Computer-Aided Engineering and Mechatronics in the Design of Apparel Equipment

**PIs:** T. G. Clapp and J. W. Eischen (North Carolina State University), F. W. Paul and C. D. Rahn (Clemson University).

**GRADUATE STUDENTS:** W. Clifton (Mechanical Engineering-NCSU), S. Mast- (Mechanical Engineering-Clemson).

**TEAM LEADER:** J. W. Eischen

**ANNUAL REPORT:** March 1995-July 1995.

**ABSTRACT**

This research project combines computer-aided-engineering methods with practical control strategies to develop precise fabric handling capabilities. The primary goal is to develop mechatronic design concepts for assembly processes such as: folding, joining, placing, and locating that take into account variability in fabric material properties such as weight and stiffness. Advanced three-dimensional modeling of fabric drape and manipulation using the finite element method will be simplified for the design of fabric handling control systems. Controls that stabilize the fabric motion and allow accurate handling with minimum wrinkling will be investigated. Proof of concept demonstrations will be constructed to show techniques for systematically adjusting for material property variation. Project objectives and relevance to National Textile Center goals are discussed. The technical approach and progress to date are reviewed.

**I. PROJECT OBJECTIVES AND RELEVANCE TO NTC GOALS**

The major objective of this research project is to combine computer-aided-engineering methods with practical control strategies to develop precise fabric handling capabilities. The primary goal is to develop mechatronic design concepts for assembly processes such as: folding, joining, placing, and locating that take into account variability in fabric material properties such as weight and stiffness. Advanced three-dimensional modeling of fabric drape and manipulation using the finite element method will be simplified for the design of fabric handling control systems. Controls that stabilize the fabric motion and allow accurate handling with minimum wrinkling will be investigated. Proof of concept demonstrations will be constructed to show techniques for systematically adjusting for material property variation. Other potential applications for this technology in future years would include 3D fabric processes such as shape pressing and sewing.

Computer-aided-engineering is prevalent in many high technology industries in the US, including automotive and aerospace. Computer simulation of manufacturing processes during the equipment design phase is an accepted procedure. This same approach must be implemented in the design of fabric handling equipment. Machinery must be en-
engineered in advance to accommodate multiple part configurations and material properties. Competitive advantage from Demand Activated Manufacturing will require this level of knowledge.

II. TECHNICAL APPROACH AND PROGRESS TO DATE

The key question and challenge for this research project is: Can computer-aided-engineering techniques that are very commonly used in the automotive and aerospace industries be applied to the design and development of fabric handling equipment? And, can the machinery be designed to accommodate multiple part configurations (shape, thickness, etc.) and material properties (weight, stiffness, etc.)?

The main barrier is that the fabric handling problem is made extremely difficult by the very nature of fabric, its extreme flexibility. This presents a severe modeling challenge, in that drape and manipulation simulation must account for large geometry changes and wrinkling. In the same regard, design and development of equipment must deal with these same difficulties. The challenge will be to use the computer simulation tool to assist in designing the handling equipment, rather than relying on traditional cut-and-try design approaches. The second barrier is the wide variability in fabric properties such as weight and stiffness. Future machinery must be made to adjust systematically to this variability. Simulation will allow designers to gain knowledge on the influence of properties on performance and then assist in designing control/adjustment features through mechatronic machine principles.

We are aware of very little work in using computer-aided-engineering methods in the design of fabric handling equipment. The MITI project in Japan apparently used this approach with some success in apparel assembly. We are aware of no such work in the US. Draper Labs past efforts in designing and building handling equipment did not specifically address variability in properties. This will be the primary focus of our research. Several researchers in the US (including Dr. Eischen at NC State) are investigating computer modeling of fabric drape. And of course, considerable work has gone into designing automated fabric handling systems. But fundamental concepts for combining these research areas in the design of new equipment has not been done.

The greatest challenge in our work will be simplifying the computer modeling of fabric drape and manipulation to the point where it is useful in assisting design of mechatronic systems and hardware. Issues of tensioning and transporting fabric must be addressed. Control systems that stabilize the fabric motion and allow accurate placement with minimum wrinkling must be addressed. Hardware proof-of-concepts that are of relevance to the textile and apparel industry must be identified.

