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# Non-Contact Shape Measurement and Machining of Curved Three-Dimensional Objects

Takeshi KISHINAMI, Tooru KAWABATA, Tadashi KOYAMA*
and
Katsumasa SAITO

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## Abstract

Utilizing a ranging system, consisting of a laser, TV-camera and N/C machine tool, three-dimensional images of curved three-dimensional objects were obtained. The object was defined by many mesh point coordinate data which were given by the laser ranging system.

After measuring curved three-dimensional objects, the mesh point coordinate data were transfered into the Interactive Machining System, which consists of computer and direct numerically controlled machine tool, in an attempt to manufacture some curved three-dimensional objects.

By using this system, we can easily and quickly machine curved three-dimensional models from untouchable curved objects.


## 1. Introduction

Machining of curved three-dimensional objects is a highly advanced new field. There are some technical barriers, such as, how to define the shape of a curved three-dimensional object and how to machine the same automatically. Generally, in order to define the shape of curved three-dimensional objects, we generally use mesh point data and interpolation formulas.

Methods for accurality and readily obtaining mesh point data are now the most important problems which must be solved by industry. A laser and TV camera non-contact ranging system will be useful method for solving the above mentioned problem. We have already developed the Interactive Machining System for machining of curved three-dimensional objects [1]. This system makes it easy for us to machine some curved three-dimensional objects, if the mesh point data are given.

This paper describes an experimental apparatus of a ranging system which consists of laser, TV camera and N/C machine tool, which is located on the spindle head of N/C machine tool instead of the cutting tool, which combines the system of laser ranging system and Interactive Machining System. Lastly, some examples of measuring results and machined objects are described.

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Department of Precision Engineering, Faculty of Enginnering, Hokkaido University, Nishi-8 Kita-13 Kita-ku, Sapporo 060 Japan.

*Toyoda Ko-ki, Robot Division, Asahi-machi, Shintomi-cho, 1-1 Kariya-shi, Aichi-ken, Japan.

## 2. Laser Ranging System

The ranging system may be briefly described as a laser which projects a beam of light on the object to be scanned, and a TV camera which detects the spot of laser light as it illuminates the curved objects. A calibration procedure determines the relative position of the laser with respect to the TV camera, so that, depth information may be derived from the video image. Fig. 1 shows a general view of the apparatus of ranging and machining systems.

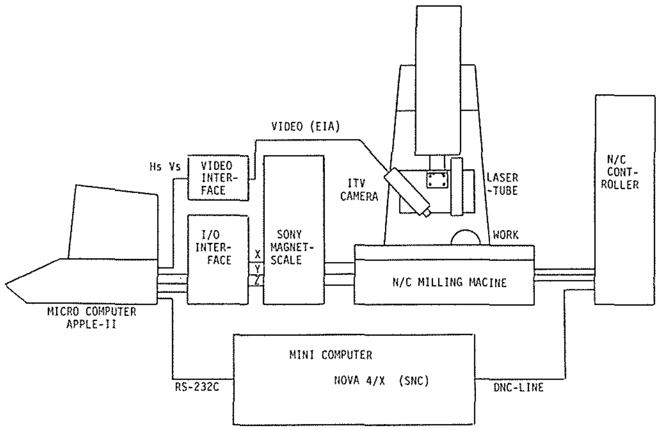


**Fig. 1** Scheme of experimental system

Ranging information are so clearly relevant to the three-dimensional shape of objects that many investigations of its use in scene analysis have by and large been ignored as to the intensity of information. Thus Agin and Binford [2] , Nitzan, Brain and Duda [3] , Shirai and Suwa [4] , and Sato and Fujita [5] have basically been concerned with various ways to describe objects by fitting surfaces to range data. But these methods are based on the fixed relative position of laser or light source, TV camera and objects.

The basic principle of the proposed method is the triangulation method which is well known. By controlling the relative position of laser and object with N/C machine tool, the coordinates of spots on the object are detected from the video image and coordinate system of N/C machine tool.

