A RANDOM SHOOTING-TIME GENERATOR USING VIBRATION SENSING AND GPS TIMING FOR HIGH PRODUCTIVITY BLENDING ACQUISITION

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ABSTRACT

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Seismic exploration is currently the most economical and effective method for exploring underground mineral resources. Currently, the distribution of underground resources with shallow burial, simple structure, and good reservoir performance has been basically grasped, however, for those underground resources with deeper burials and more complex structures, high-precision seismic exploration methods still need to be applied to obtain a clearer understanding. High productivity blending acquisition is a new exploration method that can effectively shorten the acquisition period, reduce acquisition cost, and enhance data quality. In addition, the random degree of source starting will directly affect the acquired data quality. In this paper, we propose a novel random shooting-time generation algorithm for seismic exploration. First, local clock calibration and GPS time synchronisation in a fixed time interval are carried out using the GPS timing technology and the voltage-frequency linear relationship of the voltage-controlled crystal oscillator within a shorter period. The expected shooting-time is then calculated based on the information of the source location, ready order, and time-distance rule parameters. Finally, the millisecond time of a random shooting-time within a specified window is generated using the real-time vibration sensing data to ensure randomness. The test solution shows that the dithered value of the source shooting-time generated by the proposed algorithm has the characteristics of numerical size, controllable range, and strong randomness, which is closer to the actual needs of industrial applications.

KEY WORDS: vibration sensing, GPS timing, random sequences, VCXO, periodic time synchronization, blending acquisition.

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INTRODUCTION

Oil and gas are important and necessary resources for economic development. Seismic exploration is the most economical and effective way to identify the distribution of underground oil and gas reservoirs. It is well known that an illuminating wave will reflect when it encounters interfaces in the medium with different impedances. Seismic exploration takes advantage of this principle by using controlled sources to generate artificial waves which reflect when they encounter the subsurface structure. Sensors on the ground then pick up and record these reflected waves for processing and analysis to help understand the reservoirs. The wave propagation speed in the subsurface varies from hundreds to thousands of meters per second. Thus, the source and acquisition are generally started simultaneously with a maximum error of no more than 20 μs, thereby allowing for an accurate analysis of the subsurface structure. High productivity blending acquisition is a new exploration method used to understand the oil and gas reservoirs with deeper burials and more complex structures. Unlike conventional methods, the sensors will receive mixed reflections from different sources simultaneously during blending acquisition. Therefore, whether or not the reflection waves generated by different sources can be separated effectively will directly affect the quality of the data describing the subsurface's features.

There are two main source types used for seismic exploration, namely vibroseis and pulse. Over the years, seismic exploration experts have hoped to promote the blended data separation effect by optimising the source start mode; through which they have achieved some success. In terms of vibroseis, in 1979 Silverman proposed a pioneering method for simultaneous acquisition by using source phase coding (Silverman, 1979). In 1998, Allen et al. proposed the High Fidelity Vibratory Seismic (HFVS) method, which accomplishes the high-fidelity separation with the actual pre-coded motions rather than the assumed code (Allen, 1998). In 2008, Sallas et al. used random phase encoding for long-time sweep and separated the blended data with a correlation algorithm (Sallas et al., 2008). In 2010, Bagaini and Ying used a fixed slip time and a small dithered time to obtain data with quality comparable to conventional mode (Bagaini and Ying, 2010) . These methods, all of which have been applied as mature industrial technological methods, are only applicable to onshore seismic exploration with vibroseis source. However, relatively few studies have been carried out on simultaneous acquisition with pulse sources. At present, the most popular data separation method for simultaneous pulse sources is to treat the blended interference in non-common shot domains with random noise through a traditional filtering method. So, the randomness of artificial waves generated by different sources is particularly important. In 2008, Fromyr et al. used the navigation system to predict a time based on the position and speed information of the source, then combined it with a small dithered time as the shooting-time to improve the shooting randomness (Fromyr et al., 2008). In

2008, Hampson et al. improved the shooting randomness by setting the random dithered time (Hampson et al.. 2008). In 2013 and 2014, Jilin University and CNODC conducted 2D and 3D dual-source random simultaneous acquisition experiments in both the Bohai Gulf and South China Sea (Zhang et al., 2019). However, these methods are only applicable to the high productivity blending acquisition of offshore dual pulse sources and therefore have certain limitations.

In order to increase the number of simultaneous pulse sources and further improve the randomness of the shooting time, this paper proposes a novel random shooting-time generation algorithm for two or more simultaneous pulse sources. This new algorithm generates the random shooting-time by using the shooting-time of the last shot, the current position of the source, the ready sequence, the time-distance, the vibration sensing data, and some other parameters based on GPS timing technology - all of which will improve the randomness of the shooting-time of simultaneous sources. Differing from previous works, the contributions of this paper's work are: 1) proposing a VCXO-based low-power, periodic GPS clock synchronisation algorithm; 2) describing an algorithm for generating dithered data using vibration sensing data as seeds; and 3) designing a hardware for generating random shooting times for seismic exploration based on key technologies such as vibration sensing and GPS timing.

This paper is organised as follows. Section II gives a brief description of the related technology, including the application of GPS timing technology in seismic exploration, the VCXO characteristics, and the mechanism of random number generation. Section III introduces the random shooting-time generation algorithm. The verification and discussion of the proposed algorithm are given in Section IV. Finally, Section V concludes the paper's work and outlines future work.

RELATED WORKS

Currently, GPS is one of the most widely used navigation and positioning systems in the world. It is able to transmit signals containing position and time information over areas across the entire globe. The GPS receiver continuously corrects the time difference between the local clock and the GPS system clock from the received navigation messages, resolves them to achieve synchronisation with the GPS clock, and finally realises the clock synchronisation. The process of the GPS clock synchronisation is shown in Fig. 1.

