Autoscan: A Flexible and Portable 3D Scanner

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Quantifying physical abnormalities, guiding corrective and plastic surgery, manufacturing clothing, three-dimensional CAD, and other related fields all benefit from the increasing use of 3D scanners. These scanning systems reconstruct a 3D surface as a large set of polygonal meshes. Although different technologies, such as ultrasound[1] or mechanical,[2] can acquire the data, optical scanning is preferred because it does not require contact with the surface and guarantees high resolution and accuracy. Hence, optical technology is widely used and has given birth to systems like the Cyberware 3D laser scanners.

A portable 3D scanning system called Autoscan provides flexibility, reliability, and accuracy for scanning 3D surfaces.

Although Cyberware scanning systems have become a commercial standard, they have two main drawbacks. First, for large objects they require a mechanical structure that cannot be installed or moved easily. Second, they only allow the scanning of objects within limited size ranges. Our alternative, called Autoscan, is a portable 3D scanner that combines flexibility and accuracy.

System description

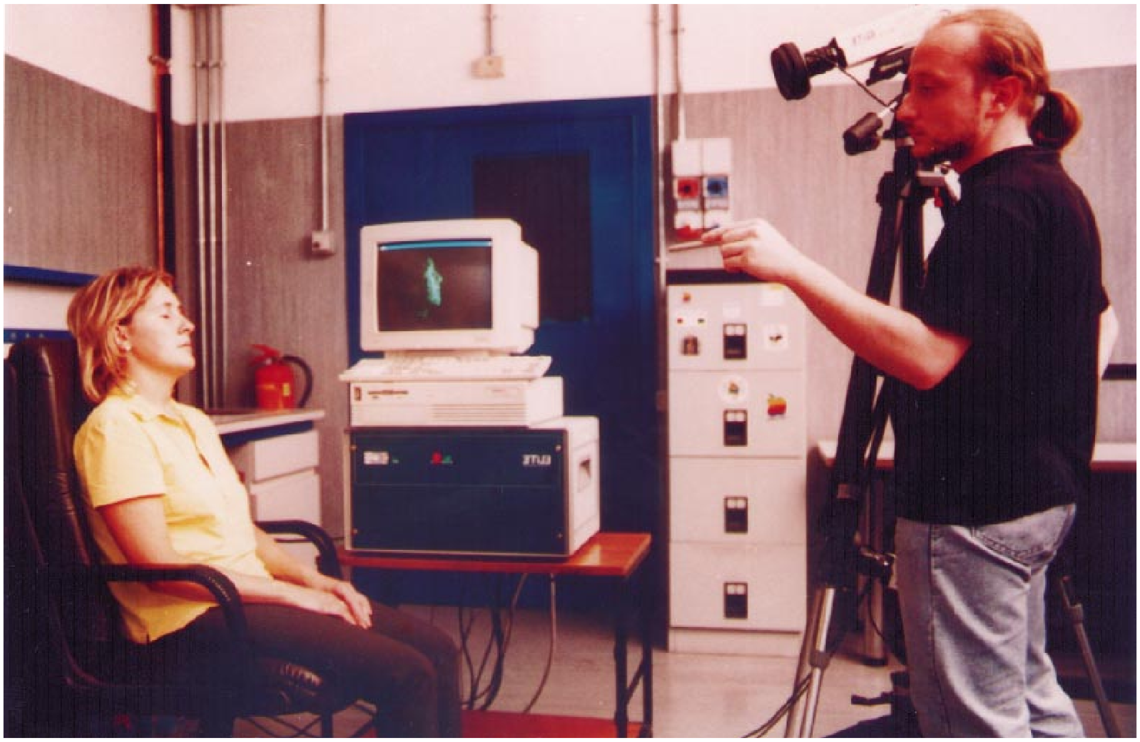
Autoscan consists of a laser pointer, a pair of video cameras, a real-time image processor (the Elite system[3]), and a computer host. The core of Autoscan, the Elite system, was designed for automatic motion analysis in the biomedical field, where motion is reconstructed from a set of markers attached to the moving subject. We introduce it here as the acquisition device for Autoscan. In this instance the markers do not have a physical nature, but are the circular spots projected on an object's surface by the laser pointer. The system recognizes these laser spots—"virtual" markers—by their shape. Figure 1 shows Autoscan being used to scan a woman's face.

Through a custom VLSI board, Elite implements a real-time bidimensional cross-correlation of the video camera image with a mask of 6×6 pixels, designed to achieve a high correlation with a circular shape and a low correlation with the background.[4] This approach offers two great advantages: The system can recognize the circular shapes in adverse lighting conditions, even outdoors, and can reach high accuracy using very small circular shapes. The 2D position of a marker (whose image diameter is two to three pixels wide) is computed as the mean position of its constituent pixels. The system weighs each pixel by its associated cross-correlation value.

