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Prosthetic shape replication using a computer controlled carving technique

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Abstract

This paper describes a carving machine which is the most recently developed module in the suite of CAD/CAM equipment for high technology manufacture and supply of prostheses. It provides the link between the Computer Aided Socket Design (CASD) system and the Rapidform socket manufacturing process. Using the coordinate data produced by the CASD system this machine, under computer guidance, carves from a large block of suitable material a three dimensional object; the equivalent of the rectified plaster model produced by conventional techniques. This provides the form for the fabrication of a socket and the facility completes an integrated system for fabricating, rapidly and cheaply, high quality lightweight prostheses for patients.

Introduction

At the end of the Computer Aided Socket Design process a set of surface coordinate data is held in the disk storage of the computer. This represents the desired internal shape of the socket for an artificial limb, ie the shape which would be evident in a rectified model produced by a prosthetist using traditional techniques with plaster. In order to convert these data into the equivalent 3D object a computer controlled machine is used which, by tracing out the surface coordinates, carves the required shape from a suitably mounted block of material.

Such computer controlled carving or milling machines are becoming widely used in general engineering industry, but because the materials to be machined in this application are soft and generate low cutting forces the machine stiffness specifications can be kept quite low. In addition, accuracy requirements are lower than in many engineering applications. These factors have permitted the Bioengineering Centre's design of carver to be built economically.

The carver can be used with data prepared from other sources and is likely to have applications in the shaping of cosmetic covers for prostheses and in the manufacture of orthopaedic footwear. It may also be used, in conjunction with a suitable digitizing system, to duplicate existing cast or socket shapes.

Carver design

A rigid, box section framework was built as the basis of the machine (Fig. 1). The cutter, an

Fig. 1. The computer controlled carver carving a stump model.

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extra long end mill with a hemispherical end form, is fitted into a special nose unit on the end of a 3,000 rpm motor which can be moved horizontally and vertically on a pair of slideways which form the X and Y machining axes.

Below the cutter the blank of material to be carved is cantilevered from a rotary table positioned with its axis (R) parallel to the cutting head's horizontal axis. Stepper motors control the movement on each of the 3 axes allowing movements accurate to 0.0125 mm on the linear axes and to 0.01 degrees of rotation.

One of the characteristics of stepper motors is a loss of torque as the stepping rates are increased. This limits the cutter accelerations which can be achieved giving rise to problems when rapid changes in displacement are required. The vertically mounted cutter and drive motor constitute a large mass which would normally have to be supported by the y axis drive motor. A gas strut has been used to balance out this load but the inertial loads remain high and experimental work was required to determine the acceleration and velocity characteristics for the system. These characteristics are represented in a 'look-up' table stored in the carver's microprocessor memory.

During machining, the X and Y axes are run at a constant speed so that the cutter traces a helical path through the blank. The data manipulation within the socket design program is carried out on the absolute radial coordinates of points arranged on a rectangular grid and before transmission to the carver's microprocessor these values are converted to relative coordinates on the appropriate helical grid (Fig. 2). For speed of operation this data manipulation is achieved by the computer used to design the socket. The data file is then transmitted to the carver through a standard RS232 serial link and if necessary a remote prosthetic centre could send the data over the telephone line to the carver at a central fabrication site. Each coordinate transmitted is accompanied by a velocity index which, by reference to the 'look-up' table held in the computer, keeps the axes synchronized together.

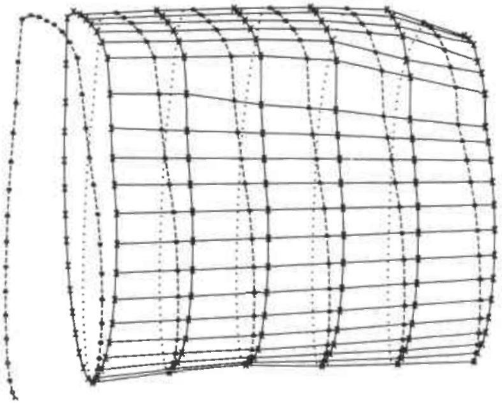

Fig. 2. The arrangement of data points (x) used in the Computer Aided Design of sockets and the corresponding helical path (o) used during the carving operation.

System operation

There is a compromise between (a) the speed of cut, (b) the coarseness of the coordinate data and (c) an acceptable finish on the replica. Any resolution can be obtained but the finer the resolution then the longer the machining time.

