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# Research and manufacture of cone-beam computed tomography (CBCT) system for industrial use

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**Abstract** Computed tomography is a transmission tomography technique; this technique allows reconstructing the cross-section images or slices of the real object. The CT was developed in the 1970s for medical diagnostic purposes. Today, the CT technique has evolved to the 7th generation using cone-beam configuration (CBCT) and Flat Panel Detector (FPD) instead of fan-beam arrangement and one dimension detector array. CBCT has greater X-ray efficiency and higher spatial resolution than the previous generation; therefore, it can be used in industrial applications such as metrology of precision machined and None-Destructive Testing (NDT). In this research, the first CBCT system in Vietnam was manufactured; this system can acquire and reconstruct three dimensions of a real object with a maximum size of 200 × 300 mm within ten minutes. The resolution of the reconstructed image is around 49 µm.

**Keywords**: *CBCT, image reconstruction, radiography, metrology, inspection.*

## I. INTRODUCTION

The first Computed Tomography (CT) system was invented by British electrical engineer Godfrey Hounsfield. The first CT system produced tomographic images with size 80x80 pixels, the 3-bit value of pixel, scanning time for each slice is about 4.5 minutes. The CT system was first used to take a brain scan of a patient at Atkinson Morley Hospital, Wimbledon, England, in 1971. Since its invention, the CT tomography system has continuously been developed to shorten scanning time, improve spatial resolution, and increase the contrast of images. Today, the latest medical CT equipment system can produce more than 200 images per second, spatial resolution less than 1mm, 16-bit pixel value [1].

The development of science and technology has made the quality of the CT system significantly increase. Modern Cone-Beam CT (CBCT) systems use X-ray tubes with micro focal spot size and use Plat Panel Detector (FPD) as radiation detectors. CBCT can obtain high-resolution reconstructed images with resolutions of micrometers scale. Therefore, since 1980, CT became famous for industrial applications such as material analysis, non-destructive testing (NDT), and metrology. The advantage of CBCT is that it can measure the sample's external profile and show the sample's internal structure without needing to cut or destroy the object [2-5]. In addition, CT images describe the distribution of radiation attenuation coefficients in the sample. Therefore, CT images also provide helpful information about the distribution of density in the model, which supports inspecting and evaluating the quality of precision machined

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parts or casting objects. Due to the increasing quality of reconstructed images, CBCT is now widely used to inspect and detect defects of tiny sizes, such as internal pitting corrosion or cracks of the object [6].

Today, the number of applications of CBCT in the industry is extensive and rapidly growing. The market for industrial CBCT systems increased from 309.5 million USD in 2011 to 591.9 million USD in 2017. The demand for industrial CBCT systems grew up strongly in countries with a lot of manufacturing factories. [7]. Currently, Vietnam is becoming the home of many large corporations such as Samsung, Denso, LG, Mitsubishi, Seoul Semiconductor, etc. In addition, the casting industry is also developing strongly in Vietnam. The manufacturing and casting industry requires modern techniques to measure, inspect and evaluate product quality. Therefore, the demand for measuring and checking systems such as CBCT is increasing enormously. However, in Vietnam, there is currently no research on the CT system using cone beams. Most of the CBCT systems used in the country are imported from abroad with high costs; in addition, the maintenance and repair process will also be costly and complicated. This paper is the summary result from the National research project "Research, design and manufactures a CT system using Cone Beam X-Ray for industrial applications". Through this project, we have successfully manufactured the first CBCT system in Vietnam named BKCT-01. BKCT-01 system uses X-ray generator from Xray WorX, Germany, FPD from Rayence, Korea, mechanical part of the transmission, control software and signal processing are made and built entirely by ourself. This project is the first step leading to the embrace of CBCT technology in Vietnam.

## II. CONTENT

### A. Subject and methods

CBCT uses multiple detector arrays and cone-beam geometry, which is good for improving the utilization of the X-Ray beam but reduces the spatial resolution in the slice thickness dimension because by using multiple detector arrays, the slide thickness now is defined by the detector size and not by the collimator. Industrial CBCT systems often use a scanning configuration called the stationary gantry. The X-Ray source and the matrix detector are fixed, and the scanning object rotates around the axis of rotation to obtain projections at different capturing angles. Figure 1 shows the general configuration of the industrial CBCT system.

