Design of real-time simulation method for infrared earth sensor signal based on FPGA architecture

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Abstract. The infrared earth sensor simulator composed by analog circuit or analog circuit with digital circuit is widely used in the field of spacecraft dynamics simulation and testing. The traditional analog methods with low level of real-time performance and poor stability are difficult to determine the parameters of system components. A real-time digital process method based on field programmable gate array was proposed. The hardware architecture was designed and implemented, and FPGA signal filtering, on-board differential calculation and earth square wave calculation algorithm were focused on. The Validation results show that the system accuracy can reach 0.005, and the signal processing process is not affected by environmental interference, has good stability, and is valuable for engineering applications.

1. Introduction
As an important optical attitude sensor of spacecraft, the infrared earth sensor will be sensitive to the infrared radiation of the earth when used in orbit, and thereby obtain the attitude information of the spacecraft relative to the earth. The infrared earth sensor consists of an optical system, a detector and processing circuitry. In the ground simulation and testing process, such as large mechanics, thermal vacuum and other test conditions, the earth infrared radiation source often cannot be used to cooperate with the test verification. Therefore, the ground simulation test equipment is required to provide the simulated earth signal and output to the processing circuitry, to complete the necessary closed-loop simulated flight verification.

At present, widely used infrared signal analog sources utilize analog circuits to construct a core signal processing unit, which uses analog circuit modules composed of an operational amplifier, such as a filter circuit and a differential circuit, to convert an infrared reference triangular pulse sequence into a square wave sequence, and then data processing is performed by an Advanced RISC Machine (ARM) or Digital Signal Processing (DSP). However, when an analog circuit is used for filtering, differentiation, etc., the component parameters are difficult to decided and have a severe drift problem, highly susceptible to environmental interference, with a poor data consistency. To this end, this paper proposed a signal source output mode of infrared earth sensor, based on FPGA all-digital signal processing method, used on-board Analog-Digital Converter (ADC) to sample infrared base wave or self-test waveform. After the sampled data was calculated by the algorithm in the FPGA, the on-board Digital-Analog Converter (DAC) was used to output the earth square wave. This method makes the signal processing and calculation completed in the form of digital signals, and overcomes the problems of noise and drift generated by the analog circuit.
2. Simulation signal processing by infrared earth sensor

2.1 Sequential relationship of signals
The infrared earth sensor targeted by the system is a cone-scanning earth sensor. A scanning device is mounted on the sensor, with an angle included between the line of sight and the scanning axis.

When the line of sight rotates around the scan axis under the motor drive, a cone is formed and faces the horizontal circle to scan, sweeping around the horizontal circle twice in one scan, and the sequential relationship is shown in Figure 1.

![Figure 1: Timing of infrared earth sensor square wave](image)

The reference signal of the infrared earth sensor presents a form of a triangular pulse ideally and serves as a periodic signal, and the sensor can calculate an accurate scanning period $T$ according to the signal. When the sensor's line of sight sweeps across the ground, its output will remain a high level and output a square wave. Therefore, the attitude deviation information of the spacecraft relative to the earth can be calculated based on the square wave width $\tau$ and the offset $\Delta \theta$ of the square wave center time and the reference pulse.

In the dynamic simulation process, the dynamics operation inversely solved the attitude information required by the spacecraft, and based on the collected reference signal of the infrared sensor, the peak time of the reference signal was identified. Combining the data of the chord width $W$ and the grounding angle $\lambda$, an earth square wave signal having a certain phase relationship with the center of the reference signal was generated and outputted to the infrared processing circuit.

The chord width $W$ and the grounding angle $\lambda$ were inputted, and the module calculated the square wave width $\tau$ and the offset $\Delta \theta$ according to the corresponding algorithm:

\[
\begin{align*}
\tau &= \frac{W}{360} \times T \\
\Delta \theta &= \frac{\tau}{2} - \frac{\lambda}{360} \times T
\end{align*}
\]

2.2 Signal modeling
According to the signal sequential relationship, the infrared signal analog source first collected the reference signal of the infrared sensor, simultaneously calculated the earth square wave pulse width and the offset from the peak of the reference signal according to the desired analog chord width $W$ and the grounding angle $\lambda$, and output the excitation signal in the form of voltage through the physical interface.

