Orthotics and Prosthetics, Volume 41, Number 4, pp. 57–65.

A Computerized Ultrasound Shape Sensing Mechanism

Virgil Faulkner, B.S., C.P.O.
Nicolas E. Walsh, M.D.
Norman G. Gall, M.D.

INTRODUCTION

The most important aspect of a lower extremity prosthesis is socket design. The design determines the prosthetic fit which affects cost, suspension of the prosthesis, comfort, energy expenditure, and ultimately the utility of the device in patient ambulation. To quote T. Walley Williams, "A socket is unique to each patient and socket fabrication and fit are the essence of the prosthetic art."[10] There are several disadvantages to the present method of prosthesis socket fabrication and fitting. First, the prosthesis is primarily the result of hand craftmanship. Because of this, there is no scientific way to quantify and accurately record details of modifications made to produce the finished socket. Second, the present method of fabrication involves making a positive plaster model, which is a modified replica of the topographical shape of the residual limb. During the fabrication process, this model is often destroyed thus eliminating any topographical record of the limb for future reference. It is well known that the average amputee will require several new sockets during the residual limb maturation process following the amputation. Many amputees will require periodic replacement of the prosthesis as long as they live.[5,9] Each time the process must start anew without the benefit of information previously gained. The lack of topographical data also makes it impossible to describe "typical" changes that occur in the residual limb, thus deterring development of a socket which would have a longer optimal fit.

Limited attempts have been made to image the residual limb for research purposes. Fernie, et al.[4] in Toronto have used a video camera and laser sensing system to provide topographical information for student prosthetists. Investigations by Oshimna and Saito[8] and Aguallo, et al.[1] using a three-dimensional digitizer for shape sensing have provided early data in the use of computer assisted design for prosthetic devices. Researchers at Baylor University are in the early investigation stages of evaluating ultrasound as a tool for predicting load shape of residual limbs.[6]

The Rehabilitation Engineering Laboratory (REL) at the University of Texas Health Science Center in San Antonio has explored three-dimensional reconstruction of the residual limb from computerized tomography image data using the CEMAX-1000 computer system with excellent data acquisition, but at a prohibitive cost.[3]

The Veteran's Administration Research and Development Section under the direction of Dr. Margaret Giannini held a four day seminar/workshop to evaluate state-of-the-art techniques of CAD/CAM in prosthetics and orthopedic footwear in the fall of 1985. Participants from the United States, Canada, and European rehabilitation communities concluded that there is a need for development and evaluation of automated shape sensing devices and CAD/CAM of artificial limbs.[11]

The greatest barrier to the implementation of CAD/CAM in prosthetics is the inability of the prosthetist to capture the exact topographical shape of the amputee's residual limb. Once objective shape information is stored in the computer, it is relatively easy to then devise a computer program that will allow the prosthetist to manipulate the shape for socket design. When this shape is perfected, it can be transmitted to a computer controlled milling machine for socket or positive model manufacture. If the previous socket design information was available, it would be possible to maximize the fit of the prosthesis each time a new one was needed, based on the computer generated data.

METHODS

To shape sense a residual limb, the Rehabilitation Engineering Laboratory at the University of Texas Health Science Center at San Antonio (REL) used an ultrasonic transducer mounted on a servomotor controlled carriage. The assembly was controlled by a personal computer and was mounted in a tank of water to provide a medium in which ultrasonic pulses/echos were transmitted. The carriage allowed the transducer to be rotated horizontally 360° in 0.5° steps and to move vertically 7″ in 0.01″ steps around the surface of a lower extremity limb placed in a stationary position in the tank (Figure 1).

