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DEVELOPMENT AND IMPLEMENTATION OF A PORTABLE NUCLEONIC COMPUTED TOMOGRAPHY SYSTEM WITH CLAMP-ON-FEATURES FOR ENGINEERING INSPECTION

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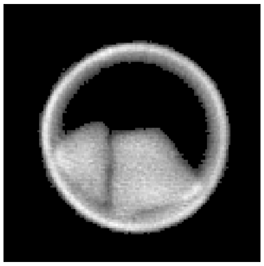
Graphical abstract



Abstract

The development and implementation of a portable nucleonic computed tomography system with clamp-on-features, called "GammaSpider", employing gamma-ray for engineering inspection is briefly discussed. Depending on the object to be inspected, a small isotopic gamma-ray source, in combination of a NaI(Tl) scintillation detector and an autonomous mechanical gantry set-up are used. The basic theoretical aspects, the system configurations and the other features are presented. This system is capable of generating high quality tomographic images and thus, offers great promise for in-situ engineering inspection. It is successfully used to inspect blockages in pipelines, to examine wooden electric poles and to study hydrodynamic behavior of multiphase flow in a bubble column. Some of the preliminary results are presented in this paper.

Keywords: Gamma-ray tomography, nucleonic system, pipe blockage, internal decay of tree, bubble column, non-destructive evaluation, image reconstruction

1.0 INTRODUCTION

Computed tomography (CT) using ionizing radiation such as gamma-ray or X-ray, is a powerful imaging technique that can provide a cross-sectional view or a volumetric view of the interior of an object as if it had been cut open for viewing. Data are collected by radiation detectors at many different angles and are then transformed into meaningful 2D or 3D image, a reconstruction of the object's interior using mathematical algorithms and computed codes. The reconstructed images of the object can be further "sliced" using image analysis software packages to provide visual information of the inner details that are hidden from our sight. The invention of the CT scanner revolutionised the field of medical diagnostic imaging because it provided more detailed and useful information than any previous non-invasive imaging techniques. For the same reason, the method is being used increasingly in industry and engineering because the attenuation of gamma-ray or X-ray is highly correlated to the atomic number and density of materials. A wide variety of applications have arisen over recent years for non-destructive evaluation (NDE) and testing tools for internal inspection of industrial components, geological objects, bioscience samples, automotive parts and archaeological artifacts [1-5]. Some of the key uses for CT scanning have been flaw detection, failure analysis, materials characterization, microscopic structures, metrology, assembly analysis and reverse engineering applications.

Among advantages of using CT techniques in engineering inspection are that they are rapid, reliable, and, for most applications, can be used in situations where no other techniques are applicable. More importantly, these techniques allow the results to be obtained in real time, thus enabling the measurements to be used for on-line process investigations and in-situ applications. Measurements are accomplished non-destructively and without changing any properties of the examined material.

Since the inception of Regional Cooperative Agreement (RCA) projects on industrial application of radioisotopes or nucleonic techniques in early 80's under the auspices of United Nations Development Programme (UNDP) and International Atomic Energy Agency (IAEA), consistent efforts have been undertaken by the Malaysian Nuclear Agency to develop nucleonic-based equipment for industrial and engineering uses. Significant progress has been made, enabling it to introduce peaceful uses of nuclear technology into well-defined industrial and engineering fields, one of which is described in the present work. This paper provides brief information on the development of a portable clamp-on nucleonic computed tomographic scanner, called "GammaSpider", specifically for in-situ NDE applications. It was designed and fabricated following the successful launched of a transportable gamma-ray tomography system for basal stem rot (BSR) detection in oil palms plantations [6]. One particular application of this newly developed nucleonic CT system in oil, gas and chemical industries, is to inspect blockages or the deposition of materials onto the inner walls of pipelines carrying raw or process materials. Other applications are to detect the formation of oleoresin in standing agarwood trees, to inspect the extent of termite damage or internal decay of electrical wooden poles and ornamental trees in municipal areas, to examine the integrity of concrete pillars in building and bridges, and to improve understanding the dynamic behaviour of multi-phase fluid flow in chemical reactors. This paper presents some preliminary results of industrial pipes, wooden poles and a chemical engineering bubble column obtained from laboratory studies and field tests.

