A Novel Approach for Intruder Localization Based on Leaky Coaxial Cable Sensor with IQ Demodulation and Synchronous Subtraction

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Abstract **─** Some aspects of the intruder detection system (IDS) based on the leaky coaxial cable (LCX) sensor are still unknown due to its complex propagation characteristics. In order to study the field disturbance mechanism of human intruder and to reduce the phase error caused by the initial state of the detection signal, a novel method of improving the localization accuracy is proposed. At the frequencies of 40MHz, 100MHz and 200MHz, the IDS based on the LCX sensor is proposed by analyzing the scattering characteristics of human intruder and using IQ demodulation method. According to the characteristics of the IDS, the electric field distribution is obtained by irradiating the human intruder from three typical radiation directions, which are front, side and low-side direction in the mentioned frequency range. Combined with the method of pulse accumulation and synchronous subtraction, the intruder localization can be easily realized by using pulse delay positioning method. The results demonstrate the improvement in localization accuracy and the decrement in false positive rate, and the positioning accuracy is less than 3 meter.

Index Terms **─** Intruder detection, LCX sensor, localization, phase error, synchronous subtraction.

I. INTRODUCTION

Leaky coaxial cable (LCX) has been intensively applied to various application scenarios for its receiving and emitting functions, such as the tunnel, the railway, the indoor communication and the positioning localization system [1~5]. The perimeter intrusion detection system (IDS) based on the LCX sensor has been widely studied because of its better concealment, flexible installation and all-weather conditions work [6~7]. Therefore, compared with other location systems, the characteristics and advantages of the IDS lie in its application scenario. The ordinary localization systems usually detect the target in the area of directional beam of the systems' antennas. However, the IDS based on LCX sensor has some completely different characteristics. As the Fig. 1 shown, the apertures on the LCX's outer conductor are similar to the array antennas [8~9], which builds a wide-belt flexible detection area instead of the area of directional beam. The closer the aperture is to the targets, the more obvious reflection effect the aperture provides. The IDS can avoid the influence of the environment and the terrain. Because most of the power is transmitted in the LCX sensor, the IDS can reach a far distance to achieve the security guarding with the small attenuation in a specific area.

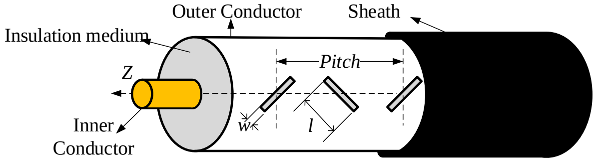

Fig. 1. Configuration of the leaky coaxial cable.

Although some IDS based on LCX sensor have been applied, there has few researches about the electromagnetic disturbance mechanism of the human intruders. Therefore, the disturbance of human body in electric field is studied, and the experiments in time-domain and frequency-domain echo signals are carried out in the radiation mode and coupling mode. Moreover, the experiment of the signal receive unit of IDS is conducted by means of the IQ-demodulation method and synchronous subtraction. On the basis of the amplitude stability of the V_{IQ}, the effects of the intruder positioning are evaluated at 40 MHz, 100 MHz and 200 MHz by referring to the time delay separately, which significantly reduces the phase error. In addition, the method of improving the positioning accuracy is further studied. Finally, the relation between echo signal quality and frequency is discussed.