An A-mode control module sends pulses at regular intervals (100HZ-10KHz) to the transducer. A pulse causes the transducer to send an ultrasonic wave front through the water. When the wave front encounters tissues of varying density, a return echo is produced, which is detected by the transducer. The pulse from the control module is also used to trigger a frequency counter configured for interval timing. The return echo from the transducer is then amplified and filtered to provide a gate signal for the frequency counter. The counter measures the elapsed time between the trigger pulse and the first return echo (Figure 2). The counter is then disarmed until the next trigger pulse. This measures only the surface of the residual limb; Tissue under the skin, bone, and the back surface of the limb is not detected. The counter reading is directly proportional to the distance between the transducer head and the surface of the limb, and the distance is accurate to within 0.002″ on a surface perpendicular to the beam axis (Figure 3). A small error occurrs when the surface being scanned is not

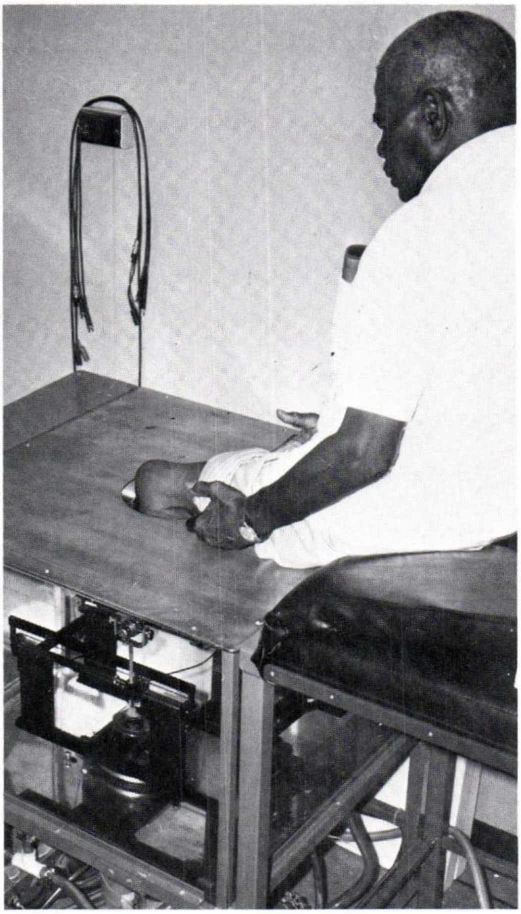


Figure 1-A. A patient's residual limb is scanned by the ultrasound shape sensing device.

