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Body Scanning and Modeling for Custom Fit Garments

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ABSTRACT

Mass customization is a new manufacturing trend in which mass-market products (e.g. apparel) are quickly modified one at a time based on customers' needs. It is an effective competing strategy for maximizing customers' satisfaction and minimizing inventory costs. An automatic body measurement system is essential for apparel mass customization. This paper introduces the development of a body-scanning system, and body size extraction methods and body modeling algorithms. The scanning system utilizes the multi-line triangulation technique to rapidly acquire the surface data of a body, and provides accurate body measurements, many of which are not measurable with conventional methods. Cubic B-spline curves are used to connect and smooth body curves. From the scanned data, a body form can be constructed using linear Coons surfaces. The body form can be used as a digital model of the body for 3D garment design and for virtual try-on of a designed garment. This body scanning system and its application software enable apparel manufacturers to provide custom design services to the consumers seeking personal-fit garments.

KEYWORDS: body scanning, body modeling, virtual garment, mass customization

1. INTRODUCTION

In 1910, the apparel industry started using size designations to produce and sell ready-to-wear clothing. A size designation represents one set of garment sizes in a sizing system designed to reflect the body sizes of most individuals in a population. Because the anthropometric data on which the ready-to-wear sizing system was based was outdated, off-the-rack clothing does not properly fit the current population. Many surveys showed that about 50% of the women surveyed cannot find well fitting clothes in the current sizing system [2, 6]. Designing garments that fit customers requires information about the individuals' body size and shape. Technology used to quickly modify mass-market products (e.g. apparel) one at a time is known as mass customization and agile manufacturing, which maximize customer satisfaction and minimize inventory costs. Mass customization becomes an effective way for the U.S. apparel industry to compete in the global market.

Apparel mass customization requires automation in at least three processes: body measurement, pattern design, and fabric cutting. In recent years, body-scanning technology became an interesting research and development field around the world [4,8,11], and a few systems are already commercially available. However, there are two major barriers that prevent those systems from being widely accepted by the apparel industry. Firstly, the prices of the body-scanning systems are often prohibitively high to the apparel industry. Secondly, the systems neither are well integrated with apparel CAD systems, nor provide designing functions that allow a customer to design or choose a garment that fits his/her body. The customer will have to rely on a professional designer to utilize the body data for alternating pattern pieces to produce a personalized garment. The apparel CAD systems currently used by designers are 2D based pattern design systems that do not include ways to visualize garments in 3D graphics. The design effects can be examined only after the garment is actually made. This non-interactive approach restrains designers' creativity. Therefore, there is still a need for an affordable system that can do body scanning, body modeling and design of virtual garments in an integrated manner to expedite the process of apparel customization.

We developed the new body scanning and 3D garment design technology targeted for small apparel business. The system now can provide rapid, non-contact scanning of a whole or partial body to obtain size information necessary for garments; create customized body forms on the computer screen as models for apparel design. A body form represents the scanned body by having a number of key measurements of the body, and can be used for evaluating the style and fit of a garment being designed.

2. BODY SCANNING

The system consists of a PC computer, a control circuit box, and a 5x8x8 (W*L*H) ft^3 dark booth (Figure 1), in which two linear stages are mounted on the front and back sides of a person. Each stage carries a multiple laser line projector (eye-safe) and a CCD camera to scan the entire body when the stage moves upward. This scanning unit is connected to the control box governed by the computer to perform triangulation measurements. All scanning and measuring commands are sent from the PC through the parallel port to the control box, which drives the scanning units to proper positions, turns on the laser projectors, and then triggers the cameras to grab images. The scanning units may stop 5-6 times to ensure the whole body to be scanned.

