Model-assisted development of a laminography inspection system

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Abstract
Traditional computed tomography (CT) is an effective method of determining the internal structure of an object through non-destructive means; however, inspection of certain objects, such as those with planar geometrics or with limited access, requires an alternate approach. An alternative is laminography and has been the focus of a number of researchers in the past decade for both medical and industrial inspections. Many research efforts rely on geometrically-simple analytical models, such as the Shepp-Logan phantom, for the development of their algorithms. Recent work at the Center for Non-Destructive Evaluation makes extensive use of a forward model, XRSIM, to study artifacts arising from the reconstruction method, the effects of complex geometries and known issues such as high density features on the laminography reconstruction process. The use of a model provides full knowledge of all aspects of the geometry and provides a means to quantitatively evaluate the impact of methods designed to reduce artifacts generated by the reconstruction methods or that are result of the part geometry. We will illustrate the use of forward simulations to quantitatively assess reconstruction algorithm development and artifact reduction.

Keywords
computerised tomography, image reconstruction, inspection, nondestructive testing, production engineering computing, nondestructive evaluation, QNDE, Aerospace Engineering, Mechanical Engineering

Disciplines

Comments
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MODEL-ASSISTED DEVELOPMENT OF A LAMINOGRAPHY INSPECTION SYSTEM

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ABSTRACT. Traditional computed tomography (CT) is an effective method of determining the internal structure of an object through non-destructive means; however, inspection of certain objects, such as those with planar geometries or with limited access, requires an alternate approach. An alternative is laminography and has been the focus of a number of researchers in the past decade for both medical and industrial inspections. Many research efforts rely on geometrically-simple analytical models, such as the Shepp-Logan phantom, for the development of their algorithms. Recent work at the Center for Non-Destructive Evaluation makes extensive use of a forward model, XRSIM, to study artifacts arising from the reconstruction method, the effects of complex geometries and known issues such as high density features on the laminography reconstruction process. The use of a model provides full knowledge of all aspects of the geometry and provides a means to quantitatively evaluate the impact of methods designed to reduce artifacts generated by the reconstruction methods or that are result of the part geometry. We will illustrate the use of forward simulations to quantitatively assess reconstruction algorithm development and artifact reduction.

Keywords: Computed Tomography, Laminography, X-ray Simulation, XRSIM
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INTRODUCTION

The need to determine the internal structure of an object through non-destructive means commonly arises in industry. One method, x-ray computed tomography, provides one of the best means to accomplish this. However, there are many inspections for which insufficient data is collected for a standard computed tomography (CT) reconstruction. Such limited-data situations commonly result from objects which are either too large to achieve full-access during the inspection, whose planar geometries only allow adequate x-ray penetration in a limited range of orientations, for systems with limited dynamic range or where there are time limitations for the data acquisition.

Using a standard CT reconstruction algorithm with a limited dataset results in instabilities in the reconstruction, introducing artifacts which reduce the quality of the reconstruction. As a result, alternative reconstruction algorithms must be considered and an example of this can be seen in parts with planar geometry where a technique known as laminography has been the focus of researchers for the past decade [1].
In order to develop reconstruction algorithms and evaluate their effectiveness along with any introduction of artifacts, experimental data on simple shapes or simple phantoms easily described with analytic shape functions are the norm. The advantage of these test data sets is that full knowledge if available for the test cases giving a clear means to evaluate the effectiveness of a reconstruction approach. However, these simple test cases often have limitations compared to noisy data and complex geometry, situations that are the particular ones of interests in an NDE inspection. Collecting data on large numbers of sample shapes and with varying noise configurations is difficult and often impossible.

Over the past years robust forward models of the physics of the image formation process have been developed [2,3]. These models include the typical white spectrum of tube sources, interaction of that spectra with CAD representations of part and defect geometry and, importantly, detector response with noise modeling. The ease at developing realistic data on which 3D reconstruction algorithms can be tested provide a powerful tool for untangling reconstruction based artifacts from noise artifacts, from defect geometry artifacts. A good example is the beam hardening effect that occurs due to the white spectrum of an x-ray tube. NDE models, for example XRSIM [4,5,6], can generate these effects representing the actual experimental conditions.