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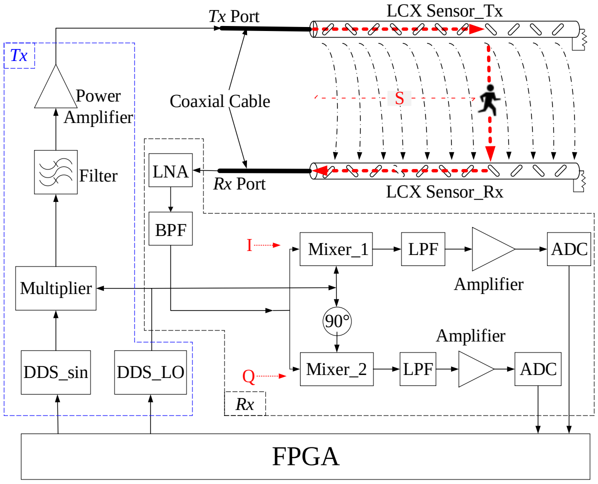
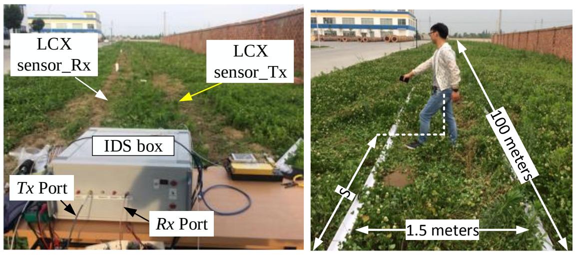
II. INTRUDER DETECTION SYSTEM AND LOCALIZATION METHOD

The configuration of the IDS based on LCX sensor is shown in Fig. 2 (a), which is mainly composed of the signal generator unit *Tx*, the signal receives unit *Rx*, LCX sensor and field programmable gate array (FPGA) processor. The LCX sensor consists of the two same LCXs [10] in IDS. The LCX sensor_Tx is used to transmit and radiate the detection signals, and LCX sensor_Rx is used to receive the echo signals. Those two LCXs form the target monitoring area of the IDS. When there is a human intrusion in monitoring area, the original environmental medium become discontinuous, and the discontinuity of the medium leads to the amplitude attenuation and the path change of the signal transmission, which results in the significant fluctuations in the field distribution at the position of the intruder.



(a) Configuration of IDS



(b) IDS and human intruder

Fig. 2. Intruder detection system based on LCX sensor.

Figure 2 (b) is the test photo of the IDS and intruder, where the signal generator *Tx* and signal receive unit *Rx* are assembled in the IDS box. In the signal transmit unit, the method of direct digital synthesizer (DDS) is used to generate the signal. Compared with the traditional frequency synthesizer, DDS has the advantages of low cost, low power consumption, high resolution and fast switching time, which is widely used in the field of telecommunication and electronic equipment [11]. In Fig. 2 (a), the signal for detecting intruder is a pulse signal with the carrier frequency f_0. The signal is produced by the mixing in multiplier of the signal of DDS_SIN and the signal of DDS_LO, where DDS_SIN is a sine wave generator and DDS_LO is a square-wave pulse generator. The detection signal is transmitted in LCX sensor_Tx after passing through a filter and a power amplifier (PA). When an intruder enters the detection area, part of the signal is reflected and received by LCX sensor _Rx. The signal receive unit can detect the intruder by monitoring the fluctuation of this echo signals. The position information of the intrusion can be obtained through the propagation delay time τ_R. The distance S is calculated by [12]:

$$S = \frac{v \cdot \tau_R}{2}, \tag{1}$$

where v is the velocity of the signal transmitting in the LCX. When there is no intruder, this echo signal received by LCX sensor_Rx is called the system response. In general, the system response is unchanged, and it is only related to factors of the laying environment and the detection signal. The signal received by LCX sensor_Rx is called the intruder response when an intruder enters or walks near the warning area. In fact, the LCX sensor_Rx receives two kinds of signals, one is the system response, and the other is the reflection signal produced by the intruder in the detection area. By extracting the change of the echo signal, the location of the intruder can be determined.