The depth calculation is based on a triangulation algorithm [3]. A simple geometry for an active laser triangulation is shown in Figure 2. The CCD camera is aligned along the Z-axis with the center of the lens located at (0, 0, 0). At a baseline distance b to the left of the camera (along the negative x-axis) is a multi-line laser generator projecting a beam of laser lines at an angle θ relative to the x-axis baseline. The point (x, y, z) is then mapped into the digitized image at the pixel (u, v) so $uz = xf$ and vz

= *yf* by similar triangles where *f* is the focal length of the camera in pixels. The measured quantities (u, v, θ) are used to compute the (x, y, z) coordinates:

$$[x, \quad y, \quad z] = \frac{b}{f\cot\theta - u}[u, v, f].$$

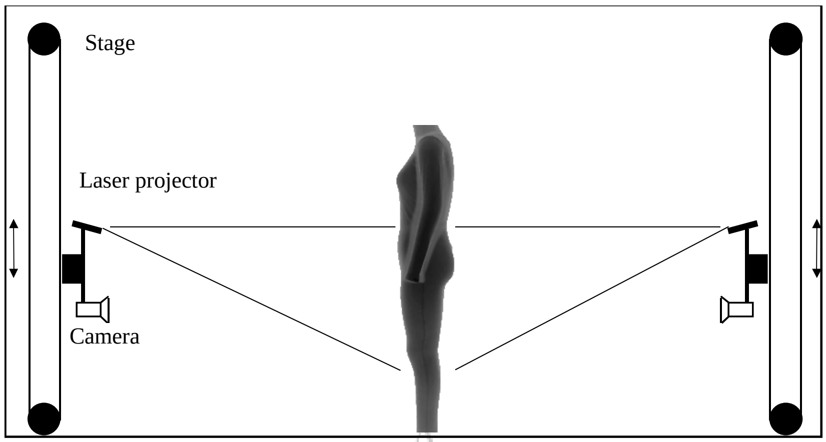


Figure 1: Booth for Body Scanning

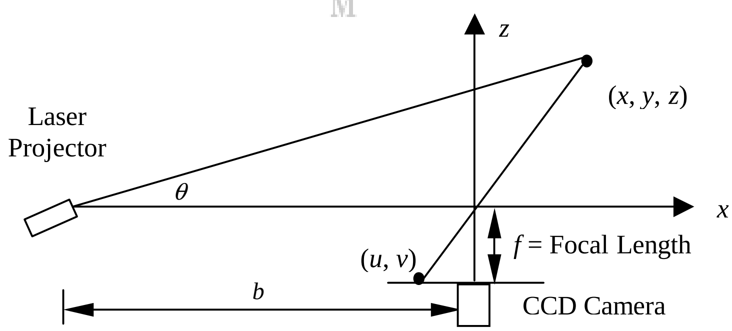
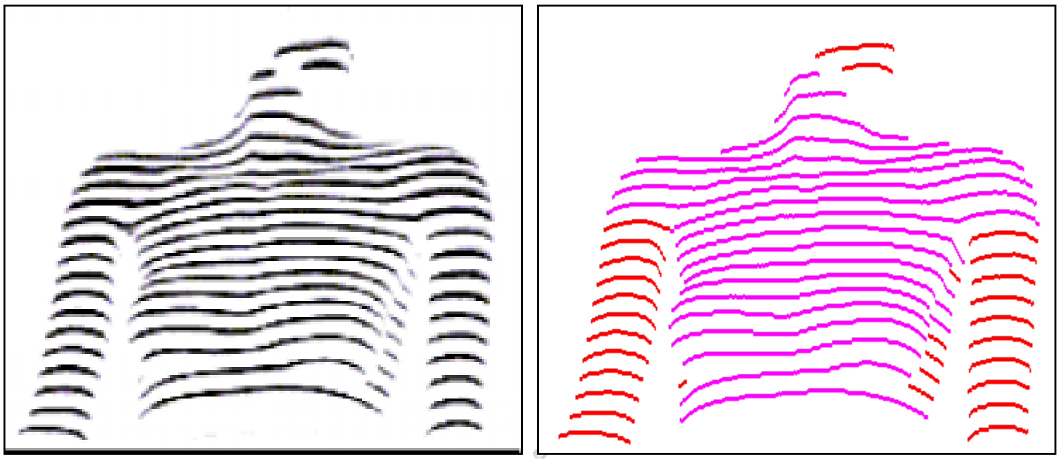


