

MULTI-MODALITY NDT IMAGE FUSION AND ITS MAPPING ON CURVED 3D CAD SURFACE

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Abstract: When performing structure integrity assessment of an aircraft component with curved surfaces based on its multiple NDT records obtained by different inspection techniques, there are two main difficulties. While one is to efficiently combine visual information from multiple NDT images for presentation to inspectors, the other is to measure accurately defect locations and their physical sizes based on component's CAD model. This paper presents a special software environment developed by the authors to integrate various information, and to display different types of NDT information in one CAD model based rendered scene with comprehensive operator interaction capabilities. The software consists of (a) versatile CAD model editing facilities for surface extraction and 3D wire-frame construction, (b) tools for projecting 3D CAD surface on to 2D plane, and aligning the projection with the NDT image acquired, (c) tools for matching multi-modality NDT images with different resolutions, (d) tools for fusing multi-modality NDT images by region-based wavelet transform, and (e) texture mapping to project the fused image on to its 3D CAD surface as a colour map. Using practical ultrasonic and thermographic images acquired from a real and curved aircraft component as examples, the software is shown to enable 3D visualisation of multi-modality NDT images superimposing on their CAD models, thereby facilitating qualitative and quantitative interpretation of the image features observed.

Introduction: In the current aerospace industry, new manufacturing processes are being introduced to produce aerostructures with new composite materials, with complex geometrical shapes, and with highly curved surfaces, to increase the performance and efficiency of modern aircrafts. This poses a number of problems for non-destructive testing (NDT). One problem is in the area of data fusion resulting from the adoption of the multi-modality NDT strategy to fully assess the structural integrity of a composite material. With each NDT modality revealing different defects of the material under inspection based on different physical properties measured, efficient integration of defect information is needed in order to yield a comprehensive diagnosis of structure health. For example, thermography can be combined with ultrasound to reveal near-surface defects and impact damages as well as delaminations and broken fibres inside the aerostructure. The multi-modality NDT strategy is also used to optimise the inspection process. For example, a fast, large field of view and non-contact NDT methods such as thermography is used first for quick initial check, and this is followed by a relatively slow and high resolution NDT method such as ultrasound for detail examination of suspected areas. Again, efficient integration of defect information is needed if it is desirable to cross validate the defects detected or to reduce ambiguities which may occur due to incomplete or missing attributes.

The other problem for NDT is in the area of data visualisation and defect measurement due to the difficulties to relate geometrically a 2D NDT image observed to a 3D complex object inspected. For example, in assessment of a defect in a highly curved area, it may not be possible for inspectors to determine its exact position due to the absence of structural image features (such as edges and holes) to provide appropriate geometrical references, its physical size may be judged to be much smaller than its true dimension due to a fixed and oblique viewing angle, and its actual shape may be significantly deformed due to perspective distortion.

Based on the methodology of combining information from multiple sources and utilising the information available in the component CAD model to aid NDT data interpretation, the paper presents a special 3D software tool, named ADSIP-NDE, developed to overcome the above inspection problems^[1-3]. Whilst high quality data fusion is achieved by extending the previously proposed region-based wavelet transform approach from 2D to 3D (with the fusion parameters optimised according to the unique geometrical and material structure contained in different parts of the component under inspection)^[4-5], data visualisation and defect measurement are addressed by 3D image mapping for 3D visualization and superimposition of the 3D CAD model to provide necessary 3D geometrical references for defect measurement.

In the following sections of the paper, the unique features of the software are presented using a real and curved aircraft component with its thermographic and ultrasonic images as an example. Presented first is the CAD Editor, a versatile 3D CAD model editing tool for extraction of CAD features and construction of simplified CAD models (this tool is needed because the standard CAD data of a component contains too much information with too many features for the purpose of NDT). Presented next is projection and alignment of a 3D component CAD model onto its 2D NDT image via 3D geometrical transformation in the section of Projecting CAD Model to NDT Images. This is followed by the section of Image Alignment, where the geometrical relationship between multi-modality NDT images is shown to be established by matching each NDT image acquired from an aircraft component to the same CAD model surface; and the section of Image Fusion, where region-based image fusion based on the wavelet transform is shown to make multi-modality NDT data sets simultaneously visible. Finally, texture mapping is presented to superimpose the fused image (or individual NDT image) onto its corresponding 3D CAD model surface in the section of Mapping Fused Image to CAD Model Surface before conclusions.

