Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 33 No. 3, July 1996
Pages 267–278

Design of a 3-D surface scanner for lower limb prosthetics: A technical note

Paul K. Commean, BEE; Kirk E. Smith, AAS; Michael W. Vannier, MD
Mallinckrodt Institute of Radiology, Washington University School of Medicine, St. Louis, MO 63110

Abstract—A three-dimensional (3-D) noncontact optical surface range sensing imaging system that captures the entire circumferential and distal end surfaces of lower limb residua in less than 1 second has been developed. The optical surface scanner (OSS) consists of four charge injection device (CID) cameras and three white light projectors, mounted on a rigid frame surrounding the subject's residuum, allowing 360° surface coverage of the lower residual limb. Anatomic 3-D computer graphics reconstruction of a residuum surface, recorded with the OSS imaging system, is used for visualization and measurement. One cubical and two spherical calibration test objects were used to obtain a system precision of less than 1 mm. In a study conducted with 13 persons with below knee (BK) amputation, the OSS system was compared to calipers, electromagnetic digitizer, and volumetric computed tomography with better than 1 mm precision on plaster positive casts and approximately 2 mm on the residual limbs.

Key words: *anthropometry, orthotics, prosthetics, surface digitization.*

INTRODUCTION

A 3-D optical surface scanning system (OSS) was developed to acquire, process, display, and replicate the surface of the human lower limb residua. Key requirements were complete coverage of the complex residuum surface with 1 mm precision, high repeatability, a data acquisition time of less than 1 second (the approximate time a person can remain motionless), and automated operation, processing, and object replication. For these reasons, we chose to adapt the Cencit head surface scanner (1) design and develop a 3-D surface imaging system for this specific medical application: lower limb residuum surface data modeling. We sought to make the system easy to operate and operationally safe in a clinical environment. The resulting system design provides complete 3-D surface coverage with high accuracy, speed, and ease of use through fully automatic operation and 3-D data processing (2,3).

Other researchers have employed several different technical approaches for active, optical, noncontact range sensing of complex 3-D surfaces. Their techniques include laser Moiré, holographic methods, and patterned light; these were used primarily for industrial applications (4). In the field of prosthetics and orthotics, many studies have been conducted by British, Canadian, and American groups where surface digitizing techniques were developed for evaluating lower limb residua. Their digitizing techniques captured the 3-D surface data via range sensing devices and were used to produce plaster positives of the residual limb by computer-assisted design/computer-assisted manufacturing (CAD/CAM) systems (5–11).

Even though CAD/CAM technology has been shown to improve the quality of fit and expedite the manufacturing process, additional work is needed to facilitate CAD/CAM modeling of body surfaces (12,13). Almost all current CAD/CAM systems acquire 3-D surface data by either optical or electromechanical digitization of the patient's plaster cast. Houston

This material is based upon work supported by the National Institutes of Health, National Center for Medical Rehabilitation Research.

Address all correspondence and requests for reprints to: Michael W. Vannier, MD, Mallinckrodt Institute of Radiology, Washington University School of Medicine, 510 South Kingshighway Boulevard, St. Louis, MO 63110.

Journal of Rehabilitation Research and Development Vol. 33 No. 3 1996

et al. showed that variations in plaster wrap casts, whether or not modified by the prosthetist, are still significant, and, with support from the Department of Veterans Affairs, developed a VA-Cyberware Lower Limb Optical Laser Digitizer that utilizes charge coupled device (CCD) cameras and near-infrared lasers built into two scan heads to capture the residual limb surface data (13). The laser light is segmented and directed by mirrors in each head to acquire 200° of surface data. The scanner digitizes a 32 cm long vertical segment in approximately 3.5 sec. The VA-Cyberware digitizer has been tested both in the laboratory and clinically, and results indicate that the scanner is accurate and repeatable.

One aspect of the OSS makes it distinctive: the integration of multiple stationary sensors that can be arranged to cover complex contoured surfaces, such as the human lower limb residuum (**Figure 1**). Another benefit of this approach is its digitization speed: less than 1 second is required for data acquisition. Automatic processing and display of the data require less than 15 minutes on a graphical workstation. The OSS was tested in locating markers placed on residual limbs. We have been successful in capturing these marker locations using both OSS and a spiral x-ray computed tomography (SXCT) scanner. The markers allow the prosthetist to correlate the 3-D data between modalities when making modifications to the socket. Applications for OSS include biomedicine, anthropometric studies, and orthotics and prosthetics design.

In comparative anthropometric studies of the lower residual limb following partial amputation, the major concerns are the precision and repeatability of the measuring modalities and the quantitative comparison of differences in solid model forms derived from 3-D surface scans as compared to the subject's residuum. An effective measurement method must be precise, reproducible, and time efficient. Traditionally, quantification of the residuum has been based on measurements made by rulers, tape measures, calipers, and manual palpation by a prosthetist to form a negative plaster cast of the residuum. These traditional measuring devices and methods are time intensive; the surface data cannot be stored for reuse to make modified sockets and perform comparative studies, and only linear surface measurements of external features are possible. 3-D OSS overcomes some of these limitations, since the external surface can be quickly captured and stored for later use to check socket fabrication and to perform related experimental studies.

