8

3D body scanning

W YU

8.1 Introduction

For the spatial analysis of clothing appearance and fit, a 3D digitisation of body form and clothing surface is essential. Since the late 1980s, 3D body scanning has received great attention and wide application in the clothing field. Variation in body size and shape can be assessed quantitatively and expressed by contour maps or polygons. The following are four main clothing applications of body scanning: non-contact body measurements for size survey, pattern generation for customisation, a tailor-made mannequin for a target market, and clothing fit evaluation of appearance, such as drape, wrinkling and bagging. Other than clothing, it can be applied also in the medical field for the screening of spinal deformities, the bust and abdomen volume during pregnancy, facial palsy and fat distribution. Animation and sculpture are also a possibility, but will not be discussed in this chapter.

Amongst so many possible applications, the main applicable result of 3D body scanning is the point data cloud to be used for the generation of virtual or physical dress model, critical landmarks and anthropometric data to guide the design and sizing of garments. One significant advantage of most 3D body scanners is the rapid scanning time and more accurate reproducible measurements. This machine generates an unlimited number of linear and nonlinear measurements of the human body in just a few seconds. It also delivers the output in a digital format which can be integrated automatically into apparel CAD systems such as Gerber and Lectra. This makes it possible to create garments which can mould to the three-dimensional shapes of unique human bodies.

This chapter reviews the development, technologies and application of non-contact body measurement and garment analysis systems in four categories: moiré topography, laser scanning, infrared scanning and photogrammetry. The methods using ultrasound and MM wave technologies are not included in this publication.

8.2 Global development of body scanners

Early in the fifteenth century, Leonardo da Vinci[1] was fascinated by the survey of the human body. The idea was adapted, and the methods were assimilated into the possibilities of today. Since the late 1800s, anthropologists used tape measures and callipers which are still being utilised for measuring the human body.[2] These methods are time consuming and often not accurate. Therefore, many researchers all over the world have directed their efforts towards obtaining more reliable measurements and 3D profiles of the human body using various techniques. These developments are described here in three geographic categories: Asia, America and Europe.

8.2.1 Asian development

In Asia, Japan was the first country to develop non-conventional measuring devices to capture the 2D and 3D body profiles of human subjects. The methods include sliding gauge, gypsum moulding, silhouetter, moiré camera, infrared scanner and laser scanner.

Japan

Sliding gauge

Research and development of 3D body scanners in Japan show a typical step-by-step technological transformation process from linear to 2D before reaching 3D, from contact to non-contact from photographic to moiré contour and infrared to laser.

In a big leap from linear tape measurements, a manual sliding gauge has been cleverly developed to trace the 2D sectional curves of the human body (Fig. 8.1). It used a series of aluminium sticks, equal in length and 5 mm in diameter, which were pushed smoothly towards the body surface, thus the curve connecting the

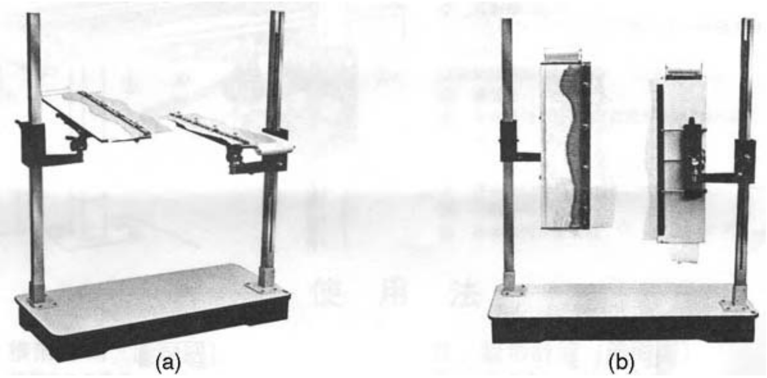

Figure 8.1 (a) Horizontal sliding gauge and (b) vertical sliding gauge. Source: Yamakoshi Seisakusho Co., Ltd.

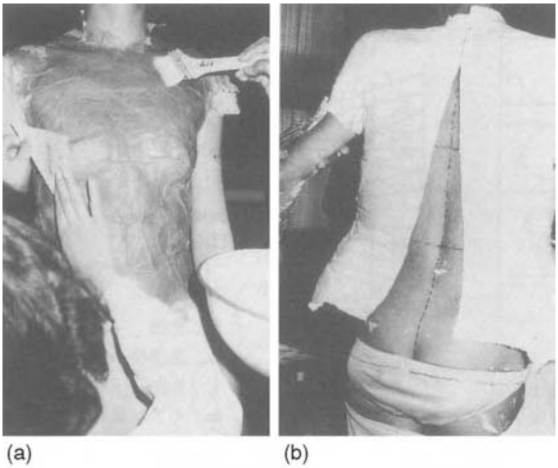

Figure 8.2 (a) Algin Method and (b) Gypsum Method. Source: By courtesy of Asakura Publishing Co., Ltd., Fig. 2.19 in Yoshiko Nakaho *et al*: *Clothing Construction*, 1995. Asakura Publishing Co., Ltd, Tokyo, Japan.

points of the other ends of the sticks was traced on paper for further computation of body measurements and sectional areas. Based on this concept, a mechanical sliding gauge instrument was later developed for measuring a complete set of body measurements in three dimensions. However, it has not been widely accepted by academic institutions because of its bulkiness and clumsy procedure.

Algin/gypsum moulding

To obtain a continuous 3D profile of a human body, direct skin-contact moulding methods, algin or gypsum have been used (Fig. 8.2). The researcher uses a brush to paint the liquid material to cover the skin under investigation, allowing it to dry, and then removing the dried 'shell' from the body surface, where the information of the 3D body shape was copied as the inner part of the shell. This is a direct method of taking body measurements, but too expensive for use.

Silhouetter

For non-contact measurement, a 'silhouetter' has been developed to capture a 2D photograph of a body contour with a background of a calibrated standard grid. This system consists of a booth with a large grid wall, a series of fluorescent light tubes and an instant camera (Fig. 8.3). A computerised silhouette analyser,[4] which electronically processes data on the contours, was also developed by Wacoal in 1984.

Moiré camera

Developed from photography, shadow moiré topography has been applied in the academic field for research on the 3D observation of the human body and its

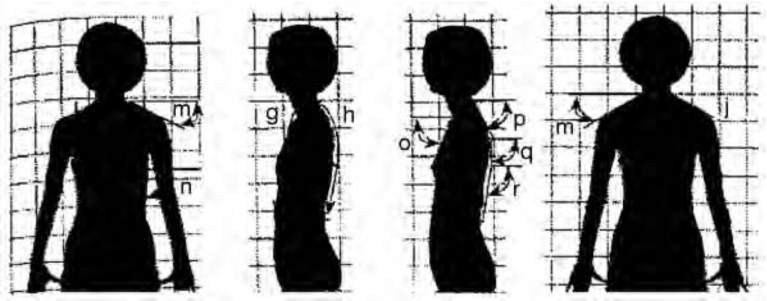

Figure 8.3 Silhouette analyser. Source: Reprinted from Applied Ergonomics, 23(3), Gazzuolo *et al*, 'Predicting garment pattern dimensions from photographic and anthropometric data' Copyright (1992), with permission from Elsevier.[16]

relationship to clothing patterns. In the 1980s, Fujinon used projection moiré topography to produce a moiré camera which has also been widely used in clothing research (Fig. 8.4). With a great reduction in size and weight and increased portability, the moiré scanner became commercially available from Fujinon in the 1990s. It is mainly used for the screening of spinal deformity of schoolchildren.

Infrared scanner

With the limited digital technology available in the 1980s, moiré images always contained noise which caused difficulties in terms of automatic processing. Therefore, Japanese researchers shifted their attention to infrared and laser technologies in the 1990s. Hamamatsu and Conusette are two major companies selling commercial infrared body scanners.

Conusette's products are particularly designed for mass customisation of ladies' foundation garments. Therefore, only the upper torso of a scanned body is analysed (Fig. 8.5). This system provides a whole body balance check, judging the most suitable underwear for the body's current shape, and uses computer graphics to simulate the future development of the body. Ageing simulation shows what the body will look like after five or ten years, based on the shape of the present figure. By superimposing the present figure over the future figure, ladies can formulate fashion, diet and healthcare plans.[5]

Laser scanner

At present, laser-based technology has become the key trend for 3D body scanning. Voxelan, originally developed by NKK in Japan, was taken over by the Hamano Engineering Company in 1990. It offers several series of laser scanners for measuring the head, half body and the whole body (Fig. 8.6). About 80 companies and institutions in Japan have used Voxelan's laser system since it was introduced.