The formula for calculating the difference between the local clock and the GPS clock is shown in eq. (1):

$$\Delta t = \Delta t_{PR} - (t_L' - t_{GPS}) \quad , \tag{1}$$

where Δt_{PR} is the delay generated by the pseudo-range. t_L' is the clock time of the receiver. t_{GPS} is the GPS clock time. Δt_{PR} is calculated by eq. (2) and eq. (3):

$$\Delta t_{PR} = R^*/c \quad , \tag{2}$$

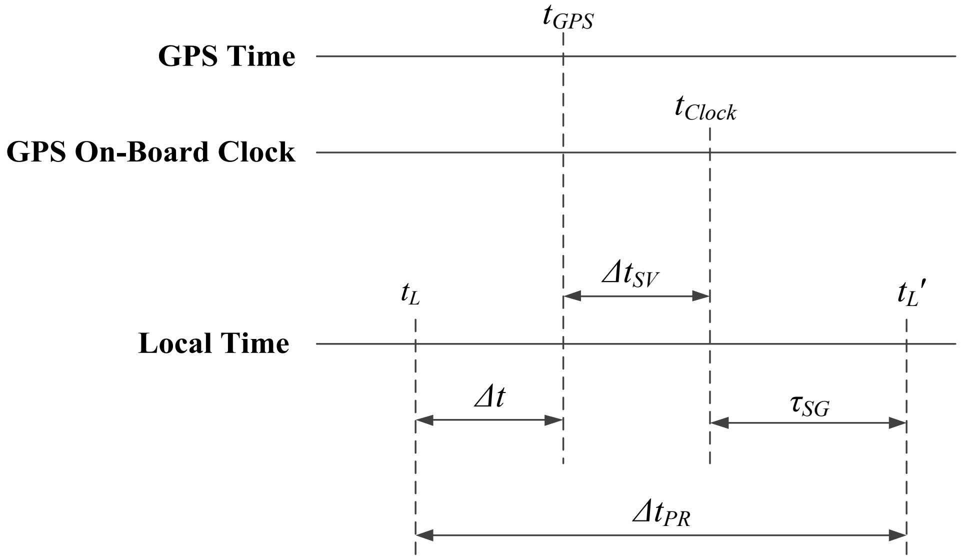


Fig. 1. GPS clock synchronization schematic diagram.

where R^* is the pseudo-range, c is the speed of light. Combining with Fig. 1, further derivation of eq. (2) :

$$\Delta t_{PR} = \Delta t + \Delta t_{GPS} + \tau_{SG} \quad , \tag{3}$$

where Δt_{GPS} is the difference between the GPS time and the on-board atomic clock time. τ_{SG} is the total satellite-ground delay, which can be calculated by eq. (4):

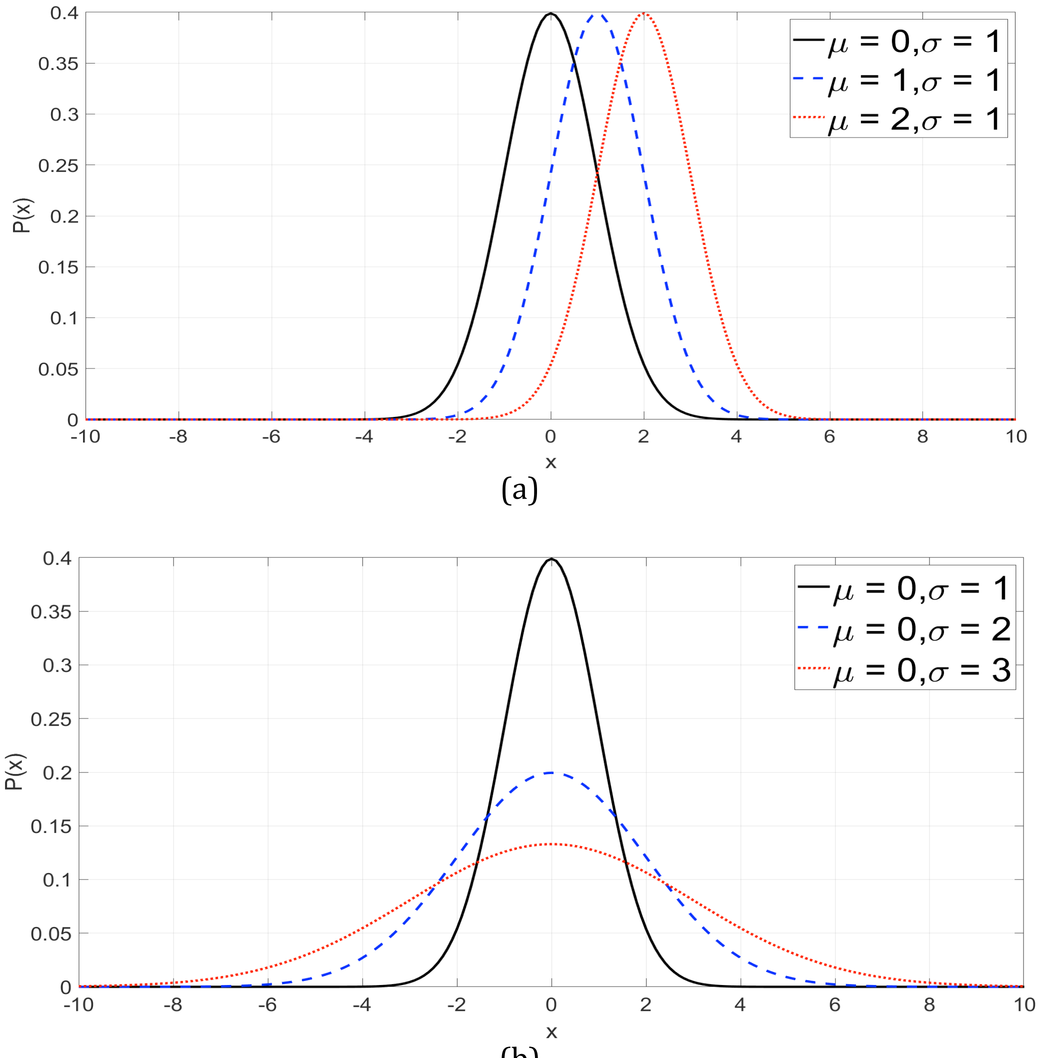
$$\tau_{SG} = \tau_R + \tau_E + \tau_A + \tau_L \quad , \tag{4}$$

where τ_R is the theoretical signal transmission. τ_E is the delay due to the ionosphere. τ_A is the delay due to the troposphere. τ_L is the delay caused by receiver.