2-1 Experimental Apparatus of Ranging System

The non-contact laser ranging system consists of laser, TV camera (SONY AVC-1500) and micro-computer (Apple II). We use a helium-neon laser emitting about 5mW of red light at wave length of 6328A°. Since, the laser tube is portable, so we can easily set it on the spindle head of N/C machine tool. To simplify the calculation of a laser spot position on an object, we use the fixed relative position between laser tube and TV camera on one bracket (see Fig. 1).

The x, y coordinates are taken into the micro-computer from the scale counters of N/C machine tool. And the z coordinate of a spot on an object is taken in via the video image of TV camera.

2-2 Measuring Method

The bracket on which the laser tube and TV camera are fixed, is set on the spindle head of N/C machine tool instead of the cutting tool. Measuring is done by moving the laser ranging system with N/C machine tool over the surface of the object that is to be measured.

Fig. 2 shows the scheme of laser ranging system. X, Y and Z coordinates are fixed as shown in Fig. 2. And the partial coordinate system on a target plane of TV camera is called H-V coordinate on H-V plane.

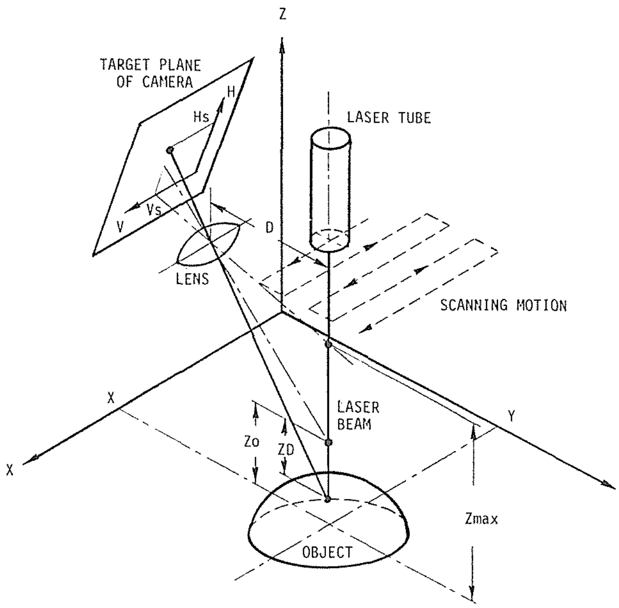


**Fig. 2** Scheme of laser ranging system

The distance from the lens center to laser beam is defined by D as shown in Fig. 2. The angle between laser beam axis and the lens center axis of TV camera is defined by $\theta$. f is the distance from the center of the lens to the target plane (H-V plane). Hs, Vs are the coordinates of the laser spot image on an H-V plane.

The laser beam is set vertical to Y-Y plane, and the TV camera is set at a position D distance away from the laser beam at an angle $\theta$ as the laser beam axis. The origin on H-V plane of TV camera is the point where the electron beam begins its scan ; the direction of scanning is plus coordinate direction.

During the measuring operation, the position of the laser spot changes H coordinate about on H-V plane, because the relative position of laser tube and TV camera is fixed, and the laser spot on the object moves on the plane which involves the laser beam axis and lens center axis. The distance Zd between the laser spot position on the object and the cross point of laser beam axis and lens center axis, as shown in Fig. 3, is given by the equation (1).

$$Zd=\frac{D}{\tan(\theta-\varphi)} \tag{1}$$

where,

$$\varphi=\tan^{-1}\left[\frac{Hs-Ho}{f}\right]$$

Ho : H coordinate of the lens center axis on H-V plane.

Then, Z coordinate of the spot on the object is given by equation (2).