2.0 METHODS AND SYSTEM DEVELOPMENT

2.1 Principle of Computed Tomography

Gamma-ray tomography is based on the principle of measuring the attenuation of a beam of radiation transmitted through an object. Based on large number of such attenuation measurements along several paths through the object, an image of the absorption coefficients within the scanned section is reconstructed [7].

The CT image is a map of the distribution of the linear attenuation coefficient, μ. This is the probability of the attenuation of gamma-rays per unit length within the object, and is a function of material density, atomic number and the energy of the incident photons. The linear attenuation coefficient is given by the product of the mass attenuation coefficient, μm, and the density, ρ

$$\mu = \mu_m . \rho \tag{1}$$

GammaSpider uses highly collimated incident beams of gamma-rays from a radioisotope source, depending on the object to be inspected, either Am-241, Ba-133, Cs-137 or Co-60 with small activity levels. The transmitted intensity data recoded by a radiation detector is be converted to an image representing differences in attenuation in the specimen using the Beer-Lambert's law to relate the incident intensity (Io) and the transmitted intensity (I) to the linear attenuation coefficient as a function of position, μ(x),within the object [7].

$$I = I_0 \exp \int_0^d \left[-\mu(x)\right] dx \tag{2}$$

in which d is a distance along a gamma-ray path from source to detector and x is a dummy variable of integration over distance.

By taking gamma-ray projections of an object from many different angles, a 2D or 3D reconstruction of the object can be achieved. Several mathematical algorithms can be used to reconstruct virtual slices through the object, which enabled a visualisation of the distribution of several features of different linear attenuation coefficient.

2.2 Design Consideration

As a tool for engineering inspection, design criteria of the portable scanner were established. Among many important factors, the scanner should be:

- Small, portable, lightweight, and generator or battery-powered for use in remote locations.
- Easily installed and removed.
- Operated by one or two operators.
- Fast enough in scan and image reconstruction time to provide immediate results.
- Sufficiently accurate, repeatable & quick to analyse and then provide meaningful data concerning the size and extent of abnormalities in the inspected objects.
- Non-intrusive and non-destructive method.
- Low cost.

Based on the above criteria, a portable and clamp-on type of nucleonic computed tomography system employing gamma-ray has been designed and developed. The following sections describe its development and practical use in the laboratory and the fields, detailing its working envelope and applications.

2.3 System Development and Configuration

The portable CT system weight about 30kg and consists of two major parts, the mechanical hardware and the system software. The hardware section comprises five main components: a radioactive source with holder and collimator, a radiation detector with holder and collimator, a pair of linear translation arms each 80cm in length, a circular motion frame (C-frame) 80cm in inner diameter, and an electronic and power supply box. All these are mounted on a hexagonal shape of clamp-on jig. The system software consists of three main programmes: system control & data acquisition, pre-processing & analysis, and image reconstruction. The schematic diagram of system layout is given in Figure 1. The complete system is totally autonomous and is transported by two technicians. The system is powered by a portable electric generator with full capacity of 16 hours non-stop operation petrol tank.

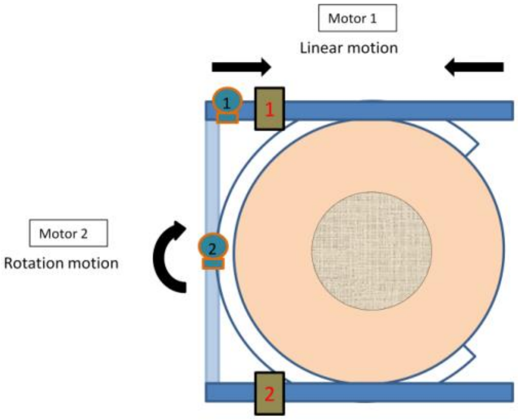


Figure 1 Schematic diagram of the mechanical system for GammaSpider, showing (1) radioactive source holder and (2) radiation detector

2.4 Radiation Source and Detector

Depending on its intended use and the object to be tested, radioisotope source chosen are 3.7GBq of Am-241, 0.555GBq of Ba-133, 0.37GBq of Cs-137 or 0.185GBq of Co-60. The Cs-137 source has half-life of 30.1 years and emits gamma-rays with photon energy of 662keV, which is suitable for a typical industrial pipe of average diameter about 10 to 40cm. Am-241 (half-life 432.2 years and photon energy 59.9keV) is normally used for testing of wooden poles and trees, Ba-133 (half-life 10.51 years with a spectrum of photon energy range and the average 517keV) for imaging 20cm diameter laboratory scale bubble columns whereas Co-60 (half-life 5.27 years and photon energies 1.1732MeV and 1.3325MeV), is suitable for concrete pillar inspection. The source holder is made of tungsten and is designed with in-built radiological safety features to ensure that exposure will not exceed 2.5 µSv/h at 1m distance.

