DEVELOPMENT OF CMOS-BASED OPTICAL COMPUTED TOMOGRAPHY IMAGING SYSTEM

by

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LIST OF ABBREVIATIONS

3D	three-dimensional
APS	active pixel sensor
ART	algebraic reconstruction technique
CCD	charge coupled device
CIS	CMOS image sensor
CMOS	complementary metal oxide semiconductor
CT	computed tomography
dB	decibel
DN	digital number
FBP	filtered backprojection
FPN	fixed pattern noise
GUI	graphical user interface
IMRT	intensity modulated radiotherapy
LED	light emitting diode
MOS	metal oxide semiconductor
MRI	magnetic resonance imaging
OCT	optical computed tomography
PPS	passive pixel sensor
SIRT	statistical image reconstruction technique
UV	ultraviolet
Vis	visible
QA	quality assurance

PEMBANGUNAN SISTEM PENGIMEJAN TOMOGRAFI BERKOMPUTER OPTIKAL BERASASKAN CMOS

ABSTRAK

Kemajuan dalam semikonduktor oksida logam pelengkap (CMOS) sensor piksel aktif (APS) mempunyai banyak potensi untuk aplikasi teknik pengimejan optik. CMOS APS mempunyai kadar bingkai yang tinggi dan fungsi pemprosesan isyarat pada cip yang tidak terdapat pada teknologi terdahulu, peranti gandingan cas (CCD). Ciri-ciri ini boleh meningkatkan kelajuan pengimejan dan kualiti sistem optik CT. Objektif kajian ini ialah untuk mencirikan prestasi sistem pengimejan optik CT berasaskan CMOS yang dibangunkan secara dalaman dan menyiasat keupayaan sistem optik CT tersebut untuk pengimejan fantom air. Optikal CT dibangunkan dan dibahagikan kepada dua subsistem, sistem pengimejan CMOS dan sistem putaran objek atau bahan. Sensor itu dicirikan dan mempunyai nilai hingar yang rendah iaitu 13.3 e^- tanpa penyejukan. Sistem optikal CT menangkap 200 imej unjuran dalam masa 200 saat semasa imbasan. Kelinearan dan keseragaman optik CT dicirikan menggunakan fantom airyang diisi dengan cecair berwarna hijau untuk meniru dosimeter radiokromik. Keputusan menunjukkan bahawa sistem ini mempunyai kelinearan $R^2 = 0.9903$ bagi imej unjuran. Kelinearan imej yang dibina semula tanpa menggunakan filter dan menggunakan filter Hann mempunyai koefisien korelasi masing-masing bernilai 0.9863 dan 0.9797. Walaubagaimanapun, profil keseragaman imej yang dibina semula dengan CT menunjukkan kehadiran artifak. Pembuktian konsep dilakukan melalui pengimejan sebuah catur posisi benteng yang legap kepada cahaya. Buah catur ini boleh digambarkan oleh sistem optik CT. Sebagai kesimpulan, sistem optik CT yang dibangunkan secara dalaman mempunyai keupayaan memberi

DEVELOPMENT OF CMOS-BASED OPTICAL COMPUTED TOMOGRAPHY IMAGING SYSTEM

ABSTRACT

Advances in complementary metal oxide semiconductor (CMOS) active pixel sensor (APS) technology have potentials for application in optical computed tomography (CT) imaging technique. CMOS APS has high speed read out and on-chip signal processing not available from the predecessor technology, charge coupled device (CCD). These features may improve the imaging speed and quality of an optical CT system. The objectives of this study are to characterise the performance of an in-house developed CMOS-based optical CT imaging system and investigate the feasibility of the system for optical CT imaging using a water phantom. The developed optical CT imaging consisted of two integrated subsystems, the CMOS imaging system and the sample rotational platform. The sensor was characterised and has low read noise value of 13.3 e^- without cooling. The optical CT system captures 200 projection images within 200 seconds during a scan. The uniformity and the linearity of the optical CT was characterised using a water phantom filled with green dye solution to mimic radiochromic dosimeter. The results show that the system has a good linearity of R^2 = 0.9903 for the projection images. The linearity of the reconstructed images without using filter and with Hann filter has a correlation coefficient of 0.9863, and 0.9797, respectively. However, the uniformity profile of the CT reconstructed images indicated the presence of artefacts. A proof of concept study was performed by imaging a chess rook piece that is opaque to light. The chess piece can be visualised by the optical CT system. In conclusions, the in-house developed optical CT system can visualise optical images in 3D with good linearity at fast

can visualise optical images in 3D with good linearity at fast imaging speed, but the system can be optimised further to improve the artefacts in the images.

CHAPTER 1

INTRODUCTION

This chapter will provide an overview of the development of the optical CT system in Section 1.1. Section 1.2 will discuss the limitations of current optical CT systems and how CMOS can replace the CCD to improve the system. Problem statement and objectives of the study will be included in section 1.3 and section 1.4 respectively. Scope of the research and significance of the study will be described in section 1.5 and section 1.6 respectively. The last section 1.7 will give the outline of the thesis.

1.1. Development of the Optical CT System

Optical computed tomography (CT) system is a relatively new method developed to measure 3D dosimetry from a volume of radiochromic dosimeters such as gels and polymers. Previously, magnetic resonance imaging (MRI) and computed tomography were used to measure dose from the 3D dosimeters [3]. Optical CT system can be classified into two main types, the first type is a laser-based optical CT system which uses a laser to scan across the dosimeter and the transmitted light was collected by the diode. The second type is charge coupled device (CCD) camera-based optical CT system which uses the CCD camera to capture the projection image of an object illuminated with a broad light source [3].

The first generation of the laser-based optical CT system was developed by Gore *et al.* (1996) and is commercially available as OCTOPUS system by MGS Research Ltd [4,5]. This system uses a single laser beam (He-Ne laser, 623 nm wavelength) similar to raster scanning system and is known to be accurate but relatively slow scanning speed. A single slice of 128 × 128 pixels takes about 12 minutes to obtain. In the first version of the OCTOPUS, the sample was rotated for 360° and the projection images were collected for each planar image [6,7]. Later, the OCTOPUS system was improved and named as OCTOPUS ×5. This system has improved in terms of the imaging time to nearly 8-9 minutes per slice and the rotation of the sample was reduced to 180° [6].