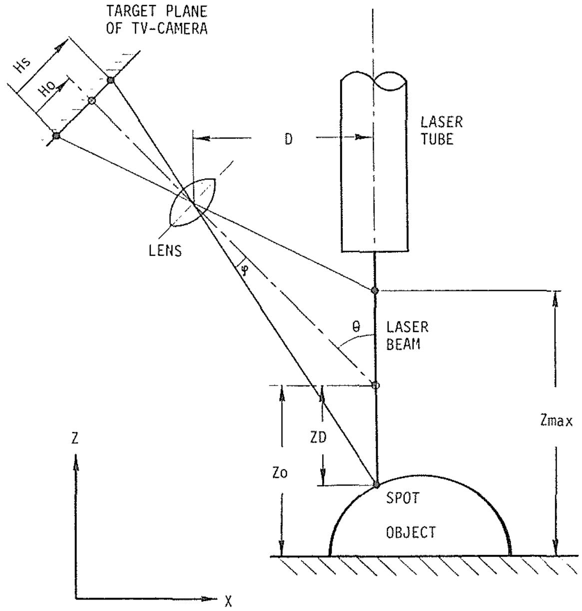


**Fig. 3** Geometrical Rerationship among Laser, TV and Object

$$Z = Zo - Zd \tag{2}$$

where, Zo is the distance from Y-Y plane to the cross point of laser axis and lens center axis.

2-3 Hardware

In order to obtain the position of the laser spot image, as quickly as possible hardware circuit which consists of three main circuits, that are, a syncronizing separator circuit to separate the horizontal and vertical syncronizing signals of the video signal, counter circuit for detecting the spot position, and trigger circuit for recognition of the spike pulse which is given by the spot image on the target plane of TV camera.

The video output signal was obtained by scanning the target plane of TV camera, and sent to the special hardware circuit. Fig. 4 shows an example of the vdieo output signal. The first wide downward pulse is the vertical syncronizing pulse. This vertical syncronizing pulse is the beginning signal of a screen data. The next narrow down-ward pulse is the horizontal syncronizing pulse which is the beginning of one horizontal line in a screen.

The spike pulse between two horizontal syncronizing pulses corresponds to the boundary of spot image on target plane. By watching and averaging a number of spike pulses on some horizontal lines, we can estimate the position of laser spot image on the target plane. In Fig. 4, the position of the spot image on H-V coordinate corresponds to the time Tvs and Ths on video signal. In order to detect the time Tvs and Ths, the interval time Tv and Th between vertical syncronizing pulses and horizontal syncronizing pulses respectively are divided into 256 small interval times with an 8 bit counter, and the special hardware circuit has a function to start and stop the Tv counter and Th counter by detecting the syncronizing pulse and spike pulse.

In the Th counter, by watching the contents of Th counter when detecting the spike

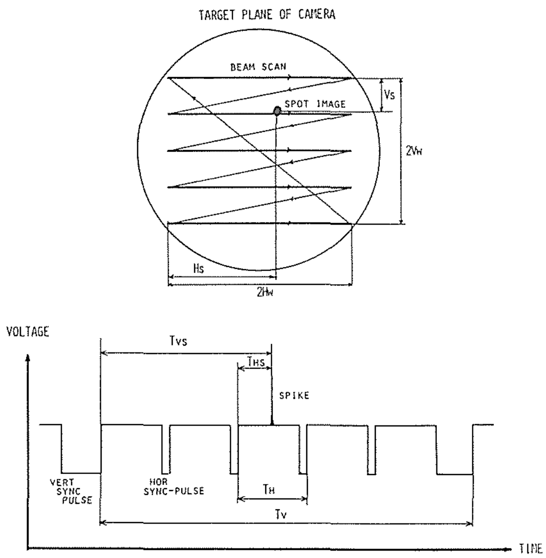


**Fig. 4** Video Signal

pulse, we can easily know the horizontal position of spot on the screen. On the other hand, in the Tv counter, by counting how many horizontal syncronizing pulses have passed until detecting the spike pulse, we can easily know the vertical position of spot image on the target plane of TV camera.

For detecting the spike pulse, we prepared a trigger circuit which makes a spike pulse if the brightness of a spot image is over the threshold level. And this spike pulse also plays a role for data ready flag. When the data ready flag is received at the micro-computer, the contents of Th and Ty counters are sent fed to the micro-computer. Fig. 5 shows the block diagram of the special hardware circuit which was used in this system.