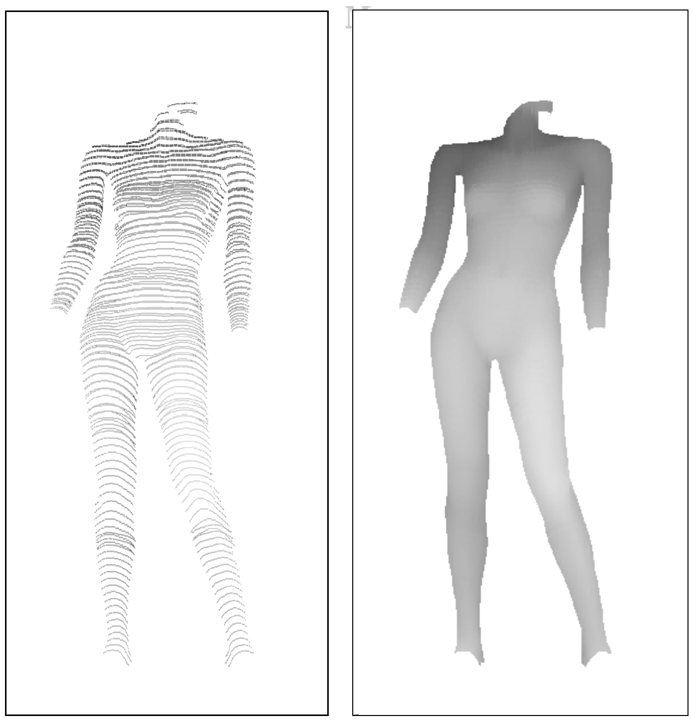
Figure 2: Laser Triangulation Geometry

To calculate the coordinates (x, y, z) of body, the laser lines in the originate image must be traced and the projection angle for each line must be determined. Figure 3a shows one of the grabbed images that contains 19 laser lines with different projection angles. With a given setup, the projection angle of the midst laser line and the inter-beam angle are both known. After a line is traced, the coordinate of all the pixels on the line (u, v) and the projection angle θ can be determined. Therefore, their corresponding 3D (x, y, z) coordinated can be calculated using the above equation. However, the projected laser lines on the body are not uniform in brightness. At abrupt changes, laser lines appear blurry and even broken. To correct this problem, various image-processing techniques, such as adaptive thresholding and curve fitting [10], must be applied to deal with complex situations of broken lines. Figures 3a and 3b show the original lines and the traced lines of an upper body.



a. Laser Lines b. Traced Lines

Figure 3: Tracing Laser Lines



a. Merged Scan Lines b. 3D Image

Figure 4: Frontal Body Image

When the traced lines of all the captured images are converted into the (x, y, z) space and superimposed in a new image based on their relative scanning positions, the lines covering a whole body can be obtained (Figure 4a). Much denser points in the regions of breast, waist, crotch, and knees, are seen in the figure, resulting from the overlapping of laser lines in two consecutive images. The purpose of overlapping is to acquire more information from body areas that have more complex shapes. With the interpolation and fitting procedures, the regions between two lines are smoothly added so that the body surface can be recovered (Figure 4b). In Figure 4b, the range information is represented by the brightness of each pixel on the body.

3. BODY MEASUREMENT

After both front and back body surfaces are scanned, the two images can be combined and body dimensions can be measured on the 3D data. There are many pre-defined key measurements that are used for apparel design [1,5]. These key measurements are associated with certain landmarks of the body. They type of a body measurement can be the distance or angle between two landmarks (e.g., yoke and should slope), the length of a surface curve (e.g., crotch), and the circumference of the body at a landmark (e.g., bust). The measurements can be used to generate a body-form or directly be sent to a 2D CAD system for pattern alteration. It takes three major steps to extract body dimensions from the 3D body data.

(1) Locate body landmarks, such as waist, chest and neck. Based on basic features of body, most landmarks can be automatically detected. Since human body shapes vary dramatically, manual intervention may also be needed to adjust landmarks for correct measurements.