The second generation of the optical CT system was developed by Doran *et al.* (2001). It consists of broad light source and a charge coupled device image sensor [8]. The broad light beam passed through the samples and the projection images were collected by the image sensor [7]. Krstajic *et al.* (2006) has modified the system by adding new focusing optics to improve the imaging capabilities and a high powered LED [2].

Generally, the broad light source camera-based optical CT system produces faster scanning time compared to the laser-based optical CT system [3]. However, the current camera-based optical CT systems has a major drawback that they required around 15 minutes for scanning and reconstruction for clinical applications [5]. Another disadvantages of the broad light source optical CT system is image artefacts caused by the light scattering. The scattering of the light is caused by the refractive index inhomogeneities causing light to refract [3].

Therefore, in this study a camera-based optical CT system was developed using recent advances in sensor technology to reduce the scanning and the reconstruction time.

1.2. CMOS Image Sensor Technology

There are two types of optical image sensors, complementary metal-oxide semiconductor (CMOS) and charge coupled device (CCD). Both image sensors transform photons (light) into electrons (electrical signals) during optical imaging [9]. However, the design for CMOS allows additional functionality such as higher imaging speed and in-pixel signal processing. In this research, CMOS was used in the optical computed tomography imaging system because it offered several useful features for application in optical CT system.

CMOS image sensor is typically designed with an additional capacitor that were put in parallel in each pixel. By having additional electronic circuit for each pixel, every pixel can be read out individually without having the signal to be shifted along the pixel rows as in charge coupled device. Thus, the image information can be read out much faster than charge coupled device and the artefacts caused by overexposure such as blooming and smearing can be reduced. In charge coupled device image sensor, the photons were transported to a central A/D converter with the supports of the vertical and horizontal shift registers, similarly to the 'bucket chain' and it requires a lot of time for the charge to transfer. This results in a disadvantage in term of the high resolution sensors in which the charge must be transferred to the central amplifier by many shifting operations based on the large number of pixels. And it will limit the maximum frame rate of the image sensor [9].

With the advancing technology in the active pixel sensor, it implements an amplifier per pixel with simple source follower circuit that can help to improve the pixel performance and to minimal the power dissipation because its amplifier is only activated during the readout process [10]. The CMOS image sensor offers on-chip functionality and high speed imaging that are useful for optical CT system [11].

1.3. Problem Statement

CMOS image sensor offers an on-chip functionality and higher imaging speed compared to the charge coupled device image sensor. Thus, it can be used in an optical CT system replacing the charge coupled device image sensor. The existing optical CT system mostly used charge coupled device as its image sensor. The first generation of the optical CT system developed by Gore *et. al* (1996) known as OCTOPUS required 12 minutes to obtain an image of the single slice [6,7]. Then, the OCTOPUS system has been improved and the imaging time for the system was 5 minutes per slice and full 3D scan took around 16 hours [12]. The second generation of the optical CT system was developed by Doran *et. al* (2001) and this system required 5.8 s for each projection and total imaging time of 38 minutes [8]. Huang WT *et. al* (2015) has implemented a high-resolution charge coupled device camera in the in-house optical CT system and it took less than 17 minutes to complete the image acquisition [13]. This shows that the CCD-based optical CT system requires longer time for imaging acquisition.

1.4. Research Objectives

The general aim of this study is to develop an optical computed tomography (OCT) imaging system that utilises recent advances in CMOS image sensor, which may benefit to visualise three dimensional (3-D) dose distribution from radiotherapy. Specific objectives of the study are:

1. To characterise the performance of the CMOS image sensor in terms of the sensor conversion gain, read noise, shot noise, full well capacity and its dynamic range.
2. To develop an optical CT system that consists of two integrated subsystems, the CMOS imaging system and the sample rotational platform.
3. To characterise the projection and reconstructed images from the optical CT system by acquiring images of the phantom.

1.5. Scope of the Research

The scope of this research project is focused on the development of the optical CT system. The study includes characterisation of a CMOS image sensor to determine the suitability of the image sensor for the system. The optical CT system was developed into two integrated subsystems, the CMOS imaging system and the object or sample rotational platform. This system was controlled by a graphical user interface developed using LabVIEW software. The optical CT system was characterised using green dye solution of various concentrations to resemble the colour of PRESAGE radiochromic dosimeter from its response to the radiation dose. Two types of the images were analysed, the projection images and the reconstructed images by measuring the attenuation coefficient of the dye solutions. However, in this research study, the optical CT system will not be tested using the PRESAGE dosimeter. It focus only on the usage of the green dye solution.

1.6. Significant of the Study

1. The study aims to develop a CMOS-based optical computed tomography that offers high speed imaging compared with the CCD.

2. The in-house developed optical CT system can be used as a quality assurance tool for the radiotherapy

1.7. Outline of the Thesis

This thesis is comprised of five chapters and are listed as follows:

Chapter 1 (Introduction) introduces the current limitation of existing optical CT system and discussed briefly the CMOS image sensor technology that is used in this research project. It also lists the objectives of the study, the scope of the research, the significant of the study and the arrangements of the thesis.

Chapter 2 (Literature Review) discusses the two types of the optical image sensors, CMOS and CCD and its architecture. It is also explain the methods to measure the electro-optical characterisation of the CMOS image sensor. The basic of the optical CT system, starting with the types of the optical CT system, the principles of image reconstruction, followed by the artefacts in optical CT imaging and lastly the optical CT application in radiotherapy are also describe in this chapter.

Chapter 3 (Materials and Methods) describes details descriptions of materials and methods used in this study in order to achieve the objectives of the research. The first part is characterising the CMOS image sensor using photon transfer curve, mean-variance technique, dark noise, and frame rate. The second part is setting up the optical CT system, developing the GUI to control the system and the third part is characterising the projection images and reconstructed images by calculating the linearity and uniformity for both images. After that, a proof of concept study is performed by imaging a piece of chess rook to investigate the accuracy of the optical CT system. And the last part is the flow chart to summarise all the methods involved in this research study.