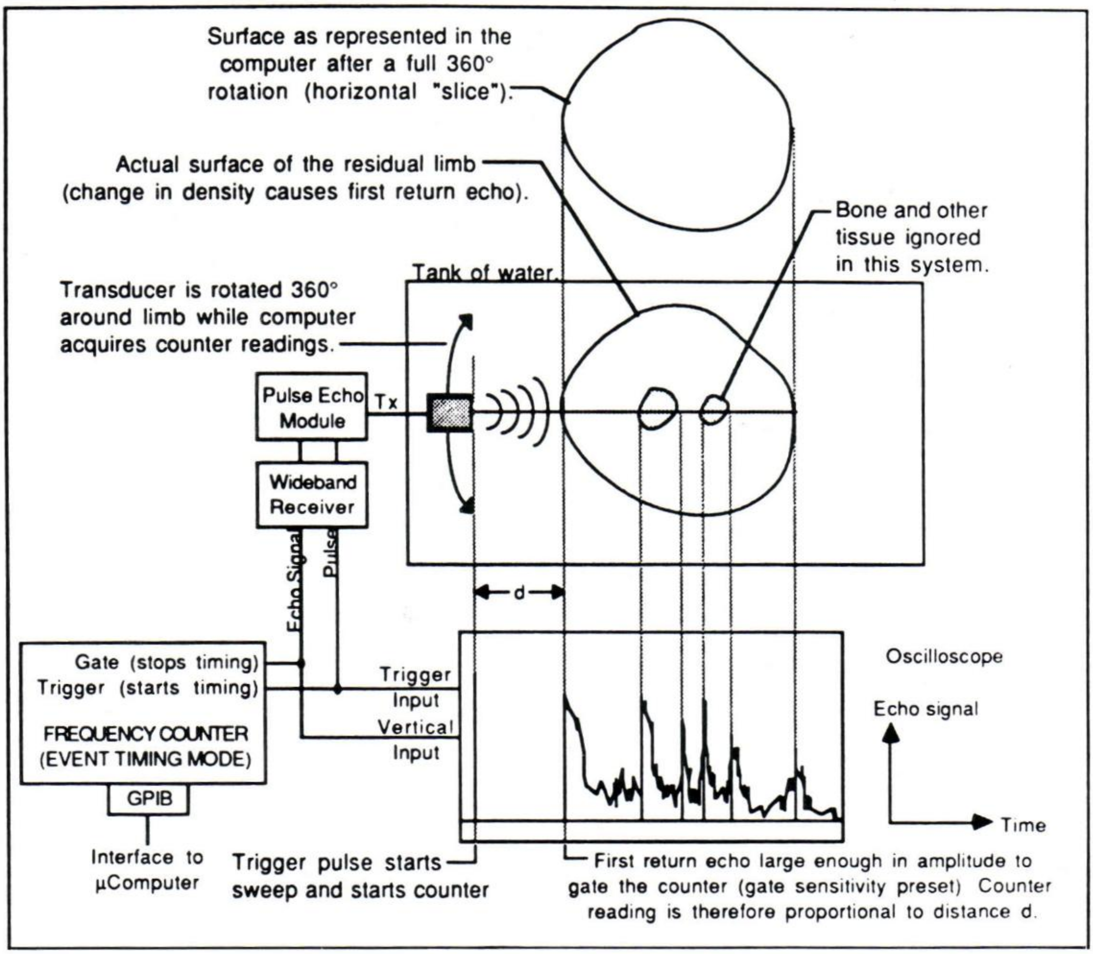


Figure 2. Operation of the A-mode Ultrasonic transducer and analog electrics subsystem.

perpendicular to the beam axis (Figure 4). This error can be minimized by selecting a transducer with the appropriate focal length and beam pattern.

The computer controls the position of the transducer by sending a pulse train through a parallel interface circuit to the servomotor controllers (Figure 5). Data representing the distance from the transducer to the residual limb surface is acquired from the frequency counter through a GPIB interface board (Figure 6). As the computer rotates the transducer around the limb, readings are taken from the frequency counter and converted to absolute x and y coordinates. These coordinates represent a horizontal "slice" of the residual limb surface. After a full 360° rotation, the transducer is moved vertically a known distance and another slice is acquired. Each slice is located on a known z coordinate and is combined with the x and y data to reconstruct the topological surface of the residual limb.

The program which runs the data acquisition procedure may be configured by the operator by varying the number of data points per slice (280 max), the number of slices acquired (99 max), the distance between slices (0.01″ to 7″), etc. This program is also used to convert the data into a format compatible with the commercially available "Advanced Space Graphics" CAD program. This software product is used to display, rotate, translate, scale, and modify the topological surface (Figure

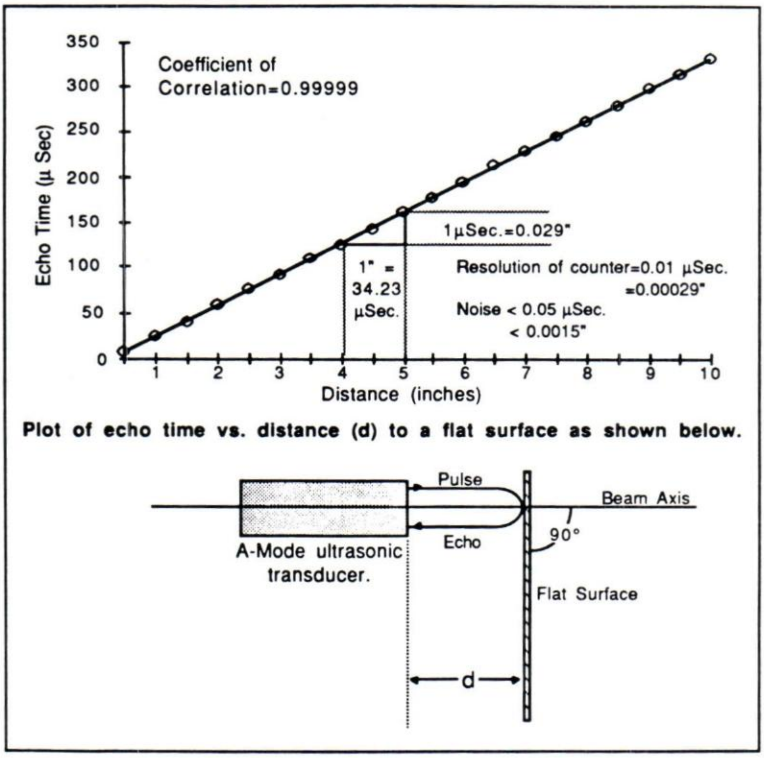


Figure 3. Arrangement used to measure accuracy of the ultrasonic transducer.

