High Performance Computing Applied to Manufacturing Engineering Geometry Problems

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Applications

• Sheet metal forming strain analysis
  – Laser scanning,
  – MPI, NVIDIA GPU

• Machining process optimization
  – Multi-Core Intel, ACIS
Sheet Metal Forming Strain Analysis

- Automotive Body
Sheet Metal Forming Strain Analysis

• Forming Process

Toyota Motor Corporation
Sheet Metal Forming Strain Analysis

• Material Testing – Erichsen test, etc.

Inland Steel Company

1-tension; 4-biaxial stretching
Sheet Metal Forming Strain Analysis

• Forming Limit Diagram

The ellipse axis lengths $L_1$ and $L_2$ are then measured. For each ellipse, the true strains are expressed as

$$
\varepsilon_1 = \int_{L_0}^{L_1} \frac{dL}{L} = \ln \left( \frac{L_1}{L_0} \right);
$$

$$
\varepsilon_2 = \int_{L_0}^{L_2} \frac{dL}{L} = \ln \left( \frac{L_2}{L_0} \right);
$$

where $L_0$ is the original circle diameter.

S.P. Keeler, 2002
Sheet Metal Forming Strain Analysis

• Laser Scanning

Scanner Intensity Image

Adaptive Threshold Image
Sheet Metal Forming Strain Analysis

- Image Processing (parallel)
  - 3 x 3 pixel Square Mask Gaussian Noise Reduction

\[
G(a, b) = c \cdot \exp \left( \frac{-(a^2 + b^2)}{2\sigma^2} \right)
\]

where \( c = \sum_{a=-1}^{1} \sum_{b=-1}^{1} \exp \left( \frac{-(a^2 + b^2)}{2\sigma^2} \right) \)^{-1}, \((a, b)\) is the mask element position and \( \sigma = 2 \).
Sheet Metal Forming Strain Analysis

- Image Processing (parallel)
  - 7 x7 pixel Adaptive Thresholding
  - Circle grid width is 3 pixels

Let $g(x, y)$ be the intensity level at the central pixel of a window $f$ having size $(2sw+1) \times (2sw+1)$, where $sw=3$ is the object (circle/ellipse edge) width in pixels. Based on the 8 neighboring window pixels $P_i, i=0...7$, the current pixel is set to a value $b(x, y)$ using the following formula:

$$b(x, y) = \begin{cases} 1 & \text{if } \bigvee_{i=0}^{3} (B(P_i) \land B(P_{i+1}) \land B(P_{i+4}) \land B(P_{i+5})) \\ 0 & \text{otherwise} \end{cases}$$

where $B(P_i)$ is a Boolean operation that is TRUE if $\text{ave}(P_i) - g(x, y) > T$, and FALSE otherwise. The operators $\lor$ and $\land$ respectively denote logical OR and AND. The subscript $i$ arithmetic is modulo 8. The value of $\text{ave}(P_i)$ is formulated as:

$$\text{ave}(P_i) = \frac{\sum_{a=0}^{2sw} \sum_{b=0}^{2sw} P_i(x_{a,b}, y_{a,b})}{(2sw+1)^2}$$
Sheet Metal Forming Strain Analysis

• Image Processing (parallel)
  – 7 x 7 pixel Adaptive Thresholding
    • Circle grid width is 3 pixels

and the adaptive thresholding value is calculated using the algorithm:

1) Calculate $f_{\text{max}} = \text{MAX}(f)$, $f_{\text{min}} = \text{MIN}(f)$ and $f_{\text{ave}} = \text{ave}(f)$

2) Calculate $|f_{\text{max}} - f_{\text{ave}}|$ and $|f_{\text{min}} - f_{\text{ave}}|$.

3) If $|f_{\text{max}} - f_{\text{ave}}| < |f_{\text{min}} - f_{\text{ave}}|$, $T = \left(\frac{2}{3} f_{\text{min}} + \frac{1}{3} f_{\text{ave}}\right) \cdot \alpha$

4) If $|f_{\text{max}} - f_{\text{ave}}| < |f_{\text{min}} - f_{\text{ave}}|$, $T = \left(\frac{1}{3} f_{\text{min}} + \frac{2}{3} f_{\text{ave}}\right) \cdot \alpha$

5) If $|f_{\text{max}} - f_{\text{ave}}| = |f_{\text{min}} - f_{\text{ave}}|$, increase the window size to $(2sw+3) \times (2sw+3)$ and repeat from step 1. If $|f_{\text{max}} - f_{\text{ave}}| = |f_{\text{min}} - f_{\text{ave}}|$ again, $T = f_{\text{ave}} \cdot \alpha$.

