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A Review of the Optical Tomography System

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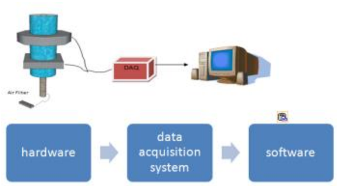
Graphical abstract



Abstract

Tomography is a method that has been used for image reconstruction in the medical and engineering fields. Optical tomography is one of the various methods applied in tomography systems. This tomography method is widely used in the medical and processing industries fields because of its special characteristics, such as immunity to electrical noise and interference, high resolution and its hard field sensors. The basic principle of the optical tomography system in measuring an object is based on its wave and radiation source. This article is a review of the characteristics of light and its interaction with matter, the types of optical tomography system, the basic construction of an optical tomography system, types of optoelectronic sensors and image reconstruction.

Keywords: Tomography; optical tomography system; light; optoelectronic sensor

1.0 INTRODUCTION

The word tomography comes from the Greek words; ‘tomo’ meaning section and ‘graph’ meaning image [1]. More than ten different tomography methods exist. There is a variety of types of tomography method, such as capacitance tomography, resistance tomography, optical tomography and ultrasonic tomography. In the early stages of the development of the tomography system, it proved its capabilities in the medical field in providing valuable information on biological matter for analysis and diagnosis purposes. Nowadays, process tomography systems are widely used in industry for plant monitoring purposes because this method is non-intrusive and a non-invasive. The reason for the increasing development of the tomography system is to help researchers or scientists to visualize the internal characteristics of matter, for example, to measure concentration, velocity, mass flow rate, and particle size distributions [2].

The optical tomography system is a famous tomography method used in medical and processing industries. The optical tomography system is considered to be a hard field sensor because the sensing field is based on the measurement of the attenuation or absorption of radiation [3]. Generally, the main concept of an optical tomography system is to analyse the structure and composition of objects by examining the waves or radiation intensity after crossing the measured object [4]. The sensors of an optical tomography system are known as optoelectronic sensors. The basic construction of an optical tomography system consists of three parts: hardware, data acquisition system and software. This type of tomography system has many advantages compared to other soft field sensors. Below, some of the advantages of the optical tomography system are given:

i. Immunity to electrical noise or interference
ii. High resolution where small wavelengths can give high resolution
iii. Negligible response time due to the speed of light. The speed of light in a vacuum is constant at $4 \times 10^8\ m/s$ [5].

Optical tomography systems can be divided into three different techniques: emission tomography, tomography for low scattering samples and tomography for highly scattered samples [6].

2.0 LIGHT AND ELECTROMAGNETIC WAVES

Examples of optoelectronic sensors include light emitting diodes (LEDs), laser diodes or infrared lasers for transmitters and photodiodes, phototransistors and charge couple devices for receivers. Optoelectronic sensors play an important role in the optical tomography system, as the basic concept of the optical tomography system is based on the interaction of light and particles and this interaction provides the readings of its compositions and structures. In an optical tomography system, it is important to study the characteristics of lights. It is important to analyse the information on how light is absorbed or emitted by matter because this is the type of data that researchers have to observe to measure the composition or molecular structures of solids, liquids, and gases. Usually, an object such as a solid material has high optical absorption and such solid materials are known as opaque objects. An object that allows partial light penetration, such as a frosted window, is known as a translucent object. Finally, those objects that allow almost 100% light penetration, such as a glass window, are known as transparent objects. [4]. In conclusion, the performance of optical tomography is highly dependent on the right choice of optoelectronic sensor and whether the matter itself is opaque, translucent, or transparent.

Light generally means electromagnetic waves with wavelengths within $4 \times 10^{-7}\, m\ to\ 7 \times 10^{-7}\, m$ [7]. This range of wavelength is known as the visible region where the frequency of light is visible and can be seen by the naked eye. Figure 1 shows the electromagnetic spectrum classified on the basis of wavelength and radiation type [7].

