Edge illumination X-ray phase contrast imaging with equiangular time-delay integration scanning: EXPITIS

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ABSTRACT

A micro-CT scanner creates 3D images of a small specimen's x-ray attenuation. Edge illumination phase contrast X-ray imaging (EIPCXI) is a method of imaging how the specimen refracts X-rays. Equiangular time-delay integration (EATDI) is a method whereby the specimen is moved in an arc about the X-ray source whilst simultaneously reading out the CCD X-ray camera. By synchronizing the movement with the shifting of the image on the CCD, the recorded image averages out all defects and irregularities. A feasibility prototype scanner combining both EIPCXI and EATDI techniques has been built and tested.

Keywords: Tomography; Phase-contrast imaging; Time-delay integration.

1. INTRODUCTION

- Conventional X-ray images depict the intensity of an X-ray beam as it is attenuated by the object under investigation. By taking multiple images at different angles, it is possible to reconstruct a 3D representation of the X-ray attenuation property of this object. The ability to resolve features in the object depends on the relative differences in their X-ray attenuation coefficient. Where attenuation is low, or features to be resolved have a similar X-ray attenuation, feature segmentation may be impossible. Phase-contrast imaging, as its name implies, depends on shifts in the phase of the X-rays as they propagate through the specimen and can be up to a thousand times as sensitive as attenuation contrast (1-3). Edge-illumination X-ray phase contrast imaging (EIXPCI) is a method whereby carefully aligned X-ray masks convert shifts in X-ray phase to changes in intensity (4), with developments at UCL enabling this to be used with a conventional laboratory X-ray source (5). Equiangular time-delay integration scanning (EATDI), developed at QMUL (6) is a method whereby the object under investigation moves in an arc around the X-ray source whilst simultaneously reading out a CCD imaging system. This eliminates the effects of inhomogeneities in either the detector elements or the X-ray field, both of which constrain the attainable contrast ratio.
- This project aims to combine EIXPCI with EATDI to offer an unprecedented X-ray phase contrast ratio. A further advantage of EATDI in this system is that irregularities and defects in the mask are "averaged out", together with other inhomogeneities in the X-ray field and detector components (scintillator, optical coupling and CCD). The only limit to attainable contrast ratio is exposure time.
- As anticipated, mask alignment was a simple matter. The detector mask was simply bolted in front of the detector, with no alignment necessary. The sample mask magnification and orientation were adjusted to obtain an even field with no Moiré pattern, and the translation was adjusted for the correct phasing. Non-TDI (static) X-ray images were brighter in the centre, with intensity falling off to the left and right. This was due to the angulation of the beam with respect to the mask slits. The TDI image was uniform in the horizontal direction. Images of a Perspex rod showed a bright edge on one side and dark on the other, indicating phase contrast. The EXPITIS phase contrast imaging principle was thus successfully demonstrated.

2. STATE OF THE ART

EIXPCI (Fig 1) requires two X-ray masks. Mask M2 is mounted on the detector and the spacing of its slits must exactly match the pixel pitch of the detector. The slit-spacing on Mask M1 matches that of M2 accounting for the geometric magnification. Mask M1 divides the X-ray