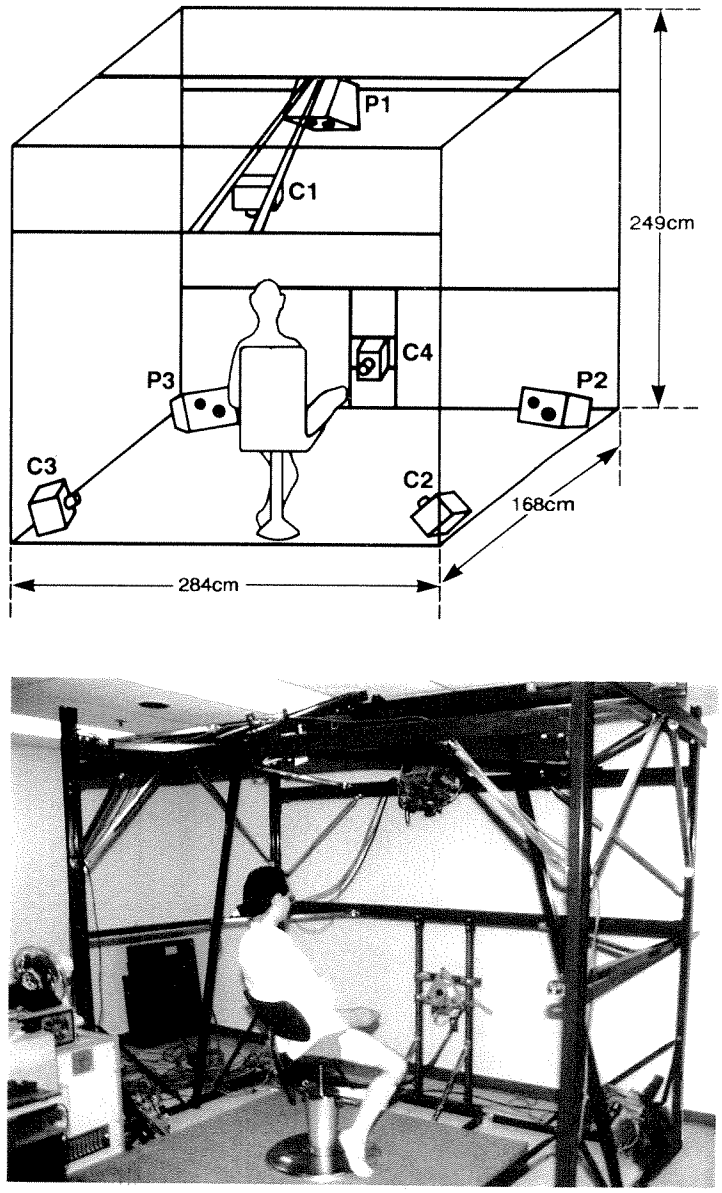

Figure 1.
Top: A line drawing of a subject seated in the prosthetic 3-D optical surface scanner system. The camera directly in front of the residuum labeled C4 captures the distal end of the residuum. The cameras (C) and projectors (P) are located at the base and top of the structure. Bottom: A subject is seated in the 3-D optical surface scanner prepared to be scanned.

METHODS

Geometric Design Concept for the 3-D Residuum Optical Surface Scanner

The 3-D residuum OSS (**Figure 1**) was developed for digitizing the residuum surface with 360° coverage within a 1 second scan acquisition time. Rather than a

single, moving sensor (1), we used a stationary, multiple-sensor design in which the sensors cover the surface in multiple segments. In addition, the Cencit multiple-sensor design consisting of a camera (**Figure 2**) and projector (**Figure 3**) pair was chosen for its flexibility in sensor positioning, and its established repeatability and accuracy in previous studies conducted by our laboratory when measuring facial changes on the human head (14–17). The sensor design incorporates projection of structured incoherent light in a predetermined pattern onto the subject, viewed by an area camera image sensor offset approximately 35° from the projector. This offset establishes a triangulation baseline. The sensors capture portions of the residuum surface, like the distal end, that are not viewable by other methods, such as a single sensor rotating about the subject.

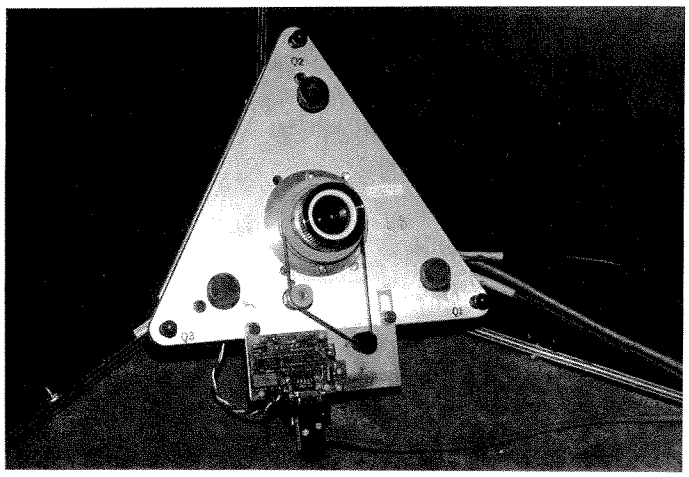

Figure 2.
A charge injection device (CID) area sensor with contiguous pixels and a progressive readout is used to capture the individual strobe flashes from the projector. A full frame image consists of 256 by 253 pixels. The cameras operate with a pixel clock of 72 megaHertz and a frame rate of 72 Hertz.

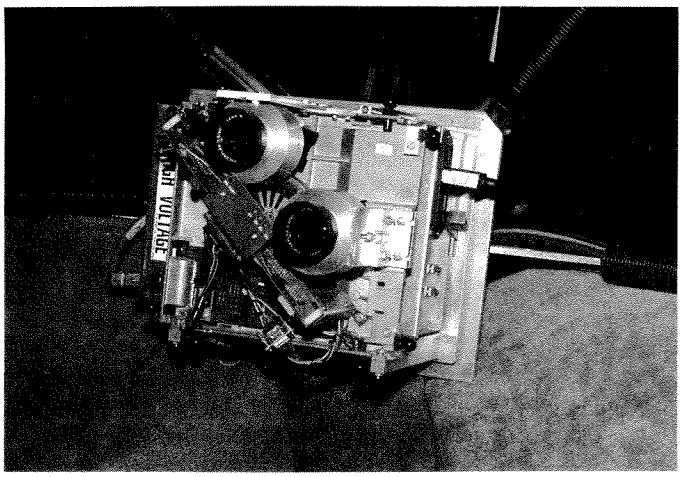

Figure 3.
The projector consists of a strobe and pattern projection system (3). The eight separate patterns are coded in such a manner as to allow multiple profiles to be projected simultaneously; the mensuration software can then decode and reconstruct the 3-D surface.

With the multiple sensor design, we are able to digitize surface segments, not just single profile lines. This feature allows us to achieve the speed requirement and reduce the amount of image memory and processing needed for the prosthetic surface scanner. To capture an entire surface segment, many light profiles are projected at once; thus, each image contains many contour lines or profiles. The problem with this approach is the difficulty of uniquely identifying each separate contour in the sensed image in order to solve for the 3-D surface correctly. The problem was solved in the Cencit, Inc. design (2,3) for scanning the 3-D surface of the human head. Identification of individual contours is based on the interleaving pattern, which is coded in such a way that contours can be uniquely identified in subsequent processing (2,3). Cencit also solved the problem of integrating multiple sensors (cameras and projectors) to capture a complete 360° coverage of the human head with a single scan (1).