As shown in Fig. 2 (a), the output of the Multiplier is defined as the detection signal:

$$S_T(t)=A_T \cdot rect(\frac{t-t_R/2}{t_R/2})\cos(2\pi f_0 t+\varphi_0), \tag{2}$$

where A_T is the amplitude of the detection sigan l, t_R is the length of the pulse, f_0 is the carrier frequency. φ_0 presents the initial phase, which is a random value when the IDS starts to work. The detection signal transits in the LCX sensor_Tx and radiates out through the apertures on the outer conductor of the LCX. The detection signal transmits back to signal receive unit when this signal meets the human intruder. The echo signal is given by:

$$S_R(t) = A_R \cdot rect(\frac{t-t_R/2}{t_R/2})\cos(2\pi f_0 t + \varphi_0 + k_c v \cdot \tau_R), \tag{3}$$

where A_R is the amplitude of the echo siganl, k_c is the number of the waves in the LCX. Then the echo signal is divided into I-signal and Q-signal for IQ-demodulation after passing through a low-noise amplifier (LNA) and a band-pass filter (BPF). Meanwhile, the high-order mode interference is reduced.

In signal analysis, the signal vector can be decomposed into two components of the same frequency and the amplitude but the phase difference of 90 degrees [13]. Amplitude, frequency and phase can be described completely by the description of the vector, it is really useful for IQ demodulation in this paper. The local oscillator (LO) signals are $LO_{\sin} = A_{LO} sin(2\pi ft + \phi_{LO})$ and $LO_{\cos} = A_{LO}\cos(2\pi ft + \phi_{LO})$ respectively, which are a pair of orthogonal signal vectors. After passing through Mixer_1 and Mixer_2, the signal demodulation was obtained by:

$$V_I(t) = \frac{A_R A_{LO}}{2} \cdot rect(\frac{t - t_R/2}{t_R/2})\sin(\phi_{LO} - \varphi_0 - 2k_c \cdot S) \text{ ,(4)}$$

$$V_Q(t) = \frac{A_R A_{LO}}{2} \cdot rect(\frac{t - t_R/2}{t_R/2})\cos(\phi_{LO} - \varphi_0 - 2k_c \cdot S) \text{ ,(5)}$$

where A_{LO} is the amplitude of LO siganl. It is possible that $V_I(t)$ or $V_Q(t)$ can equal zero because of the appropriate phase $\phi_{LO} - \varphi_0 - 2k_c \cdot S$ in (4) ~ (5). The value of the phase will directly affect the amplitude of the demodulated echo signal $V_I(t)$ and $V_Q(t)$. If there is a phase that makes the amplitude of zero or be lower than the alarm threshold value of IDS, then the intruder will be missed. So there is a blind area for the location of the intrusion, and the blind area is uncertain because the initial phase of the detection signal is uncertain when IDS works. The uncertainty of the phase will lead to the uncertainty of the position of the blind area. It will greatly reduce the accuracy of the location detection of the IDS if we consider $V_I(t)$ or $V_Q(t)$ as the only echo signal. In this case, when an intruder enters the detection area at some R that makes the appropriate phase, the intruder could not be found. Fortunately, $V_I(t)$ and $V_Q(t)$ are not both zero and orthogonal to each other. Therefore, the sum amplitude of the two signals vector can ensure a good result, which can be obtained by:

$$V_{IQ}(t) = \sqrt{(V_I(t))^2 + (V_Q(t))^2} = \frac{A_R A_{LO}}{2} \cdot rect(\frac{t - t_R/2}{t_R/2}) \text{ . (6)}$$

In (6), the amplitude of the echo signal $V_{IQ}(t)$ is a constant, it helps to reduce the alarm rate and provide a standard threshold value, which guarantees the accurate detection rate.

The distance S is only related to the delay time t_R of the echo signal in (1), and t_R can be calculated by the difference between system response $V_{IQ\text{-}system}(t)$ and intruder response $V_{IQ\text{-}intruder}(t)$. This processing method is called synchronous subtraction.

