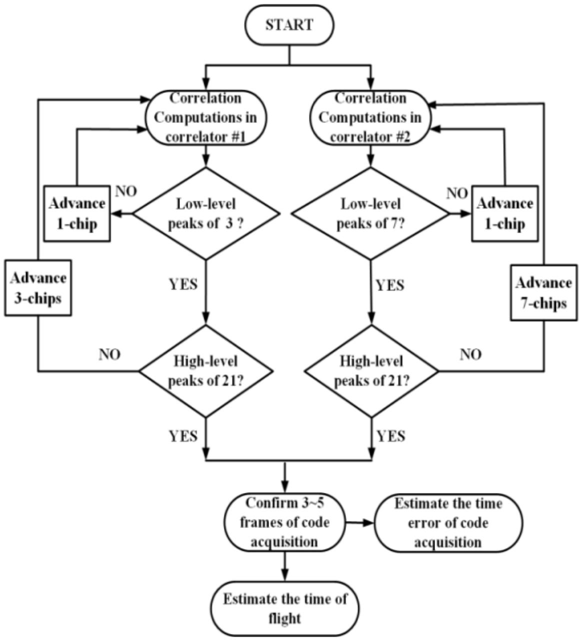


Figure 6. Flow chart for composite PN codes' correlation acquisitions.

In actual, codes correlation acquisition are not necessarily in the best or the worst acquired time, but may fall in the possible instant between the two extremes. Therefore, we will use probability distribution to analyze the possible cases to estimate the average of the time spent. We will further take the average of the time span to improve the indoor positioning accuracy. In the proposed positioning system, the main impact factor is the correlation characteristics of the composite PN sequence codes because the codes periods are not in symmetrical lengths. The time of flight between indoor transmitters and robot receiver are measured from the time instant the ultrasonic signals been emitted from corner transceivers to the time instant the acquisition peak detection been confirmed at the robot.

The time error of code acquisition is caused by the system that spends time searching for the relative sequence. Because the sequence is not sure to fall in the best or the worst acquired time so we need to calculate this acquired time to estimate the time error of code acquisition. We assume the time error of code acquisition about 2~3 code cycle lengths. Therefore, every signal has a different time error of code acquisition because of different code length. For example, the M-sequence code length n_1=31 spends about 62~93 bits shift time to capture the signal and the composite code $n_2=3\times 7$ spends about 42~63 bits shift time to capture the signal. In our positioning method, we use these values of the time error of code acquisition to enhance our indoor positioning accuracy.

C. *Determine the position of the robot receiver*

In order to obtain the position of the robot, the range measurement is acquired by TDOA of the ultrasonic signals of the transceivers. The TDOA will be biased by the time error of code acquisition that can degrade the positioning estimate. Therefore, the time error of code acquisition needs included in the calculation. Figure 7 is taken to illustrate three transceivers functions in expression (7) below to locate the position of an object receiver.

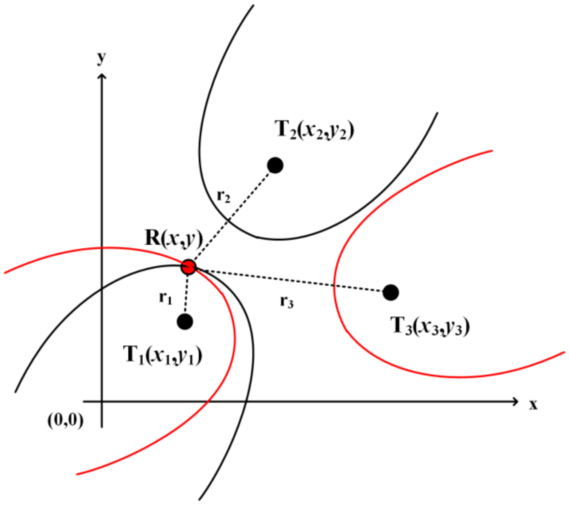


Figure 7. Overviews of TDOA evaluation.

