A Navigation Ranging Scheme with True Random Entangled Microwave Signals

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Abstract: Focusing on the problem of vulnerable anti-deception and weak anti-jamming ability in classical pseudo random code correlation ranging, we present a navigation ranging scheme with true random entangled microwave signals. One path of the entangled microwave signals uses for transmitting signal and another path of the signals preserves at locality. Firstly, the target that possesses the function of quantum repeater receives transmitting signal and forwards it to the locality. Then, correlation detection is implemented between the forwarded signal and the local delayed signal. Finally, the target distance can be calculated by delay measurement. We analyze the ranging precision and anti-deception ability. Results indicate that the scheme not only is superior to classical code correlation ranging precision, but also has very strong anti-deception ability and anti-multipath interference ability, which will enhance the security of the navigation ranging system. Our investigation has significant application prospects.

Index Terms: entangled microwave signals, true random, ranging, anti-deception jamming, anti-multipath interference.

1. Introduction

Code correlation ranging is a common navigation method that using the relevant receivers to measure the delay of transmitting code and receiving code, and then to gain the propagation distance of electric-wave. The pseudo random code is generally adopted owing to its superior autocorrelation property. GPS is one of the typical satellite navigation systems that making use of pseudo random code correlation ranging [1]. There are excellent performances in ranging precision, anti-jamming, multiplexing and so on. Nevertheless, it can be cracked when the attacker has enough computing capability. Hence, it is vulnerable to being attacked such as deception and disruption [2]. In addition, narrow code-width is required to achieve high-precision measurement, while long random sequences are required to achieve long-distance measurement. These two requirements are contradictory. Therefore, we desiderate effective true random signals to solve these problems essentially.

In fact, the difference between true random and pseudo random is whether next result can be predicted. True random must derive from the real physical phenomenon in nature, such as radioactive disintegration, circuit noise, atmospheric noise, etc. C. E. Shannon indicated that the signal with white noise statistical characteristic is best to achieve effective and reliable communication [3]. White noise is a true random signal with excellent autocorrelation characteristic. However, there are still technical difficulties for the generation, processing or copy of white noise. In order to seek two correlated true random processes, we spontaneously bethink of quantum entanglement. Entanglement indicates indistinguishable non-localized correlation among two or multi subsystems [4]. Continuous variable entanglement is a reflection of the correlation between vacuum quantum noise fluctuations [5], [6]. So, entanglement in two subsystems is equivalent to two true random signals with correlated property.

H. Guo et al. proposed a method to generate true random numbers using single photon source [7]. They demonstrate its practical application. MIT first presented the concept of Quantum Position System [8], which used entangled photons to achieve spatial three-dimensional positioning. Security can be enhanced in this method [9]. H. M. Huang et al. designed a scheme for quantum positioning based on entangled photon pair. Analysis shows that the scheme is secure [10]. In addition, G. Fang et al. designed a hyperbola positioning scheme based on continuous entangled light and bell state direct measurement [11]. However, the optical-domain propagation in open space is severely...
affected by environment, which will lead to finite operating distance. L. Seth et al. proposed microwave quantum radar [12]. A pair of entangled photons is used as detecting medium, with one being sent to probe the target region and another being retained at the source. The microwave reflection collected from the target region is then combined with the retained part in a joint quantum measurement. Similarly, there also exist difficulties in the detection and capture of microwave single photon. Moreover, the direct reflection via target will destroy the entangled characteristic.

In view of the above problems and research status, we present a navigation ranging scheme realized by true random continuous variable entangled microwave signals. It is suitable for replacing the pseudo random code as true random signal source. Besides, it can be regarded as the carrier signal without being modulated.

2. Characteristics of entangled microwave signals

In experiments, entangled microwave signals can be generated by superconducting circuit quantum electrodynamics systems, cavity quantum electrodynamics systems, and electro-opto-mechanical systems [13]-[22]. Characteristics of entangled microwave signals manifest in the non-localized correlation between the quadrature components of the signal field [23], [24].