Successful algorithm development requires full knowledge of all inspection and sample properties. This is not possible with experimentally-collected data due to measurement noise and deviation of the sample from some “nominal” condition. One way to address this is to use analytical models. Such models, however, only work for very basic shapes such as spheres with piecewise-constant composition. Even when applied to simple samples, an analytical approach becomes complicated when the inspection is limited. As a result, the use of numerical simulations has become necessary.

Historically, the use of such simulations has been limited by the computational complexity of modeling the interaction of x-rays with matter. A commonly-used approach involves the Shepp-Logan phantom [7], which simplifies the problem by using simple shapes with piecewise-constant composition. While these simplifications are an improvement over an analytical model, they still fail to capture the geometric and composition complexity found in real samples.

Advances in computer technology, coupled with the development of a physics-based forward model, such as the program XRSIM developed at the Center for NDE, now allow for the capture of realistic complexity while maintaining full knowledge of the inspection and sample. Full knowledge of the inspection provides a means to leverage a priori knowledge to improve the performance of algorithms while full knowledge of the sample allows for direct, quantitative comparison between the reconstruction results and the actual object.

**RECONSTRUCTION ALGORITHMS**

Two reconstruction algorithms have been implemented to illustrate the use of advanced NDE simulation models in algorithm development. The first, known as “shift-and-add”, is a well-known algorithm for digital laminography. The second, referred-to here as “direct mapping”, is an alternative approach to back-projection.

**Shift-and-Add Reconstruction**

Shift-and-add reconstruction [1] uses coordinated motion between the x-ray source, detector, and inspection sample to acquire the projection images used as input for the reconstruction algorithm. For a stationary source, the sample and detector are constrained
to move in parallel planes. This motion constraint maintains constant magnification for each point within the sample. As a result of the projection process, features in different locations will be projected onto varying locations on the detector, and the relative motion of a feature's projection on the detector to the detector itself is a function of the feature's location within the sample. Within the sample, planes parallel to the detector can be reconstructed by simply adding the input images together. Features in the same plane will lie in the same location on the detector, reinforcing their appearance. Out-of-plane features, however, will appear blurred due to their varying location on the detector. The plane-of-focus can be selected by applying an offset to each input image prior to summation, thus allowing the reconstruction of an infinite number of planes from a finite number of projection images.

This method is very fast and it produces a result identical to back-projection. If the projection images are not modified prior to reconstruction, the resulting reconstruction is identical to unfiltered back-projection and suffers from the same blurring issues. Filters can be applied to the projection images prior to reconstruction to make the result identical to filtered back-projection. This filtered result suffers from the same artifacts found in filtered back-projection limited data as used with traditional CT algorithms. The biggest drawback of this method is the physical space required to perform the translations.

**Direct-Mapping Reconstruction**

To address the translational-range issue encountered with shift-and-add reconstruction, an alternative algorithm is introduced which allows for the replacement of translations with rotations. This makes the space requirements for an inspection manageable and also allows for the sample motion during the inspection to be fully-general so that an inspection can be tailored to the specific attributes of the sample.

Direct-mapping begins by defining a reconstruction volume which contains the space occupied by the sample. This volume can be of arbitrary shape to suit the geometry of the sample. Next, the volume is divided into small voxels which are independently reconstructed. These voxels begin with an initial value of 0, and after the reconstruction process contain the CT number associated with their portion of the sample. Let us consider a single arbitrary voxel. This voxel encloses a known region within the sample, and its position is calculated for each input image collected during the inspection. As the sample moves during the inspection the location of this voxel is calculated so that the voxel always encloses the same portion of the sample. Then, for each input exposure, the voxel's position is projected onto the detector. The value recorded on the detector is then added to the value stored in the voxel. This projection followed by addition is repeated for each input image, and the entire process is performed on all voxels.