Assume that, r_1, r_2 and r_3 are the estimated time of flight obtained from the number of frame peak between local and received code sequences. Once we get these estimates, we subtract them to each other to obtain ΔT_{12}, ΔT_{13}, and ΔT_{23}. We then substitute these flight time differences into (7) to solve the TDOA:

$$d_{ij} = c * (\Delta T_{ij} + e_{ij}), \quad \text{where } i \neq j$$

$$= \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2} \quad (7)$$

where (x, y), (x_i, y_i) and (x_j, y_j) are respectively the real and the estimated position of robot receiver to the i-th and j-th transceiver, i,j = 1, 2, 3; d_{ij} are the value of TDOA; c is the ultrasonic wave speed; ΔT_{ij} is time difference measured by code acquisitions; and e_{ij} is the value of the time error of code acquisition to subtract with each other. The equations above represent hyperbolas, and their intersection gives the estimated positioning of the receiver.

The solution of equation derived a wide variety of algorithms because finding the solution is not easy as the equations are nonlinear. There are many methods to solve equations in this research problem. One direct solving method is Taylor-series method (TSA). It is the simplifying method, but the solutions are not divergent or converge toward a local suboptimal result if the unsuitable initial point was given. Fang Algorithm (Fang), Chan Algorithm (Chan), and Total Least Squares Algorithm (LTS) provides better performance than TSA. In order to optimize location result, evolution computing techniques will be applied to this working. Evolution computing techniques are based on principles of biological evolution, such as natural selection and genetic inheritance, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Artificial Bee Colony algorithm (ABC).

IV. NUMERICAL SIMULATION RESULTS

In order to analyze the positioning accuracy between traditional M-sequence code and composite M-code which we proposed, we use M-sequence code length n_1=31 and composite code length n_2=3×7 to simulate. The robot was placed in the coordinate (x=3m, y=3m and z=0m). The three transceivers are located at three corners (x=0m, y=0m and z=5m) (x=0m, y=10m and z=5m) and (x=8m, y=0m and z=5m), in the numerical simulation, we assume the robot on the ground so we don't consider the z-axis. Transceiver #1 is assigned with composite codes ($T^0C_1 \oplus C_2$) = (1, 1, 0, ⋯) ⊕ (1, 1, 1, 0, 0, 1, 0, ⋯), transceiver #2 assigned with signature codes ($T^1C_1 \oplus C_2$) = (0, 1, 1, ⋯) ⊕ (1, 1, 1, 0, 0, 1, 0, ⋯), and transceiver #3 assigned with signature codes ($T^2C_1 \oplus C_2$) = (1, 0, 1, ⋯) ⊕ (1, 1, 1, 0, 0, 1, 0, ⋯).

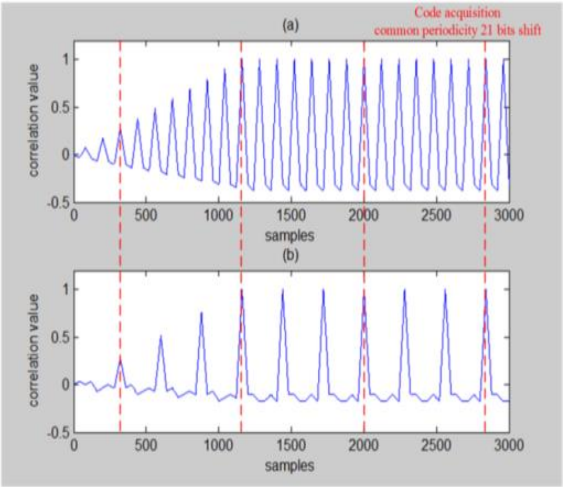


Figure 8. Correlations of composite signal with component signature codes; (a). with M-sequence code C_1 = (1,1,0); (b). with M-sequence code C_2 = (1,1,1,0,0,1,0).

Figure 8 illustrates the receiver performs the correlation operation with transceivers #1. The periodicity of Figure 8(a) is 3 bits shift and the periodicity of Figure 8(b) is 7 bits shift, therefore their common periodicity is 21 bits shift. From Figure 8, the first red line is the first common peak of code acquisition, which will change with the first incoming frame because the order of frame may not be C_1 = (1, 1, 0). Therefore, the receiver will search for next common peak by common periodicity 21 bits shift to capture their relative signals. These time spent are the error time of code acquisition. Once the receiver captures the peaks completely, the receiver estimates its error time of code acquisition of signals and time of flight.

Figure 9 illustrates correlation operations of robot receiver with transceivers #1-#3 on the relative composite codes. The cycle of peak is 21 bits shift as shown in Figure 9. The different numbers of cycle is caused by the different distance between the receiver and transceivers. We use these data to estimate the numbers of cycle, and calculate the time of flight and the error of code acquisition.