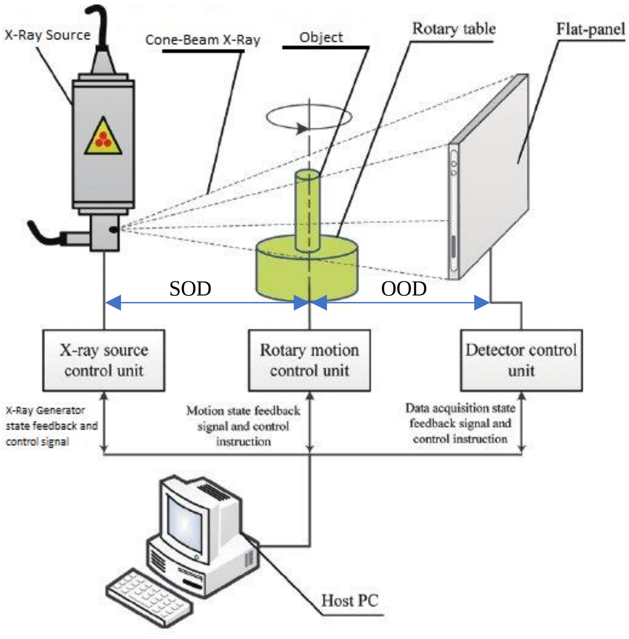


**Fig. 1.** CBCT's configuration

The reconstructed image quality depends on the focal spot size of the X-ray tube, the resolution of FPD, the precise motion of the mechanical system, and the reconstruction algorithm. This study uses a microfocus XWT-240-CT X-Ray tube from X-Ray WorX and

1215A FPD from Rayence, Korea to manufacture a CBCT system. Table 1 describes the typical specifications of the X-ray generator and the FPD plate.

**Table I.** Specification of BKCT-01 system

| | | | |
|---|---|---|---|
| **X-ray Source** | X-ray tube voltage range: 0 – 240kV | | |
| | X-ray tube current range: 0 – 3 mA | | |
| | Spot size: 4µm | | |
| **Matrix detector FPD** | | ***Normal mode*** | ***Binning mode*** |
| | Imaging size (pixel) | 2944x2352 | 1472x1176 |
| | Pixel pitch | 49 µm | 99 µm |
| | Resolution | 10.1 LP/mm | 5.0 LP/mm |
| | Framerate | 8 fps | 32 fps |
| | Digital converter | 14 bits | 14 bits |

The BKCT-01 system uses the filter back-projected reconstruction (FBP) algorithm to obtain the reconstructed image from projections. The reconstruction formula of the FBP algorithm is described below [8].

$$g(t,s,z)=\int_{0}^{2\pi}\frac{SOD^2}{\left(SOD^2-s\right)^2}Q_\beta\left(\frac{SOD\times t}{SOD-s},\frac{SOD\times z}{SOD-s}\right)d\beta \qquad (1)$$

Where: $g(t,s,z)$ is a 3D reconstructed object of the sample, SOD is the Source to Object Distance, $Q_\beta\left(\frac{SOD\times t}{SOD-s},\frac{SOD\times z}{SOD-s}\right)$ is weighted projection of sample at rotated angle β, $Q_\beta(p,\zeta)=R'_\beta(p,\zeta)*\frac{1}{2}h(p)$ is a filtered projection of sample, and β is scanning angle.

In this paper, we will focus on presenting the process of building mechanical drive, controller method of the system. In this study, we have manufactured a CBCT system capable of capturing objects with a larger size than the size of the PFD. Typically, the stationary gantry can only scan samples with a smaller size than that of the detector. The configuration of the CBCT system on the BKCT-01 system has been improved in which the FPD can make a translational motion in the image acquisition plane to expand the projection field, as shown in Figure 2.