As shown in Figure 2, the ideal infrared reference signal is a typical triangular pulse period signal. Let the period be $T$, the pulse width be $Tk$, the amplitude be $VB$, the time be $t$, and the time-domain function of the waveform is:
In order to determine the correctness of the model, this paper verified it on the real built physical platform, and the verification results are shown in Figure. 3.

![Reference signal of infrared earth sensor](image)

**Figure.2 Reference signal of infrared earth sensor**

In this verification, the pulse width $T_k=8$ms and the amplitude $V_{Basewave} = 10$V were set, and the reference signal was generated and output. Figure. 3 shows the actual output signal by the physical platform captured by the oscilloscope Tek. In the signal capture process, the rising edge trigger mode was used, with the trigger voltage of 2.12V, and the actual output voltage was 5 units, with the unit of 2.0V/cell. The pulse width was calculated to be 8.00ms by the oscilloscope. The actual signal consisted with the expectation.

**2.3 Detection at peak time**

As shown in Figure. 4, the simulation of the chord width and the attitude angle is achieved by the peak position of the earth square wave relative to the reference signal. Therefore, the accurate representation of the peak time of the reference signal is a key matter of the system implementation. This paper used the differential method to find the peak time.

$$g(t) = \begin{cases} \frac{2V_a}{T_k} & 0 \leq t \leq \frac{T_k}{2} \\ \left(1 - \frac{2t}{T_k}\right) V_a & \frac{T_k}{2} \leq t \leq T_k \\ 0 & T_k \leq t \leq T \end{cases}$$

(2)
The first-order differentiation of the time-domain model \( g(t) \) of the infrared reference signal was carried out:

\[
\frac{dg(t)}{dt} = \begin{cases} 
\frac{2V_{\text{Basewave}}}{T_k} & 0 \leq t \leq \frac{T_k}{2} \\
-\frac{2V_{\text{Basewave}}}{T_k} & \frac{T_k}{2} < t < T_k \\
0 & T_k \leq t \leq T 
\end{cases}
\]  

(3)

So the waveform shown in Figure. 4(b) can be obtained. During the rising process of the reference triangular pulse \((0 \leq t \leq \frac{T_k}{2})\), the differentiation result is \(V_{\text{Basewave}}\), a positive constant, while during the falling process \((\frac{T_k}{2} \leq t \leq T_k)\), the differentiation result is \(-\frac{2V_{\text{Basewave}}}{T_k}\), a negative constant. Therefore, a falling edge is generated at the peak time \(\frac{T_k}{2}\) of the reference triangular pulse, and making use of this characteristic, the trigger signal can be obtained..

2.4 Signal processing

As shown in Figure. 5, the infrared signal analog source collects the infrared sensor reference signal, and performs a first-order differential operation on the signal to obtain a square wave pulse. However, since the square wave sequence has a negative constant, the complexity of the digital signal processing will be increased, so the negative value was removed using a digital comparator. Then, a square wave sequence with the falling edge aligned with the peak time of the reference signal was obtained. With the falling edge of the square wave taken as the time reference, on the basis of the desired chord width \(W\) and the grounding angle \(\lambda\), the pulse width of the earth square wave and its offset from the peak time of the reference signal were calculated, and the excitation signal in the form of voltage was output through the physical interface.
3. Design of all digital signal simulation system based on FPGA

3.1 Platform hardware design
This paper designed and achieved the analog source hardware architecture shown in Figure. 6. The core components of the board include one ADC with a sampling rate of 750 kHz, a resolution of 16-bit, and an input range of ±10V; one DAC with an updating rate of 1 MHz, a resolution of 16-bit, and an output range of ±10V; and one FPGA device Virtex-5 LX110. The FPGA controlled the ADC to collect the reference triangle pulse outputted from the detector unit of the infrared earth sensor, and then performed the operation of differentiation, filtering, and earth square wave calculation on the originally collected data. Finally, the DAC outputted the generated analog earth square wave to the processing unit of the infrared earth sensor circuitry.