Dual-path entangled microwave signals $\hat{S}_1, \hat{S}_2$ are expressed as [25]

$$\hat{S}_1 = a\cosh r + \hat{b}^\dagger \sinh r$$

$$\hat{S}_2 = \hat{b}\cosh r + \hat{a}^\dagger \sinh r$$

Where, $\hat{a}, \hat{b}, \hat{a}^\dagger, \hat{b}^\dagger$ are the photon annihilation operator and creation operator, respectively. $r$ denotes the squeezed parameter. Eq.(1) indicates the relation of dual-path entangled microwave signals. The quadrature components of $\hat{S}_1$ and $\hat{S}_2$ are expressed as

$$\hat{X}_{\hat{S}_1} = \frac{1}{2} (\hat{S}_1 + \hat{S}_1^\dagger) = \frac{1}{2} [(\hat{a} + \hat{a}^\dagger)\cosh r + (\hat{b} + \hat{b}^\dagger)\sinh r]$$

$$\hat{Y}_{\hat{S}_1} = \frac{1}{2} (\hat{S}_1 - \hat{S}_1^\dagger) = \frac{1}{2} [(\hat{a} - \hat{a}^\dagger)\cosh r - (\hat{b} - \hat{b}^\dagger)\sinh r]$$

$$\hat{X}_{\hat{S}_2} = \frac{1}{2} (\hat{S}_2 + \hat{S}_2^\dagger) = \frac{1}{2} [(\hat{b} + \hat{b}^\dagger)\cosh r + (\hat{a} + \hat{a}^\dagger)\sinh r]$$

$$\hat{Y}_{\hat{S}_2} = \frac{1}{2} (\hat{S}_2 - \hat{S}_2^\dagger) = \frac{1}{2} [(\hat{b} - \hat{b}^\dagger)\cosh r - (\hat{a} - \hat{a}^\dagger)\sinh r]$$

Calculating the variances, we obtain that

$$\langle \delta^2 (\hat{X}_{\hat{S}_1} - \hat{X}_{\hat{S}_1}) \rangle = \frac{1}{2} e^{-2r}$$

$$\langle \delta^2 (\hat{Y}_{\hat{S}_1} + \hat{Y}_{\hat{S}_1}) \rangle = \frac{1}{2} e^{-2r}$$

Eq.(2) shows the relation of the quadrature components of dual-path entangled microwave signals in identical direction. We can see that the dual-path signals tend to ideal entanglement when squeezed parameter $r$ is large. Fig.1 illustrates the fluctuation of entangled microwave signals.

$$\hat{X}_{\hat{S}_1} \quad \hat{X}_{\hat{S}_2}$$

$$\hat{Y}_{\hat{S}_1} \quad \hat{Y}_{\hat{S}_2}$$

Fig.1. Schematics of the fluctuation of entangled microwave signals. The yellow and blue denote the signals $\hat{S}_1, \hat{S}_2$ respectively. There is vacuum quantum noise limit in two quadrature components for one path of the signals. For two paths of
the signals in the identical direction, the quadrature components can break through the vacuum quantum noise limit. We can see that the quadrature components of $X$ direction are positively correlated and the quadrature components of $Y$ direction are negatively correlated.

The entanglement of entangled microwave signals reflects in the correlation of vacuum quantum noise fluctuations. The fluctuation is real physical phenomenon in nature. The signals look like the white noise. For any path of the signals, it is completely random and true random. The value of the next moment is unpredictable. No random process is correlated with the signals. However, for two paths of the signals, they are correlated and only two of them are correlated. Therefore, correlation detection can be implemented by extracting the quadrature components of the signals in the identical direction. As a result of the one-path randomicity and two-path correlativity, the problems of classical pseudo code ranging will be effectively solved for the application of navigation. And the key performances of the system such as security and anti-jamming ability can be enhanced.

3. Ranging scheme

Based on the characteristics of entangled microwave signals, we designed a specific navigation ranging scheme, as shown in Fig.2.