$$\alpha = \begin{cases} 
1 & \text{if } f_{\text{ave}} < 90 \\
0.33 & \text{if } 90 \leq f_{\text{ave}} < 130 \\
0.2 & \text{if } 130 \leq f_{\text{ave}} < 170 \\
0.1 & \text{if } f_{\text{ave}} \geq 170 
\end{cases}$$
Sheet Metal Forming Strain Analysis

• Image Processing
  – Data Point Grouping (serial)
    • Digitizer point spacing ~0.1 mm
    • Circle minimum separation 0.381 mm
    • Group all points within <0.3 mm distance
    • Merge partial circles/ellipses based on center

  – Least Squares Ellipse Fitting (parallel)
    • Begin with best fit plane
    • Optimize using Orthogonal Distance Regression*

Sheet Metal Forming Strain Analysis

• Least Squares Fitting

Plane: Find $p$ and $v$ to minimize the sum

$$S = \sum_{m=1}^{M} \|c_m\|^2$$

Line: Find $p$ and $v$ to minimize the sum

$$S = \sum_{m=1}^{M} \|d_m\|^2$$
Sheet Metal Forming Strain Analysis

• Least Squares Fitting
  • Finding $p$

For planes, $\|c_m\|^2 = (s_{m,n} - p) \cdot v$

$$S = \sum_{m=1}^{M} \sum_{n=1}^{3} \left[ (s_{m,n} - p_n) v_n \right]^2 = \sum_{n=1}^{3} \sum_{m=1}^{M} \left[ (s_{m,n} - p_n) v_n \right]^2$$

Setting the partial derivatives with respect to $p$ equal to zero

$$0 = \frac{\partial S}{\partial p_q} = -2 \sum_{m=1}^{M} (s_{m,q} - p_q) v_q^2$$

Because $\|v\| = 1$ the $v_q$ terms cannot all be zero, implying that

$$0 = \sum_{m=1}^{M} (s_{m,q} - p_q) \quad \text{or} \quad p_q = \frac{1}{M} \sum_{m=1}^{M} s_{m,q}$$
Sheet Metal Forming Strain Analysis

• Least Squares Fitting
  – Finding \( \nu \)

If \( a_m = s_m - p \) then

\[
S = \sum_{m=1}^{M} \sum_{n=1}^{3} a_{m,n} \nu_n^2 = \nu^T A^T A \nu
\]

where

\[
A = \begin{bmatrix}
a_{1,1} & \cdots & a_{1,3} \\
\vdots & \ddots & \vdots \\
a_{m,1} & \cdots & a_{m,3}
\end{bmatrix}
\]

This is an ellipsoid quadratic form in \( \nu \). The three extreme values of the sum occur when \( \nu \) is aligned with one of the principal directions (unit length eigenvectors) of \( A^T A \). Note that \( A \) and \( A^T A \) have the same unit length eigenvectors, denoted \( \nu_a, \nu_b, \text{ and } \nu_c \). If \( A^T A \) has corresponding eigenvalues \( \lambda_a^2, \lambda_b^2, \lambda_c^2 \), then \( A \) will have corresponding eigenvalues \( \lambda_a < \lambda_b < \lambda_c \). These are the semi-lengths of the axes of \( \nu^T A^T A \nu \), and the extreme values of the sum of squares \( S \). The minimum value is \( S_a = \lambda_a^2 \) and \( \nu = \nu_a \) is the desired normal vector for the OLS plane.
Sheet Metal Forming Strain Analysis

• Least Squares Fitting
  – Quadratic Forms

\[
S = \sum_{m=1}^{M} \left[ \sum_{n=1}^{3} a_{m,n} v_n \right]^2 = \sum_{m=1}^{M} \left[ \sum_{n=1}^{3} a_{m,n} v_n \right] \left[ \sum_{q=1}^{3} a_{m,q} v_q \right] = \sum_{n=1}^{3} v_n \left[ \sum_{q=1}^{3} \left( \sum_{m=1}^{M} a_{m,n} a_{m,q} \right) v_q \right]
\]

\[
= \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix} \cdot \begin{bmatrix}
\sum_{m=1}^{M} a_{m,1} a_{m,1} & \sum_{m=1}^{M} a_{m,1} a_{m,2} & \sum_{m=1}^{M} a_{m,1} a_{m,3} \\
\sum_{m=1}^{M} a_{m,2} a_{m,1} & \sum_{m=1}^{M} a_{m,2} a_{m,2} & \sum_{m=1}^{M} a_{m,2} a_{m,3} \\
\sum_{m=1}^{M} a_{m,3} a_{m,1} & \sum_{m=1}^{M} a_{m,3} a_{m,2} & \sum_{m=1}^{M} a_{m,3} a_{m,3}
\end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}
\]

\[
= \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix} \cdot \begin{bmatrix}
a_{1,1} & \cdots & a_{m,1} \\
\vdots & \ddots & \vdots \\
a_{1,3} & \cdots & a_{m,3}
\end{bmatrix} \cdot \begin{bmatrix} a_{1,1} & \cdots & a_{1,3} \\
\vdots & \ddots & \vdots \\
a_{m,1} & \cdots & a_{m,3}
\end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = v^T A^T A v
\]
Sheet Metal Forming Strain Analysis

- Least Squares Fitting
  - Ellipsoid $S = v^T A^T A v$

$\lambda_a < \lambda_b < \lambda_c$
Sheet Metal Forming Strain Analysis

• Least Squares Fitting
  – Circles, ellipses, etc.

