Proceedings of the 2005 IEEE
International Conference on Mechatronics
July 10-12, 2005, Taipei, Taiwan

An Integrated Scanning System for Reconstructing 3D Color Models of General Objects

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***Abstract* - This paper develops an integrated scanning system for reconstructing 3D color models of general objects. First, a laser scanner is used to digitize the 3D shape of an object. When scanning the darker surface of an object, laser beams with different laser power are emitted onto the object surface to obtain adaptive scan lines, and the scan line with best quality is automatically selected to improve the quality of the scan data. 3D triangular meshes are constructed from scan data points and the 3D surface model of the object can be obtained. Then, a digital camera is used to capture color texture images of the object. A texture mapping method is developed to automatically wrap texture images onto triangular meshes to form the 3D color model of the object. Finally, an integrated scanning system is established by combining a laser scanner and a digital camera. Using this system, 3D color models of two tested objects are reconstructed and good results are obtained.**

***Index Terms* - 3D model reconstruction, shape digitizing, texture mapping, reverse engineering**

I. INTRODUCTION

In recent years, due to the small quantity, multi-forms, and short life span of products, reverse engineering has been broadly applied in the product design and manufacturing industry. In reverse engineering, traditional methods for capturing shapes of objects can be generally classified into two broad categories: contact and non-contact measuring methods [1, 2]. In contact measuring method, the measuring tool is usually a probe or a stylus, and there is a direct contact between the tool tip and the object surface. Non-contact measuring method is a newly emerging measurement technology. It uses light as the main tool in acquiring shapes of objects. As in the laser digitizer, structured light is used for capturing the shape data of objects. Unfortunately, current contact or non-contact measuring methods can only acquire object's 3D shapes. No intrinsic color information of objects is included [3]. However, 3D model without color information does not satisfy the requirements of demonstration in terms of realism. In modern visual applications, such as computer animation, online shopping, antique digitization, advertising, etc., 3D models with color information are required. Additional information about the original color texture of the object has to be warped onto the surface of 3D model to improve its appearance. This process is called the texture mapping [4].

This paper develops an integrated scanning system for reconstructing object's 3D color model. It combines both the laser scanning technology and texture mapping technique in the reconstructing process. In the section 2, the approach for the reconstructing object's 3D color model is introduced, while the section 3 describes the integrated scanning system. The section 4 gives an application example, and in the section 5 some conclusions are presented.

II. RECONSTRUCTING OBJECT'S 3D COLOR MODEL

2.1 Object Shape Digitizing

A typical laser scanner, as shown in Fig.1, uses a laser diode to emit a laser beam on the object surface and captures the reflected light by two monochrome CCD cameras. With given the positions of the laser head and CCD cameras, coordinates of the object surface can be calculated by using the triangulation principle or coordinate mapping method [5].

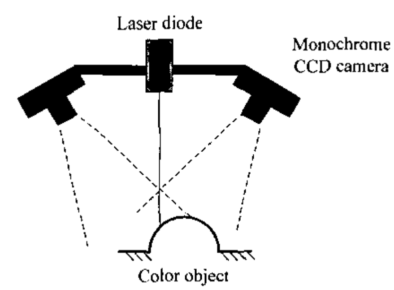

Fig. 1 Laser scanner with a laser diode and two monochrome CCD cameras

When the laser diode emits a laser beam on the color surface of an object, the darker color having lower reflection rate will absorb the laser light and affect the quality of scan data. In order to have consistent reflection rate of object surfaces, red or white paint is sprayed on the surface of color objects. However, the purpose of this paper is to reconstruct color models of objects. Paint should not be sprayed on the object surface such that the original object color information will not be changed.

In general, dark surfaces need larger laser diode power and bright surfaces need less power. For object surface with a specific reflection rate, the power of the laser diode should be adjusted to a suitable value for obtaining the best quality of scan line data. As shown in Table 1, for measuring the same scan line by laser beams with different laser diode power, images captured from CCD camera are different and number of identified data points for each laser beam is also different.