CAD Editor: The standard CAD model of a component typically contains a large amount of data with too much information and with too many features for NDT purposes. Hence a CAD editor was developed to facilitate construction of a simplified CAD model based on useful features selected from the original CAD model. In the implementation, simplification of a CAD model is performed within four views of the CAD Editor window shown in Figure 1, namely, Sourceview, Preview, Targetview and Recyclebin. Whilst the Sourceview shows the original CAD model imported, the Preview displays the object currently selected from the CAD model shown in the Sourceview. The Targetview shows the simplified CAD model constructed with the features selected from the original CAD model, and any object erased from the Targetview will be displayed in the Recyclebin and can be restored. In Figure 1, for the original CAD model of a real and curved aircraft component shown in the Sourceview, the simplified CAD model shown in the Targetview consists of a surface shown as golden shell, curves shown as red wire frame, and vertices shown as yellow line cross.

To help users to select the correct entity in a large and complex CAD model, a dynamic selection is implemented to automatically highlight the object in the current viewing window as the mouse cursor moves over it. Group selection tool is also implemented. Selectable CAD model features include shapes, vertices, edges, wires, faces, shells, solids or compounds.

To facilitate visualisation of the original CAD data as well as the simplified CAD model, a number of highly interactive tools have been included, such as dynamic rotation, panning, zooming, mouse driven light control, real-time cross sectioning, render shading, texture rendering, wire frame and hidden line removal. Furthermore, colours and materials can be set for each individual part or entity. Transparency of parts can be manipulated, allowing convenient viewing of complex assemblies.

To handle various CAD data generated by different engineering design software packages, the software has been designed to read the most common CAD formats, such as IGES format (5.3) and STEP format (AP202, AP214).

