Case Studies in the Use of Computed Tomography for Non-Destructive Testing, Inspection and Measurement

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Abstract

X-ray Computed Tomography (CT) allows visualisation of the physical structures in the interior of an object without physically opening or cutting it. After an introductory review of X-ray computed tomography and its applicability to industrial non-destructive testing and evaluation this paper presents details of a range of case studies where this technology has enabled non-destructive testing, failure analysis or performance evaluation of industrial products and components.

The paper also highlights SIMTech’s research contributions to further extend and improve the usefulness of X-ray CT as a tool for industrial NDT&E including methods for automated system calibration, preferred orientation and planar reconstruction, simplified operation and automated interpretation of CT results.

Keywords: Computed Tomography, CT, reconstruction, NDT, visualisation

1. Overview of Computed Tomography

X-ray CT is a non-destructive inspection technique which provides cross-sectional images in planes through a component. The principle of third generation CT imaging, as used in the industrial context, is illustrated in figure 1. The component is placed on a precision turntable in the divergent beam of X-rays generated by an industrial X-ray source. A detector array (line or area array) is used to measure the intensities of the X-ray beam transmitted through the component, as the component is rotated in the beam. A mathematical algorithm is then used to generate (or “reconstruct”) the CT images from the measured transmitted intensities [1-3].
The resultant CT images are true cross-sectional images, and show the geometry of the component in the plane of the cross-section. If an X-ray source with a small size (micro-focus source) is used, then the spatial resolution achievable can be very high in the region of 10 microns for mm sized components. The CT image values (grey-levels) provide information on the material’s X-ray attenuation coefficient at each point in the image. There is considerable current interest in the correction for a number of effects, including especially “beam hardening”, which would allow the CT grey levels to be converted to values which are directly proportional to the local material density.

Cabinet-based systems for real-time radiography contain suitable X-ray sources and detectors for industrial X-ray CT, and can be upgraded to provide a CT capability by addition of a precision turntable and a PC with appropriate image acquisition cards, motor control capabilities and software for image reconstruction and display. This arrangement is shown schematically in figure 2.

Figure 1 – Third generation X-ray CT principle.

Figure 2 – Overview of the CT inspection and measurement process.
2. SIMTech CT Research Contributions

2.1 Central Ray Determination

All computed tomography (CT) reconstruction algorithms used today require the knowledge of the central ray, which is the projection of the centre-of-rotation (COR) on the detector. One common practice is to determine it using a wire phantom made of a dense metal material before the CT scan of the object to be inspected. An alternative is to visually examine the sinogram generated from the middle column in X-ray detector. The former is time consuming and inefficient whereas the latter is subjective and unreliable.

Several methods of automating this process have been developed at SIMTech that do not require phantom scans or manual interpretation [4-6]. The methods directly use the projection data acquired during the scan of the actual component. Image processing techniques are used to extract the boundaries of the object within the sinogram. Knowledge of the position of the boundary in relation to the rotation of the object can be used to determine the position of the central ray. The accuracy can be further improved through the incorporation of curve fitting when identifying the position of the boundary.

![Figure 3](image-url)

Figure 3 – (a) Illustration of position of central ray, (b) Example of typical sinogram for an object with materials of varying density.

![Figure 4](image-url)

Figure 4 – Impact of error in the determination of the central ray position. The image on the left is correctly reconstructed whereas the same data produces a meaningless result with a small error in the central ray position.
Figure 3(a) defines the meaning of the central ray. Figure 3(b) shows an example of a typical sinogram for an object comprising materials of different densities. The boundaries of one of the elements within the object are indicated as is the determined position of the central ray.

Figure 4 shows the effect of a small error in the central ray position. The object in this example is a small section of a printed circuit board which has several layers at the upper and lower surfaces connected by plated-through-holes. When the data is correctly reconstructed, as in the image on the left, it is possible to inspect and measure both the layers and the plated-through-hole without difficulties. However, as shown in the image on the right, even a small error in the central ray position leads to a reconstructed image from which no useful information can be extracted.

