Continuous wave diffuse optical tomography using multimode plastic fiber for non-destructive test of diffused material

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A simple hardware system of continuous wave diffuse optical tomography (CW DOT) is proposed and demonstrated for non-destructive test using multimode plastic fiber. The multimode plastic fiber transmits a signal that is scattered and captured by the receiver. The system consists of a near infrared (NIR) light source, a mechanical rotation stage for the object and detector, a silicon detector, a set of fiber, a driver for the data acquisition system and computerized data analysis software. The NIR with wavelength of 808 nm is launched onto the object surface and the scattered signal is collected by a set of fiber. The object is put on a mechanical rotation stage, which consist of 16 holes for light transmission and reception, respectively. A fiber probe for the acquisition of the received signal is connected to the mechanical rotation stage for the detector. The mechanical rotation stage for the object and detector can both be rotated and controlled by a data acquisition system driver. A simple CW DOT hardware system is used to scan an object. The object used in the experiment is a circle of homogeneous polyvinyl chloride and an anomaly which is inserted into the homogeneous object. The intensity of the scattered signal from various positions of the source-detector pair is reconstructed by a linear single step reconstruction. The stability of the rotation mechanical stage for the object and detector are tested and show that the rotation stage have high stability. The results of the image reconstruction show that this system can be used for scanning an object which has the same image reconstruction as the original object. Therefore, the developed CW DOT system has been successfully constructed.

1. Introduction

In recent years, optical medical modalities have drawn significant attention from researchers. Visible and near infrared (NIR) light have been used for surface reflectance, trans-illumination and transmission based imaging modalities. Diffuse optical tomography (DOT) is one of the promising imaging modalities that provide the spatial distribution of optical properties (absorption coefficient, scattering coefficients, and refractive index) within the object from measurements at the boundary using visible and NIR as the probing radiation. The light illuminates the tissue through the optical fibers to multiple points positioned on the surface of the object. Another set of fiber is used to collect the transmitted or reflected light intensities at the boundary [1–4]. Using these limited boundary measurements of the exiting light, the optical properties of the tissue are estimated by making use of a model-based image-reconstruction algorithm and can be displayed as two or three dimensional images [5].

In general, optical imaging systems that are used to obtain the data at the boundary for image reconstruction can be divided into three different categories: steady-state domain (SSD) or continuous wave domain method (CW) [6,7,8], frequency domain method (FD) [9,10,11], and time resolved domain method [12,13,14]. In the time-resolved methods, a short laser pulse is used as a probe signal, and the temporal distribution of photons transmitted from the tissue surface is detected using either a synchronous scan streak camera or a time-correlated single photon counting (TCSPC) system. In the frequency domain method, an amplitude-modulated light source is used to illuminate the object and the phase shift and demodulation of the transmitted light are measured, usually using a heterodyne detection method. The time resolved and frequency domain methods exhibit high temporal resolutions (in the pico second range for the time resolved and nanosecond for the frequency domain). But, they have the disadvantages of high cost and complexity in the equipment [2,15]. In the SSD (CW) system, the light source continuously emits light onto the object and the amplitude of the outgoing light from the boundary is measured. The continuous intensity system has the advantage of low cost and high dynamic range, as well as a relatively high signal to noise ratio (SNR) [2,15].

Optical fiber-based sensor technology offers the possibility of developing a variety of physical sensors for a wide range of physical parameter. The use of optical fiber samples for the development of optical fiber sensor allows us to obtain very high performances in their response to

many physical parameters (displacement, pressure, temperature, electric field, etc) compared to conventional transducers [16]. In this paper, a set of multimode plastic fiber is used to transmit signal and the scattered light from the object is detected using a simple continuous wave diffuse optical tomography (CW DOT) hardware system. This system is used for non-destructive test diffuse plastic material (PVC), which is used in many product industry, such as medical equipment, plus construction, automotive and electrical cabling. Before being blended with other ingredients to give formulations for a wide range of products, the basic form of PVC is a white powder and PVC is made from vinyl chloride monomer molecule. Since the PVC is a diffused material, the light that is launched onto the PVC object will be scattered.