III. EXPERIMENTAL RESULTS

A. Analysis on the mechanism of the field disturbance caused by the human intruder

The parameters of the LCX sensor are defined as follows: the dielectric constant of the insulation medium is 1.247, dielectric loss angle tangent is 1.7e-5 and the pitch is 1 meter. According to the classification method of LCX's working modes theory [12], the LCX is in the radiation mode when the frequency is higher than 142 MHz, or the LCX is in the coupling mode when the frequency is lower than 142MHz. Figure 3 shows the human intruder model and the propagation characteristics of electric field (E-field) when the frequency is at 40MHz, 100 MHz and 200MHz separately. The human intruder is irradiated from 3 typical directions by a source of plane wave, respectively. The normal vector of the side plane is $\overrightarrow{a_s} = \overrightarrow{a_z}$. Similarly, the normal vector of the front plane is $\overrightarrow{a_f} = -\overrightarrow{a_y}$, and the normal vector of the low-side plane is $\overrightarrow{a_{ls}} = \overrightarrow{a_x} + \overrightarrow{a_z}$.

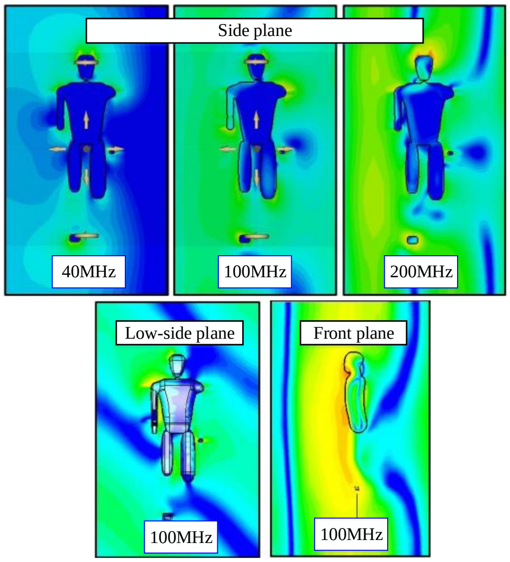


Fig. 3. Human intruder model and E-field distribution.

The simulation results show that the discontinuity of the electromagnetic wave is obvious in Fig. 3, and the scattering effect is more serious, especially in the complex part of the human intruder, such as the head and extremities of the arms and limbs. Besides, the E-field will quickly decay when the electromagnetic wave enters the trunk of the human intruder. The results indicate human intruder can disturb the electromagnetic field in mentioned frequency range. Therefore, the IDS based on LCX sensor proves to be a feasible method in practical.

The IDS based on LCX sensor is shown in Fig. 2 (b). The LCX sensor_Tx and LCX sensor_Rx are placed parallel on the ground. The detection range of the LCX sensor is 100 meters long, and the spacing between the two LCX is set to 1.5 meters. The *Tx* produces a single frequency pulse as the detection signal of the pulse period T=2 ms and the pulse width τ = 200 ns. After amplified by a power amplify (PA), the detection signal is send into the LCX sensor_Tx. Signal receive unit is connected to the LCX sensor_Rx. Figure 4 shows the inside components of the IDS box.

The influence of the human intruder on the electromagnetic field established by LCX sensor can be analyzed by the changes of the echo signals in the time domain and the frequency domain. Figure 5 (a) shows the comparison of the echo signal with intruder or without intruder in frequency spectrum, and it can be seen that their waveforms are basically the same. Moreover, the intensity of the echo signal with an intruder is slightly greater than that of no intruder. So the appearance of human affects the echo signal and reflection is obvious in the frequency range, and it is reasonable that human intruder is sensitive to the wavelength. Moreover, the normalization waveform records at different intrusion positions are shown in Figs. 5 (b) ~ (c) in the time domain.