3.2 FPGA differential algorithm
There are many options to implement the digital differential algorithm, such as Euler method, trapezoidal method, Runge-Kutta method, etc. This article used the relatively simple Euler method to reduce hardware resource consumption, to perform differential operation on the collected triangular pulse signal. The collected signal was set as \( g(k) \), then:

\[
g(k) = \frac{g(kT_s) - g(kT_s - T_s)}{T_s}
\]

where: \( T_s \) is the sampling period; \( g(kT_s) \) is the sampling value of the triangular pulse collected this time; \( g(kT_s - T_s) \) is the sampling value of the triangular pulse in the previous period.
Through the above algorithm operation, the actual effect of the verification on the physical platform is shown in Figure 7. Figure 7(a) shows the first-order differentiation results obtained by the operation, and the falling edge consistent with the expectation can be obtained at the moment $T_{k}^{2}$. As can be seen from Figure 7(b), the system can correctly process the triangular pulses of continuous cycles. However, it can be found from the observation on the results collected by the oscilloscope, the signal doping has relatively high-frequency noise.

3.3 Filtering and comparison processing

In practical applications, the numerical differential operation on the originally collected data will have obvious high-frequency noise, which makes the subsequent algorithm unable to use the operation result of $g(k)$. Through analyses, it is mainly caused by two reasons.

Random interference on input signal—Since the infrared sensor is under the environment of the electrical signal of the complex spacecraft’s large system, and connected to the analog device with long-line transmission, the interference signal is mixed before the system collects the signal.

Quantization errors—Analog signals will introduce quantization errors when the ADC is digitizing. Let the interference signal be $n(k)$, that is the noise at time $k$, and the signal model becomes:

$$g(k) = \frac{g(kT) - g(kT - T)}{T} + \frac{n(kT) - n(kT - T)}{T}$$

Thus, the actually processed signal is a superposition of the differentiated signal and the noise signal. After FFT of the signal, it is known that the high-frequency component is at 500 Hz. Therefore, a second-order Butterworth low-pass filter was designed in this paper, and its amplitude-frequency characteristics
are shown in Figure. 8. The low-pass filter has a cutoff frequency of 1 kHz and has achieved good results in practical applications.

![Digital filter characteristics](image)

Figure.8 Digital filter characteristics

As shown in Figure. 9, the smoothness of the differentiated signal after filtering has reached the engineering requirements. After the processing by the digital comparator, the square wave with a positive pulse width can be obtained, as shown in Figure. 10.

As the verification results shown in Figure. 10, the algorithm can realize the detection at the peak time of the original triangular pulse. As a result of the differentiation, it will likely obtain a smooth and strictly aligned square wave signal falling edge at the peak time of the triangular pulse.

![Result of differential base-wave after filtering process](image)

Figure.9 Result of differential base-wave after filtering process
3.4 Calculation and generation of earth square wave

In the FPGA, the clock with 40MHz was used as the system reference, and the digital phase-locked loop (DPLL) was used to divide clocks with 1MHz as the trigger signal of the earth square wave calculation logic. The actual period was indirectly obtained by counting the intervals of the falling edges of two adjacent square waves, with the counter bit width of 32 bits.

The IP core was utilized to realize the communication between the FPGA and the PXI bus, and to receive the chord width and attitude angle data required for the simulation calculation. The module calculated the square wave width $\tau$ and the offset $\Delta \theta$ according to the formula (1), and then controls the DAC to output. The test results are shown in Figure. 11.
4. Conclusions
The experimental verification showed that the all-digital simulation method based on FPGA technology could better meet the requirements of infrared signal simulation, having the following advantages:

1) Effectively avoiding the difficulty in selecting the component parameters encountered in the simulation processing and calculation using the analog circuit, and improving the universalization requirements of the infrared signal source;

2) Effectively solving the problem that the infrared signal source is susceptible to environmental interference, and improving the anti-interference performance and stability of the infrared signal in large-scale tests such as thermal vacuum and mechanics;

3) The system used a clock with 40MHz as the reference, with a stability of 0.0001. Simultaneously, the ADC for analog input adopted a resolution of 16-bit, the accuracy of 0.15mV, and the sampling rate of 100 kHz, which ensured the quantization precision of the infrared base wave. The analog output utilized the resolution of 16-bit and the update rate of 1 MS/s, ensuring the accuracy and real-time capability of the computed back-wave output. The actual testing showed the overall system accuracy was 0.005.

Since this method met the universalization requirements for the simulation of infrared signal sources, it can be applied to more model tests using the attitude of the infrared earth sensor.

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