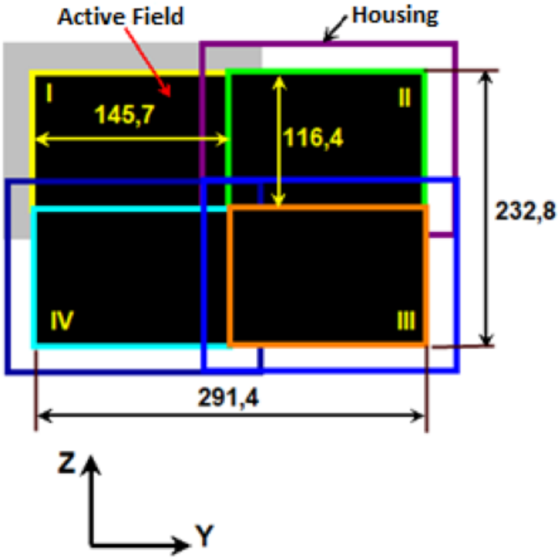


**Fig. 2.** Movement method of FPD in BKCT-01

The BKCT-01 system has two operating modes: minor sample scanning mode (samples are smaller than the size of a film plate) and large sample scanning mode. After pressing the start button in minor sample scanning mode, the X-Ray source will emit a beam; then, the controller will control the FPD to acquire the first projection. After that, the FPD will transmit that projection to the PC; then, the central controller sent a command to rotate the sample with a step of 0.5 or 1 degree. At the end of that rotation, the controller will control the film to record the second projection. The above process will be repeated until enough projection is obtained over the 360-degree rotation of the sample. The control mechanism is quite different in the large sample scanning mode. Firstly, the FPD stays in the I position of the large projection field and proceeds the data acquisition cycle similar to in a smaller sample mode. After 360 degrees of rotation, the FPD moves to the II, III, IV position and repeats the scanning process. As a result, the computer gets four small projection fields at each projection angle. By synchronizing four small projection fields, we will obtain the total projection of the sample.

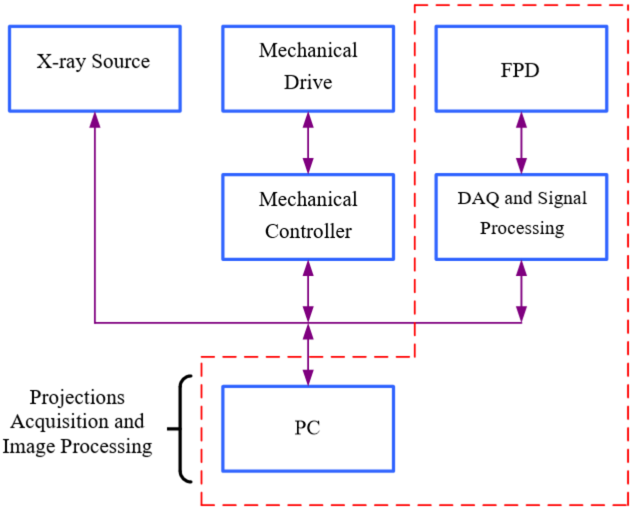


**Fig. 3.** Block diagram of central control software

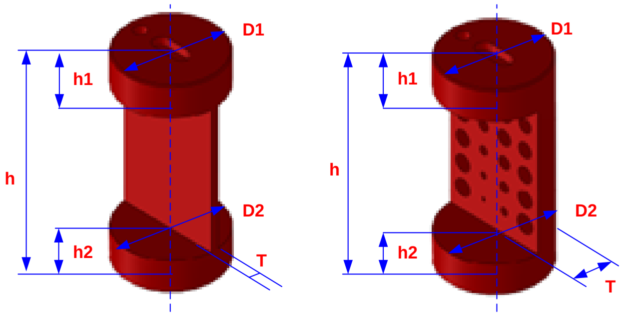


**Fig. 4.** Standard sample for evaluation of system

The central control software has the role of synchronously controlling the operation of the X-Ray source, the data acquisition process, and the mechanical controller. The block diagram of the central control software is shown in Figure 3.

In this report, the standard samples are used to evaluate the quality of the reconstructed images from the BKCT-01 system. The size of the standard samples measured by the BKCT-01 system will be compared with other methods such as caliper, optical measurement, and coordinates measuring machine (CMM) to evaluate the resolution of the reconstructed image. Figure 4 describes the drawing of one standard sample.

### B. Result

Figure 5 shows the actual picture of the BKCT-01 system. The dimension of the BKCT-01 system is 1.2x1.8x2.0 m3; the primary radiation shielding material is a sheet of lead with a thickness of 12mm in the primary beam direction, 6mm on the other sides, the mass of the whole system up to 3 tons.

