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DETECTION AND ANALYSIS OF JADE MATERIAL USING OPTICAL COHERENCE TOMOGRAPHY

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ABSTRACT

Jade is a type of rare and expensive stone. The current approaches for jade exploration and processing are blindly and wasteful. Capable of performing high resolution, cross-sectional sensing of the internal structure of materials, Optical Coherence Tomography (OCT) could be used to greatly facilitate these jade procedures. By detecting the signal intensity and analysing the internal texture, OCT system can indicate if the jade exists and what the type it could be. It provides a tool to guide the artist in designing and making the jade artworks. It also can be used for discrimination of the fake antique jade wares, as well as anti-counterfeiters on the jade market. In this paper, we present how a Swept-Source OCT system to detect and analysis the internal features of jades. Algorithms for feature extraction and classification are described and experimental results with various unearthed jades are demonstrated.

Key words: optical coherence tomography, jade estimation, texture analysis, artwork diagnostics, pattern recognition.

1. INTRODUCTION

Optical coherence tomography (OCT) is an emerging technology for high-resolution cross-sectional imaging of 3D structures. The first OCT system was reported by Fujimoto et al in 1991 [1], and then the OCT technology has been attracting attentions of researchers all around world [2,3].

OCT relies on the interferometric measurement of coherent back scattering variation to probe the structure of test samples such as biological tissues or other turbid materials. It takes advantage of the short temporal coherence of a broadband light source to achieve precise optical sectioning in depth.

Advantages of OCT vs. other volume-sensing systems are:

1) Higher resolution. This feature enables greater visualization of fine details of the sample. Resolution for different systems are: OCT, 5-10 microns; ultrasound, 150 microns; high resolution computerized tomography (CT), 300 microns; magnetic resonance imaging (MRI), 1,000 µm, respectively;

2) Noninvasive, non-contact. This feature increase safety and ease of use, which is important for the applications where the sample is precious and delicate;

3) Fiber-optics delivery. As fiber diameter is normally 125 microns, it allows OCT to be used in very small probing space, such as tiny hole, slot and crack;

4) High speed. The new generation of OCT technology has no mechanical scanning procedures, which enables high-speed 3D sensing, particularly for the full-field OCT;

5) Potential for additional information of the testing sample. The new optical property of samples could be explored by functional OCT. For examples, polarization contrast, Doppler effect, as well as spectroscopic information;

6) Use of non-harmful radiation. This feature provides a safe working environment for both testing sample and system user, unlike traditional CT working with X-ray and ultrasound relying on mechanical vibration.

In the past decade, OCT systems have been developed mainly for medical and biomedical applications, especially for the diagnostics of ophthalmology, dermatology, dentistry and cardiology. To explore the capabilities of OCT system for probing the internal features of an object, references [4,5] reported the applications for multiple-layer information

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retrieval and internal biometrics [6,7]. In addition, because OCT has the voxel resolution of micrometer size, it has potential applications in material investigation [8] and artwork diagnostics. Reference [9] describes OCT diagnostics used for museum objects, involving stratigraphic applications; varnish layer analysis; structural analysis and profilometric applications.

As an expensive natural stone, jade has a worldwide market. In the jade industry, there are four main steps in the procedure: detection, assessment, cutting, and artistically carving, which are basically based on human eyes and/or experiences. Given the advantages listed above, OCT may pave a new avenue to lead the traditional procedure to volume data based machine vision system. This paper describes and discusses the potential applications of using OCT technology to jade cross-sectional imaging, analysis, and presents experimental results of different types of jades.

2. OPTICAL COHERENCE TOMOGRAPHY

For the direct imaging, such as ordinary photography, all the layers reflected from the underneath of an object will be fused together. However, in optical coherence tomography imaging, due to the introduction of a coherence gate generated by an interferometer and broadband light source, the fused layers could be separated from each other.

As well known, the detection of light waves from an interferometer can be expressed as:

$$I_d = E_s^2 + E_r^2 + 2E_s\, E_r \cos(2\Delta L / \lambda_0), \quad (1)$$

where, λ_0 is the central wavelength, ΔL is the optical path difference between two arms, E_s, E_r are electromagnetic waves from sample arm and reference arm, respectively.