2. Experimental setup

Fig. 1 shows a schematic diagram of the experimental procedure. Our focus is to design and build the mechanical and hardware system, primarily on the design and construction of the mechanical rotation stage the object and detector; and also the design of the driver for controlling the motion of the mechanical stages. The performance of the system is tested by: first, testing the stability of the motion of the mechanical stages; and second, scanning the object with this system to acquire the reconstruction data.
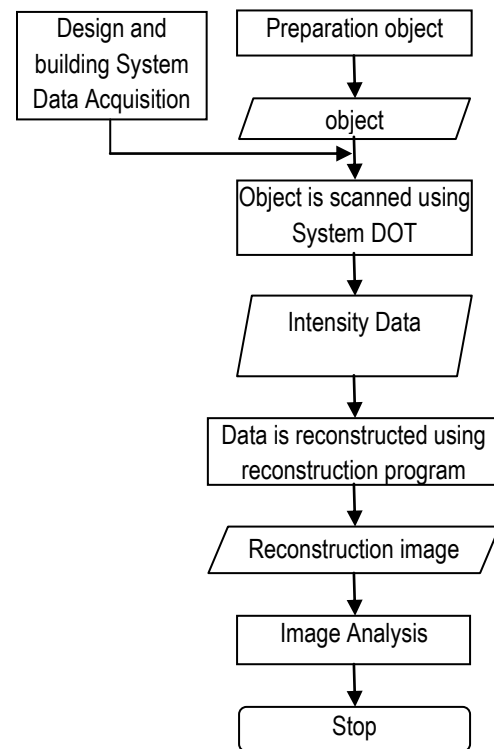

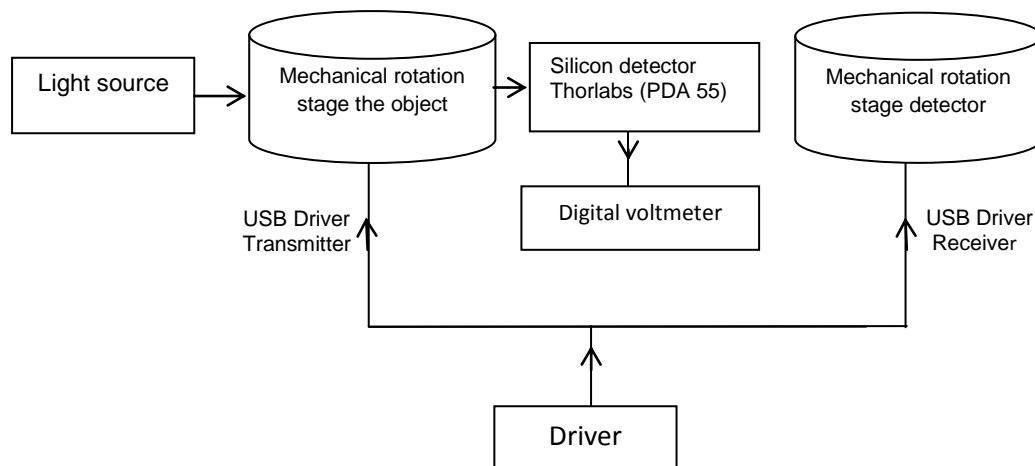*Fig. 1. A schematic diagram for the experimental procedure.*

Fig. 2. A block diagram of the simple CW DOT hardware system.

