X-ray image chain synchronization control scheme design and performance evaluation

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Abstract—This paper describes the working principle of the image chain’s imaging system and analyzes the two imaging modes of the X-ray source as well as the two synchronization modes of the flat panel detector, with the goal of completing the design of the image chain’s system imaging. Two schemes of synchronous control of the image chain, hardware control and software control, are achieved on the basis of the design of the image chain’s imaging system. According to the experimental results, the hardware synchronization control, in comparison with the software synchronization control, enormously reduces the X-ray radiation time and the radiation received by the object as well as generating a lower CPU occupancy rate, which improves the safety of the performance of the image chain imaging system. Therefore, it can be concluded that hardware synchronization control is safer and more practical than software synchronization control. Lightweight cone-beam CT can be developed for use in mobile field hospitals and intensive care units to reduce the difficulty of doctors’ operations.

1. INTRODUCTION

Cone Beam Computed Tomography (CBCT), namely, is a cone beam projection computer reconstruction tomography device\textsuperscript{[3]}. The nature of CBCT is that during the rotation of the X-ray source and detector fixed around the center of the region of interest, the X-ray source emits the ionizing radiation of the cone beam passing across the circle of the beam limiter through the projecting body onto the detector plate\textsuperscript{[2]} in order to obtain multiple continuous plane projection images. This allows researchers to obtain data as cross-sectional uniform images\textsuperscript{[3]} with the display of a professional 3D reconstruction algorithm. At present, CBCT has rapidly developed and spread to many specialized medical industry, including radiotherapy\textsuperscript{[6]}, nuclear medicine, neurology, cardiovascular, urology, surgery, pediatrics, otolaryngology, trauma and orthopedics, oral and maxillofacial\textsuperscript{[4]} and breast and other applications.
As the increasing clinical practice of CT, conventional CT requires hundreds to thousands of X-ray exposures on the rotating circle and the radiation dose is relatively large. The radiation received by patients when taking CBCT is a concerning safety issue to the society[14]. The product of the tube current and the exposure time determines the total doses of X-rays exposed at one time[15]. Currently, based on the premise of the same image quality, the main measure to reduce the radiation is by diminishing the exposure time of each image. Therefore, which kind of X-ray irradiation method is used to reduce the exposure time is essential CBCT research.

In the CBCT image chain imaging system, the X-ray source has continuous exposure and pulsed exposure during the entire scanning process[12]. Continuous exposure means that the X-ray source is continuously exposed during the entire scanning process with the advantage of the simple operation, but the inclining radiation dose received by the projecting body might induce potential problems[7]. On the contrary, pulse exposure lets the X-ray source be in a ready state and wait for the detector to send a trigger signal to the X-ray source. When the X-ray source receives the trigger signal, it starts to perform the exposure acquisition operation, and then waits for the next time the detector sends the trigger signal. This method decreases the radiation received by the projecting body, and however, since the trigger signal is sent from the detector to the X-ray source, it is necessary to control the synchronization of the X-ray source and the detector[8].

Some CBCT systems adopt the X-ray continuous exposure method, which requires the frame to have superior mechanical properties and fast rotations to reduce X-ray radiation time, combined with high demands for flat panel detectors of real-time imaging, resulting in high CBCT costs[9]. In this paper, two different CBCT image chain control schemes (software control and hardware control) are designed using X-ray continuous exposure and pulsed exposure for exposure control by analyzing exposure time, CPU occupancy rate, radiation dose and picture clarity under different control schemes.

2. Methods and Materials

2.1 Image chain imaging components

The imaging components of the image chain are shown in Fig.1 mainly include Detector, X-ray source, Relay and Dose Area Product(DAP).
The detector used in this paper is an X-ray dynamic flat panel detector based on amorphous silicon thin film transistor technology (YiRui Mercu1717V®). This product of size 43cmx43cm utilizes fast reading technology in a speed of approximately 30 frames per second. It is mainly applied in fluoroscopy, gastrointestinal radiography, endoscopy, urology, plastic surgery, splicing, and peripheral intervention, and meanwhile it can also provide high-quality radiographic images with an effective area of 427.008×427.008mm and a pixel size of 139um[5]. The synchronization mode with the high-voltage generator supports synchronization input (Syncin) and synchronization output (Syncout) to develop real-time imaging technology.

The X-ray source is the integrated X-ray source provided by Spellman (MMB125PN15X5802). The control of the X-ray source is accomplished through RS232 serial communication and digital IO interface, and the digital IO control signals include PREP and EXPOSURE signals. The interactions between users and machines are through the RS232 interface to configure the working mode, exposure mode, exposure parameters of the X-ray source and the state of the X-ray source while the controls of the exposure start, stop and exposure sequence are through the digital IO interface[11].