When a partial coherent light source with a Gaussian spectral distribution is used in the interferometer,

$$I_d = E_s^2 + E_r^2 + 2E_s\, E_r \exp(-4 \ln2\, \Delta L / Lc^2) \cos(\Delta L/ \lambda 0). \quad (2)$$

Where, $\exp(-4 \ln2\, \Delta L / Lc^2) \cos((\Delta L/ \lambda_0)$ is called coherence function, and Lc is the coherence length, given by

$$Lc = (2 \ln2 /\pi\pi)\, (\lambda_0^2 / \Delta \lambda) = 0.44\, \lambda_0 / \Delta \lambda\ . \quad (3)$$

In OCT system, Lc acts as the coherence gate, which directly determines the depth resolution of an OCT system.

The first generation OCT is Time Domain OCT system (TD-OCT), which is based on a Michelson interferometer. In TD-OCT system, a mechanic moving device is introduced to scan difference layer at different depth by moving the reference mirror. As the light source is broadband, when the mirror moves, the interferometer will produce a window of moving interference fringes, i.e. coherence gate, which scans through the sample. For the ordinary camera imaging, all the reflected/scattered light from different layers are collected together and eventually form a fused image. However, in the OCT imaging, only the layer whose optical length is the same as that in reference arm has been modulated by the interfering fringes, i.e., windowed by the coherence gate. By a specially designed algorithm, the image this layer can be extracted from others. The broader the bandwidth the source possesses, the narrower the gate and the finer resolution the extracted cross-sectional image achieves.

Considering the scanning procedure in TD-OCT is actually a procedure of convolution, Es in Eq. (1) can be expressed by

$$E_s \propto\ E_r \otimes\otimes h_s\ , \quad (4)$$

where hs is the impulse response of the sample. Its Fourier transform becomes

$$S_s(\omega) \propto\ S_r\, (\omega) \cdot H\, (\omega)\ . \quad (5)$$

$S_r(\omega)$, and $H(\omega)$ are Fourier transform of E_r and h_s , respectively. Actually, $S_r(\omega) = ½ S_0(\omega)$ where $S_0(\omega)$ is the light source spectrum. Considering the interferometer structure, the signal detected by sensor is given by

$$I_d(\omega) = | S_r(\omega) + S_r(\omega) H(\omega) |^2 = S(\omega) [1+ H(\omega)]^2 , \quad (6)$$

where, $S(\omega) = ¼ S_0^2(\omega)$.

Equation (6) is the foundation of Fourier Domain OCT (FD-OCT), the second generation of OCT. Actually, FD-OCT can be further divided by Swept-Source OCT (SS-OCT) and Spectral Domain OCT (SD-OCT) [23, 24]. SD-OCT gets the full broadband $I_d(\omega)$ in one shot but collects the signal in series from the linear detector array. However, SS-OCT collects the spectral signal in series by changing the wavelength of the light source. To build the internal construction, both systems need additional Fourier transforms, implemented by either hardware or software. FD-OCT and SD-OCT have several advantages over TD-OCT. Because of no mechanic scanning, the FD-OCT system is significantly faster, 50 to 100 times, than TD-OCT. In addition, both FD OCT and SS OCT have better sensitivity and signal noise ratio [10].

3. OCT TECHNOLOGY APPLIED TO JADE

Jade can be classified into two groups: nephrite jade or jadeite jade. Nephrite jade, (a silicate of calcium and magnesium), is the historical Chinese jade, or “stone of heaven”, a stone revered by the Chinese for more than 5000 years. Nephrite is prized for its special qualities: its extreme toughness, (the toughest of any natural stone), its alluring translucency and a smooth polished feel. Colors of nephrite jade range from pure white to all shades of green. Jadeite jade, (silicate of sodium and aluminum), is a relatively new jade introduced to China from Burma in 1784. Gem quality of jadeite is extremely rare and thus extremely expensive. Jadeite is slightly harder than nephrite jade. It is often color enhanced. Colors of jadeite range from white to black with intense greens and lavender being the most sought after.

There are 4 distinct steps in the procedure of jade.

1) Exploration. This process involves drilling into the mountain side with water cooled diamond tipped core drills. The cores are then extracted and examined by eyes to determine if the jade will meet the gem grade requirements suitable for the finished products and gem stones.