**Fig. 5.** The picture of BKCT-01 system

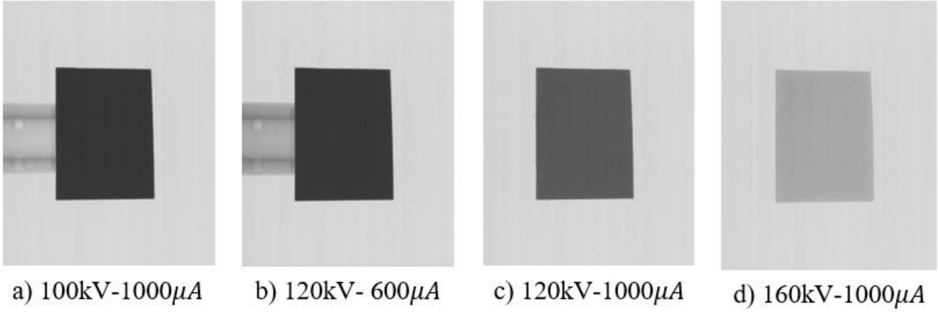
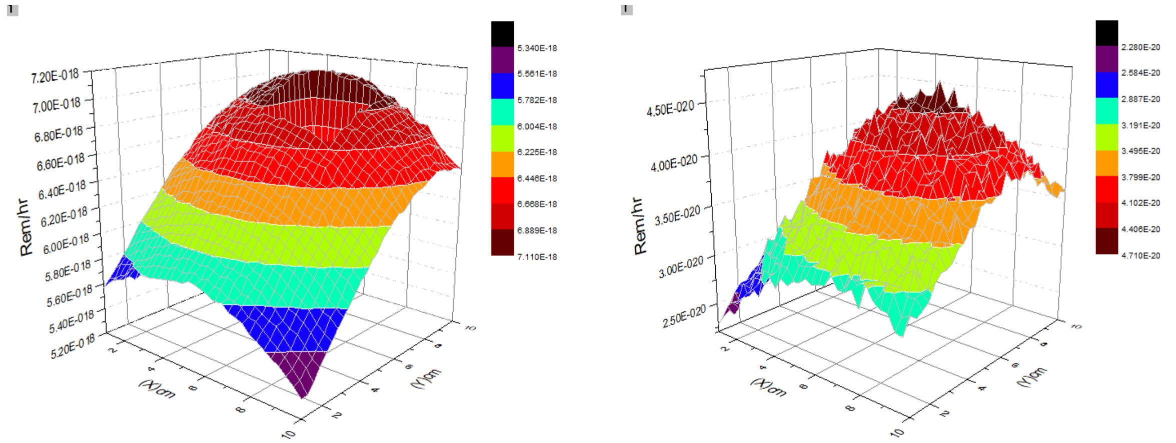

a) 100kV-1000$\mu A$ b) 120kV- 600$\mu A$ c) 120kV-1000$\mu A$ d) 160kV-1000$\mu A$

**Fig. 6.** Projection of sample with difference X-Ray intensity

Figure 6 displays the projection of the object when changing exposure conditions. Figure 7 describes the radiation test results of the equipment system; the exposure dose rate is measured at the sides of the BKCT-01 when the X-ray generator operates at maximum power (240kV high voltage, 1.3mA beam current). The emission time of each test was 10 minutes. The dimensions of the sample in Figure 4 measured from the reconstructed image of BKCT-01 and other methods are listed in Table II.

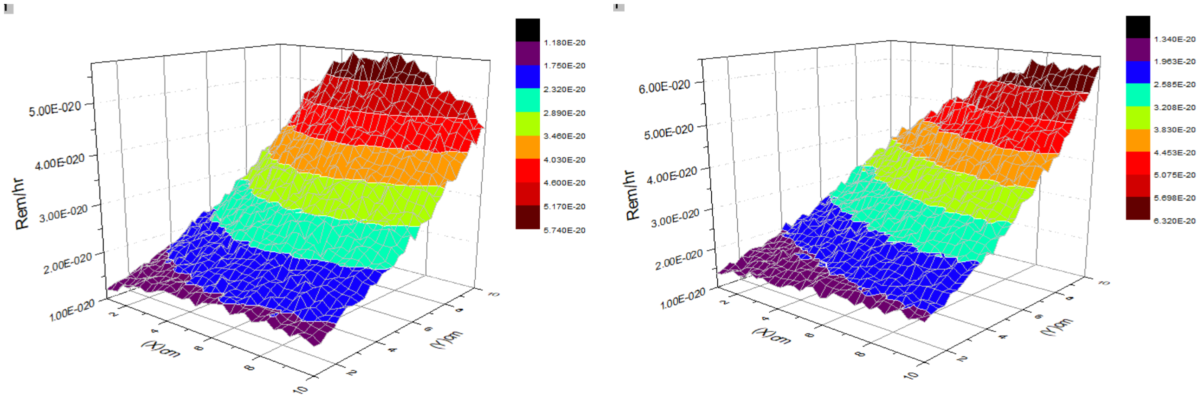
**Table II.** Dimension of standard sample in Figure 4 measured by different methods

