

## Whole body scanners

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### Abstract

Whole body scanning is a useful technique with applications in the apparel industry, human systems engineering and medical field. A worldwide review of whole body scanners describes eight commercially available systems. The scanners differ considerably in price (US\$50 000–410 000), resolution (1–8 mm) and speed (0.2–3 s). Most scanners use laser stripe projection; other techniques are patterned light projection and stereo photogrammetry. To cover a high percentage of the body surface area, the arrangement of the projection devices and cameras have to be chosen wisely. It depends on the application area, which configuration is best suited for the job. © 1998 Elsevier Science Limited. All rights reserved.

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### 1. Introduction

The aim of this article is to provide an overview of currently available whole body scanners. A whole body scanner is an optical 3D measuring system that produces a digital copy of the surface geometry of the human body (Fig. 1). The limited amount of available literature is mainly devoted to technical aspects of a single whole body scanner. Consequently, a general overview of this emerging area is missing.

It is not until last decade that automated whole body scanners emerged on the market. Manufacturers of these systems combined knowledge on optics, image processing and mechanics. These different work fields make it difficult to localize the manufacturers, even with modern media like the internet. Prior to the purchase of a whole body scanner for our institute, we performed a worldwide market survey and identified eight commercially available systems. The description of these systems can be of value for anyone who wants to use a whole body scanner for their specific application.

Applications of whole body scanners are now rapidly evolving. Typical application areas of whole body scanners include: anthropometric research, the clothing industry (individually tailored clothing), the entertainment industry (e.g. special effects in movies), computer animation (see Displays 15(3), 1994) and medicine (a wide range of appli-

cations such as prosthetics and plastic surgery). A recent review of applications is provided by Jones and Rioux [1].

In traditional anthropometry, devices such as calipers and tapes are used to determine the dimensions of the human body. The measuring process is time-consuming, expensive and error prone. 3D-Scanning offers a technique to capture the body dimensions in a fast and reproducible way. One of the most important benefits is that the data of the subject can be stored on disks and retrieved when necessary. New software that recognises features of the human body can always be applied to existing data sets. Also, the number of anthropometric variables that can be derived from a scanned human body is almost without limits. Disadvantages of 3D-scanning compared to traditional anthropometry include the investment in a scanner, missing data because of shading (e.g., the arm-pits and crotch areas are often shaded), and occurrence of errors owing to movement artifacts. Some parts of the body are of special interest to anthropometrists, such as the bony protrusions. These points are hard to identify on a whole body scan. Therefore, researchers at Wright Patterson Air Force Base placed markers on the skin corresponding to these locations. Subsequently, the markers were identified and labelled by dedicated software. Whole body scanning is used in a large scale anthropometric survey in Japan [2]. Currently, a multinational survey, called CAESAR (Civilian American and European Surface Anthropometry Resource), is undertaken in the US, The Netherlands and Italy [3].

For clothing applications, the subject is scanned and body dimensions related to clothing are derived from the scan.

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Fig. 1. A whole body scan of a subject by a Cyberware WB4 scanner.

These dimensions are then transferred to software packages that are dedicated to design of clothing. Single layer cutting machines then transfer the patterns into products that are sewn together. This made-to-measure chain enables the creating of individualized products, which is compatible with the current trend in our Western society to move away from mass production.

In ergonomics, whole body scans provide an effective method to improve the computer man models that are used for ergonomic design and evaluation. Currently, over a 100 different man models are used for this purpose. These man models are constructed based on knowledge on anthro-

pometry, joint rotation centers, mass of body segments etc. The models are interfaced with a CAD (Computer Assisted Design)-model of an existing or designed environment. Considering the widespread use of those models, it is surprising to see how poorly these models are validated. Whole body scans provide an opportunity to determine if the underlying anthropometry of the man model is sound. The model can be built according to the required anthropometric input and can be compared to the body scan.

Whole body scans are used for a wide variety of medical applications. Scans of limbs after amputation provide the input for prosthesis design. In plastic surgery, the scan of a face can be modified interactively on a computer according to the requirements of a client. This model serves as a 'template' for the surgeon during operation and to judge the success of the operation postoperatively. Other medical applications include tracking the development of the foetus based on scans of pregnant women, development of special masks for burned faces etc. [1].

Some typical problems are associated with the use of whole body scanners: shading effects in the arm pits and crotch, light absorption by the hair and skin, movement artifacts and data processing and handling [4]. The technical challenges are related to the kind of scanning technology that is used, which is discussed in detail later in this article. In general, the whole body scanner is a rather bulky device. The main reason is that the depth of focus is small when the camera is close to the object.

In this article the basic principles of 3D scanning are given, followed by a description of a selection of whole body scanners including their technical features, summarized in a table. It should be noted that most companies offer several versions of the systems described, tuned to the specific application of the customer. This article, however, only considers the standard systems. Many other companies do not have a scanner off the shelf, but are working on it. This discussion compares the different systems and highlights some areas for further research.