2) Breaking Out. After the jade cores have been examined and quality has been determined, the miners will analyze the face looking for cleavage points. These natural joints can be exploited to remove the jade. More core holes will be drilled, and heavy hydraulic spreaders will be inserted into these cracks to push the jade apart.

3) Cutting. After the jade boulders have been broken out, they are then taken to huge diamond saws to be reduced to manageable sizes. The sawyer will also cut windows into the boulder to better expose the texture of the jade inside.

4) Artistically carving. The jade sculptors will finally make the raw jades, small or big, into art crafts. Normally there are marks and textures exist inside the raw jade, which create a lot of challenges and opportunities to the artist in designing and carving. A beautifully carved jade should maximally use the jade material and creatively borrow the internal aliens.

By means of OCT technologies, all the 4 steps of the jade procedure could be greatly facilitated. In the Exploration step, the cores can be examined by OCT system. Instead of cutting off a large area at the core for visual observation, a small hole is drilled into the core and then a tiny fiber probe of OCT is inserted to analyze if the jade is there and what is the type and quality of the jade. In Breaking Out step, OCT technology can also be used to find the natural joints or flaws inside the core for cleavage. It will greatly reduce the waste of material and increase the accuracy of the quality analysis. In Cutting step, to explore the beauty inside, the normal way is to cut a window into the boulder. However, this blindly bulk trials definitely waste and damage the jade, particularly when the jade is a high quality one. However, by using an OCT system, it will make the waste and damage to the minimal level. In the last step, Artistically Carving, the most annoying issue is that the artist has to guess what is hidden underneath the surface of the jade, especially the existence and features of the marks and textures. If the guess is wrong, an almost perfect art work may be destroyed and devalued by the unknown internal structure at the last minute. However, with the help of the OCT system, the sculptor can see through the material in depth and therefore, successfully master the jade carving to a perfect ending.

Another potential application is the discrimination of the fake antique jadewares, which is critical in the antique market. The real ancient jade always carries some ooze and deposit on and under the surface, after hundreds or thousands years burial. The optical penetration features, for examples, the signal intensity decay and texture pattern, are different between the real one and fake one. These features can be detected and described by an OCT system and specially designed algorithms.

In addition, even for the expensive non-antique jades, there are so many counterfeiters on the market. OCT technology could also be used to recognize the artificial ones by analysing the optical and structural features. For example, the miniature air bubbles exist inside many manmade jades that are normally invisible by human eyes, however, the capability of detecting these miniatures at a micro meter level, is the strength of OCM systems.

In [11], authors proposed a method to monitoring the subsurface morphologies of archaic jades by using of OCT technology. However, due to the limited imaging depth of their OCT system, the more accurate analysis of the jade, particularly the internal texture analysis, could not be performed. The OCT system we developed for jade application is a swept-laser based system, which has the probing range of 8 mm with a depth resolution of 7 μm. It can be used to distinguish the jade and non-jade materials and analyse the internal texture features of different jades. More details of the system configuration and experimental results for different jades OCT imaging are provided in the next section.

4. EXPERIMENTS AND RESULTS

The OCT setup used in experiments is illustrated in Figure 1. The wept source is a commercially available swept laser with a scanning frequency of 20 kHz, a spectral range of 110 nm centred at 1320 nm and a optical power of 10 mW (SANTEC, Japan). The light is directed through a 2 x 2 fibre coupler on the reference mirror and the sample arm. The optical tip is mounted on a galvo-scanner, which focuses the light on the sample through a fibre ball lens. The back scattered / reflected signals from both mirror and sample are input into a second 2 x 2 fibre coupler configured in a Mach-Zehnder geometry. Its two outputs become the input in a balanced detector (New Focus). The output of balanced detection is recorded with a digitizer (Alazartech) at a 100 MHz sampling rate. The signal is re-sampled to equal frequency intervals and subjected to an inverse Fourier transform. The resolution of the setup is 7 μm for axial direction.