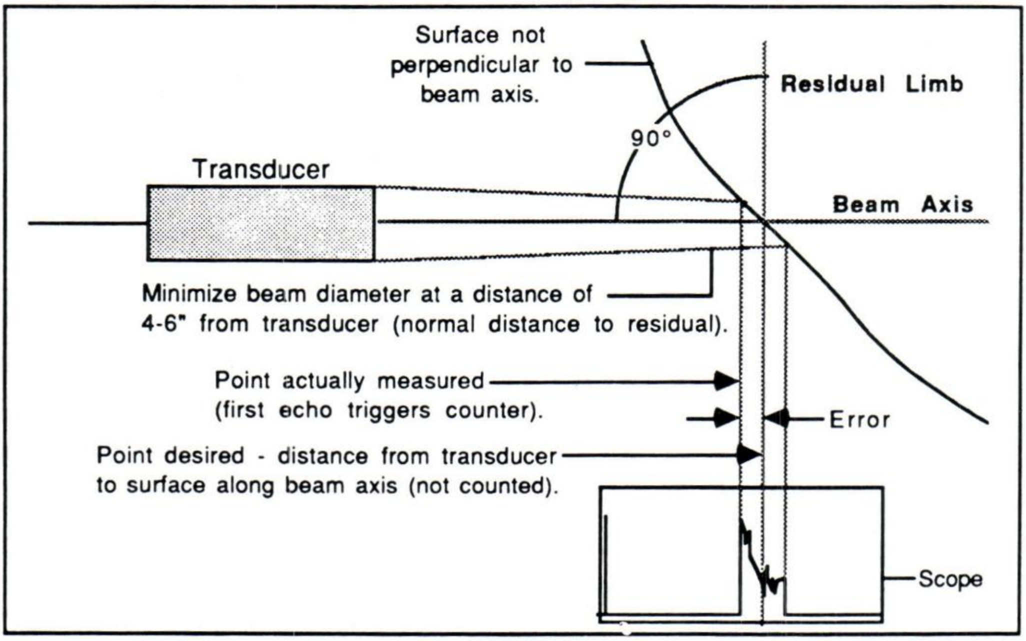


Figure 4. Effect of ultrasonic beam pattern on accuracy when scanning a surface non-perpendicular to beam axis.