The USB-4761 based on the USB bus is a relay output and isolated digital input and output module. It offers 8 isolated digital inputs with 2500VDC isolation protection for receiving digital inputs in noisy environments, and eight-channels relay output for on/off control equipment or small power switches. In order to facilitate monitoring, each relay has a red LED indicator that indicates its on/off status. USB-4761 has 8 optically isolated digital input channels, which is suitable for digital input under noisy environment or with drifting voltage.

The dose area product device adopts the equipment (ACCUDAP-D123) from Shenyang Accurate Company, which is composed of a flat transparent ionization chamber and signal measurement circuits. When X-rays pass through the transparent ionization chamber, a signal current is generated with current proportional to the product of the radiated area and the air kerma. The built-in signal measurement circuit amplifies, digitizes and calculates the generated signal current, and the processed signal is transmitted to the host computer through the RS485 serial port to display. The unit of dose area product is usually expressed in μGy.m². In application, the flat transparent ionization chamber must cover the entire radiation field area, perpendicular to the ray beam, and under most circumstances, it is installed on the integrated X-ray source port. Both the exposure parameters and the irradiation field size of the X-ray machine might affect the parameter reading.

2.2 Image chain control scheme design

**Detector synchronization trigger mode:** The control scheme is based on the synchronization trigger mode of the detector[13]. The YiRui’s detector in this paper contains two synchronization trigger modes: Syncin and Syncout. When the X-ray source is in the pulse exposure mode, the Syncin mode sets the X-ray source to synchronize the flat panel. To be more specific, the X-ray source sends a FrameReq_in (default as high valid trigger) request, and the flat panel detector responds to the FPD_Enable (default as low valid trigger) signal before X-ray source emits rays with the flat-panel detector collecting the pictures as demonstrated in Fig.2. In contrast, the Syncout mode is the tablet synchronous high voltage with the tablet sending out a FPD_enable_p (default as high valid trigger) request, and regardless of the existence of a response, the picture is taken as indicated in Fig.3.
Fig. 2 Syncin timing diagram (where $T_0$ is the cost of signal processing inside the panel, $T_1$ is the exposure time of the ray source, $T_2$ is the time for reading the image data collected by the detector, and $T_3$ is the time for the detector to quickly clean up.)

Fig. 3 Timing diagram of Syncout

**X-ray source exposure mode:** The synchronous trigger mode of the detector requires the X-ray source to support both the pulse exposure and the continuous exposure. The continuous exposure mode means that the X-ray source is always in the exposure state, and does not regard the acquired image signal sent by the flat panel detector as the trigger condition, while the pulse exposure mode means that the X-ray source is in the pre-exposure state, and the exposure of the X-ray source depends on whether the flat panel detector is in the pre-exposure state, sending out the image acquisition signal. If the image acquisition signal is received, the X-ray source performs the exposure operation, and otherwise no other operations should be conducted.
Soft/Hardware synchronization control scheme design: This article uses two control schemes for comparison, including software control and hardware control. Under the premise of different control schemes, two different acquisition methods, single frame acquisition and continuous acquisition, are designed, and the performance of software control and hardware control is evaluated through multiple experiments. To ensure authentic experiment results, under the prerequisites of the same exposure conditions and parameters for the two control schemes, the scale of the voltage and the current is selected to be 70kV and 3mA, and the trigger mode and exposure mode are set to match the different control schemes of the detector and the radiation source.

The detector of the software control is in Syncout trigger mode and the ray source is in continuous exposure mode. The host computer connected to the industrial computer through RS485 serial communication is in charge of sending control instructions. After completing the analysis of the host computer instructions, the industrial computer sends operating instructions to the X-ray source, the detector, relays, DAP and other hardware devices, and following the hardware devices finishing each step of the operation, they will successively reply to the completion status of the industrial computer and the upper computer, with the next operation decided by the upper computer according to the reply status. If the feedback information is Y as illustrated in Fig.4, proceed to the next step, and otherwise stop the entire software control process.

The flat panel detector of the hardware control is in Syncin trigger mode and the ray source is in the pulse exposure mode. After the industrial computer completing the analysis of the host computer instructions and sending the operating instructions to the hardware device, the X-ray source passes the Automatic Exposure Control (AEC) to receive the pulse signal of the flat-panel detector to complete the entire exposure acquisition process by itself with no need of any status feedback.

Corresponding to two different control schemes, two distinctive experiments are designed, respectively single-frame acquisition and continuous acquisition. Single frame collection is created to imitate doctors to collect a picture at a specific location, while continuous collection is to continuously collect multiple two-dimensional pictures according to the doctor's needs for reconstruction of the three-dimensional model. More specifically, the continuous collection experiment designed here is to collect 400 pictures to simulate the situation for practical applications in the future.