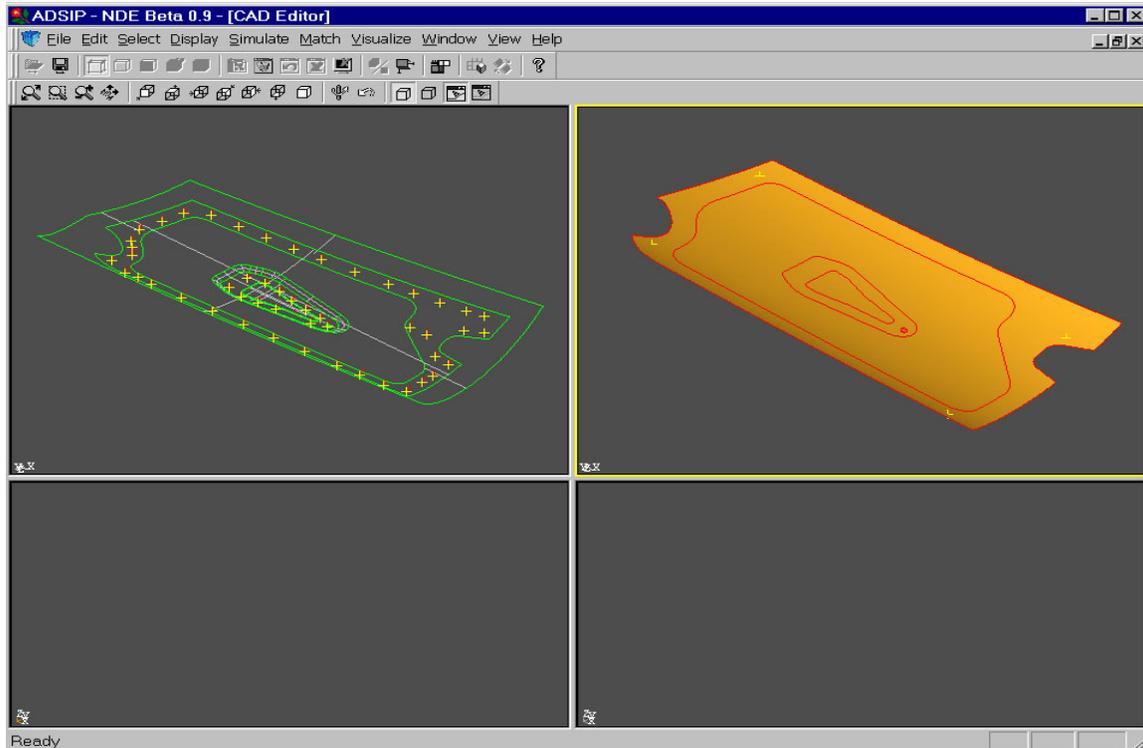
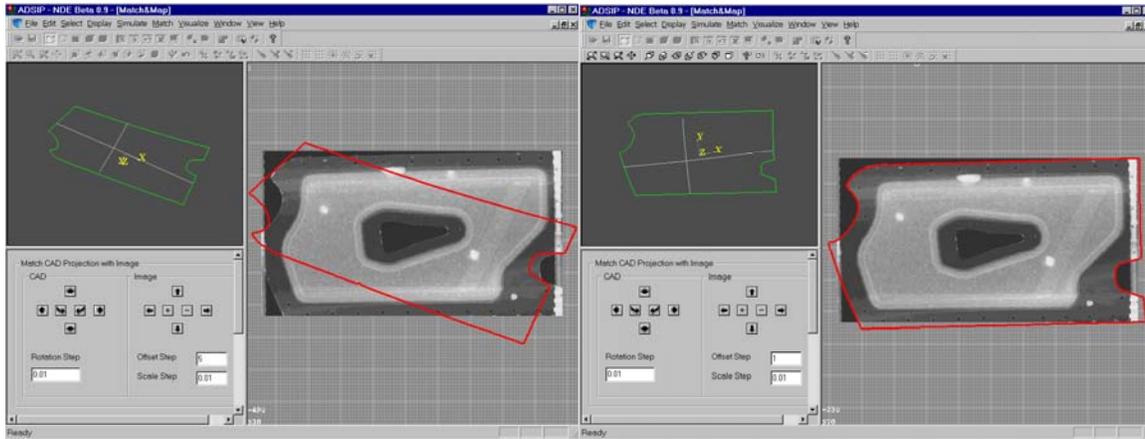


Figure 1. Sourceview (top left) showing imported CAD model, Targetview (topright) showing simplified model, Preview (bottom left), and Recyclebin (bottom right)

Projecting CAD Model to NDT Images: To establish the geometrical relationship between a 3D CAD model and its associated 2D NDT image, it is required to project the simplified CAD model onto 2D plane and aligns the projected CAD model with the NDT image. A number of automatic algorithms for alignment of images and CAD models have been previously presented ^[6-7], and they are based on the alignment of a small set of carefully selected features such as straight lines and circles. In this developed software an interactive manual image alignment tool is implemented to allow users to project a 3D CAD model via 3D geometrical transformation onto the corresponding NDT image acquired, with the advantages of handling components with complex geometrical structures and NDT images with perspective distortions.

Figure 2(a) shows the surface from the simplified CAD model and the ultrasonic image of an aircraft component before alignment in the Match&Map interface of the software. In the Match&Map interface, the 3Dview is used to display the 3D CAD model, the 2Dview is used to display the 2D projection of the 3D CAD model as well as the NDT image, and the Control Dialog provides fine matching adjustment. Essentially, users use the mouse driven functionality and the Control Dialog to rotate and scale the 3D CAD model and to move the NDT image until a best match is obtained. A zoom tool is also provided to achieve a match with high accuracy. Figure 2(b) shows the surface and the ultrasonic image shown in Figure 2(a) after matching. Once the matching process is completed, users save the relative position and orientation of the image plane with respect to the 3D CAD model. It is worthy mentioning that other CAD features, such as curves and vertices shown in the simplified CAD model in Figure 1, can also be used for 2D projection and 3D matching.