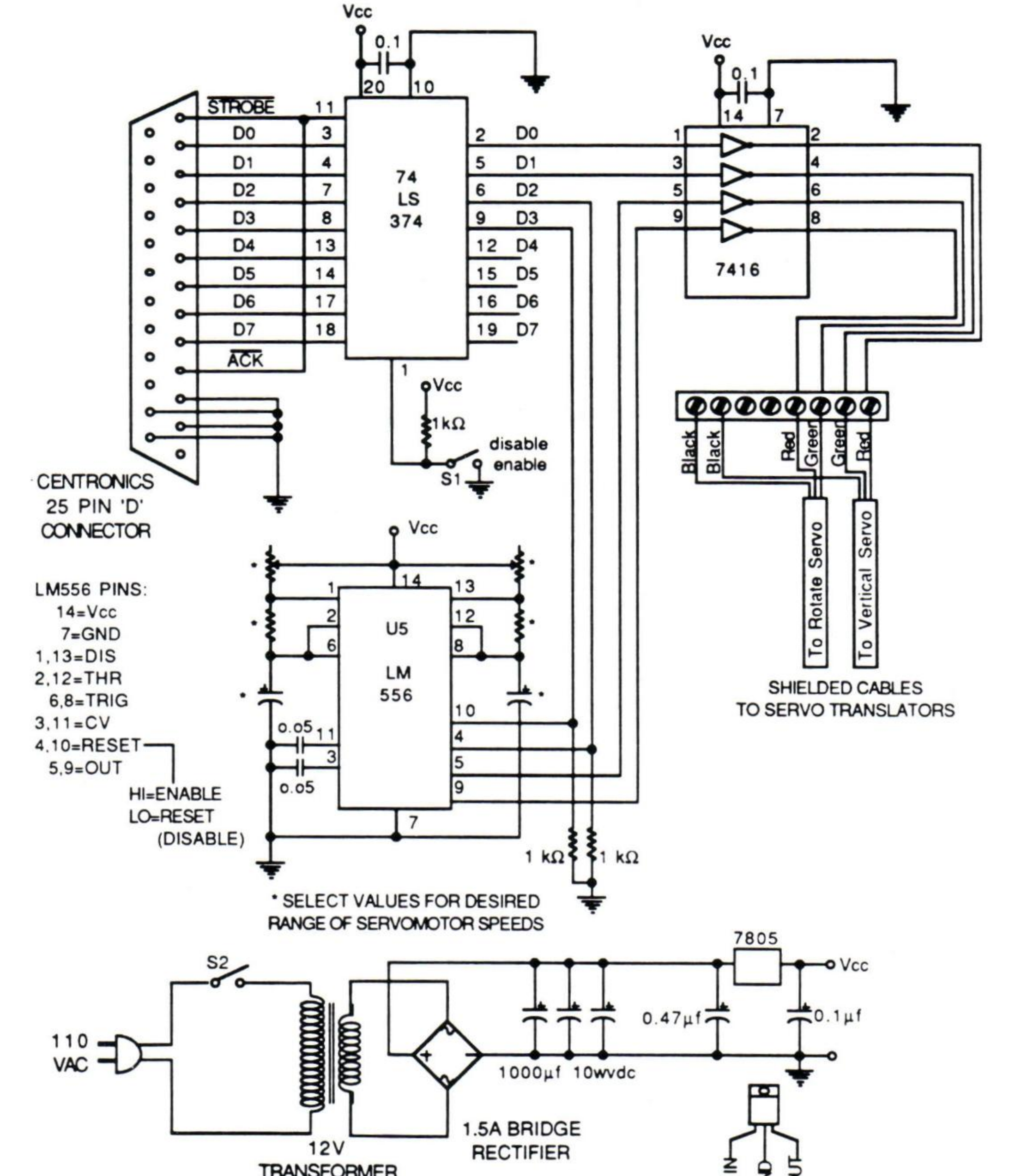
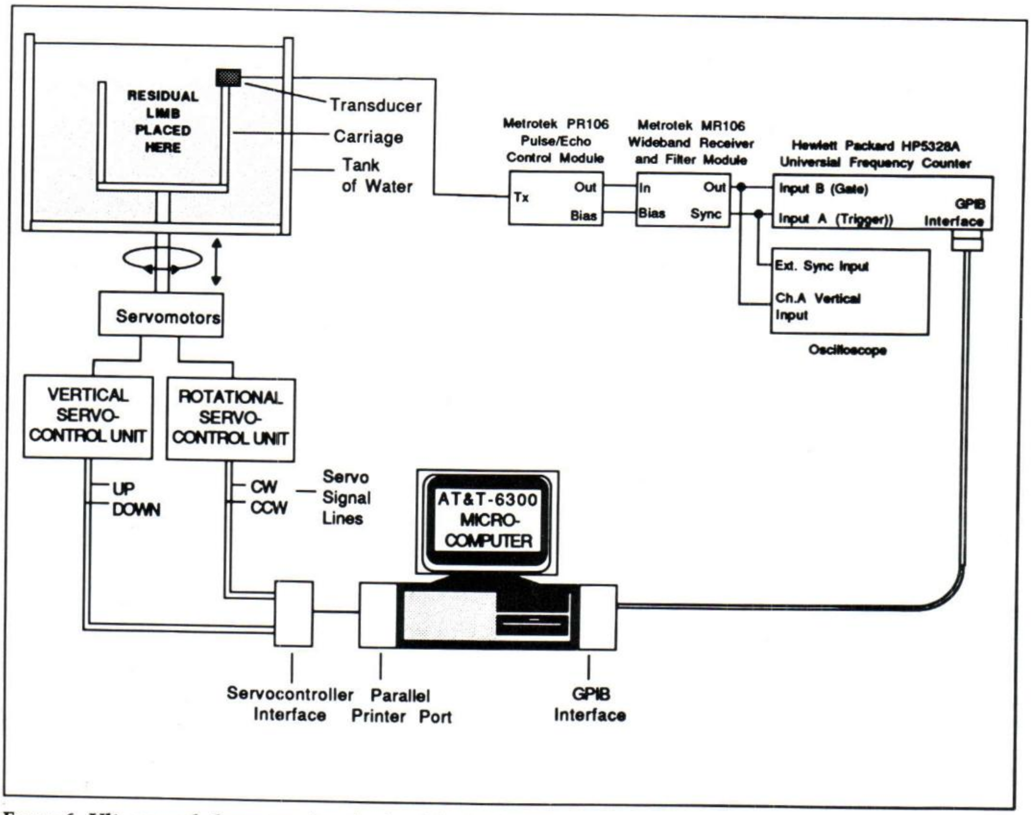