Fig. 2 shows a schematic diagram of the simple CW DOT hardware system. The system consists of a NIR light source, a mechanical rotation stage for the object, a silicon detector, a mechanical rotation stage for the detector, a set of fiber, a driver for the data acquisition system and a computerized data analysis software. The NIR with wavelength of 808 nm and power of 25 mW is launched onto the object surface through a hole (d=3mm) on the mechanical rotation object stage. The scattered signal from the object is collected by a set of fiber through a hole (d=2mm) at the mechanical rotation object stage. The mechanical rotation object stage consists of 16 holes for light transmission to the silicon detector (Thorlabs PDA 55).The electrical output of detector is connected to digital multimeter. The mechanical rotation object stage is rotated to allow the transmission of the laser to the object. The configuration of the mechanical rotation stage is shown in Fig. 3. A set of receiving fiber probe is connected to a mechanical rotation detector stage. The configuration of mechanical rotation detector stage is shown in Fig. 4. The rotation of the mechanical object and detector stage is controlled by the data acquisition system driver.
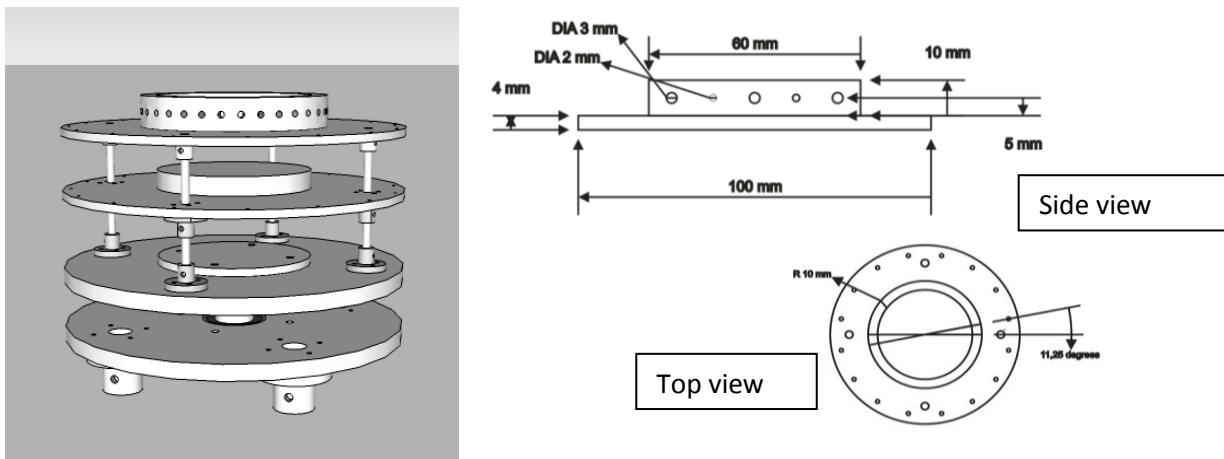
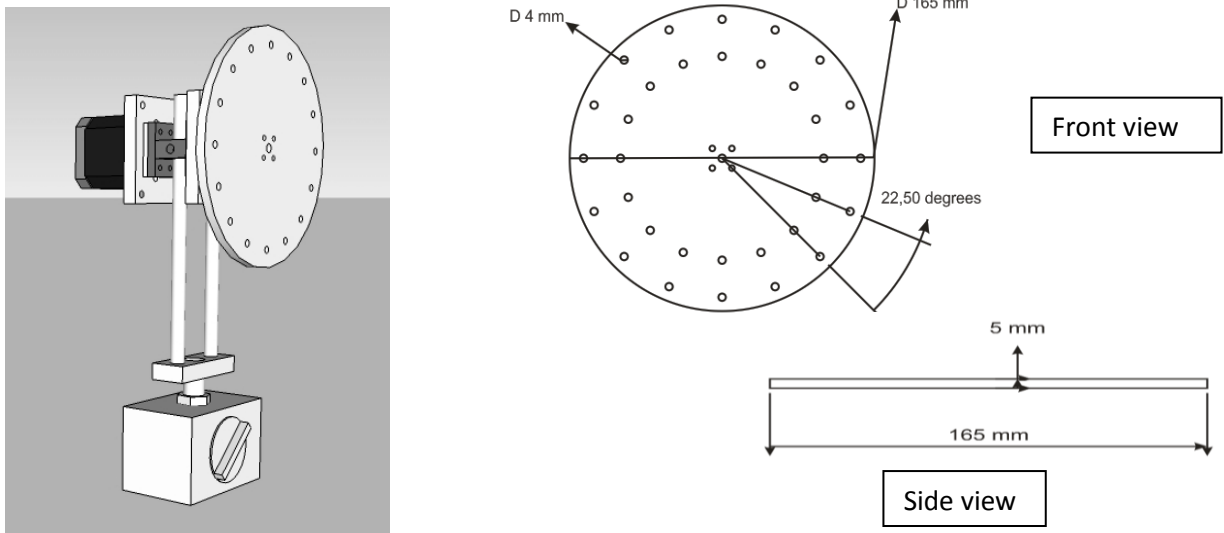*Fig. 3. A configuration of the mechanical rotation object stage.*

Fig. 4. A configuration of the mechanical rotation detector stage.