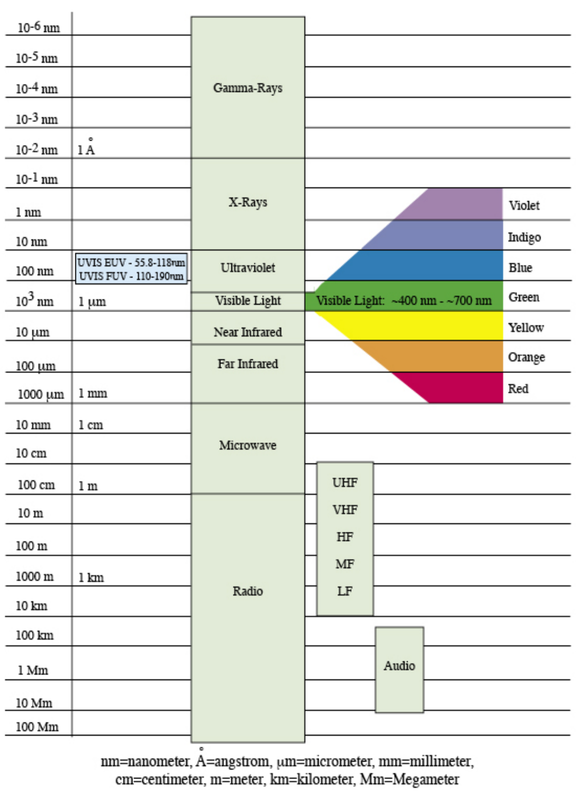


Figure 1 The electromagnetic spectrum (EM) classification [7]

From the classification of the EM above, visible light is between the small wavelength of ultraviolet radiation and the wavelength of near infrared radiation. Gamma rays and X-rays comprise a high energy region of the spectrum while microwave and radio waves comprise the low energy region of the spectrum and longer wavelengths [8]. For the short wavelengths, such as ultraviolet, the source of radiation cannot be seen by our eyes but its existence can be seen by the presence of sunburn on our skins. For the infrared wavelength, we cannot see the source of radiation but we can feel the heat that is absorbed by matter [9].

Different sources of radiation have their own specialities and uses in certain applications that can fulfil the matter requirement. For example, X-ray radiation is suitable for medical purposes, especially dealing with structures and the quantification of the density or concentration of minerals. Such application is very important in detecting bone tumours, for example [10], while microwave tomography is suitable for soft tissue image reconstruction [11]. By using the microwave tomography system, biological tissues can be differentiated based on dielectric properties, as high contrast shows muscle and low contrast shows fat and bones. Microwave tomography can provide information on the physiological state of tissues as well as the anatomical structure of an organ [11]

3.0 THE INTERACTION OF LIGHT WITH MATTER

Each object or matter consists of atom and molecules. The main structure of an atom can be seen in Figure 2. The combination of a number of atoms produces molecules.

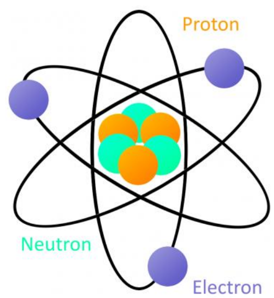


Figure 2 The structure of atoms [12]

In real life, when light interacts with matter it is actually reacting with the charge of the particles, such as the electrons and the protons. This interaction can be related to absorption, fluorescence, scattering, dispersion or oscillating phenomena. Electrical forces exist when positive ions attract negative ions or positive ions repel other positive charges. This is related to the Maxwell equations which consist of four basic electromagnetic theories: Faraday's Law, Ampere's Circuit Laws, Gauss's Law for Electrical Fields and Gauss's Law for Magnetic Fields [8]. Electrical fields are generated by attraction or repellent forces from the particle charges, while magnetic fields are generated from the moving of the particle charges.

Absorption of light is a phenomenon that happens when light strikes matter. When an electron in the matter interacts with light, it absorbs the energy of the photon at a specific frequency and goes to a higher energy state. For example, an object is red in colour because the object absorbs the other spectrum regions, such as blue and green, and it scatters only red light [8]. This absorption phenomenon is very important in monitoring the metabolic activity of living things [4]. The absorption function of the energy of photons gives varying densities of electron states. This situation is similar to the medium that exists with chromospheres. For example, heme is a chromophore that exists within protein haemoglobin. The degree of saturation of haemoglobin can be calculated by measuring the absorption spectrum of heme, depending on the degree of oxygenation of an iron atom at the centre of a porphyrin [4]. This is one of the uses of optical tomography in the analysis and diagnosis of cell tissues.