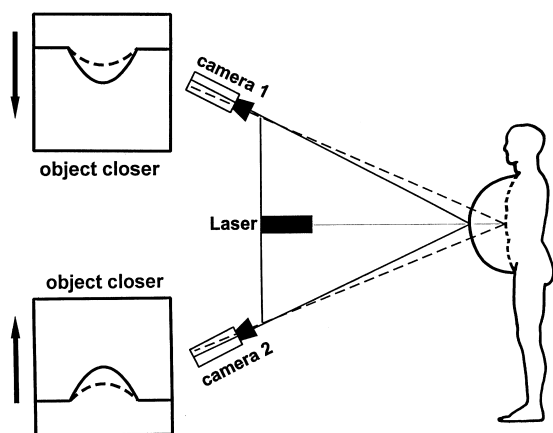


Fig. 2. Optical triangulation technique to determine the location of the human skin. The projected line as registered by the camera is shown next to the camera.

## 2. Scanner operation

The 3D scanners capture the outside surface of the human body by means of an optical technique. A whole body scanner consists of:

- one or more light sources that project a line or other pattern on the human body;
- cameras that capture the image of the projected light on the body;
- software to extract the depth structure of the body surface from the images;
- a computer and screen to visualize the 3D surface.

Most scanners project a horizontal laser line on the body. The lasers and cameras are mounted on a vertically moving

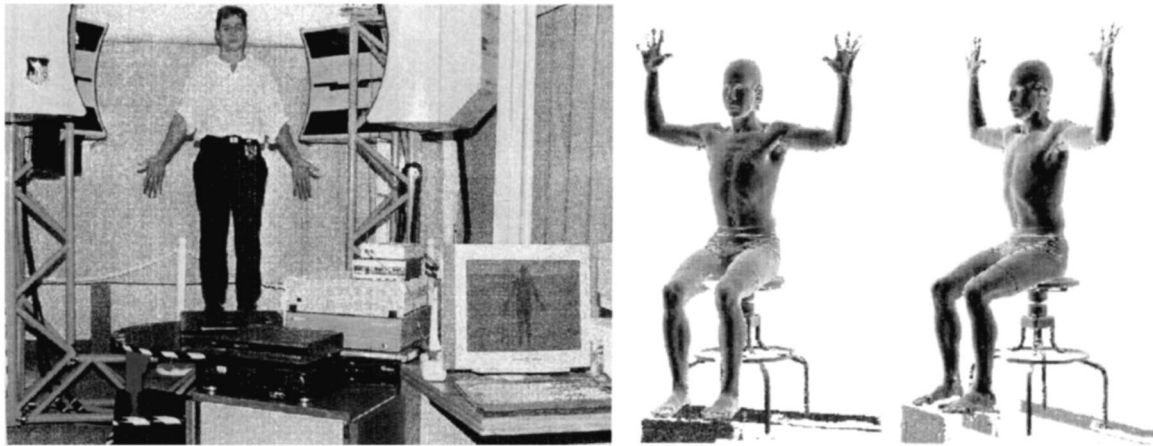


Fig. 3. The Cyberware WB4 with a scan example.

frame, called a scanning head. In Fig. 2 the principle of this technique is shown for a thin and for a fat man.

In this figure, the laser line is projected on the stomach of the thin and of a fat man. The image of the camera is shown next to the camera. Two cameras are used in order to avoid shading (in this case the upper and lower part of the stomach

should be 'seen'). The horizontal projection line is visible in the camera as a curved line representing the shape of the stomach. The curved line for the fat man is located more towards the bottom of the image for the top camera. The closer a projected point is to the camera, the lower its vertical position in this image. For the bottom camera the reverse