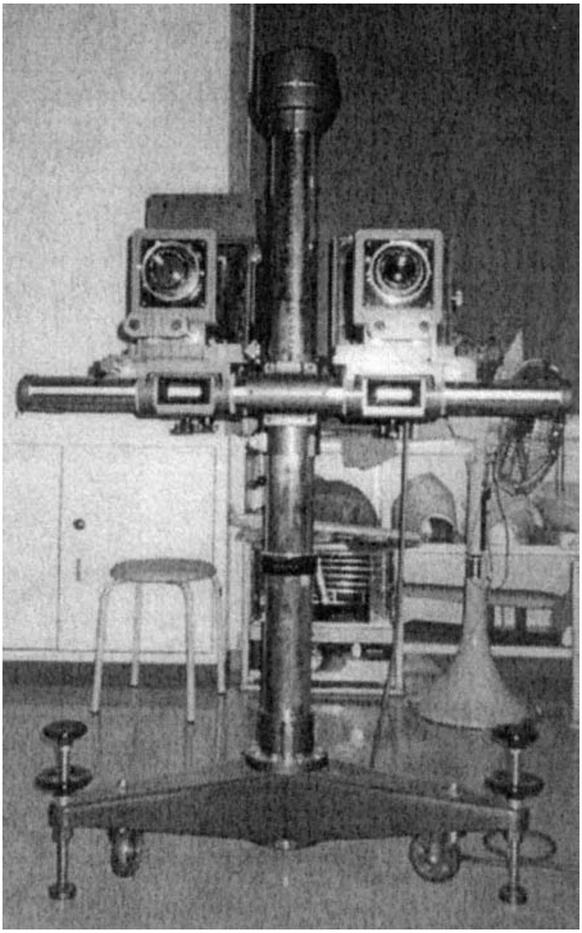

Figure 8.4 Fujinon Moiré Camera in 1980s. Source: Fujinon: *www.fujinon.co.jp*

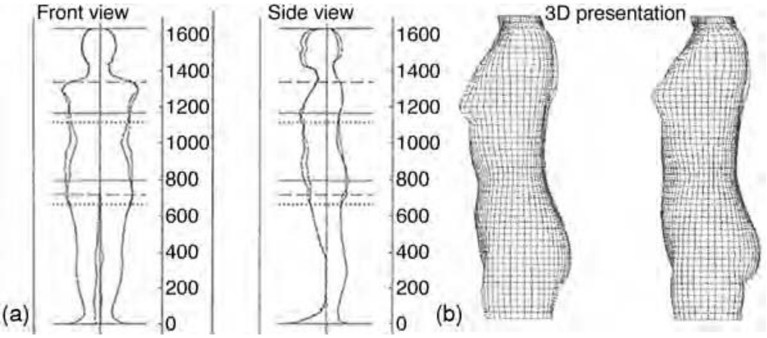

Figure 8.5 Output of Conusette's scan. Source: Hokuriku Co. Ltd., sample print screen from Conusette Infrared body scanner, 2003.

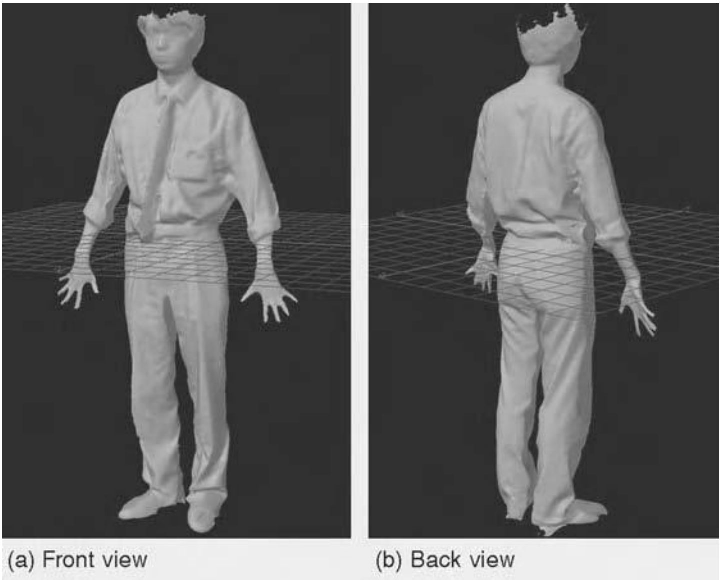

Figure 8.6 Digital output from Voxelan laser scanner. Source: Measured by VOXELAN.

In 2001, a non-contact 3D form measurement device, called ‘Cubic’, was developed in a joint industry-university research project with Bunka Women’s University, Japan. It uses halogen light and takes about one second to obtain the body measurements, with an accuracy of 1 to 3 mm, depending on the image coverage (Fig. 8.7). The machine structure is light in weight and fit for easy transportation. Customerised software is provided in accordance with its needs. Texture and colour indications are also possible.

China

Hong Kong

In Hong Kong, the University of Science and Technology (HKUST) developed a computer-aided system in 1998 for three-dimensional mannequin generation and

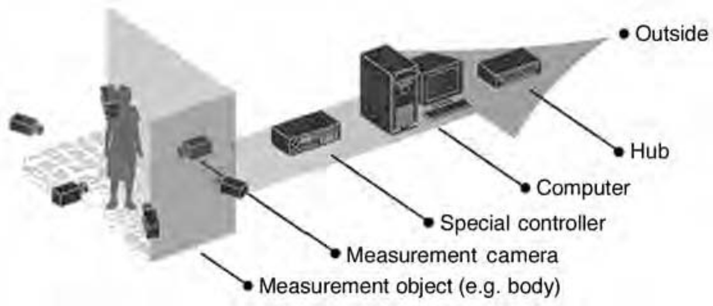

Figure 8.7 Cubic’s hardware structure. Source: *http://www.cubic-inc.co.jp*

Figure 8.8 Close look at CubiCam.

garment design. Twelve images of 2D outlines, at six angles and two levels, were captured using digital cameras. Using a parametric feature-based design, simulated mannequins of men, women and children of varying ages and different sizes were demonstrated. The garment patterns were graphically sewn together and overlaid on the CAD-based mannequin. The garment models can also simulate the effects of different fabric materials based on fabric objective measurement.[6]

The present author, attached to the Hong Kong Polytechnic University, has patented a low-cost and compact body scanner called 'CubiCam' based on modified moiré topography (Fig. 8.8).[7] 'Cubi' means 3D, 'Cam' sounds like a little camera, quick, easy, cheap and cheerful. It is best used for body measurement, shape capturing, e-fitting and e-commerce on fashion and/or medical products. The hardware operates without a dark room, high power or professional calibration. There are six 'S' advantages: small, slim, saving, simple to use, swift and safe. It measures 160 mm W × 405 mm D × 390 mm H, which makes it the smallest 3D body scanner on the market. It is slim, as the lens

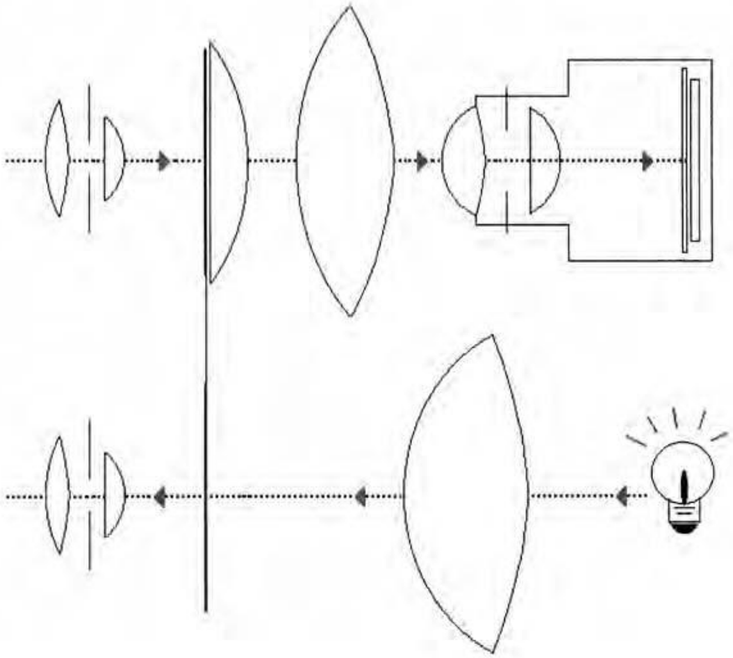

Figure 8.9 CubiCam's optical design. Source: Yu *et al.*, 1999.[20]

has a wide coverage of 925 mm (horizontal) × 1110 mm (vertical) at a short distance of 1200 mm (Fig. 8.9). A low-cost design is achievable because only one digital camera is required. It is simple to use due to its simple installation without high power voltage. Calibration is easy with this portable design. It is also swift, since less than 1/1500th of a second is required for image capture. It could enhance better accuracy with minimal body movement. The scanner works under normal lighting conditions with no laser, infrared or harmful radiation, therefore it is intrinsically safe.[8]

Taiwan

In Taiwan, the Industrial Technology Research Institute (ITRI) developed a portable 3D scanner 'Gemini' using opto-electronic application technology. A laser beam was projected to measure the body's surface profile dimensions. To avoid blind spots, ITRI used six optical detectors that performed simultaneous 360° inspections. It also utilised in-house developed 3D data integration and editing software to achieve high speed human body scanning. This technology has been transferred to domestic manufacturers. In February 2000, ITRI installed a scanner in the Chang Gung Memorial Hospital to collect 3D data of the human body. A total of 4500 people were scanned by the year 2002. Gemini was primarily designed for medical use, but now ITRI has also built up a database linked to the Taiwan Body Bank and provides information to garment manufacturers.