Fluorescence depends on the nature of the electrons and photons of the material. Fluorescence occurs when a photon emits at a higher wavelength compared to the wavelength of the photons that are absorbed by the photoelectric effect, that is electrons [4]. This fluorescence spectrum depends on the physical and chemical characteristics. Actually, these kinds of fluorophores exist naturally in living tissues. This spectral analysis of auto fluorescence helps the optical tomography system to easily characterize or differentiate living tissue and helps to detect the existence of tumours at an early stage [4].

There are two types of scattering phenomena: inelastic and elastic. Inelastic scattering occurs when the energy of a photon does not permit the transition of an electron. With elastic scattering, the energy and the momentum of the photon remain constant in magnitude but the direction of the propagation of the photon changes [4]. The scattering process can be a model of a gas that consists of a group of atoms that separate far apart from each other. This condition will make the electromagnetic wave scatter in all directions. Blue sky exists because of the scattering phenomenon that is known as Raleigh scattering, where the light from the Sun generates uniform scattering in our sky [4].

Dispersion happens when light goes through a prism, the light will travel at different speeds and different wavelengths. Oscillating dipoles occur when light interacts with atoms in matter; the electron of that matter will oscillate. This oscillation will produce a secondary electromagnetic wave. Then, this new electromagnetic wave will combine with the primary electromagnetic wave and produce a new wave. This new wave has different phases and it will change the velocity of the light [4].

Diffraction is another phenomenon of light that interacts with matter. Diffraction can be seen by the naked eye when electromagnetic waves encounter an obstacle, such as a compact disc, where we can see rainbow colours on it. Figure 3 below illustrates diffraction phenomena where the small opening gives greater diffraction.

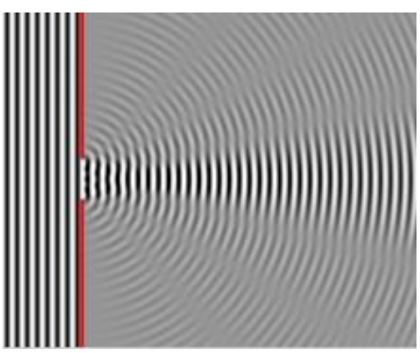


Figure 3 Illustration of the diffraction process [13]

4.0 TYPES OF OPTICAL TOMOGRAPHY SYSTEM

An optical tomography system can be categorized into three main groups: optical emission tomography, optical tomography for low scattering media and optical tomography for high scattering media [6]. Examples of applications for optical emission tomography are plasmas and flames because both emit optical radiation. It is related to measuring temperature [6]. Optical tomography was used to capture images of low scattering media and is also related to atmospheric measurements. Atmospheric measurement here means the activities of monitoring, for example, forest fire emissions, volcanic emissions, or industrial emissions [14] [15] [16]. This kind of optical tomography system is similar to the existing application known as gas absorption spectroscopy, which is used for monitoring gas concentration. Other types of optical tomography for low scattering media include: open path absorption gas phase tomography, differential optical absorption spectroscopy and the light detection and ranging system (LIDAR) [14] [15] [16]].

The optical tomography system that can measure highly scattered media is famous in the medical and processing industries. One example is known as optical projection tomography, which is widely used in biomedical applications. For this type of tomography system, the sample is enclosed in a vertical cylindrical vessel with a small diameter and the source of the light is focused on the sample in a narrow cone. Then, the light that is transmitted is projected by a set of microscope lenses onto a camera chip.

Laminar optical tomography (LOT) is suitable for non-contact measurement. Its basic concept is based on the detection of light that emerges from a strong sample at different distances from the point of the illumination source. The measurement is based on the distance of the received light [6]. Diffuse optical tomography (DOT) is suitable for measuring samples that are large in size compared to those samples used in optical projection tomography or LOT. This type of tomography is mainly based on time resolved measurements. The migration time of single photons reveals the optical path length.