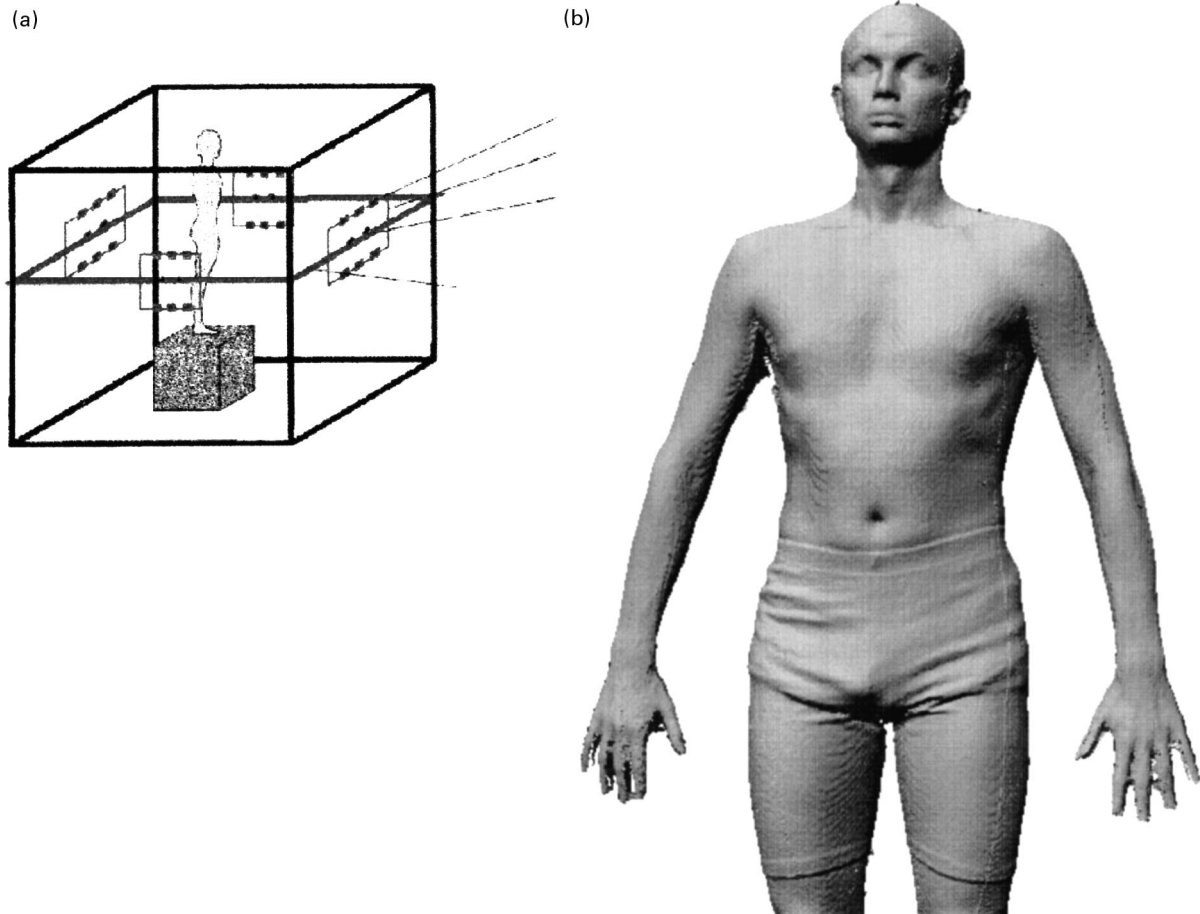


Fig. 4. The Vitronic Viro 3D-2400 with a scan example.

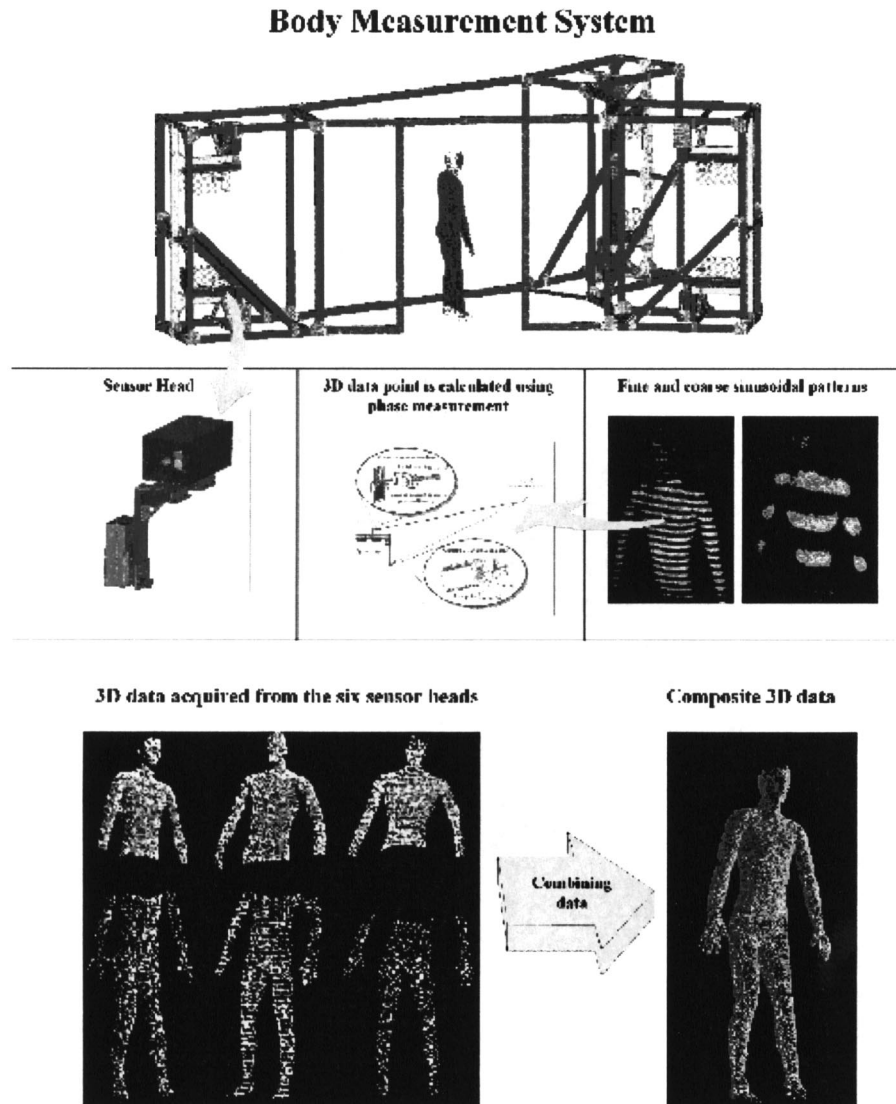


Fig. 5. The TC<sup>2</sup> scanning system with a scan example.

is true. In this way the depth information ( $x$ -coordinate) is retrieved. The height of the scanning head is continuously measured while moving and yields the  $z$ -coordinate of the subjects' skin.

In order to retrieve a complete image of the human body, several scanning heads have to be used. The minimum number of scanning heads is two (front and back of the body) and the maximum found in our survey is four. The use of multiple cameras reduces the shading effects, because of the captured surface area of the body increases.