8.2.2 American development

Early in 1964, the first full-scale male dummy was designed using anthropometric measurements employing a simple three-dimensional technique.[9] Vietorisz used a light source and an arrangement of photo detectors to measure a person's silhouette. In the late 1970s, systems utilising lasers were developed. In 1977 Clerget, Germain and Kryze were the first to illuminate their measured objects with a scanning laser beam.[10] David and Lloyd Addleman developed a scanning laser beam system in 1985, which is now marketed as Cyberware.

Using laser scanning, Cyberware has revolutionised computer graphics so as to work with true human faces and forms. The first body scanner was announced in 1987 for surface digitising and the measurement of a living human body. This trend began in the mid-1980s for the head, face and other body parts (hands, feet and the torso) and has recently evolved into whole-body imaging. In May 1995, Cyberware announced the introduction of the first 3D scanners to capture the shape and colour of the entire human body in one pass.[9] It was mainly applied to measuring individuals in the US Air Force for perfect fit uniforms and the Computerisation Anthropometric Research and Design Laboratories, with over 30 industrial partners in 2002.

In 1998, TC^2 made their first commercial 3D body scanner available to the clothing industry. Soon after its announcement, four systems were delivered to Levi Strauss, US Navy, North Carolina State University and Clarity Fit Technologies. Using this system, Lands' End has successfully carried out 14 city mobile scanning tours. In 2001, the first made-to-measure apparel store was launched at Brooks Brothers in New York. Due to its good support, TC^2 was selected by the Donghua University in China and several national size surveys, such as the 'SizeUK' project in 2000, 'SizeUSA' in 2002 and 'Size MX' in Mexico in 2004.[11]

8.2.3 European development

United Kingdom

The earliest 3D body scanning system in Britain, the Loughborough Anthropometric Shadow Scanner (LASS) was patented in 1987. Loughborough University has interrogated the 3D body data in collaboration with manufacturing companies including Marks & Spencer, Courtaulds Lingerie, Kennett & Lindsell, Bairdwear, Bentwood, Celestion and Fermark. The body data was obtained by scanning 155 women of various shapes and sizes using LASS, which enables accurate 3D measurements of the entire human body to be obtained in approximately three minutes.[12]

The UK Defence Clothing and Textile Agency (DCTA) in Colchester collaborated with researchers at the National Engineering Laboratory in Glasgow, Scotland. In 1996 they developed a 3D measurement system known as Auto-Mate.

DCTA operates a body measurement booth and offers either access to direct body measurement data, taken by a computer, or the facility and operators to take the measurements customers require for a given population. The design team provides corporate tailoring and offers designs in the form of demonstration garment/pilot models or fashion drawings. Their Ballistics Protection unit offers the design and the construction of body armour to provide the levels of protection required by their customers.

In 1996, Wicks and Wilson went into partnership with a London teaching hospital, needing a commercial partner, as part of a 3D facial scanning project. This project led to the development of TriForm systems using the moiré fringe technique, for head and body scanning.[13] It established a partnership with Body Shape Scanners Inc. in the USA and developed the new Body shape software aimed specifically at health clubs. The TriForm 3D body scanners have been used by David Lloyd Leisure Centres throughout the UK to track changes and improvements to the body shapes of their club members since October 2002.

France

Telmat Industrie developed the SYMCAD automated body measuring system. It was used by the French Navy to improve the fit of their uniforms in 1995. Recently the new 3D version was used within the clothing industry. It can capture the 3D shape of the customer instantaneously, and therefore is not affected by movement such as breathing, which could be detrimental during a scanning process. Each measurement is automatically calculated within ±2 mm accuracy (Fig. 8.10). Nottingham Trent University has used SYMCAD in the analysis of human size and shape for the purpose of manufacturing clothing since the late 1990s.

For the first time, in 1998, the SYMCAD system was linked to the GGT Accumark MTM made-to-measure system, and then automatically to the GGT Cutting Edge knife, providing instantaneous and automatic customer fit garments. The Hollings Faculty of the Manchester Metropolitan University also used this booth to capture human body images and developed their MICROFIT made-to-measure systems.[14] Similar systems include the AssyCAD system, which also allows customer-specific data management, automatic alterations and direct marker making, where standard patterns are augmented with measurements for the desired adjustments. Data can be entered via GOweb which provides a medium through which standard collections and tailored garments can be offered. The customer can individually select the desired details, such as pockets, collars, colours and fabrics. According to Assyst, the

Figure 8.10 SYMCAD OptiFit. Source: SYMCAD OptiFit: 3D body measurement booth by TELMAT Industrie (France) ©2003.

system allows presentations of various collections or brand names at 'virtual tailor' at the Internet shopping centre.

Germany
Tecmath is strong at the ergonomic simulation of human beings in the automotive industry. The company has been actively involved in the field of clothing since 1995, providing 2D and 3D scanners, called Vitus. More than 150 body scanners have been sold to retailers, e.g. C&A, armies and research institutes in the field of mass customisation and clothing.[15] Tecmath has become the leading supplier of 3D body scanners in recent years. Since October 2002 the Human Solutions division of Tecmath has formed an independent company.

8.3 Principles and operations of body scanning technologies

All body scanning technologies use optical devices for non-contact measurements. Before the development of 3D methods, various types of 2D photographic methods, such as silhouetter, were commonly used to present a complicated body profile. Since the 1980s, 3D body scanning technologies have grown rapidly and they can be grouped into four categories: structure light, laser, infrared and photogrammetry.

3D scanning is a procedure used to build a digital 3D copy of a physical surface. The main difficulty resides in obtaining the actual shape of the surface, that is, the volume which the surface occupies in space. In the 3D scanning process, the digitiser, camera or scanner acquires range images, very much like contour maps. They are then processed by modelling software and converted to point positions in space. The shape acquisition can be sequential, one point or line at a time. Others are computer-controlled sensors. The technology may also obtain colour information of the body texture, which is automatically fitted to the digital surface. This is all done without contact and in a short period of time.

8.3.1 2D photographic methods

Basic principle

The basic photographic set up of a silhoutter is shown schematically in Fig. 8.11. Each subject was photographed from three perspectives: anterior, lateral and posterior. Three black and white 127 × 178 mm photographs were developed and a vernier calliper was used to measure the length, width and depth on the photographs. Angles were transferred to tracing paper and measured with a protractor. Locations of photographic dimensions are defined. Technical limitations forced the researchers to measure photographs of the 50 female subjects manually, the intention being to provide the theoretical justification and methodology for a low-cost automated process of data collection, using video capture and computerised processing of visual data.[16]

Loughborough University – LASS

Using LASS, a person is required to stand as still as possible when the strips of light are projected onto the body and measured by TV cameras. This procedure is repeated 150 times whilst the subject is rotated through 360°. Four strips of light are used to allow adjustment for any movement. The strips are projected at

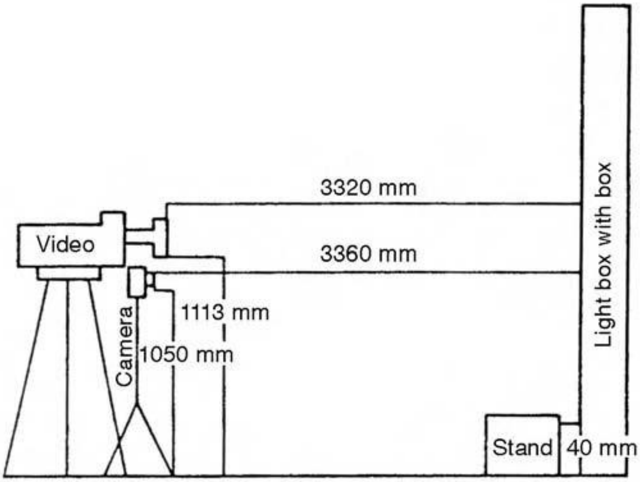

Figure 8.11 Schematic set up of 2D photographic methods. Source: Reprinted from Applied Ergonomics, 23(3), Gazzuolo *et al* 'Predicting garment pattern dimensions from photographic and anthropometric data' Copyright (1992), with permission from Elsevier.[16]