Table 1 Scan line data for using adaptive scan line capturing process

Images captured from CCD camera					
Laser power/P_{min}	1.00	1.13	1.25	1.38	1.50
No. of data points	157	160	175	189	190
$\bar{d}$ (mm)	0.364	0.362	0.351	0.352	0.361

An adaptive scan line capturing process is implemented to solve problems induced by darker surfaces. Assume that the power of the laser diode can be adjusted between $P_{\min}$ and $P_{\max}$, where $P_{\min}$ is the minimum power and $P_{\max}$ is the maximum power. Let $P_{\min}$ be the initial laser diode power for each scan line. If the number of data points in scan line is less then a given threshold value, a power adjustment process is executed. t sets scan line are acquired with t different power values which are equal spaced between $P_{\min}$ and $P_{\max}$. However, large power also induces noise in scan line data. The noise can be indicated by the average distance of each scan line points. The definition of average distance $\bar{d}_i$ for all points in the *i-th* scan line can be written as:

$$\bar{d}_i = \frac{\sum_{j=1}^{N_i-1} \left\| \vec{p}^{\,i}_{j+1} - \vec{p}^{\,i}_j \right\|}{N_i - 1}, \quad i = 1,\ldots,t \tag{1}$$

where $\vec{p}^{\,i}_j$ is the *j-th* point vector of the *i-th* scan line, and N_i is the number of data points in the *i-th* scan line. The number of fitted data points will be increased with the increased power of the laser diode, and $\bar{d}_i$ will become smaller. On the other hand, the noise will also be increased with the increased power of the laser diode, and $\bar{d}_i$ will become larger because noise points are distant from regular points. So, the average distance of a scan line points has a relative minimum value when the power of the laser diode is increased, and the power with the relative minimum average distance is considered as the optimum laser diode power for the object surface. As shown in Table 1, when the laser power is increased to 125% of $P_{\min}$, the $\bar{d}$ has the local minimum value. At the optimum laser diode power, the number of data points is increased to 111.4% of points with $P_{\min}$ laser power.

2.2 3D Model reconstruction

After obtaining scan lines of object surface, the 3D surface model can be reconstructed by building triangular meshes over these scan lines. For all scan lines of the object surface, it is assumed that scan lines are in the same direction and do not cross each other. For two adjacent scan lines, non-overlapping triangular meshes can be built up between these two lines. Since the number of data points in each scan line is different, triangular meshes can be built up in many ways. The mesh with shortest edges will be selected in sequence. Fig.2 shows how the triangular meshes are established between two adjacent scan lines.

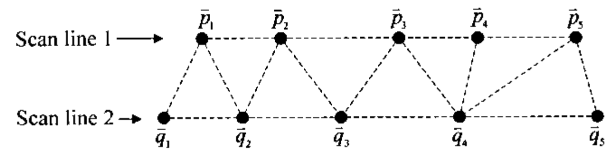

Fig.2 Building triangular meshes between two adjacent scan lines

2.3 Object silhouettes obtained from digital images

In addition to reconstruct object's 3D surface model, a digital camera is also used to capture color texture images of the object surface. In order to maps texture images onto the 3D surface model, it is required to build up the relationship between 2D texture images and 3D triangular meshes. In this paper, object silhouettes are used to increase the accuracy of coordinate mapping in the texture mapping process. The section introduces the silhouette capturing method first, and detailed approach about texture mapping will be described at section 2.4.

In the photography, if a bright back light is applied behind objects, part of the back light will be covered by the object and a shadow of object silhouette will be produced. A digital camera is used to get this high-contrast image. Furthermore, the image contrast stretching process [6] is applied to the high-contrast image to strengthen the image contrast, and a clear object silhouette can be obtained.

Assume that r is gray level of the original image, and s is the enhanced gray level after the contrast stretching process. The gray-level transformation function T has the form as following:

$$s = T(r) \tag{2}$$

The effect of this transformation is to produce an image of higher contrast than the original by darkening the levels below a given threshold value and brightening the levels above the threshold value in the original image. For example, if $T(r)$ is a step function as shown in Fig.3, $T(r)$ will produce a two-level (binary) image. Fig.4 is an example for object silhouettes at different viewing angles using the proposed method.

