A manufacturing system for contoured foam cushions

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Abstract—The design, application and evaluation of a specialized, personal computer–based manufacturing system for contouring foam cushions is presented. The topics discussed include both the hardware configuration and the software design. The target applications of this device are local or centralized fabrication of custom-contoured seat cushions. Although the technologies used for the development and implementation of this system are not new, using a personal-computer-based (PC) controller in place of a stand-alone numerically controlled (NC) motion controller significantly reduced the cost associated with this component. Further reductions in cost resulted from an optimization of the mechanical configuration for the dedicated task of carving foam cushions.

Key words: CAD/CAM seating, custom-contoured seating, manufacture of custom-contoured seat cushions, seat cushions.

INTRODUCTION

Custom-contoured seat and body support systems are good alternatives to off-the-shelf and semicustom seating systems used for pressure relief, posture control, and positioning. Clinical evaluations of prototype systems developed at the University of Virginia have shown that, in most cases, posture support has been better and interface pressures have been more uniform than with commercially available cushions (1). Also, tissue distortion has been shown to be reduced (2). These and other benefits of custom-contoured seat support surfaces have been documented (3,4,5). However, only recently—over the past 5 to 7 years—have the benefits from the advances in computer-aided design and computer-aided manufacturing (CAD/CAM) seating been available to practicing clinicians.

The CAD/CAM technologies that have made the contour measurement, data processing, and manufacturing processes possible have been prohibitively expensive until recent developments in personal computer hardware, software, and peripherals. The most notable advances in technology that have contributed to the reduction in costs of CAD/CAM systems were the introduction of the personal computers, advances in specialized data acquisition hardware, and the introduction of low-cost digital signal processing (DSP) integrated circuits used for servomotor control and filtering.

A traditional solution for contouring foam or other materials is to develop a semicustom system consisting of a stand-alone numerical control (NC) processor, a servomotor-driven three-(or more)-degree-of-freedom mill, and the necessary drive and interface components. Such a system, however, will
be unnecessarily expensive. Numerical control machine controllers are designed with certain features and flexibility in programming and operation that are not necessary for a dedicated controller used for contouring foam. For example, typical features include interpreters for industry standard RS-274-D and RS-447 languages, onboard nonvolatile memory for program storage, and CRTs to convey information to the operator. Because contouring is a complex machining process, NC machines with contouring capability are usually positioned toward the high end of an already expensive product line. For example, the Aerotech UNIDEX 16 motion controller system with contouring capability would cost $12,000 to $20,000. In comparison, the PC-based controllers range in cost from $1,000 to $3,000. The primary advantage of using a PC-based controller is that it lowers the costs associated with the controller.

The mechanical aspects of the system have been substantially optimized for contouring foam cushions. In place of the commonly implemented Cartesian (X-Y-Z) coordinate mill with three translational degrees of freedom, the mill is a cylindrical (Z-r-φ) coordinate mill with two translational and one rotary degree of freedom. The advantages of this configuration are discussed in the following section.

One of the beneficial qualities of resilient foam body supports is the low cost of raw materials. A typical 3 x 18 x 18-inch high resiliency polyurethane foam cushion could be purchased for $5 to $7 in 1991. To make a valid cost comparison with other types of seat cushions and body supports, several other cost factors must be considered. These costs include: the cost of the carving machine, the cost of the materials and equipment necessary to waterproof the cushions, the level of technician expertise required to operate the equipment, the level of attention required of the technician during the carving process, the throughput of the carving machine, and the material and labor costs associated with upholstering the cushions. Of these cost factors, all but the costs associated with waterproofing and upholstering the cushion are affected by the design of the carving machine. A reliable and relatively inexpensive manufacturing process is therefore essential if CAD/CAM custom seating systems are to be made available at competitive prices.

Figure 1.
Foam contouring machine.