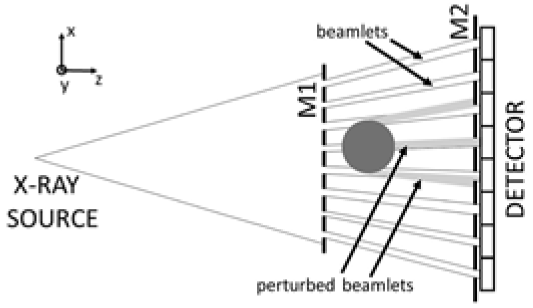

Fig 1 Top-down schematic of the setup for the lab implementation of EIXPCI

beam into beamlets and is typically positioned so that the centre of each beamlet is aligned with one edge of each slot in Mask M2. When beamlets are refracted by the sample object, more or less of the beamlet (depending on the direction of the refraction) passes through the slot in M2 to reach the detector. While making the system sensitive to phase effects, the introduction of the masks does not make it insensitive to attenuation. By illuminating opposite edges of the slits in M2, the phase signal can be, with attenuation remaining unaffected. This provides the opportunity for “phase retrieval” approaches, where processing two images collected with the pre-sample mask displaced in different position allows extracting “pure phase” and “pure attenuation” images. The approach can be implemented in CT, by acquiring and processing two separate scans (7). To overcome the need to acquire two separate scans, “single-shot” approaches to phase retrieval were developed. While initially these were only applicable to homogeneous samples (8), they have more recently been upgraded to allow for some degree of inhomogeneity (9).

In EATDI, the specimen moves in an arc, centred on the X-ray focus, through the field of view (Fig 2). The detector comprises a scintillator coated onto a cylindrically concave fibre-optic faceplate that converts the equiangular rays to approximately equispatial rays. This is then coupled to a CCD camera, orientated and read out such that the charge shift in the CCD exactly matches the motion of the moving image. Any static X-ray shadow (that is, not formed by the specimen as it moves around the source) will be averaged out. In Fig. 3 a tooth embedded in PMMA is placed on a sample stage, with a dining fork placed in front of the detector. The image on the left is a static image, whilst that on the right was taken with EATDI enabled.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The addition of EATDI to EIXPCI bestows the following advantages:

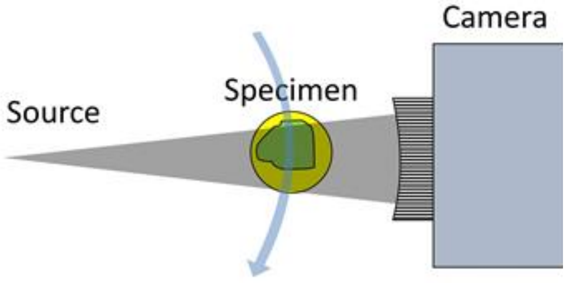

Fig. 2 Top-down schematic of equiangular time-delay integration scanning.

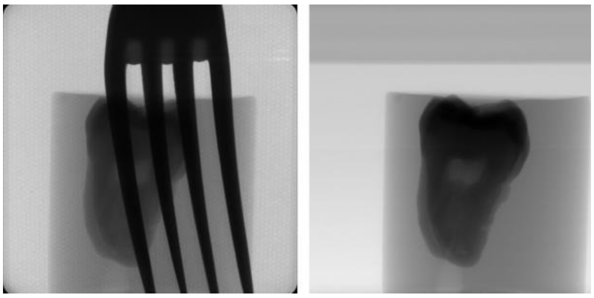

Fig 3 Static X-ray projection of an embedded tooth specimen with a dining fork in front of the detector (left). Same projection (fork still in place) in EATDI mode, showing horizontal averaging of X-ray field (right).

1. There is no longer a need to align the detector mask (M2 in Fig. 1) with the detector pixels. In the EATDI image, the detector mask will effectively become invisible, as demonstrated in Fig. 3.
2. The slit spacing can be set independently of the pixel geometry. This means that the mask geometry can be optimised for maximum phase contrast and the spacing can be smaller or larger than the detector pixel spacing.
3. EATDI imaging is tolerant to mask defects. When quoting for this project, the manufacturer specified 95 % of the mask area to be free from defects. This will not be a problem in this case, but would otherwise cause serious image artefacts.
4. The image width can be larger than the detector width. Although a wider detector could be used, the masks elements are made up of 200 µm thick gold, thus there is a limit on detector width before the beam angle with respect to the sides of the slits becomes too high.

