Integration time interpolation control of space-borne TDICCD

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Abstract. Spacecraft orbits around the earth are basically elliptical orbits. That the altitude varies with motion of the remote sensing satellites results the ground resolution varies. Adjusting the integration time of image sensor can remain the accurate ground resolution. Similarly, the change of the satellites attitude leads to the variation of the ground resolution, which can be correct by adjusting the integration time of the image sensor. This paper presents an integration time interpolation arithmetic, which increases the adjustment rate of integration time of image sensor to make the space borne image sensor adapt to changes in orbit timely to ensure ground resolution. The arithmetic is implemented in FPGA, and this paper describes the results in the end.

1. Introduction
The orbit of spacecraft orbiting the earth is an ellipse in a plane passing through the center of the earth. The earth center is in a focus of the ellipse. The distance from the earth's center is constantly changing during the operation of the satellite, thus the resolution of the ground will also change. When the remote sensing satellite camera is in orbit, it can improve the time resolution of ground by adjusting its attitude and side swing imaging. When the space camera uses side-tilt imaging, the feature point corresponding to the center and the edge of field of view is far from the sub-satellite point, and has a large difference in longitude and latitude, resulting in a change in the oblique distance, a change in ground resolution in camera flight direction, and the inconsistency between the charge transfer speed of the image sensor and the imaging speed of the ground target, which eventually causes the image to blur and the MTF to decrease. In addition, due to the different field of view angles on the detector array, the satellite side pendulum will inevitably cause geometric deformation. At the same time, due to the side swing, the camera deviates from the sub-satellite point for imaging, which makes the angle of the sun, the angle between the line connecting the satellite and the target and the ground change, and causes the change of the camera's entrance pupil energy. These are the factors that influence the ground observation of remote sensing satellite camera when the satellite is side swinging. The first two factors affect the ground resolution and image quality of the space camera. The accurate integration time can be determined by calculating the GSD in the flight direction based on the coordinates of the instantaneous projection footprint of the satellite camera to the ground when the satellite is side swinging. By controlling the integration time of image detector in real time by the on-board FPGA, the image blur caused by unsynchronized TDICCD imaging can be eliminated, thus improve the image quality.
2. Relationship between TDI-CCD integration time and speed-to-height ratio

The characteristic of time-integrated delayed charge-coupled device (TDICCD) is to use multiple levels of photosensitive cells to integrate the same target multiple times, and superimpose the weak signal of each integration into a strong signal, so that the signal to noise ratio and dynamic range of the image are improved. The TDICCD's charge transfer speed needs to match the target's imaging speed in order to present a clear picture, otherwise the image will be blurred. The speed-to-height ratio refers to the ratio of the moving linear velocity of the camera relative to the imaging height of the subject during the imaging process, which is equal to the angular velocity of the image of the captured object moving on the focal plane of the camera. In the case where the integration time and the field angle remain unchanged, in order to keep the charge transfer speed of the TDICCD synchronized with the image speed of the target, the speed-height ratio must be kept constant.[6-8] The relationship between the camera detector’s integration time and the speed-height ratio can be expressed by the following relationship:

\[ T_i = \frac{1}{R_e \sqrt{G \times m_e}} \times p \times H \times \frac{(H \times R_e)^{3/2}}{f} \]  

(1)

\( T_i \) represents the integration time of TDI-CCD, \( R_e \) represents the earth’s radius of 6371km, \( G \) is the gravitational constant \( 6.67 \times 10^{-11} \text{N} \cdot \text{m}^2/\text{kg}^2 \), \( m_e \) is the mass of the earth, \( p \) is the size of the pixel, \( H \) is the distance from the satellite to the sub-satellite point, and \( f \) is the focal length of the camera.

When the satellite camera is tilted sideways, the camera's field of view angle and relative speed-to-height ratio will change. If the integration time is unchanged, the image will be blurred and the MTF will decrease. The integration time corresponding to the relative speed-to-height ratio and field of view must be adjusted to ensure the image quality.

3. FGPA implementation of integration time interpolation control

3.1. Interpolation algorithm for integration time

To improve the field of view and time resolution, the satellite uses pitch or side swing imaging. Since the satellite attitude changes will cause the speed-to-height ratio between the imaging points of the space camera to change, if the constant integration time is used, the imaging of the edge image points will be blurred and the camera imaging quality will be affected. As can be seen from the second chapter, the integration time of the space camera is inversely proportional to the instantaneous speed-height ratio, different integration times need to be used under different attitudes. By adjusting the camera integration time at a high frequency, the quality of the space camera can be guaranteed, which is why the integration of the space time interpolation algorithm is used to control the space camera.