To test the performance of the proposed imaging system, this system is used to scan an object. The object is a circle of homogeneous polyvinyl chloride with a diameter (d) of 30 mm with inserted anomaly. An anomaly has a diameter of 6 mm at 4mm from edge, d=6 mm for two anomaly with same size, and d =5 mm and 10 mm for two anomaly with different sizes as shown in Fig. 5. The object is put on the mechanical rotation object stage and scanned at various positions of the source-detector pair.
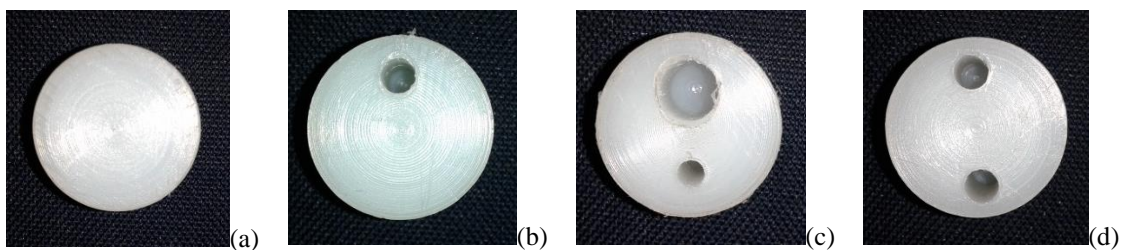

Fig. 5. Object a) Homogeneous (referens); b). one anomaly c) two anomaly with different sizes;
d) two anomaly with the same size.

The scattered signal intensity for various positions of the source detector pair is reconstructed by using a linear single step reconstruction. Image reconstruction is done based on the diffusion equation and the finite element method, and sought from boundary-value measurements. The result is used to validate the setup of the developed CV DOT system.

During the image reconstruction, both forward and inverse computations are investigated. Firstly, the forward computation is performed to obtain the intensity out of a phantom for a given source, and the initial-guess scattering and absorption coefficients. Secondly, the inverse computation is performed to compute the scattering and absorption coefficients for a known light source and the measured intensities. The modelling described here uses light propagation through diffusive media via diffusion approximation of the Boltzmann equation.

In the CW case, the diffusion equation (DE) can be written as

$$-D(r)\nabla\phi(r) + \mu_a(r)\phi(r) = q(r) \qquad (1)$$

Where r is the location in the tissue domain Ω, $\Phi(\mathbf{r})$ is the photon density distribution, $\mu_a(\mathbf{r})$ is the absorption coefficient distribution, $q(\mathbf{r})$ is the source term, D is the diffusion coefficient given by $D = 1/[3(\mu a + \mu_s')]$, where $\mu_s' = (1-g)\mu_s$ is the reduced scattering coefficient, μ_s is the scattering coefficient, and g is the anisotropic factor. The finite element method (FEM) is used to solve equation (1) and generate the modelled data $F(\mu_a)$ for a given distribution of the absorption coefficient.

Writing the Taylor series expansion of $F(\mu_a)$ around the initial distribution of the absorption coefficient μ_{a0},

$$F(\mu_a) = F(\mu_{a0}) + F'(\mu_a - \mu_{a0}) + (\mu_a - \mu_{a0})F''(\mu_a - \mu_{a0}) + \cdots \qquad (2)$$

Where, $F' = J = \frac{\partial F(\mu_a)}{\partial \mu_a}$ is the Jacobian and similarly G'' is the second order derivative. Ignoring the higher order terming by assuming that the initial guess is very close to the solution gives rise to the linearization inverse problem [4]

$$\Delta M = J\Delta\mu \qquad (3)$$

Where, $\Delta\mu = (\mu_a - \mu_{a0})$, and $\Delta M = F(\mu_a) - F(\mu_{a0})$. The Jacobian matrix is usually very large, ill-conditioned, and ill-posedness of the inverse problem. In order to tackle this condition, a regularization parameter is used to stabilize solution, so equation (3) is described as

$$[J^T J + \lambda I][\Delta\mu] = J^T \Delta M. \qquad (4)$$

Equation (4) is used to generate the image reconstruction. ΔM measures the boundary data by evaluating the difference between two states. $\Delta M = F_{ref} - F_{an}$, where F_{ref} and F_{an} correspond to the data acquired without and with a change in optical properties [3]. The value of $\Delta\mu$, which is required from reconstruction process is mapped into circular cross section with triangle element of pixels as shown in Fig. 6.
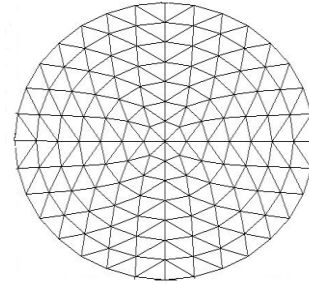

Fig. 6. A circular cross section with triangle element of pixels.