Previously, the QMUL team has worked with Cardiff University and MIT to recover text from damaged scrolls and folded letters respectively (10). In both cases, the enhanced contrast ratio offered by time-delay integration enabled the visualisation of text written with iron-containing ink. Carbon-based inks, however, are not visible with attenuation-based X-ray techniques, although phase-contrast synchrotron X-ray tomography has been used to image carbon-based ink in burnt Herculaneum scrolls, albeit with little readability. It is hoped that the enhanced contrast capability of an EXPITIS-based scanner would improve on this capability. Another major application is the imaging of biological soft tissue. Again, in this instance, attenuation contrast is low although it can be enhanced with X-ray contrast agents. Penetration of stains into the tissue is a problem, however, whereas phase contrast can directly image soft tissue structures.

4. PROJECT RESULTS

Design of the X-ray masks is critical for ensuring optimal phase contrast. The ideal pitch for the slits depends on a number of factors. Without EATDI, the detector slit pitch would be fixed at the pixel spacing, but in this case, there is no such constraint. If the slits are too close together, beamlets will span more than one slit. If a beamlet is diffracted out of one slit and into another the intensity changes are opposite and sensitivity is reduced. If the spacing is too large, the sensitivity is reduced because there are fewer beamlets. The spacing between the sample and detector masks must also be large enough to allow good displacement of the refracted beamlets. However, positioning the sample mask close to the source means that the sample mask pitch must be reduced to match the projected spacing at the detector mask. It was thus first necessary to measure the size of the X-ray focal spot. By imaging a smooth tungsten rod, it was found that 50 % of the focal spot was contained within 15 µm. Based on this, the detector pitch was set as 58 µm (this allowed the possibility to match the CCD binned pixel spacing to allow comparisons with and without EATDI). The source to detector distance was increased to 0.8 m (up from 0.25 m used for attenuation contrast), and the sample mask pitch was set to 36 µm. The open fraction of both masks was set to ¼ (based on experience at UCL), giving slit widths of 9.0 µm and 14.5 µm for the sample and detector masks respectively. The fibre-optic scintillator faceplate used in EATDI, is normally cylindrically concave, and the radius is determined such that equiangular spaced X-rays correspond approximately to the equally spaced detector pixels. The maximum spacing error (causing image blurring) is the difference between the arc length subtended by the source from the centre to the edge of the detector and the linear distance. With the increased source to detector distance of 0.8 m, even a flat faceplate gave a maximum spatial error of only 14 µm, which is less than ¼ of the binned pixel pitch, thus a flat faceplate was used.

The combination of increasing the source to camera distance, 1:4 open ration of the masks and offsetting of the masks for maximum phase sensitivity gave a total reduction in intensity by a calculated factor of 88. To simulate the exposure obtainable by a source with 100 times the power, 100 10 second exposure images were summed. Mask alignment was performed by adjusting the sample mask's distance, from the source, translation and rotation whilst observing Moiré patterns and measuring intensity. The procedure was simple and took only minutes to complete. The angulation of the X-ray beam with respect to the slits caused an intensity drop-off at the left and right of the image. This was averaged out with EATDI scanning, which gave a flat field horizontally. Stepping the sample mask across 36 µm (the repetition interval) gave a sinusoidal variation in intensity. For maximum phase sensitivity, the mask was positioned at the steepest slope of the intensity curve. Swapping from the positive to negative slope gave opposite phase polarity.

To demonstrate phase sensitivity, a test sample comprising of a polycarbonate container filled with granulated sugar was used. Images with a total exposure time of 1000 s (40 kV, 400 µA) were recorded for both positive and negative phase sensitivity (Fig. 4a and 4b respectively). The sum of these images yielded an attenuation only image (Fig 4c) and the difference gave an attenuation-modulated phase image (Fig 4d). Note, this is actually the derivative of phase with horizontal distance. Due to long exposure times, it has not yet been possible to collect a full data set for tomographic reconstruction, but this is planned for the future.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Before reaching TRL 5-7, some intermediate goals must be reached. The proof-of-concept scanner relied on the use of an existing X-ray system with an X-ray enclosure of sufficient size to hold the EIXPCI and EATDI components. This was a microfocus source with a manufacturer's quoted spot-size of 5 µm, although at the voltage appropriate for phase contrast imaging (40 kV) only 15 µm was attained. The maximum power of this system is 16 watts, giving a very low X-ray flux at the required 0.8 m source-detector distance. Rotating anode sources with 50 to 100 times this power are available and such a source will be required to obtain full tomographic data sets within a reasonable time.