The integration time interpolation algorithm is to receive the integration time code sent by the satellite service, and control the integration time of TDICCD at a fixed frequency according to the corresponding algorithm.

The satellite service calculates the instantaneous TDICCD integration time \( T_i \), in advance based on the current satellite orbit. Send the integration time and integration time execution time \( T_{exe} \) to the video processor of TDICCD according to a certain frequency \( f_1 \). The video processor would get a difference \( \Delta \) between the two adjacent integration times received, and send the integration time to the control module of TDICCD according to high frequency \( f_2 \) to control TDICCD. \( f_1 \) and \( f_2 \) are in Hertz. Due to the limitation of star service transmission capacity, \( f_1 \) is generally single digits, and \( f_2 \) is generally several tens of hertz.

The number of interpolations required to control the TDICCD at \( f_2 \) is \( n \):

\[ n = f_2/f_1 \]  

(2)

The integration time value sent at \( f_2 \) is \( T_{interpolation} \)

\[ T_{interpolation} = \text{round}(T_{icur} + \Delta/n) \]  

(3)

The sending moment value corresponding to the integration time send at \( f_2 \) frequency is \( T_{exe} \):

\[ T_{exe} = \text{round}(T_{exe,cur} + (T_{exe,i} - T_{exe,i-1})/n) \]  

(4)
In the formula, the sending time of the current integration time is \( T_{\text{exe.cur}} \); the sending time of the \( i \)-th integration time sent by satellite service is \( T_{\text{exe.i}} \); the sending time of the \( i \)-th integration time sent by satellite service is \( T_{\text{exe.i-1}} \).

3.2. Implementation of the integration time interpolation algorithm
The algorithm has been implemented in FPGA for the first time and fully verified. In specific project, TDICCD works in two modes: constant integration time mode and interpolation operation mode. In FPGA design, not only need to consider the processing mechanism when two different modes work independently, but also consider the problems brought by the switching of the two modes. In order to increase the stability and compatibility of the system, and take the actual situation is consideration, timing relationship is obtained as shown in Figure 1.

The figure lists the processing after receiving the integration time 12 times. The upper part shows the integration time and the sending time. The dotted line in the lower part shows the integration time after interpolation. The red line is the theoretical value and the black line is the actual sent value. There are 6 special cases, which are indicated in the figure: CASE1, CASE2, CASE3, CASE4, CASE5, CASE6.

CASE1: The received integration time is earlier than its sending time, last integration time is maintained.
CASE2: The integration time interval between C5 and C6 is greater than the agreed time interval\( \Delta T \). After C6 is received, interpolation is performed and the identification bit is generated;
CASE3: The integration time interval between C7 and C8 is less than the agreed time interval\( \Delta T \). After performing the interpolation operation, the integration time is sent according to the agreed sending time;
CASE4: C8 is interpolation operation, C9 is non-interpolation operation, that is, the conversion from interpolation operation to non-interpolation operation. At this time, C8 and C9 are processed as non-interpolation operation;
CASE5: C10 is non-interpolation operation, C11 is interpolation operation, that is, the conversion from non-interpolation to interpolation operation. At this time, the interpolation operation module is reset to zero, C10 is sent, and C11 is sent at the new sending frequency after interpolation.
CASE6: Both C11 and C12 are interpolation operations, and the time interval\( \gg \Delta T \). For C11, no integration time is sent. After receiving C13, the interpolation operation is performed according to the new sending frequency.

Fig.1 The schematic diagram of the management of the integration time of TDICCD
Legend: C1-C12: the integration time sent by star service; T1-T12: the sending time corresponding to C1-C12; \( \Delta T \): the agreed time interval of star service integration; the horizontal axis is the sending time

3.3. FPGA Design of Integration Time Interpolation transmission
The key to the integration time interpolation operation is to precisely control the integration time of the detector according to the sending time of the star service. Because of the satellite orbit changes, it is necessary to adjust the attitude of the satellite to observe the Earth’s target object. To ensure the imaging quality, the integration time of the detector needs to be adjusted in real time.