A NaI(Tl) scintillation detector of 2.5cm x 2.5cm is used to detect the transmitted gamma-ray after traversing through the test object. The detector is placed in a lead-stainless steel clad holder, and is connected to a Ludlum model 2200 portable scaler/ratemeter for data recording, and then to a laptop computer using an RS-232 interface for mechanical control and data acquisition.

The radioactive source and radiation detector holders are mounted on two separate, but linked, aluminium sliders placed in the linear translation C-frame spaced 80cm apart.

2.5 Motion Control and Data Acquisition System

The motion control of the nucleonic imaging system consists of two stepper motors complete with associated electrical and electronic components. One motor is used to synchronously move the source and the detector holders mounted on the linear translation arms to simulate a parallel beam scanning, while the other motor is used to rotate both translation arms on the C-frame gantry at a preset projection angle from 0□ to 180□. The motors use on the shelf motor driver called Dual Axis EMP400 series. The driver allows data input of 32 sequence program to control the motor. Each sequence can be programmed to control the step, velocity and direction accordingly. There are two ways to execute these sequences, either by using in-built software or by using home-made command. A communication protocol between computer and EMP400 is established by using ADAM4050 and ADAM4561 modules. The ADAM4050 is a 7 channels digital input and output module while ADAM4561 is a USB type-A connector to communicate between ADAM4050 and laptop computer [8].

A software package for data acquisition has also been developed. The data acquisition involves the collection of data from a Ludlum model 2200 scaler/ratemeter. This is a single channel scaler/ratemeter which uses a baud rate of 2400bps and needs special command to acquire the data. The scaler/ratemeter is used to record the transmitted gamma-rays after traversing through a test object, and then send the raw data to a laptop computer for storage and further processing. This recorded data is displayed on the computer screen during a scanning process.

2.6 Scanning Process

Before commencing a scan the system is placed so that the test object is at the centre of the C-frame. Then, the operator will select the scanning parameters; linear step, rotary step angle and time of counting interval. After completing the scan, the data is checked and corrected before the final CT image reconstruction stage. The reconstructed image is displayed on the screen for immediate check.

Figure 2 shows the flow chart on how parameters can be set before a scan may take place. The offset parameter is used to determine the scanning length. It is guided the operator to choose the starting point. At present, four start points can be chosen, namely 0, 5, 10 or 15cm whereas for the rotary motion, the movement is set to 1, 5, 10, 20 or 60 degree angular increments. For example; if a user chooses the offset of 5cm, both source and detector holders will move 5cm forward from their home and they will stop 5cm before the maximum translation length. This will end up a total of 10cm less than the maximum length resulting in a total scanning length of 40cm. This is important to make sure the centre of rotation remains the same for all sizes of the test object. There are four linear distant available that correlated to their offset which are 50, 40, 30 and 10cm. Since the input parameters are important for a proper and efficient scanning, if user failed to set these parameters, then the system will automatically use the default values [8].

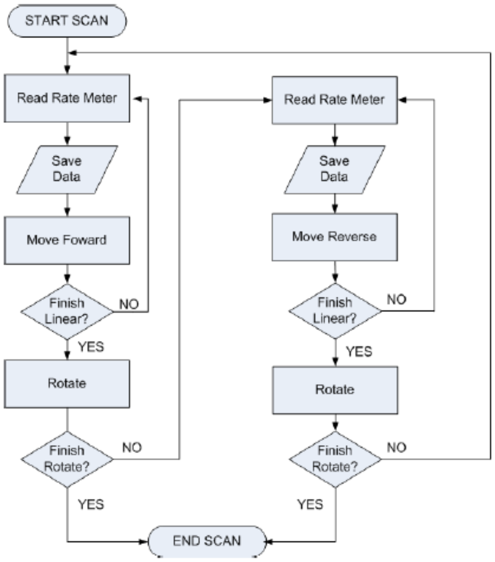


Figure 2 Flow chat for scanning protocols of the GammaSpider

After completing the scan, the data is checked and corrected as noted previously before the final CT image reconstruction stage. The reconstructed image is displayed on the screen for immediate diagnosis.