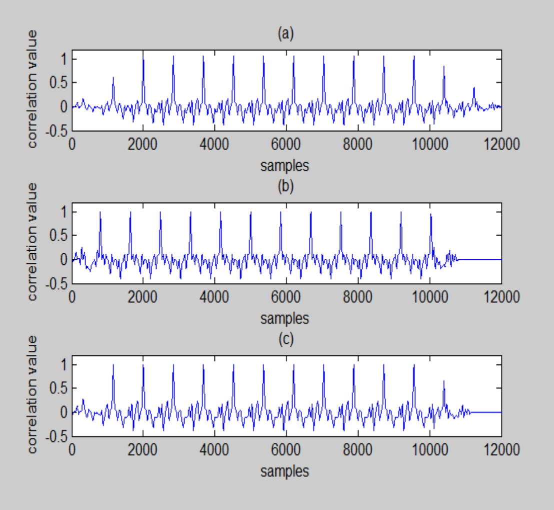


Figure 9. Robot correlation operations with transceivers; (a). with transceiver #1 on composite codes ($T^0C_1\oplus C_2$); (b). with transceiver #2 on codes ($T^1C_1\oplus C_2$); (c). with transceiver #3 on codes ($T^2C_1\oplus C_2$).

Table II shows estimates of time of flight and robot distance to the three transceivers. Through calculating the number of frame peak between local code and received sequence, we estimate the time of flight and then the distance between transceivers and the robot. The estimated position errors are not over 10-cm, thus achieves our goal on enhancing indoor robot positioning accuracy.

TABLE II. ESTIMATE OF THE DISTANCE BETWEEN TRANSCEIVERS AND THE ROBOT.

	Estimate time difference	Estimate range	Real range
With transceiver#1	0.0179 sec	6.1934 m	6.1644 m
With transceiver#2	0.0232 sec	8.0272 m	7.9372 m
With transceiver#3	0.0221 sec	7.6466 m	7.6811 m

For comparison, we assign the central robot and the corner transceivers with comparative M-sequence codes of period length n=31. Figure 10 gives possible correlation spectra on correlating received code sequence from transceiver #1 and local signature codes in the robot. Note that, with such conventional PN code sequences, two-levels of correlation magnitude is possible and single branch correlator circuit can be taken for codes acquisition operation.

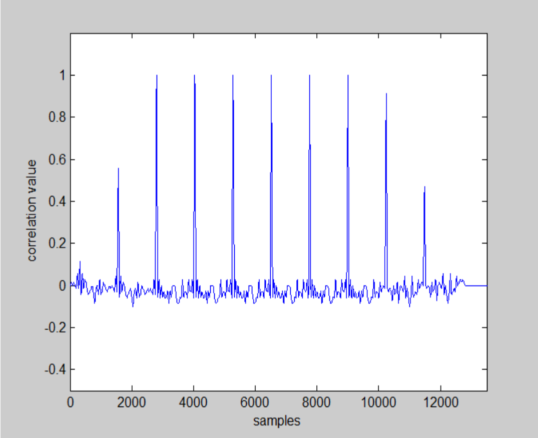


Figure 10. Correlation operation with transceiver #1 on 31 bits M-sequence code.

On comparing Figures 9 and 10, we find that the number of frame cycles of 31 bits M-sequence code is less than those using composite codes to do correlation operations at the same distance. Because of a large code length cycle, the receiver spends much shift time to capture the signal so that the error time of code acquisition is more than using composite code to do correlation operation. The mean of the distance errors is about 20 cm, so using composite code is more precise than using M-sequence code.

V. CONCLUSIONS

We have proposed a composite code acquisition to implement indoor ultrasonic robot positioning based on DSSS system. Each transceiver is modulated the ultrasonic signal with a 3×7 bits composite code, which has a particular auto-correlation and cross-correlation in a cycle. By using code acquisition the robot receiver detects the arrival time of codes and the error time of code acquisition, and the robot will use these information to determine its absolute location.

By comparing our solution with traditional M-sequence code, we find that composite codes behave more advantages. First, the code length is more flexible, it is not limited by 2^m-1. Second, other robot users are difficult to acquire the location of the designated robot because the code combination is more complex. Third, under the same location distance, the positioning accuracy and the code acquisition time-error are more precise with composite coding than the conventional M-sequence coding. This is

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because correlation acquisition takes more cycles than that using pure M-sequence codes.

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