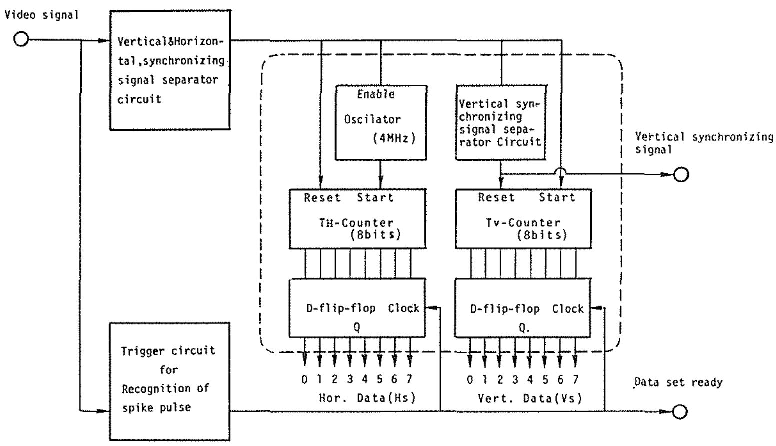


**Fig. 5** Block diagram of Hardware circuit

The micro-computer(Apple II) has 48 kbytes of memory that are free for use, a printer, mini-floppy (140 kbytes) disk and CRT. The interface that connects the ranging system and micro-computer contains a decoder circuit to decode the address of the micro-computer. By using a data bus and an address bus and read/write signal, the ranging system and micro-computer send and receive data between each other.

The micro-computer is also connected to X, Y coordinate scales of N/C machine tool. If the micro-computer desires the X, Y coordinates, it must first send a hold signal to the scale controller to lock the scale buffers, at the second, the micro-computer reads the contents of scalle buffers to obtain the X, Y coordinates. After the coordinates are read, the micro-computer then sends a release signal to the scale controller.

2-4 Software

The software of a ranging system consists of three parts. The first part plays the role of obtaining the coordinate information from N/C machine tool and laser ranging system. The second part is the software to calculate the Z coordinate from the input of laser ranging system. The third part is the software that sends the necessary data to the Interactive Machining System for machining the object shape.

We will explain each part in detail. The first part is written by MC-6502 ASSEMBLER to maintain high speed processing, because the ranging system sends one screen information every 1/60 second. The micro-computer sends a start signal to the ranging system, then the micro-computer waits for the data ready signal to come from the ranging system. The micro-computer receives certain spot point information from the ranging system for one screen. By averaging the point coordinates, the center coordinate of laser spot is calculated in the micro-computer. At the same time, the micro-computer gets the X, Y coordinates from the N/C machine tool.

2-5 Data Structure

The required data structure for the Interactive Machining System must be a mesh array structure in topological space. The most simple way of getting mesh point data of objects is by continuously moving a N/C machine tool under the scanning mode on the X-Y plane, to satisfly the restriction. In order to do so, when the difference dX and dY regarding the X-coordinate and Y-coordinate, exceed a certain fixed value, the holding signal is transmitted to X, Y coordinate scale buffers, and the contents of X and Y scale buffers are read by a micro-computer. At the same time, the Z coordinate is also read by a micro-computer.

Each coordinate data for one mesh point, consists of eight bytes in length, as show in Fig. 6. The first byte is used to indicate the end of data record. Normally this byte is zero, but at the last data, it is set to FF in hexadecimal. The second and third bytes indicate the row and column number of mesh array. The fourth and fifth bytes are for the X coordinate in binary. The sixth and seventh bytes indicate the Y coordinate in binary. The last byte is the Z coordinate. The Z coordinate is directly stored from the ranging system. When the N/C machine tool stops moving for more than 2 seconds, the micro-computer automatically judges the end of measuring operation and stores the data on the mini-floppy disk.

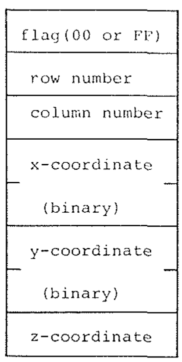


**Fig. 6** Data structure for ranging system

The second part of software takes the data from the disk and transfers binary data to decimal data and the true Z coordinate value is calculated by the caliburation method shown below. The second part is written in BASIC language and has the ability to display the data on CRT in a three dimensionally graphic mode, and to calculate the normal vector on each mesh point.