2.2 Automatic Interpretation of CT Results

2.2.1 Non-destructive Assessment of Porosity

The lack of specific commercial software to analyse CT slice images of metal foams prompted the development of an automated toolbox for reliable and fast characterisation. The CT slice images are first segmented before functionally important parameters are extracted. The segmentation method uses the marker-based watershed transform, supplemented by edge linking. 2D characterisation derives key parameters of individual pores as well as group statistics such as distribution and wall thickness. A key contribution is in the refinement of the segmentation step where the use of edge linking greatly improves the reliability of the segmentation process. This allows the automated analysis to consistently process different types of foam whilst providing a factor of 10 improvement in speed compared to manual segmentation [7, 8].

![Comparison between automatic and manual segmentation of reconstructed CT images for non-destructive analysis of pore distribution.](image)

2.2.2 Detection of Distortion in Regular Structures

Computed tomography generates significant quantities of data. An analysis may generate thousands of slice images requiring examination by a skilled operator. It is a common requirement to look for small differences between images. This process can be automated using intelligent image processing techniques, but it is time consuming due to the high content level of full-field reconstructed images.
The Hough Transform offers a means to represent lines in the spatial domain as points in the Hough space. The location of the point in the Hough space indicates the orientation and distance of the line relative to a fixed origin. The magnitude or intensity of the point is an indication of the straightness of the line it represents.

Automated interpretation can make use of the alternative representation to reduce the amount of data that must be processed. Consider the “good” cross-sectional slice in figure 6 (upper row, left) the structure is defined by 9 lines – 2 for the upper and lower sample skins and 7 for the support pillars. These are represented in the Hough space (lower row, left) by 9 peaks. Hence, in order to identify deviations from the ideal cross-section we can simply transform subsequent slices to the Hough space and look for deviations in peak magnitude, position and profile. In the middle column of figure 6 there is little change in the peaks representing the skins, but the peaks representing the support pillars are expanded due to the change in nature of their appearance in the spatial domain. In the right most column of figure 6 the five peaks have been smeared over a wider area and are no longer identical to each other. In other words the irregular distortion in the support pillars in the spatial domain can easily be extracted from the Hough space.

This procedure can be extended to any structure based on a regular and repeating pattern of features. In the simplest case deviation from expectation can be rapidly identified. Using more sophisticated analysis it can be shown to be possible to quantify the level and type of deviation.

Figure 6 – CT reconstructed cross-sections through a honeycomb supported reinforced composite panel (upper row) with corresponding representation in the Hough space.
2.3 Preferred Orientation

A common requirement from the electronics and semiconductor industries is to present the reconstructed model of an electronic package as a series of layer sections aligned to the key elements of the device itself that can be conveniently linked to the manufacturing processes used.

This type of application-specific CT inspection task poses some challenges to conventional CT reconstruction technology, with which an object is generally reconstructed with a tilted orientation with respect to the dimensions of the reconstruction box. With a tilted orientation, the common practice for obtaining the individual layers of a reconstructed object is to manually define a clip-plane parallel to the layer plane and then to clip the object along the normal of the clip-plane. Commercially available software packages usually use this approach which is generally very time-consuming even for experienced users.

The tilted orientation of a reconstructed planar object comes from two sources. Firstly, almost all CT reconstruction algorithms use a default scanning start angle, for example zero, for the reconstruction. However, in reality, an object may be scanned with any initial orientation, as illustrated in figure 7(a). A difference between the default start angle and an actual start angle would lead to the titling of the planar object cross-section with respect to the reconstruction matrix. Secondly, when mounting a planar object to the rotary unit, its primary plane may form a small angle with respect to the rotation axis as shown in figure 7(b). This situation would cause the reconstructed object to be misaligned in the third dimension after assembling a set of CT slices into a 3D model.