### 3. Scanning systems

#### 3.1. Cyberware WB4

The Cyberware WB4 whole body scanner is one of the first scanning systems in the world which generates a high

resolution data set of the outer surface of the human body. Cyberware has a relatively long history of manufacturing laser scanners. Their head scanner became the state of the art. Cyberware has sold at least four whole body scanning systems worldwide: three in the USA (the CARD-lab at Wright Patterson Air Force Base, the National Institute of Occupational Safety and Health (NIOSH) and the Army Research Labs in Natick) and one in Japan. A fifth scanner is present at the companies headquarters in California and is mainly used in the movie industry.

The system has four scanning heads mounted on a rigid frame. Two motors generate the vertical movement. A picture of the scanner with a scan example is shown in Fig. 3.

The scanner has a horizontal resolution of 5 mm and the vertical lines are 2 mm apart and are interlaced. The horizontal resolution is mainly determined by the resolution of the CCD chip in the camera. The vertical resolution is deter-

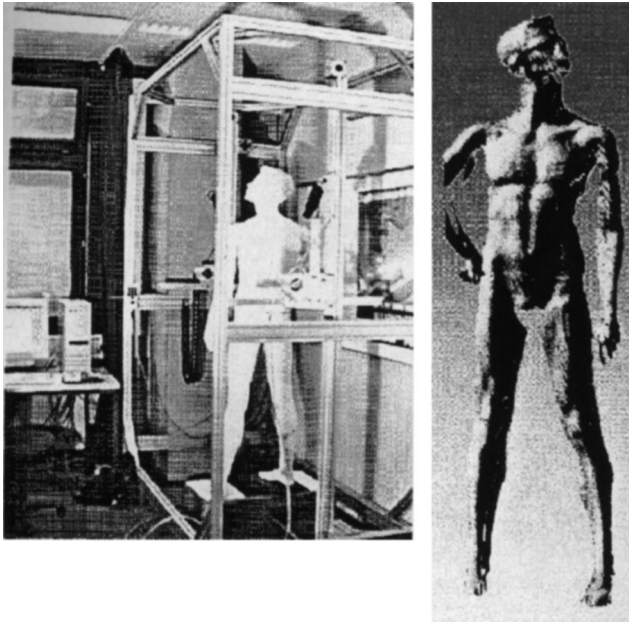


Fig. 6. The TecMath scanner with a scan example.

mined by the camera speed (50 Hz) and the speed of the vertically moving scanning heads (20 to scan a space of 2 m in height).

A study concerning the principle of operation and accuracy of the Cyberware WB4 is published by Daanen et al. [5].

The main calibration is performed by Cyberware, but the user can adjust the software settings. The sensitivity for ambient light is also under software control.

### 3.2. Vitronic viro 3D-1600 and 2400

Vitronic is a company specialising in image processing. Based on this expertise they have built a whole body scanner. Two versions are currently available in the market: the Viro 3D-1600 with 16 CCD cameras and the VIRO 3D-2400 with 24 cameras. The latter version is shown in Fig. 4 with a scan example.

In the 2400 model Vitronic uses four separately controlled motors to move the rigid scanning head frame up- and downwards. In the 1600 model only one motor is used. There are four scanning heads. The Vitronic has the best resolution of the mentioned systems: the resolution is 1–2 mm in every direction. This relatively high resolution is mainly caused by the large number of cameras that is used. The arrangement of 12 cameras in a horizontal plane above the scanning line and 12 cameras below the scanning line enables capture of a large surface area of the body and minimizes shading effects. In the 2400 model, the laser stripe is composed of eight different laser sources. The data is exported in voxels (3D-coordinates), not in meshes (wireframes). The output can be converted to a format that can be used to control milling machines. The Vitronic 3D-

2400 is used as an aid to make sculptures of humans in different body positions.

### 3.3. TC<sup>2</sup>

TC<sup>2</sup> is a company which is specialized in education, research and development for the apparel industry. Recently, they developed a whole body scanner based on a structured light pattern projection technique. The system is described by Demers et al. [6]. Later, the system will be commercialised for a price of about US\$100 000.

The system has two frontal views and one straight on the back. In order to get adequate height coverage, there are six views in total: three upper views and three lower views. Each sensor consists of a projector and a camera forming a vertical triangulation with the object. The projector contains a two-dimensional patterned grating which is projected on the body. The pattern varies in intensity sinusoidally in one direction, and is invariant in the perpendicular direction. The phase of the sinusoidal pattern is shifted in four steps with  $\pi/2$  rad resulting in four images of the scene. Using these images, the phase at each pixel can be determined. Both coarse and fine grating patterns are employed. The coarse grating is meant to resolve ambiguous surface discontinuities measured with the fine grating. Fig. 5 shows the set-up of the system and a scan example.

### 3.4. TecMath

One of TecMath's core products is the digital man model 'Ramsis'. It is an articulated man model which can be interfaced with CAD models (in particular for the automotive industry) for assessing, for instance, the work space and visibility. In order to optimize the anthropometric background of the model, TecMath developed a whole body scanner. The system has two scanning heads: one for the front and one for the back of the body. A laser stripe is projected on the body to retrieve the shape. The sides of the body are not represented in the scan by this method, but the input is sufficient to optimize the Ramsis model. The scanner and an example of a scan are shown in Fig. 6. Owing to a custom high speed line image camera, the scanner is fast for a laser based system. The scan time is less than 2 s.