(a) Before matching

(b) After matching

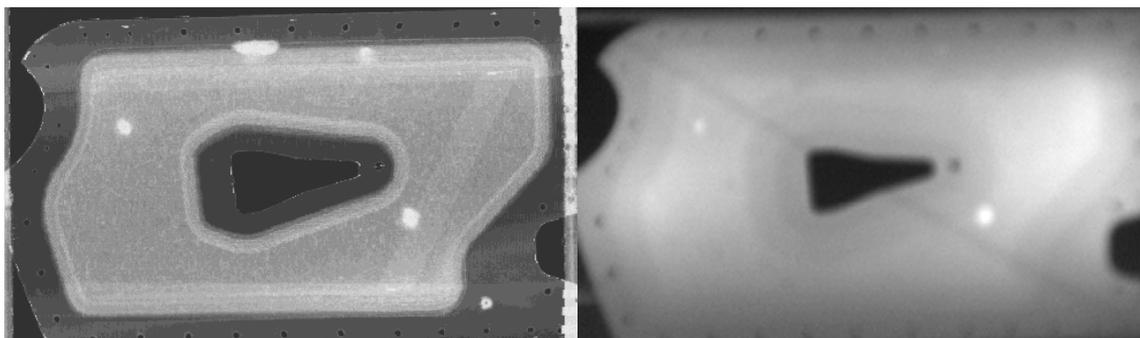
Figure 2. 3D CAD model and ultrasonic image

Image Alignment: Due to different resolutions of different NDT techniques resulting in different image sizes for the same component and perspective distortions inherent in image acquisition, it is not possible to directly fuse multi-modality NDT images without first performing image alignment. One possible way to correctly align multi-modality NDT images is to use the component CAD model as an intermediate geometrical reference. By matching the image of each NDT modality with the same CAD model as described in the previous section, a correspondence between the multi-modality NDT images is established indirectly via the CAD model. The precise geometrical transformation for image alignment is then determined based on a number of control points selected from the CAD model and projected to the multi-modality NDT images.

As an example, the steps for the CAD model based alignment of two NDT images are as follows:

- (i) Select a geometrical reference from the CAD model for image alignment, such as a surface for a curved aircraft component.
- (ii) Match each NDT image with the selected geometrical reference respectively by using the Match&Map interface of the software, thereby establishing the correspondence between the two images to be aligned via the CAD model.
- (iii) Select at least three well separated control points from the CAD model.
- (iv) Project the selected control points onto the two NDT images to yield the corresponding pairs of associated control points.
- (v) Apply the Least Mean Square (LMS) method to the pairs of associated control points to estimate the global affine transformation to achieve image alignment.
- (vi) Align and resample the lower resolution image based on bilinear interpolation to yield the registered image with the same resolution and image size as the other one.

Figures 3(a) and 3(b) show the final results of aligned ultrasonic and thermographic images. This was achieved by matching respectively the ultrasonic and thermographic images to the CAD surface selected, projecting four vertices in the CAD model onto the two images to yield pairs of associated control points, and aligning and resampling the thermographic image based on the transform parameters obtained.



(a) Original ultrasonic image

(b) Registered thermographic image

Figure 3. Image alignment

Image Fusion: With multi-modality NDT images correctly aligned, fusion can be simply achieved on a pixel-by-pixel basis in the spatial domain by assigning different colours to different NDT modalities. However, there is a problem associated with the pixel-by-pixel fusion. As an aircraft component is likely to consist of different material structures, improvement of defect/structure visibility in one part of the aircraft component in the fused image is likely to be accompanied by deterioration of the defect/structure visibility in another part of the aircraft component. This has led to the previously proposed approach of region-based wavelet fusion to improve fusion quality, whereby image fusion is performed based on component sub-structure with the fusion parameters optimised according to the unique geometrical and material structure contained in different parts of the component under inspection.