| **Methods** | **h (mm)** | **D1 (mm)** | **D2 (mm)** | **h1 (mm)** | **h2 (mm)** | **T (mm)** |
|---|---|---|---|---|---|---|
| ***CBCT*** | 25.40 | 12.70 | 12.70 | 4.00 | 4.00 | 6.35 |
| ***Caliper*** | 25.382 ±0.024 | 12.673 ±0.023 | 12.655 ±0.027 | 3.971 ±0.024 | 3.971 ±0.024 | 6.344 ±0.022 |
| ***Optical measurement*** | 25.3863 ±0.0013 | 12.6637 ±0.0012 | 12.6383 ±0.0013 | 3.9574 ±0.0013 | 3.9845 ±0.0012 | 6.3456 ±0.0011 |
| ***CMM*** | 25.392 ±0.023 | 12.673 ±0.023 | 12.643 ±0.025 | 3.962 ±0.024 | 3.991 ±0.021 | 6.35 ±0.022 |



*a) Left side (primary beam)*

*b) Right side (leakage beam)*



*c) Front side (right side of source)*

*d) Ceiling side*

**Fig. 7.** The distribution of exposure dose of BKCT-01

Figure 9 shows a 2D tomographic image and a 3D reconstructed object of a cylindrical sample made by PVC with dimensions of 200 mm × 300 mm (diameter × height).

Figure 10 shows a tomographic image of a 32700 Lithium battery. The 3D reconstructed object is cut in half, presented as a color image for easy viewing.

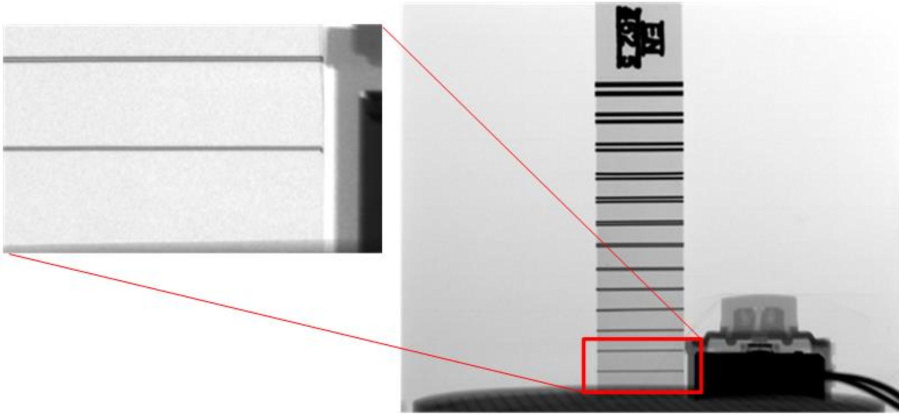
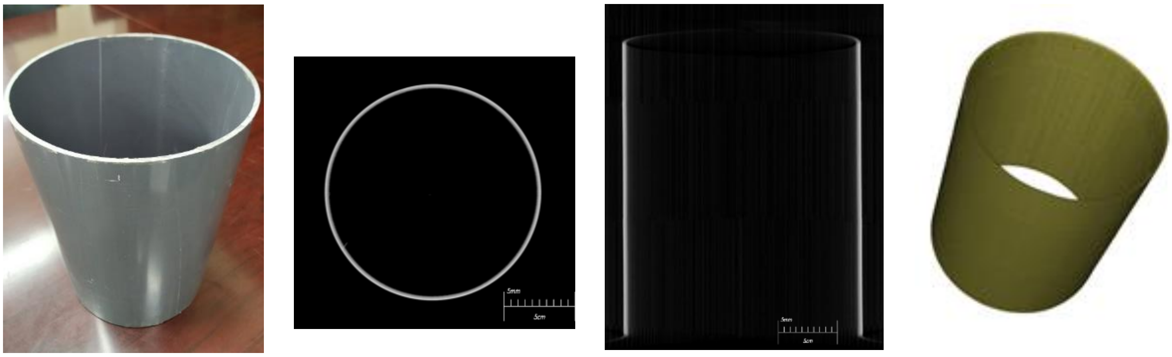