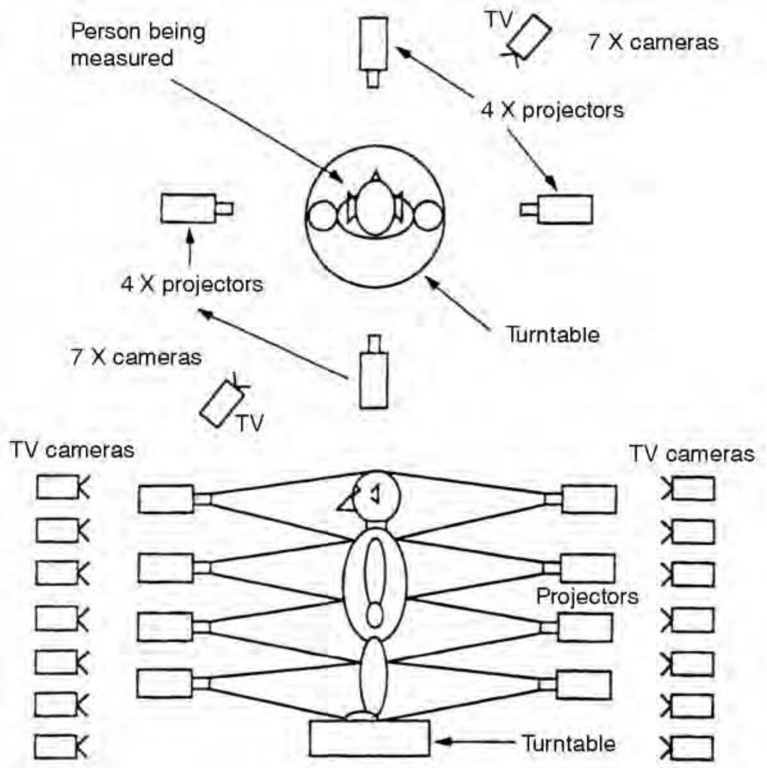

Figure 8.12 Schematic set up of LASS system. Source: Reprinted from *Endeavour*, 13(4), 'The Loughborough Anthropometric Shadow Scanner (LASS)', Jones PRM, *et al*, 162–168., Copyright 1989, with permission from Elsevier.[12]

an angle, so the observed deviation at any point depends on the radius of the body at that point. The exact radius can then be calculated. The set up of the LASS system is shown schematically in Fig. 8.12.

Loughborough's curve-fitting process treats the body as a series of horizontal 'slices', each of which can be edited in 2D. Sixteen data points are fitted around each slice and the process is repeated for 32 slices, each chosen to correspond to a particular anatomical landmark. The 3D body surface can then be re-created. Finally, the arms are edited out and the surface smoothed.[12]

Telmat-SYMCAD

In the SYMCAD booth, a person stands in the middle of the booth dressed only in underwear. A digital camera captures the front and profile images of the silhouette. By tracing the outlines of the silhouette, the software calculates their dimensions, even allowing for posture.

HKUST's computer vision

Fourteen cameras and two projectors are used without involving a sophisticated lens. The data are basically generated from 2D profiles and the 3D human model is generated by digital ellipses. It requires a large space, lengthy capturing time and a completely dark environment.

8.3.2 Structure light

Structure light-based scanning is widely used in the clothing field because it is much less expensive than the laser. Within this category, there are mainly two types of different technologies used: moiré topography and phase shift. Examples of products include CubiCam, TC^2 and Wicks and Wilson.

Moiré topography

As an optical phenomenon, moiré fringes were referred to in scientific literature more than 100 years ago, but the early authors referred to them as 'watery or wavy patterns'. Moiré topography is a contour mapping technique, which involves positioning a grating close to an object and observing its shadow on the object through the grating. For the measurement and display of an object's three-dimensional form, two techniques, namely shadow and projection moiré topography, are commonly applied.

Shadow moiré topography

In the shadow moiré technique, a linear grating is placed close to the surface to be evaluated. A shadow of the grating is cast onto the object when illuminated by a light source. The shadow pattern thus formed is distorted as a result of the three-dimensional shape of the object. Moiré fringes are generated when a camera records the superimposed shadow pattern through the grating. Initially in 1969, Pirodda[17] introduced this concept, and considerable interest[18, 19] in its application followed.

The basic advantage of moiré photography is to overcome the fundamental limitation of conventional photographs in that each image is not solely a two-dimensional projection of a three-dimensional object, but is actually a three-dimensional 'map' of the surface since measurements on these photographs can be correctly scaled. The depth data in the form of the fringes with the linear measurements of image, can allow measurements in space. This gives permanent records of body morphology, and also reliable cross-sectional measurements.

Takasaki[19] initially introduced an application of moiré fringes for the measurement of the human body in 1970 (Fig. 8.13). At that time, difficulties still existed in getting a good fringe contrast due to the following factors: large size and depth required; limitations of exposure time for a living body; and poor contrast due to the blurring of the shadow of the grating cast on a living body.

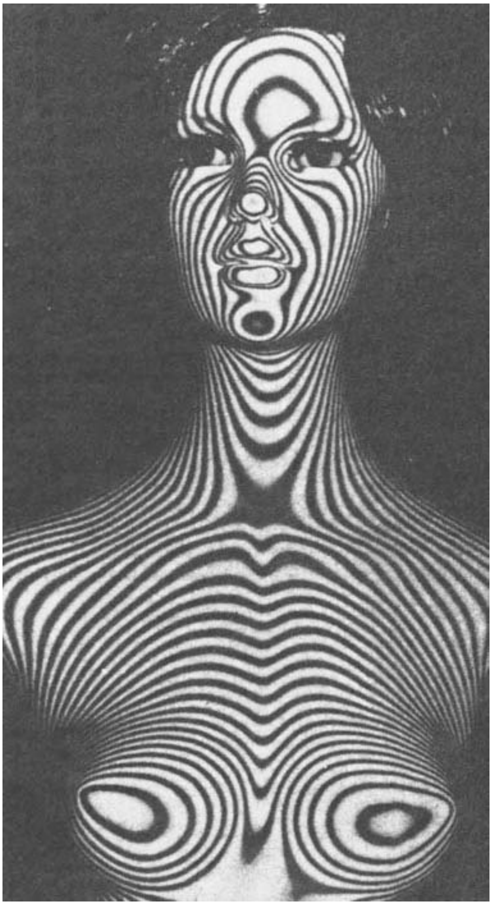

Figure 8.13 Figure of moiré image of human body. Source: Takasaki 1973.[19]

Detailed techniques for improvements were given three years later by Takasaki.[19]

Projection moiré topography
In the projection moiré technique, the specimen is obtained by projecting the image of a grid onto the object. The specimen grid is photographed together with a separate reference grid, and the moiré pattern is formed in the image plane of the recording camera as a result of the interference of the two grid images.

Hong Kong Polytechnic University – CubiCam
Initially, 3D body scanners faced common obstacles, such as high cost, complicated installation, large space and darkroom requirements. In 1999, The Hong Kong Polytechnic University invented a 3D body scanner, CubiCam[20] to provide a satisfactory technological solution. Based on a modification from

projection moiré topography, CubiCam uses normal flashlight for quick illumination. It can form high-contrast, high-resolution moiré topographic contours of the human body surface at a short distance under ambient light within a second. Inaccuracies caused by body movement or breathing have been eliminated. The whole system can be easily transported because a darkroom and heavy installation are not required. The system utilises the optical interference caused by two identical high-density gratings. Once the reference grating is projected onto the surface of the human body by an objective lens, its varying dimension will deform the grid line shadow. This deformed style of grating will then be captured simultaneously by another identical objective lens.

Consideration has to be given to the fact that a moiré photograph is a central-perspective representation of the photographed object. Different scale factors therefore apply to the fringes, depending on the distance from the camera they represent. Also, the depth interval of successive fringes is not constant but increases with the distance from the camera.

Nuoro Ailun – complex phase tracing (CPT) technique

Nuoro Ailun has built an instrument, using moiré technique, to capture two images of the object with projected sinusoidal fringe pattern for the human back topography measurement and shape analysis. They called this technology the complex phase tracing (CPT) technique. This construction has several advantages, such as short time image acquisition, insensitivity to the external illumination, fast image processing and portability of the instrument. It also does not require a phase unwrapping procedure. It can also access the natural image of the patient without a superimposed fringe pattern. During construction of the instrument, three particular solutions, namely regarding illumination, projection system and new fringe generator were patented. The proposed modification of the PLL and CPT technique was presented. Hence, a new method of image registration and processing was applied. The prototype of the system was tested in collaboration with the Rome Catholic University in the preparation of the medical software for the human back shape analysis.

RSI – DigiScan

RSI's DigiScan 2000 system is the first 3D scanner following the principles of modularity and standard components integration. Customers can purchase a scanning solution tailored to their needs. The user selects the projector having the resolution, image size and brightness they require, and at the price they can afford. The system can be configured to allow for body digitising. A 2.5 × 2.5 × 2.5 m cabin house, two projectors and 12 cameras are used (Fig. 8.14). Mirrors guide the projected light onto the person's body surface, which is observed by the cameras. Shape measurement and texture acquisition are completed within two seconds.