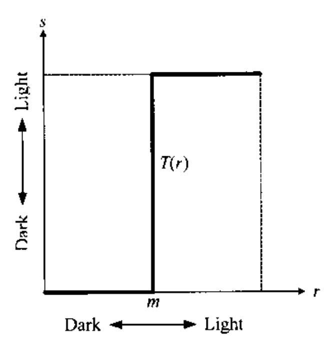

Fig.3 Gray-level transformation functions for contrast enhancement

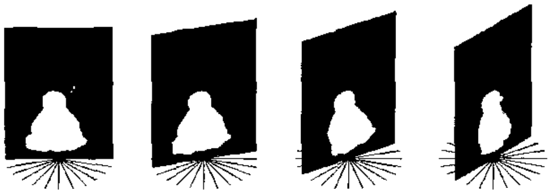

Fig.4 Object silhouettes at different viewing angles

2.4 Texture mapping

Texture mapping is an image synthesis technique in which 2D texture images are mapped onto surfaces of a 3D model, and then the color 3D surfaces are projected onto a 2D screen for displaying. In this paper the texture image is obtained from a digital camera and the 3D model surface is represented as triangular meshes. The process of texture mapping can be subdivided into two steps [7, 8], as shown in Fig.5. The first step is called parameterization, in which the 2D texture space is mapped onto the 3D model space, i.e. a mapping function is established to map a specific part of texture image onto each triangular mesh. The second step is called the viewing projection, in which 3D model space is mapped onto the screen space. By varying the viewing directions, arbitrary views of the parameterized model can be obtained. The detail process of the viewing projection is not investigated in this paper.

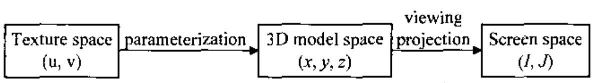

Fig.5 The relationship between texture space, 3D model space, and screen space

The proposed texture mapping process is described as following [9]. First, a digital camera is located at $\theta_i(i=1,\dots k)$ angle relative to the target object, and one color texture image is captured at each position angle around the object, as shown in Fig.6(a). Because the maximum view angle of a digital camera is less than 180 degree, it needs more than two texture images to cover the whole object surface. To increase the accuracy of coordinate mapping in the texture mapping process, object silhouettes are also needed at the same angular positions. For each texture image, the corresponding silhouette is used as mask to remove the background of each image. Then, the projection transformation between the 3D model space and the texture space need be built up. At each angular position $\theta_i(i=1,\dots k)$, a point $p(x,y,z)$ in the 3D model space will be transferred to an point $p(y',z')$ after parallel projecting. The projection transformation equation can be written as:

$$[0 \quad y' \quad z' \quad 1]^{T} = \mathbf{M}_{p}[x \quad y \quad z \quad 1]^{T} \tag{3}$$

$$\mathbf{M}_{p} = \begin{bmatrix} \sin^2\theta & -\sin\theta\cos\theta & 0 & 0 \\ -\sin\theta\cos\theta & \cos^2\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where $\mathbf{M}_p$ is the transformation matrix. The parallel projection at $\theta = 0^\circ$ is shown in Fig.6(b). In Fig.6(b), a projected bounding rectangle, containing all projected triangular meshes at the projection plane, can be found. The width and the height of the rectangle are denoted as w_c and h_c. Similarly, texture bounding rectangle from the texture image at the same θ angle can also be found, as shown in Fig.6(c). The width and the height of the texture bounding rectangle are denoted as w_t and h_t respectively. Two ratio factors λ_u and λ_v are defined as:

$$\lambda_u = \frac{w_t}{w_c}, \lambda_v = \frac{h_t}{h_c} \tag{5}$$

Assume that the reference point of projected bounding rectangle is (y'_c, z'_c) and the reference point of texture bounding rectangle is $(0,0)$. The coordinate transformation equation can be written as:

$$[u \quad v \quad 1]^{T} = \mathbf{M}_{c}[y' \quad z' \quad 1]^{T} \tag{6}$$

$$\mathbf{M}_{c} = \begin{bmatrix} 0 & \lambda_y & 0 & 0 \\ 0 & 0 & \lambda_z & 0 \\ 0 & -\lambda_y y'_c & -\lambda_z z'_c & 1 \end{bmatrix} \tag{7}$$

where $\mathbf{M}_c$ is the transformation matrix, and (u,v) is the transferred coordinates. By using these two coordinate transformations, the 2D texture image and 3D triangular meshes with different coordinate systems are transformed into a unified coordinate system.

Usually, the mapping result is distorted for triangular meshes around the rim of the object. So, mapping operation is only applied to meshes corresponding to the central region of the texture image. This paper uses the inward offset silhouette as the selecting mask to eliminate triangular meshes around the rim of the object, as shown in Fig.6(d).

The final result of the texture mapping process is shown in Fig.6(e).