COMPUTER SIMULATION

A computer simulation tool has been developed that allows modeling of various fabric manipulation processes that occur during manufacturing. Fabric parts are modeled as very
flexible elastic beams that can accommodate stretching and bending in a single plane. The
governing equilibrium equations are solved using the finite element method. The nonlinear
moment curvature response is measured directly with the Kawabata Test System, or with
a simpler drape test. Realistic manipulation processes involve interaction of fabric parts
with other objects such as: work surfaces, robot manipulators, other fabrics. Therefore,
the ability to model contact has been implemented. A key aspect of this research will
be development of a capability to determine optimum ways to manipulate fabric parts
while minimizing sliding of the fabric or forces generated in the fabric. This feature will
play an important role in developing automated equipment to handle fabric parts while
maintaining positional control and minimizing wrinkling or buckling.

Figure 1 shows an initial simulation of fabric folding. As discussed in the following
section, folding has been selected as the first manipulation process for study in our research.
The figure shows intermediate drape configurations as the right end of a fabric strip,
initially flat on a work table, is manipulated along a path that minimizes sliding of the left
end of the fabric.

Figure 1- Folding Manipulation- Intermediate Drape Shapes

<table>
<thead>
<tr>
<th>Fabric Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>65% polyester/35% cotton twill weave, cream color,</td>
</tr>
<tr>
<td>bleached, dyed, finished, and preshrunk in a resin finish.</td>
</tr>
<tr>
<td>( t = 0.0406 ) cm</td>
</tr>
<tr>
<td>( A = 0.0406 \text{ cm}^2 )</td>
</tr>
<tr>
<td>( I = 5.58 \times 10^{-6} \text{ cm}^4 )</td>
</tr>
<tr>
<td>( \omega = 0.0255 \text{ gmf/cm}^2 )</td>
</tr>
<tr>
<td>( EA_{\text{eff}} = 2809.0 \text{ gmf/cm} )</td>
</tr>
<tr>
<td>( EI_{\text{eff}} = 0.386 \text{ gmf-cm}^2/\text{cm} )</td>
</tr>
</tbody>
</table>

Figure 2 is a schematic showing the algorithm we are using to determine manipulator
paths that minimize fabric motion on a work surface. A series of candidate paths are
proposed. Then the simulation code is run for each path in order to determine which path
yields the least motion of the free end of the fabric.
Objective:
Minimum
Free End
Movement
Final Configuration

Path Design:
Manipulator Trajectories

Initial Configuration

Folding Manipulation - Path Determination

Figure 2- Path Optimization

EXPERIMENTAL IMPLEMENTATION

This section details the progress to date in the experimental implementation of a mechatronic apparel handling operation. The chosen operation is described, the experimental apparatus is discussed, and the automation algorithm is detailed.

Automated Fabric Folding

The folding of a fabric strip was chosen as the initial apparel handling operation to be automated. Folding often occurs in apparel manufacturing, usually as a precursor to sewing or other joining operations. Folding involves grasping one end of the fabric, moving it through a three-dimensional trajectory, and laying it on top of the other end. The fabric is initially flat and straight. In the final configuration, the two layers of fabric rest aligned on top of each other. After folding, it is desired that the fabric be precisely aligned to a specific location on the work table.

Mechatronic Implementation

For large scale industrial implementation of automated folding, special purpose, mechatronic machines will be developed. The system will feed cut, stacked fabric pieces, manipulate the fabric, and output a precisely positioned folded piece.
General purpose robots, however, are more suited to the proof-of-concept experiments in this research. The robot allows accurate motion of the gripped fabric end and is computer interfaced so that complex control algorithms using precise sensors can be implemented. There are currently nine industrial robots that could be used for this application in the Mechatronics Laboratory at Clemson University. To date, a three-axis, hydraulic RTX robot and a five-axis PUMA robot have been used. Figure 3 shows the PUMA robot manipulating a fabric strip.

The PUMA robots are controlled by a SUN workstation. The workstation downloads a desired robot trajectory in either the joint coordinate space or Cartesian space. The robot interpolates between the desired trajectory points to provide smooth motion of the robot. The "C" program that runs the robot allows for sophisticated algorithms involving sensor input.