The Cencit head surface scanner was originally designed for a portrait sculpture application. The scanners were placed in commercial studios to allow generation of head replicas or "portrait sculptures" in lieu of photographs. The scanner acquired the 3-D surface data of the head in 0.75 seconds while the individual was seated in the scanner. The 3-D data was processed and replicated at a central fabrication facility, using a milling machine with a special tool to carve the likeness of the individual from a cylindrical block of moist plaster. The machined plaster block was finished by artists, dried, and delivered to the commercial site for sale to the customer (1).

Using components from the Cencit 3-D human head surface scanner (18) and reconfiguring the cameras and projectors, we found the surface of the human below knee (BK) residuum could be scanned by combining surface segments obtained from only four cameras and three projectors. Three cameras and projector sensors are spaced circumferentially around the residual limb, and the fourth camera is placed in

Journal of Rehabilitation Research and Development Vol. 33 No. 3 1996

front of the subject's residuum (**Figure 1**). This provides coverage of areas (such as the distal end) that could not be "seen" by a single sensor restricted to motion in a plane. With this configuration, we found the surface of the residuum was covered by at least one sensor and the distal end was covered by two or more sensors, thus providing a substantial amount of overlap in the critical areas of the residuum including the distal end. Surface data from 12 subjects participating in the study are shown in **Figure 4**, depicting the various sizes and shapes of residual limbs scanned by the OSS.

To integrate multiple surface segments successfully, each segment must be sufficiently precise so that the seams, or merges, between any two overlapping segments are not noticeable. This imposes a stringent precision requirement upon each sensor. A BK residuum study was conducted to compare precision and repeatability of the OSS with caliper, electromagnetic digitizer, and SXCT measurements (19–21). The resultant design is unique in its combination of complex 3-D surface coverage, precision, repeatability, speed, and ease of use through fully automated operation and 3-D processing.

Figure 4.
OSS surface data rendering of skin surface for 12 persons with BK amputation.

Scanning and Data Processing

The projector contains a pattern wheel with eight separate 45° windows, each containing a set of coded circular bar patterns (2) which are projected onto the subject (**Figure 5**). Four of the eight separate windows contain a unique set of patterns and the other four windows contain the complements of the original four patterns. Currently, there are a total of 158 profiles in the four patterns. The patterns consist of accurately drawn bars with varying coded widths. For a complete scanning process, all eight patterns from a projector are captured by a paired camera in the scanner system. Each of these eight patterns is captured sequentially in the camera image and surveyed (**Figure 6**).

Mensuration software analyzes the 2-D video data provided by the residuum surface scanner by searching along the rows of pixels (scan lines) in the camera, one row at a time, to find profiles. The properties of the conjugate reticle patterns that allow unique identification of each profile edge are:

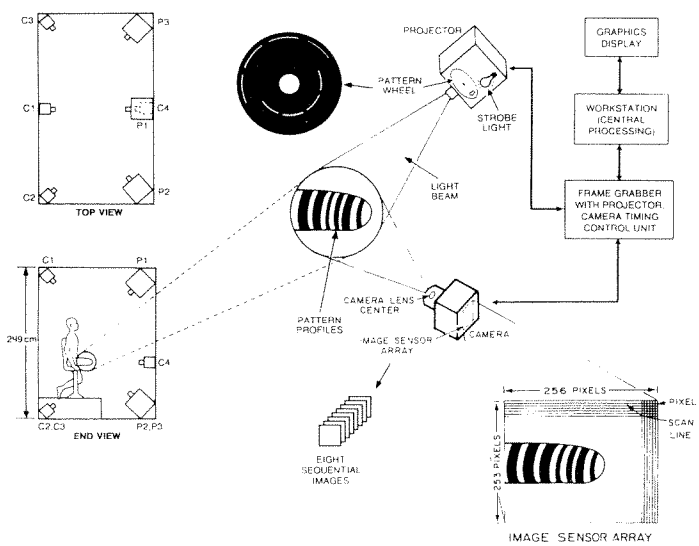

Figure 5.
Projection of a single set of patterns from one of eight pattern windows contained in the pattern wheel onto a subject's residuum produces profiles that are captured by the camera image sensor array and read out by the frame grabber into its memory.

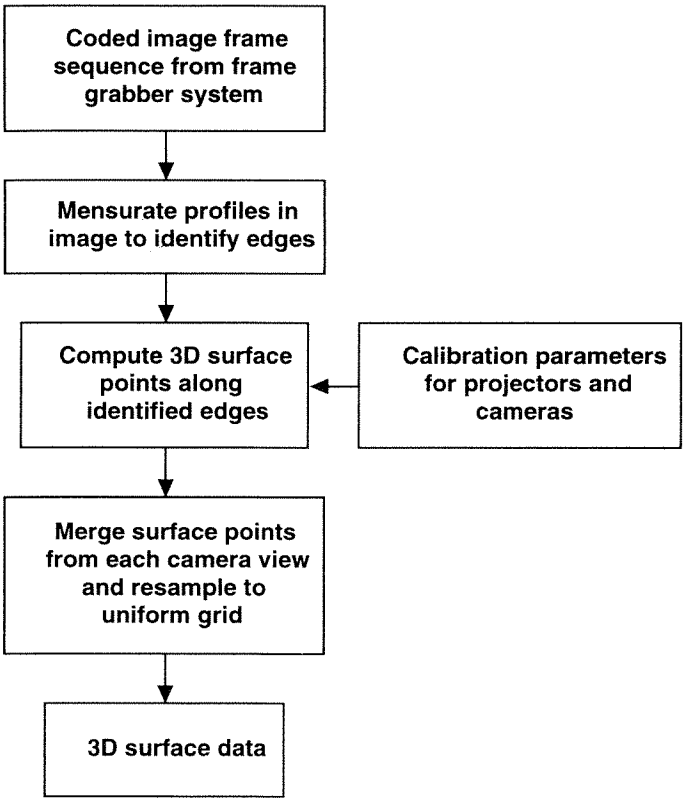

Figure 6.
The OSS acquisition, reconstruction, and data processing flowchart.