3.0 RESULTS AND DISCUSSION OF CASE STUDIES

3.1 Imaging Blockages in Pipelines

In process industries, in particular oil, gas and chemical industry, the precipitation of scale onto the inner walls of pipelines carrying raw or process materials poses a significant challenge as scale deposits such as sulfates, hydrates and carbonates may reduce the cross-section flow area and even lead to blockage of entire sections of the pipework. Therefore, undetected and untreated scale deposits in the pipework will eventually lead to costly production down-time and maintenance work.

GammaSpider can be used to inspect this problem without the need to stop the plant operation. It can be clamped to any pipes of size ranging from 10 to 40cm in diameter, with or without insulation materials as given in Figure 3. A few tests were conducted on pipes carrying slurry materials at a pulp and paper factory in Kajang, Malaysia. Some of the results which were conducted on 30cm diameter pipe during plant shut down are given in Figure 4(a) and Figure 4(b).

Figure 3 GammaSpider, a portable-clamp-on gamma-ray tomography system installed on a pipework

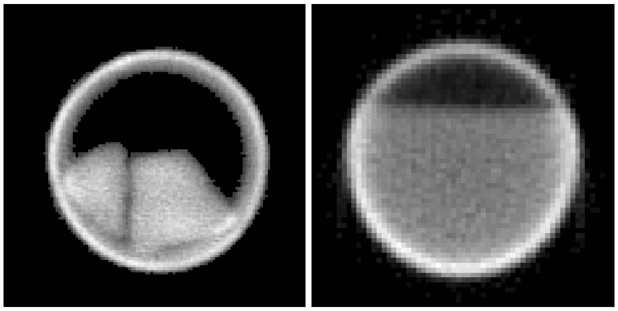

(a) (b)

Figure 4 Image reconstruction of pipe with different thickness of (a) hard coherent deposit and (b) loose slurry deposit at the bottom section

3.2 Detection of Internal Decay in Electrical Wooden Pole and Ornamental Tree

GammaSpider was used to determine the size and location of the internal deficiency of electrical wooden poles (58cm in perimeter) and an ornamental tree (53cm in perimeter) in Hulu Langat, Selangor, Malaysia. The system employed a low-energy gamma-ray source of Am-241. The strength of the source was about 3.7GBq where the active geometry was 3mm in diameter with 10mm in length and double encapsulated in a very thin stainless steel capsule.

In-situ experimental results as shown in Figure 5(a) and (b) reveal that differences in the mapped grey levels indicating different attenuation values between the holes area and its surrounding area were obvious. The ratio of the holes area to the total cross-sectional area exceeded 9.8% and 4.5% for the wooden pole and ornamental tree, respectively. Therefore, the location and size of the hole in the tree trunk cross-section could be easily detected by this technique.

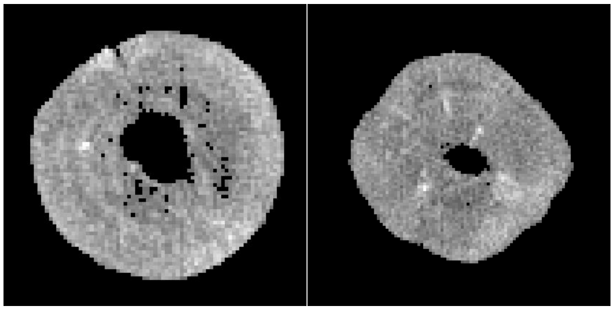

(a) (b)

Figure 5 Tomographic images of (a) a wooden pole and (b) an ornamental tree obtained by the GammaSpider

3.3 Study of Gas Hold-Up in Bubble Column

Design and scale-up of multiphase reactors for chemical process industry require proper understanding of fluid dynamic which in turn often relies on experimental investigation of the 2D or 3D and frequently multiphase flow fields. Thus, non-invasive methods that have the ability to provide the relevant measurements throughout the flow fields without disturbing the flow are clearly advantageous.

To study gas-liquid phase behaviour in a bubble column, the nucleonic tomography system employing 0.555GBq of Ba-133 was used. A column, made up of 3mm thick plexi-glass, was 2.5m high and 20cm in diameter. At the bottom of the experimental column, it is designed complete with a special holder to fix a sparger plate for dispersing air (to represents the gas phase) to the column. The gas is feed via a flexible hose which can withstand high pressure of 6 bar. Five different designs of the sparger plate can used and are given in Figure 6. In this study, a sparger plate with 1mm diameter holes arranged in triangular grid 16mm was used (bottom right in Figure 6).