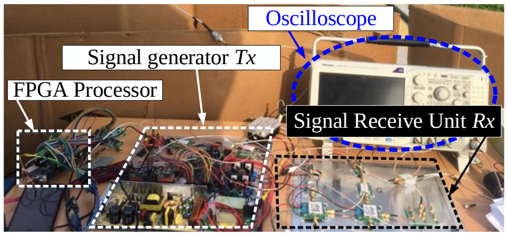
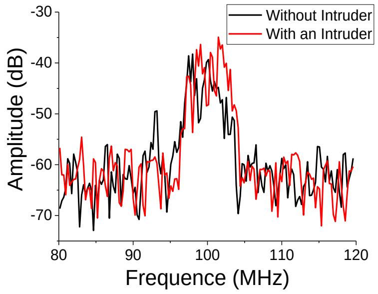
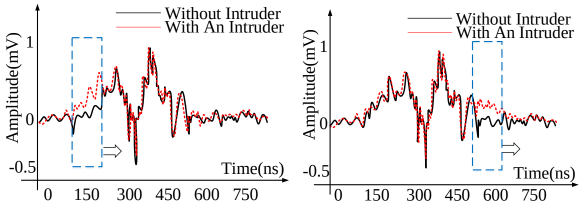


Fig. 4. The components in the IDS box.



(a) Frequency domain



(b) Closer distance (c) Farther distance

Fig. 5. Frequency domain and time domain with intruder or without intruder (detail of detection signal: the pulse period T=2 ms, the pulse width t_R = 200 ns, the carrier frequency f_0=100MHz)

Figures 5 (b) ~ 5 (c) are related to three positons from near and far, the blue dashed box presents the difference of the system response and the intruder response. When an intruder moves along the LCX sensor, it can be observed that the different waveforms are in the time domain. It is obvious that the blue dashed box moves to right when the intruder is walking to the end of the LCX sensor. In other words, it proves that intrusion position is also corresponding to the delay time of the intruder response.

In fact, as shown in Figs. 5 (b) ~ 5 (c), the waveforms of the system response or the intruder response in time domain is not an ideal smooth waveform, on the contrary, it composes of two peaks and one valley, the reason for such waveform is that the distribution of signal intensity is not uniform along the LCX sensor, where there are two areas with strong reflection and one area with relatively weak reflection. The number and amplitude of the peak are related to the environment around the LCX sensor, the type of LCX, or the climate conditions. Therefore, the system response is not always the same, and it is easy to be affected by the factors such as water content of soil, climate and vegetation status. In order to ensure the real and accurate results, it is very necessary to calibrate reference systems response regularly.

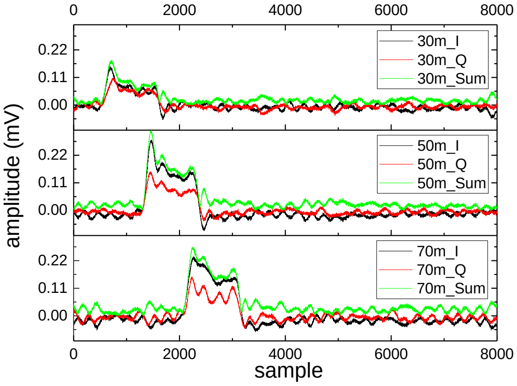
B. Experimental and calculated results of localization

As shown in Fig. 2 (b), the length of the LCX is 100 meters long, and the echo signal passes through the band-pass filter (BPF) after being amplified by the low-noise amplifier (LNA). The demodulated I-signal and Q-signal are obtained after the echo signal is mixed with LO_{sin} and LO_{cos}, respectively. The FPGA processor receives I-signal and Q-signal by the analog-digital converter (ADC).

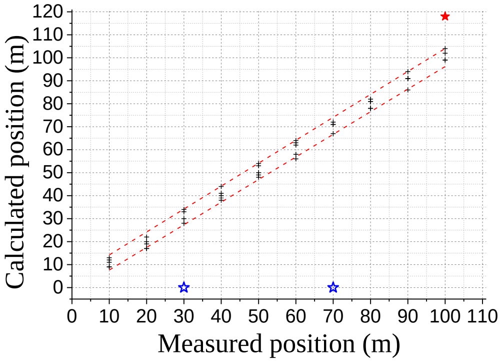
The pulse accumulation and synchronous subtraction are very important signal processing in this paper, and those two methods can eliminate the interference of the environmental changes, which is a very flexible signal processing in IDS. The pulse accumulation is used to reduce the noise by adding the finite echo signals repeatedly, and the synchronous subtraction is used to locate the intruder accurately by calculating the difference between system response and intruder response.