In addition to allowing fully-general motion, direct-mapping also provides an opportunity to consider all input values prior to their addition to a voxel. This provides a means to incorporate filter algorithms into the reconstruction process itself rather than applying filters either before or after the reconstruction is performed.

The flexibility of the direct-mapping reconstruction algorithm allows for making maximum use of a forward model when generating input data. Complex inspection geometries can be used for complicated samples due to the general motion allowed with direct-mapping.
TEST-DATA GENERATION

Algorithm development was performed using data generated by XRSIM, a physics-based forward model developed at the Center for NDE. Use of XRSIM allows for full knowledge of the inspection and the sample itself. Additionally, complicating factors such as photon scattering and detector noise can be selectively enabled or disabled to examine their effects on the reconstruction algorithms. Addressing such complexity during the algorithm-development stage using simulated data is much faster and more cost-effective than developing an algorithm using simple models and later attempting to make adjustments using experimental data.

The ability of the direct-mapping algorithm to perform reconstructions from experimental data was also verified using data collected using a micro-focus CT inspection system. This system rotates the sample about a single axis when acquiring data. Successful application of the direct-mapping algorithm to experimentally-collected data demonstrates both the algorithm’s ability to handle real data and the power of using a complex forward model when developing the algorithm.

ALGORITHM IMPLEMENTATION

Both reconstruction algorithms were implemented within a custom application written at the Center for NDE. User-controlled parameters, such as filter selection, output file name, location of input files, algorithm to use, and reconstruction resolution are set using a graphical interface. Alternatively, a configuration file can be created for use with a text-based version for use on Beowulf clusters and remote execution. Both versions use OpenMP to leverage multiple processors and multiple processor cores on a single machine, when available. The independence of each voxel during the reconstruction process makes the problem well-suited for parallel-computing and the use of parallelism allows large reconstructions to be completed within a reasonable amount of time. The interface for this application can be seen in Fig. 1.

FIGURE 1. Interface of reconstruction application.
RECONSTRUCTION RESULTS: SIMPLE GEOMETRIES

Shift-and-Add Algorithm

The shift-and-add algorithm was developed using a model of a 3 centimeter thick aluminum plate containing a small (1 millimeter diameter) spherical inclusion of nickel. The shapes were initially kept simple to prevent algorithm-induced artifacts from appearing to be due to the sample or flaw geometry. The reconstruction was performed without the use of any filters, making the result equivalent to an unfiltered back-projection. The result can be seen in Fig. 2, and the motion used during the reconstruction, as well as the plane shown in Fig. 2, can be seen in Fig. 3. This particular inspection used 21 input images with the sample translated 1.9 centimeters between exposures.

In Fig. 2, the bold black line shows the location of the true boundary of the object. In a perfect reconstruction, all points outside this box would be white. The dark spot seen in the upper-left is the small nickel inclusion. The large attenuation difference between aluminum and nickel produces a high contrast region in the reconstruction volume and it is readily seen that this region introduces artifacts in other portions of the volume.

Edge artifacts can also be seen in Fig. 2. These artifacts are generated by two compounding sources. The first of these sources is the x-ray beam itself. There is a portion of the rays which enter the top face of the sample and exit the side rather than the bottom. These rays have a shorter path length through the sample than those which enter the top and exit the bottom, resulting in less attenuation. This lower attenuation mimics a low-density region during the reconstruction process. Compounding this is the shift applied during the reconstruction process that serves to spread the lower-intensity values over a wider area of the reconstruction, producing the “hourglass” edges visible in Fig. 2.