Unlike the linear OLS plane fitting problem, for circles, ellipses, etc., the problem is non-linear, and an iterative algorithm must be used. For the 2D circle with centre $p$ and radius $r$, the orthogonal distance error for a point $s_m$ is

\[
d_m = \left[ \sum_{n=1}^{2} (s_{m,n} - p_n)^2 \right]^{1/2} - r
\]

and the OLS sum to minimize is

\[
S = \sum_m d_m^2
\]

For an ellipse, the fit begins with a plane fit $ax^2+by^2+cxy+dx+ey=f$ and followed by iteration to the OLS fit.
Sheet Metal Forming Strain Analysis

• Parallel Computing using SHARCNET MPI

Noise Reduction / Thresholding

Ellipse Fitting
Sheet Metal Forming Strain Analysis

- Parallel Computing using MPI
    - 1 Master, 7 slaves
  - Execution Time
    - Reduced from 709 s to 115 s
    - 5.8 million scan points
  - Ellipse Fitting
    - Consumes 88% of time
  - Data Communication
    - Limits speedup

![Graph showing execution time reduction with increasing number of slave processors]
Sheet Metal Forming Strain Analysis

- Graphical Results
Sheet Metal Forming Strain Analysis

• Graphical Results
Sheet Metal Forming Strain Analysis

• Graphical Results
Sheet Metal Forming Strain Analysis

• Computer Vision and Square Grids
Sheet Metal Forming Strain Analysis

• Forming Limit Diagram

\[
\begin{bmatrix}
  x_1 \\
  y_1 \\
\end{bmatrix} = \begin{bmatrix}
  F_{11} & F_{12} \\
  F_{21} & F_{22} \\
\end{bmatrix} \cdot \begin{bmatrix}
  X_1 \\
  Y_1 \\
\end{bmatrix}, \quad \begin{bmatrix}
  x_2 \\
  y_2 \\
\end{bmatrix} = \begin{bmatrix}
  F_{11} & F_{12} \\
  F_{21} & F_{22} \\
\end{bmatrix} \cdot \begin{bmatrix}
  X_2 \\
  Y_2 \\
\end{bmatrix}
\]

A = (X_1, y_1), A' = (x_2, y_1), B = (X_2, y_2), B' = (x_2, y_2)

can now be solved for F. The eigenvalues \( \lambda_{1,2} \) of F can be computed using the singular value decomposition (SVD) and satisfy the relationship \( \varepsilon_{1,2} = \ln(\lambda_{1,2}) \) where, same as before, \( \varepsilon_1 \) and \( \varepsilon_2 \) are the surface true strains. The third or thickness strain can then be calculated using \( \varepsilon_3 = -\varepsilon_1 - \varepsilon_2 \).
Sheet Metal Forming Strain Analysis

- NVIDIA Parallel Computing
  - Portable arm CMM continuous monocular 15 fps video sequence

[Diagram of the process involving camera, joint encoders, video data, video/position data synchronization, GPU-accelerated grid intersection measurement, 2D grid intersections, calibration parameters, strain analysis, and strain output.]
Sheet Metal Forming Strain Analysis

- NVIDIA Parallel Computing
  - Used Scale Space “convolution” implementation
  - Motion blur, out of focus blur robustness

<table>
<thead>
<tr>
<th>Image Size</th>
<th>Δt</th>
<th>Multiply (GFLOPS)</th>
<th>Add (GFLOPS)</th>
<th>FMA (GFLOPS)</th>
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<tbody>
<tr>
<td>1024 × 768</td>
<td>1</td>
<td>0.76</td>
<td>1.23</td>
<td>1.32</td>
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<tr>
<td></td>
<td>3</td>
<td>1.89</td>
<td>3.68</td>
<td>3.59</td>
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<td></td>
<td>6</td>
<td>3.59</td>
<td>7.36</td>
<td>6.98</td>
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<td>2448 × 2048</td>
<td>1</td>
<td>4.81</td>
<td>7.82</td>
<td>8.42</td>
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<tr>
<td></td>
<td>3</td>
<td>12.0</td>
<td>23.5</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>22.9</td>
<td>46.9</td>
<td>44.5</td>
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</table>