GPS has been maturely applied to many industries with the continuous development and innovation of science and technology. The related products are also complete, and the time accuracy of the GPS receiver that can be easily purchased is generally 30 ns to 150 ns, which will not exceed 1μs due to the circuit design, selected antenna, and many other factors (Allan and Weiss, 1980; Davis and Weiss, 1982; Weiss et al., 1997; Mannermaa et al., 1999; Mumford, 2003). The GPS signal has excellent features, such as low noise, strong anti-interference ability, high timing accuracy, low cost and so on, allowing it to fully meet the time accuracy requirements of seismic exploration. In recent years, GPS timing technology has been gradually integrated into seismic exploration, and new systems such as nodal and wireless seismic instruments based on GPS timing technology have emerged. In addition, the dominant cabled system could also support continuous acquisition by using GPS timing technology. Therefore, it is highly feasible to use GPS clock time which has a low application cost and a high time accuracy as the time basis. Power consumption and local clock accuracy are two important aspects of the random shooting-time generator. Pallier et al. (2020) said that the accuracy of GPS time synchronisation can be guaranteed by using a periodic synchronisation method combined with the correction algorithm, and the system power consumption can be greatly reduced (Pallier et al., 2020). However, this method does not adjust the crystal frequency itself, which has certain application limitations. At present, the commonly used high precision crystal oscillators are the oven-controlled crystal oscillator (OCXO), the temperature compensated crystal oscillator (TCXO), and the voltage-controlled crystal oscillator (VCXO)(Cantor et al., 1999; Gobato et al., 2019; Tian et al., 2020). The OCXO uses an oven to maintain a constant temperature for the crystal oscillator to minimise the frequency offset caused by temperature variation. The power consumption is generally above 1W, with high precision of the oscillation signal. The TCXO reduces the oscillation frequency variation through an additional temperature compensation circuit, but the oscillator frequency will deviate because the welding temperature is much higher than the allowable temperature of the TCXO, and is difficult to maintain. The VCXO maintains the oscillation frequency by using control voltage to fine-tune it. This provides the advantage of good transmission performance, strong anti-interference, and power saving. The power consumption of TCXO and VCXO is generally 5 mW to 200 mW, and the oscillation accuracy is relatively high. Therefore, the VCXO is selected as the system clock source of the random shooting time generator from the aspects of power consumption, frequency accuracy, drift characteristics and application convenience, etc.

Another key problem to be solved in generating random shooting-time is a way of designing and implementing a random number generator with good statistical and random characteristics. According to the difference between the randomness sources and the generation principles, random number generators are mainly divided into True Random Number Generators (TRNGs) and Pseudo Random Number Generators (PRNGs) (Ma et al., 2019). TRNGs collect randomness from physical events such as vibration, temperature, and noise to generate an unpredictable sequence (Choi et al. 2021; Vasileiadis et al., 2021). PRNGs extend a pre-obtained value or sequence commonly known as a seed into a desired random number using a stretching function (Cang et al., 2021; Kishnamoorthi et al., 2021; Liu et al., 2021). The high productivity blending acquisition has special requirements for source controlling. On the one hand, the generated shooting times should have strong random distribution characteristics. On the other hand, the generated shooting time should have strong dithered characteristics. Essentially, the random shooting time needs to generate a number sequence with random distribution near a certain value. Normal distribution, also known as Gaussian distribution, is an important distribution in mathematics, physics, engineering and some other fields. Its probability density function is:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} exp\,(-\frac{(x-\mu)^2}{2\sigma^2}) \quad , \tag{5}$$



(a)

(b)

Fig. 2. The normal distribution curves with different μ and different σ.

where μ is the expected value of the normal distribution, which determines the position of the random number, and σ is the standard deviation of the normal distribution, which determines the amplitude of the normal distribution. *f(x)* is called standard normal distribution when $\mu = 0$,and $\sigma = 1$. The normal distribution curves with different μ and different σ are shown in Fig 2. The normal distribution is therefore chosen as the probability distribution density to generate random shooting time, which effectively guarantees the randomness and controllability of the generated random shooting time. The analogue geophone used in seismic exploration is an electro-magnetic vibration sensor, which is a mass-spring electromagnetic system. Its response characteristics change slightly with temperature, so the random characteristics of vibration sensing data caused by environmental vibration and temperature can be used to further enhance the randomness of the generated shooting time.

METHOD

The hardware implementation structure of the random shooting time generation algorithm for seismic exploration proposed in this paper is composed mostly of a GPS receiver, VCXO, MCU, ADC vibration sensors and related auxiliary circuits. The GPS receiver starts periodically and outputs the time information including the PPS signal and related epoch to MCU. The MCU then calculates the time deviation between the local clock and the GPS clock which is corrected by the regulation voltage with high accuracy from the ADC to achieve GPS time synchronisation and local clock calibration. After completing these tasks, the MCU will generate the required shooting time based on the source position, time-distance rule, vibration sensing, and some other parameters. The proposed random shooting time generation algorithm for seismic exploration based on vibration sensing and GPS timing has the following advantages: 1) The high time-synchronisation accuracy with low economic cost can be easily achieved by using GPS time as the time basis of generated shooting time. This method is more suitable and convenient for industrial application. 2) The average power consumption of the generator can be greatly reduced by using VCXO and periodic GPS synchronisation. 3) The mature data processing method for seismic exploration can be utilised by using vibration sensing data as the seed to improve the randomness of the generated normal distribution data.

There are two main concerns in the paper’s work: one is the realisation method of low power and high precision GPS clock synchronisation; another is the generation of the random shooting time for seismic exploration that conforms to normal random distribution characteristics.

VCXO Frequency adjustment

The VCXO adjusts the oscillation frequency through the control voltage which rises with the oscillation frequency. However, the voltage-frequency curves of the same model VCXO differs due to various reasons such as manufacturing processes, structural design, production batches etc. Therefore, the key problem to be solved for GPS clock synchronisation is to obtain the relationship between the control voltage and the oscillation frequency. The relationship between the control voltage and the oscillation frequency can be regarded approximately as a linear relationship because the field temperature will not change drastically in the short term, as shown in Fig. 3.