According to Coons' patch interpolation, we can completely define the curved patch shape with four corner points coordinates, 8 tangent vectors and 4 twist vectors by equation (3).

$$Q(u, v) = [F0, F1, G0, G1]_{t=u}\ [B]\ [F0, F1, G0, G1]_{t=v} \tag{3}$$

where,

$$[B] = \begin{bmatrix} Q00 & Q01 & Qv00 & Qv01 \\ Q10 & Q11 & Qv10 & Qv11 \\ Qu00 & Qu01 & Quv00 & Quv01 \\ Qu10 & Qu11 & Quv10 & Quv11 \end{bmatrix}$$

$$[F0, F1, G0, G1] = [t^3, t^2, t, 1] \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

Qij : point (i, j) coordinate vector
Quij : u-direction tangent vector on point (i, j)
Qvij : v-direction tangent vector on point (i, j)
Quvij : twist vector on point (i, j)

If at $i=0, 1/3, 2/3, 1$, $j=0, 1/3, 2/3, 1$, point coordinate vectors are known, we can easily derive the equation (4) from equation (3).

$$[B] = [F]^{-1}\ [D]\ [F^T]^{-1} \tag{4}$$

where,

$$[F] = \begin{bmatrix} F0(0) & F1(0) & G0(0) & G1(0) \\ F0(1/3) & F1(1/3) & G0(1/3) & G1(1/3) \\ F0(2/3) & F1(2/3) & G0(2/3) & G1(2/3) \\ F0(1) & F1(1) & G0(1) & G1(1) \end{bmatrix}$$

$$[D] = \begin{bmatrix} Q(0, 0) & Q(0, 1/3) & Q(0, 2/3) & Q(0, 1) \\ Q(1/3, 0) & Q(1/3, 1/3) & Q(1/3, 2/3) & Q(1/3, 1) \\ Q(2/3, 0) & Q(2/3, 1/3) & Q(2/3, 2/3) & Q(2/3, 1) \\ Q(1, 0) & Q(1, 1/3) & Q(1, 2/3) & Q(1, 1) \end{bmatrix}$$

And normal vector is defined by equation (5).

$$N(i, j) = Qu(i, j) \times Qv(i, j) \tag{5}$$

At the final stage, the third part of the software plays the role of sending this calculated data to the Interactive Machining System through the RS-232C general purpose interface. To avoid transmitting error, we use a hand shake communication method. The mini-computer receives all data from micro-computer, rearranges the data to required data structure of the Interactive Machining System as shown in Fig. 7. After doing these operations, it is possible to draw the shape on the graphic display and to machine the object shape by additing the cutting conditions in the Interactive Machining System. Fig. 8 shows the block diagram of non-contact measuring and machining system for curved three-dimensional objects.

