Development of low-cost industrial x-ray computed tomography system based on digital fluoroscopy

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Abstract. Computed tomography (CT) offers an effective method of non-destructive testing for quality control in the manufacturing of complex parts. Using CT allows examination any internal anomaly of a sample like a defect, internal porosity, void detection, and cracks. However, commercial X-ray CT equipment on markets is expensive. So it is required to develop low-cost X-ray CT equipment that provides good image quality and fast scanning. This paper describes the development of digital fluoroscopy-based X-ray CT system. It consists of an X-ray source, a rotary table system, a digital fluoroscopy detector, and a computer. This research uses a fluorescent screen to make the X-ray image visible which then digitized by a CMOS camera. The real-time radiographic image can be visualized and interpreted using a computer. These advantages make acquisition time for scanning images is reduced to only a few seconds. This equipment is relatively cheaper than the same system used in industry. It has been tested with an object of an aluminum step wedge cylinder by scanning 361 images, which were then reconstructed using the Octopus Reconstruction 8.9 software with a filtered back-projection method. The resulting image quality is quite good as it is easily interpreted by the user's eyesight. The implication of this research is the possibility of producing a low-cost X-ray CT equipment made within the country.

1. Introduction
Currently, the manufacturing industry requires strict quality control but with shorter and faster product life cycles. Product quality control with accurate and efficient measurement techniques can reduce costs and waste during the product manufacturing process. X-Ray Computed Tomography (CT) proposes a solution to decipher internal structural details of samples non-destructively in the manufacturing industry. Nowadays the application of CT in the industry is permitting examination of any internal anomaly of a sample such as a defect, internal porosity, cracks, void detection, and dimensional measurements. Development of commercial X-ray CT technologies that have fast scanning capabilities, the capability of the CT system to analyzing multi-material objects, and equipment advances are rapidly increasing [1]. Commercial X-ray CT equipment on markets is expensive because it is imported, so industrial low-cost x-ray CT equipment that provides good image quality and fast scanning is expected. Therefore, low-cost digital fluoroscopy–based X-ray CT system for industrial applications is urged to be developed.

An X-ray CT system consists of a detector for radiographic image acquisition, an X-ray source for generating an X-ray beam, a sample manipulation system, and a computer for image acquisition,
reconstruction, and analysis [2], [3]. The performance of the detector directly influences the quality of the acquired radiographic image. Germany’s Federal Institute for Materials Research and Testing (BAM) has developed a digital fluoroscopy detector for industrial radiology. In the fluoroscopy detector, the conventional film is replaced with a fluorescent screen for making an X-ray image visible and then digitized by a camera[4]. The real-time radiographic image can be visualized and interpreted using a computer. Reliability and significant cost savings from the use of digital fluoroscopy detectors for industrial radiology applications have been published by the International Atomic Energy Agency (IAEA) and researcher [4]–[8]. The cost of a digital fluoroscopy detector is about 10-20% of the commercial detector such as computed radiography, film digitization, image intensifier, and flat-panel but provide similar image quality[4].

However, no research has developed this detector for use on industrial X-ray CT. Moreover, the fluorescence screen size of this detector is only 115 mm × 155 mm, so it is not effective when used for industrial CT applications. So the dimensions and configuration this detector need to be optimized. Digital fluoroscopy detector has been redesign with new detector casing (housing and shielding), optimized optical components, and scale-up fluorescence screen size. An X-ray tube was used for generating the X-ray beam and rotary table was used as a sample manipulation system. To determine the performance of this CT device, testing by using an aluminum step wedge cylinder as a sample to get 361 scanning images has been conducted. The data set that has been obtained is then be reconstructed into images using Octopus Reconstruction 8.9 software.

This research aims to produce prototype X-ray CT for industries. The developed system has been tested and it has the following features: low-cost, easy to operate, and able to be used for manufacturing industrial applications. The implications of this paper provide a useful basis for future research in developing industrial X-ray CT based on digital fluoroscopy system, so the possibility of producing a low-cost X-ray CT equipment domestically becomes greater.