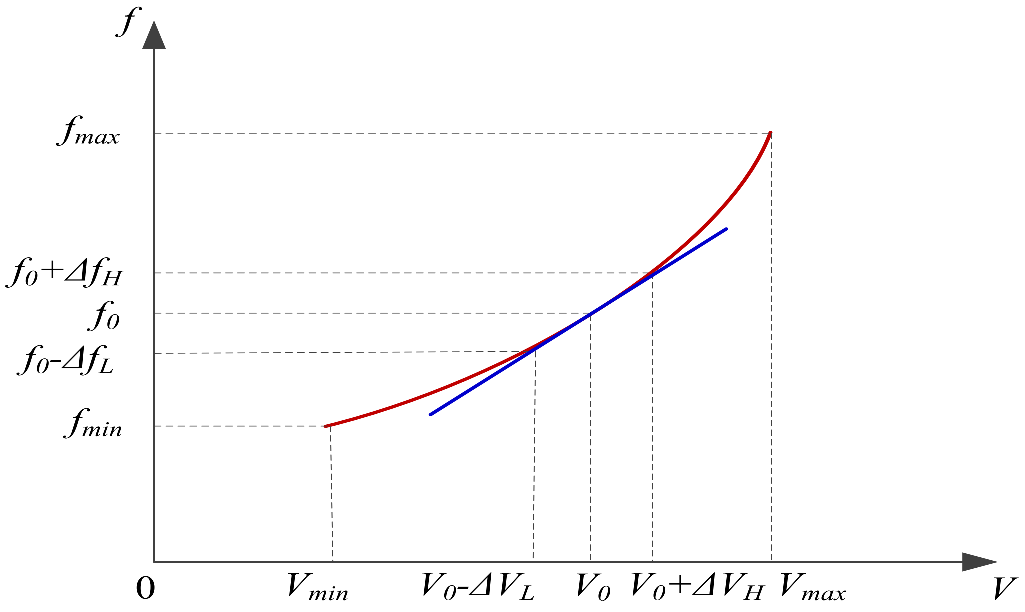


Fig. 3. Voltage-Frequency characteristic curve of VCXO.

In Fig. 3, V_0 is the center oscillation frequency control voltage, （V_0-ΔV_L，V_0+ΔV_H） is the fine-tuning control voltage range, （f_0-Δf_L，f_0+Δf_H） is the frequency variation range.

The steps for obtaining the oscillation frequency adjustment parameter are described according to the hardware architecture:

1) According to the technical parameters of the selected VCXO, the MCU enables the DAC to output the control voltage which makes the VCXO output oscillation signal near its nominal center frequency.

2) The clock frequencies of Timer1, Timer2 and Timer5 of

STM32L475 are initialized to the same frequency F. Timer1 is set as the rising edge capturer. Timer2 is set as the simulated PPS generator. Timer5 is set as upward counting sequence counter.

3) Timer2 starts to output the simulated PPS, and Timer5 starts counting when Timer1 captures the first PPS from GPS receiver.

4) Timer5 counts during continuous k ($k \geq 1$) PPS rising edges over a periodic time under the initial control value C_1 output by MCU, denoted as N_1.

5) The MCU adjusts the DAC to increase the control voltage to C_2, and Timer5 counts during continuous k ($k \geq 1$) PPS rising edges over a periodic time, denoted as N_2.

6) The frequency adjustment parameter c_0 which represents the count value of Timer5 for each DAC control increment could be calculated by eq.(6):

$$c_0 = \frac{N_2 - N_1}{C_2 - C_1} \quad . \tag{6}$$

Periodic GPS clock synchronization

The data acquisition and source shooting must be synchronised strictly during seismic exploration, and different geological targets have different requirements for synchronisation accuracy, generally no more than 20μs. As shown in Fig 3, the MCU configures the RTC time at the PPS rising edge after receiving the valid time information from the GPS receiver. Then, the deviation between the local clock and the GPS clock, which could be adjusted by using the VCXO's characteristics, will be obtained at every fixed time interval, and the time accuracy of RTC could then be guaranteed. In this process, the incremental PID algorithm is used to adjust the oscillation frequency of VCXO.

Suppose *u(k)* is the control value output by the *k* PID calculation after GPS information is validated. According to the idea of PID algorithm, we can see the relationship between u(k) and the counter value of Timer5 which needs to be adjusted:

$$u(k) = K_p * e(k) + K_i * \sum_{j=0}^{k} e(j) + K_d * [e(k) - e(k-1)] \quad , \tag{7}$$

where *e*(k) is the error between the pre-set value of the *k* PID and the value of Timer5 needs to be adjusted. K_p is the proportional amplification coefficient of PID algorithm. K_i is the integral parameter. K_d is the differential parameter. From eq. (7), we know that *u(k)* will cause a significant change in VCXO's frequency if a certain calculation overflow or other issue occurs. This problem can be solved by using the incremental PID algorithm:

$$\Delta u(k) = C(k) - C(k-1) \quad , \tag{8}$$

In formula (8), $\Delta u(k)$ is the difference between the control value of current and previous PID calculation. If we substitute eq. (7) into eq. (8) , we get:

$$\Delta u(k) = K_p * \Delta e(k) + K_i * e(k) + K_d[\Delta e(k) - \Delta e(k-1)] \ , \tag{9}$$

where $\Delta e(k) = e(k) - e(k-1)$ is the difference between the k and the k-1 value of Timer5. Finally, the output variation *ΔC (k)* of DAC is calculated by eq. (6) and eq. (9):

$$\Delta C(k) = \frac{\Delta u(k)}{c_n} \quad , \tag{10}$$

Dithered time generation

The normal distribution is a common probability density distribution function widely used in many fields. In the field of seismic exploration, well-established data processing methods are used for filtering or attenuating random noise with normal distribution characteristics. This paper proposes to use the vibration sensing data acquired by the high-precision ADC as the seed to generate the dithered time conforming to the normal distribution.