1. identify which of the eight patterns creates the profile by associating it with the projection and capture sequence;
2. determine whether the light transition at the edge of each profile being measured is from dark to light or light to dark;
3. for the other three unique sets of patterns, determine if a light or dark area lies at the same corresponding physical location as the profile being surveyed;
4. determine the pattern number of the profile immediately before and after the current profile.

Once each of these properties is known, look-up tables are used to uniquely identify the profile. After the profile has been identified within a pixel, subpixel interpolation is used for improved precision. Identification and subpixel interpolation are repeated for each profile in a row of pixels and for each row of pixels within the single camera image to produce a set of labeled 2-D data points. This is a simplified description of pattern coding and mensuration processing. The complete details of the complex pattern coding and mensuration processing are available (2,3).

The labeled 2-D points produced by mensuration are processed by a "2-D to 3-D" algorithm to produce a set of 3-D contours. The 2-D to 3-D software maps the 2-D points in the image plane into 3-D space. To perform the point mapping, the profile number is used along with the projector calibration parameters to determine the equation of the cone that was projected into space to form the identified profile. A point on this profile in the image plane is projected into space through the camera lens center, defining a line. Since the point location within the image sensor and the camera parameters are known, the equation of the line in 3-D space is known. Two points of intersection of this line with the cone in 3-D space are computed and the point lying in the scan volume is chosen. This procedure is repeated for all points along all the profiles within a single camera image and for all camera images. The set of 3-D points selected in this manner lie on the surface of the scanned residuum. The process of mensuration and 2-D to 3-D mapping continues for all camera/projector pairs forming multiple 3-D surface patches. The surface patches, which consist of unedited overlapping XYZ data points from multiple camera and projector views, are combined using 3-D transformations and 3-D resampling. The 3-D points are resampled onto a uniform cylindrical grid consisting of 512 equally spaced radial components and 256 equally spaced vertical locations. The location of each point on the grid is determined by summing and averaging the distance of the nonuniform points lying within a chosen distance about the grid point. The mathematical equations which describe the projected cone and line in space have been presented in detail (22).

The resulting surface model contains approximately 64K (512×128, since the residuum is contained in approximately half of the vertical axis) cylindrical coordinate 3-D data points. This achieves better than a 1 mm spatial precision, with averaging, over smooth surfaces of convex non-overlapping objects such as limb residua.

Physical Constraints on the Structure Size

The OSS was developed for conducting a research study on lower limbs, and the following constraints were placed on its physical dimensions: 1) The structure must fit within a minimum ceiling height of 3.5 m; 2) The entry way of the structure must be at least 1.65 m high; and 3) The height of the ceiling of the structure

above the raised floor inside the structure must also be at least 1.65 m.

In addition to the size constraints, the geometry of the structure is constrained by the following 3-D scanner system criteria: a) 1 second or less digitizing time was required to help eliminate subject movement; b) high surface resolution, precision, and repeatability were necessary; c) complete coverage of the residuum was needed with a scan volume of a 33×33×33 cm cube, and d) the structure must consist of inexpensive support members which allow for quick, easy design and reconfiguration along with providing solid mounting positions.

To meet these criteria, the following configuration of sensors and structural members were selected:

1. Multiple projector and camera units would be used to project and capture patterns from multiple units simultaneously to ensure a 1 second or less digitizing time.
2. Three projector and camera units would be installed at equal intervals (120°) about the center of the structure to ensure complete coverage; also one camera would be centrally located so that the residuum distal end could be captured to ensure complete coverage.
3. The cameras would be offset from the projectors to allow the cameras to form the triangulation baseline to facilitate resolution, precision, and repeatability.
4. Slotted steel structural members with node attachment hardware would allow for infinite variability, ease in construction, and provide a low cost design solution.

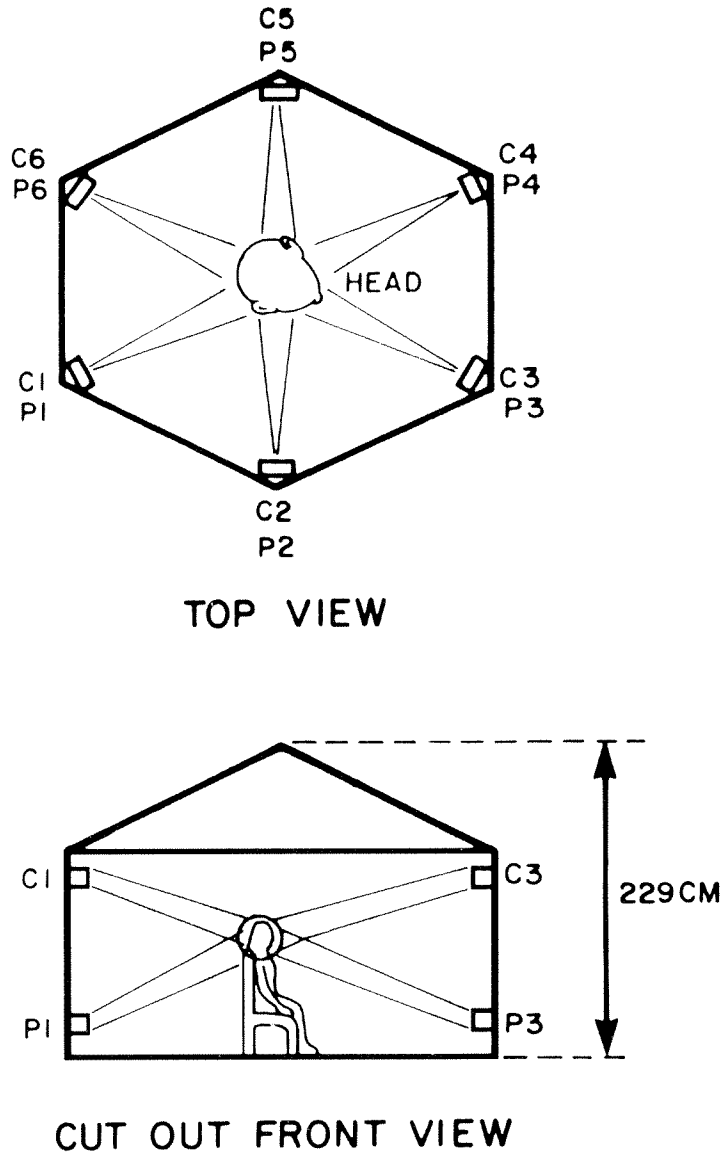

Figure 7.
The Cencit human head OSS is contained within a hexagonally shaped chamber, where the six projectors (P1–P6) and six cameras (C1–C6) are located about the subject at two different elevations and the vertical projector/camera pairs are spaced at 60° intervals about the chamber walls. The chamber also eliminated external lighting, and its walls were used to mount the projectors and cameras.