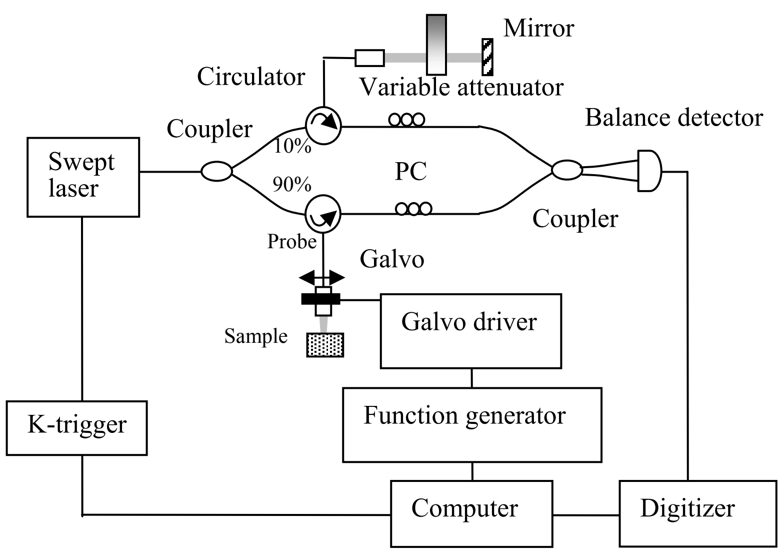

Figure 1. Swept-Source OCT used in experiments

In order to find the optical property of a jade, we firstly measured the intensities of OCT signal reflected or back scattered from the jade body and non-jade material deposited on surface. The photo inside Fig. 2(a) shows a jade (dark green-like) with some deposit (white-like) material wrapped on it. Two OCT A-scans (depth scan), A-scan 1 and A-scan 2, were performed upon the non-jade area and jade body area. Figure 2(b) and (c) show the plots of A-scan 1 and A-scan 2 signals, respectively. In these plots, the first peak represents the DC component, the second peak results from interlayer interference. The third peak is caused by the surface of the testing object. It is easy to see that there is about 20dB difference in the OCT signal intensity between jade and non-jade materials. Hence, the intensity of the OCT signal provides an effective indication for detecting the jade presence. In this case, the threshold can be set as -40 dB.

To explore the internal structures, different types of jades, numbered 1-6 shown in Fig.3 (a)-(f), were then tested. Differing to the en-face image, the A-scan OCT image contains some open-air area, which is non-object and needs to be removed before doing texture analysis. We have designed a two-step algorithm to segment the object area. In the first step, a binary mask was created by finding the maximum points in each vertical line (A-scan line). Because the maximum pixel may not be located at the object border, the second step is needed to remove these vertical thorns. The segmented OCT image is called SgOCT image, in which the pixels in open-air area are not counted in jade analysis.

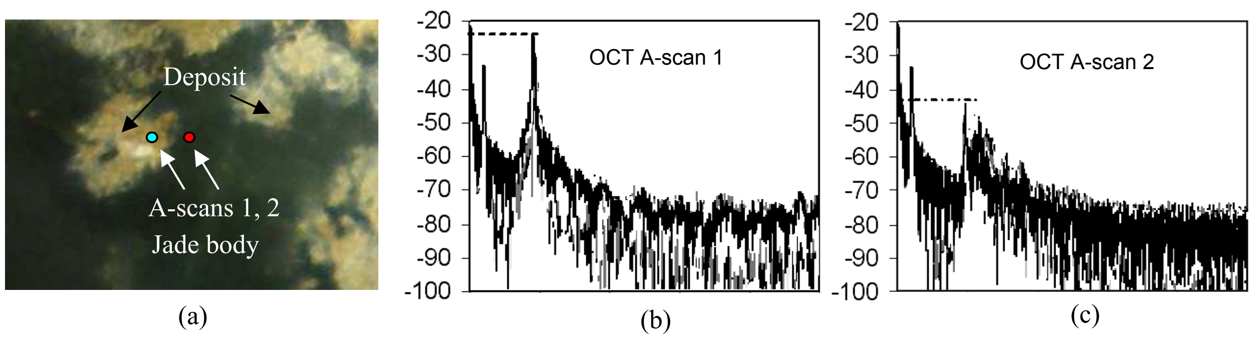

Figure 2. Two A-scans on jade body and non-jade material

Reference [12-14] reported different methods to analyse the texture features, especially for the biology samples. As for the jade texture, we proposed to extract six parameters from an A-scan OCT image. They are 1) Entropy of the SgOCT image; 2) Half-peak width of the histogram of the SgOCT; 3) Standard deviation of histogram of SgOCT; 4) Average gray value of SgOCT; 5) Standard deviation of SgOCT; 6) Variance of SgOCT. Table 1 provides the values of these parameters of six jades shown in Fig. 7. For each set of parameters, all the values are normalized from 0 to 1, which was done by subtracting the minimum and then dividing by the maximum.