Assuming that the acquired vibration sensing data t_0 is used as the seed for generating dithered time, the process is as follows. First, the seed t_0 is used to generate n random numbers $x_1, x_2, \ldots, x_n$ that conform to the uniform distribution in the (0,1) range.

$$\begin{cases} t_i = a * t_{i-1} + b - \lfloor \frac{a * t_{i-1} + b}{base}) * base \rfloor \\ \qquad x_i = t_i / base \end{cases} \quad , \tag{11}$$

where *a*, *b* and *base* are pre-set constants. t_i is the parameter used in the calculation process and denotes the random vibration sensing data when I = 0. x_i is the random numbers in (0,1) range. "⍰⍰" denotes downward rounding calculation. Then, the $x_1, x_2, \ldots, x_n$ generated by eq. (11) with the uniform distribution characteristics are used to obtain the dithered time by eq. (12):

$$y = \mu + \sigma * \frac{-\frac{n}{2} + \sum_{i=1}^{n} x_i}{\sqrt{n/12}} \quad , \tag{12}$$

where μ and σ are the mathematical expectation and standard deviation of a normally distributed random number, respectively. When used to generate dithered time, μ is used to characterise the minimum time interval between current and previous source calculated according to the time-distance rule. σ is used to control the dithered range based on μ.

Validation and discussion

In order to verify the effectiveness of the proposed algorithm, STM32L475 is selected as the MCU, MAX-8C is used as the GPS receiver, and the ADS1292 with high A/D conversion precision is adopted. The geophone used for seismic data acquisition acquires the vibration signals. The test board shown in Fig. 4 is designed according to the hardware architecture as described before. During the test, in order to verify the GPS synchronisation solution, we use a high-precision oscilloscope to analyze the time difference between the simulated PPS and the true PPS.

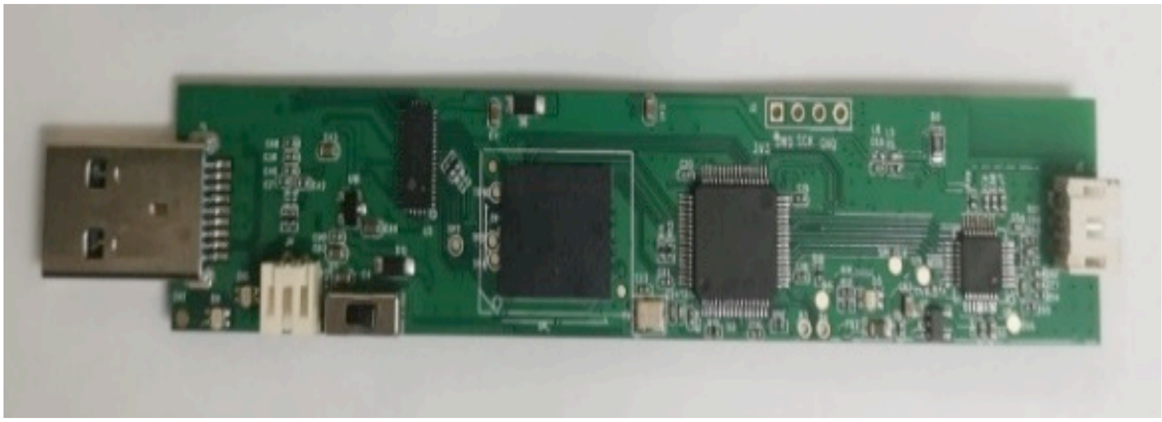


Fig. 4. The test board.

GPS synchronisation accuracy

The two test boards, which are Board A and Board B, are used in the same environment with good GPS signal reception conditions. Board A records the time error of the local clock every 5 minutes and corrects the clock deviation by the proposed algorithm. Board B records the time error of the local clock every 5 minutes but does not correct it. At the beginning and end of the test, the oscilloscope is used to analyse the time difference between the simulated PPS and the true PPS. Fig. 5 shows that the time deviation of Board B without frequency adjustment is an accumulating trend. The clock deviation over one hour is nearly 100μs, while the value of Board B with frequency adjustment is below 10 μs.