Placement of Sensors within the Structure

Given these configuration requirements on the sensors (projectors and cameras), we specified camera and projector positions based on the similar scan volumes for the residuum and the human head (33×33×37.5 cm) in the Cencit head surface scanner (18). The prosthetic scanner is basically the Cencit head scanner (**Figure 7**) placed on its side with three circumferential projectors and cameras separated 120° from each other, and the addition of a center camera to capture the distal end. Eliminating the three projectors and cameras from the head scanner to produce the prosthetic scanner reduced overlapping surface patches.

Each of the three projectors (P1, P2, and P3) and three cameras (C1, C2, and C3) are spaced at 120° intervals about the horizontal centerline of the scanning volume (**Figure 1**). The projectors and cameras are physically secured to a rigid structure using slotted members that allow easy adjustment of position and orientation. The cameras are spatially offset from the projectors at approximately 35°. Camera (C4) was positioned such that it lies on the centerline of the scanning volume to allow sampling of the distal end.

Since fewer cameras and projectors were required to meet the prosthetic fitting system requirements, physical hardware changes to the electronics were not necessary other than to modify the cabling to allow the distal end camera (C4) to capture data from all three projectors, each of the other three cameras only captures data from its adjoining projector (C1 from P1, C2 from P2, C3 from P3).

Calibration

The scanner was calibrated using a cube and two spheres with different diameters shown in **Figure 8.** The calibration process requires approximately 2 hours to acquire various cube and sphere scans and approximately 8 hours of iterative computation on the workstation (model 4D-340, Silicon Graphics, Inc., Mountain View, CA) to determine the camera and projector parameters. We have found that the cameras and projectors remain calibrated for at least 1 year and can remain calibrated for many years, provided the structure and sensors are not moved.

The calibration software is robust since only approximate locations and orientations of the cameras and projectors in 3-D space are necessary for estimating the initial calibration parameters. The locations were approximated using a measuring tape to determine the distances between the cameras and projectors. The angular orientations of the cameras and projectors were approximated using a protractor.

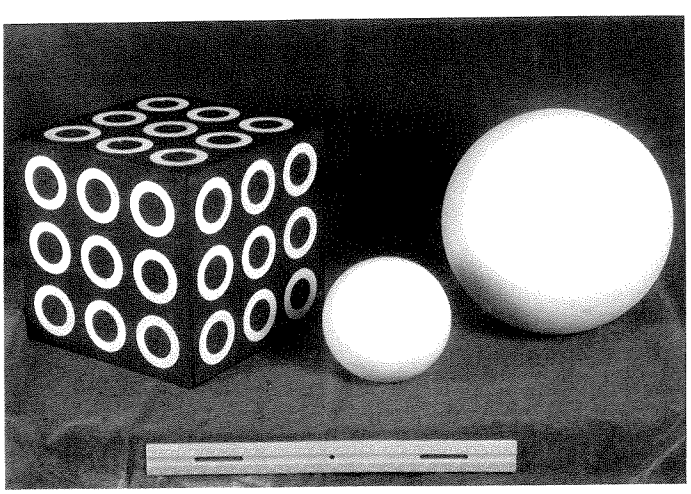

Figure 8.
A calibration cube containing precisely located rings with known diameters is shown. The 20.32 cm sphere is a bowling ball with a rod attached to allow suspension within the scan volume; it has been painted white. The 11.43 cm sphere is a duck pin bowling ball that has also been painted white.

The cameras and projectors are calibrated using software algorithms that have been described in detail (22). This process is briefly described here to aid in understanding calibration. First, the cameras are calibrated before the projectors using a cube test object (**Figure 8**). The cube is placed in a known orientation in the center of the scan volume and a single scan taken where multiple profiles are projected onto the cube faces from each projector and captured by the cameras. Due to the absence of three interleaved projectors, as compared to the Cencit head scanner, three faces of the cube were not fully illuminated during the scan. To compensate, lights were arranged about the cube to properly expose the white rings on these faces as seen by the three cameras (C1, C2, and C3) spaced at 120° intervals about the structure.

Faces of the cube, illuminated either by the multiple projector profiles or external lighting, are processed by the mensuration program to create high quality images of the cube faces. These 2-D images containing the white rings appear elliptical in the camera image sensor plane. The nonlinear relationship between the observable coordinates of the center of the rings in the image plane and the parameters is estimated. Each ring is analytically projected onto the image plane, using nominal parameters of the camera geometry and the established nonlinear relationship. Each observed ellipse captured from the cube faces is correlated with its corresponding analytically projected ring to determine the observed ring center coordinates. The nonlinear equations are linearized, and the error between the observed ellipse coordinates and the analytical coordinates is determined. The error between the two sets of coordinates is driven to a small value by repeatedly varying the nominal camera parameters (displacements, rotations, lens center, and lens focal length) using a Kalman filter (22).

The projectors were calibrated using several scans of two different diameter spheres. The 20.32 cm sphere (**Figure 8**) was placed into the scan volume and scanned at several different locations. That sphere was replaced with the 11.43 cm sphere and the process repeated. A set of circular profiles are projected onto the spheres from the projectors. These profiles are observed in the cameras. For each of the various sphere scans, mensuration created 2-D photograph type images and identified the edges of the projected patterns on the spheres as observed by the cameras. Using the 2-D to

3-D process previously described, which maps a point on the image plane (2-D point) to a point in 3-D space (3-D point), the set of points belonging to a profile in the image plane is transformed into a set of 3-D points nominally lying on the sphere using nominal projector geometry parameters—the displacements, rotations, lens focal length, and radii of the various projector profiles (22).

The set of 3-D points lying on the sphere is entered in a least squares fit procedure to compute the nominal radius and the center of the sphere. The coordinates of the sphere center and its calculated radius are compared to the known physical values to establish error. This error is driven to a small predetermined value by varying the projector parameters using a Kalman filter (22).