FIGURE 5.

Figure 5. Servo translator interface to the centering parallel port.



Fgure 6. Ultrasound shape sensing device, block diagram.

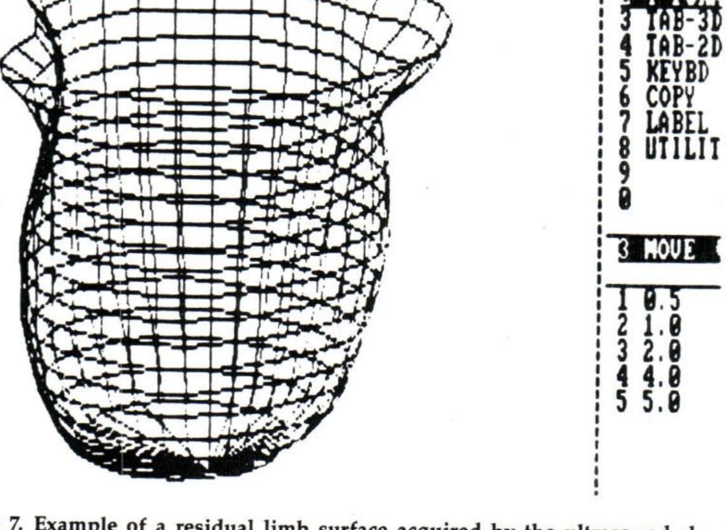


Figure 7. Example of a residual limb surface acquired by the ultrasound shape sensing device and displayed with the advanced space graphics program.

7). The REL has developed software to reformat the data for compatibility with a Computer Controlled Milling Machine.

RESULTS

The ultrasound shape sensing device currently in use at the San Antonio REL is capable of producing an accurate computer generated topographical image of a residual limb. The system is composed of two basic subsystems; the ultrasound and analog electronics subsystem, and the computer based data acquisition and control subsystem.

An image of a patient's residual limb is automatically generated in about ten minutes; the time is determined by the residual limb's length. The data representing the topological shape of the limb is stored on the computer's hard disk unit as a set of x, y, and z coordinates. This data is then available for modification by a number of custom and commercially available application programs. The ideal program would allow a prosthetist to easily modify the data, reshaping the topological surface according to normal prosthetic principles. The final version of the data may be sent via modem to a fabrication facility for socket or positive model manufacture.

DISCUSSION

The ultrasound shape sensing device (USSD) was developed as a proof of principle project. It has demonstrated high resolution for the perpendicular areas of the residual limb, but is less accurate when describing the distal end by utilizing the present scanner pathway. The USSD is limited to seven inches of vertical movement with the present carriage assembly. This is an inadequate range for patients with longer residual limbs. Therefore, these design limitations are being corrected.

Future hardware enhancements of the system will allow it to quickly and accurately capture the residual limb's surface and bone topography. Software enhancements will include a smoothing routine for the topological surface, utilizing user-friendly real-time interaction.

