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Introducing an Application of a Charged Coupled Device (CCD) in an Optical Tomography System

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Graphical abstract

Abstract

A tomographic system is a method used for capturing an image of an internal object section. Optical tomography is one method which widely used in medical and industrial fields. This paper reviews several applications of Charged Coupled Devices (CCD) and introduces an application of a CCD in an optical tomography system. Most of the previous research used this component for displacement measurement and as a video camera. This paper discusses its basic principle of operation, basic construction, its criteria, application, and its advantages compared to other optoelectronic sensors available in today's market. The applications of this sensor in fields such as astronomy and medical has proved the ability and the good performance of CCD in capturing images. This sensor should widen its usage in optical tomography fields because it can give high performance in image reconstruction.

Keywords: Tomography; optical tomography; Charged Coupled Device (CCD); applications

1.0 INTRODUCTION

The development of tomography systems is mainly in medical and industrial areas. The main used of tomography system is to capture cross-sectional, internal object images for analysis and monitoring purposes [1]. There are several types of tomography system such as, electrical tomography system, optical tomography system, ultrasonic tomography system, microwave tomography system, X-ray and many more. All these systems have their own limitations. The word tomography comes from Greek words where 'tomo' meaning section and 'graphies' meaning images [2]. Tomographic imaging systems were started in 1950 in medical field and became more popular starting 1990 in industrial field [2]. The most attractive features of a tomography system is; the system may be non invasive, it may be robust, can operate to capture images for fast moving fluids and some of the systems are portable [3].

This research paper focuses on the review and the application of Charged Coupled Device (CCD) in an optical tomography system. The optical tomography system is a well known method in the tomography field. The sensor used in optical tomography system is known as a hard field sensor. For optical tomography system, the sensor only depends on the change of the light attenuation or absorption [2]. Besides, optical tomography systems are immune to electrical noise and interference, have high resolution and high speed [4] compared to other tomography systems such as Electrical Resistance Tomography (ERT), Electrical Capacitance Tomography (ECT), and Electrical Impedance Tomography (EIT). The high performance and cost of X-ray tomography or Positron Emission Tomography (PET) cannot be fairly compared to an optical tomography system. Unfortunately, these last two types of tomography provide hazardous radiation that may harm human life. So the best way to avoid the excessive of hazardous radiation is by using optical tomography method.

In an optical tomography system, there are many types of sensor that being used in university research, industries and medical fields. The examples of the sensor that widely used are fiber optic [5], Light Emitting Diode (LED) with phototransistor, laser diode with photodiode, infrared [6], Complementary Metal Oxide Semiconductor (CMOS) [7] and CCD sensor [8].

CCD sensor is a multifunction electronic component with high demand in today's industries. This type of sensor is very special in its architecture design where it consists of more than a thousand numbers of very small sensor which sensitive to light sources. In an optical tomography system, high number of sensors will give higher resolution of image reconstruction. But for the sensor that have fixed diameter such as fiber optic, photodiodes, and phototransistor, they will face size and resolution limitation problem. For CCD sensor, the size of its optical sensor can be a few microns and this allows the existence of a thousand sensors in one projection. **Figure 1** shows the image of CCD Linear for Sony ILX555K. This type of sensor is low noise interference, fast detection speed [9] and high resolution [10], [11], [12].

Figure 1 Charged Coupled Device (CCD) Linear Sensor Sony ILX555K

The inventors of the CCD are Boyle and Smith from Bells Laboratories. The development of the CCD was started at 1970 [12]. At an early stage of development, CCD was used as a memory storage. After a few years, this electronic component became popular as one of the optoelectronic sensors for image detection.

The basic principle that used by is based on electrical charge moving. The sensor of this component is made by a Metal Oxide Semiconductor (MOS) capacitor. When the light strikes onto the surface of the CCD, photon charges will attract an electron charge to escape from its covalence band. The number of electrons produced depends on the number of photons striking the glass of this detector. Then electrons will be shifted to the next sensor until it reaches the last sensor. Last sensor will send the data to the computer to process and produce an image reconstruction [13].