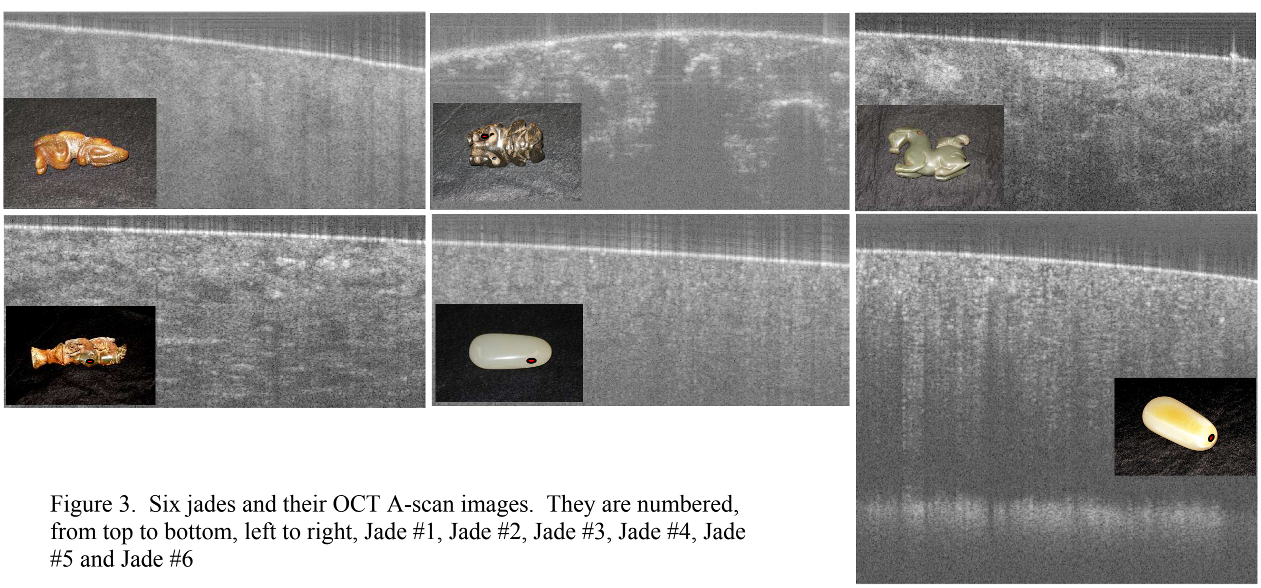

Figure 3. Six jades and their OCT A-scan images. They are numbered, from top to bottom, left to right, Jade #1, Jade #2, Jade #3, Jade #4, Jade #5 and Jade #6

Six-parameter can form a texture vector:

$$\mathbf{V}_i = a_1 f_{1i} \mathbf{v}_1 + a_2 f_{2i} \mathbf{v}_2 + a_3 f_{3i} \mathbf{v}_3 + a_4 f_{4i} \mathbf{v}_4 + a_5 f_{5i} \mathbf{v}_5 + a_6 f_{6i} \mathbf{v}_6, \quad i=1,2,\ldots 6. \qquad (8)$$

Where, $f_1 - f_6$ are the normalized values of parameters in Table 1. $\mathbf{v}_1$ - $\mathbf{v}_6$ are the unit vectors representing each parameter, respectively. Table 2 gives the variances of each parameter for different jades. a_1 - a_6 are weighting factors, whose values are given by the order of the values of variances. For example, the parameter with the maximal variance has a weighting factor 6, and the one with minimal variance has a factor 1, simply because we have six vector components. All these weighting factors are listed in the send row of Table 2.