Recently we have developed an automated algorithm that enables users to reconstruct planar objects with corrected orientation [9]. This technology first uses the projection data of the object to automatically determine the actual start angle of a scan. This angle is used for performing CT reconstruction to obtain an aligned orientation of an object slice with respect to the reconstruction matrix. After reconstructing all slices, the height position of the object cross-section on each slice is calculated and their relationship is used to perform an image shifting operation to all slices to correct the tilting problem of the object to the rotation axis. As a result, the primary plane of the reconstructed object will be parallel to one of the planes of the reconstruction box. With such an orientation, displaying and extracting layers becomes a trivial operation.

![Figure 7 - The scanning start position of planar object. (a) The scan may start with an angle different to the default angle for reconstruction; (b) The object may be mounted to the rotator with a tilting angle with respect to the rotation axis.]
2.4 Determination of Voxel Size for Accurate dimensional Measurements

X-ray CT is increasingly used as an instrument for dimensional metrology, it is enables the measurement of both internal and external features otherwise impossible to resolve using traditional tactile and optical techniques [10,11].

A CT volume is a voxel based data-set; thus, dimensional information evaluated from a CT volume, put simply, is the product of the number of voxels and the voxel size; it is important to highlight that sub-voxel feature detection is commonplace, so dimensional measurements are not limited to voxel scale resolution. Conventionally, voxel size is defined based on the position of a workpiece relative to the X-ray source and detector, and is therefore prone to axis position errors, errors in the geometric alignment of the CT system’s hardware, and the positional drift of the X-ray focal spot. A common method to reduce voxel size errors is the use of a reference workpiece scanned in the X-ray CT system at the same measurement settings used for the actual workpiece. By reconstructing the reference workpiece, a reference dimension can be evaluated and this then used to adjust the voxel size of the actual workpiece. This reference dimension must be threshold independent, namely it is determined without the influence of edge detection thresholds.

Recently we have made use of a reference workpiece to significantly reduce errors in dimensional measurements evaluated via X-ray CT. The reference workpiece features three ruby spheres, see figure 8(a), the centre-to-centre distances of which present threshold independent dimensions, since it is assumed the centre of a sphere remains constant irrespective of surface determination. Reference measurements of the three centre-to-centre distances have been evaluated via a high precision optical profiler; by comparing the reference measurements to measurement results obtained via X-ray CT, it is possible to re-scale the voxel size, thus achieving more accurate dimensional measurements. Figure 8(b) shows the measurement error of the reference workpiece with and without voxel size correction.

Figure 8 - (a) Ruby sphere workpiece for voxel size correction. (b) Measurement error for the dimensions of the ruby sphere workpiece evaluated via X-ray CT, with and without voxel size correction.
3 Case Studies

3.1 Targeted CT inspection of voids in semiconductor packaging

3.1.1 Problem Description

Inspection of new packaging materials or processes is a frequent application of CT. For this kind of application, in many cases, one is only interested in those soldering layers between the device layers. Figure 9 shows a sample which consists of three parts: the AIN substrate ($l_a=3048\mu m$, $w_a=2032\mu m$, $t_a=1524\mu m$), the aluminum solder interface layer ($l_s=889\mu m$, $w_s=356\mu m$, $t_s=25\mu m$) and the AuSn device layer ($l_d=1400\mu m$, $w_d=400\mu m$, $t_d=100\mu m$). Our target is to examine the quality of the soldering layer after the soldering process.

3.1.2 Challenges

It is obvious that, compared to the substrate, the device layer and the solder layer are thin. If we reconstruct the whole object with the reconstruction volume limited in size by practicalities of computer hardware, the resolution usually won’t allow us to obtain the details of the solder layer.