Residuum Measurements

Thirteen adults with BK amputation were recruited, gave informed consent, and participated in the residua study. The group consisted of 9 males and 4 females, ranging in age from 31 to 76 years. Since the population of St. Louis and its surrounding area predominately consists of Caucasians and African Americans, only these two races were included in the study. Two African American females, one African American male, two Caucasian females and eight Caucasian males participated in the study (19).

This study compared the precision and repeatability of the OSS with measurements by: traditional caliper (model CD-18, Digimatic 500-505-50 series, ±0.001 in (25.4 μm) Mitutoyo Corporation, Japan); 3Space electromagnetic digitizer (Kaiser Aerospace and Electronics Co., Colchester, VT); and SXCT (Somatom Plus S, Siemens Medical System, Inc., Iselin, NJ). Six 0.635 cm diameter markers were placed on the subject's residuum as follows: three were placed proximally at 120° intervals about the residuum in a plane with the first marker being placed on the patellar tendon, and three additional markers were placed distally at 120° intervals about the residuum with the first being placed near the distal end of the tibia. Caliper measurements were taken twice between all the markers to produce 15 measurement pairs. The markers were also digitized twice with an electromagnetic digitizer and the distances calculated. Then the subject was seated in the OSS as shown in **Figure 1**, and two scans were taken of the residuum. The four 2-D camera views of the residuum along with the 3-D texture mapped surface data can be seen in **Figure 9.** The resulting 3-D surface data from each scan

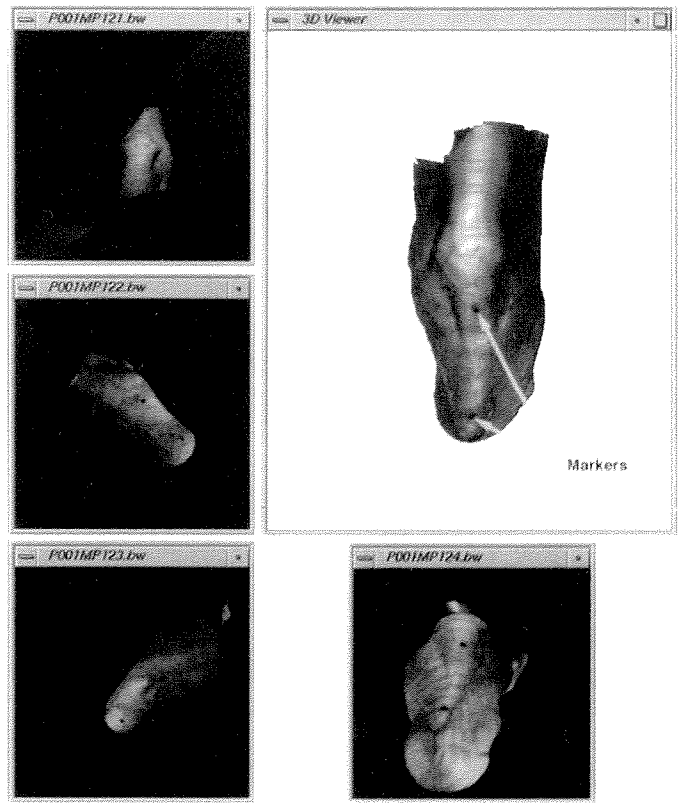

Figure 9.
Texture-mapped 3-D surface data of a subject's residuum with markers attached. The four 2-D camera views are created by mensuration, one from each camera.

with the markers texture-mapped onto the 3-D surface data was displayed in a cylindrical format (**Figure 10**). For each OSS scan, the markers were measured twice, using a program developed in our laboratory. The subject was taken to the SXCT scanner and his or her residuum scanned twice. Measurements between the six markers were taken using ANALYZE (Mayo Biomedical Imaging Resource, Rochester, MN) software (23,24). For each SXCT scan, the markers were measured twice. The repeated measures of each scan were necessary to determine the error due to the operator making the measurements on the computer screen and the error due to the measurement device.

All the measurements and scans just described taken with the calipers, digitizer, OSS, and SXCT scanner constitute a single measurement session. Several weeks later, the same subject returned for a second session where all the measurements were repeated as performed in the first. During the second visit, the markers were placed on the residuum in approximately the same locations as during the first, but since bony

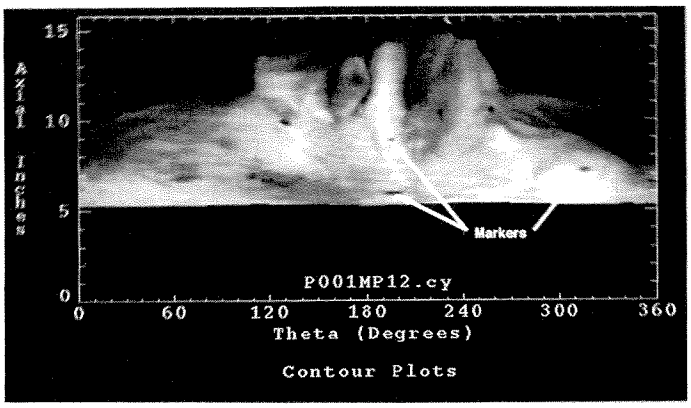

Figure 10.
The 3-D surface data are displayed in a cylindrical format with the six texture-mapped marker locations.

landmarks were not used in either session, exact placement was impossible.

Repeatability and Precision Assessment

Laboratory tests have shown the OSS to be repeatable and precise when capturing the surface of the subject's residuum, and plaster positive casts thereof, when compared to caliper measurements and other measuring methods. We used plaster positive casts of each residuum during the study to isolate measurement error sources (19). The casts serve as a stable reference standard to eliminate variation due to: 1) subject movement during measurement; 2) residual limb swelling or shrinkage during the 3 to 4 hour measurement protocol; 3) operator movement (since the calipers and electromagnetic digitizer could not be placed directly on the markers that were located on the subject's skin causing a potential change in the marker location due to soft tissue movement as compared to steadying these devices on the plaster cast markers); 4) translucent skin effects when using the OSS; and 5) marker location movement due to the soft tissue changing shape and/or leg position change when the subject moves from one measurement device to another. Using the plaster casts allowed us to determine the best possible repeatability and precision for each measurement device.