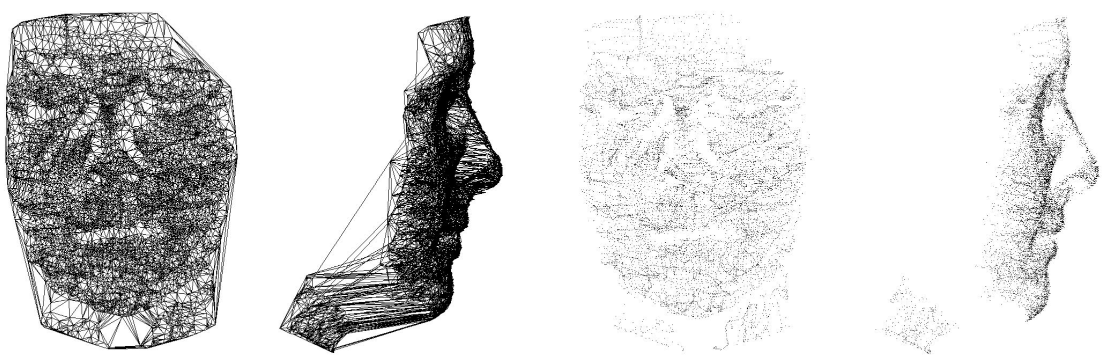
This weighing procedure enables a theoretical maximal resolution of 1/65,536 and an experimentally assessed accuracy of at least 1/10th of a pixel (worst case error).[4] When the pixels of a spot are partially hidden, the resolution drops to 1 pixel for that spot. Highly degraded, and thus poorly detected, spots are automatically discarded. Shape recognition represents a clear improvement with respect to other 3D scanners based on spot detection. The 2D position of the laser spot on the focal plane of both video cameras is sent to the host computer. This host computer, a standard 486PC in our case, reconstructs and displays the spots 3D position in real time. The system is completed by a laser pointer, which is a commercial five milliwatt (mW), semiconductor red laser, and a pair of charge-coupled device (CCD) video cameras with 256×256 pixels and a frame rate of 100 Hz. We carry out the scanning procedure manually by moving the laser spot over the surface. Real-time feedback from the host monitor helps direct the laser beam. This provides a great advantage, as it lets us increase the number of sampled points in those regions where the surface is more variable. Figure 2 (left) shows an example of this around Lorena's mouth, while the images on the right in Figure 2 demonstrate how this permits generating a denser tessellation in these regions. The right-hand images show the plotted meshes obtained through Delaunay triangulation.[5]

We also built the converters for Softimage and SGI Powerflip. Figure 3 shows the surface produced by Softimage Mental Ray renderer with Gouraud shading. Filtering has been achieved through Softimage's "automatic discontinuity" function, which performs a weighed average of the normals to adjacent triangles.

This system's key feature is its flexibility. Autoscan's



1 **An acquisition session: The laser pointer and the Elite system are shown in action with Lorena's assistance.**



2 **The set of points digitized on Lorena's face: lateral and frontal views (left) and the surface reconstructed through tesselation (right).**

set-up accommodates the size of the object to be scanned. The only constraint is that the angle between the two video cameras should be at least 60 degrees to guarantee high accuracy in the 3D data. For the acquisition of the face in Figure 2, we needed a 0.5m × 0.5m field of view. We equipped the video cameras with macro-zoom lenses and vertically displaced them, one 0.5m from the floor and the other 1.5m above, with the subject 1.2m from the cameras. The 3D position of the spots is accurate to about 0.1 mm.

For larger scenes, we mounted wide-angle lenses and set the cameras further apart. We recorded plastic models of sizes up to 4m × 4m. There is no theoretical limit on the dimensions, provided the laser used produces large enough spots. Calibration is relatively easy, requiring the survey of a rigid bar moving inside the working volume for two minutes. Autoscan's overall weight is about 15 kg (including the Elite and the cameras), making the system easily portable. The additional weight of a laptop host is negligible.

3 **Lorena's scanned face rendered by Softimage.**

3D Scanning Optical Technology

Laser scanners can be divided into two large groups depending on the scanning modality employed: spot and line scanners. Our system is based on spot scanning, which Rioux pioneered.[7] The first commercial spot-scanning product was the Hyscan, marketed in the late 1980s by Hymarc Inc. Hyscan used a laser beam deflected by synchronized mirrors and detected by a pair of sensors. Digibot II's improved version mounts the detectors and the laser emitter on a single rail that translates from the bottom upwards. The object is positioned on a rotating support that allows 360-degree scanning.