### 3.5. Telmat

Telmat produces computer systems and consumer specific solution in the computer industry. Several years ago they developed a shadow scanner called SYMCAD intended for the clothing industry. SYMCAD captures the frontal and lateral view of the human shape and assesses the clothing parameters, such as inside leg length from these shadows. SYMCAD is operational in several locations in France and in the UK. The French Navy found that the number of returned clothing items was drastically reduced after they started using SYMCAD. The system is recently extended

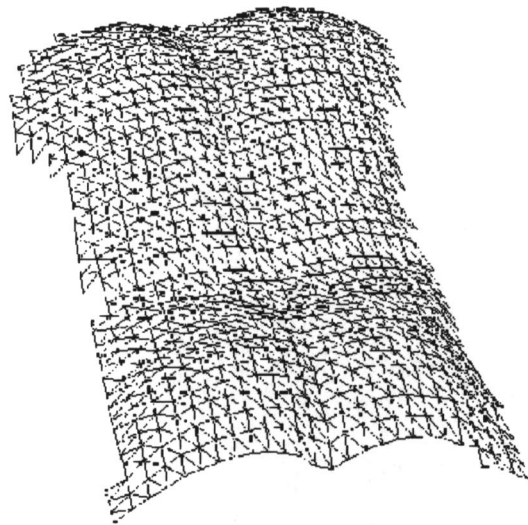
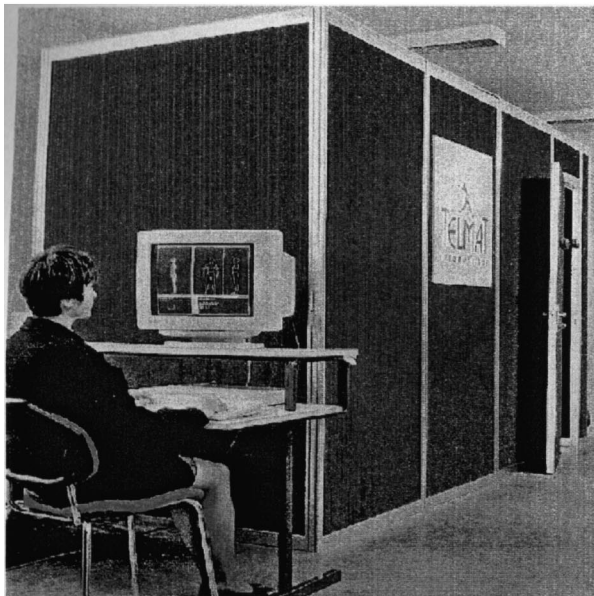


Fig. 7. The Telmat scanner box with a scan example.

with a 3D-feature. Patterned light is projected on the body and the same camera that is used for detecting the shadows now also determines the 3D shape. The subject is scanned from the front, and the back side, and the images are 'glued' on the shadow. The scanner is mounted in a special box and the data processing is done outside the box, which guarantees privacy for the subjects. Fig. 7 gives an impression of the scanner box and a scan of the back.

### 3.6. Turing

The Turing C3D 3D-scanning system is in the final stage of development. The system consists of stereovision pods which have been proven successfully in other applications. Each pod consists of two cameras and a projector. The projector projects a random pattern of dots when the natural texture of the skin is insufficient for stereo matching. The skin or these dots provide sufficient information within the

stereo pair images to find points of correspondence (with a variant of the Multi-Scale Signal Matching (MSSM) algorithm) between the stereo pairs. By using the known relative orientation between the two cameras the 3D coordinates of the dots can be calculated. The system can also capture the texture of the surface. The scanning time is less than 0.2 s for one pod, scanning both texture and shape. Fig. 8 shows an overview of the C3D architecture and a scan of the face [7].

### 3.7. Hamano voxelan

This scanner was originally developed by NKK (Japan) but later taken over by Hamano Engineering (Japan). An extensive anthropometric survey was performed in Japan using this scanner [2]. The scanner works with two rotary mirrors that project vertical laser stripes on the body. Over 180° of the body is covered, so the sides of the body can be

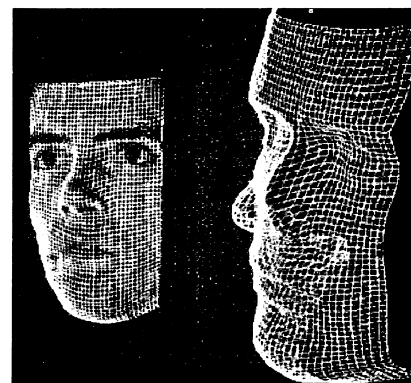
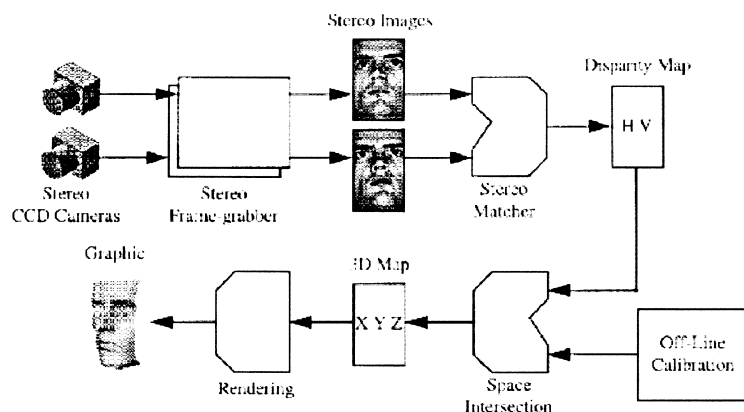


Fig. 8. The Turing scanner with a scan example.