Two fabric position sensing techniques are currently being investigated. First, a video camera has been interfaced into the PUMA workstation. The camera image can be processed to provide fabric edge position measurements. This system has limited resolution and response time, however. The second sensor consists of a array of optic fibers that are aligned in a slot. The fibers are bundled and connected to a optoelectronic sensor. The slot is embedded in the work table and illuminated from above. The output signal from the sensor is proportional to the position of the fabric shadow on the work table.
Automation Algorithm

The intelligence of the mechatronic system resides in the automation algorithm. This is embedded in the “C” program that controls the robot. Figure 4 shows the block diagram of the overall system. The algorithm consists of finite element feedforward control and model based feedback control. Sensors, the robot manipulator, and the fabric dynamics complete the system. The input to the system is the desired fabric motion which, in this case, is the folding operation. The two control algorithms combine to generate a desired trajectory for the robot gripper. This motion, combined with the fabric properties and characteristics, produce the actual motion of the fabric.

![Block Diagram of the Automation Algorithm](image)

Figure 4: Block Diagram of the Automation Algorithm

The finite element feedforward control is based on the optimal trajectories numerically generated by the finite element simulation code developed in this research. If the fabric modeling is accurate and the fabric properties are known accurately, then this control algorithm alone provides accurate folding. Variations in the fabric properties, however, can reduce the accuracy of the folding operation.

The model based feedback control algorithm helps increase the robustness of the system to fabric property variations. The methods currently being investigated use free edge measurement only at the beginning and end of each folding operation. This obviates the necessity for fast fabric position measurements. Multiple folding operations are performed to search for the best robotic trajectory. Initially, the numerically generated trajectory is
performed. The error at the end of the operation is measured. If the error is less than a threshold value, the folding operation is a success. If not, the robot picks up the fabric, lays it down, and attempts another trajectory. For each successive iteration, the robot starts with the fabric in the same location but slightly modifies the robot trajectory to achieve zero motion of the fabric at the end of the operation. This method is currently being implemented and results are expected soon.

FABRIC PROPERTY CHARACTERIZATION

A set of seven test fabrics have been selected for the research project. Critical properties including weight (w), thickness (t), and Kawabata bending rigidity (B) have been measured in the laboratory at the NCSU College of Textiles. These properties are used as input to the finite element simulation code to predict drape behavior during manipulation. Following is a list of the fabrics and the associated properties.

#1 Acetate Satin, 1 x 1 plain weave, 116epi and 64ppi, $w = 118g/m^2$, $t = 0.25mm$, $B = 0.28gf - cm^2/cm$.

#2 Cotton Organdy, 1 x 1 plain weave, 68epi and 68ppi, $w = 65g/m^2$, $t = 0.31mm$, $B = 0.70gf - cm^2/cm$.

#3 Combed Cotton Velveteen, 1 x 1 plain weave, 68epi and 100ppi, $w = 280g/m^2$, $t = 1.2mm$, $B = 0.12gf - cm^2/cm$.

#4 Viscose Twill, 2 x 2 twill, right hand, 45" weave, 144epi and 80ppi, $w = 96g/m^2$, $t = 0.13mm$, $B = 0.22gf - cm^2/cm$.

#5 Merc. Combed Cotton Poplin, 1 x 1 plain weave, 100epi and 52ppi, $w = 191g/m^2$, $t = 0.42mm$, $B = 0.36gf - cm^2/cm$.

#6 Merc. Cotton Twill, 2 x 1 twill weave, 88epi and 52ppi, $w = 277g/m^2$, $t = 0.66mm$, $B = 0.66gf - cm^2/cm$.

#7 Dacron 54/Cotton, 65/35 Poplin, 1 x 1 plain weave, 112epi and 64ppi, $w = 154g/m^2$, $t = 0.38mm$, $B = 0.09gf - cm^2/cm$.

III. INDUSTRY COLLABORATION

A video tape has been prepared to illustrate the capabilities of our Puma robot and the associated sensors. This tape will be used in upcoming meetings with industry to facilitate understanding our research approach. Jud Early at TC² is supportive of the goals and objectives of this research project and has agreed to meet with us and provide input regarding the direction of our experimental work. Contacts are also being arranged with several textile companies in order to seek further input. It is our intention to tailor our experimental investigation towards fabric handling problems that are relevant to industry problems.