Other researchers have designed and implemented specialized carving machines for custom seat cushions and body supports. Reger, et al. developed a two-dimensional carving system that required the “stacking” of slices of carved foam together to form a three-dimensional contour (6). In the field of prosthetics, the automated manufacture of prosthetic sockets has been used for some time (7). The process of contouring foam seat cushions is similar
in many respects to the processes of forming custom-fitted sockets, yet becomes slightly more complex because of the noncylindrical nature of the shapes and more expensive because of the range of motion required by the larger size of the finished product.

METHOD

System design
The manufacturing system is a specialized three-degree-of-freedom milling machine designed to contour high-resiliency polyurethane foam, ethafoam, or viscoelastic foam cushions. The narrowly focused nature of the application allowed for considerable cost savings and optimization in the design of the machine (8). Figure 1 is a photograph of the portion of the cutting machine where the foam is positioned and cut.

System configuration
The foam is fixed to a controlled, rotary platform while the cutting tool is translated vertically along the z-axis and horizontally along a radius of the rotating table. The typical tool path is a variable-height spiral beginning at the center and ending near the outer edge of the foam. The cutting tool is a custom-made double-edged blade attached to the end of a vertical spindle driven at approximately 7,000 rpm by an AC synchronous motor. A drawing of the cutting tool is shown in Figure 2. The cutting machine is controlled by a PC bus-based controller. The controller is a Superior Electric model SPC-703 controller board. It features three axes of servomotor control, program-interrupt capability, on-the-fly velocity changes, and following error monitoring. The output is an analog velocity command. Closed-loop proportional, integral, and differential (PID) control is implemented on this controller board with a 32-bit DSP chip on each of the three axes. The PC-based design has two primary advantages over stand-alone CNC designs: cost and programming flexibility.

A minimum of three degrees of freedom is required for contouring, satisfied by the one rotary and two translational degrees of freedom of the cutting tool. The cylindrical coordinate configuration significantly reduced the system cost over one based on the three translational degrees of freedom of more conventional Cartesian coordinate system configurations. Much of the cost of mechanical positioning systems results from the precision machining necessary for the translational stages and from the cost of precision linear motion bearings. By reducing the number of translational stages from three to two, a cost savings was realized. Also, because of the nature of cylindrical coordinate systems, one of the translational stages is shortened to half the stroke that would otherwise be required in an X-Y-Z configuration. The cylindrical configuration is best suited for motions that are primarily circular. For the contouring of foam seat cushions, circular—or spiral—tool paths and rectangular tool paths are equally appropriate.

Figure 2.
Cutting tool diagram. (The cutting tool was designed and built by Paul Mitchell of Orange, VA in 1990.)
Each of the three drives is provided by permanent magnet DC servomotors driven by pulse-width modulated (PWM) amplifiers with feedback provided by incremental optical encoders. The motors are Aerotech model 1050 servomotors. These motors are rated for peak and continuous torque output of 2.52 and 0.35 N-m, respectively, maximal speed of 6,000 rpm, and a maximal terminal voltage of 72 V. The amplifiers used to drive the motors from the \( \pm 10 \) volt current command outputs of the Superior Electric controller are Aerotech model DS8020 PWM servo amplifiers housed in an Aerotech model DSHR three-axis chassis. These amplifiers are capable of providing 10 A continuous or 20 A peak output current to each of the three motors, with a peak output voltage of \( \pm 80 \) V. The rated peak and continuous output power per axis are 1,460 and 765 W, respectively (9). The incremental optical encoders used are Hewlett Packard model HEDS-6010s. A 200 cycle per revolution model is used on the vertical z-axis and 1,000 cycle per revolution models are used on the rotary and radial axes. Lower resolution encoders are necessary on the z-axis because it is required to move at higher velocities than the other degrees of freedom. All three encoders provide two channel (A-B) quadrature output plus index pulse. A system diagram is shown in Figure 3.

The recommended minimal microcomputer configuration is an IBM PC-AT compatible personal computer with an Intel 80286—or compatible—microprocessor driven at 12 MHz. A math coprocessor is recommended to shorten the time required for the calculation of the tool path parameters. The math coprocessor, however, would have no effect on the program during the cutting, as the path parameters are calculated before this operation and are retrieved from RAM as needed during the cutting process.