To facilitate implementation of different fusion strategies for different material structures to improve fusion quality, it is necessary to perform structure decomposition to divide the NDT image into several regions having the same material structure. However, due to the complex structure and curved surface of aircraft components, structure decomposition requires linking between the structural/material information available in the 3D CAD data and the 2D NDT images acquired. For example, from the CAD model shown in Figure 1 consisting of a thick and curved structure of an irregular shape surrounded by thin and narrow edges both inside and outside, the aligned NDT images shown in Figure 3 can be divided into three regions. With the CAD model in 3D and NDT images in 2D, a 3D to 2D conversion is needed to project the 3D boundaries to the corresponding 2D contours separating the thick structure from the thin edges. By using the Match&Map interface of the software to correctly project the CAD model to the NDT image plane, the proposed structure decomposition method consists of the following steps:

- (i) Select structure boundaries based on wire frame from the 3D CAD model.
- (ii) Generate a clipping plane that is perpendicular to the NDT image plane.
- (iii) Move the clipping plane across the image plane row-by-row and column-by-column according to the image resolution.
- (iv) Find the intersection points between the clipping plane and the structure boundary and project these intersection points back to the image plane.
- (v) Digitise the projected intersection points to yield a binary image with boundary contours.
- (vi) Apply a binary morphological filter to fill the gaps along the boundary contours.
- (vii) Create structure masks for different regions by applying the region growing method to the binary contour image based on a seed point selected by users for each area enclosed by boundary contours.

Using the CAD model shown in Figure 1 as an example, the proposed structure decomposition method is illustrated in Figure 4. In Figure 4(a), the clipping plane is shown in green, the 3D structure boundaries selected are shown as the wire frame in red, and the projected 2D boundary contours are shown in white in the image plane. The final result of structure decomposition is shown in Figure 4(b), where the middle thick structure is represented by green, inner edge strip by blue, and outer edge strip by red.

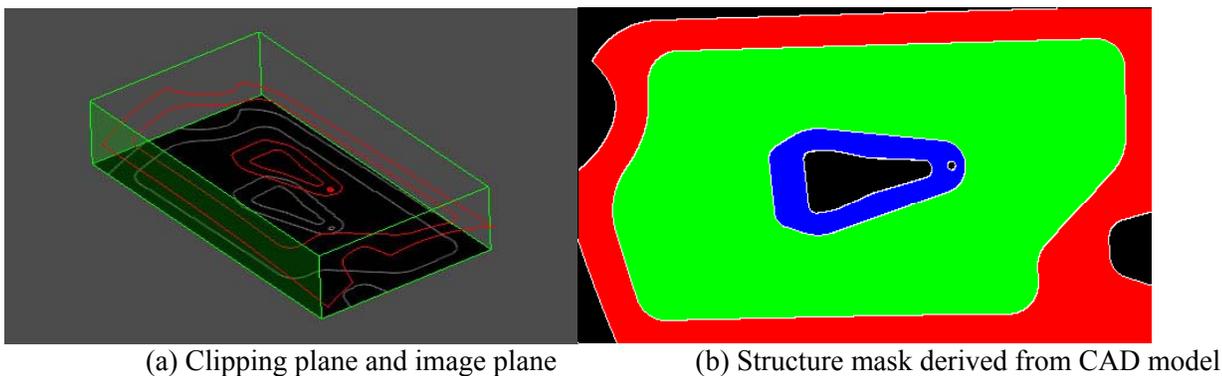
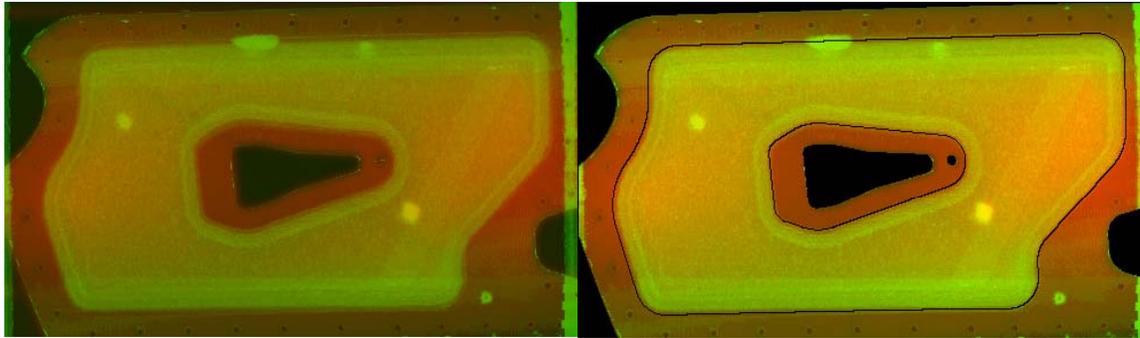