3.1.3 Solution

To obtain sufficient reconstruction resolution for the solder layer, we conducted a targeted planar reconstruction for the object [12, 13]. Planar CT reconstruction is a novel technology developed in SIMTech which allows us to reconstruct a particular planar ROI with a desired reconstruction resolution (as long as it doesn’t exceed the system resolution) and preferred orientation. When applied to this application, we first determine the orientation and position parameters of the solder layer with the scanning data, then we define and reconstruct only the volume which just covers this ROI (the device and solder layer) as shown in figure 10(a). To evaluate the soldering quality, one slice of the solder layer near the device is shown in figure 10(b), from which we can see a lots of voids that would, finally, degrade the performance of the device.

Figure 9 - A semiconductor packaging sample.
3.2 Internal structure inspection of mobile phone camera lens

3.2.1 Problem description

Nowadays the design and manufacturing of mobile phone cameras become increasingly challenging due to the pressures coming from two opposite directions: better and better performance and smaller and smaller size. With every new design, engineers need to evaluate the assembly quality of various kinds of miniaturised optical, mechanical and electrical components in the prototype development process; and as a general requirement, micro-CT is an ideal tool to address this issue in terms of its size, composition of materials and so on.

3.2.2 Challenges

In a mobile phone camera, there are many materials of different density: glues, glass, plastic parts, metal wires and so on; a proper selection of X-ray system parameters is important for a good CT scan. Besides, to minimise the effect of beam-hardening caused by large density contrast, one also should consider the appropriate mounting orientation of the sample.

3.2.3 Results

Figure 11 and figure 12 are respectively an X-ray 2D image of a mobile phone camera, and its CT images obtained by clipping the reconstructed 3D object from different angles. Obviously 3D CT images provide us much more information about the location, orientation of each mini parts and how they are assembled together.
Figure 11 – 2D X-ray projection image of a mobile phone camera.

Figure 12 – CT images clipped from different angles.
3.3 Internal form and dimensional measurement of injection moulded plastic components

3.3.1 Problem Description

Injection moulding is a common mass-production method for plastic components. For the type and size of component considered here the mould can contain as many as 64 or 128 cavities yielding large numbers of components per injection cycle. During the design and development stage test components are examined from all cavities to ensure that they satisfy a number of critical dimensions. In order to ensure the product quality, the wearing of the mould and possible modifications of the production process have to be measured and visualised as early as possible, at minimum costs. This process is usually referred to as first article inspection.

3.3.2 Challenges

Conventional approaches to first article inspection use traditional tools such as coordinate measuring machines (CMM) and shadowgraphs to measure critical dimensions. Where those critical dimensions are related to internal features it is necessary to destructively cut or otherwise expose them to the measurement tool. Measurement based on CT allows both internal and external features to be assessed with the same tool without the need for costly and potential result-influencing sample preparation.

3.3.3 Solution

The sample was mounted to a small rod to allow it to be mounted on the rotation axis of the CT machine. A full scan based on 540 projections captured during a 360° rotation of the sample was reconstructed. The axial voxel resolution was approximately 12 microns. The reconstructed volume was imported into the VGStudio MAX V2.1 visualisation and analysis software from VolumeGraphics GmbH. This type of visualisation software generally presents the user with cross-sectional views of the sample from three orthogonal directions known as the axial (perpendicular to the axis of rotation), sagittal (side view) or coronal (plan view) slices. This can be seen in figure 13.

Once the data has been imported a range of image processing and visualisation tools can be used to remove noise and other outliers. The user is able to align known orthogonal planes, or other geometric primitives, on the object with a Cartesian coordinate set. Subsequently GD&T type measurements can be made on geometric primitives fitted to the CT-reconstructed point cloud data itself. If design data is available in a suitable CAD format then the reconstructed data can also be compared with the design data after registration of the two data sets.

An example of the same analysis applied to a defective sample can be seen in figure 14.
Figure 13 – Axial (a), coronal (b) and sagittal (c) and 3D views of a good component.

Figure 13 - Axial (a), coronal (b) and sagittal (c) and 3D views of a defective component.
3.4 **Determination of the cause of leakage in an assembled bio-medical device**

3.4.1 **Problem Description**

In this case study it was required to identify the cause of leakage encountered when using the medical device assembly shown in figure 15(a). Previous experiments had identified the source of the leakage to lie in the region where a paper disc was ultrasonically bonded onto the plastic body of the component.