2. Experimental Methods
The block diagram of the developed X-ray CT system based on digital fluoroscopy system which consists of a digital fluoroscopy detector, an X-ray source, a rotary table, and a computer to acquire and analyze image data is shown in Figure 1. An X-ray tube Rigaku RF-300EGM2 (130 kV ~ 300 kV) is used for emitting an X-ray beam. Fluoroscopy detector is operated to scan projection images of the specimen object from various angles, while the specimen objects is rotated using a rotary table. The URS150BPP rotation stage is manufactured by Newport as a rotary table, it provides precision 360° continuous motion with centered load capacity until 300 N. The image that is acquired by a computer and image acquisition software, is then be processed and analyzed for reconstruction process.

![Figure 1. Block diagram of X-ray CT Based on digital fluoroscopy system.](image-url)
The digital fluoroscopy detector used in this research is a modification from the design developed by BAM. This research using DRZ-High (phosphor Gd2O2S) fluorescent screen for making an X-ray image visible and then digitized by a Blackfly BFS-U3-200S6 CMOS camera. The overall dimensions of the digital fluoroscopy detector designed by BAM are 285 mm × 195 mm × 182 mm, and its approximate weight is 30 kg [4]. The dimensions of the fluorescence screen in the BAM design are only 115 mm × 155 mm [4], so it is not effective when used for testing larger size specimens. Because of this limitation, National Nuclear Energy Agency (BATAN) redesigned this digital fluoroscopy detector. Modification of fluoroscopy detectors by BATAN can increase the dimensions of the fluorescence screen to 197 mm × 294 mm. The overall dimensions of the digital fluoroscopy detector designed by BATAN are 432 mm × 314 mm × 304 mm, and its approximate weight is 40 kg. The digital fluoroscopy detector is designed by BAM and BATAN as shown in Figure 2.

![Digital fluoroscopy detectors (BAM) and BATAN](image)

**Figure 2.** The digital fluoroscopy detector designed by BAM and developed by BATAN.

2.1. Acquisition image projection

In testing, this developed system using an aluminum step wedge cylinder with a thickness difference of each step is 5 mm. Figure 3 is an aluminum photograph of the step wedge cylinder. Cone-beam geometry technique is used for image scanning, as it offers the advantage of scanning speed and is relatively effective and easy to test penetrated material [2].

![Aluminum step wedge cylinder](image)

**Figure 3.** Aluminum step wedge cylinder.

The number of image projections is 361 images, with the difference of angle of each image is 0.997. The more image projections, the better the image reconstruction results, but the acquisition and reconstruction time is longer. Besides, more image projections produce large data that requires sufficient storage space [2]. In this testing, the source to object distance is 120 cm and the source to detector distance is 135.6 cm. The X-ray voltage used is 230 kV and the current is 5 mA. Figure 4.a is the configuration of the image scanning setup using X-ray CT devices. Image acquisition software that is specifically developed for this research is built using LabVIEW programming language [9]. The
computer system and image acquisition software to generate a radiographic image is shown in Figure 4.b

![Figure 4.a](image.png)

**Figure 4.a.** Configuration of image scanning setup using X-ray CT devices.

![Figure 4.b](image.png)

**Figure 4.b.** A computer system and image acquisition software to generate radiographic image.

2.2. **Image reconstruction**

Image reconstruction requires image datasets, which consist of several projected images from various angles, dark images, and flat field images. The dark image is the images without objects and no exposure of X-ray, while the flat field image is the images without objects but with exposure of X-ray. Dark image and flat field images are used for image calibration or normalization process. This research utilized Octopus Reconstruction 8.9 software for image reconstruction, while the reconstruction method applied is filtered back-projection (FBP) algorithm [3]. The block diagram of the image reconstruction process is shown in Figure 5.