Once a high-power system is running, it will be necessary to demonstrate its efficacy in key applications. The ability to read text written in carbon-based inks in damaged historical scrolls would be an amazing breakthrough. However, although this might justify the

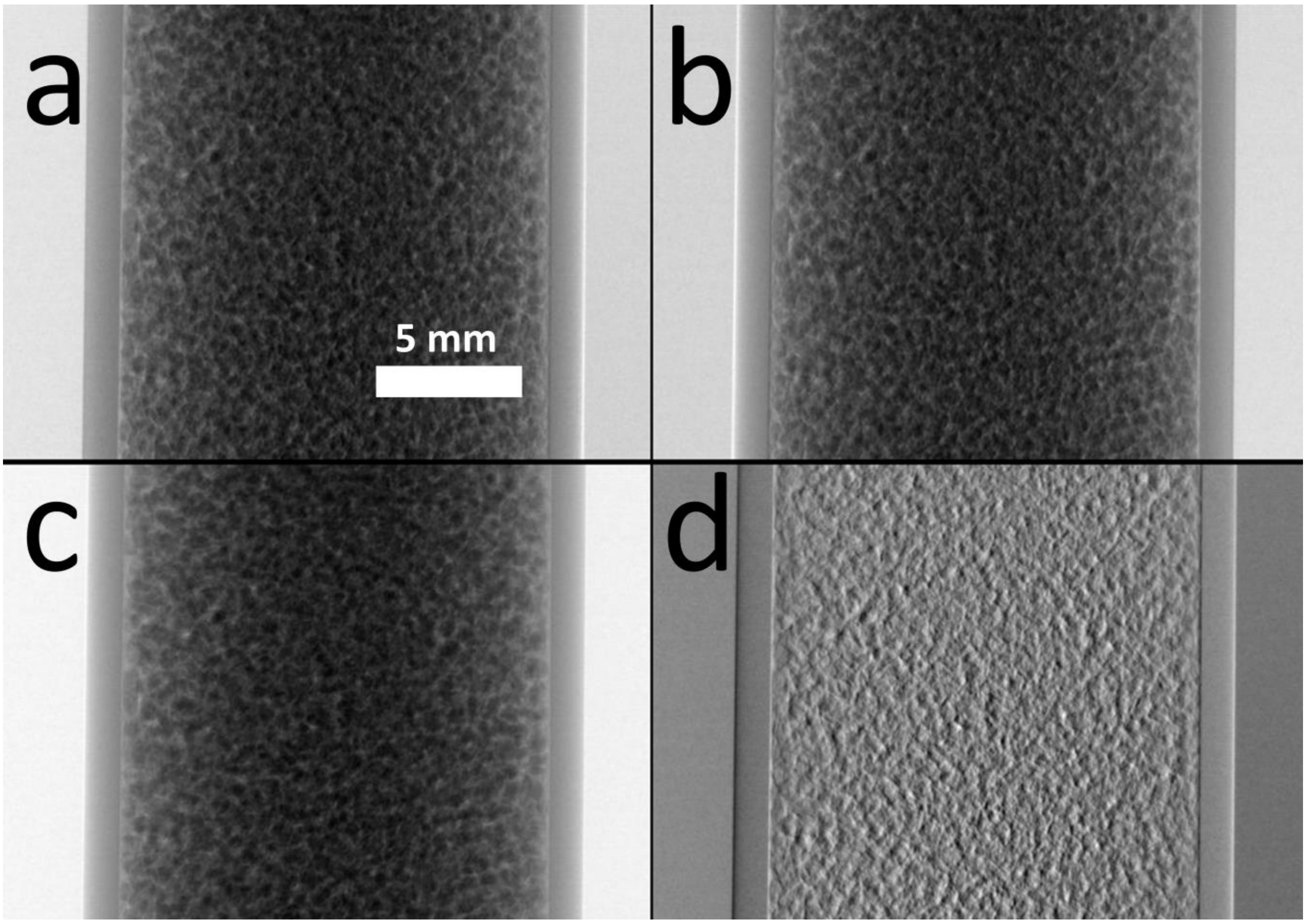

Fig 4 Single EXPITIS images of a polycarbonate container filled with granulated sugar. (a) Negative phase shift. (b) Positive phase shift. (c) Sum of phase shift images. (d) Difference of phase shift images.

cost of a single system, such a capability would not create a volume market. If it were possible to improve the 3D identification and segmentation of cancerous tissue in biopsy samples, a larger market would be envisaged.

Another method of increasing the marketability of the EXPITIS technology would be to use it as an additional mode in an existing or modified system. This might add a relatively small increase in the overall cost of the system that could justify its use when the needs arise.

5.2. Project Synergies and Outreach

For a direct translation of the EXPITIS concept we would look at partnering up with a microfabrication company (NB a world-leading one is already part of our consortium), plus ideally detector and source developers. The consortium would also benefit from inclusion of a group experienced in data analysis who would be able to further develop the phase-retrieval and reconstruction methodology. We would also look at partnering with other ATTRACT groups to maximise the capability of the system.

We are also looking at this as an opportunity to think more widely, e.g. as an “X-ray imaging 2.0” instrument that could incorporate features that we are developing through other ATTRACT projects, e.g. novel CT methods to either consider extensions of the dynamic concept to 3D or, more simply, have the “dynamic” aspect as an added fixture to a system that can do fast 3D multi-modal x-ray scanning, even if simply in planar (or “stereoscopic”) mode. The same consortium could develop optimised systems for synchrotron environments to enable a new range of studies.
Long scan times will be necessary to achieve the highest contrast ratios, but there may be a benefit from combining with the Phase 1 “ML-CYCLO-CT” project: Combining cycloidal computed tomography with machine learning: a mechanism to disrupt the costly