**Fig. 8.** Reconstructed image of the sample with duplex IQI



*a) Sample* *b) Horizontal Slide* *c) Vertical Slide* *d) 3D reconstructed object*

**Fig. 9.** PVC sample (a) and 2D (b and c), 3D reconstructed data(d)

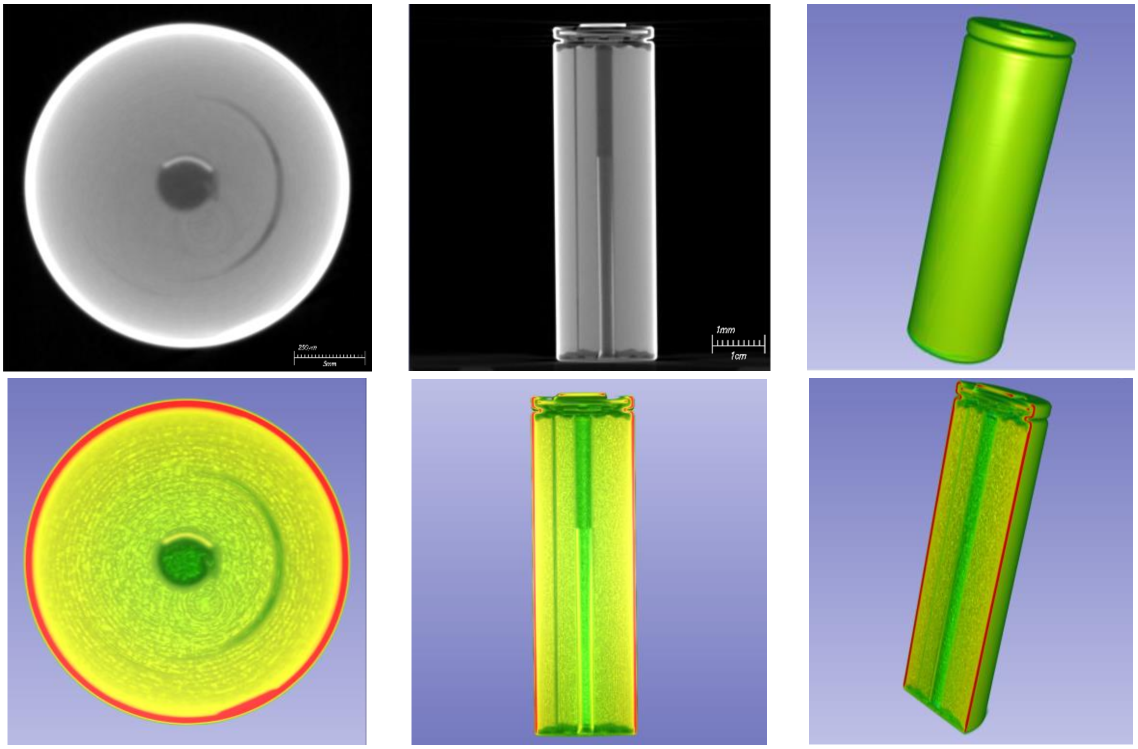


**Fig. 10.** 2D and 3D Reconstructed image of 32700 Lithium Battery

### C. Discussion

The results shown in Figure 6 show that the control software has adequately worked with the designed function. The software can turn on and off the X-Ray generator, adjust the exposure dose, and control the FPD to capture and receive an image with the correction of integration time and capturing frame rate. When designing and manufacturing radioactive equipment, the most important thing is considering radiation safety and protection; the exposure dose to the operator must be kept as low as possible. Figure 7 shows the values of exposure dose rate are measured at four sides of the system. The results show that the dose-equivalent values at locations 2m away from the machine surface is less than 0.12 mSv/week (design limit for radiation workers). Thus, the controlled radiation area for the

BKVT-01 system is an area with a distance of 2m from the sides of the system.

A standard sample can be used to evaluate the resolution of the reconstructed image by measuring the size of the standard sample using CBCT and comparing it with other measurement methods. The results from Table 2 show that the deviation between the measured dimensions by CBCT and of optical measurement does not exceed 62 µm. EN 462-5 Duplex IQI was used to evaluate the spatial resolution of the system further. The results from Figure 8 show that one can clearly distinguish the two pairs of wire 13 of Duplex IQI, which means that the spatial resolution of the reconstructed image is 50 µm. In order to increase the spatial resolution, one can increase the image magnification factor. BKCT-01 system can magnify the image of the sample by five times. Therefore, the spatial resolution of the slide can be increased by five times but, the scannable sample size will be five times smaller than in normal mode. The resolution of 10µm of the reconstructed image is equivalent to other measuring systems available on the market.