Figure 8.14 RSI DigiScan 2000. Source: RSI.

Phase shift

TC^2 (Textile and Clothing Technology Corporation) has built up a custom apparel design and manufacturing system using a moiré-based light projection system, known as PMP (phase measuring profilometry) (Fig. 8.15).[21] This method involves shifting the grating preset distances in the direction of the varying phase, and capturing images at each position. It uses a white light source to project a contour pattern (sinusoidal fringes) on the surface of the object. As irregularities in the shape of the target object distort the projected grating, the resulting fringe patterns describe the surface contour. By using the four captured images, the phase pixel can be determined.

The system is currently configured using three platforms with two cameras mounted vertically on each. Two platforms are positioned in front of a subject at about 30 degrees from the centre; and the third platform is located directly behind the subject. The six separate camera images are integrated to form the

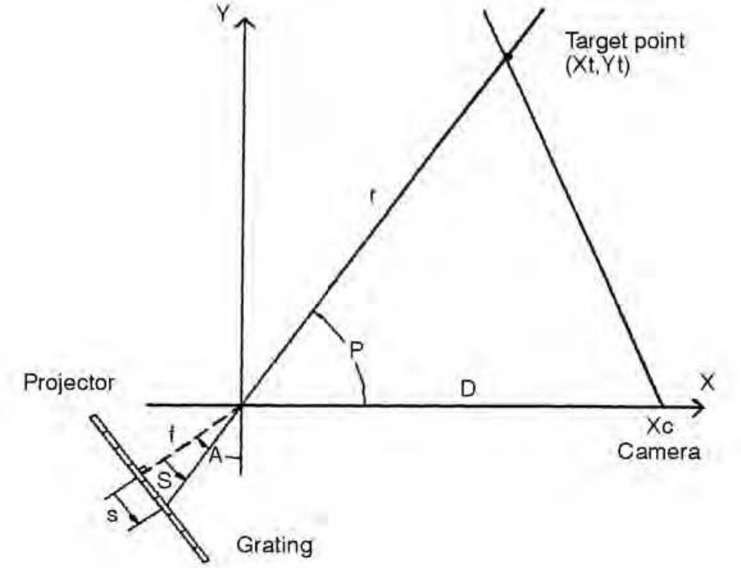

Figure 8.15 TC^2 PMP theory. Source: Textile/ Clothing Technology Corporation by Demers M. H., Hurley J. D. and Wulpern R. C., 'Three-dimensional Surface Capture for Body Measurement Using Projected Sinusoidal Patterns', *SPIE vol. 3023*, March 1997, p. 21.

complete image. The total body coverage is estimated at about 95%. The estimated scanned volume is approximately 2 m high × 1 m wide × 1 m long. Image resolution is 1–2 mm, with an accuracy of about 3 mm. Images obtained from the system are black and white.

In the UK, in 1998 Wicks and Wilson[13] developed TriForm, using a white halogen light. The whole body is captured in less than ten seconds and a full colour 3D point cloud is processed and displayed in less than one minute. The curtained booth provides privacy for the person being scanned who will ideally be wearing light form fitting clothing or underwear (Fig. 8.16). Various configurations of TriForm 3D scanners are available, including specialised units for capturing the human head, legs or whole body.

Each unit includes a projector and a camera. The projector shines horizontal patterns of striped light onto the surface to be scanned. The camera captures each of the patterns as they are projected. The TriForm body scanner has a total of four capture units, each using mirrors to capture the surface of the body from two directions, giving a total of eight views. As soon as the images have been captured, they are automatically passed to a PC controller where the distortions in the patterns are analysed and the coordinates of the 3D surface are calculated. Approximately 1.5 million points are calculated to describe the entire body.

Figure 8.16 TriForm 3D body scanner. Source: TriForm 3D body scanner manufactured by Wicks and Wilson.[13]

Telmat – OptiFit
According to Telmat, OptiFit is their latest development. It comprises body measurement extraction software, including body shape analysis and data transfer modules to link to the CAD/CAM systems. It is insensitive to body movement and not affected by the colour of the underclothes. Only 50 ft^2 of floor space is required. Associated with it is the Body Card, a card which contains the customer's body measurements in the required format. It is extremely suitable for the retail industry. Moreover, it could also operate as a mobile version, to undertake measurement surveys at geographically dispersed locations. OptiFit is also used for generating a consistent body measurement database of any target population and is a statistical tool for the definition of optimised size charts.

Telmat acquires pieces of information in 1/25th of a second. It takes 30 seconds for the cameras to move along the beams and acquire data of the whole body. This system is able to generate 70 precise body measurements. It takes less than 15 seconds for the system to extract this data. All the resulting measurement data can be integrated into apparel CAD systems, such as Gerber

Technology's AccuMark system or Lectra System's Modaris software.[22] Telmat also developed the framework of a partnership with the French Navy.[23]

8.3.3 Laser scanning

Basic principle

The scanner projects a line of laser light right around the body. The laser line is reflected into cameras located in each of the scan heads. Data is obtained using a triangulation method in which a strip of light is emitted from laser diodes onto the surface of the scanned object, and then viewed simultaneously from two locations, using an arrangement of mirrors. Viewed from an angle, the laser stripe appears deformed by the object's shape. CCD sensors record the deformations and create a digitised image of the subject. The cameras positioned within each of the scanning heads move vertically along the length of the scanning volume.[21] The laser scanner generates RGB colour values, and uses a process of identifying colour-coded landmarks for data extraction. Figure 8.17 shows a schematic presentation of 3D Scanner's ModelMaker.

Cyberware

Cyberware first introduced the whole-body laser scanners, WB2 and WB4, for clothing applications. The anthropometry group at Wright-Patterson Air Force Base acquired the first WB4 which cost $410,000 in April 1998. It scans the entire human body of a cylindrical volume 2 m high with a diameter of 1.2 m, in colour, in 12 seconds. WB2 and WB4 use two or four scanning units, mounted on vertical towers, respectively (Fig. 8.18). The WB4's use of four instruments improves accuracy on the sides of the body and in difficult-to-reach areas, such as under a person's arms, soles of the feet and the groin.[9] With a person standing on either scanner's platform, the instruments start at the person's head and move

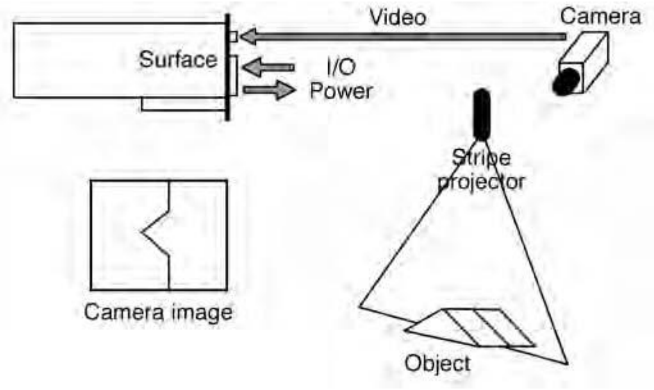

Figure 8.17 3D Scanner's ModelMaker. Source: 3-D Scanner's ModelMaker. *www.3-Dscanners.com*

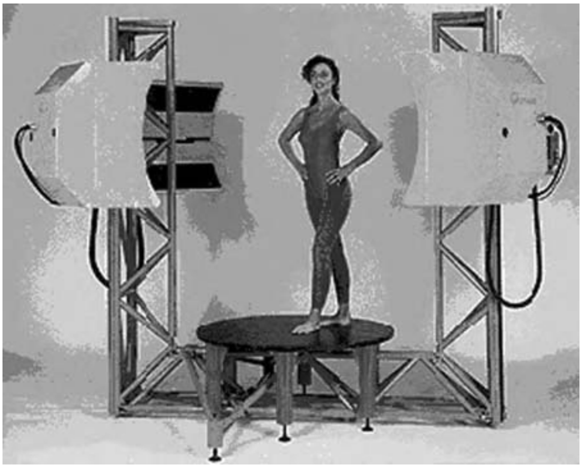

Figure 8.18 Cyberware WB4 Scanner. Source: Cyberware.

down to scan the entire body. Within seconds after completing a scan, graphic tools at the workstation let users view the results. The CyZip software then combines the models from the multiple scanning units into one smooth and complete 3D model of the human body.

The WB scanners are also of special interest to animators, anthropologists and designers, who can obtain alternatives to inaccurate models of the body, based on over-simplified or stylised forms. The WBX version is for clothing measurement, which can be generated with a substantial reduction in complexity, size and cost. The cycle time was reduced to 20 seconds and the price reduced to $150,000.[24] The WBX was tested at the Marine Corps Recruit Depot in San Diego.

A scan results in two data sets, each the size of about half a megabyte and containing geometric and texture information. Each format is based on a regular grid of 512 angles and 450 points in a vertical direction. Image resolution ranges between 2 to 4 mm in the X- and Y-axes and less than 1 mm along the Z-axis. The digitising speed for the maximum scanned volume is about 17 seconds, which yields about 400,000 3D co-ordinates on the surface of an adult human body.