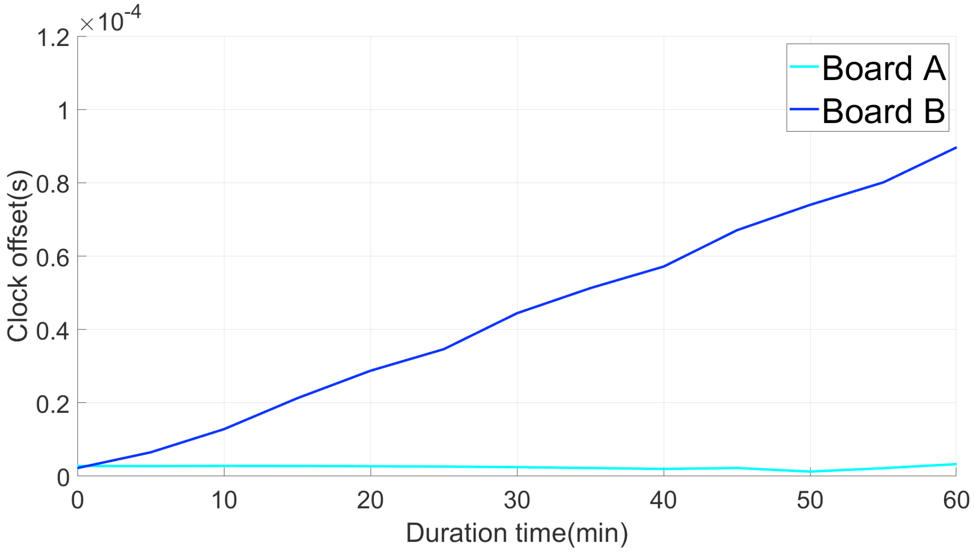
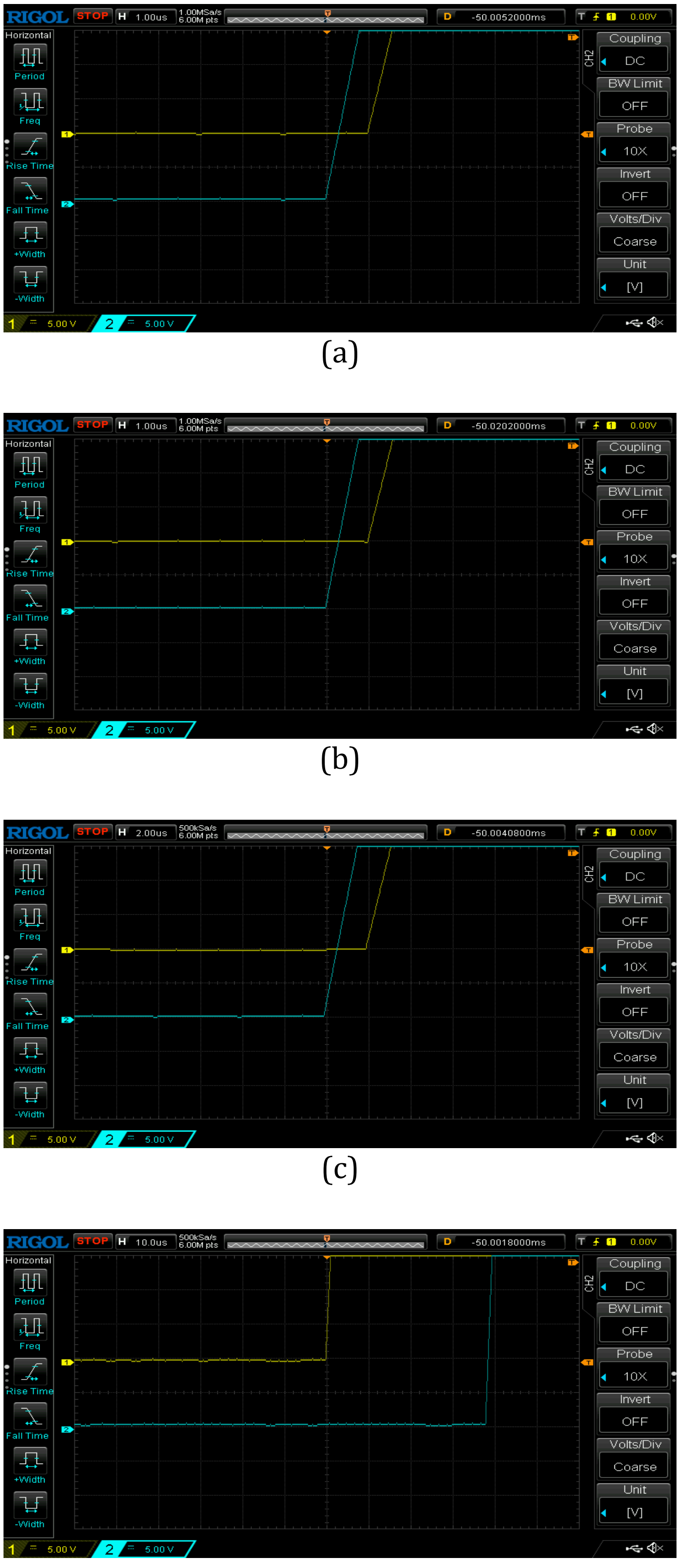


Fig. 5. Time offset recorded by Board A and Board B in 1 hour.

The same conclusion is given by the oscilloscope analysis results shown in Fig. 6. The yellow line in Fig. 6 is the simulated PPS from MCU, and the light blue line is the true PPS from GPS receiver. (a) and (c) show the initial time difference of Board A and B, while (b) and (d) show the time difference of Board A and Board B after one hour. The time difference of simulated PPS from Board A and the true PPS is within 10 μs, but Board B has reached nearly 100 μs after one hour, which verifies the effectiveness of the periodic GPS clock synchronisation.

Random shooting time generation

The ADS1292 is used to collect the vibration sensing data as the seed to generate the random shooting-time in Board A and Board B. 2000 random shooting times with the time interval of 8 s and dithered time of 300ms are generated to prove the availability of the dithered time generation algorithm. The probability distribution of this data is shown in Fig. 7, which achieves the expected design goal.



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(d)

Fig. 6. The time difference between the simulated PPS and the true PPS.

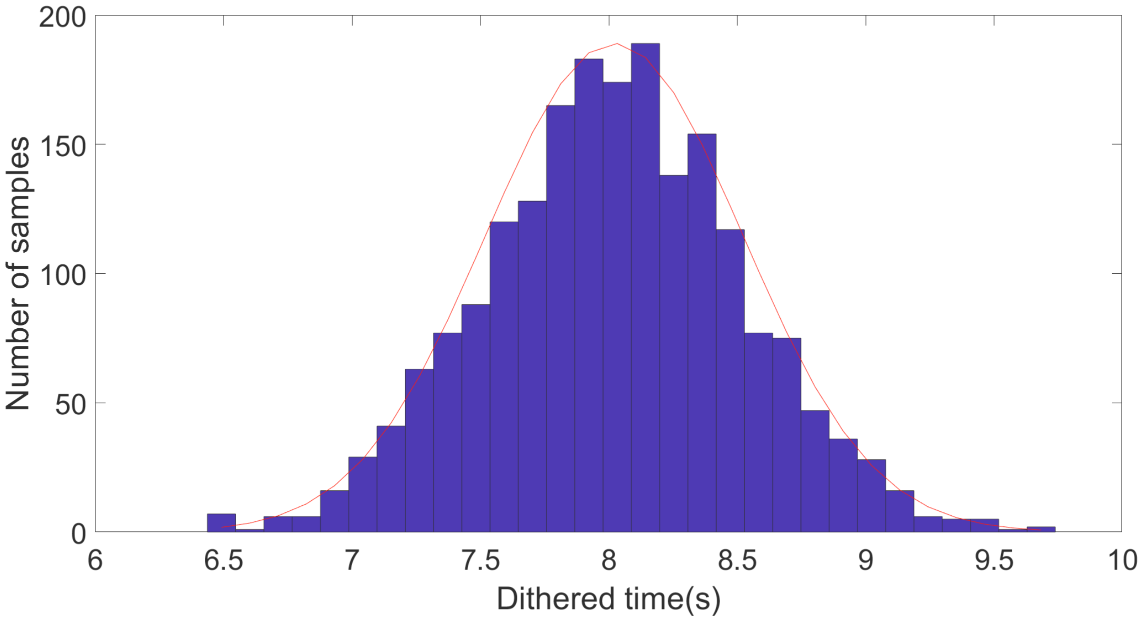


Fig. 7. The distribution map of generated random shooting times.