(2) Process the data using fitting techniques, such as B-spline curves, to smooth and connect points of a cross-section at one landmark or a space curve between two landmarks.

(3) Compute the measurements such as circumference, distance, angle, etc.

Calculating body circumferences at landmarks is a major task in body size extraction from a scanned body image. B-spline curve approximation provides an effective way of representing body cross sections. Given a set of defining polygon vertices (control points), $\{\mathbf{P}_i \mid 0 \le i \le n\}$, a B-spline curve $\mathbf{C}(u)$ is given by [7,9]

$$\mathbf{C}(u) = \sum_{i=0}^{n} B_{i,p}(u)\mathbf{P}_i, \qquad 0 \le u \le 1$$

where u is a parameter, and $\{B_{i,p}(u) | 0 \le i \le n\}$ are pth degree B-spline basis functions, which are recursively defined as

$$B_{i,0}(u) = \begin{cases} 1 & \text{if } u_i \le u \le u_{i+1} \\ 0 & \text{otherwise} \end{cases}, \text{ and}$$

$$B_{i,p}(u) = \frac{u - u_i}{u_{i+p} - u_i} B_{i,p-1}(u) + \frac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} B_{i+1,p-1}(u)$$

.

The values of u_i are the elements of a knot vector, $U = \{u_i \,|\, 0 \le i \le n + p + 1\}$, which is a monotonically increasing series of real numbers. Usually, u_p and u_{n+1} are set as the starting and end points of u. When the range of u is [0, 1], $u_p = 0$ and $u_{n+1} = 1$.

To guarantee the curve $\mathbf{C}(u)$ to be closed and $\mathbf{C}^{p-1}(u)$ continuous anywhere, the knot vector U and the control points $\mathbf{P}_i$ should meet the following conditions:

1. $u_j = u_{j+n-p+1} - 1,\ \ u_{j+n+2} = u_{j+p+1} + 1,\ \ 0 \le j < p$ (knot vector);

2. $\mathbf{P}_{i+n-p+1} = \mathbf{P}_i,\ \ 0 \le i < p$ (control point).

The first condition requires that the distribution of the last 2*p*+1 knots holds the same pattern as that of the first 2*p*+1 knots. This condition makes the basis functions associated with these knots are identical. The second condition requires that the last *p* control points duplicate the first *p* ones. It can be deduced that $\mathbf{C}^{(r)}(0) = \mathbf{C}^{(r)}(1),\ \ 0 \le r < p$. Figure 5 shows these conditions in the *p*=3 case (cubic B-spline curves). The last seven knots have the same distribution as the first seven knots, making the last three basis functions identical to the first three ones.