RECONSTRUCTION RESULTS: COMPLEX GEOMETRIES

Direct-Mapping Algorithm

The direct-mapping algorithm was used to explore artifacts introduced by more-complex sample and flaw geometries. Use of this algorithm allowed for the collection of a full dataset that could then be used with a standard CT reconstruction algorithm used at the Center for NDE. Use of a standard CT algorithm assists in identifying artifacts introduced as a result of the limited dataset. The direct-mapping algorithm can also be used with a full dataset, in which case it produces a result nearly identical to standard CT provided two conditions are met. First, magnification must be kept less than 3. Higher magnifications can cause artifacts when portions of the reconstruction volume are sufficiently far away from the beam centerline. Direct-mapping doesn’t have fan-beam artifacts as it uses cone-beam geometry when projecting the voxel position onto the detector. Second, voxel size must be kept similar to detector pixel size. When these sizes are dissimilar the direct-mapping algorithm introduces artifacts due to its current method of projecting the voxel positions onto the detector, whereas the standard CT algorithm has a more-robust method of handling the dissimilarity. When both of these conditions are met, the differences in results between direct-mapping and standard CT become minimized, and with proper filter choice the difference becomes negligible.

While direct-mapping is nearly equivalent to standard CT for full datasets, it is equivalent to shift-and-add for limited datasets. As a result, the artifacts found when direct-mapping is applied to complex geometries are indicative of artifacts that will be found when shift-and-add is applied to the same situation.
FIGURE 2. Slice of reconstruction volume showing artifacts introduced through unfiltered shift-and-add reconstruction.

FIGURE 3. Schematic showing the motion used during the shift-and-add simulation and the reconstruction plane shown in Fig. 2.

The aluminum casting used to test direct-mapping with complex geometries is shown in Fig. 4. During the simulated inspection, the sample was rotated about its long axis, oriented lower-left to upper-right in the figure. A model of a real flaw, also seen in Fig. 4, was inserted into the casting near the upper end just before the circular cross-section region. This position was chosen to create interaction between artifacts generated by the sample geometry and those generated by the flaw. The flaw model itself was generated using data from a high-resolution CT scan of casting porosity, thus it captures realistic complexity for a type of flaw anticipated in the modeled casting.
Reconstruction results for this sample can be seen in Fig. 5. The reconstruction on the left used a full 360-degree rotation dataset with a projection image acquired every degree. The reconstruction on the right used an 80-degree subset, with a projection image every 4-degrees. It is important to note that both reconstructions came from the same dataset. Also, both reconstructions pre-filtered the input data with a ramp filter in the frequency-domain. This is a common filter in standard CT algorithms and its effectiveness is demonstrated by the clarity of the image on the left. While the filter does help sharpen some features in the limited dataset reconstruction, it also introduces several hard edges which are aligned with the limiting orientations of the inspection. These hard edges are not physically present in the sample, and their appearance in the reconstruction indicates that alternative processing is required to obtain high-quality reconstructions.

The limited dataset reconstruction shows that the correct dimensions of the flaw are much more difficult to obtain. Additionally, artifacts from the flaw interact with artifacts from the sample as well as with artifacts from itself. These interactions demonstrate the power of using a physics-based forward model during algorithm development. By knowing the exact sample and flaw geometries it is possible to evaluate the quality of the limited dataset reconstruction without having to perform a full dataset reconstruction. In this case the full dataset reconstruction provides a means to verify the direct-mapping algorithm is working correctly.

CONCLUSIONS

We have illustrated the need for CT algorithms that can produce high-quality reconstructions when only a limited dataset is available. Common CT filters introduce unwanted artifacts, and using no filters does not provide adequate clarity in the reconstruction. We have also demonstrated the advantages to using a physics-based forward model, such as XRSIM, while developing reconstruction algorithms.

To address the need for improved data processing, future work will explore means of using a priori knowledge of the inspection and sample to improve the reconstruction result. One means of doing so will involve the identification of high-contrast features within the reconstruction volume and then iteratively removing their effects from nearby
voxels. Another means will involve the use of fiducial markers to assist in determining the spatial extent of the sample. Once the spatial extent of the sample is established we can refine voxel values based on their position relative to the now-known position of the sample.

Input data to test data processing routines will continue to be generated by XRSIM so that we may maintain full knowledge of all inspection parameters and sample properties. As data processing routines become more-refined their effects can be quantified by comparing the results to the XRSIM simulation, providing an objective means of evaluating processing algorithms.

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