Chapter 4 (Results and Discussions) presents the analysis of the data and discussions throughout the research. This chapter is divided into four parts similarly to Chapter 3, first on characterisation of the CMOS image sensor, second on development of the optical CT system and the third on the characterisation of the images from the optical CT system and the proof of concept study. The last subsection in this chapter is summarising the results obtained in the study.

Chapter 5 (Conclusions and Future Works) summarises the finding of the research project in this thesis. The future works are also suggested to improve the performance of the optical CT system in the future.

CHAPTER 2

LITERATURE REVIEW

This chapter will provide an introduction and review of the literatures on complementary metal oxide semiconductor (CMOS) image sensor and optical computed tomography (OCT) imaging system. Section 2.1 will introduce the optical image sensor, the CMOS and its predecessor technology (the charge coupled device (CCD)), and comparison between the two types of image sensors. Techniques for electro-optical characterisation of the CMOS image sensor will be explained in section 2.2. In section 2.3, the optical CT imaging system, the principles of image reconstruction, the issues that commonly occurred in the optical CT and the application of the optical CT in the radiotherapy will be explained in detail.

2.1. Optical Image Sensor

An optical image sensor is a semiconductor device that detects and transforms optical light into electronic signal. It can detect a wide range of visible light wavelength up to the infrared region [11]. This semiconductor device is widely used in digital cameras, consumer electronics, surveillance and medical diagnostic [10]. There are two types of image sensors that are available today, the charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS). The charge coupled device was developed in late 1960's while the CMOS active pixel sensor (APS) was proposed in the early 1990s [14,15].

This section outlines the development of the CCD and CMOS APS, their operating principles and the advantages.

2.1.1 Charge Coupled Device

Since 1960s, the silicon devices has been adopted for the detection of radiation [14–16]. The interest on the metal oxide semiconductor was increasing and the arrays were designed [14,15]. In 1969, Boyle and Smith invented a semiconductor device, a charge coupled device at the Bell Labs [17]. Its application of charge coupled device as an image sensor was first reported by Tompsett, Amelio and Smith in 1970 and after that the charge coupled device became the main imaging device [15,17].

Charge coupled device contains thousands or millions of pixels or light sensitive cells. The pixels produce electric charge proportional to the amount of the light they received. These pixels can be arranged in either a single line array or in an area array. The total number of pixels that makes up the light sensitive area of the device is a factor that determines the resolution of the image sensor. The first area array of the charge coupled device with the resolution of 100 x 100 pixels was manufactured by Fairchild in 1974 [18].

There are three common layouts for the charge coupled device architecture as illustrated in Figure 2.1. The first architecture of the charge coupled device is full frame architecture. It consists of photodetector and charge transfer device [17]. When an incident light (photon) falls on the array of the pixels, the photodetector will convert the light into electron and the electric charge will be transferred to the signal amplifier through column and row transfer [19,20]. A mechanical shutter was required for this type of device to avoid smearing the image during the readout [17]. The second architecture is frame transfer. The frame transfer architecture consists of image pixel at the top part of the sensor, used for the photodetection and a shielded region at the bottom of the sensor as a frame store. The data will be shifted out via the bottom CCDs and horizontal CCD to the output amplifier during the integration time of the next frame. And the third architecture is inter-line transfer. This device was suggested to reduce the smear and eliminate the mechanical shutter [17]. It contains shielded regions on device to allow the next image to be integrated during the readout [21].

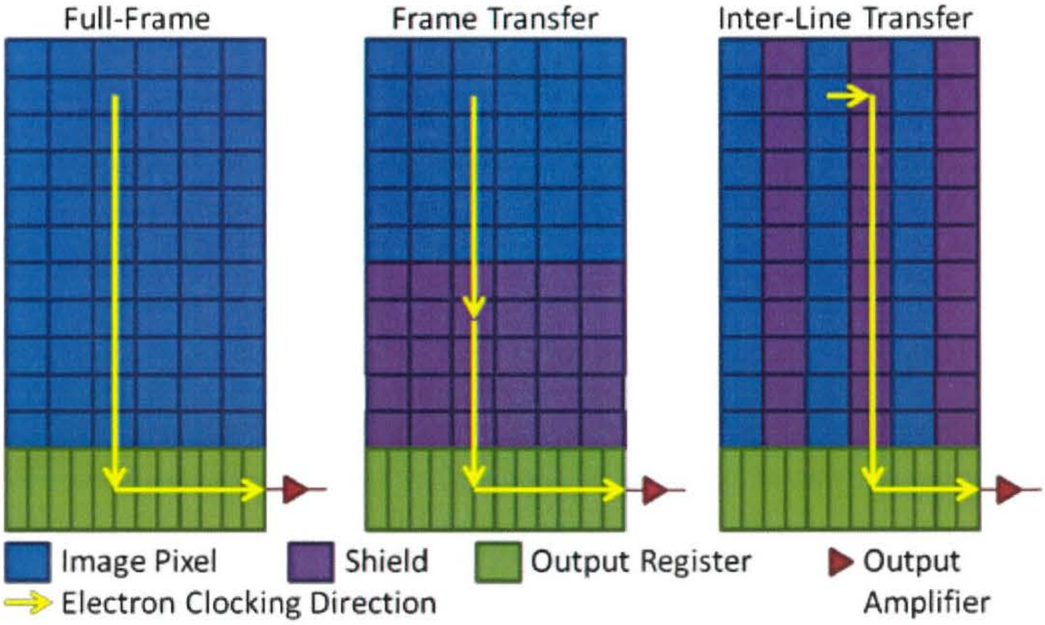

Figure 2.1 Comparison of the electron charge readout for three common charge coupled device designs, i.e., full-frame, frame transfer and inter-line transfer [21]