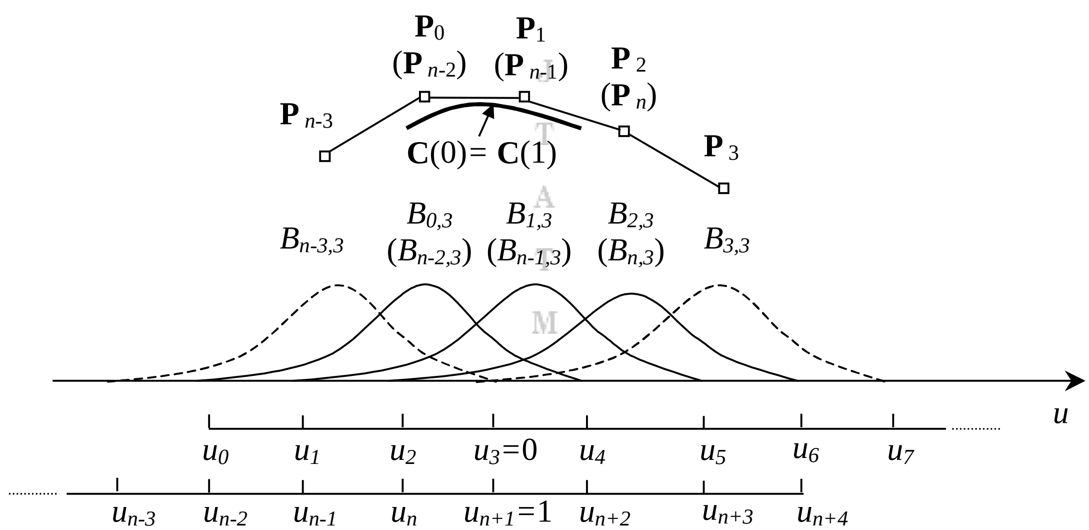


Figure 5: Knot Vector and Control Point Conditions for Closed and Smooth Curves

After *p* and *U* are selected, the B-spline curve is solely dependent on the selection of the control points $\mathbf{P}_i$. $\mathbf{P}_i$ may be determined with some approximation or interpolation scheme. If a set of ordered data points from a closed curve, $\{\mathbf{Q}_k \mid 0 \le k \le m \text{ and } \mathbf{Q}_0 = \mathbf{Q}_m\}$, are known, the data set $\{\mathbf{Q}_k\}$ can be approximated by a B-spline curve $\mathbf{C}(u)$ using the least square method [7],

$$\min \sum_{k=0}^{m} \left\| \mathrm{C}(\bar{u}_k) - \mathrm{Q}_k \right\|^2 ,$$

where $\{\bar{u}_k \mid 0 \le k \le m\}$ are the calculated parameter values according to the displacement of $\{\mathbf{Q}_k\}$, and,

$$\mathbf{C}(\bar{u}_k) = \sum_{i=0}^{n} B_{i,p}(\bar{u}_k)\mathbf{P}_{i \bmod (n-p+1)} .$$

$\mathbf{P}_{i \bmod (n-p+1)}$ makes the last *p* control points ($\mathbf{P}_{n-p+1}, \ldots, \mathbf{P}_n$.) identical to the first *p* control points ($\mathbf{P}_0, \mathbf{P}_1, \ldots, \mathbf{P}_{p-1}$.). Assume that $\mathbf{P}$ is a vector of the *n*-*p*+1 distinct control points, $\mathbf{Q}$ is the vector of *m* data points, and *N* is a matrix, $N = \{N_{k,i} \mid 0 \le k \le m, 0 \le i \le n-p\}$, derived from the basis functions as follows:

$$N_{k,i} = \begin{cases} \left(B_{i,p} + B_{i+n-p+1,p}\right)(\bar{u}_k), & 0 \le i < p \\ B_{i,p}(\bar{u}_k), & p \le i \le n-p \end{cases}$$

.

The least-square equation can be expressed in a matrix format:

$$\min \left\| N\mathbf{P} - \mathbf{Q} \right\|^2 .$$

Then $\mathbf{P}$ can be calculated by solving the following linear system:

$$(N^T N)\mathbf{P} = N^T \mathbf{Q} .$$

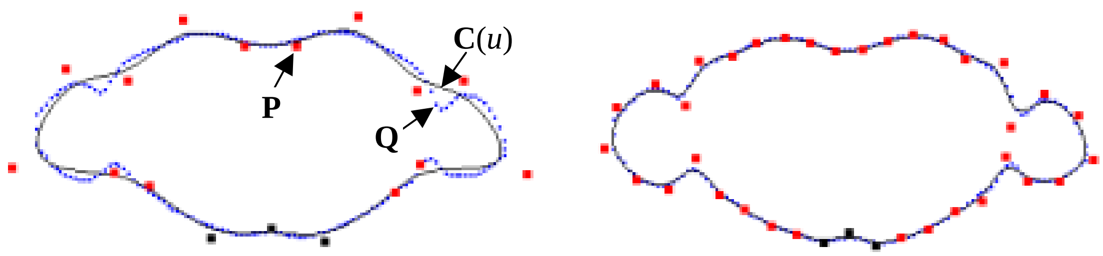
This algorithm may be summarized as follows:

(1) Compute the parameters $\{\bar{u}_k \mid 0 \le k \le m\}$ according to the displacement of data points $\{\mathbf{Q}_k \mid 0 \le k \le m\}$, where the chord length is adopted.