Figure 4. Structure decomposition

The software provides users four different image fusion methods, with one method based on direct fusion of multi-modality NDT images in the spatial domain on a pixel-by-pixel basis, and three methods based on indirect fusion of multi-modality images via their wavelets coefficients in the wavelet domain^[4-5]. For two of the wavelet

fusion methods, namely, fusion by averaging and fusion by energy comparison, fusion rules do not depend on the material structures. Whilst the fusion by averaging constructs the fused image based on a weighted average of the wavelet coefficients, the fusion by energy comparison constructs the fused image based on the wavelet coefficients with significant local energy. For the third wavelet fusion method based on region, different thresholds can be assigned to different decomposed regions, thereby allowing the fused image to be constructed based on the wavelet coefficients responsible for the representation of the most predominant features in each region and of suspected defects.

Using the aligned ultrasonic and thermographic images shown in Figure 3, Figure 5 shows the difference between the results of the spatial domain fusion and the region-based wavelet fusion, with the ultrasonic and thermographic data represented by green and red colours respectively. It should be apparent that the region-based wavelet fusion provides a better image for defect interpretation, as it shows simultaneously the internal structural information and defect information in a sharper and higher contrast image.



(a) Spatial domain fusion

(b) Region-based wavelet fusion

Figure 5. Fusion of ultrasonic and thermographic images

Mapping Fused Image to CAD Model Surface: With the multi-modality images fused, the final stage is to map it to the CAD model surface for 3D visualization and defect measurement. This is achieved by the software via texture mapping. Essentially, the fused image (or any NDT image) is treated as in the texture space, and is mapped to its corresponding 3D CAD model surface in direct proportion, to associate each pixel in the fused image with their corresponding 3D surface positions.

In mapping the fused image (or any NDT image) to the CAD model surface, a triangular mesh is first generated to approximate the CAD model surface. To allow users to configure the mapping quality, the density of the triangular mesh is set by a relative deflection coefficient that defines the maximum distance from a point on the surface to the corresponding point on its approximate triangulation. The next step is to project the vertices of the triangular mesh onto the fused image plane to compute texture coordinates, thereby establishing the geometrical correspondence for texture mapping between each triangular patch on the component surface and the corresponding area in the fused NDT image. The last step is surface rendering to map the fused image on the surface for viewing based on the geometrically associated 3D vertex coordinates and 2D texture coordinates. Essentially, the 3D vertex coordinates are used to define the area of each triangle based on the lines connected two vertices, each point in the triangle area is used to determine the corresponding texture coordinate in the fused image, and the associated pixel value in the fused image is mapped on the surface point-by-point as texture. Linear interpolation is used if there is no one-to-one correspondence.

To assist defect visualisation, a wide range of visualisation facilities are provided, which include interactive zoom-in on region of interest for close up views of specific data region, and superimposition of selected CAD model objects or entire CAD model on the texture mapped surface. Render shading, wire frame and hidden line removal can be set for individual parts of a CAD model. In addition, transparency of parts can be manipulated to allow simplified viewing of complex assemblies. For the CAD model shown in Figure 1 and the fused image shown in Figure 5(b), Figure 6 shows the Visualiser window of the software displaying the fused image overlaid with vertices, wire frame and render shading on the curved CAD model surface.