2.1.2 CMOS Image Sensor

CMOS image sensor (CIS) technology was proposed in 1960's but due to the high dark current and high fixed pattern noise (FPN) using the fabrication technology available during that time, the charge coupled device was dominant because it gave far superior images [10,22]. In the early 1990s, through two inspired efforts, have brought to the resurgence in a CMOS image sensor development. The highly functional single chip imaging system was created as the first effort where the low cost was the driving factor. This was initiated by researchers at Linkoping University in Sweden and at the University of Edinburgh in Scotland. Then, the NASA required a highly miniaturised, low power, imaging instrumentation system for the next generation deep space exploration of spacecraft and this led to the second effort. This effort was managed by the U.S Jet Propulsion Laboratory (JPL) with consecutive transfer of the technology to National Semiconductor, AT&T Bell Labs, Kodak and a few major U.S companies and the foundation of Photobit. This has led to the greater advances in the CMOS image sensor and development of the CMOS APS [16]. With recent developments, the device-to-device mismatch has been decreased significantly. The fixed pattern noise is no longer a problem for CMOS image sensor and specialised photodiodes have been developed in the CMOS process, which offers low dark current. Above all, by integrating the active circuits and the photodiode together in the pixel (Figure 2.2), it allows the CMOS image sensor to achieve better performance compared to the charge coupled device in many aspects. The low cost in comparison with the charge coupled device due to the standard CMOS fabrication process also plays an important role [22].

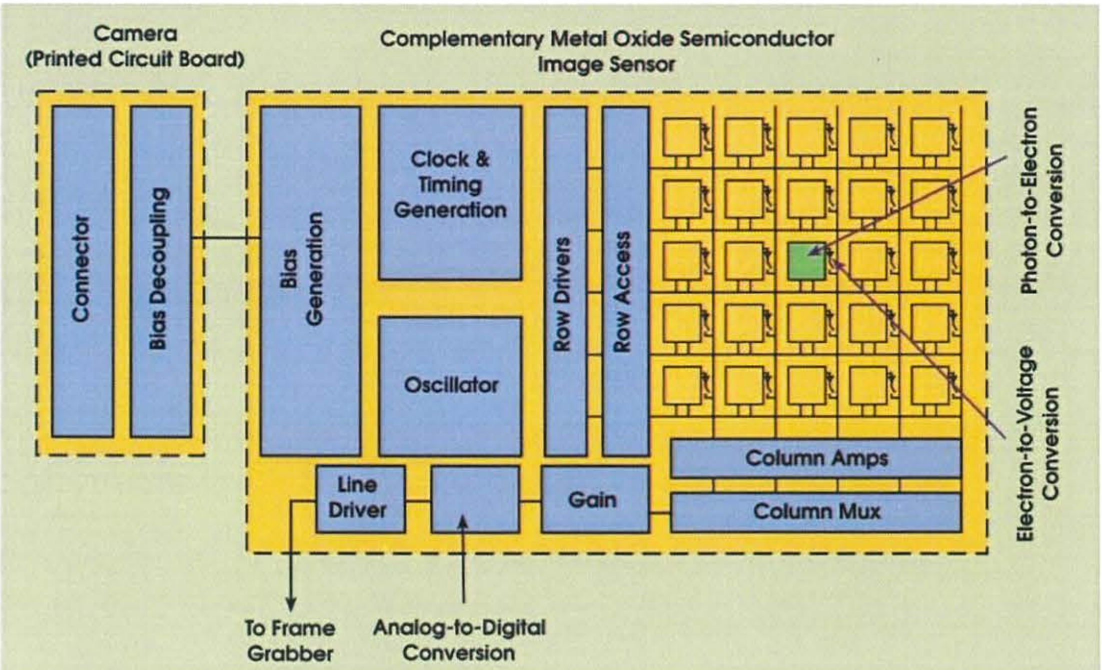

Figure 2.2 The schematic of CMOS image sensor readout circuit connected to the printed circuit board of the camera [23]

The conversion of the charge to voltage takes place in each pixel for CMOS image sensor as shown in Figure 2.2. Unlike the charge coupled device, it transfers each pixel's charge packet to the common output structures, converts it to the voltage, buffers it and send it off chips, as displayed in Figure 2.3. Most functions of the CCD image sensor take place outside the sensor and the printed circuit board can be easily changed without redesigning the image sensor [23].

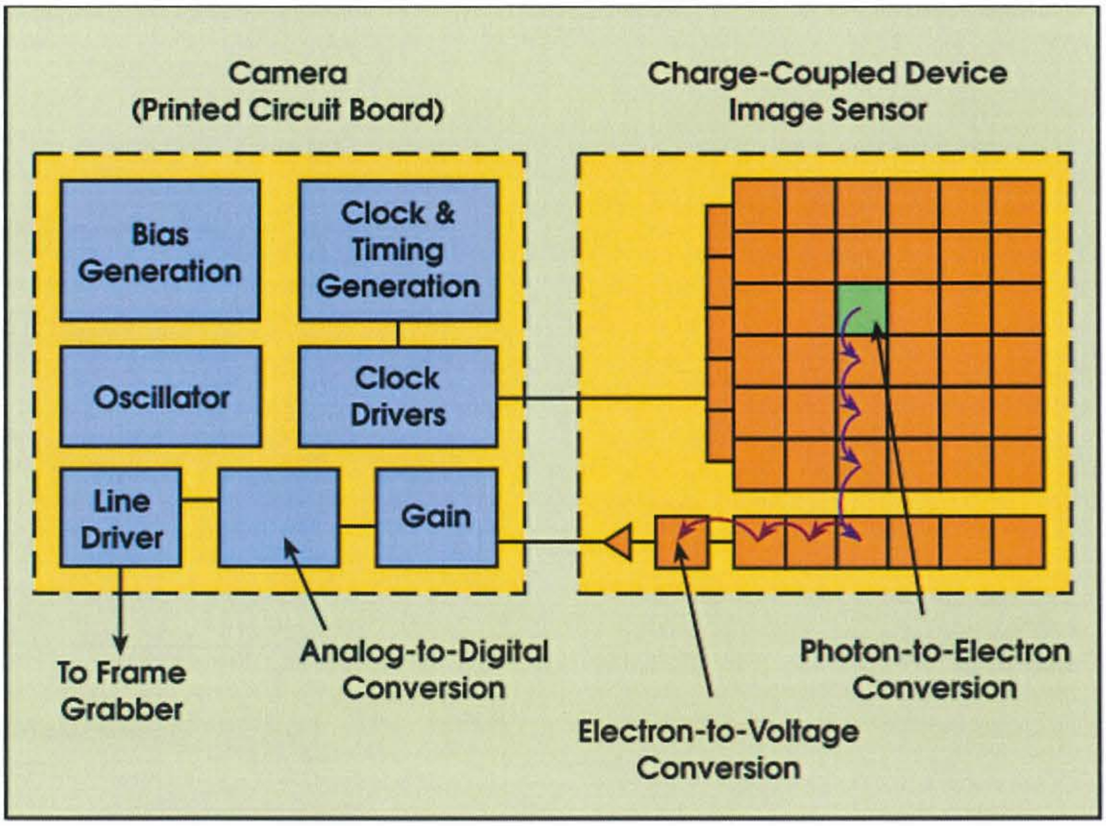

Figure 2.3 The schematic of the CCD image sensor circuits that consist of the readout circuit to convert the photon to voltage and camera printed circuit board for analogue to digital conversion [23]