Table 1. Normalized values of 6 parameters

		Jade 1	Jade 2	Jade 3	Jade 4	Jade 5	Jade 6
f_1	Entropy	0.2941	0.2618	1.0000	0.2471	0.3088	0
f_2	Half peak width	0.6543	0	1.0000	0.6543	0.6162	0.1924
f_3	Std. dev. entropy	0.5972	0.8665	0	0.6573	0.6198	1.0000
f_4	Av. gray image	0.8160	0.6748	0.6288	1.0000	0.6656	0
f_5	Std. Dev. image	0	0.1882	0.5926	0.2750	0.2103	1.0000
f_6	Var. of image	0.6024	0.6491	0	0.6298	0.5987	1.0000

Table 2. Variances and weighting factors for each vector components

	f_1	f_2	f_3	f_4	f_5	f_6
Variance	0.1136	0.1307	0.1183	0.1143	0.1301	0.1042
a_i	2	6	4	3	5	1

The intensity of the texture vector of jade #i is given by

$$|\mathbf{V}_i|^2 = \Sigma_j (a_j f_{ji})^2, \quad j=1,2,\ldots 6, \tag{9}$$

which can be used to numerically distinguish the type of jade. The intensities of texture vector of six jades used in experiments are given in Table 3 and shown in Fig. 9. From these results, six jades can be classified at different |Vi |2 values. Among them, jade #1 and #5 have closed values. Looking at Fig. 7(a) and 7(e), apparently, the textures of these two jades look kind of similar.

Table 3. Intensities of texture vector for six jades

	Jade 1	Jade 2	Jade 3	Jade 4	Jade 5	Jade 6
$\|\mathbf{V}\|^2$	27.8189	17.6935	52.3397	33.8558	25.6501	43.3324

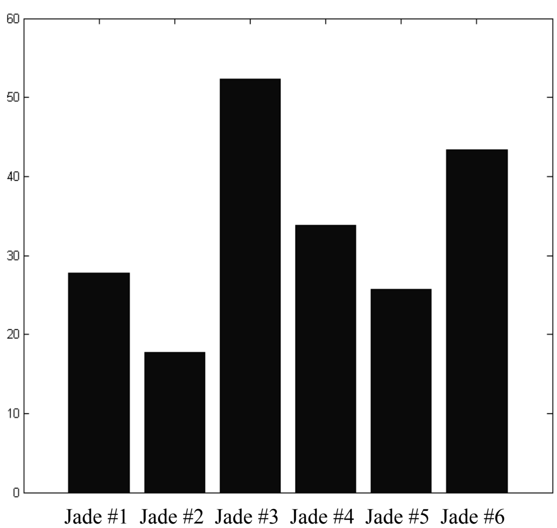

Figure 4. Intensities of texture vector of 6 jades

5. SUMMERY AND DISCUSSION

Optical coherence tomography paves a new avenue for exploring and analysing the internal structure of an object. The micron level resolution makes it unique to other tomographic imaging technology. OCT technology has potential applications to many fields, including medical, security, environment, and industrial. In this paper, we have briefly described the principle of different OCT systems and shown the possibility of their application in jade exploration and analysis.

Because the jade is almost translucent to the IR light and has internal texture associated with different type, this property can be used to detect the presence of jade. Experiments show that there is a big difference, around 20 dB, of the reflected/back scattered OCT signals between the jade body and the non-jade wrapping material. And also, almost no structure is detected in the non-jade material in the depth due to the weak signal. Based on the jade samples we currently have, we proposed a texture analysis method upon their OCT signal. Six parameters were used to numerically describe the texture pattern of the jades. To the best of our knowledge, it is the first time, the internal crossing-sectional structure and texture of jade materials is extracted and analyzed. Experimental results show that the OCT technology could be a useful tool for the jade exploration and analysis by machine vision. For example, by drilling a tiny hole in the boulder of jade, and placing a fibre probe into it, the OCT system can provide a solution if there is jade inside and what kind of the type it could be. It will greatly facilitate the traditional jade procedure. In addition, with the help of an OCT system, it could avoid the waste in raw material preparing as well as reduce the risk in artistically carving. Another important application is the anti-counterfeit of the expensive jadeware. Although we do not have counterfeit samples at present time for testing, we believe that it is possible to distinguish the real and fake ones based on their internal structures and texture patterns. This will be our plan for future work.

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