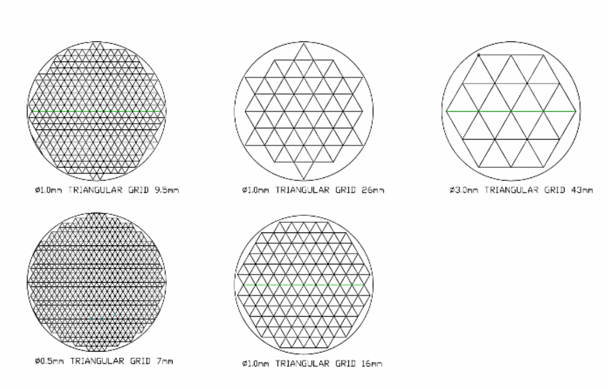


Figure 6 Sparger plates made of stainless steel of 1mm thickness

Three different gas flow rates were applied to the column, to represent superficial gas velocities of 2.09, 4.72 and 9.44cm/s. The flow rate is measured by a rotameter and manually controlled by a valve. The experimental set-up and the tomography scanner are given in Figure 7 and during this study, the column was half-filled with water to represent the liquid phase. During scanning, 5sec counting time was used for each scanning position and time averaged (5 hours) tomographic images for each gas superficial velocity were reconstructed and compared with image obtained from still water.

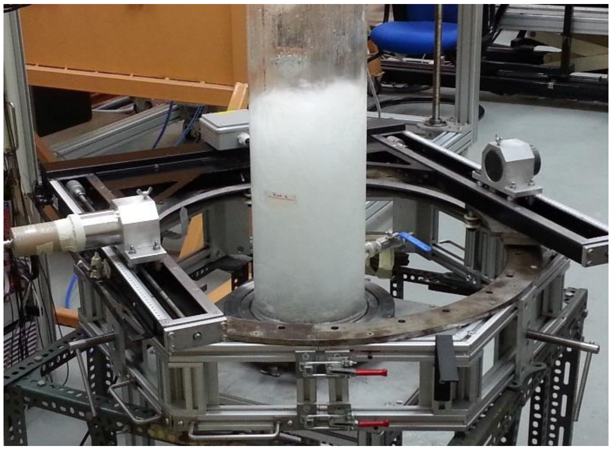
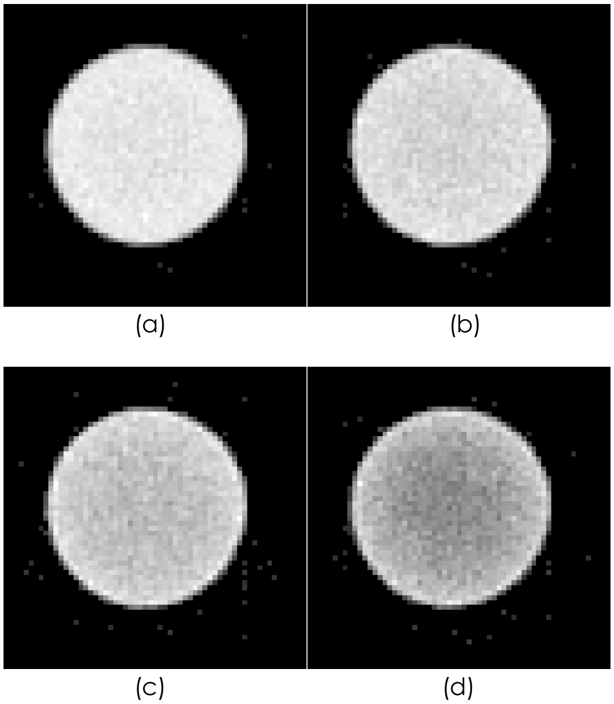


Figure 7 GammaSpider uses to study hydrodynamic behaviour of gas-water in a bubble column

Figure 8(a) to 8(d) shows CT images obtained from the laboratory experiment. The black features in each image represent air, whereas the bright is the water. In these images, it is noted that pure white and pure black areas are represented by 255 and 0, respectively. The images indicate correct representation and good contrast between the air and the water.



