### Imperial College London



# Limited view X-ray CT for dimensional analysis

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NON-DESTRUCTIVE EVALUATION GROUP



- Industrial X-ray CT
- Inverse Tomographic Imaging
- Application to turbine blade imaging
- Application to additive manufactured sample
- Conclusions

Industrial X-ray CT

- Additive manufacturing
  - Complex shapes
  - Safety critical
- X-ray CT provides
  - Powerful inspection tool
  - Dimensional analysis
  - Quality control of components







Industrial X-ray CT Filtered back projection

#### **Advantages**

- Fast computational time
- Low memory requirements
- Multiple years of experience

#### Disadvantages

- Difficult to apply non-uniform ray sampling
- Requires consistent sampling interval
- 100-1000s of projections required
- Cannot incorporate prior information
- Long data acquisition time can lead to manufacturing bottlenecks
- **Goal:** Accurate image of the interior of an object using minimal X-ray data for reduced acquisition time and system costs









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### Inverse tomographic imaging

- Alternative to Fourier methods
- Relate the projection data to the image with a model

#### **Advantages**

- Sampling flexibly
- Incorporation of prior information
- Reduction of computing costs and increasing processor power

#### Disadvantages

- Slow compute time for large images
- Restricted to iterative methods due to size of problem



### Inverse tomographic imaging Least squares methods

Iterative algorithms

#### **Algebraic Reconstruction Technique - ART**

- 1<sup>st</sup> used in medial imaging in the 1970s
- Updates image one row of **A** at a time
- Fast convergence
- Non-negative pixel values

#### Simultaneous Iterative Reconstruction Technique - SIRT

- Simultaneous version of ART
- Non-negative pixel values
- Easy incorporation of pixel constraints



### Inverse tomographic imaging Total variation (TV)

- Advanced signal processing allowing sub sampled signals to be reconstructed
- TV ideally suited in reconstructing signals with sharp edges
- 2 iterative algorithms

#### Hybrid ART-TV method

- 2 step approach
  - 1. Solve ART iteration
  - 2. TV step to de-noise image from 1.
- Non-negative pixel values

#### **Gradient descent with TV regularisation**

Direct incorporation of TV method



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### Application to turbine blade imaging Imaging results

1° sampling<br/>ARTART positivitySIRTART-TVImage: Simpling<br/>ARTImage: Simpling<br/>ARTImage: Simpling<br/>ART positivityImage: Simpling<br/>Simpling<br/>ARTImage: Simpling<br/>ART positivityImage: Simpling<br/>ART positivity



TV gradient



### Application to turbine blade imaging Wall thickness analysis





### Application to turbine blade imaging Wall thickness analysis



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### Application to additive manufactured sample Dimensional analysis

- Additive manufactured plastic sample with multiple small features
- Compare X-ray results with physical measurements and manufacturers tolerances





### Application to additive manufactured sample Imaging results



### Application to additive manufactured sample Dimensional analysis



Green - within measured precision (± 0.05mm).

Blue, red – x2 precision of the physical measurements and within the manufacturers quoted build resolution ( $\pm$  0.2 mm).

Grey - outside the manufacturers build resolution (± 0.2 mm).

White - no thickness measurement.

### Application to additive manufactured sample Effect of sample complexity

- Synthetic experiment compares the full additive manufactured object with a circular sample
- Full object display similar results to experimental data.
- Circular sample is less 'complex' than the full object
  - Reduction in object complexity
  - Reduction in the number of internal features
- Accurate reconstruction of simpler sample



### Conclusions

- Inversion methods capable of producing accurate CT reconstructions and dimensional measurements with limited data
- Reduction in X-ray projections by at least an order of magnitude
- Object complexity a factor in the number of X-ray projections needed
- Inclusion of pixel constraints knowledge greatly improves the reconstruction
- TV methods do not significantly improve the reconstruction vs ART or SIRT

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