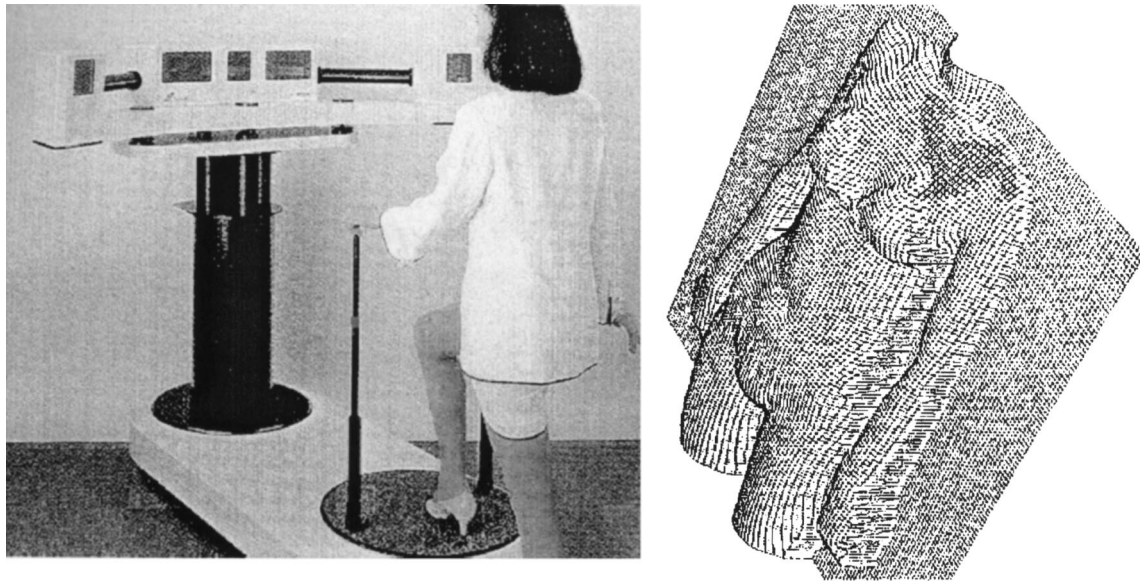


Fig. 9. The NKK scanner with a scan example.

measured. After one side is scanned, the body has to rotate 180°, whereafter the back side is scanned. The match of the front and back side may be imperfect because the body posture may have been changed from the first to the second scan. The total scan time, without repositioning, is relatively long: 30 s. The result consists of two pictures which are merged to create one single object. Fig. 9 shows the scanning setup and a front side scan.

### 3.8. Hamamatsu

The whole body scanner of Hamamatsu is a stripe scanner, but instead of using a laser the system projects an infrared line on the body [8]. Where all system CCD cameras, Hamamatsu uses special photodiodes which are sensitive to

infrared light. Fig. 10 shows the measurement rig and a sample of a scan.

### 3.9. Overview

An overview of the scanner specifications is shown in Table 1. The price is only roughly indicated. The mentioned points of contact (POC) can give an updated cost estimate. The measurement angles indicate the angle between neighbouring scanning heads. For the Cyberware WB4, for instance, the scanning heads are arranged in a rectangular formation instead of the squared orientation. The scanning volume and scanner dimension are shown in metres and indicates height  $\times$  diameter or height  $\times$  width  $\times$  depth. The resolution is shown in depth, horizontal and vertical.

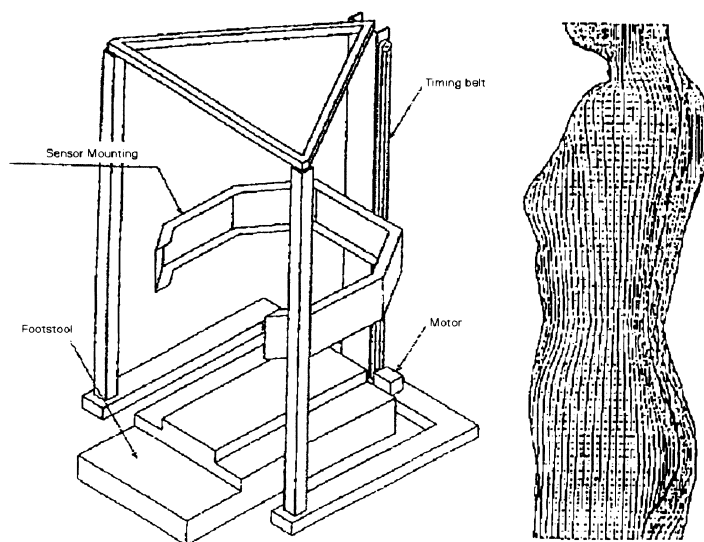


Fig. 10. The Hamamatsu scanner with a scan example.

Table 1  
Overview of the scanner specifications.