Firstly, using the entangled microwave signals generator to generate dual-path entangled microwave signals $S_1$ and $S_2$. Then, sending the signal $S_1$ to the target and leaving the signal $S_2$ in the locality. When $S_1$ is received by the target, it is forwarded back to the locality at once. The introduced delay in the process of receiving and forwarding is $\tau_0$. The target receiver can be considered as a quantum repeater, which has the function of no destroying the entanglement. We know that entanglement will be destroyed if the signals lose energy, whereas quantum repeater can forward the entangled signals without losing energy. This is the biggest difference from the direct target reflection which is implemented by classical repeater. Reason is that the locality and the target are cooperative relationship. Hence, such a design can be adopted to prevent disentanglement. Next, the target-forwarding signal $S_1$ and locality-preserving signal $S_2$ are sent to the IQ mixer. They multiply with the local oscillator in the IQ mixer to remove high frequency information and extract the quadrature components of entangled microwave signals. The frequency of the local oscillator is the same with the center frequency of entangled microwave signals. Whether extracted quadrature components are I or Q depends on the phase of the local oscillator. Where, the locality-preserving signal $S_2$ needs to be delayed for a definite time $\tau$. Finally, extracted quadrature components information is sent to the data processor. They will be processed by correlation detection. And the delay is determined by seeking the correlation peak of these two quadrature components. Hereby, the target distance $d$ can be calculated by

$$d = \frac{c}{2}(\tau - \tau_0) \quad (4)$$

Where, $c$ is the velocity of light.
The most prominent advantage of entangled microwave signals is that there are only two correlated random processes. No third random process that is correlated with them can be found. It is the core of security and secret. Furthermore, it is also requisite to ensure that the precision of entangled microwave signals is not lower than classical pseudo random code correlation. Therefore, we will analyze the ranging precision, anti-deception jamming ability and anti-multipath interference ability of our scheme.

4. Performance analysis

4.1 Precision

Precision is one of the primary performances that are considered in navigation system. Here, it is equivalent to the ranging measurement error. Taking the quadrature components of $X$ direction for example, the correlation function is expressed as

$$R_{\hat{X}_S \hat{X}_S}(\tau) = \left\langle \hat{X}_S(t) \hat{X}_S(t+\tau) \right\rangle = \frac{1}{T} \int_0^T \hat{X}_S(t) \hat{X}_S(t+\tau) dt$$

(5)

Where, $T$ is the measurement time. After sampling the data of quadrature components, we can calculate the cross correlation and find the correlation peak. Then the delay $\tau$ can be acquired. Due to the existence of error, the estimated value $\tilde{\tau}$ reads

$$\tilde{\tau} = \max_{\tau} R_{\hat{X}_S \hat{X}_S}(\tau)$$

(6)

It can be observed in Eq.(4) that the ranging error is determined by the measured time error. Therefore, the ranging precision is also determined by the precision of measured time. When the sampling rate is large enough (satisfy the Nyquist sampling theorem), the width of correlation peak is only related to the bandwidth of signal [26]. In experiments, the center frequency of entangled microwave signals is generally in GHz band and the bandwidth is in the order of 100 MHz. Hence, we analyzed with $B=100$MHz. The width of correlation peak

$$t_{cp} = \frac{1}{B}$$

(7)

is 10ns. If 1% of the width can be distinguished, the measured time error reads $\Delta t_{cp} = 0.1$ns. We simulate the cross correlation detection of entangled microwave signals and classical pseudo random code in MATLAB. It is shown in Fig.3(a).

So, the ranging error

$$\Delta d = \Delta t_{cp} \times c$$

(8)

is 3cm, viz., the ranging precision is 3cm. Then, we compare it with classical pseudo random code correlation ranging. In satellite navigation system, P code is the highest-precision pseudo random code presently. The code rate is $T_p = 10.23$MHz/s [27]. So, the width of correlation peak is

$$t_{cp} = \frac{1}{10.23} \approx 97.8$ns.$$  

Even if 1% of the width can be distinguished, the measured time error will be $\Delta t = 0.978$ns $> 0.1$ns, as shown in Fig.3(b). Therefore, the ranging precision of entangled microwave signals is superior to classical pseudo random code.
4.2 Anti-deception jamming

Deception jamming contains autonomous deception jamming and repeated deception jamming. Autonomous deception jamming means that the enemy jamming system sends a false signal, which is generated itself. And the locality receives the false information. Repeated deception jamming is a repeater technique that manipulates received signal and retransmits it to change the return. This technique can change the delay in transmission of the signal. So the locality will receive deceptive information. Fig.4(a) shows the result of cross correlation detection when the pseudo random code is deceived. We can see that only received delay is changed, and the correlation peak still exists. Hence, the false distance will be acquired.