relationship between spatial resolution and radiation dose.

5.3. Technology application and demonstration cases

With the ability to image soft tissue, the key Societal Challenge application will be in "Health, demographic change and wellbeing." Previously, the QMUL team have worked with other researchers at QMUL to study tendon morphology with micro-CT using a variety of contrast agents in an attempt to highlight morphological features. If, as hoped, the EXPITIS technology is more successful in this, it will be a key application to demonstrate its capabilities.

Although the use of EXPITIS technology in a multi-modal imaging instrument is envisaged, a single-mode instrument may appeal to national facilities that already have a variety of imaging modes available

5.4. Technology commercialization

Both Queen Mary University of London and University College London have existing links with X-ray equipment manufacturers, medical and biological researchers, conservationists and a diamond company (imaging faults in diamonds is a possible application). All future sources of funding would be considered in consultation with Queen Mary Innovation and UCL Business.

5.5. Envisioned risks

The primary risk is in finding sufficient demand for a very unique capability. It would first be necessary to create a prototype high intensity system to fully demonstrate this capability.

5.6. Liaison with Student Teams and Socio-Economic Study

This project was undertaken in the Dental Physical Sciences group within the Institute of Dentistry at QMUL, which runs an MSc course in Oral Biology where projects involving dental applications could be run. For further hardware and software development with MSc Students we would partner with the School of Electronic Engineering and Computer Science (collaboration between these two school is well established).

QMUL's previous work with historical scrolls and film has featured on prime-time television and news items that have promoted public discussion of the research. The authors have considerable experience in public engagement and will liaise with PR teams at QMUL and UCL.

6. ACKNOWLEDGEMENT

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