![Block diagram](image.png)

**Figure 5.** Block diagram of image reconstruction process.

3. **Results and Discussion**

After developing the low-cost industrial x-ray CT system based on the digital fluoroscopy, and performing this CT equipment using a sample object of aluminum step wedge cylinder that has a thickness of each step is 5 mm, 10 mm, 15 mm, and 20 mm, it is demonstrated that the real-time radiographic image can be visualized and interpreted using the computer which has been installed image acquisition software developed by BATAN. The results of radiographic images of the object of aluminum step wedge cylinder are shown in Figure 6.a. The resulting 2D radiographic image quality is quite good therefore it is easily interpreted by the user's eyesight although this equipment relatively
cheaper than the same system used in industry such as flat panel, computed radiography, film digitization, and image intensifier.

![Figure 6.a. The results of radiographic images with objects of aluminum step wedge cylinder](image1)

![Figure 6.b. The software selected for automatic image acquisition will automatically capture and store processes](image2)

In the image acquisition process for tomography purpose, the rotary table is controlled and run by a LabVIEW-based code that is integrated with the image acquisition software. This software has a real-time viewer that displays the scanning process of the object and the radiographic images being acquired. The software for image acquisition will automatically capture and store the images as shown in Figure 6.b. The specimen object is rotated until 360 degrees on a rotary table and set with a high-resolution step (i.e. 0.997 degree per step) as required by digital radiographs. The resolution of this dataset determines the final quality of the generated three-dimensional CT dataset.

The acquisition time for this dataset (scanning of 361 images) takes less than 10 minutes. One of the key capabilities of this X-ray CT equipment for industrial applications is its scanning speed. With fast scanning, the ability to reduce the radiation dose received by the operator is gained [2]. Based on its scanning speed of the images, this CT equipment can fulfill the criteria for industrial applications.

The image reconstruction software used in this research is Octopus Reconstruction 8.9 software. Before the image reconstruction, the projection data have to be pre-processed previously. The first step in pre-processing is image normalization which includes dark image and flat field image correction to projection data. After that, to remove spatial and intensity non-linearities introduces by this equipment, so that geometry and shadow correction is performed on all projected images. Then corrected images are reconstructed using a filtered back-projection (FBP) algorithm so that the three-dimensional set is generated. This software has a real-time viewer that displays the image reconstruction process as shown in Figure 7. The results of the image reconstruction are presented using an Octopus Visualization 8.9 software as shown in Figure 8. This software provides ease of use and the complete data set can be sliced open (cross-section) in all directions to expose internal details of the specimen object.

![Figure 7. Image reconstruction using Octopus Reconstruction 8.9 software](image3)

![Figure 8. Visualization of the results of image reconstruction using Octopus Visualization 8.9 software](image4)
Figure 9. Cross-section image or slice of aluminum step wedge cylinder.

Figure 9 shows the slice images of the reconstructed volume at four different thicknesses of the specimen object. Each cross-section slice image is clearly visible. Based on the sectional view of this sample, it is clearly indicating that no found defect or crack in the specimen. In future research, testing with samples that already have defects or cracks and different types of material will be conducted.

4. Conclusions
In this research, a low-cost X-ray CT system based on digital fluoroscopy for industrial applications was developed and tested. The CT equipment consists of four parts that are digital fluoroscopy detector, X-ray source, rotary table for sample manipulation system, and a computer to acquire and analyze the image data. The digital fluoroscopy detector used in this research is redesigned detector with increases in the dimensions of the fluorescence screen to 197 mm x 294 mm. For testing purposes, an aluminum step wedge cylinder specimen with a thickness difference of each step is 5 mm is used. Despite its low-cost compared to the other detector usually used in the industry, the resulting 2D radiographic image quality is quite good, so it is easily interpreted by the user's eyesight. The results of a cross-section slice image at four different thickness of the specimen object is visible and no found crack in the object. In addition to that, this CT equipment is suitable for industrial applications because of its fast scanning capability.

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