Scanner	Cyberware WB4	Hamamatsu	Hamano Eng. Voxelan	TC <sup>2</sup>	TecMath	Telmat	Turing C3D	Vitronic Viro 3-D 1600 (2400)
POC	Sue Addleman	Kenneth Kaufmann	Mr. Hamano	Judd Early	Rainer Trieb	Jean-Loup Remesson	Tim Nibblet	Klaus Buecher
City	Monterey, CA	Bridgewater	Sakado, Takatsu	Cary, NC	Kaiserslautern	Strasbourg	Glasgow	Wiesbaden
Address	2110 Del Monte Ave.	360 Foothill Road	KSP-D339, 3-2-1	211 Gregson drive	Postfach 3049	4 Rue Thomas Mann	University Ave., Boyd Orr Bldg.	Hasengartenstr. 14a
ZIP	CA 93940	08807-0910	Kawasaki 213	27511/7909	67653	67200	G118NN	65189
Country	USA	USA	Japan	USA	Germany	France	UK	Germany
Tel.	14086571450	9082310960	81448192168	9193802156	496312053420	+ 33388277129	141376410	61171520
Fax	14086571494	9082319374	81448192171	9193802183	496312052803	+ 33388277132	1413390796	611715233
Email	Sue@cyberware.com	kenprc@pipeline.com	www.ksp.or.jp/he	..@tc2.com	Trieb@tecmath.de	jlr@telmat.fr	tim@turing.gla.ac.uk	bm@vitronic.de
Website	Www.cyberware.com		US\$200k	www.tc2.com	www.tecmath.de	www.telmat-net.fr/symcad	turing.gla.ac.uk	www.vitronic.de
Price indication	US\$410k	US\$100k	US\$200k	US\$200k	US\$100k	US\$50k	US\$200k	US\$180k (US\$250k)
Technique	Laser	LED	Slit-light laser	Light pattern proj.	Laser	B&W fringe	Light pattern proj.	Laser
# projectors	8	8	4	6	2	1	Variable	4 (8)
# CCD	4	8	2	6	2	1	Variable	16 (24)
Measurement angles	75,180,255,360	2,8,172,178,182,188,352,358	Irrelevant	60,150,150	0,180	0,90,180	0,75,180,255	30,150,210,330, (0,90,180,270)
Scanning volume	2 × 1.2 cm cylindrical	200 × 90 × 50	11 × 0.74	1.1 × 1.1 × 2	2.2 × 0.8 × 0.8	210 × 110	2.1 × 1.2 × 0.8 (2.0 × 1.0)	2.1 × 1.2 × 0.8 (2.0 × 1.0)
Scanner dimension (meters)	3.8(w) × 3. (D) × 2.9(H)	275 × 159 × 167			2.8 × 1.9 × 1.1	240 × 150 × 400	3.05 × 2.5 × 1.8 (3.8 × 3.8 × 4.8)	3.05 × 2.5 × 1.8 (3.8 × 3.8 × 4.8)
Scanning duration (s)	17	7	30	2–8	1.5	3 × 1/30	< .2	21 (20)
Color	Yes	No	No	No	Option	No	Option	option
Merging	Yes	Yes	Offline by body markers	Yes	No	In progress	Yes	Yes
Range resolution (mm)	0.5	1	?	1	3	0.8	3–5	2 (1)
Horizontal resolution (mm)	5	7.5	3.4	2	8	1.4	1-Jan	2 (1)
Vertical resolution (mm)	2	5	3.4	2	5	1.4	1.5	2
Eye safe	Yes, Class I	Yes	Yes	Yes	Yes	Yes	Yes	yes
Scan direction	Vertical	Top–bottom	Irrelevant	Irrelevant	Vertical	Instant 3D capture	Instant 3D capture	Vertical
Supplied Software	CyScan, CyPie	Visual basic/C + + application	Unknown	Dedicated (included)	Quick visualisation	Clothing specific	Quick visualisation	Vitronic C + +
Size of a scanned subject (Mb)	8	0.3		6		0.25	Variable	6
Hardware needed	SG Indigo 2	PC	PC	PC (included)	PC	Unix system, PC in progress	PC	PC
Application areas	Anthropometry, apparel design & computer graphics	Clothing fit	Anthropometry	Clothing fit	Human modelling	Custom-made and made- to-measure apparel	Anthropometry, movie industry	Arts, anthropometry



This indicates the distance between neighbouring points in mm. The supplied software varies from scanner to scanner. In all scanners the acquisition software is included and software that visualizes the scanning results. Some scanners offer processing software from very general (e.g. Vitronic) to dedicated (e.g. Telmat).

## 4. Discussion

### 4.1. Projection technique

Although the basic triangulation technique is similar for the whole body scanners, they differ in the way the light is projected on the body and in the way the image is captured. Most scanners project a horizontal line on the human body (Cyberware, Vitronic, TecMath, Hamamatsu) and use vertically moving scanning heads. A scanning head contains the projection and imaging system for one viewpoint. NKK projects two vertical laser lines which move over the body in the horizontal plane. The camera is mounted steady. Hamamatsu generates the line by light emitting diodes (LEDs). Cyberware, Vitronic, TecMath and NKK use lasers. The remaining systems (TC<sup>2</sup>, Telmat and Turing) have no moving components. Two scanning systems project structured light stripes on the body (TC<sup>2</sup>, Telmat). The Turing system projects a random dot pattern on the body.