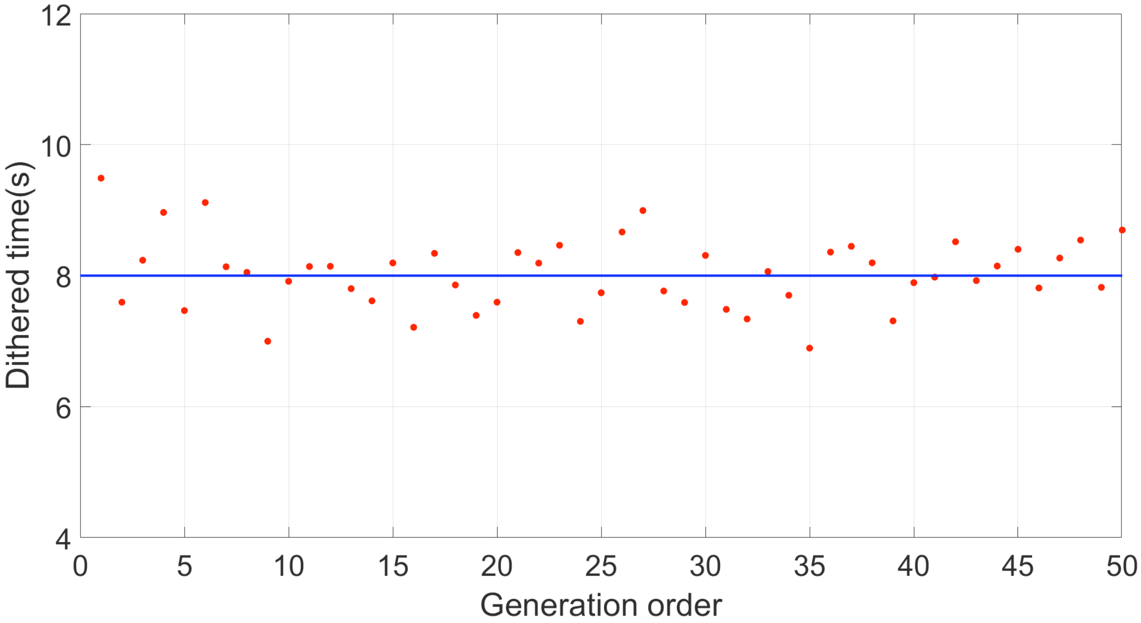


Fig. 8. The dithered level of generated shooting times.

The dithered level of two or more adjacent shooting times also directly affects the quality of the generated random shooting times. The generated random shooting times are displayed with the generation order as the horizontal axis and the shooting-time as the vertical axis. As shown in Fig. 8, the adjacent shooting times have strong incoherence.

DISCUSSION

The accuracy of the random shooting times is determined by the accuracy of the local clock. It is well known that the frequency of the crystal oscillator will change with the ambient temperature, and the VCXO is no exception. The algorithm proposed in this paper maintains the accuracy of the local clock by periodic GPS clock synchronisation, so the synchronisation cycle will directly affect the accuracy of the generated random shooting time. Fig. 9 shows the clock offset of different synchronisation cycles in 24 hours.

It can be seen from Fig. 9 that the smaller the synchronisation cycle, the stronger the adaptability of the algorithm to environmental temperature changes. However, the working power consumption of MAX-8C is about 48 mW, and the standby power consumption is about 11 mW. To reduce the working power consumption of the seismic exploration random shooting-time generator, the final choice of GPS clock synchronisation cycle is 5 minutes, and the average working power consumption of Board A is about 50 mW.