(2) Choose the knot vector $U = \{u_j \mid 0 \le j \le s\}$, which should reflect the distribution of $\{\bar{u}_k\}$ and be under the restriction of condition 1.

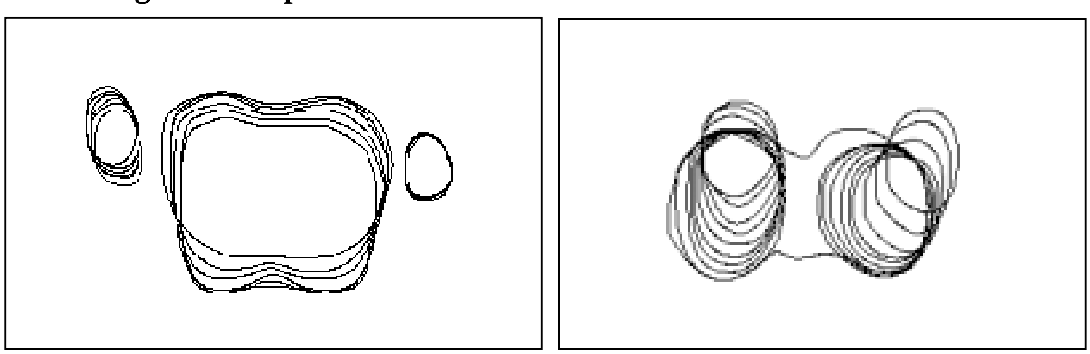
(3) Calculate the first *n*-*p*+1 control points $\mathbf{P} = \{\mathbf{P}_i \mid 0 \le i \le n-p\}$ and assign the first *p* control points to the last *p* ones.

The number of the control points $n+1$ has significant influence on the fitting accuracy of the B-spline curve. Figure 6 shows two B-spline curves that fit the same set of data $\mathbf{Q}$ when $n+1=20$ and $n+1=40$, respectively. It was found that a B-spline curve with 40 control points can provide a sufficient accuracy for fitting a body cross section.



n+1=2 *n*+1=40

Figure 6: B-spline Curves with Different Control Points



a. Upper body b. Lower body

Figure 7: Multiple Cross-Sections of the Body

The B-spline approximation of body cross sections can provide both the body size and shape information at specific locations. Particularly, when multiple cross-sections are superimposed, one can visualize the rate of change in size and shape along the body's vertical axis (Figure 7).

4. BODY MODELING

3D body modeling is a procedure to generate a body form on the computer screen using a set of key measurements from a scanned body. A body form, also called dress form, serves as a personalized model for style manipulation and fit adjustment. A computer generated body form allows a designer to freely rotate and zoom the form for viewing and measuring the body shape.

A human body represents a fairly complex surface. To construct a body form, a body needs to be divided into a number of relatively simple sub-surfaces that can be approximated by surface functions. For example, an upper torso can be divided into seven sections: neck, shoulder, chest above waist, abdomen (Figure 8). Each section has four of edges whose reference parameters u and v are between 0 and 1, i.e., $u,v \in [0,1]$.

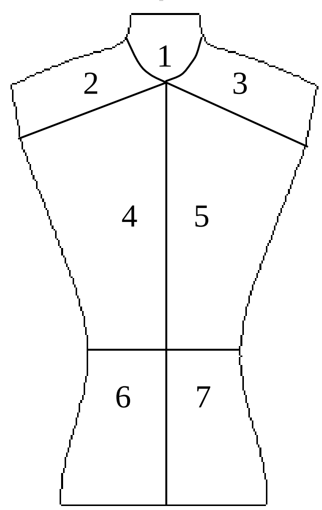


Figure 8: Sections of Body Form

To create a four-edge surface, the four crossing points of the edges and the suitable curve formula for the edges need to be determined using key measurements of the scanned body. The surface can be then formed by using a linear Coons surface [9]:

$$P(u,v) = -\left[-1, u, 1-u\right]\begin{bmatrix} 0 & P_{u0} & P_{u1} \\ P_{0v} & P_{00} & P_{01} \\ P_{1v} & P_{10} & P_{11} \end{bmatrix}\begin{bmatrix} -1 \\ v \\ 1-v \end{bmatrix}, \quad u,v \in [0,1],$$

where $P_{u0}, P_{u1}, P_{0v}, P_{1v}$ denote the given edges, $P_{00}, P_{01}, P_{10}, P_{11}$ denote the given points respectively, and $P(u,v) = P_{uv} = \{x_{uv}, y_{uv}, z_{uv}\}$ is a point on the surface. The equations for the four edges of one section is designed as follows:

$$P_{u0} = P_{00} + [P_{10} - P_{00}]\begin{bmatrix} 1-\cos(u\pi/2) & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & \sin(u\pi/2) \end{bmatrix},$$

$$P_{u1} = P_{01} + [P_{11} - P_{01}]\begin{bmatrix} 1-\cos(u\pi/2) & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & \sin(u\pi/2) \end{bmatrix},$$

$$P_{0v} = P_{00} + [P_{01} - P_{00}]\begin{bmatrix} (1-\cos(v\pi))/2 & 0 & 0 \\ 0 & v & 0 \\ 0 & 0 & v \end{bmatrix}, \text{ and,}$$

$$P_{1v} = P_{10} + [P_{11} - P_{10}]\begin{bmatrix} v & 0 & 0 \\ 0 & v & 0 \\ 0 & 0 & (1-\cos(v\pi))/2 \end{bmatrix}.$$

Figure 9 shows the neck and should patches and a 3D body form for an upper body.

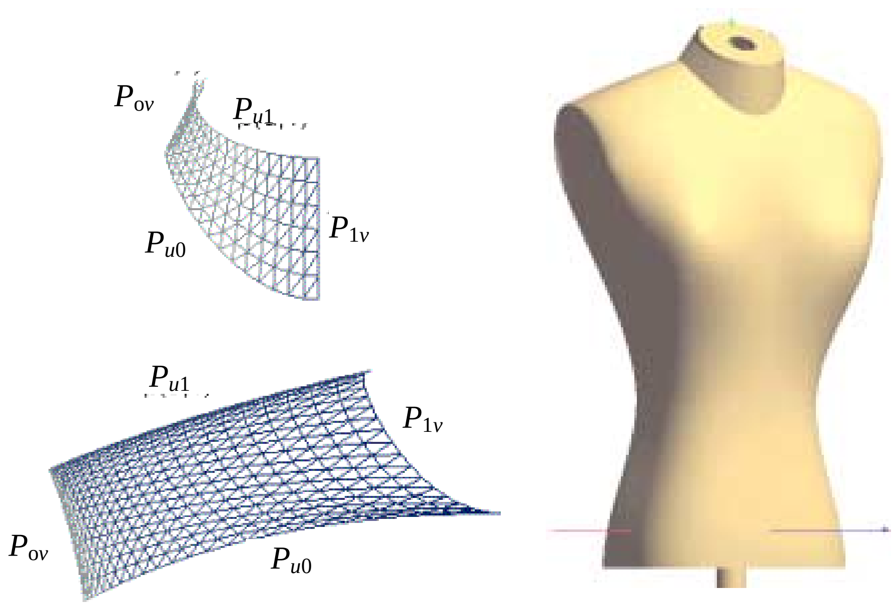
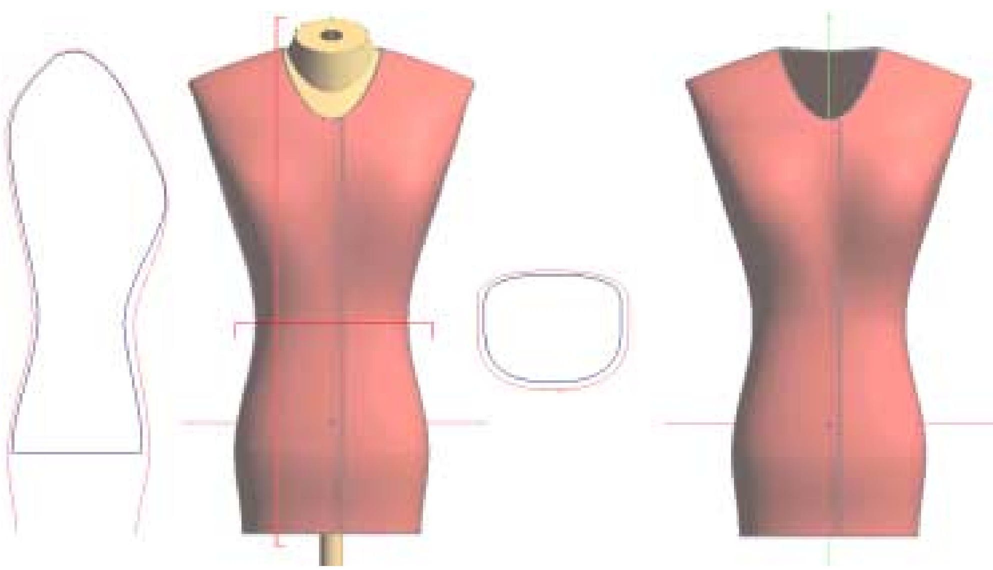