The advantage of a laser stripe system over structured light projection and stereo-photogrammetry is that only one line needs to be analysed. Decoding is more complex for structured light. TC<sup>2</sup> uses special phase shifting algorithms to capture the spatial coordinates. Turing uses special algorithms to find points of correspondence in the two stereo images. However, the latter systems have no moving components which increases the life cycle of the scanning system and also increases the safety for the scanned subjects. In order to cover the entire body with structured light, the projector (and cameras) have to be on a large distance of the body or multiple scan heads have to be used. The first option increases the size of the total scanning system, unless mirrors are used. Therefore, some companies (e.g. TC<sup>2</sup>) use separate scanning heads for the upper and lower part of the body.

In the Cyberware WB4, the cameras are not mounted above and below the light source, but rather integrated in a single unit. Mirrors above and below the laser project their images on a single CCD chip. The advantage is that less cameras are needed than without mirrors, but however, the complexity of the analysis increases.

### 4.2. Scanning time

In contrast to industrial scanners, whole body scanners need to scan the body fast in order to reduce human body movement artifacts. The scanning time of whole body scanners ranges from less than a second for the stereo-photogrammetry method to about 20 s for some laser stripe

systems. During the scan, the subjects may sway their whole body or may move body parts, like rotation of the head. Daanen et al. [9] showed that the magnitude of the sway in human subjects and the head rotation could be considerably reduced (more than 50%) by placing a positioning device on the head. Reducing the scanning duration from 20 to 5 s reduces the error due to front/backward sway by only about 30%. Increasing the scanning speed goes to the expense of vertical resolution and increases the electro-mechanical demands. Therefore, one should not blindly strive for the highest speed, but determine the optimum in the trade off. Only when the scan time is subsecond, the movement artifacts almost disappear.

### 4.3. Projector/camera position

In a horizontal stripe scanner the scanning heads are moving parallel to the longitudinal axis of the body. The NKK scanner is the only one which uses vertical laser stripes. In the Cyberware, Vitronic and Hamamatsu systems, cameras or mirrors are mounted above and below the projection system. This enables the capture of for instance the top of the head and the chin area. In the TecMath scanner the cameras are mounted only above the laser projector. This means that the lower side of some body parts is not very well represented. The NKK has the cameras mounted at a fixed position between the rotating laser projectors. Again, body parts like the shoulders and crotch do not show up very well.

The TC<sup>2</sup> 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 seen by four cameras and the back by two cameras. As the viewpoint of the scanning head is lower than the shoulder, the top of the shoulder does not show up very well.

In stereo-photogrammetry the images have to be seen by both cameras in order to be able to retrieve the 3D-information. Therefore, the cameras are often placed close together. Consequently, several camera pairs are needed to cover the entire body. Fortunately, cameras for stereophotogrammetry are relatively cheap and the use of multiple pods enables flexible operation. For instance, the pods can be placed closer to the face if more detail is necessary. Both Telmat and NKK scan the subject twice: first the front of the body is scanned and then the back is scanned. NKK merges the data by using markers on the shoulders. Telmat merges the data by 'glueing' the front and back scans on the shadow scan of the body. The disadvantage of this procedure is that people may attain a different posture during the front and back scans, so that the final image may be distorted.

### 4.4. Body position

All scanners are constructed to scan standing subjects. When the scanning space is large enough, the sitting position can also be captured. A diameter of 1.2 m is necessary to do so. As the scanners work with projectors, shadowing

can occur. This can have two reasons. First, the laser light may be intercepted by body parts that stick out, leaving a shadow on other parts. As the light source is missing there, shadows appear as holes in the scan. Second, the laser line may be projected on the body, but the cameras cannot see the laser line. This may happen for instance in concavities like the umbilicus. The body should be positioned in such a way that shadowing is minimal. Brunsman et al. [10] showed that for the standing position the subjects should not face the scanning heads as most shadowing occurs in that position. Brunsman et al. [10] also showed that a rectangular setup with angles of 75° and 105° between neighbouring scanning heads showed better results than a squared configuration.

#### 4.5. Texture

Only the Cyberware and Turing systems have as a standard the ability to capture the texture of the body. Cyberware has a color camera built in the scanning head and the color image is merged with the depth information. This gives a realistic appearance. The Turing system applies black and white cameras for geometry and optional color cameras to determine the texture. The texture is useful, for instance, in increasing the immersion feeling of virtual environments, medical applications and marker detection. Marker detection is a method used in 3D-surface anthropometry to determine the exact location of certain spots on the body which are marked by dots of defined colour and size.

#### 4.6. Software

The software of all scanning systems includes the data-acquisition system and quick visualisation software. Some scanners generate 3D point clouds, like the Vitronic. Others, like the Cyberware WB4 generate point clouds and meshes. Mesh output is preferred because generating a mesh out of a 3D point cloud is a complex and time consuming job. The generated data sets should be perfectly merged i.e. the images of each camera should be integrated without seams. One software package is dedicated to whole body scans: Integrate [11]. This program is developed at the Computerized Anthropometric Research and Design laboratories at Wright Patterson Air Force base.

## 5. Conclusions

An increasing number of whole body scanners is entering the market. Eight systems are identified that are able to produce whole body scans. Scanners using laser stripe projection are the most developed ones. However, stereo photogrammetric methods seem promising, as they use low cost elements and are fast and flexible.

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