An algorithm, offered by Fujio Yamaguchi[12] may be used to accomplish this curve smoothing. This method is extremely fast and simple, requiring no multiplication or division by the computer. This routine will add more points to those already existing in the data set and smooth the topological surface. Because points are added, fewer points need to be acquired in

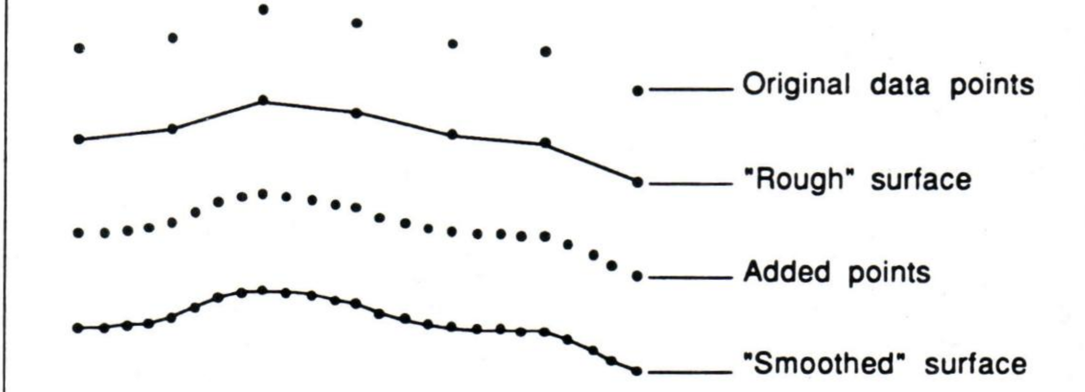


Figure 8. Example of how the curve smoothing routing would add points to a topological surface.

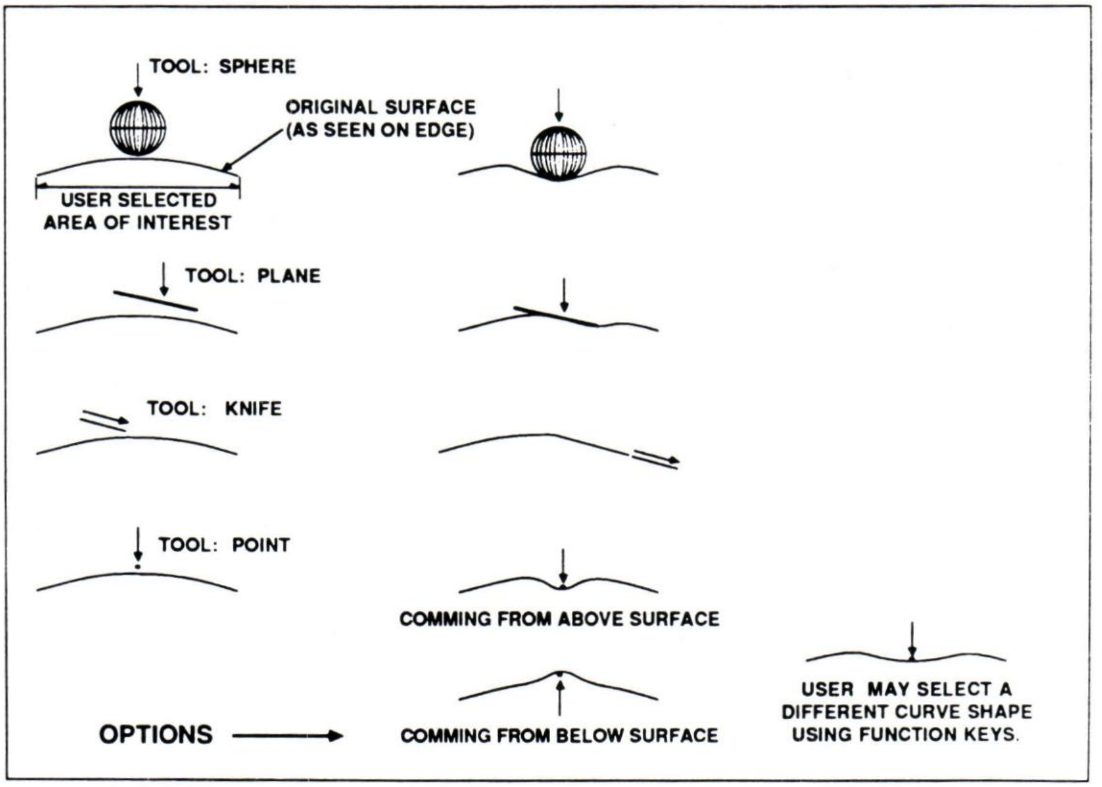


Figure 9. Examples of surface modification routines. The graphics cursor is shown as a "tool," and is used to modify the surface in real-time.

the scanning process, resulting in a decreased amount of time necessary to scan a patient (Figure 8).