Figure 9: Neck and Shoulder Patches and Body Form

5. VIRTUAL GARMENT

A virtual garment can be directly created on the body form by following the shape of the 3D body form and taking a desirable ease to ensure the personal fit. The software provides a tool that allows the user to cut through the garment and body form horizontally and vertically to check and change the ease at any position by specifying a gap distance (Figure 10a). The structure lines including seam lines, outlines, and grain lines can be also added. After the design is finished, the garment can be taken off from the body form and flattened into 2D pattern pieces for further modification in an apparel CAD system (Figure 10b).



a. Ease evaluation b. Virtual garment

Figure 10: Virtual Garment and Ease

CONCLUSIONS

In this paper, we presented a newly developed human body scanner for apparel mass customization. Based on the multi-line triangulation and computational geometry techniques, the scanner can quickly acquire the 3D images of the front and back sides of a body, automatically extract key dimensions that are important for apparel design, create customized body forms, and generate virtual garments that fit on the body forms. This body scanning system and its application software would enable apparel manufacturers to provide custom design services to the consumers seeking personal fit garments.

REFERENCES

1. H. Armstang, *PatternMaking for Fashion Design*, HarperCollins College Publishers, New York (1995).
2. S. Ashdown, "Introduction to Sizing and Fit Research", *Symposium of Fit 2000*, http://car.clemson.edu/fit2000/ (2000).
3. P.J. Besl, *Surfaces in Range Image Understanding*. Springer-Verlag, New York, (1990).

4. T. Furukawa, J. Gu, W. Lee and N. Magnenat-Thalmann, *3D Clothes Modeling from Photo Cloned Human Body*, in Virtual Worlds, Springer-Verlag, pp159-170 (2000).
5. C.Y. Jongsuk and C. Jasper, "Key Dimensions of Women's Ready-to-Wear Apparel: Developing a Consumer Size-labeling System". *Clothing and Textile Research Journal*, 14, 89-95 (1996).
6. J. Holusha, "*Producing Custom-Made Clothes for the Masses*". New York Times.
7. P. Les and T. Wayne, *The NURBS Book (2nd Edition)*, Springer (1997).
8. R.P. Pargas, N.J. Staples and J. S. Davis, "Automatic Measurement Extraction for Apparel from a Three-Dimensional Body Scan", *Optics and Lasers in Engineering*, **28**, 157-172 (1997).
9. D.F. Rogers, and J.A. Adams, *Mathematical Elements for Computer Graphics*. McGraw-Hill (1990).
10. A. Rosenfeld and A. Kak, *Digital Picture Processing*, vols. 1 and 2. Academic Press, New York (1982).
11. B. Xu and S.V. Svinivasan, "3D Body Imaging and Measurement for Apparel Customization", *J. of Textile Institute*, **90**, 104-120 (1999).

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