Extensive studies of shape measurement systems have been completed. Both numerical simulations and controlled experiments have been performed. Results have shown that, for fringe patterns having sensor plane fringe spacing from 3 to 30 pixels, the resulting phase error can be reduced to less than 0.02 radians by controlling the spatial frequency of the signal and noise, as well as the contrast in the pattern.

Studies of data integration methodologies have also been completed. Results demonstrate that the procedure developed by the authors is both robust and accurate when registering and integrating multiple, overlapped data sets. The effects of key variables in the registration process have been quantified through numerical simulations. Results indicate that when the feature size divided by the overlapped region size, $\alpha = \text{fsizes} \leq 0.5$, and the mesh size divided by the feature size, $\beta = \text{mshs} \leq 0.25$, the algorithm can accurately and efficiently register and integrate multiple data sets with a relative error, $e = \text{raim}s \leq 10\%$.

Finally, studies of automated registration processes have been performed. Local differential geometry properties such as gaussian curvature, $K$, and mean curvature, $H$, along with their signs have been used to successfully automate the process of integration of separate shape measurement data sets.
MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
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P.O. Box 12211
Research Triangle Park, NC 27709-2211

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☐ Manuscript (1 copy)        ☒ Final Progress Report (Orig + 2 copies)
☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: DAAH-04-96-1-0420

REPORT TITLE: Final Report for "Integrated Shape Measurement System for Rapid Shape Measurement, Model Verification and NDE.

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Michael A. Sutton

Enclosure 3
1. **Statement of the Problem Studied and Significance**

This research was directed towards the development and experimental verification of a stereo-vision measurement methodology which will be used to (a) accurately determine the three-dimensional shape of a complex component either in the initial or deformed states, (b) convert the measured surface displacement data into a functional form using surface fitting methods such as wavelet transformations and (c) perform these operations rapidly.

The significance of this work is in two areas. Firstly, the measurement of surface shape and rapid conversion of the measurements into an accurate functional relationship is a major step in improving existing computer-aided engineering applications for more rapid design and manufacture of components. Secondly, the experimental data base for the deformation of complex structural components is essential to the verification of solid model equation solvers (e.g., finite difference, finite element, boundary element) for large structures. This is particularly important since government organizations such as NASA have proposed a GLOBAL--LOCAL analysis methodology to ensure that local variations (e.g., small cracks, rivets, frame reinforcing members) can be properly accounted for in the model.

2. **Summary of Most Important Results**

*Measurement Methodology*
An accurate camera calibration procedure and improved phase extraction procedures using a modified Hilbert Transform [1,2] with Laplacian Pyramid and Flood-Fill algorithms have been developed and successfully demonstrated for measurement of the full (X, Y, Z) positions of surface points using single frequency, fringe projection profiling methods [3]. Detailed numerical simulations and controlled baseline experiments have been performed to quantify the key error sources in the measurement process and verify the accuracy of the approach.

Simulation results indicate that, for fringe patterns having sensor plane fringe spacing from 3 to 30 pixels, the resulting phase error can be reduced to less than 0.02 radians provided that

(a) the spatial frequency of the background noise sources meets the inequality

\[ k = \frac{2\pi}{\lambda} < 0.01, \]

(b) the multiplicative noise terms have spatial frequency content at least three times smaller than the fringe pattern,

(c) the multiplicative noise factors have an amplitude at least ten times smaller than the fringe pattern

(d) the recorded fringe patterns have an amplitude of at least 64 gray levels and the recorded fringe patterns have a random noise to signal amplitude ratio < 0.010.

Baseline experiments have been performed which demonstrate that the error sources (e.g., random intensity fluctuations, contrast reduction) quantified in the numerical simulations are in good agreement with physical measurements. Specifically, results indicate random spatial changes in the intensity pattern due to variations in
object surface reflectivity introduce negligible bias and a random variation of 0.05 radians in the extracted phase for almost all experiments performed.

To demonstrate the method for applications, spatial (X, Y, Z) data has been obtained by both coordinate measurement machine (CMM) and fringe projection for both a planar surface and a turbine blade. Results indicate that (a) the CMM measurements are in good agreement with fringe projection data for both cases and (b) simulation estimates for the fringe projection errors are consistent with measurements.

Taken together, the experimental studies and numerical simulations confirm that very high accuracy shape measurements can be made with single frequency projected grids. Specifically, phase errors of less than 0.04 radians on a pixel-by-pixel basis are achievable for a wide range of fringe density using the proposed method. Furthermore, the experimental and numerical results demonstrate conclusively that it is possible to design both a fringe projection system and a measurement process to achieve a pre-specified accuracy and resolution in the point-to-point measurement of the spatial (X, Y, Z) positions.

**Data Synthesis**

Efficient, accurate integration of multiple sets of surface profile data without requiring accurate relative positional information is an important step in the reverse engineering process. Results from the current work [4] demonstrate that the procedure developed by the authors is both robust and accurate when registering and integrating multiple, overlapped data sets. The effects of key variables in the registration process have been quantified through numerical simulations. Results indicate that when
the feature size divided by the overlapped region size, \( \alpha = fs/ls \leq 0.5 \), and the mesh size divided by the feature size, \( \beta = ms/fs \leq 0.25 \), the algorithm can accurately and efficiently register and integrate multiple data sets with a relative error, \( \epsilon = ralms \leq 10\% \).

It is important to note that we have selected curvature as the dominant surface feature for this work. Currently we are performing additional tests to determine which surface features are best for registration and integration of multiple overlapped data sets.

**Automatic Registration**

A study of the viability of various mathematical representations for surface features for automating the registration process is presented [5]. Local differential geometry properties such as gaussian curvature, \( K \), and mean curvature, \( H \), along with their signs are used to categorize local surface shapes into one of eight invariant basic quadric types [6]. Each data cloud is processed to eliminate outlier points and triangulized to obtain a polygonal mesh. After smoothing of the polygon meshes, features were extracted by region growth segmentation based on surface types. Results from our studies indicate that (a) measurement noise deforms the shape and number of features found on the surface as a result of the segmentation, making it unlikely that identical feature patterns can be located in the overlapping region, (b) provided that the shape measurement accuracy is consistently maintained at a threshold value, similar features can be identified in the overlapped regions of neighboring point clouds and (c) for a wide range of typical applications, automation of the registration process is shown to be feasible using local features.

3. **Listing of Publications**
Book Chapters


Papers accepted or published in peer-reviewed journals


Papers published in non-peer-reviewed journals or conference proceedings


Papers presented at meetings, but not published in conference proceedings

NONE

Manuscripts in review
1. Peng Cheng, Ning Li, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, "Automated Point Cloud Registration with Invariant Surface Feature", in review with *Intl Journal of Experimental Mechanics*

Technical reports to ARO


4. Listing of Graduate Students with Degrees

<table>
<thead>
<tr>
<th>Name</th>
<th>Degree</th>
<th>Date of Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr. Peng Cheng</td>
<td>Ph.D. in Mech. Engr</td>
<td>Summer, 2001</td>
</tr>
<tr>
<td>Mr. Wenzhong Zhao</td>
<td>Ph.D. in Mech. Engr</td>
<td>Fall, 2001</td>
</tr>
<tr>
<td>Mr. Jeffrey D. Helm</td>
<td>Ph.D. in Mech. Engr</td>
<td>Summer, 1999</td>
</tr>
<tr>
<td>Mr. Hubert Schreier</td>
<td>Ph.D. in Mech. Engr</td>
<td>Summer, 2001</td>
</tr>
</tbody>
</table>

5. Report of Inventions

NONE

6. Bibliography