III. INTEGRATED SCANNING SYSTEM

Based on the proposed approach, an integrated scanning system is developed. This system is composed of a laser head, a digital camera, a light control system, and a stage with 4 degrees of freedom. The control software is developed by Visual C++ .NET and AutoCAD ObjectARX Library. The AutoCAD software is used as the graphic engine to manipulate scan data and triangular meshes, while the 3D animation 3ds max software is used to reconstruct the 3D color model and display the results of rendered color images. The developed integrated scanning system is shown in Fig.7, and the configuration of the system is shown in Fig.8.

The process for reconstructing 3D color model by using the developed integrated scanning system is described briefly as following. First, the object is placed on the rotary stage for scanning operation. The shape is digitized by the laser head at each predefined angular position. When digitizing the darker surface, the proposed adaptive scan line capturing process is applied to reduce the noise and improve the quality of scan data. After the scanning operation, some data pre-processing operations, such as data reduction, data redistribution and data smoothing [10], will be also applied on scan data points. 3D triangular meshes are constructed from data points and the 3D model of the object can be obtained.

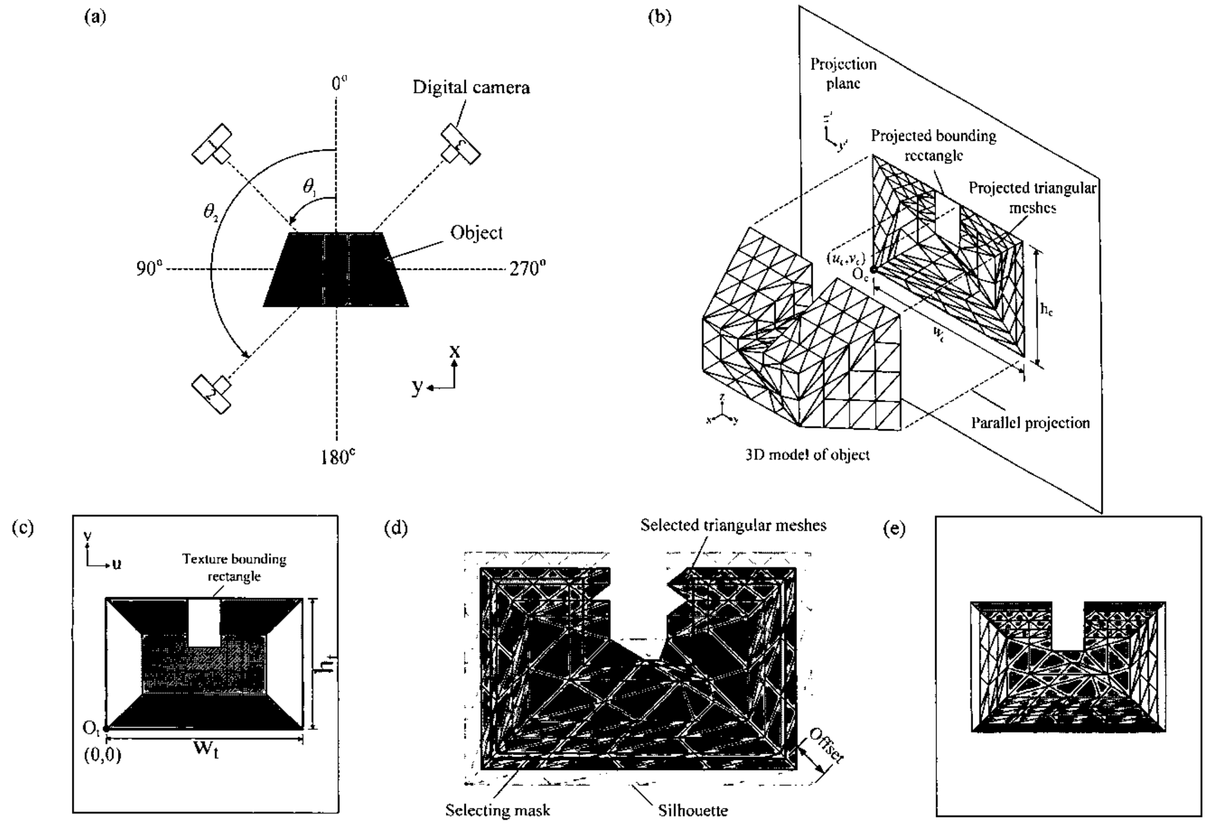

Fig.6 Texture mapping process: (a) position angle definition; (b) parallel projection; (c) texture image; (d) selecting triangular meshes; (e) the final result