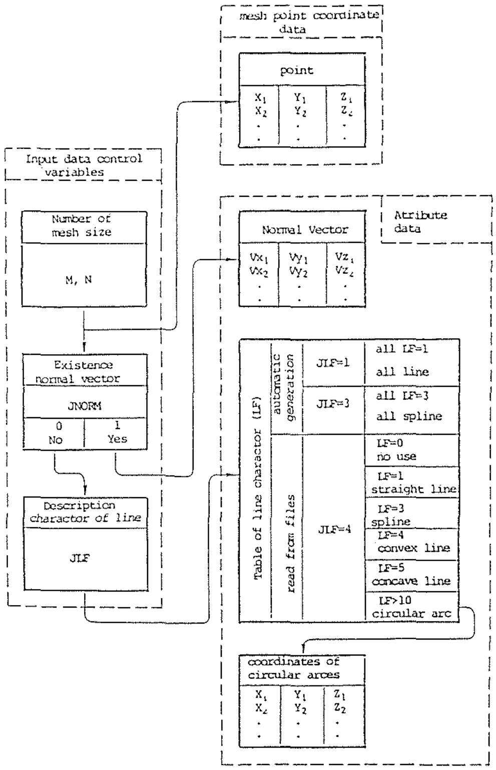


**Fig. 7** Data structure for Interactive Machining System

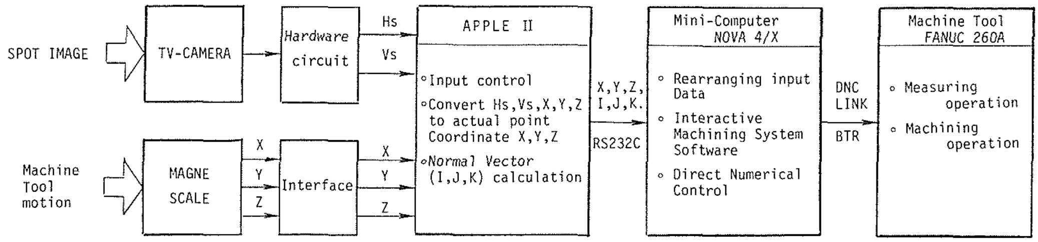


**Fig. 8** Block Diagram of Non-Contact Measuring and Machining System for curved object

## 3. Interactive Machining System

When the required curved three-dimensional object is given by the mesh point data which consists of a large set of point vectors and surface normal vectors from the laser ranging system, a perfect expression of curved object and offset curved surface which is needed for generating the cutter path, are constructed in mini-computer by using Coons' patch interpolation.

In case of machining of curved three-dimensional objects by using N/C milling machine and ball-end mill, the center of ball nose of ball-end mill must be on the r (radius of cutter) -offset curved surface (so-called tool surface) against the required curved surface