Implemented with 3 scales

Estimated Number of Convolution Operations per Second

<table>
<thead>
<tr>
<th>Kernel Name</th>
<th>GPU Time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Space Generation</td>
<td>6.25</td>
</tr>
<tr>
<td>Metric Computation</td>
<td>15.55</td>
</tr>
<tr>
<td>Isosurface Interpolation</td>
<td>21.71</td>
</tr>
<tr>
<td>Ridge Segment Linking</td>
<td>2.32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45.83</strong></td>
</tr>
</tbody>
</table>
Sheet Metal Forming Strain Analysis

• NVIDIA Parallel Computing
  — Detection Results
Sheet Metal Forming Strain Analysis

- Intel 2.8 GHz Core i7 - Topological Motion Tracking

### Processing Stage

<table>
<thead>
<tr>
<th>Processing Stage</th>
<th>Execution Time (ms)</th>
<th>Percent Time</th>
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</thead>
<tbody>
<tr>
<td>Adaptive Thresholding</td>
<td>4.1</td>
<td>7.84%</td>
</tr>
<tr>
<td>Morphological Operations</td>
<td>7.6</td>
<td>14.53%</td>
</tr>
<tr>
<td>Connected Component Labeling &amp; Metric computation</td>
<td>37.8</td>
<td>72.28%</td>
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<tr>
<td>Delaunay Triangulation &amp; Quadrilateral Formation</td>
<td>0.5</td>
<td>0.96%</td>
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<tr>
<td>Grid Axis Alignment</td>
<td>0.3</td>
<td>0.57%</td>
</tr>
<tr>
<td>Topological formation and filtering</td>
<td>0.3</td>
<td>0.57%</td>
</tr>
<tr>
<td>Interframe Registration</td>
<td>0.3</td>
<td>0.57%</td>
</tr>
<tr>
<td>Interframe Transform Computation</td>
<td>0.4</td>
<td>0.76%</td>
</tr>
<tr>
<td>Total</td>
<td>51.3</td>
<td>100%</td>
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</tbody>
</table>
Machining Process Optimization

- Metal Stamping, Plastic Injection Molding

Stamping Die Machining

Electrically Heated Hot Runner (Husky Injection Moulding)
Machining Process Optimization

- CAD/CAM based CNC tool path creation
Machining Process Optimization

- Cutting Tool Engagement Calculations
Machining Process Optimization

- Cutting Tool Engagement Calculations

**Hot Runner Optimization**
(20% time savings)

**2001 Round-Robin ACIS Simulation**
(2x Dual CPU 500 MHz Pentium III)
Machining Process Optimization

- Quadrant Groups, 4 instances

<table>
<thead>
<tr>
<th>Test Case Number</th>
<th>Create Groups (s)</th>
<th>Boolean Subtract (s)</th>
<th>Machining Simulation (s)</th>
<th>ACIS Instance Total (s)</th>
<th>CL-DATA Re-combine (s)</th>
<th>Grand Total (s)</th>
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</thead>
<tbody>
<tr>
<td>i</td>
<td>31.0</td>
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<td></td>
<td></td>
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<td>428.4</td>
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<td>vi-(a)</td>
<td>27.2</td>
<td>73.3</td>
<td>100.5</td>
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<td>138.5</td>
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<tr>
<td>vi-(b)</td>
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<td>54.2</td>
<td>77.0</td>
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<td>115.0</td>
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<tr>
<td>vi-(c)</td>
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<td>67.6</td>
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<td>7.0</td>
<td>105.6</td>
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<tr>
<td>vi-(d)</td>
<td>12.7</td>
<td>29.7</td>
<td>42.4</td>
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<td>80.4</td>
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</tbody>
</table>
Machining Process Optimization

• Z-Map Method
  – Similar to mowing blades of grass
Machining Process Optimization

• Z-Map vs. B-Rep Method
  – B-Rep more accurate and more robust
Machining Process Optimization

- ACIS B-Rep Parallel Computing Algorithm

0.5 mm increment along tool path:
1 core – 59 s, 8 cores – 11 s
Machining Process Optimization

• Mesh Based Simulation
Machining Process Optimization

- Mesh Based Simulation – computing time
Current Projects

• NSERC CANRIMT Virtual Machining Strategic Network
  – Canadian Network 2010-2015
  – $1,000,000 per year, McMaster share ~20%
    • Drs. Elbestawi, Ng, Spence, Veldhuis, Koshy
    • WebEx Graduate Courses
  – Laser Scanner - 5-Axis Machine Tool
  – Calibration, Point Cloud Processing, etc.
Current Projects

– Laser scanner – 5-axis machine tool

Makino 5-axis machine tool
Current Projects

– Inkjet Printed Sheet Metal Strain Dot Grids
Acknowledgements

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- Mechanical Engineering Technical Staff
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