![Fig.4 Software control](image-url)
2.3 Performance evaluation experiment
The main difference between the software control process and the hardware control process is the synchronous trigger mode of the detector and the exposure mode of the X-ray source, which could be visualized in Fig.5(a)(b). In the software synchronization control process, it is necessary to configure the X-ray source in continuous exposure mode, the detector in Syncout mode, and the relay and related dose equipment (DAP, CPU occupancy rate, timer) in the ready state. After the completion of the configuration, the X-ray source directly performs the exposure operation should be directly performed by the X-ray source with images collected by the detector. After the image acquisition, the exposure needs to be manually stopped, and the process ends with the restoration of the collected image data, radiation dose, CPU occupation, and radiation time. For the hardware synchronization control process, it is imperative to first configure the X-ray source to pulse exposure mode as well as detector to Syncin mode, and then turn on the relay and related metering equipment (DAP, CPU occupancy, timer). Then, the X-ray source must be manually set to the pre-exposure mode. When the detector needs to collect images, the X-ray source emits rays for exposure through a trigger signal. After the collection is completed, the X-ray source automatically stops exposure to save the collected image data, radiation dose, CPU occupation and radiation time, ending the entire process.
Software control

- Configure X-Ray (Continuous exposure)
- Configure detector (Syncout trigger)
- Configure relay
- Configure metering equipment (DAP, CPU, Timer)

Configuration success

- X-Ray exposure

Start taking pictures

- Detector acquisition (Single/Continuous)

Acquisition end

- X-Ray manual stop exposure

Save data

Process end

Fig.5(a) Software trigger synchronization control scheme flowchart
Fig. 5(b) Hardware trigger synchronization control scheme flowchart
Fig. 6 indicates the main interface of the X-ray image chain synchronous imaging control system software, including the relay interface, the X-ray source interface, the detector interface, the synchronization control interface, the radiation time interface, the CPU occupancy rate interface, the radiation dose interface and the image display interface. The relay interface mainly controls the preparation state and exposure state of the X-ray source, and the current, voltage and exposure mode during exposure are managed by the X-ray source interface. Moreover, the detector interface mostly sets the detector trigger mode and the number of pictures collected. The synchronization control interface is in charge of the hardware control and software control, and the whole process can be realized with only a single button. The radiation time, radiation dose and CPU occupancy rate interface can respectively display the current synchronization control time cost, CPU occupancy rate and radiation dose in real time.

3. Results and Analysis
This paper carried out two different experiments of software control and hardware control under the conditions of 70kV and 3mA, aiming to compare the radiation dose, exposure time and CPU occupancy rate of the object in the two different control modes.

In the design of the radiation dose control experiment, researchers conducted experiments of 100, 200, 300, 400, 500, 600, and 700 images respectively, and recorded the radiation dose under different collection numbers through the DAP device (see Fig.7). The experimental results show that the X-ray...
source adopts the pulse exposure mode when the hardware control is used. When each image is taken, the X-ray exposure is several milliseconds, and the total X-ray radiation time during the entire exposure process is only a few seconds, which is compared with the continuous software control. The exposure time to complete the entire experiment is tens of seconds, so the hardware control method greatly reduces the X-ray radiation dose.

![Fig.7 Radiation dose statistics](image)

The control experiment of exposure time is conducted through collecting 400 pictures under two different synchronous control methods with the hardware control time of 26.7s and the software control time of 32.7 s. Experimental results show that when using hardware control, the process time is significantly less than the software control time. Moreover, through different collection experiments of 100, 200, 300, and 400 sheets, it is illustrated that as the number of collected sheets increases, the time expenditure gap between the software and hardware control procedures increases.

According to the control experiment of the CPU occupancy rate during the exposure process, the CPU occupancy rate during the exposure process is regularly queried through the CPU module and recorded in an Excel table with the visualization of a line graph. It is obvious that the CPU occupancy rate is lower during the hardware control process (see Fig.8) than during the software control process (see Fig.9).

![Fig.8 Hardware synchronization control CPU occupancy rate](image)
Fig. 9 Software synchronous control of CPU occupancy

In terms of the image quality, we used a CT calibration phantom to conduct a single-frame acquisition experiment and found that the images reached a resolution of 10 mm (See Fig. 10),

Fig. 10 Imaging precision map

the interval of each small circle is 10 mm. However, in the use of pig elbow to simulate the human body for cone-beam CT imaging experiments, there is no significant difference between software synchronization control and hardware synchronization control in image quality [10] (See Fig. 11).

Fig. 11 Imaging results in soft/hard control mode
4. Conclusion
Based on the realization of the hardware control and software control of the image chain, this article focuses on the advantages and disadvantages of software control and hardware control. The results of numerous experiments show that the stability of the synchronization program, and X-ray images can be obtained in both software and hardware trigger modes. Under equal conditions, hardware control outcompetes software control in terms of radiation dose, overhead time, and CPU occupancy rate. The conclusion of this experiment is to provide more advanced imaging support for intensive care, emergency department. It is convenient for doctors to perform low-dose CT imaging during the operation. Provide intraoperative navigation for surgery and increase the success rate of the doctor during the operation.

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