Conclusions: In this paper, a special software environment is presented for inspection of aircraft components with complex geometries and curved surface by integrating and displaying different types of NDT information in one CAD model based rendered scene with comprehensive operator interaction capabilities. This is achieved by a number of unique tools developed for projection of data between 2D and 3D as well as region-based wavelet fusion

of multi-modality NDT images to show simultaneously the most important features in each data set. Combined with a wide range of interactive 3D manipulation and visualisation facilities, the software is thought to benefit the whole NDT community, as it will help to improve the safety standard by offering an ideal tool for more reliable and accurate characterization of flaws and defects.

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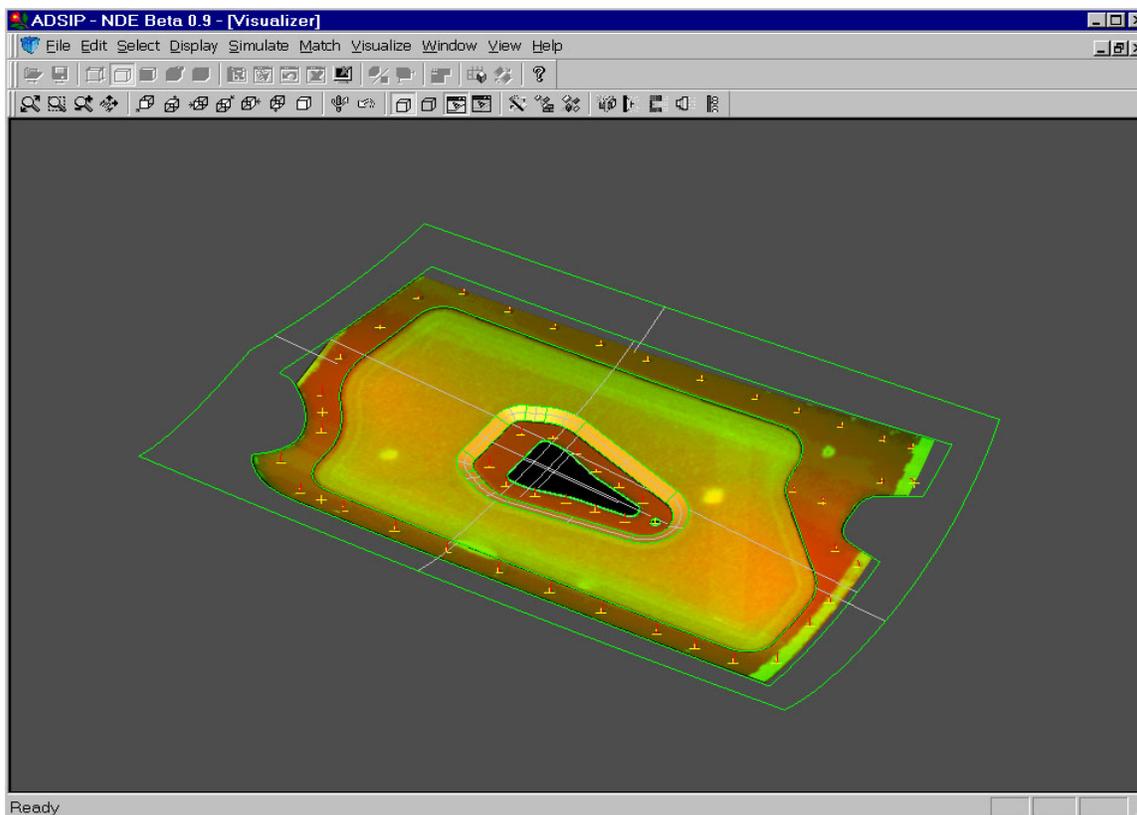


Figure 6. Vertices, wire frame, render shading, and fused image on 3D curved surface

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