The CCD was used in many engineering fields such as astronomy, medical and process industries. Different field has different requirement of CCD. For an example, the high quality of CCD required by astronomy field because it needs a robust component that can deal with the drastic changes of temperature and high capability of capturing outer space image. Meanwhile for process industries, usually it is low cost and consists of two types of sensor; colour CCD and monochromatic CCD. The colour sensor is usually used in video and photographic cameras, while the monochromatic sensor is used in facsimile machines and scanners. For medical purposes, the high resolution and accuracy of CCD is needed because this detector is used to capture images of bone structure or soft tissues for diagnosis and analysis.

■2.0 BASIC CONSTRUCTION OF THE CHARGED COUPLED DEVICE (CCD)

There are two types of CCD sensor available in global markets; area CCD and linear CCD. For the CCD Linear Sensor, the optical sensors are aligned in one direct line. There are many names to acknowledge the optical sensors which built in the CCD. These sensors can be known as cells, photo sites, picture elements and photo elements [12]. It is generally used to convert the light strike signal (analogue signal) into electrical signal.

The basic function of changing an optical analogue signal into electrical signal in the CCD sensor can be visualized as a process of collecting rain in a bucket [12], [10]. A droplet of rainfall can be represented as a photon that falls onto the surface of CCD. Each cells will be represented as a bucket collecting the rainfall. The cell fills to a certain level dependent on the amount of light. The energy stored in the cell is then locked and clocked out sequentially.

After it is full with water or in real case the cell is full with photon charged, it will pour the water or transfer the photon to the next bucket or cell. This process will keep going on until it reaches final cell. This final cell will send the output signal to the computer for data processing [10]. **Figure 2** shows how the process of transferring data within a numerous number of cells in a CCD sensor.

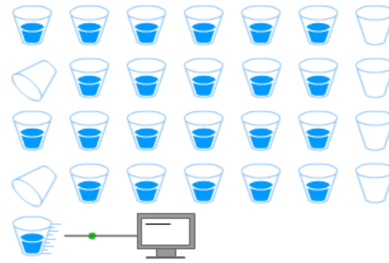

Figure 2 Process of transferring data from one pixel to another in Charged Coupled Device (CCD) sensor. [10]

In **Figure 3,** it shows the image of transferring signals from one cell to another for colour CCD sensor. This **Figure 3** also represents a bucket as a cell number.

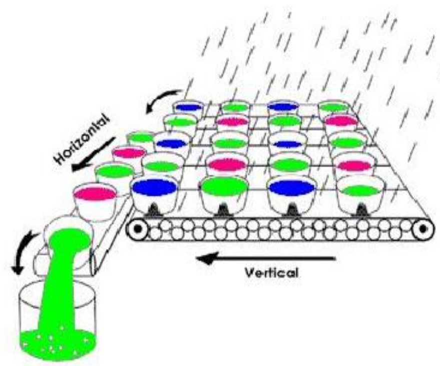

Figure 3 Process of transferring data from one pixel to another in colour Charged Coupled Device (CCD) sensor [14]

In 1991, the researchers found that CCD Linear sensor with colour scheme had disadvantages. This colour CCD Linear Sensor needs a large memory for output signals because CCD needs to scan three times for three different colours [15], [16].

CCD can be classified as an integrated circuit that contains numerous numbers of small photo element that have high sensitivity to light energy. At an early stage of the CCD development, it was used to store and transfer analogue signals or information in the form of electrical charge. The CCD sensor is formed as a very small size of capacitor [17], [18]. **Figure 4** shows the cross section of each small photo element in CCD sensor.

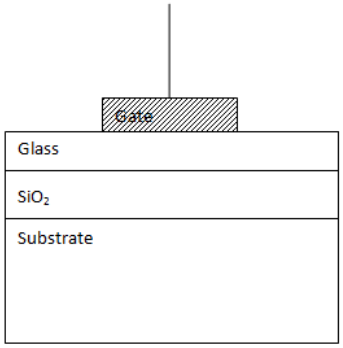

Figure 4 Cross section of Metal Oxide Semiconductor (MOS) capacitor

This sensor is a tiny Metal Oxide Semiconductor (MOS) cell that can be microns in size [19], [20]. It contains four layers; first is a gate where the photon strikes, glass as an insulator, Silicone Oxide (SiO_2) and the substrate. Photons that come from light sources will strike the silicone element. This photon will transmit its energy and produce the photoelectric effect. This transmission of energy will break the covalence band of silicone and cause electrons to freely escape [21]. The number of electrons produced was proportional to the number of incident photons [12] [22]. Below are the steps for CCD to get its data [23];