The foam blank is positioned on the rotary table with an adjustable frame that is capable of accommodating a large variety of cushion sizes and thicknesses. The diameter of the rotating table is 36 inches. The maximal stroke of the vertical degree of freedom is 8.75 inches. While being carved, the foam is held flat on the table by means of a suction created by a vacuum connected through the hollow center portion of the machine frame. Added restraint for the foam is possible by pinning it to the frame with sharp wooden spikes. This configuration is depicted in Figure 4.

Software design

User control of the machine is accomplished entirely through software. The input to the cutting system is an array of deflection data representing the contour. The cutting path is generated by fitting bilinearly blended cubic spline Coons patches to the data and extracting the necessary points for the spiral cutting path. Coons has developed a method for interpolating a surface patch between boundary
Figure 5.
Coons patch coordinate definitions.

curves (10, 11). First, cubic splines are fitted to the data grid in both the x and y directions. Then, for an individual element of the surface defined by its four boundary splines, \( c_1(x), c_2(x), d_1(y), \) and \( d_2(y) \), the bilinearly blended surface interpolant \( s(x, y) \) is defined as

\[
s(x, y) = \frac{1}{2} \left[ \frac{d_1(y)}{y - y_0} \right] \left[ \frac{c_1(x)}{x - x_0} \right] \left[ \frac{y_1 - y}{y - y_0} \right] - \frac{1}{2} \left[ \frac{d_2(y)}{y - y_0} \right] \left[ \frac{c_2(x)}{x - x_0} \right] \left[ \frac{y_1 - y}{y - y_0} \right]
\]

where \( x, x_0, x_1, y, y_0 \) and \( y_1 \) are defined as in Figure 5.

Surface fidelity is maintained, first, by compensating for the tool radius with the cutting path and, second, by imposing a dependency of the cutting path point spacing on the contour gradient.

The compensation for the tool radius is computed by using the radius of the tool end, and approximations for the slope of the contour in the x and y directions. The slope of the surface at the point \( (x, y) \) is approximated by the first order finite differences as follows:

\[
\Theta_x \approx \tan^{-1} \left( \frac{s(x,y) - s(x - \Delta x, y)}{\Delta x} \right)
\]

\[
\Theta_y \approx \tan^{-1} \left( \frac{s(x,y) - s(x, y - \Delta y)}{\Delta y} \right)
\]

where \( s(x, y) \) is the depth of the contour at the point \( (x, y) \). The tool radius compensation for the x and y directions individually are

\[
d_{comp,x} \approx r \left( \frac{1}{\sin(\Theta_x)} - 1 \right)
\]

\[
d_{comp,y} \approx r \left( \frac{1}{\sin(\Theta_y)} - 1 \right)
\]

As the gradient of the contour, \( G(x, y) \), increases, the distance between the points on the cutting path must decrease to maintain a consistent reproduction of the prescribed surface. For this reason, the distance between points along the spiraling cutting path decreases as the tangential gradient of the contour increases and vice versa. This is implemented by setting a threshold on the vertical displacement from one data point to the next and assigning a point to the cutting path each time the threshold is exceeded. To compensate the cutting path for high gradients in the radial direction, the distance (or pitch) between spirals decreases as the radial gradient of the contour increases and vice versa. Implementation of this involves finding the maximal radial gradient in each \( 2\pi \) rad spiral segment before setting the cutting path over that segment. If the maximal gradient exceeds the preset threshold on the radial gradient, the pitch of the spiral will be decreased and a new search must be initiated. The thresholds on the gradients and the search distances are set as parameters in the software.

The actual cutting path generated is a combination of position and velocity commands for each of the three degrees of freedom. Each point in the cutting path is assigned position and velocity values. The motion from one point to the next proceeds as follows:
1. A break point for the rotary axis is set to the angular position of the next point on the cutting path.