The difference of the system response and the intruder response is shown in Fig. 6 (a). When an intruder enters the detection area at 30 meters, 50 meters, and 70 meters separately, the subtraction results of I-signal are 30m_I, 50m_I and 70m_I, the subtraction results of Q-signal is 30m_Q, 50m_Q and 70m_Q. The sum represents the subtraction result of IQ-signal by equation (6). Obviously, a pulse is obtained from the subtraction results, which indicates the position of the human intruder.

It can be seen that the peak value of the I-signal or Q-signal is small in some results. It is not accurate only to consider the subtraction result of I-signal or the subtraction result of Q-signal as the intruder's position, because the subtraction results of I-signal are not always better than the Q-signal in all positions by (4) ~ (5). As shown in Fig. 6 (a), the difference of I-signal and Q-signal becomes large from 30 meters to 70 meters. Therefore, it is possible to avoid this error and improve the detection probability by calculating the square root of the subtraction results of I-signal and Q-signal according to (6). The curves of square root are 30m_sum, 50m_sum and 70m_sum. It can be seen that the positioning accuracy is ± 3 meter from Fig. 6 (b), the statistics data indicates that there are 48 alarms in 50 intrusions, including a false alarm (red star marker) at 100 meters, two missed intrusions (blue star marker). Therefore, the false positive rate of IDS is 2/50*100% = 4%, and the false positive rate is lower than (1+2)/50* 100% = 6%.



(a) Localization result at three positions



(b) The statistical data of the detection results

Fig. 6. Localization result (Detection signal: the pulse period T=2 ms, the pulse width t_R=200 ns, frequency f_0=100MHz).

Figure 7 is the localization results of 40 MHz and 200 MHz.

The results of square root are obvious, while the amplitudes of 200 MHz and 40MHz are all less than that of 100MHz. Besides, compared with carried frequency of 200MHz, 40 MHz has a higher noise, though the amplitude of 40 MHz is less than that of 200MHz. It shows that 100 MHz has the best localization effect.

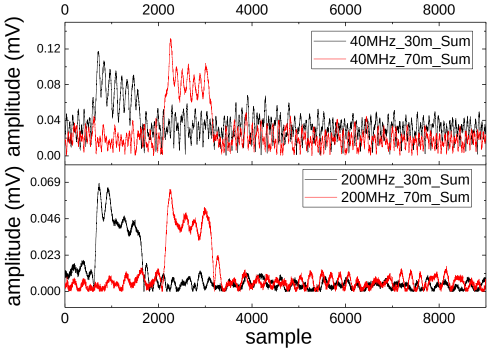


Fig. 7. Localization result of two positions with the method (Detection signal: the pulse period T=2 ms, the pulse width t_R=200ns, frequency f_0=40MHz/200MHz).

IV. CONCLUSION

A novel and effective general method for intruder localization using the IQ demodulation and synchronous subtraction is proposed in this paper, and it is suitable for the frequencies of 40 MHz, 100MHz and 200 MHz. In the studied frequency range, the scattering characteristics of human intruder is significant, which confirms the possibility of human detection and localization. Among those carrier frequencies, there is the largest reflection when the carrier frequency is 100MHz. The mechanism of the field disturbance caused by the human intruder can be measured by analyzing the field and the time domain or the frequency domain of the echo signal. In sum, the method of using IQ demodulation and synchronous subtraction can achieve high precision positioning of intrusion and avoid the inaccurate localization caused the phase error. The IDS positioning accuracy is improved effectively, and the results satisfy the calculated results, which is less than 3 meters.

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