1. The photo element will receive photons from incident light
2. The attraction of the photon and its energy transfer will let electrons free themselves and begin to charge
3. Charged electrons will transfer to the image registers
4. Electrons in the charge register will go to buffer register one by one

There are many criteria which can be considered by researchers to improve CCD performances. Generally, there are seven criteria of CCD in dealing with its performance. The seven criteria are; Quantum Efficiency (QE), signal noise per ratio, spectral sensitivity, transfer efficiency, spatial resolution, blooming and the dark current. This paper will simplify these seven criteria related to the performance of the CCD linear array or area image array sensor.

A detector that has the highest percentage Quantum Efficiency (QE) can be classified as the best detector. Quantum Efficiency (QE) for this sensor is equal to the ratio of the average number of detecting photons per cell over the average number of incident photons per cell. CCD is reported to have a high percentage of Quantum Efficiency (QE) which is 40 percent to 90 percent compared to other optoelectronic sensors [24]. While for signal noise per ratio of CCD can be based on Equation 1 below [24];

$$\left(\frac{Signal}{Noise}\right)^2 = \left(\frac{N}{\sigma}\right)^2 \text{.....................Equation 1}$$

Equation 1 shows that perfect detector will give value approximate to *N*. *N* here refers to the number of photons received by the detector while σ is the standard deviation of measured signal [25].

Spectral sensitivity is the wavelength range of the light source that the CCD can capture. The standard range wavelength for CCD is within 400nm to 1000nm. This range covers the visible and much of the infrared spectrum [26]. For spatial resolution, the greater size of a optical sensor area will cause a decreasing in image resolution. The small size of the optical sensor area is highly suggested to produce high quality and sharpness of image reconstruction. Unfortunately, for certain types of optoelectronic sensor, they have their limitation of size such as a photodiode and a phototransistor. For CCD, varying size of sensor can be found in today's market.

Transfer efficiency is the measurement of electron being transferred from one cell to another cell. Usually, not a hundred percent of electron charged will be transferred to its neighbour. There are many possibilities that can affect the transferring process such as temperature, charged trapping, small number of charges in one cell and switching [27].

Blooming is the process where very high numbers of electrons are produced in a number of cell and the excess electrons still exist after the transferring process. This may occur when the CCD is exposed with too high intensity light sources or strong illumination [24], [28]. Available CCD sensor in the market comes with an anti-blooming component to solve the above problem. Anti- blooming component is an electrode applied between two numbers of cells to allow the excessive of electron flow into the drain [24]. Dark current is another phenomenon that happens to CCD. Dark current will happen when the signal is detected, although the sensor is placed in dark area. Dark current happen because of the effect of surrounding temperature [24]. Dark current is negligible when the surrounding temperature is -100^{0}C. But, if this value decreases until -120^{0}C, the sensor will not function appropriately [24]. Usually, this dark current need to be controlled when applying the CCD in the astronomy field because it deal with highly or drastic changes values of temperature.

All the criteria mentioned above highly discussed by researchers throughout the world because all these criteria affect the CCD performance and its quality of image reconstruction.

■3.0 APPLICATIONS OF CHARGED COUPLED DEVICES (CCD)

CCD widely used in many areas such as astronomy, medical, process industries, remote sensing application [29] and electronic appliances. Different fields have different criteria for the CCD involved. There are three main criteria need to be considered in selecting the CCD. First criteria are its cost, followed by consumer use and finally it's size. [30] There are many electronic companies that produce CCD sensors all over the world, such as Thomson, Ford Aerospace, Reticon, Kodak, Texas Instrument, Toshiba, and Sony. This shows that CCDs play an important role in imaging industries.

At an early stage in the development of CCD, it was being applied in solid state cameras in 1970 to 1975 by Smith and Boyle [31], who were the inventor of this sensor. These CCDs were used for broadcast television usage too [32].

Starting in 1983, this sensor was introduced in the astronomy field [32]. Then, many big companies started producing this type of sensor for the requirement of astronomy technology. CCD that are applied in astronomy field are high cost. The astronomical engineering usually used area arrays of CCDs to capture an image of outer space. The largest size of CCD being reported recently is mounted on a 6" wafer size [10].