3. Results and discussions

The simple CW DOT hardware system is used to scan the diffuse plastic material (PVC) as shown in Fig. 5. Furthermore, the rotation stability of the mechanical object and detector stage are tested. Fig. 6 and 7 show the stability results of the mechanical rotation object and detector stage, respectively, when used with different source powers.
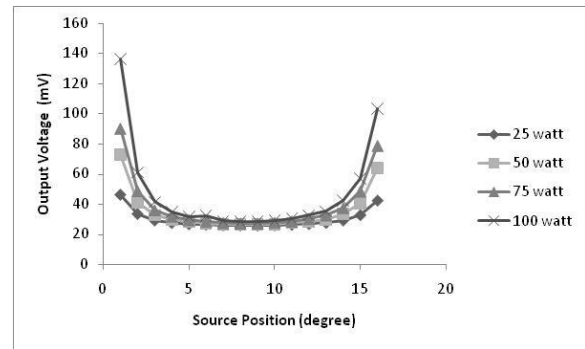

Fig. 7. Profile stability of rotation mechanical object stage at different source powers.
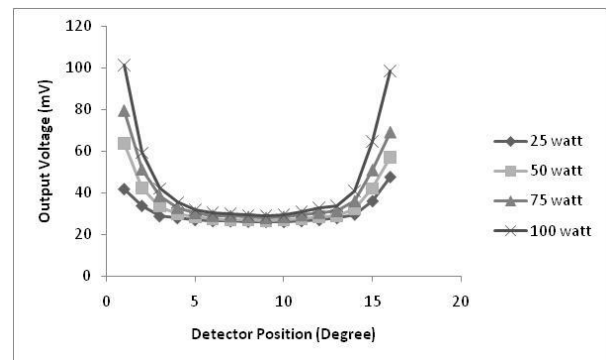

Fig. 8. Profile stability of rotation mechanical detector stage at different source powers.

The standard deviation measurement is observed from 0 to 0.38 at various source positions source and from 0 to 0.08 at various detector positions. Fig. 7 and 8 show the same trend for the line profile measurements at various source and detector positions. The standard deviation measurement in Fig. 7 and 8 indicate that the mechanical rotation object and detector stage have high stability, enabling the CW DOT system to be used to scan an object. Fig. 9 shows the image reconstruction of the object with anomaly. The results for the image reconstruction show that image reconstructions have the same configuration with the original objects. Fig. 9 shows that the designed system can be used to scan an object, therefore the CW DOT system has been successfully developed.
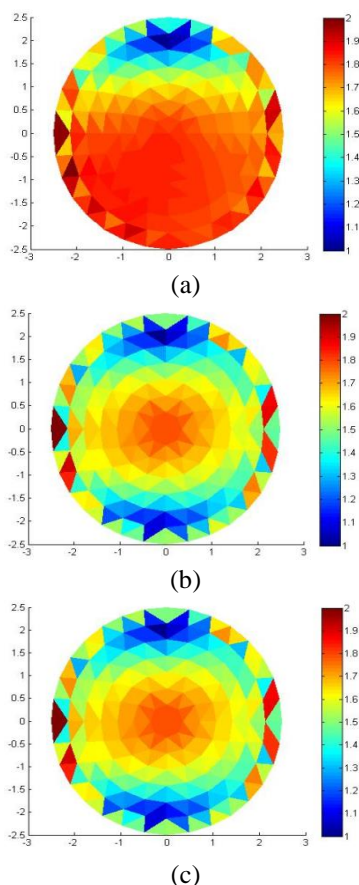
reconstruction as the original object. The simplicity of the CW DOT design has advantages such as low operation cost and potential use in medicine.

Fig. 9. Image reconstruction of an object with: a). one anomaly; b) two anomalies of different sizes; c) two anomalies with the same size.

4. Conclusion

A simple hardware system of continuous wave diffuse optical tomography (CW DOT) is constructed for non-destructive testing of diffused plastic material using multimode plastic fiber probe, which is used to transmit a signal that is scattered and captured by the receiver. The rotation stability of the mechanical rotation stage for the object and detector demonstrate high stability. The results of the image reconstruction show that this system can be used for scanning an object with the same image

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