Different from pseudo random code, any path of entangled microwave signals is completely random. It is the natural physics characteristics. Entangled signal cannot be copied. In other words, a signal correlated with entangled signal cannot be produced. Thus, autonomous deception jamming can be fundamentally prevented. At the same time, characteristics of entangled microwave signals are present in the electric field. When the signals are received, the electric field is converted into the electric current. The process can be viewed as one measurement. The uncertain non-classical quantum state will collapse into a certain classical state. And there are no longer entangled characteristics. Therefore, if entangled microwave signals are subjected to repeated deception jamming, the signals will lose the entangled characteristics when the enemy jamming system receives the signals. The forwarded signal will be treated as a noise and won’t be recognized by the local receiver. Fig.4(b) shows the result of cross correlation detection when the entangled microwave signals are deceived.

![Cross-Correlation Delay μs](image)

(a) Cross-Correlation Delay [μs] 0 0.1 0.3 0.5 -0.5 -0.3 -0.1 0 1

(b) Cross-Correlation Delay [μs] 0 0.1 0.3 0.5 -0.5 -0.3 -0.1 0 1

Fig.4. (a) The cross correlation detection when the pseudo random code is deceived. We set the delay=0.3μs. The correlation peak still exists. (b) The cross correlation detection when the entangled microwave signals are deceived. There is no correlation peak in a long period of time for the local delay.

It can be observed in Fig.4(b) that no correlation peak exists in a long period of time for the local delay. Therefore, the ranging scheme with entangled microwave signals has very strong anti-deception jamming ability.

4.3 Anti-multipath interference

In many practical applications of navigation system, multipath interference is a common phenomenon that is caused by buildings or rolling terrain [25]. The main reason is the periodicity of classical microwave signal. After multipath propagation, signals are the combinations of direct signal and delaying signal. They cannot be distinguished by receiver, which will cause the measurement error. Theoretically, multipath interference cannot be avoided entirely. Firstly, we simulate the result of pseudo random code with multipath interference, as shown in Fig.5(a).

![Cross-Correlation Delay μs](image)

(a) Cross-Correlation Delay [μs] 0 0.1 -0.1 0.2 0.3 0.4

(b) Cross-Correlation Delay [μs] 0 0.1 -0.1 0.2 0.3 0.4

Fig.5. (a) Schematics of the correlation peak with multipath interference. Difference between the direct signal and multipath signal is delay. From left to right, the multipath delay is increased. And the width of correlation peak also increases. (b) The
correlation peak of entangled microwave signals with multipath interference. We superpose delay signal on the direct signal. The width of correlation peak is also 10ns.

When there is the existence of multipath interference, we can see that the correlation peak of pseudo random code will overlap, which will lead to the increase of width. Hence, the precision of navigation ranging measurement will be severely affected.

Then, we simulated the result of entangled microwave signals with multipath interference, as shown in Fig.5(b). We can see that the correlation peak width of entangled microwave signals is invariable compared with Fig.3(a). Reason lies in the randomicity of entangled microwave signals, i.e. non-periodicity. Multipath signals are treated as noise to be suppressed in detecting end. Consequently, the effect of multipath interference can be eliminated completely via entangled microwave signals and the measurement precision can also be improved.

5. Conclusion
In this paper, we present a navigation ranging scheme with true random entangled microwave signals. Compared with classical code correlation ranging, the ranging precision of entangled microwave signals is higher. Especially, entangled microwave signals have very strong anti-deception jamming ability and anti-multipath interference ability. The enemy disturbing and deceiving can be prevented effectively. So, the security can be enhanced effectively. Furthermore, the design of target receiver with a quantum repeater is innovative. Entanglement can be guaranteed to not be destroyed in the process of propagation. Our scheme and design will provide a reference for practical applications. And entangled microwave signals will have significant application potential. In the future, we expect for experimental measurement to verify the feasibility and optimize the ranging scheme.

References