The basic principle of detecting an object using a CCD is based on its application. For example in the astronomy field, the area array CCD is used for detecting stars, planet or meteor from million thousand distance from our earth by the light reflection. So, the actual concept is by detecting the spot of bright light, while the background of unspotted area is dark. This is how it can detect the existence of stars using CCD [33]. The selling cost of CCD for astronomy may reach into the thousand dollars [30].

Then, in 1991, CCD was widely used in the photographic world. Many digital cameras have been released based on CCD technology that produce high resolution images [32]. The cost for a CCD used in a digital camera is inexpensive compared the one used in the telescope. Besides, its characteristics and sizes of pixel are different because they are based on consumer requirements [30]. The professional photographer needs a high resolution digital camera as an investment, while for the amateur, an inexpensive camera is adequate.

CCDs are also used in the medical field, especially in X-ray tomography systems. Usually the construction of the camera for the X-ray system consists of several CCD sensors. CCDs were used in X-ray tomography systems because its information can be used to produce very high resolution image reconstructions where the sharp and the accurate image result is important in the medical field. This type of detector has high potential to detect the high density object such as bone structure and can give information related to the any chemical state of changes [34]. The CCD is good in giving useful information about soft tissue characteristics when applied in X-Ray tomography systems [35], [36].

This type of sensor is also applied in some electrical appliances such as facsimile machines and scanners [37]. The cost for this sensor is low because it is being used in electrical appliances that are mass produced and no special requirements for the sensor related to its output quality.

In the twentieth, the CCD Linear Sensor has been applied in other applications such as optical displacement sensor [38] [39] , surface detection sensor [40], thickness detection sensor [41] [42], and a scanning system [43] [44]. The CCD Linear sensor is unique because it can measure the displacement, thickness, or detect an object based on its basic principle; measuring the light intensity received by its sensitive cells. This type of sensor is suitable for non contact measurement systems because of its capability to read data based on the shadow of the object cast on its surface.

According to Li [38], the CCD can be used to measure online displacement based on the light reflection concept and this sensor has a capability to measure very small displacements because its sensitive cells size can reach micron values. Yang Ni *et al.* [41] show this sensor is capable of detecting the thickness of a transparent object such as a glass plate.

■4.0 AN APPLICATION OF CHARGED COUPLED DEVICE (CCD) IN AN OPTICAL TOMOGRAPHY SYSTEM

The CCD is a multifunction electronic component which can be used as memory storage, correlater, optical detector and for videogrammetry [12], [22], [45]. In process industries, the CCD is used for detecting solid particles, because, the CCD is able to detect dark areas [8] [46].

According to the previous research done by Mariani Idroas [8], she used a CCD Linear Sensor to detect solid objects. The type of sensor she used is a Sony ILX551A which has 0.014mm x 0.014mm size of a pixel. In her research, she used this sensor to detect solid objects based on measuring the light intensity received by the detector. In her case study, she used a pipeline diameter 80mm and filled it with non flowing pure water [8], [20]. Pure water is used to minimize noise in the experiment, but in practice the device should handle a certain level of contamination. If this detector receives too high a light intensity, it may damage its cells. The laser diode was used as a transmitter because of its monochromatic light sources. The laser diode is the best combination for the CCD because the laser is a good monochromatic light and high precision of beam [22].

Application of the sensor in capturing an image of air bubbles using a video camera is widely used in process industries,-because of the high demand for a bubble detector that is non invasive and non intrusive. CCD used to monitor their production and for plant security. Bubble detectors are usually used in petroleum refining, oil and gas pipeline system, geothermal wells, steam generation in boilers and burners, and steam condensation system [47]. Unfortunately, video cameras that use CCDs are high cost, bulky and complex circuit is involved [48]. Besides that, CCD camera only captured images of air bubble flow from the side of the pipeline system.

To solve this problem, researchers in the tomography field suggested using Electrical Capacitance Tomography (ECT). Unfortunately, ECT gives a low resolution of the image when the data is reconstructed [47]. The optical tomography system is the best approach of detecting the air bubbles in a pipeline system because it can give high resolution of the image after reconstruction, low cost and no hazardous radiation emission involved [49]. The selection of the sensor very important for optical tomography. Based on the researched done by Yang Ni [41], she had proved the capability of CCD detected the transparent object. Even the small differences of the light reflection and light absorption effect [50] value between transparent object and air can be detected by the CCD devices.