The CMOS image sensor was designed with the capacitor in parallel to each pixel that act as a charge storage. This capacitor will be charged by photoelectric current whenever the pixel was exposed to the light. This photons then will be changed to the electrons and later it will be transformed into the measurable voltage directly at each pixel's own associated circuit. This voltage would then be able to be made accessible to the analogue signal processor. The value of the voltage created depends on the brightness and the exposure time. The image information in CMOS image sensor can be read much more faster than charge coupled device because the charge is not being shifted to the other output structures [9].

2.1.2(a) CMOS Architecture

Basically, CMOS image sensor consists of four main blocks, as Figure 2.4 shows. The first block is pixel array. It contains millions of pixels sensor to capture the light intensity passing through [24]. The row and column selector are also known as address decoder, allows the pixels to be randomly selected and read [25]. This will increase the readout speed of an identified area of interest, something that is difficult to be carried out in charge coupled device [21]. The timing and control blocks ensure that every pixel is synchronised with each other and to control the pixel array. And lastly the analogue signal processor converts the analogue voltage signals to the digital signals [10].

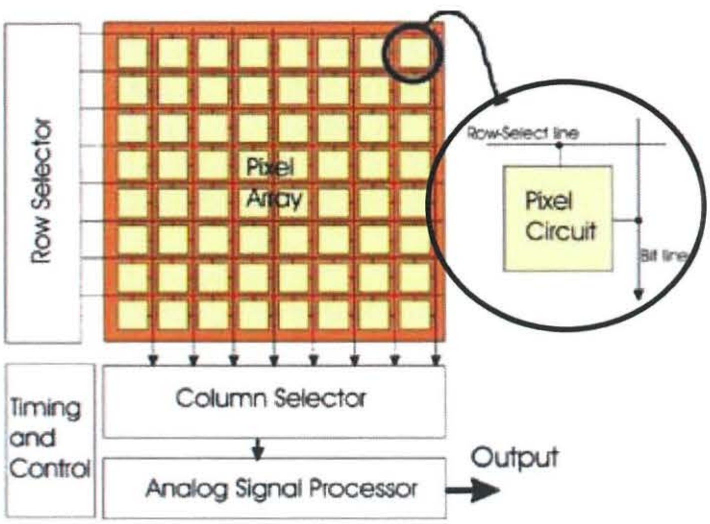

Figure 2.4 The architecture of the CMOS image sensor that consists of the pixel array, the row and column selector, the timing and control and analogue digital processor and the inset displays the pixel circuit for each pixel [10]

There are two types of the readout procedures designed in the CMOS image sensor, the global shutter process and the rolling shutter process. In the global shutter process, all pixels including a sample and hold circuit, reset and integrate at the same time. Meanwhile in the rolling shutter process, the readout process happened one row at a time, the difference of timing diagram is shown in Figure 2.5. Image captured by the rolling shutter is normally blurred for a high speed moving object. However, the frame rate of the rolling shutter process is faster compared to the frame rate of the global shutter [22].

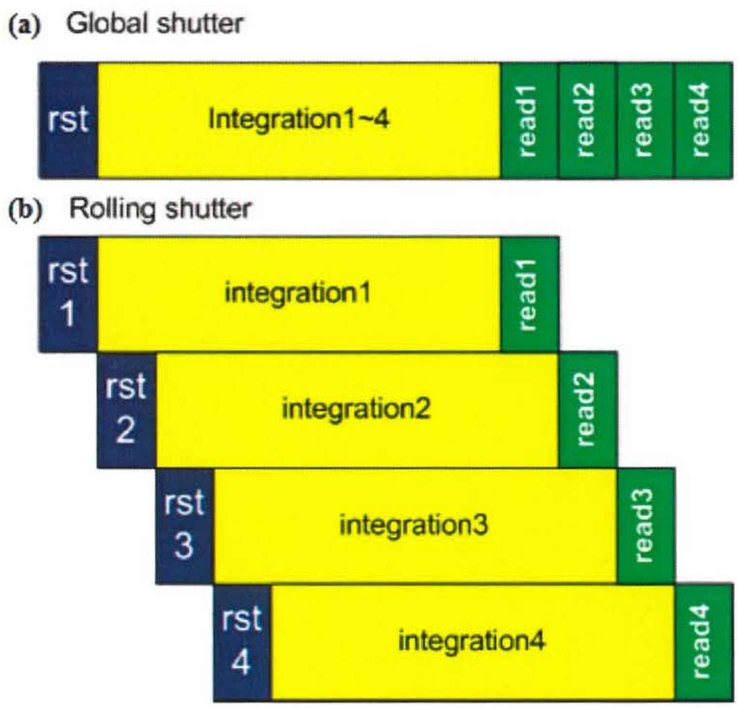

Figure 2.5 The timing diagram of (a) global shutter and (b) rolling shutter readout of a CMOS image sensor [22]

2.1.2(b) CMOS Pixel Circuits

Principally, the pixel circuits of the CMOS image sensor are divided into passive pixel sensor (PPS) and active pixel sensor (APS).

The PPS was the first generation of the CMOS image sensor. It was introduced in 1967 by Weckler [16]. It consists of the photodiode and an addressing transistor that acts as a switch without an internal amplification, see Figure 2.6. However, the PPS suffers from a large fill factor, small pixel size capability, high noise and low sensitivity as well. This caused from the mismatch between the large vertical bus capacitance and the small pixel capacitance [10,26].