TecMath

TecMath's system takes several pictures of the person in different postures, using a special video camera in front of a light source of four diode lasers with diffraction optics. Measurement time is only two seconds, ensuring minimal scanning error due to postural sway or body movements, with simultaneous scanning of the front and back of the person. Interpretation is done with a 3D human model, known as RAMSIS, an ergonomic tool. Accuracy is reported to be within 1 cm of the body height, and the scanned range of the body height is

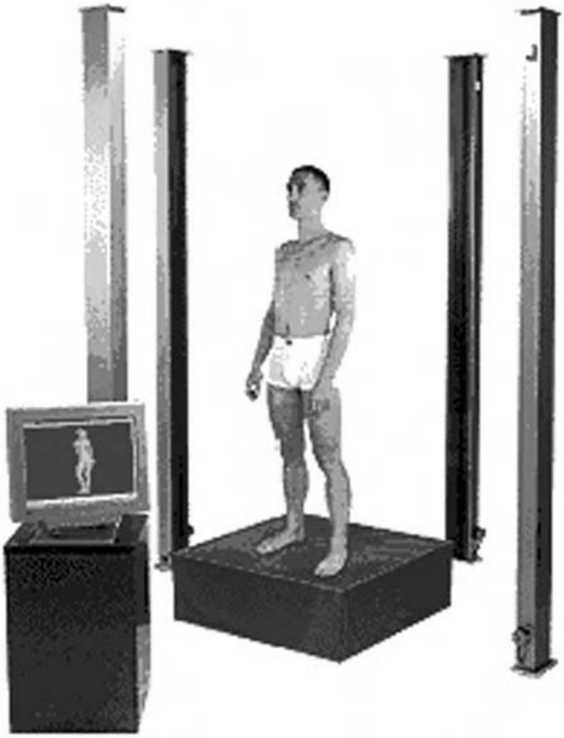

Figure 8.19 Vitus body scanner. Source: Human-Solutions.

from 1 m to approximately 2.2 m. The measured data enable input to CAD systems for automated made-to-measure pattern construction or adaptation. The system interfaces with third party pattern design systems, such as Gerber Technology and GRAFIS.[25]

Contour and Vitus are TecMath's products in human solutions. Contour has been used to develop the fit of army clothing and to select sizes from tables, which contain basic body dimensions for companies, such as KAKA, DoB and Bundeswehr.[15] Vitus is a 3D scanning system with an automatic calibration facility and an option for colour texture. It allows visualisation of up to 16 million triangles (Fig. 8.19).

Hamano-Voxelan

The Voxelan scanner is the only scanner which uses vertical laser stripes. The model HEV-1800HSW (Fig. 8.20) is used for the whole body measurement; HEC-300DS is for face scanning and HEV-50S is for wrinkle measurement. The resolution ranges from 0.8 mm for the body to 0.02 mm for wrinkles. The virtual body is generated from the measured shape data as cyberspace representations. A bird's-eye view of a wired form can be obtained, so the perimeter and area of cross-section as well as diameter across its sides can be measured.

Figure 8.20 Voxelan's HEV-1800HSW scanner. Source: Measured by VOXELAN.

Cubic

Traditional measurement devices weigh over 100 kg and involve a measurement time of over 10 seconds. In contrast to this, 'Cubic' has the highest measuring speed, less than 1 second, and weighs a lot less. The flexible structure of Cubic can cope with various business interests due to its hardware structure. It is active in various fields. The specifications of the device and the application software can be customised in accordance with the customer's needs.

Polhemus – FastScan

FastScan is the industry's most portable and lightweight handheld scanner (Fig. 8.21). The measurements are made by smoothly sweeping the wand over the object, an image of the object simultaneously appearing on the computer screen and the finished scan is processed so as to combine overlapping sweeps. The three-dimensional data can then be saved for loading into other programs.

FastScan is designed to scan non-metallic, opaque objects. It works by projecting a fan of laser light onto the object, while cameras on the wand view the laser from either side to record the 3D surfaces of the object. It incorporates Polhemus' patented Fastrak motion tracking technology in the wand itself. The magnetic tracker is used to determine the position and orientation of the wand, enabling the computer to reconstruct the full three-dimensional surface of the object. By attaching a second tracker receiver one could scan moveable objects as well.

8.3.4 Infrared technology

Basic principle

An infrared (IR) imaging sensor operates in the IR region of the electromagnetic spectrum. A lens coupled to a detector, which converts the IR energy to an

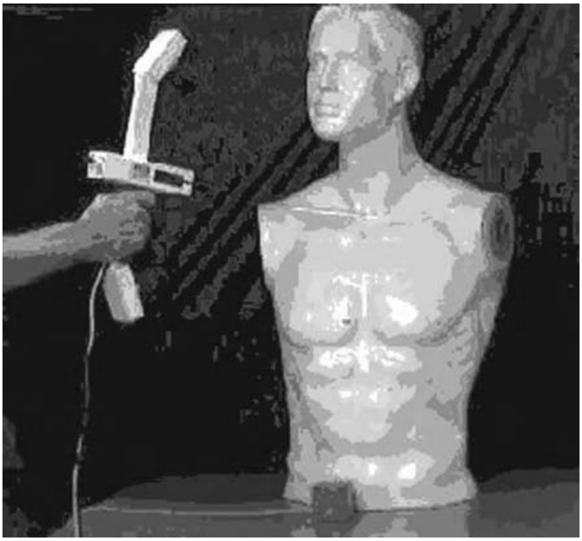

Figure 8.21 FastScan scanner. Source: Polhemus.

electrical signal, focusses on the scene.[26] Figure 8.22 shows a schematic representation of an IR sensor.

With an infrared LED and a semiconductor position-sensing detector (PSD), triangulation is used for the rapid, non-contact measurement of three-dimensional shapes of target objects. It measures the 3D shapes of the human body by positioning multiple distance sensors around the person being measured.

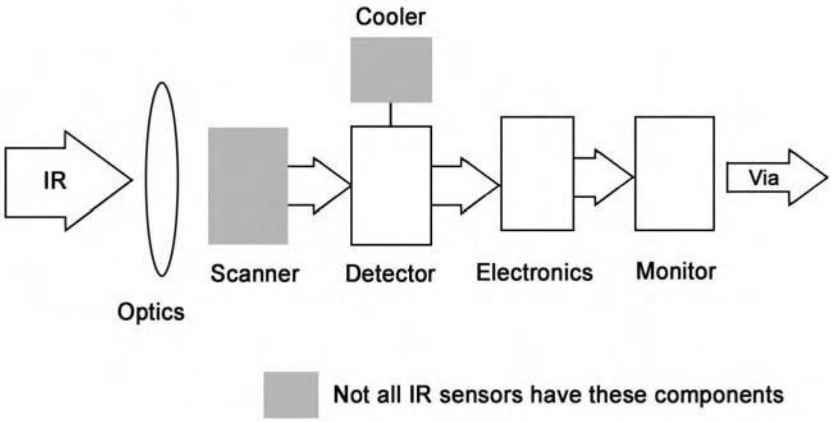

Figure 8.22 IR sensor. Source: Crawford, 1998.[26]

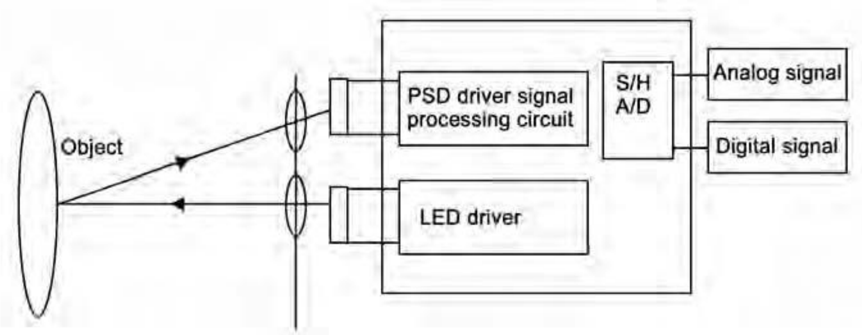

Figure 8.23 LED with PSD system. Source: Kaufmann, 1997.[27]

Hamamatsu
The Hamamatsu's Body Lines (BL) scanning system uses a near infrared LED (light emitting diode) to obtain data scans. The detector lens is a combination of spherical and cylindrical lenses which generate a slit beam on the position sensitive detectors (PSD) (Fig. 8.23). According to Kaufmann,[27] PSD's are used to compensate for the shadowing of one of the detectors. Hamamatsu worked with the University College of London in human modelling.

Hokuriku – Conusette
Conusette was developed to give women beautiful bodies. Therefore, only the bust, waist, and hip sizes are measured. Thereafter, the system provides a whole body balance check, judges the most suitable underwear for the body's present shape, and uses computer graphics to simulate future body changes. Ageing simulation shows what the future holds for the female body at any given age, based on the shape of the present figure. By superimposing the present figure onto the future figure, ladies can formulate fashion, dieting and healthcare plans.