The precision and repeatability of the OSS were obtained using a nested analysis of variance procedure. The precision and repeatability of the Cencit head scanner used for locating and measuring landmarks on the human head have been reported (17). Precision (given in standard deviations) is the average absolute difference between repeated measures of the same subject. Repeatability is the precision of the measurement relative to the differences among subjects contrasted in this study (17).

RESULTS

Repeatability for all measurement methods between sessions was low due to the difference between the marker locations at different measurement sessions. The variation was approximately 70 percent between subjects, 30 percent between sessions, and a very small amount between measurements of a single scan or between scans for all measurement devices for both the subjects and their casts. Measurements taken at any one session were very repeatable, differing only about 1 mm or 1 percent on average of the mean values for measurements taken directly on subjects (19). The error standard deviation (between repeats within a scan and between scans combined) for linear measurements of subject measurements is typically 1.8 mm for OSS, 0.75 mm for measurements with calipers, 1.35 mm for measurements with the digitizer, and 0.9 mm for measurements with SXCT. The error standard deviation for linear measurements of plaster cast measurements is typically 0.6 mm for measurements with the OSS, 0.2 mm for measurements with calipers, 0.3 mm for measurements with the digitizer, and 0.6 mm for measurements with SXCT (19).

Precision for all measurement methods of measurements taken directly on subjects were found to have random differences from caliper measurements of approximately 2.0 mm (1.6 percent of the mean) for electromagnetic digitizer and OSS, and 3.5 mm (3.0 percent of the mean) for SXCT (19). The mean distance measurement for all measurements, for both the subjects and casts, was 122.73 mm. Precision of the measurements taken on the casts showed much smaller average random differences of approximately 0.65 mm to 0.8 mm (0.5–0.7 percent of the mean value) from the caliper measurements for the digitizer, OSS, and SXCT methods (19).

Repeatability of measurements between and within scans of SXCT data (0.9 mm) was closer to the caliper repeatability (0.75 mm) than the OSS (1.8 mm) and digitizer (1.35 mm). This was attributed to improved conspicuousness of marker center locations on SXCT scans. Additional analysis was performed on the SXCT data to determine whether the three longitudinal measurements (distal to proximal) had precision errors different from the remaining 12 of 15 measurements.

The longitudinal measurements should be least affected by the subjects lying their residua relaxed on the table. We found the longitudinal measurements to have errors (average 2.37 mm) which were more similar to the digitizer and OSS, instead of 3.5 mm average error as the other 12 SXCT measurements.

DISCUSSION

We developed a new OSS for scanning lower residual limbs to provide rapid, accurate, and repeatable measurements, and overcome limitations of other surface scanner technologies. Ordinary white light was used for capturing the surface data of the residual limb instead of the laser light used by many other surface scanners.

Our goal in testing the OSS repeatability and precision was to verify that OSS is indeed comparable to traditional measuring methods (calipers) and other measuring devices. We found the repeatability and precision of OSS measurements to be lower on living subjects than on their plaster casts. This was due to the normal physiological changes in the residuum shape compared to the unchanging casts and various errors associated with each measurement device when measuring the subject's residuum. A detailed description of the errors associated with each measurement device follows.

Caliper errors on subjects are larger than those on plaster casts; this may be due in part to the operator's inability to hold the calipers in place while taking the measurements. The operator is required to hold the calipers suspended in space while observing paired marker locations (one at a time) while keeping the caliper tips centered. This problem does not arise with the plaster casts, since the tips of the calipers could be placed and steadied against the markers on the cast surface. Also, the distance between the markers on the subject's residuum could change if the subject allowed his or her knee to bend or move while the measurements were being taken.

Electromagnetic digitizer errors on subjects are larger, and there are several possible explanations. Operator hand motion while taking the digitizer measurements is likely. Another problem: the object being measured must remain motionless during the entire measurement session. The digitizer only captures the x, y, and z location of a point in space. If the subject moves between points being digitized, the distance between these points and any future points being measured will change. The digitizing process for all six markers took approximately 30 seconds.

For the OSS, the errors in measurements on subjects could be attributed to the subject moving during the 0.75 second scan, the operator's inability to see the marker center due to low contrast between the skin and the dot, and the oblong and sometimes irregular marker shape, and the finite pixel size in the monitor (only discrete pixel locations were chosen when measurements were taken, no subpixel interpolation was performed).

SXCT errors in measurements on subjects may be due to supine residuum orientation. The residuum is relaxed during SXCT scans, but is held tensed and suspended in space for the other measurement methods, causing a change in shape. We felt the subjects would not be able to remain motionless with their residual limb suspended in space for a 32 second SXCT scan, thus the requirement for supine positioning with their leg relaxed on the table. If the subject moved during the scan, we would have the same x, y, and z location in 3-D space problem as associated with the electromagnetic digitizer; in addition, the data may be blurred to the point that the markers could not be found.

Measurements on subjects using the four various measurement devices were influenced by many factors not present in measurements on the positive plaster casts. Most of the error sources can be easily controlled. To steady the operator's hand during caliper and electromagnetic digitizer measurements, supports can be used to rest the elbows or arms, and the subject's residual limb could be supported and held tightly with fixtures to reduce movement. The center of the markers used in the OSS could be automatically found using software techniques. We improved the SXCT scanning process by supporting the dorsal aspect of the residuum just above the knee and instructing the subject to tense their residuum during the scan. From several preliminary scans, this SXCT protocol appears to work well.

Since the 3-D residuum surface scanner was designed for capturing the human residuum, the scan volume is limited (approximately a 33 cm cube). Objects larger than the scan volume are not accurately captured, since only the area within the scan volume was calibrated. BK residua have been scanned in the OSS system, but testing of persons with above knee (AK) amputation has not been performed. For the AK residuum, the geometry of the groin area will not be captured with the subject in the same orientation as

when the prosthetist casts that particular region, potentially introducing errors in measurements. This is due to having the scanner system oriented so that subjects are required to be seated instead of standing during scanning. This problem may be overcome by having the subject lie supine in the scanner.