Optical coherence tomography (OCT) uses an interferometer to measure interference. Interference here means the variations in wave amplitude that occur when the waves of the same or different frequencies come together. Figure 4 shows the schematic for OCT. The main concept of OCT is the source of light which, when cohered, is transmitted into a beam splitter. This beam splitter divides the light into two; one half goes to the sample arm and the other goes to the reference arm. The light that reflects back from both arms is recombined by the beam splitter. Then, the recombined light will be sent to a detector. As we know, the first light that is sent to the interferometer is monochromatic with a single frequency. Then, the same interferometer will receive another two monochromatic light waves that have different frequencies. These different frequencies will be examined [6].

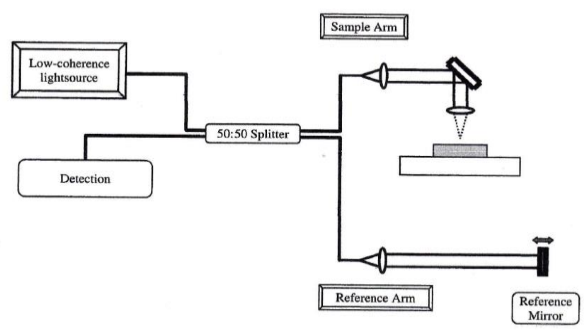


Figure 4 A schematic diagram for optical coherence tomography (OCT) [8]

Another type of optical tomography system with highly scattered media is fluorescence tomography, where the basic principle is almost the same as DOT but the differentiation is based on image reconstruction which is complicated. This is because this tomography system still measures the photon migration time through the medium, but it is convoluted by the fluorescence lifetime [6].

■5.0 BASIC CONSTRUCTION OF THE OPTICAL TOMOGRAPHY SYSTEM

An optical tomography system consists of three main parts: hardware, data acquisition system and software. The hardware consists of three main sub-parts: transmitter, plant system and receiver. The selection of the transmitter and receiver depends on the types of object to be measured.

The types of projection also need to be considered. In optical tomography, there are two types of projection: parallel projection and fan beam projection. For parallel projection, one transmitter will transmit its source to one receiver placed in front of it; while in fan beam projection, one transmitter will transmit its source to a number of receivers. The optical tomography system also has two different models: the optical path length model and the optical attenuation model. The optical path length model is based on an optical sensing beam. This model measures the existence of an object by detecting the changes in its sensing beam. The optical attenuation model measures the existence of an object by the changes in light intensity due to absorption of the light beam as it travels through different types of material [17].

A basic block diagram of the optical tomography system is shown in Figure 5. Different types of tomography methods have the same basic block diagram, the only differences among them being the types of sensors used.

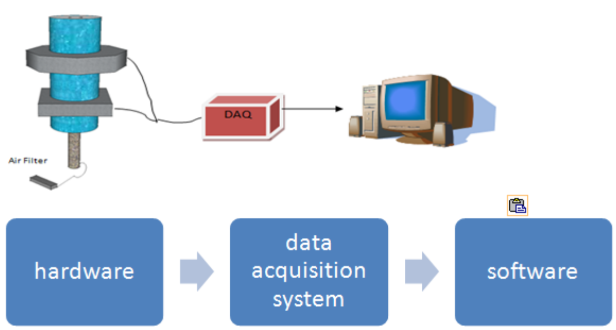


Figure 5 Basic block diagram of the optical tomography system

■6.0 TYPES OF SENSOR IN THE OPTICAL TOMOGRAPHY SYSTEM

The right selection of transmitter and receiver is very important to produce high quality image reconstructions. The main concept of optical tomography is to read the data obtained from the hardware based at the intersection of the light beam and the particle flows. The greater the number of particles intersecting with the light beam, the higher the voltage produced. This shows the linear relationships between the cross section of the number of particles and the voltage measurement [18]. In selecting appropriate sensors for the optical tomography system, the faster settling time of the optoelectronics and the high coverage of the emitters are the most important things to be considered [19].