Figure 9 shows the results of the scanning and reconstruction process for a large-sized sample. The sample has a hollow cylinder shape with 200mm × 300mm (diameter × height). The size of the sample is much larger than the size of the FPD shown in Table I. By scanning each part of the object, then combining the sub-projections to form a complete projection, the BKCT-01 can produce a reconstructed object of a large sample. However, the scanning time for these samples can be up to 10 minutes per each.

Because of the ability to investigate the sample's internal structure, BKCT-01 helps inspect closed structures such as batteries or casting parts. Figure 10 shows 2D and 3D reconstructions of the 32700-lithium battery. The cross-section of the reconstructed image shows that the battery has blistering, unevenly arranged electrode layers, and gaps between the batteries (it may explode when used). The electrode layer is present at one location and runs along the battery body, as shown in the vertical slice image. The image reconstruction software of the BKCT-01 can also display reconstructed images in color images, so it helps users easily observe abnormalities appearing in the sample.

Several metrology methods are currently used in industry, such as CBCT, CMM, optical metrology, caliper, or micrometer. Using X-Ray, CBCT is the only method allowing measurement of internal dimensions without destroying or cutting the component. This is particularly important for complex cast objects or additively manufactured parts that often involve non-reachable inner geometries. CBCT also allows measuring components in the assembled state. This also is an important thing when the size difference between components may ruin the whole assembly process. The reconstructed image reveals information about the density distribution of the sample. Therefore, CBCT can also measure and analyze the composition, density of materials that other metrology methods cannot perform. The successful manufacture of the first CBCT system in industry opens a new era in precision metrology in Vietnam. Nowadays, the demand for accurate measurement methods is growing strongly; commercial CBCT systems are available in the domestic market used by several factories. However, there are only few facilities can calibrate and verify the CBCT systems. These services are still dependent on foreign manufacturers, which causes high costs and limits the system's applicability. Mastering CBCT technology enables us to localize the equipment system and helps us build national calibration and verification laboratories that can be qualified and certified by international standardization organizations. It can help the modern CBCT system be used more and more widely, contributing to promoting the domestic processing and manufacturing industry.

## III. CONCLUSION

In this research, a CBCT named BKCT-01 was successfully built. The system can achieve 3D reconstructed object of samples made of light materials (low atomic number) such as aluminum, plastic, and semiconductor materials. The BKCT-01 system can inspect precision machined parts, electronic components, electronic circuits, or casting products from aluminum or plastic.

BKCT-01 is a very complex system; the process of designing and manufacturing the system requires close coordination between fields such as nuclear engineering, mechanics, control, and programming. In order to obtain a reconstructed image of an object with good quality, the mechanical system must be designed very accurately; the control mechanism of the device system is capable of synchronizing movements, compensating for machining errors. Especially for the case of large-sized objects, the FPD will move to expand the field of view. The controller is built to synchronize these movements so that partial projections of the object can be acquired and then stitched together precisely to obtain the full projections of the sample. The scanning time for a large sample is much longer than that for a small sample. The scanning time of the sample with a size of 200mm×300mm (diameter×height) is about 10 minutes; this is an acceptable number compared to other measuring methods.

The BKCT-01 has a spatial resolution of about 50 µm in non-magnified imaging mode. The spatial resolution of the reconstructed image can reach 10µm when scanning the object in magnification mode. However, with the highest magnification factor, the scannable sample size reduces five times compared to that in normal mode. The BKCT-01 system can be used for non-destructive testing purposes to investigate the quality of electronic components, electronic circuits, and quality of batteries, or can also be used to measure precision mechanical components.

Based on the initial successes, the BKCT-01 can continue to be researched to improve its technical features further to better meet the diverse requirements of the industry better. The next development direction maybe uses of the FPD with more incredible speed and efficiency to investigate more closely the physical effects affecting the quality of the reconstructed image or study the application of artificial intelligence in signal acquisition and processing to improve the quality of the image, shorten the scanning time, and make it possible to scan sample made from heavy materials, larger in size.

## ACKNOWLEDGMENTS

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