The VA-Cyberware prototype digitizer has advanced CAD/CAM technology by *in vivo* digitization of residual limbs. The surface information obtained from our non-contact scanning system can be compared to the SXCT scan data to determine the soft tissue thickness over the bone. Knowing the soft tissue thickness, we believe, will greatly enhance the ability of the prosthetist to modify the socket, with minimal future alterations, by allowing him or her to modify the socket design using quantitative techniques based on the location of the bone within the residuum. The OSS can be used for follow-up examinations by the prosthetist to quantify the amount of swelling or atrophy without subjecting the patient to multiple SXCT scans. If bony landmarks can be accurately and repeatably determined, surface scans can be registered with the original SXCT scan data, allowing the prosthetist to estimate the soft tissue change relative to the bone surface over time.

CONCLUSION

A new residual limb OSS with the capability of rapidly capturing the complete residuum, including the distal end, has been shown to be precise and repeatable in its ability to measure distances. In a study using 13 adult volunteers with BK ampututation, we proved the OSS to be substantially equivalent when compared with calipers, electromagnetic digitizer, and SXCT. When automatic marker center location software is available for the OSS scanner, it may be suitable for routine clinical use as a quantitative measurement tool. Prosthetists, orthotists, anthropometrists, and physicians can utilize the OSS for compiling residual limb databases, quantifying residual limb changes over time, and improve the prosthetic and orthotic fitting process. The surface data obtained from the OSS can be registered using landmark locations with the surface/internal volumetric SXCT data to greatly improve the understanding of the residuum soft tissue morphology and shape relative to the internal bone shape and location within the soft tissue. The OSS and SXCT scanner system combination may serve as a teaching tool for prosthetists, orthotists, and anthropometrists, providing them with surface and internal 3-D anatomical data not otherwise available.

ACKNOWLEDGMENTS

The original Cencit, Inc. portrait sculpture scanning system was developed by Dr. John Grindon. This work was supported, in part, by the National Institutes of Health, National Center for Medical Rehabilitation Research project RO1 HD30169. We wish to thank Universal Vision Partners for their support. The ANALYZE software system was provided by Dr. Richard Robb and associates of the Mayo Biomedical Imaging Resource in Rochester, MN. We appreciate the cooperation of James Weber, President, Gil Christley, CPO, and Marsha Klunk, CPO, of the Orthotic and Prosthetic Laboratories, Inc., St. Louis, MO, for expert advice and for producing the plaster casts.

REFERENCES

1. Grindon JR. Non-contact 3-D surface digitization of the human head. In: Proceedings of the National Computer Graphics Association Conference, 1989:1:132–41.
2. Grindon JR. Optical means for making measurements of surface contours. U.S. Patent No. 4,846,577 issued July 11, 1989.
3. Grindon JR. Means for projecting patterns of light. U.S. Patent No. 4,871,256 issued Oct. 3, 1989.
4. Besl PJ. Active optical range imaging sensors. Machine Vis Appl 1988:1:127–52.
5. Vannier MW, Pilgrim T, Bhatia G, Brunsden B, Commean P. Facial surface scanner. IEEE Comput Graph Appl 1991:11(6):72–80.
6. Topper AK, Fernie GR. Computer-aided design and computer-aided manufacturing (CAD/CAM) in prosthetics. Clin Orthop 1990:256:39–43.
7. Krouskop TA, Muilenberg AL, Doughtery DR, Winningham DJ. Computer-aided design of a prosthetic socket for an above-knee amputee. J Rehabil Res Dev. 1987:24(2):31–8.
8. Lord M, Jones D. Issues and themes in computer aided design for external prosthetics and orthotics. J Biomed Eng 1988:10:491–8.
9. Saunders CG, Bannon M, Sabiston RM et al. The CANFIT system: shape management technology for prosthetic and orthotic applications. J Prosthet Orthot 1989:1(3):122–30.
10. Boone DA, Burgess EM. Automated fabrication of mobility aids: clinical demonstration of the UCL computer aided socket design system. J Prosthet Orthot 1989:1(3):187–90.
11. Sidles JA, Boone DA, Harlan JS, Burgess EM. Rectification maps: a new method for describing residual limb and socket shapes. J Prosthet Orthot 1989:1(3):149–53.

12. Houston VL, Burgess EM, Childress DS et al. Automated fabrication of mobility aids (AFMA): below-knee CASD/CAM testing and evaluation program results. J Rehabil Res Dev 1992:29(4):78–124.
13. Houston VL, Mason CP, Beattie AC et al. The VA-Cyberware lower limb prosthetics-orthotics optical laser digitizer. J Rehabil Res Dev 1995:32(1):55–73.
14. Vannier MW, Pilgrim T, Bhatia G, Brunsden B, Commean PK. Facial surface scanner, IEEE Comput Graph Appl 1991: 11(6):72–80.
15. Vannier MW, Bhatia G, Commean PK, Pilgrim TK, Brunsden B. Medical facial surface scanner, medical imaging VI. In: SPIE Proceedings 1992:1653:177–84.
16. Bhatia G, Vannier MW, Smith KE, Commean PK, Riolo J, Young LV. Quantification of facial surface change using a structured light scanner. Ann Plast Surg 1994:94(6):768–74.
17. Kohn LAP, Cheverud JM, Bhatia G, Commean PK, Smith KE, Vannier MW. Anthropometric optical surface imaging system repeatability, precision, and validation. Ann Plast Surg 1995:34:362–71.
18. Commean PK, Smith KE, Bhatia G, Vannier MW. Geometric design of a multisensor structured light range digitizer. Opt Eng 1994:33(4):1349–58.
19. Commean PK, Smith KE, Cheverud J, Vannier MW. Below knee residua surface measurement precision and repeatability. Arch Phys Med Rehabil. In press.
20. Smith KE, Vannier MW, Commean PK. Spiral CT volumetry of below knee residua, IEEE Trans Rehabil Eng 1995:3(3): 235–41.
21. Smith KE, Commean PK, Bhatia G, Vannier MW. Validation of spiral CT and optical surface scanning for use lower limb remnant volumetry. Prosthet Orthot Int 1995:19:97–107.
22. Godhwani A, Bhatia G, Vannier MW. Calibration considerations in a multisensor 3-D scanner. Opt Eng 1994:33(4): 1359–67.
23. Robb RA, Hanson DP, Karwoski RA, Larson AG, Workman EL, Stacy MC. Analyze: a comprehensive, operator-interactive software package for multidimensional medical image display and analysis. Comput Med Imaging Graph 1989:13(6):433–54.
24. Robb RA. Three-dimensional biomedical imaging: principles and practice. New York: VCH Publishers, Inc., 1994.