A method described by Brewer and Anderson[2] for designing a CAD program allowing free form modification of a surface will be used for modification (Figure 9). This program provides the display of selected areas of interest including points to be modified, so other points will not be affected. The user may then select a "tool" to modify the surface. The tool is displayed on the cathode ray tube and may be moved about with the cursor control keys. As the tool is moved to the surface, all points in the area of interest are modified. How the points are modified depends on the tool selected and its characteristics. This offers a vast improvement over the Advanced Space Graphics Program, which only allows modifications on a point by point basis.

CONCLUSION

The current system for prosthesis design and fabrication is a very expensive and time consuming endeavor, which is beyond the reach of many third world countries[7]; CAD/CAM may make prosthetics and orthotics available to amuptees in these regions.

The greatest barrier to the implementation of a computerized system for making these apliances is the inability of the prosthetist to capture the exact topographical shape of the affected limb. A proof of concept ultrasound shape sensing device, that provides a computer controlled method to obtain descriptive topographic data of an amputee's residual limb, has been developed. While design limitations of the prototype device require modification, the application of ultrasound technology for topographical quantification of residual limbs appears promising.

REFERENCES

[1]Aguallo, G.M., V.W. Faulkner and R.G. Waggner, "Digitizing the Positive Model of the Residual Limb With the Preceptor®," The 14th Annual Minority Biomedical Research Support Symposium, New Orleans, Louisiana, April, 1986.

[2]Brewer, J.A. and D.C. Anderson, "Visual Interview with Overhauser Curves and Surfaces," *Computer Graphics,* 11, Summer, 1977.

[3]Faulkner, V.W. and N. Walsh, "Computerized Tomography as an Aid to Prosthetic Socket Design," Proceedings 38th Annual Conference on Engineering in Medicine & Biology, Baltimore, Maryland, September, 1986.

[4]Fernie, G.R., A.P. Halsall and K. Ruder, "Shape Sensing as an Educational Aid for Student Prosthetists," *Prosthetics and Orthotics International,* 8, 1984, pp. 87–100.

[5]Klasson, B, "Computer-Aided Design, Computer-Aided Manufacturer and Other Computer Aids in Prosthetics and Orthotics," *Prosthetics and Orthotics International,* 9, April, 1985, pp. 3–11.

[6]Krouskop, T.A., B.L. Goode, D.R. Dougherty and E.H. Hemmen, "Predicting Load Shape of an Amputee's Residual Limb," Proceedings 8th Annual Conference on Rehabilitation Engineering, RESNA, Memphis, Tennessee, 1985, pp. 222–223.

[7]Neumann, W.M., "Academy News," *AOPA Almanac,* 36(10), October, 1987, p. 46.

[8]Oshima, T. and Y. Saito, "CAD/CAM System Applied To The Foot Shape For The Prosthetic Device," Proceedings 8th Annual Conference on Rehabilitation Engineering, RESNA, Memphis, Tennessee, 1985, pp. 222–223.

[9]Stokosa, J., "Prosthetics for Lower Limb Amputees," *Haimovici H: Vascular Surgery,* Norwalk, Connecticut, Appleton-Century-Crofts, 1984.

[10]Williams, T.W., "The Boston Elbow; The Path to a Mature Myoelectric Prosthesis," *Engineering for the Human Body, SOMA,* 1, July, 1986, pp. 29–33.

[11]Wilson, A.B., "Rehabilitation Research and Development Service," Workshop on the Application of CAD/CAM Techniques to Prosthetics, La Jolla, California, September 19–20, 1986, p. 3016.

[12]Yamaguchi, F., "A New Curve Fitting Method Using a CRT Computer Display," *Computer Graphics and Image Processing,* Academic Press, 1973, p. 7.

AUTHORS

Virgil Faulkner, B.S., C.P.O., is Assistant Professor at the University of Texas Health Science Center, Department of Physical Medicine and Rehabilitation, 7703 Floyd Curl Drive, San Antonio, Texas 78284.

Nicolas E. Walsh, M.D., is Associate Professor at the University of Texas Health Science Center in San Antonio, Texas.

Norman G. Gall, M.D., is also an Associate Professor at the University of Texas Health Science Center in San Antonio, Texas.