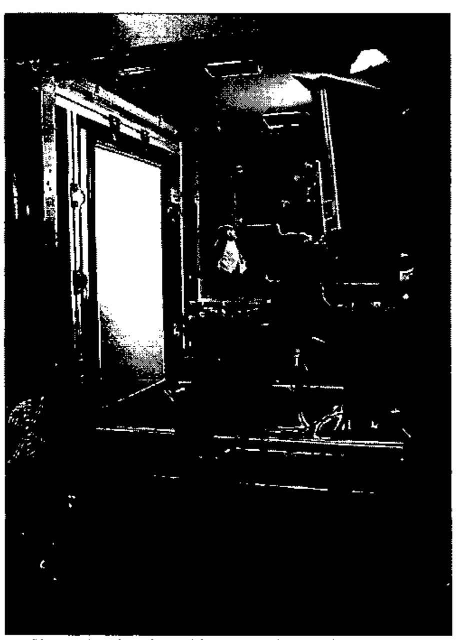

Fig.7 The developed integrated scanning system

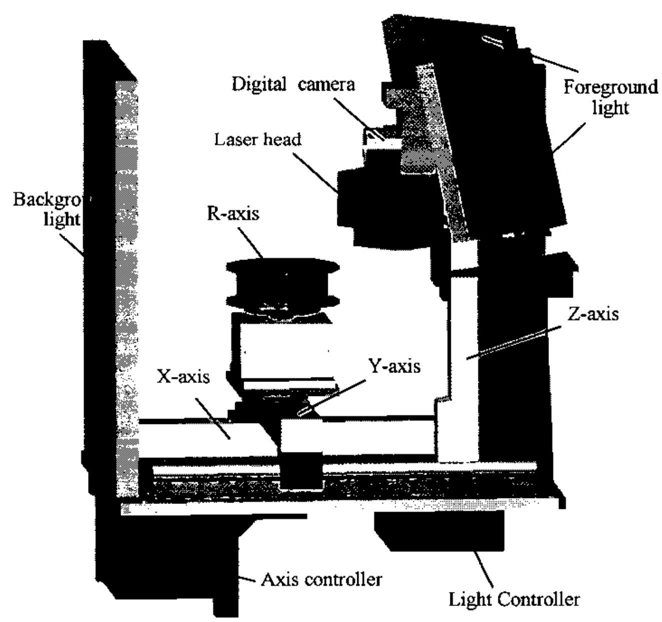

Fig.8 System configuration

As for digital images, both general color images and high-contrast images are needed to reconstruct the 3D color model of the object. When capturing general color images, foreground lights are turned on and background lights are turned off. When capturing high-contrast images, foreground lights are turned off and background lights are turned on. For each high-contrast image, the image contrast stretching process is applied to obtain the object silhouette. Further, the object silhouette is also used as mask to remove complex background textures such that image texture inside the object silhouette is simplified.

Finally, several color images of the object are warped onto 3D triangular meshes to form the 3D color model. The whole 3D color model reconstruction procedure is shown in Fig.9.