8.3.5 Photogrammetry

A normal picture on paper or film is photographed with only one lens and cannot convey a true spatial perception. The use of two lenses, imitating the eyes, can create such a spatial image. When we examine a stereo picture, we form a perception of space in our mind (Fig. 8.24).[28]

If two charge coupled device (CCD) cameras are placed at some parallax angle, two slightly different images of the same object are obtained. The distance between the points on the object and the base plane can be calculated by geometrical analysis of the difference between the two images (Fig. 8.25). Where the distance on the image planes of the two cameras differ and the distance between the camera and the centre of object is known, the normal distance between a target point and the base plane can be determined.[29]

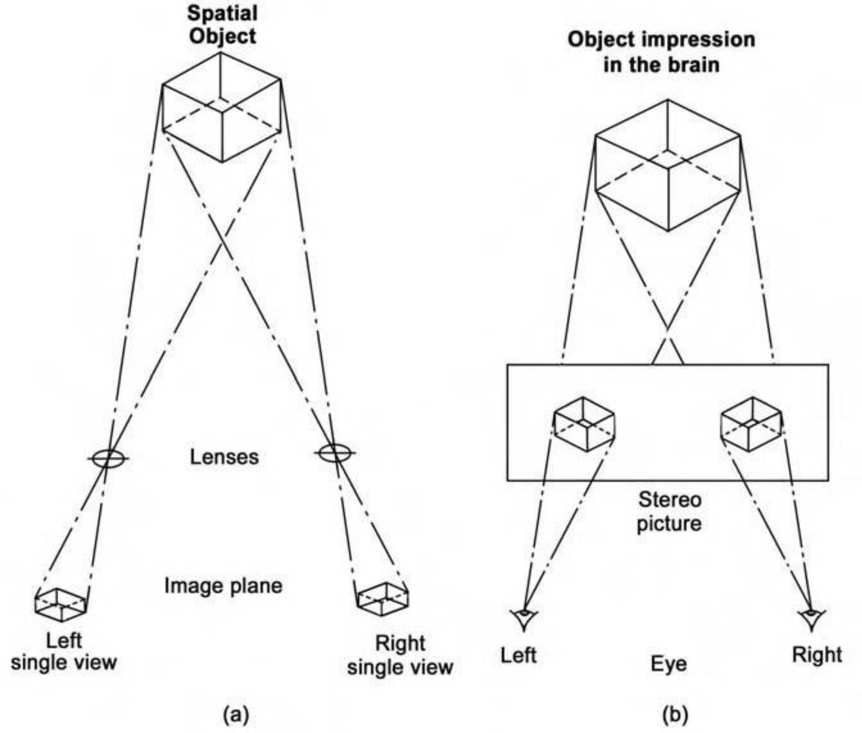

Figure 8.24 Stereo picture. Source: Stereoscopy.com/ Alexander Klein.

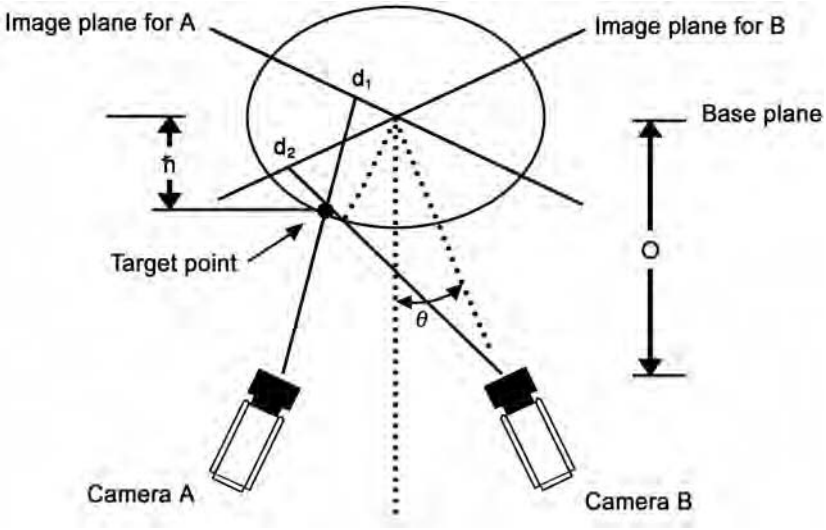

Figure 8.25 Schematic diagram of stereoscopy. Source: Tae and Sung 2000.[29]

The universal procedure to obtain a complete digital 3D model by means of optical digitising involves first acquiring a variety of partial views of the surface, as seen from a selection of angles, in order to cover all the surfaces of the object. For instance, when digitising a head, the usual procedure would be to acquire seven partial views, two of the front, at an angle, one on each side, for each of the ears, two of the back, again at an angle, and finally one of the top. These partial models are brought into a common system of co-ordinates and then combined to reproduce the overall shape of the object. They are then merged to produce a single polygonal model which includes all the surfaces captured during the digitising process.

Inspeck – Capturor II

A 3D Capturor II, being introduced by Inspeck, uses halogen light technology to digitise a view in less than a second. Involuntary movement during image acquisition is of little consequence compared to laser acquisitions. It can also scan hair and provide textures more realistically. The texture of each partial model is merged to form a single texture for the merged model which results in a complete 3D model.[30]

A complete 3D model, in 360°, can be obtained by taking multiple image acquisitions using a single digitiser. The multiple views can be combined in Inspeck's EM software. It also allows the simplification of polygons, editing texture (2D/3D) and exporting to various 3D graphics software packages, such as Softimage©, 3D Studio Max and Maya. If the 3D model needs to be animated, more functionality, such as NURBS generation, subsurface and morphing tools will increase and accelerate workflow. Another possibility is to configure more than one digitiser to work together as a system. Multiple digitisers can be combined for a single image acquisition of a human subject. This is what Inspeck calls the multi-head system. These systems come with a calibration target, which eliminates time-consuming view alignment steps.

Cubic

In Japan, Cubic uses halogen lights for illumination while the 3D image of the human body is captured by two CCD cameras placed at an angle. This system has two models (Fig. 8.26). One is a compact measurement device that uses only one lamp and therefore is light in weight and gives an accuracy of 1 mm. The other is an entire body measurement device, which uses four lamps and covers a body of 700 mm high, giving a precision of 3 mm.[31]

8.4 Benchmarking

3D body scanning technology has become more popular in the clothing industry. Many applications have been developed. This allows retailers to retain their old

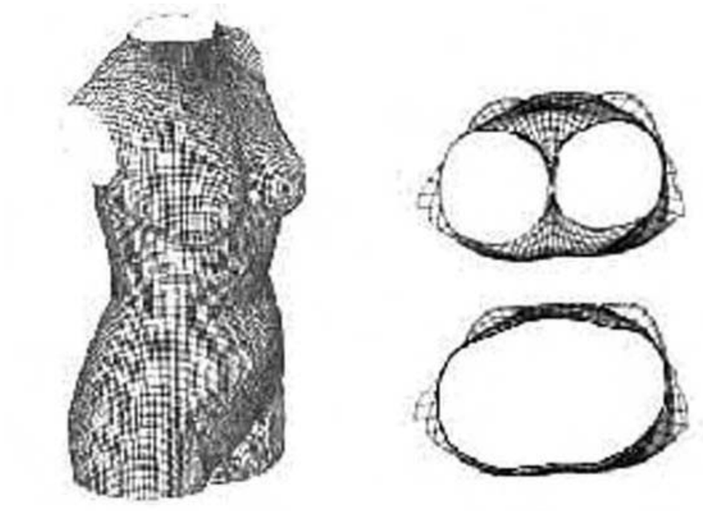

Figure 8.26 Cubic Compact Model and Entire Body Model. Source: http://www.cubic-inc.co.jp.[31]

customers with a value added professional service and to attract new customers who demand personal fit. Different 3D body scanners have distinct features and advantages. Table 8.1 lists the major 3D scanner manufacturers, and Table 8.2 provides a comparison between different body scanners.