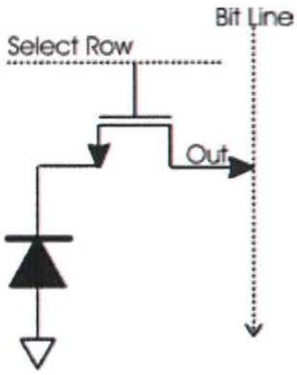

Figure 2.6 The schematic diagram of the photodiode type of passive pixel sensor [10]

The problems of the PPS were resolved using the active pixel circuit approach. The APS circuit implements an amplifier per pixel, with simple source-follower, see Figure 2.7 [10,26]. The APS circuit consists of the photodiode, the reset transistor, the driver of the source follower, and the addressing transistor.

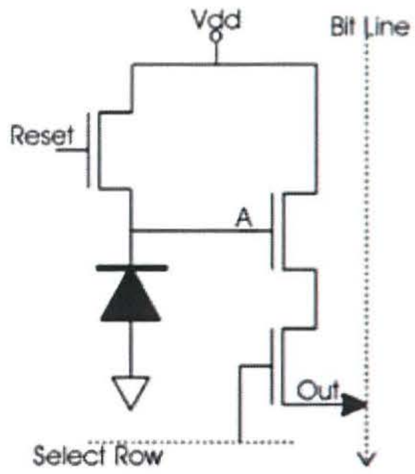

Figure 2.7 The schematic diagram of the photodiode type of active pixel sensor [10]

The performance of the pixel has been improved with the insertion of the amplifier and it helps to minimise the power dissipation of the CMOS APS, generally less than CCD's, because the amplifier is only activated during the readout [10]. By introducing the APS, it has contributed to the major improvement in the noise performance.

2.2. Electro-optical Characterisation of the CMOS Image Sensor

A CMOS image sensor needs to be characterised prior to the application of the optical CT system due to the additional random noise not detected in charge coupled device [27]. Besides that, the effect of the sensor temperature and different data acquisition hardware used play an important role in the performance of the CMOS APS [28]. For the characterisation, few performance parameters will be measured. The parameters are read noise, dark current, shot noise, conversion gain, full well capacity and dynamic range. These parameters can be derived from the mean-variance analysis and photon transfer curve. Read noise is the random noise measured under dark conditions and can be seen by acquiring a dark image. The imprecision in the measurement of each photoelectron charge packet by the read amplifier has contributed to the read noise. Basically, the dark current is unwanted source of charge generated by the pixels and varies from pixel to pixel. This variation contributes to the read noise floor [29,30]

Dark current is dependent on the temperature and arises through heat-induced release of electrons from the silicon chip under total dark conditions. It is one of the fundamental noise sources in the semiconductors imagers. To maximise the signal-to-noise, the reduction in the dark noise is necessary and this can be reduced by lowering the operating temperature. The sources of the dark current in the silicon are introduced during the device fabrication and design, the pre-processing and device post processing [21,30].

Next parameter is the shot noise. It originates from the way of the photon arrives on a detector, known as stochastic process. The arrival of the photon on the detector is illustrated in the Figure 2.8 using a Monte Carlo simulations. The number of photon interacting per pixel varies from zero to four [31]. The photons are generated from the light source at random times. Because of it, there will be noise in the observed intensity of light. These noises, according to the physics of light states, is equivalent to the square root of the number of photons generated by the light source. Hence, it is called as shot noise [32].

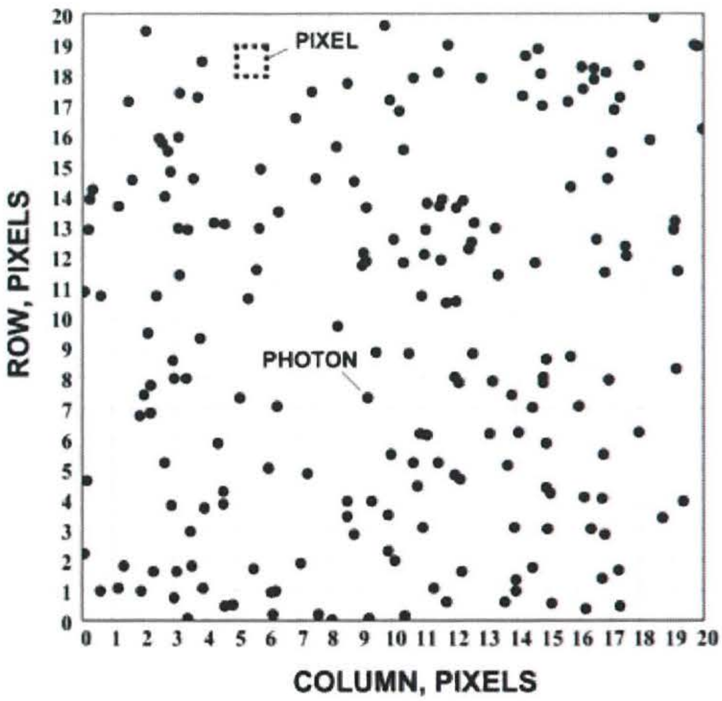

Figure 2.8 Monte Carlo simulation showing the interaction of the photon with a 20 × 20 pixel region [31]

Conversion of photons to electrons is the first step in digitising. The ratio of electrons generated from photons during the digitisation process is called Quantum Efficiency (QE). It measures the efficiency of the conversion. The more electrons in a pixel were converted, the more sensitive is the sensor. For example, there are 6 photons fall on the sensor, but only 3 were converted to electrons. This sensor only has QE of 50% [32].

All electrons are stored within a pixel, known as well before digitisation process. The number of electrons that are stored in a well is called Saturation Capacity or Well Depth. If the number of electrons exceed the capacity of the saturation, additional electrons will not be stored [32].

Another parameter to be measured during evaluating camera performance is the dynamic range. This parameter is the ratio of noise observed by the camera versus the signal [32].

Conversion gain, K (e^-/DN) is described as the number of electrons represented by each digital number. The read noise, full well capacity and dynamic range can be calculated from the sensor conversion gain [30].