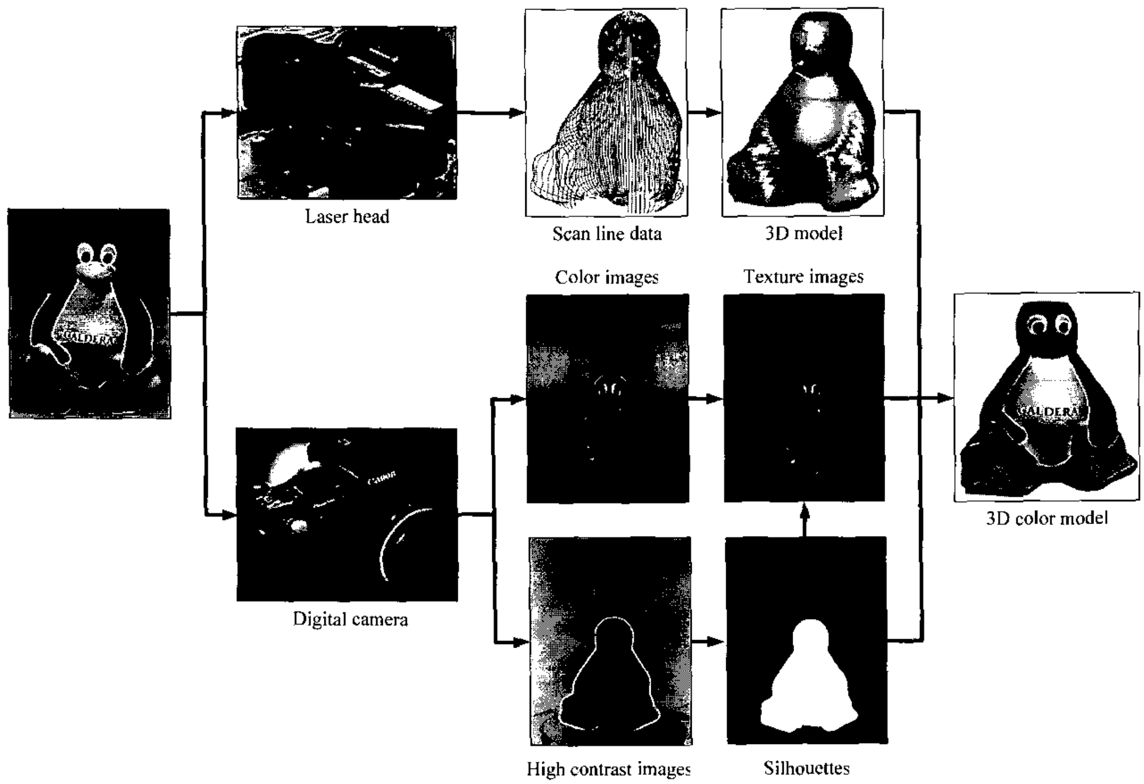

Fig. 9 3D color model reconstruction procedure

IV. APPLICATION EXAMPLES

A doll product is used to test and verify the proposed procedure for 3D color model reconstruction. The doll photo is shown in Fig.10(a). First, the laser scanner emits laser beam on the object surface and digitizes the shapes of the doll at 100 angular positions with 3.6 degree step. When digitizing the darker object surfaces, the adaptive scan line capturing process is executed. After digitizing, 27,656 points are obtained, and scan lines are shown in Fig.10(b). Data pre-processing operations are applied on the scan data points, and then 3D triangular meshes are established. The 3D model which contains 29,998 triangular meshes is shown in Fig.10(c). Next, the digital camera and the light system are used to capture 4 color texture images at 4 angular positions with 90 degree step. Finally, color texture images are wrapped onto 3D triangular meshes by the proposed texture mapping technique, as shown in Fig.10(d). The final the 3D color model of the doll is shown in Fig.10(e). Another example, the penguin doll, is also tested with the same procedure and the result is shown in Fig.9.

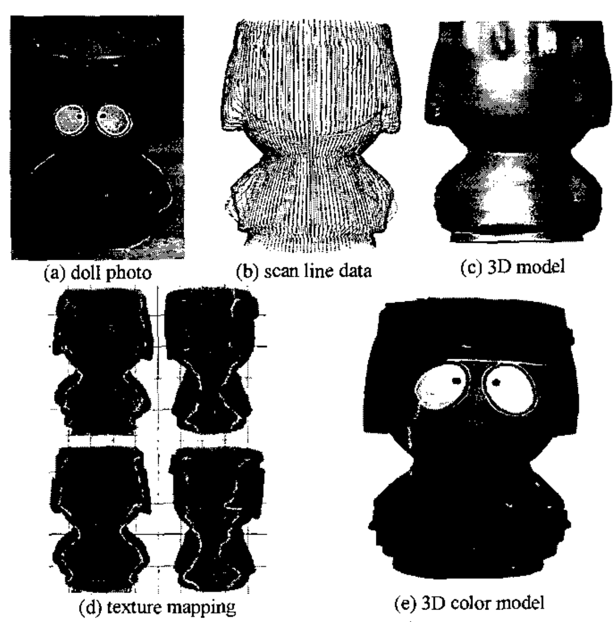

Fig.10 Application example

V. CONCLUSIONS

This paper develops an integrated scanning system for reconstructing 3D color models of general objects. In object shape digitizing process, an adaptive scan line capturing method is proposed to improve the data point's quality in darker surfaces of the object.

In addition, a digital camera is also used to capture color texture images of the object. Color texture images are then warped onto 3D triangular meshes to form the 3D color model of object rapidly. An integrated scanning system is developed. It is tested in establishing 3D color models of general objects, and good results are obtained. The developed systematic procedure for reconstructing 3D color models of objects can be broadly applied in the product design, multi-media, games, animation, and antique digitization areas.

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