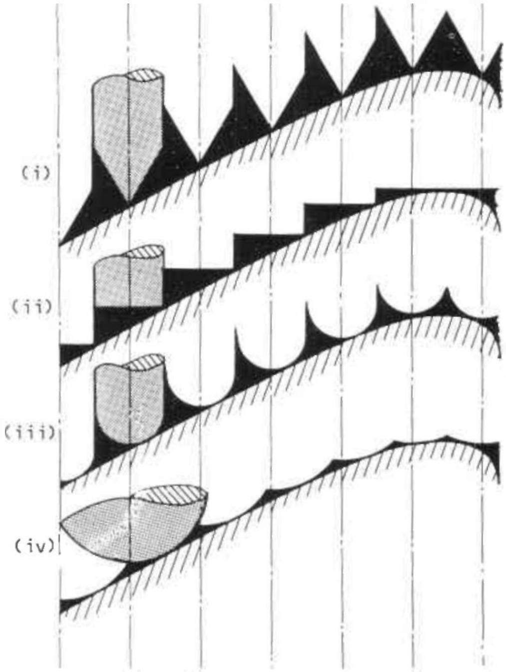

Fig. 3. Material left between successive passes of
i) A conical cutter
ii) A flat ended cutter
iii) A small spherical cutter
iv) A large spherical cutter

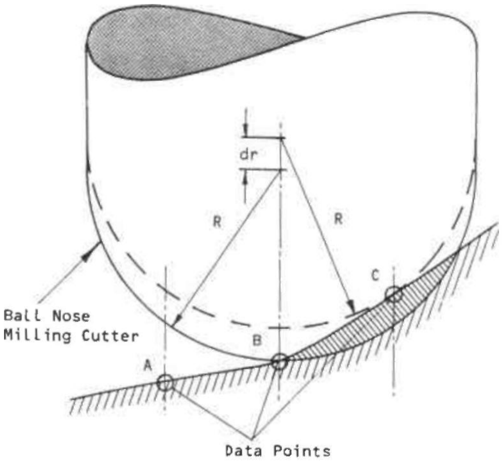

Fig. 4. The radial adjustment, dr, necessary with a large cutter to avoid inadvertently removing material from a neighbouring point, C, while machining point B.

With coordinates at 10 degree increments around the surface on a 6.35 mm pitch helix (as provided by the MERU CASD program), the speed of cut could be set so as to yield an overall machining time for completely shaping a positive (cast) of about 10 minutes. The resulting ridges are illustrated in Figure 3 in the form of successive passes by cutters with different end forms and for different sizes of cutter. Although a large diameter cutter gives a smoother surface than a small cutter, it introduces the chance that, while machining one point, the cutter will inadvertently remove some material from neighbouring points (Fig. 4). Since the 18 mm cutter currently used is wider than the pitch of the helical path the program used to prepare the data for the carver includes an interference checking routine which, when required by a particular combination of local surface geometry and cutter size, can make radial adjustments to the cutter position. The selection of the cutter size used in the carver is a compromise between the cusp size and the need to make interference adjustments.

The first three illustrations in Figure 3 show the cusp lying midway between the centre line of successive cutter paths. This suggests that an intermediate pass by the cutter, using interpolated data, would reduce the height of the ridges on the model. Unfortunately, as Figure 3 (iv) shows, on the generalized surface the position of the cusp appears to move relative to the cutter centre line. It is considered essential to eliminate the need for any hand finishing to the carved model before it is used. Options which are being explored include following the cutter with a hot air jet if wax is the medium, or employing a second high speed milling pass along an intermediate helical path to clean off the ridges.

Several materials have been used for the blocks from which the socket model is carved. Rigid polyurethane foam cuts very easily and is quite widely used in the prosthetics industry but produces an abrasive dust when carved. This, together with the toxicity of the raw material, its tendency to blunt cutting tools and the difficulty of removing the positive from a finished socket has led to its being rejected from the Bioengineering Centre system.

Instead, wax of various grades has been used for most of the work. This has a number of advantages—it is easy to cut and self lubricating, reducing tool wear; it is clean and odourless when it is cut; it does not produce dust; and it is re-usable over and over again. However, it has not been easy to produce flawless large wax blocks. Voids can occur as the material cools and shrinks, requiring careful control to be exercised throughout. This has increased reliability, but further work is proceeding on alternative materials and a number of blends of plaster, for example, are currently being evaluated.

Results

The carving process with wax blanks has been used regularly over a period of more than a year with a depth of cut of up to three inches (75 mm). When the carved positive is used to form a socket in the Rapidform machine some slight melting of the surface of the wax does occur during the brief time when it is elevated into the oven. During this time, however the thermoplastic preform which is being shaped into the final socket effects a seal on the wax under vacuum conditions. Thus, there is no place for the wax to go, volume is preserved, and any changes in contour are within the tolerance of the rest of the system. Consequently final socket fit is sensibly unaffected by the computer aided manufacturing processes of carving in wax and vacuum forming in thermoplastic.

The carver has been used in the U.K. trials of the CASD system and the overall principles of the process have been proven.

Conclusions

This specially developed shape replication machine is able to generate the shape of a typical below-knee stump within about ten minutes. Thus, in routine practice, it is possible to reach the stage of having a rectified replica of a patient's stump (equivalent to a plaster cast) in an elapsed time of less than 30 minutes. It fills an essential role in the high technology procedures being proposed and explored in the U.K. and Canada—bringing fully integrated prosthetic treatment systems a further step forward.

There are of course many areas for improvement. A better material for blanks would exhibit a combination of carvability, low cost and ease of removal from the finished socket. An algorithm needs to be developed for improving surface finish. Applications of the carver to produce cosmeses and to model foot deformities need to be pursued. Finally, the actual form of the machine and its method of operation, conventional though it is in engineering practice, needs to be questioned. There may very well be a better approach for this particular bioengineering application.

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