2.2.1 Mean-Variance Analysis

Mean-variance analysis is known as a 'gold standard' to derive the conversion gain and read noise for charge coupled device [30]. This technique has been introduced by Holdsworth *et al.* (1990) [33]. The graph of the signal and noise is plotted until the saturation point, where the pixel cannot hold additional charge and spilled to the adjacent pixel (Figure 2.9). The intercept of the graph is the sensor read noise and the gradient of the graph is the sensor conversion gain, $K = G^{-1}$ [30,33].

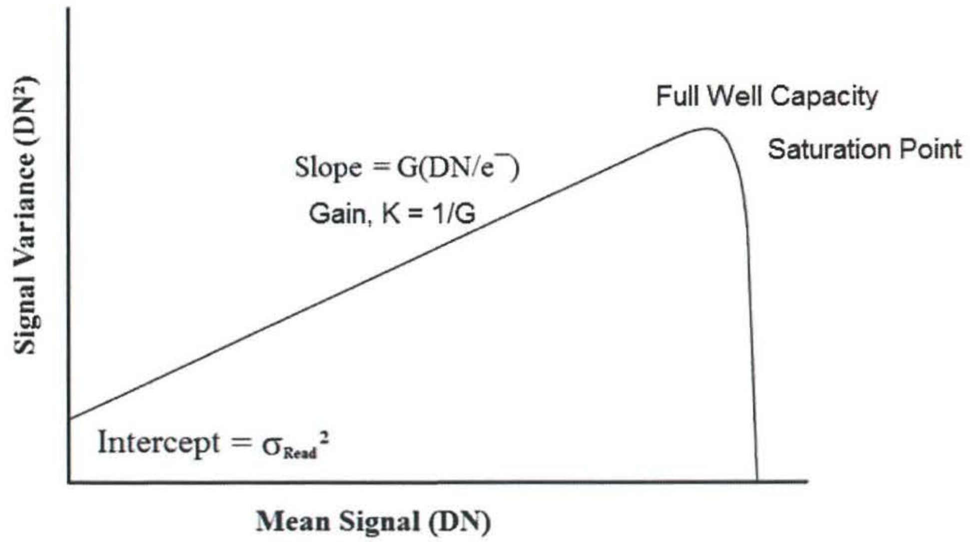

Figure 2.9 Mean-variance graph shows the linear response until the saturation point [30]

2.2.2 Photon Transfer Curve

A photon transfer curve (PTC) can also be used to determine the sensor conversion gain by plotting a log-log plot of total image noise (the standard deviation of pixel intensity values) as a function of signal intensity (the average pixel intensity value) under uniform light illumination [29,30]. An ideal photon transfer curve response is illustrated in Figure 2.10.

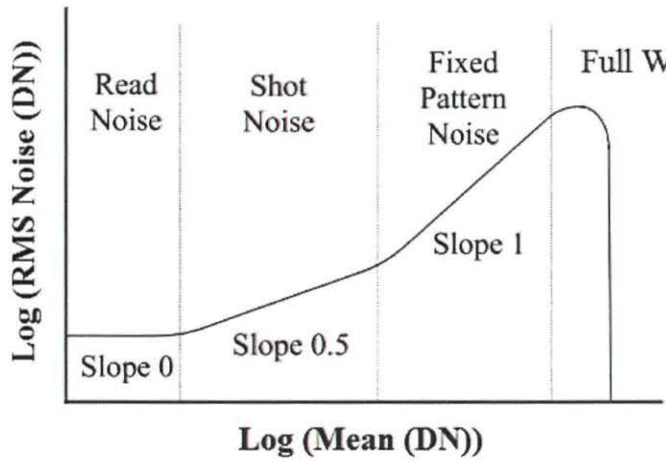

Figure 2.10 Photon transfer curve reveals the three main noise sources of the sensor [30]

Read noise is dominant at a low signal level and has a gradient of zero. It is signal-independent noise. Shot noise becomes dominant as the illumination increases and exhibits a gradient of 0.5. At relatively high-level illumination, the fixed pattern noise (FPN) increases proportionally with the signal and a gradient of 1 is observed. The fixed pattern noise will increase until it reaches a saturation point, where the photodiode cannot hold any additional charge and it will spill over to the adjacent wells, referred to as full well capacity [30]. Before determining the sensor conversion gain, the noise sources other than shot noise need to be removed. This can be achieved by subtracting two images at the same illumination level to eliminate the fixed pattern noise. By removing the fixed pattern noise, the photon transfer curve will continue with the slope of 0.5 until it reached full well capacity, as displayed in Figure 2.11 [30,34].

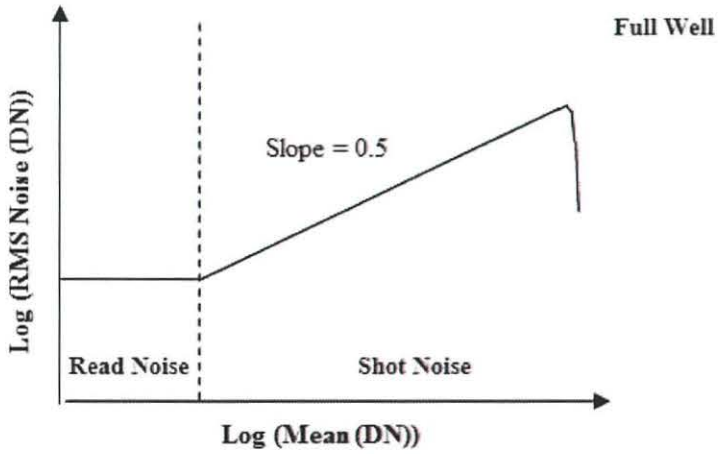

Figure 2.11 The photon transfer curve after the elimination of the fixed pattern noise shows two regions of noises, read noise and shot noise [34]

2.3. Optical CT System

One of the main modalities to treat cancer is modern radiotherapy, where it delivers high radiation dose to the tumour whilst sparing the healthy tissues. Thus, it is important to have a highly sensitive dosimetry system to accurately map doses to the tumour and surrounding tissues. A dosimetry system that is able to record the integrated absorbed dose in 3D needs to be establish for radiotherapy dosimetry application to evaluate the accuracy of the dose distribution [7].