Fibre optics has been used in the optical tomography system since 1996 to measure silica sand flows [20]. Such sensors are suitable for applications in the food and sanitation fields, and also in the medical field because the probe is small in size, is safe in operation, and has high sensitivity [21]. Many optical fibres can be involved in the tomography system to produce high resolution images because the sensor is small in diameter [22]. The advantages of using fibre optic sensors are, that they have high sensitivity to the medium attenuation of the light source, they can be applied to a limited area, they are safe and free from any electromagnetic interference and they capture data at high speed [23]. However, it is very important to pay attention to the termination of both ends of the fibre optic. Incomplete termination can cause inaccuracy of the data obtained and can result in high impact on the acceptance and emission angles of the light energy transmitted by the fibre optic [24].

An LED is a low cost user friendly transmitter. This type of sensor does not have complex circuitry. However, it can cause inaccuracy in the image reconstruction because this type of transmitter can be considered as a visible source of light when its wavelength is between 380 and 700 nm [25]. This condition is not good in an optical tomography system because the receiver will have a conflict due to other sources of visible light [25]. The size of wavelength can be disturbed by noise because this source of light can easily be deterred by the surrounding environmental light [26].

Infrared and laser diodes are suggested because both sensors are in the group of invisible light sources. Their wavelengths are between 700 nm to 1100 nm. A receiver that is synchronous with these types of transmitter can easily differentiate visible and invisible light. This can cause high accuracy in the data obtained [25]. Laser diodes can be categorized as the best transmitters for use in optical tomography sensors because they have the capability to produce flame image processing results. By using laser diodes, the optical tomography system has the capability to capture images inside the combustion chamber that deals with high temperatures and produces different visible light sources [27].

Photodiodes are widely used as receivers because of their fast response and cost effectiveness. Phototransistors are rarely used because of their slow response [22]. Photodiodes and phototransistors are actually small in size and can cover the wavelength of infrared LEDs [28].

The charged coupled device (CCD) linear sensor is another approach that can be used for image reconstruction. This type of sensor is very sensitive to dark areas. The speciality of this sensor is that only a few sensors are needed for a high resolution image reconstruction [29]. The complementary metal oxide semiconductor (CMOS) is another sensor that can be used in the optical tomography system. This type of sensor can produce high resolution image reconstructions. The advantage of CMOS is its small size and reduced complexity compared to CCD linear sensors. This is because CMOS provides on chip circuit integration, such as built in analogue to digital converters, and has lower power consumption. But it is expensive due to the high technological development [30].

■7.0 IMAGE RECONSTRUCTION

Image reconstruction is the combination of the data obtained from the sensors capturing images of an object measured from different angles and views [31]. To obtain the final image reconstruction, appropriate algorithms are applied to solve the related equations and reconstruct virtual cross section images [13]. There are three basic methods for image reconstruction: linear, iterative and heuristic. Table 1 below shows the differences among these three methods.

Table 1 List of image reconstruction methods

Method	Descriptions
Linear Method	• Is the simplest and quickest method compared to the others. Linear back projection is widely used but this method produces a poor image reconstruction for analysis. This approach was used in the early stages of medical tomography [32]. • This method produces blurry images and has difficulty in capturing scattered images. Filtering, known as the filtered back projection algorithm, has to be applied to enhance the image reconstruction [31].
Iterative Method	• It is not suitable for real-time image reconstructions because the computational load makes it too slow in processing the data [33]. • However, this method is easy to model and can handle projection noise [33].
Heuristic Method	• This method can be linear or non-linear and is based on the relationship between trained images and measurement images [34].

■8.0 CONCLUSIONS

The tomography system is a method that has been used widely in the medical and industrial processing fields. The optical tomography system is an example of the various tomography methods that can be classified as a robust system. Its sensors are hard field sensors and its measurements are not easily affected by external disturbance. A detailed study of the interaction of light sources with matter is very important because the main heart of an optical tomography system is its optoelectronic sensors that transmit and receive sources of light. Different types of optoelectronic sensors are suitable for measuring certain types of matter scattering medium. The right choice of optical tomography sensor can give high accuracy and high quality image reconstructions. The right selection of image reconstruction method also plays an important role in producing good image reconstructions for the optical tomography system.

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