According to the requirements of the specific project, star service sends the adjusted integration time and its sending time to the video controller 3s in advance at 4Hz. After interpolation, the video controller controls the integration time of the detector at the time specified by star service at 48Hz. The key points in this design are:

1) Time synchronization design and correction design. Star service and video controller are two independent systems that work under their own clock control. Due to the different clock sources, the timing logic of the two systems is completely unrelated, video controller unable to send integration time according to the star service instructions, thus the two systems need to be synchronized. At the same time, because the clock sources of the two systems are independent, a perspective correction design is required to avoid the accumulation of clock source deviations. After the two system clocks are synchronized, the integration time is controlled to be sent.

2) Integral time and sending time alignment design. Star service sends the integration time to video controller at the frequency of 4Hz, meanwhile sends the time integration time to be sent at the same time. There is a one-to-one correspondence between integration time and sent time. Once the corresponding error will cause the integration time of the detector to be inconsistent with the integration time required for imaging under the current satellite attitude, which will cause the camera’s imaging deformed, skewed or blurred, seriously affect the image quality and even unable to work properly.

3) Integration time interpolation operation design. Map the FPGA logic design according to the integration time interpolation algorithm provided in Section 3.2. The integration time interpolation operation needs to receive the integration time twice before the interpolation operation can be performed. The FPGA implementation must take into account the sequential logic design. In actual implementation, ensure the correspondence between the current camera operating mode, integration time and sending time. Once the special situations in the chapter 3.2 appearing, it should be able to handle without error accumulation, resulting in camera imaging errors. The algorithm implementation process is as shown in the figure.
4) Integration time sending control design. The integration time after interpolation is sent at a frequency of 48Hz. There is a local timer to control the time of the integration time to be sent after interpolation. Since the local clock source crystal oscillator usually has an offset of 20 ~ 100ppm, it will have 0.2us ~ 1 us delay at a 100MHz clock. The sending time of the integration time is accurate to the nanosecond level, so tolerance processing should be performed in the integration time sending module to avoid missing the integration time due to the stability of the crystal. Another transmission time difference comes from the time correction module. The source of the time correction module is the satellite service time. The star service time is different from the local clock, and there will be a time jump during the correction of the whole second. This will cause the integration time corresponding to some partial time to be missed. Tolerance processing should be done within the tolerance range to ensure that the integration time will not be missed.

3.4. Testing

Connect the instruction sending device, video processor and image acquisition device. The instruction sending device controls the current working mode. Analyze the images collected in the image acquisition device, extract the auxiliary data in the image, calculate the sending time, integration time, the sending time difference and the integration time difference between the frames to verify the accuracy of the algorithm execution.

The instruction sending device sends the integration time instruction code to video processor at a frequency of 4 Hz/s. The integration time starts from 1700 ms and decreases 24 ms in sequence. The instruction sending rule is shown in Figure 3. It can be seen that the integration time sent by the instruction issuing device decreases as the sending time increases. The interval between two adjacent instructions is 250ms, and the difference between the integration times is 24ms.
Use MATLAB to analyze the image collected by the image acquisition equipment, extract the image sending time and integration time information, the results are as shown in Figure 4. The working mode of the video processor is switched between interpolation and non-interpolation operations (as shown in Figure 4 (a)). Operate the 1/12 interpolation, sending frequency of the video processor is 48Hz / s, which is 20.833ms (as shown in Figure 4 (b)), and the integration time difference is 2ms (as shown in Figure 4 (c)).

![Figure 3 Sending order rules](image)
(a) Integration time at different transmission times  
(b) Inter-frame transmission time difference  
(c) Inter-frame integration time difference

Figure 3 Sending order rules

Figure 3 shows the integration time instruction received by the video processor. Figure 4 shows the results of the integration time and integration time sent by the video processor in different operating modes. The result meets the algorithm requirements in Chapter 3.1, and proves the accuracy of using FPGA to implement the algorithm.

4. Conclusion
This paper introduces a new space-based integration time control method, which uses the method of interpolation of ground control instructions to control the integration time of space-borne detectors at a higher speed to adapt to changes in satellite relative speed-to-height ratio. The method has been realized by FPGA and tested.

Many literatures at home and abroad have introduced the method of ground image motion compensation to solve the image motion caused by the change of the relative speed to height ratio[10-12]. In this paper, the method of on-board real-time control is used to directly control the image detector, and starts to "compensate" from the camera imaging device, so that the image is more real and accurate. The experimental results show that there is no fault in switching between integration time interpolation operation and non-interpolation operation, and the integration time output is stable during execution of the algorithm.

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