Optical computed tomography (optical CT) is a bench top 3D imaging system for radiochromic dosimeter. The optical CT consists of a light source and an image sensor to detect the light and reconstructed the dose distributions of a radiochromic dosimeters such as PRESAGE in 3D [35]. The PRESAGE becomes opaque and develops colour changes when irradiated, due to the optical property of the PRESAGE dosimeter that increases in optical density in response to the absorbed dose delivered to the dosimeter [36]. The light passing through the object is refracted and is recorded as optical density by the image sensor. Most of the optical CT available currently, use a CCD as image sensor [8,12,13,37]. Even though it provides good quality image, it has a limitation in providing on-pixel image processing and fast frame rate, which is useful in an optical CT imaging system to reduce the scanning time [7]. Optical CT is also more accessible compared to a magnetic resonance imaging (MRI) system [38,39].

2.3.1 Types of the Optical CT

The basic principle of computed tomography is a method of imaging an illuminated object from multiple directions to visualise the cross section of the object using projection data collected [40]. The first generation optical CT was introduced by Gore *et al.* (1996). The system has been commercialised into OCTOPUS system (Figure 2.12) and now available from MGS Research Ltd [4]. The single He-Ne laser beam (633 nm wavelength) was guided across a sample in a rectangular water tank by mechanically moving two synchronous mirrors in this setup and a photodiode detector was used to measure the resulting beam for each cycle of translational motions as a single projection image. The sample that was mounted on the turntable, guided by the stepper motor was rotated by a small angular increment after each full translational scan and then followed by the linear scan [36]. However, the disadvantage of this scanner lies from the slow scanning speed and only one path through the sample is measured at a time. It takes about 12 minutes to acquire a single slice with 128 x 128 pixels [7].

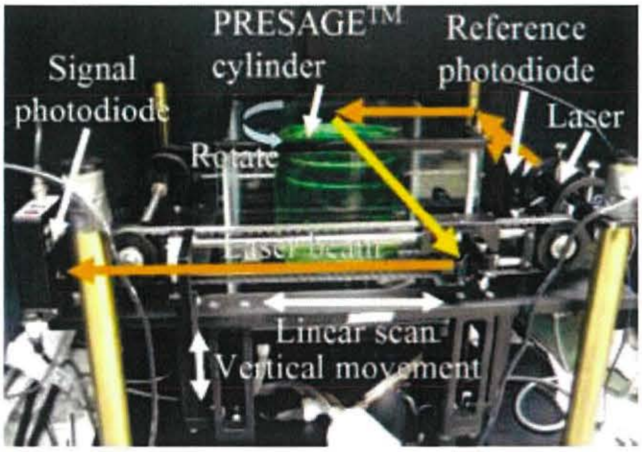

Figure 2.12 The setup of the first generation of the optical CT system developed by Gore *et. al* (1996) [1]

The second generation optical CT scanner applied a broad light source and a charge coupled device and was developed by Doran *et al.* (2001) (Figure 2.13)[8]. The setup contains a single light source, a lens system to produce a parallel light beam, a specimen tank and a secondary lens system to focus the light source into a charge coupled device. The dosimeter was placed inside the scanning tank with the refractive index matching liquid. The LED light source was placed as close as possible to the pinhole of diameter of 1 mm, which will create a parallel beam. The beam passes through the sample and is attenuated by the gel dosimeter. With the introduction of the plano-convex lens, L_2 in the setup, it has improved the focusing capabilities and provides better stray light rejection [2].

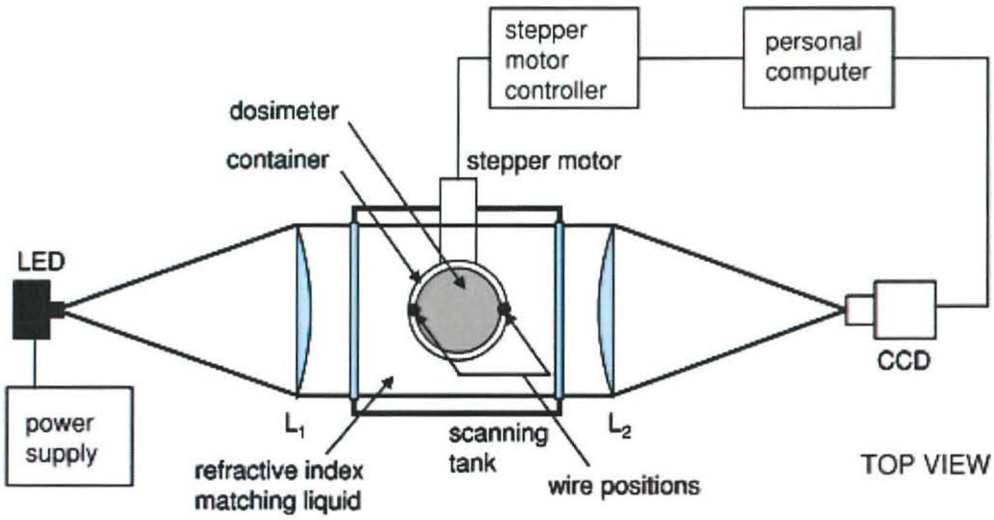

Figure 2.13 The schematic diagram of the second generation of the optical CT system developed by Doran *et. al* (2001) [2]

2.3.2 Principles of Image Reconstruction

The word tomography comes from the Greek word which implies the reconstruction from slices [41]. The term slices is used because it resembles to the object being scanned would look like if it was slice open along a plane [42]. Basically, the reconstruction of an image from its projections images is the tomographic imaging. The decrease in the intensity of the light along a series of linear paths can be measure by directing the rays of the light at an object from different orientations. Hence, Beer's Law is applied to define the decreasing in the intensity [42]. Beer Lamber Law states that the absorbance of the material is directly proportional to its thickness (path length). Beer's Law can be expressed in equation (1),

$$I = I_0 \exp(-\mu x) \quad (1)$$

where I and I_0 are the final and initial intensity of the light, μ is the linear attenuation coefficient and x is the path length of the material in which the sample is contained [42].