3.4.2 **Challenges**

Destructive sectioning of the region around the paper insert had previously been attempted without success primarily as a result of the process damaging the region making subsequent visual inspection unreliable. Attempts were made to examine the region using a scanning electron microscope (SEM). Whilst this approach did indicate some damaged fibres around the edges of the paper insert these did not correlate well with the leakage locations.

3.4.3 **Solution**

The device was scanned with CT system operating in microfocus mode with a voxel resolution in the axial direction of approximately 121 microns. The reconstructed data set comprised 1024 axial slices with 1024 x 1024 voxels in each slice. This data set was visualised as a 3D model. The manipulation tools of the iView software were used to examine the region around the paper insert (indicated in figure 15(a)) including the use of cut-plane sectioning to allow the profile of the bonding surface to be examined in detail. The feature of CT reconstructed models where voxel intensity is related to material density allowed the software to easily segment out the paper insert itself leaving the higher density plastic material to be imaged more clearly.

Based on this visualisation it was determined that the most likely source of the leakage was mis-moulding of the surface profile to which the paper insert was bonded rather than deficiencies in the bonding process itself. The cross-section through the sample in figure 15(b) clearly shows a spike rather than a flat profile.

![Figure 15](image-url)  
**Figure 15** – Section of medical device, (a) Photograph showing paper insert, (b),(c) and (d) sectioned 3D models showing irregularity of the surface to which the paper insert is bonded.
3.5 Assessment of severity of internal damage extent in honeycomb supported carbon fibre reinforced panels.

3.5.1 Problem Description

In aerospace applications honeycomb supported carbon fibre reinforced panels are often damaged following impact from birds and other foreign objects. In order to assess the repairability of damaged panels it is necessary to know the depth and extent of internal damage caused by the impact. It can also be useful to examine repaired panel to assess the quality of workmanship and the repair reliability.

3.5.2 Challenges

It is impractical for a two-sided inspection method such as computed tomography to be applied to extremely large and complex structures such as aircraft wing and fuselage sections. Hence, researchers are working on the development of single-side inspection methods based on a variety of sonic and ultrasonic techniques. However, to validate the results provided by these methods it is essential to provide a non-destructive means to provide a reference point which allows the results to be compared with physical information on the actual defect or defects.

3.5.3 Solution

Computed tomography can be applied to small sections removed from actual aerospace components or test samples that have been artificially fabricated [14]. Figure 16 shows the front and rear faces of a section cut from an aircraft nosecone.

Figure 17 shows axial and sagittal images extracted from the reconstructed data set. With appropriate calibration to allow conversion of pixel dimensions to real world coordinates the depth to which the damage extends can easily be determined. Automated image processing, based on similarity constraints, can be used to identify the point at which measurements should be made. Similarly from the sagittal image the size of the damaged area can be found. These results can then be correlated with results obtained from alternative inspection methods. Figure 18 shows sagittal slices from different depths through the sample.
Figure 16 – Sample

Figure 17 – Axial and sagittal slices taken from the damaged zone.

Figure 18 – Three sagittal slices taken at different depths below the surface of the sample.
4. Summary

This paper has provided an overview of X-ray computed tomography as a useful tool for non-destructive testing of engineering components for failure analysis, prototype evaluation and performance assessment.

Some areas of active research at SIMTech (Singapore Institute of Manufacturing Technology) have been identified which aim to extend the applicability of CT as a tool for NDT. Future work focuses on the development of high energy X-ray CT systems using single and dual X-ray sources with energies up to 450 kV, simplification and optimization of the CT scanning process, the development of novel reconstruction algorithms for both conventional and non-conventional scanning geometries and the creation of 3D image processing methods to support automated defect detection and traceable dimensional metrology.

References