Line-scanning systems rely on the detection of a row of points or a stripe. Although they are intrinsically faster, finding the correspondence of the points on the line does pose some problems.[8] The Cyberware systems use this mode of scanning. Applied Research has proposed an interesting portable version of stripe mode with its hand-held scanner. In this system, a 450-mm long stick contains two miniaturized cameras and the laser emitter. The object remains still while the stick is moved manually around the object to be scanned. A Polhemus tracker monitors the stick's position. In a new version proposed late last year, the object can also be moved if a second Polhemus tracker is positioned on the object. The drawbacks of this system are the low accuracy in uncontrolled environments and operator fatigue in wielding the stick.

Table A. Comparison of laser 3D scanners.

Name	Scanning Mode	Scanning Operation	Accuracy	Size	Speed	Portability
Cyberware WB4 (total body)	Stripe	Automatic	5 mm × 2 mm (Vertical × Radius)	2m × 1.2m (Vertical × Diameter)	60,000 points/s 16.7s	No
Cyberware Model 15	Stripe	Automatic	300 µm (X) 300 µm (Y) 50-200 µm (Z)	250 mm × 150 mm × 75 mm ($X \times Y \times Z$)	14,500 points/s 17s	Yes
Digibot II	Spot	Automatic	0.025 mm	500 mm × 500 mm (V × D)	Not given	Yes
Applied Research Hand-Held Scanner	Stripe	Manual	1 mm (over 300 mm^3)	2m × 2m × 2m (max)	50 profiles/s	Yes
Autoscan	Spot	Manual	0.03% field-of-view (3 µm / $1m^3$)	Adjustable	100 points/s	Yes

Future developments

Scanning time is a possible drawback of Autoscan. Using only one laser pointer yielding about 100 points per second corresponds approximately to 200 triangles per second (see the sidebar "3D Scanning Optical Technology"). For example, the face in Figure 2 required 150 seconds of scanning time, during which we collected roughly 15,000 3D points. Of these, 4,364 points were poorly seen by both cameras and were discarded, leaving 12,641 valid points. The tessellation carried out on this set of points consisted of 25,254 triangles.

These figures increase drastically if, instead of a single laser beam, we use a bundle of them. Moved synchronously, they would transform the Autoscan operating procedure from a spot to a stripe. The price in this case is an increase in the complexity of the tracking procedure required to correctly associate the laser spots surveyed by the two cameras.

We are working to make the tracking a real-time process. When scanning a more elaborate surface, we could add other video cameras along with their associated board inside the Elite box. The processing time does not increase for the shape correlation, and the overhead for the PC processing is negligible. The scanning system continues in real time for these scenarios.

A prototype of this multicamera scanner concept using up to eight cameras is under development. An attractive alternative approach is to survey the object in few orientations and use computational techniques to register the 3D surfaces obtained.[6]

Computation time is a very important consideration. The Elite system VLSI board we used outputs 240 Mflops continuously, the rate required to compute a 6 × 6 correlation 256 × 256 times every 10 milliseconds (about 0.15 microseconds per correlation). For the two video cameras we used, this is a total rate of 480 Mflops. This speed currently exceeds the reach of medium-range workstations (the new SGI R10000 processor peaks at 300 Mflops). However, if we restrict the correlation to a narrow area around the laser spot, say a 16 × 16 window, the required speed drops to 1.85 Mflops. We find this window by thresholding the image.

We envision embedding this kind of processing into the software of graphical workstations. This procedure wouldmake such 3D scanning a software option in the near future. ■

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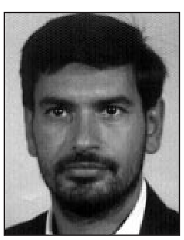

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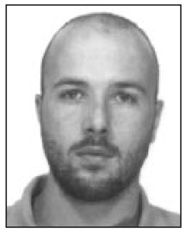

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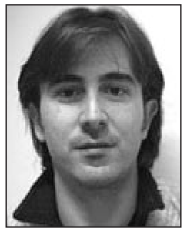

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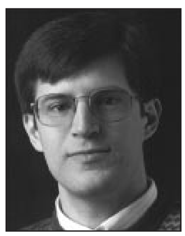

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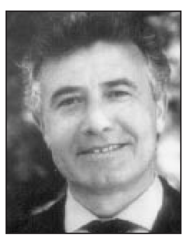

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