2. Motion toward that point is initiated at the assigned velocity.

3. Commands are issued to the controller to move the cutting tool along the vertical and radial degrees of freedom from the position values at the current point to the position values at the next point. For these motion commands, a terminal velocity is used that is slightly greater than the velocity required to move to the next position by the time motion on the rotary degree of freedom reaches the assigned break point. Velocity profiles for these moves are trapezoidal, with the acceleration and deceleration values set as parameters in software by the user. The velocities associated with each point on the cutting path are calculated using the relative distances between cutting tool positions and do not account for the acceleration and deceleration times. Also, the accelerations and decelerations are the same for each move regardless of the distance of the move. The result of not accounting for the acceleration and deceleration is that the cutting tool will reach the assigned break point on the rotary degree of freedom before the cutting tool decelerates toward the next point on the radial and vertical degrees of freedom. This introduces a small degree of smoothing to the cut contour.

4. When the break point is reached on the radial degree of freedom, a hardware interrupt is generated on the PC by the controller board. On receiving this interrupt, a new velocity is assigned to the rotary degree of freedom, and the radial and vertical degrees of freedom are issued commands to move the cutting tool toward the next point on the cutting path.

The ability of the controller to handle velocity change commands “on-the-fly” makes this control strategy possible. Also, the resulting motion of the rotary degree of freedom is devoid of starts and stops, providing a smooth motion. This is especially important given the large rotational inertia of the table. Motion on the radial degree of freedom is relatively slow and unidirectional during the cutting process, resulting in an apparently smooth operation. Motion on the vertical degree of freedom is much faster and is bidirectional. Position following error is monitored throughout each motion by the controller board. If a preset following error threshold is exceeded on any of the three degrees of freedom, an interrupt is generated and an error message is produced for the operator.

The software also provides for manual control of the machine in a jog mode. Jog mode gives the user access to a large subset of the features of the controller by way of the PC keyboard. These jog mode features include the ability to move the cutting tool along each degree of freedom independently at a specified velocity and acceleration and/or to a specified position.

RESULTS/DISCUSSION

System evaluation

The manufacturing system development was completed in May 1990. Since then, a second machine has been constructed. The first machine is presently in use in an industrial environment at Pin Dot Products, Inc., of Niles, IL. At the time of this writing, the second machine is being used at the University of Virginia for research purposes. This section will contain a description and evaluation of general performance specifications on the first machine as well as the results of a quantitative accuracy.
test performed on the second machine. Figure 7 is a photograph showing a typical cushion carved by the machine.

**Time efficiency and reliability**

The time required to carve a cushion depends on the gradients of the particular contour and the cutting path parameters selected by the user. The cutting path parameters affect cutting speed, resolution, and reliability. A set of default cutting path parameters has been established that produced contours with acceptable resolution and cut at a speed that is both reliable and acceptable. Under these default conditions, the time required to carve a contour into typical high-resiliency foam is approximately 7 minutes. To improve the texture of the carved foam, the spiral pitch can be reduced by one-third, thus increasing the carving time to approximately 10 minutes. Attempts to drive the machine faster at the higher resolution setting may result in an increased probability of encountering an error during the process.

The most common mode of failure for the process is a lifting of the foam blank off the turntable, causing the foam to become entangled in and shredded by the cutting tool. The operator of the machine must be able to recognize when a contour contains either deep portions or unusually high gradients near the edge of the foam. It is under these conditions that the foam is more likely to become picked up by the cutting tool. When this condition is recognized before hand, the operator needs to make the extra effort to secure the foam to the turntable. This can be accomplished either by holding the foam down during the cutting process (this could be dangerous), or by adding extra wooden restraints—tooth picks—in the affected area. Wooden tooth picks are used to pin the foam securely in the frame so that if the cutter runs into one or more of the toothpicks, it will be easily broken off by the cutter without interrupting the process, damaging the cutting tool, or harming the contoured cushion. When operated at the University of Virginia with the default cutting path parameters, the machine had a success rate likely greater than 95 percent. At Pin Dot, the success rate has been near 80 percent and is improving as the operators gain experience using the machine. As operators gain experience using the machine they acquire a sense for types of contours that could lead to possible failures of the process. Once a potential problem is recognized, precautions can be made to avoid a failure.