The optical devices used by the 3D body scanners can be light projectors, CCDs and light sources (halogen, infrared or laser). For the human body, the

Table 8.1 Major 3D scanner manufacturers

Scanning system	Optical method	Website
Cubic	Laser technology	www.cubic-inc.co.jp
Cyberware – WB4	Laser technology	www.cyberware.com
DCTA – Automate	Phase shift	
Fujinon – FM40SC	Moiré topography	www.fujinon.co.jp
Hamamatsu – BodyLine	Infrared technology	www.hpk.co.jp
Hamano – Voxelan HEW1800	Laser technology	www.voxelan.co.jp
Hokuriku – Conusette	Infrared technology	
Inspeck – Capturor	Photogrammetry	www.inspeck.com
Loughborough – LASS	Photogrammetry	www.lboro.ac.uk
Polhemus – FastScan	Laser technology	www.polhemus.com
Poly U – CubiCam	Moiré topography	www.cubicam.com
RSI – DigiScan2000	Phase shift	www.rsi.gmbh.de
TC^2 – ImageTwin	Phase shift	www.tc2.com
TechMath – VitusSmart	Laser technology	www.human-solutions.com/
TELMAT – SYMCAD	Phase shift	www.symcad.com
Wicks and Wilson – TriForm	Phase shift	www.wwl.co.uk

Table 8.2 Comparison between different body scanners

Scanning system	Capture time	Process time	Total time	Dimension (W × H × D)	Booth size (W × H × D)	Weight (kg)	No. of sensors	Volume (W × H × D)	Data density	Accuracy	Room condition
Cubic	1 sec	N/A	N/A	3.5 × 1.5 × 1.7	3.5 × 1.5 × 1.7	30	2	0.185 × 0.7	N/A	3 mm	Dark
Cyberware WB4	17 sec	30 sec	47 sec	3.6 × 2.92 × 3	N/A	450	8	1.2 × 2	60000 per sec	5 mm × 2 mm	Dark
Hamamatsu BodyLine	10 sec	40 sec	50 sec	1.8 × 2.3 × 1.8	N/A	250	8	1 ×1.85 × 0.6	1894400	± 0.5%	Dark
Hamano-Voxelan HEW1800	10–60 sec	N/A	N/A	N/A	4 × 2.1 ×2	N/A	8	0.75 × 1.8 × 0.6	552960	± 2 mm	Dark
Hokuriku Conusette	16	10	26	N/A	1.6 × 2.3 × 1.59	350	6	0.4 × 1.7 × 0.48	65280	± 0.5%	Dark
Inspeck Capturor	0.3	N/A	N/A	0.15 × 0.45 × 0.31	3 × 2.3 × 1	N/A	2	0.85 × 2	N/A	4 mm	Dark
Polhemus FASTSCAN	N/A	N/A	N/A	N/A	N/A	N/A	2	0.075 × 0.68	N/A	1 mm	N/A
Poly U CubiCam	1/1500 × 3 sec	30	30	0.16 × 0.36 × 0.4	1.7 × 2.2 × 1	8.6	1	0.93 × 1.11	60000	4 mm	Normal
RSI DigiScan2000	< 1	N/A	N/A	N/A	2.5 × 2.5 × 2.5	N/A	12	N/A	N/A	0.2 mm	N/A
TC^2 ImageTwin	8 sec	45 sec	53 sec	N/A	3.3 × 5.9 × 2.4	N/A	6	1.1 ×1 ×2	400000	5–60 mm	Dark
TELMAT SYMCAD	7.2 sec	< 30 sec	< 37.2 sec	N/A	3 × 1.5 × 2.4	50	N/A	Whole Body	N/A	± 2 mm	Dark
Vitronics VitusPro	8–20 sec	30 sec	40 sec	2.5 × 3.1 ×1.85	N/A	N/A	16	2.1 ×1.2	2000000	1–2 mm	Dark
Wicks and Wilson TriForm	< 12 sec	240 sec	252 sec	0.2 × 0.64 × 0.44	2.3 × 1.5 × 2.4 m	1120 × 2	8	1.95 × 0.7	300000	± 2 mm	Dark

Source: Yu *et al.*, 2001.[8]

laser must be classified as Class 1 for eye safety. Most 3D body scanners project light rays horizontally. In the Cyberware, Vitronic and Hamamatsu systems, cameras or mirrors are mounted above and below the projection system. In the TecMath scanner, the cameras are mounted only above the laser projector. This means that the lower sides of some body parts may not be well represented. The CubiCam, TC^2 and Telmat Systems project structured light stripes onto the body, but the images are captured and analysed differently.

Speed is important in the reduction of human body movement artefacts.[32] Rapid data acquisition for the structured light system is certainly a major advantage over laser scanning. Structured light and laser triangulation systems measure similar degrees of coverage on the body surface. However, all systems attempt to reduce the scanner dimensions and booth size. This is of importance, especially for the retail sector where floor space is valuable. However, if multiple scan heads are placed at a significant distance from the body, a large space is required, unless mirrors are used, as in Wicks and Wilson. For a structured light system, image distortion easily occurs due to postural differences during different scans.[33] If mirrors are used, the complexity of the analysis increases.

Higher data density means more accuracy, but it also requires a longer scanning and processing time. The data size is an essential issue when data management, storage, usage and transmission are considered. Therefore, a compromise is needed in accordance with the users' requirements. With the new technologies, most scanners are designed to share and exchange information between computer applications and can also provide automatic measurement extraction from the scanned 3D data.

Most body scanners require a dark environment, which is not suitable for moving subjects, such as children. Therefore, a normal room environment is preferred. Only CubiCam has tackled this problem, using a flash-light system.

Since the introduction of body scanners, system costs have reduced a lot. The price may or may not include the computer interface, data storage devices, technical support and maintenance, or data extraction software.

8.5 Challenges of 3D body scanning

As 3D body scanning has developed since the late 1980s, some problems have affected its potential application. Researchers have carried out experiments and discussed these problems.[34] Various technical and application problems exist depending on the way in which information is extracted and manipulated from these images.

8.5.1 Missing areas

Most body scanners have difficulties in obtaining data from some hidden areas of the human body. For example, the armpits, the crotch and the areas under the bust and chin are often shaded.[33] This causes problems with missing data.[35]

Body parts, such as the shoulders and crotch, do not show up very well due to camera positioning. The TC^2-3T6 system uses six projectors and cameras; three for the upper part of the body and three for the lower part. The front of the body is captured by four cameras and the back by two cameras. As the viewing point of the scanning head is lower than the shoulders, the tops of the shoulders may not show up very well.

8.5.2 Body posture and movement

The human body is constantly changing, even when standing still. Movement due to swaying, breathing and posture changes during scanning can readily affect measurements, such as the chest circumference.[36, 37] For example, the Cyberware laser scanner measures the human body in 15 to 20 seconds as the cameras travel from head to toe. The effects of movement on the scanning quality and overall data accuracy is potentially quite significant and affects the integrity of the 3D image. With relatively rapid data capture time of less than one second, subject movement presents fewer problems.

8.5.3 Surface texture

Surface attributes of the skin and hair can markedly affect data quality. A laser scanner has trouble recording highly reflective body surfaces. Capturing hair has been a problem due to its fine texture, complex structure and many variants. For structure light systems, light absorption presents a problem. The translucence of the human skin allows penetration by the projected light into the body as the light reflects back to the surface; it can reduce the overall fringe contrast. With the present technologies, subjects are normally required to wear standardised close-fitting clothing during the scan. The ability to capture a good scan image of different skin colour and texture becomes a great challenge for on-going research of the structured light method.

8.5.4 Accuracy

Many military and commercial applications require the ability to measure and record precisely body size and shape. The ability of a given measurement system and accompanying data extraction software to obtain accurate and repeatable anthropometric data is important.

Standard industry clothing dimensions are recorded using a tape measure, which produces some compression of fat and muscle tissue. However, scanning systems yield surface measurements without compression, and therefore give results that vary from those using traditional methods. Anthropometric dimensions, such as body length, breadth and depth, are calculated straightforwardly from the interpretation of surface geometry. However, some measurements, such as chest depth, which include relatively more soft tissue, are more likely to differ from traditional results.

The Cyberware Natick scan system generally results in measurement values lower than those obtained with traditional anthropometry. The Hamamatsu BL scanning system, however, tends to produce either similar or larger circumference measurements than those observed for traditional anthropometry. It performs best on chest and hip circumferences. Hamamatsu is suitable for women's upper torso and tight undergarments. However, it still has difficulty with neck circumferences.

8.5.5 Body landmarking

Detecting the necessary landmark feature is an essential process in all types of body scanning, given the variations of human size, shape and posture. However, there is a lack of standardisation among the different systems. Simmons and Istook[10] have reported that different systems may identify landmarks and body measurements using different definitions, relative to traditional methods. Some scanners require manual methods to identify the subject's body landmarks and affix coloured labels to the bodies.[38, 39] If it takes a significant amount of time to prepare a subject for scanning and to do the landmarking manually, the benefits of using a scanning system decrease.

8.5.6 Software requirements

The development of data extraction software is important. The images cannot be exploited fully without automated software tools for visualisation, accurate anthropometrics and analysis.

8.6 Concluding remarks

It is clear that much work remains before 3D body scanning systems can be used successfully in automated clothing design and manufacture. Accurate human body size data and other related application software must be greatly enhanced. Although the potential of 3D body scanning seems tremendous, the cost and benefits will become more apparent with time. Technology improves the speed of image capture, reduces the errors arising from body movement, improves accuracy and resolution and provides full colour as well as shape information. Probably any given method might suit some applications and not others. However, if a given system can consistently generate surface data to a known level of precision, the system should find broad acceptance.

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