The application of CCD devices in optical tomography system is highly recommended to capture a cross-sectional image of multiphase flow such as air bubble and liquid. The summarization of the application of this sensor in multiphase flow are discussed as follows.

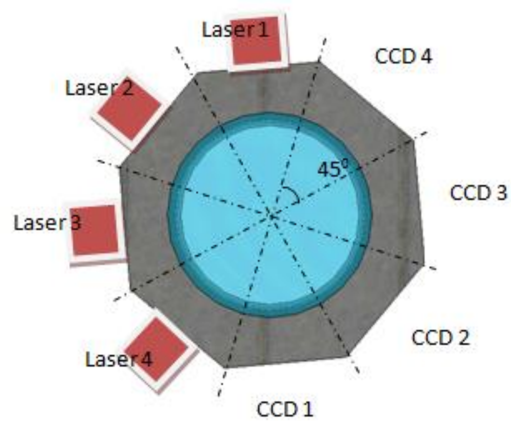

Figure 5 Orthogonal projection for CCD linear sensors and laser diodes

Figure 5 shows the orientation of CCD linear sensors and laser diodes in orthogonal projection. This projection can help the sensors viewing the cross-sectional pipeline system uniformly. For measuring the velocity of air bubble, two numbers of orthogonal plane need to be used. Besides that, the flow of the air bubble also can be recognized by analyzing the position of air bubble at the first plane and second plane. Each of the data, obtains from the CCD 1, CCD 2, CCD 3, and CCD 4 have to be combined to determine the distribution area of the gas and liquid in the pipeline system. Information on the diameter of air bubble also can be analyzed using a CCD linear sensor. The diameter of air bubble can be obtained by using data from all four numbers of CCD linear sensor by calculating the average result. More analysis, such as the shape of air bubble can be investigated too. As a conclusion, the application of CCD linear sensor for detecting solid and transparent object can give detailed analysis of any substance characteristic in the pipeline system.

■5.0 ADVANTAGES OF CHARGED COUPLED DEVICES (CCD) COMPARED TO OTHER OPTOELECTRONIC DETECTORS IN OPTICAL TOMOGRAPHY SYSTEMS

In a tomography system, the sensor is an important part to be considered because the right selection of sensor can give better image reconstruction [3].

Photodiodes and phototransistors can produce high resolution image reconstruction if the number of sensors is high. Unfortunately, it has limitations on the number of sensors which can be used due to their size and the diameter of the pipeline system involved [51]. CCD is not faced with this problem because this detector consists of more than a thousand cells and will give a higher resolution of image reconstruction. Other disadvantages of photodiodes and phototransistor are; the orientation of the transmitter and receiver need to be accurately positioned to avoid overlapping of light sources.

The Complementary Metal Oxide Semiconductor (CMOS), has its advantages and disadvantages too. Actually the basic construction of CMOS and CCD is quite similar in certain areas. The difference between CMOS and CCD is the built in analogue to digital converter component in the CMOS. The CMOS has a lower power consumption compared to the CCD [52]. But, image resolution produced the by CCD is the best compared to CMOS. CMOS architectures allow more built in circuits and it will function at very low gain, because of this it will cause more noise to be involved in the image reconstruction [11], [10]. The CCD has a Quantum Efficiency (QE) between 25-95 percent compared to CMOS, which is between 15-35 percent [10]. According to Mariani Idroas [8], the CCD commonly responds to 70 percent of the incident light which means its quantum efficiency is 70 percent. It proves this sensor is more efficient than photographic film, which captures only about 2% of the incident light [8]. Christian Buil also mentions that the CCD is good compared to photographic film because its quantum efficiency can reach from 40 percent to 80 percent [30].

■6.0 CONCLUSIONS

The Charged Coupled Device (CCD) Sensor can be considered as the best optical detector compared to other optoelectronic components. The specialty of the CCD Sensor such as small cell size and sensitive to dark area has helped the development of many industries, especially in astronomy and medical field in capturing high resolution images. The development of the CCD in optical tomography fields should be more aggressive in monitoring flow measurement systems. This type of sensor is highly recommended for use in tomography systems because this sensor can solve many problems that occur with other optical detectors such as termination problems, limitation problems, cost, low resolution, slow response for online measurement and much more.

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