(a) (b)

(c) (d)

Figure 8 Time-averaged tomographic images of bubble column (a) still water, and with superficial gas velocity of (b) 2.09cm/s (c) 4.72cm/s, and (d) 9.44cm/s.

Experimental results reveal that the gas hold-up in the bubble column is proportional with the superficial gas velocity. At 80m^3/s, bubby flow can be observed and with higher gas flow rate of 180m^3/s and 360m^3/s, the flow regime of bubby turbulent and chunk turbulent were observed, respectively. Tomographic images obtained from this study are quite consistent with the visual observation, and these clearly be noted from images in Figure 8. Statistical analysis of the grey values shows that the mean value of 228.14, 217.67, 201.01 and 166.57 for still water, superficial gas velocity 2.09, 4.72 and 9.44cm/s, respectively. Based on this preliminary study, it is concluded that tomographic images obtained are quite reliable, and thus GammaSpider can be used with great confident to study multiphase flow in opaque systems.

4.0 CONCLUSION

Although computed tomography has found extensive application in the medical field, its usage in industrial and engineering applications has been relatively recent and is now increasingly popular. However, to the best of our knowledge, the development and use of a portable clamp-on type of nucleonic computed tomography for engineering inspection as given in this paper has not been reported elsewhere.

Preliminary results obtained from case studies as described above have demonstrated the system capability and are extremely encouraging. The scanner has large potential to be applied on pipelines to determine the extent of corrosion under insulation (CUI), to detect blockages, to measure the thickness of deposit/materials built-up on the walls. It may also be used to examine termite damage in wooden electric poles and ornamental trees in municipal areas, to detect the formation of oleoresin in standing agarwood trees at a preset time after chemical inoculation, to assess the integrity of concrete pillars in building and bridges and to study multi-phase flow behavior in laboratory scale chemical reactors which in turn improve understanding in chemical reaction engineering. The scanner is low-cost, rugged, simple first generation configuration, small and lightweight, and may be used in laboratory and in remote locations.

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References

[1] J. Abdullah, G. H. P. Mohamad, M. A. Hamzah, M. S. M. Yusof, M. F. A. Rahman, F. Ismail and R. M. Zain. 2003. Development of a Portable Computed Tomographic Scanner for On-line Imaging of Industrial Piping System. *Proceedings of the 5th National Seminar on Non-Destructive Testing, Shah Alam, Malaysia, 1-3 October.*

[2] C. Denison, W. D. Carlson, and R.A. Ketcham. 1997. Three-Dimensional Quantitative Textural Analysis of Metamorphic Rocks Using High-Resolution Computed X-ray Tomography: Part I. Methods and techniques. *Journal of Metamorphic Geology*. 15: 29-44.

[3] R. J. Jansen, H. F. W. Koens, C. W. Neeft and J. Stoker. 2001. CT in the Archaeologic Study of Ancient Greek Ceramics. *Radiographics.* 21: 315-321.

[4] M. Rossi, F. Casali and D. Romani. 2000. Investigation of Small Egyptian Mummies by 3D Computed Tomography. *Proceedings of the 15th World Conference on Non-Destructive Testing, Rome, Italy.*

[5] S. Bonadies and A. B. Avril. 1993. Technical Examination of Chinese Bronzes. *Arts of Asia, March-April.*103-107.

[6] Jaafar Abdullah, Hearie Hassan, Mohamad Rabaie Shari, Salzali Mohd, Mahadi Mustapha, Airwan Affendi Mahmood, Shahrizan Jamaludin, Mohd Rosdi Ngah, Noor Hisham Hamid. 2013. GammaScorpion: Mobile Gamma-Ray Tomography System for Early Detection of Basal Stem Rot in Oil Palm Plantations. *Opt. Eng*. 52(3): 036502 (March 08, 2013); doi: 10.1117/1.OE.52.3.036502.

[7] A. C. Kak and M. Slaney. 1988. *Principles of Computerized Tomographic Imaging*. IEEE Press, New York.

[8] Maslina Mohd Ibrahim, Jaafar Abdullah, Norlida Yusoop, Nur Aira Abd Rahman, Mukhlis Mokhtar, Hanafi Ithnin, Hearie Hassan. 2014. Development of Software for Automation and Data Acquisition System for GammaSpider and SPECT. *Seminar R&D 2014 Nuklear Malaysia, 14th to 16th October 2014, Agensi Nuklear Malaysia, Bangi, Malaysia.*