**Durability**

During the carver’s first year-and-a-half of use it has had one major mechanical component failure. This failure occurred in the coupling between the motor shaft and the gear box of the motor assembly driving the radial degree of freedom. A short period of down time of the machine has also been caused by incompatibilities between the PC bus servomotor controller and other standard PC peripherals. Occasional binding problems have been reportedly caused by particles of foam contaminating the ball screw and linear slides on the vertical axis. Routine cleaning of these components has reduced the frequency of the problem. There have been several software modifications to fix minor flaws—bugs—in the software and to accommodate alternate data file formats. No other problems have been reported.

**Accuracy**

To check the accuracy of the carved cushion, a contour has been carved into foam and its depth checked against the data from which the cutting path was calculated. Table 1 contains data from nine sample points on the carved cushion. These points roughly correspond to grid locations in the data set from which the contour was generated. The specified depth of the contour at these grid locations is compared with the actual depth of the carved

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**Figure 7.**
Typical cushion.
Table 1.
Cutting error analysis data.

<table>
<thead>
<tr>
<th>Location #</th>
<th>Target Depth (mm)</th>
<th>Actual Depth* (mm)</th>
<th>Absolute Error (mm)</th>
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<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>15.8</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>47.6</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>42.9</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>14.6</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>44</td>
<td>41.3</td>
<td>2.7</td>
</tr>
<tr>
<td>6</td>
<td>43</td>
<td>40.8</td>
<td>2.2</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>13.8</td>
<td>1.2</td>
</tr>
<tr>
<td>8</td>
<td>48</td>
<td>46.6</td>
<td>1.4</td>
</tr>
<tr>
<td>9</td>
<td>44</td>
<td>45.6</td>
<td>-1.6</td>
</tr>
</tbody>
</table>

*± 0.5 mm

foam at the locations corresponding to the grid points. The actual depth was measured using a mechanical dial indicator with an accuracy of ±0.0254 mm. The value recorded in the table is the difference between the deflection of the dial indicator at location where no foam was removed and the deflection at the location of interest. Variations in the surface texture at the carved surface and the compliance of the foam make it difficult to accurately measure the depth of the contour. To account for this potential source of error, the values shown should be considered to be accurate to ±0.5 mm. Several of the nine locations were chosen such that they could be easily identified. For instance, locations one and seven are located at local maxima, and locations two and three are located at local minima. The location of these extremes was verified to coincide with the correct position in the x-y plane. The other test locations were randomly chosen.

The average and maximal absolute errors for the nine test points are 1.5 mm and 2.7 mm, respectively. At all but one of the test points the cut was shallower than the specified depth. The original design goal was to hold the error to ±1 mm. This goal was not met. The most probable cause of the consistent under-cutting error is the inability of the tool to cut foam near its lower edge. Although the sharpened portion of the tool extends to the apex of the semicircular end, resilient foam tends to be pushed away from the tool in this area rather than being separated from the foam blank as it should. The result of this is that a layer of foam remains after the tool has passed by. This type of error can be compensated for in software by uniformly adding depth to the contour data. Although it has not been shown clinically, it is likely that this error would have negligible effects on the efficacy of a contoured compliant foam cushion. First, the magnitude of the error is small enough as to not significantly alter force distributions; modifications on the order of 5 to 20 mm (depending on the type of foam used) must be made to change the force distribution in most circumstances. Also, alterations that have the greatest effect on force distribution are changes that change the shape of the interface. For example, increasing the depth on one side while decreasing the depth on the other side (to shift support from side to side) would likely change the force distribution. A common mode error like the error observed here cannot affect force distribution in this way.

CONCLUSION

The essential design goal for this system was to minimize cost. For the controller, this was accomplished by using a PC-based servomotor controller. The costs associated with the mechanical components of the system were minimized by constructing a custom three-degree-of-freedom mill. Most commercially available positioning systems are designed with error and repeatability tolerance of several orders of magnitude smaller than is required for cutting foam cushions. The task of cutting foam cushions for wheelchair support systems requires a resolution no greater than 2 mm. The high resolution of the commercially available systems increases the cost. Designing this custom machine to more relaxed error tolerance greatly reduced the cost of the machine.

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