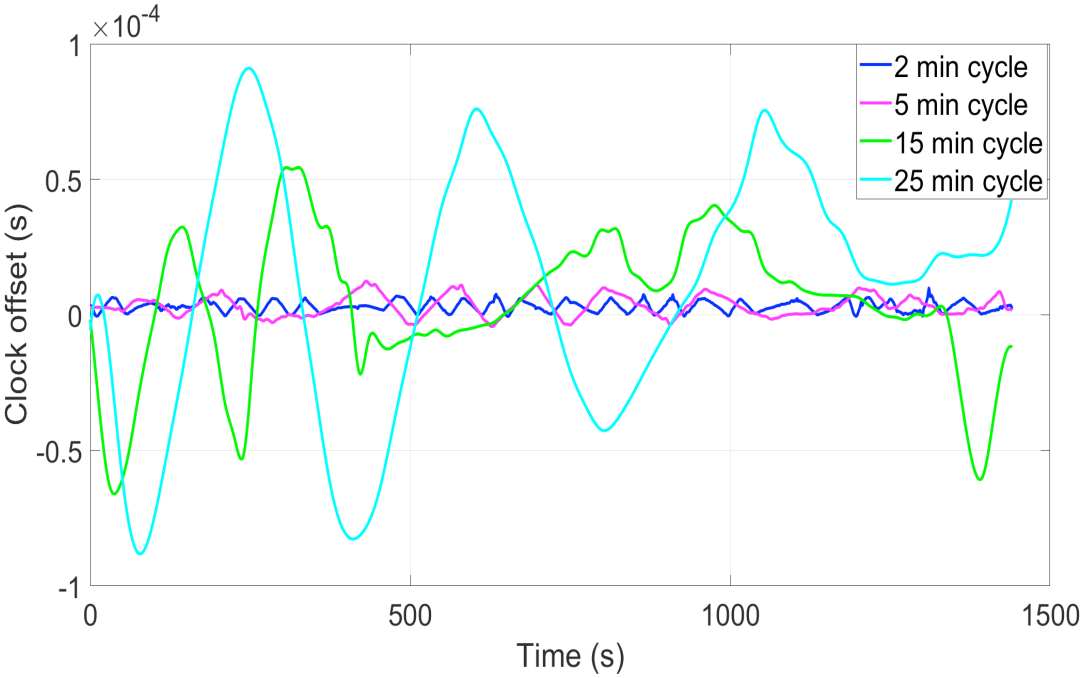
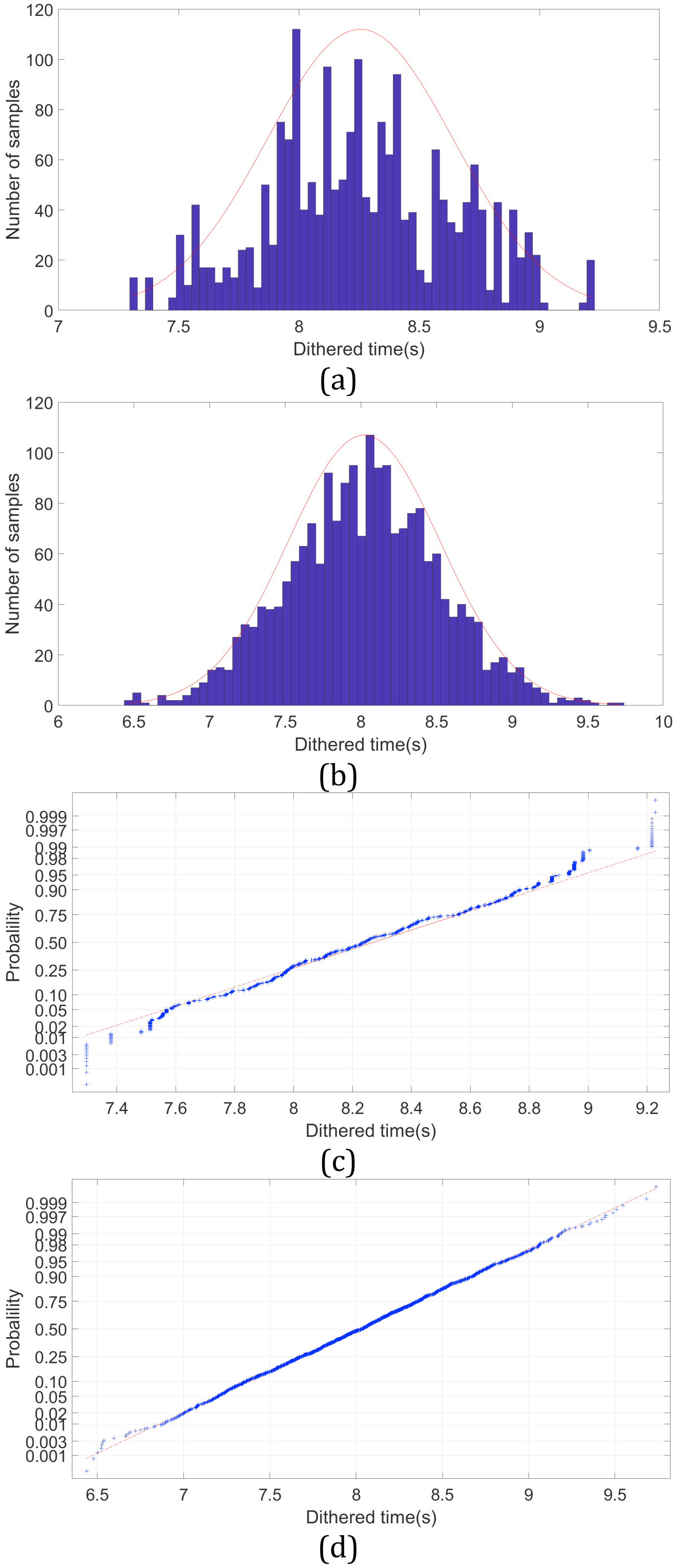


Fig. 9. Local clock offset for different GPS synchronisation cycles.

The randomness of the generated shooting time is another important indicator of the application effect of the proposed algorithm, and the quality of the random seeds is the key factor. This paper uses the data acquired by high-precision ADS1292 and the vibration sensor as seeds to generate random shooting times.



(a)

(b)

(c)

(d)

Fig. 10. Comparison of the random data generated by pseudo-random number functions and the proposed algorithm.

Fig. 10 gives the probability distribution characteristics of random numbers generated by the MCU's pseudo-random number function and the proposed algorithm. Fig. 10(a) and Fig. 10(c) are the distribution and probability map of the random numbers generated by the embedded functions of the MCU, and Fig. 10(b) and Fig. 10(d) are the distribution and probability map of the random numbers generated by the proposed algorithm. It can be seen that the shooting-time numerical sequence is generated using high-precision vibration sensing data as the seed is more consistent with the normal distribution characteristics and meets the needs of industrial applications.

The results of the run tests for the random sequences generated by the two different methods are shown in Table 1, indicating that the numerical sequences generated by the two methods have randomness, and the run numbers of the proposed algorithm in this paper is larger. That is, the randomness of the generated shooting-time sequences is relatively strong. This is more conducive to the later seismic data separation.

Table 1. The run numbers of the random datagenerated by different method.

Number of generated random data	Pseudo-random number function	Proposed algorithm
500	245	256
800	399	403
1000	501	505
2000	998	1023

CONCLUSION

The randomness of shooting timing is of great significance for high productivity blending acquisition. This paper proposes an algorithm for generating a random shooting-time based on the vibration sensing and periodic GPS synchronisation which is used for source controlling in seismic exploration. First, in order to ensure the accuracy of the time-base used to generate the random shooting time, both the GPS timing technology and linear voltage-frequency relationship of the VCXO in a short period of time are applied to adjust the local clock and synchronise it periodically with the GPS. Then, the vibration sensing data collected by the high precision ADC is used as the seed to generate the dithered shooting time with controllable values and deviations to improve the randomness of the generated shooting time.

The test board design, based on the proposed hardware architecture, is used to verify the correctness, reliability, and feasibility of the proposed algorithm for industrial applications. It is found that a 5-minute GPS clock synchronisation period can keep the local clock deviation below 10μs and also save power loss significantly, causing the average operating power consumption of the test board to be below 50 mW. Compared with the pseudo-random number functions of MCU, the proposed algorithm has the characteristics of controllable range and strong randomness, which is closer to the requirements of industrial applications.

In the future, the proposed algorithm will be applied to high precision and high efficiency oil and gas exploration practices whilst random vibration interference in the field will further improve the randomness of the shooting time generated by the proposed algorithm. At the same time however, the harsh working environment in the field will bring challenges to the hardware implementation effect of the proposed algorithm. Therefore, determining an adaptive GPS synchronisation period that can meet the requirements of the different shift conditions of the ambient temperature is the key to ensure the accuracy of generating the random shooting time. It is also the focus of the next technical research. Finally, correctly selecting the dithered parameter of the random shooting time in combination with the requirements of seismic exploration is also a matter of concern.

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