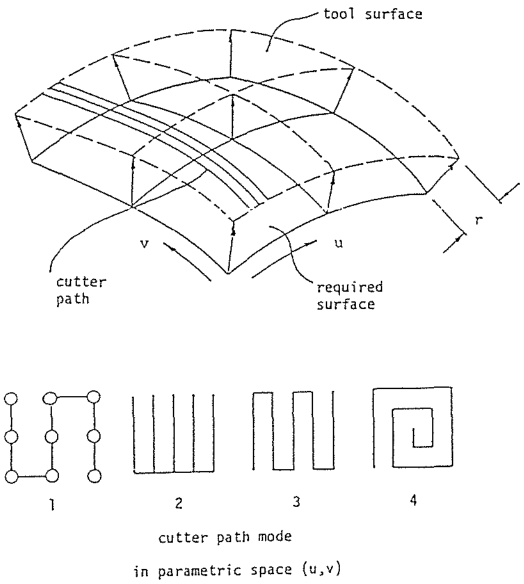


**Fig. 9** Representation of three-dimensional surface with mesh point data and cutter path modes.

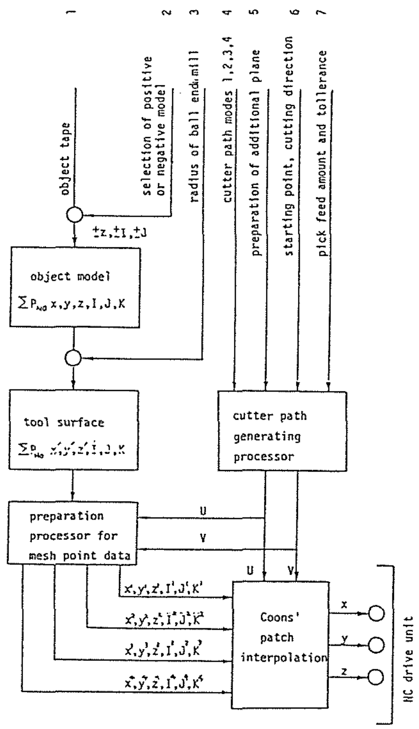


**Fig. 10** Basic structure of Interactive Machining System.

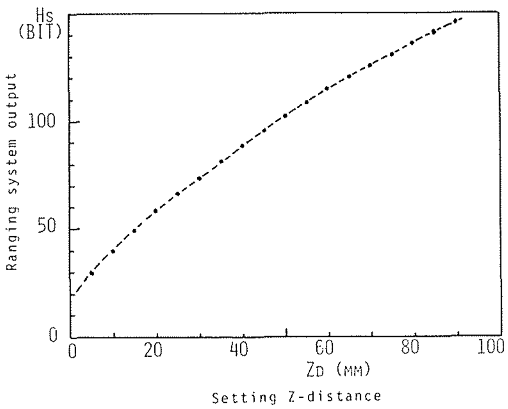


**Fig. 11** Caribration Curve

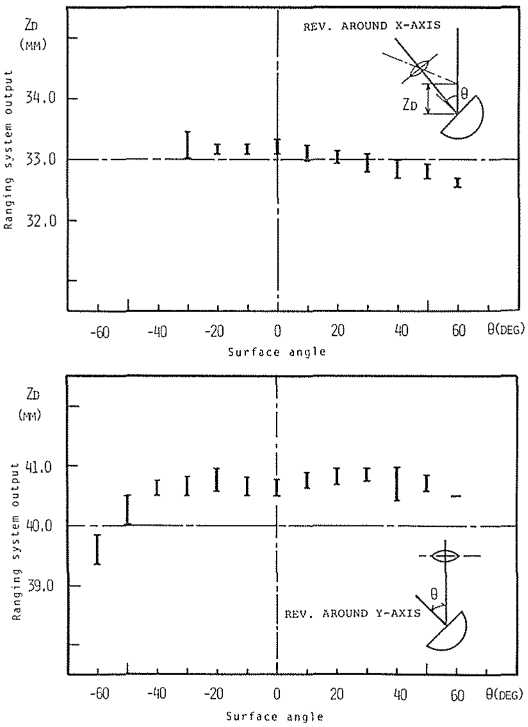


**Fig. 12** Influence of surface angle on the measuring accuracy

as shown in Fig. 9. In order to make it easy to input the cutting conditions to Interactive Machining System, we prepared four typical cutting modes for deciding the cutter paths (mode-1, 2, 3 and 4). These cutting modes are generated in parametric space to move along the constant parameter lines. And generated parametric cutting mode is converted to the real cutter path in a physical space.

In addition to these selections, we prepared some interactive input method concerning pick-feed, cutting direction and start point for an Interactive Machining System as shown in Fig. 10. By combining the selection of radius of the ball end mill, cutting mode, cutting direction, start point and pick-feed, we can carry out machining of curved three-dimensional object from rough cutting to finished cutting for the given mesh point data at the machining operation.

## 4. Results of Experiment

### 4-1 Calibration and Measuring Accuracy

According to some non-linear factors of laser ranging system, it is difficult to get the true Z distance by using only the calibration equation (1). Fig. 11 shows the relation between the data given by TV camera and the actual Z coordinate. In order to get an estimation of Z distance of laser spot on the object, we use the curve of Fig. 11 as a

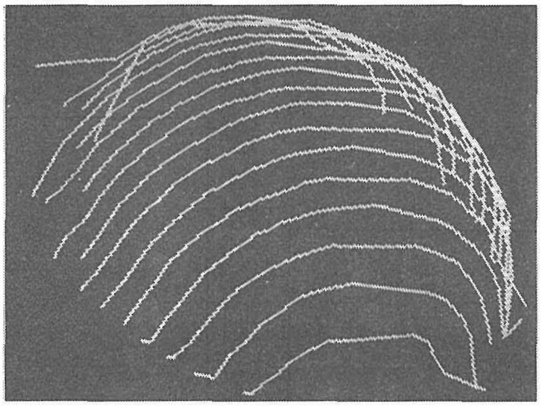

**Fig. 13** Measuring results for half ball body.

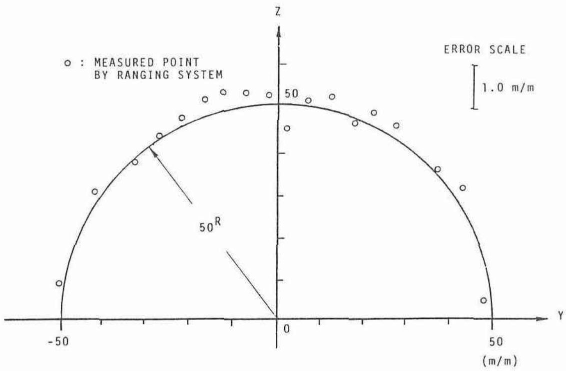


**Fig. 14** Measuring result on sectional plane of half ball body

calibration curve. Some typical points of the calibration curve were stored in micro-computer memory, and linear interpolation was applied between points to estimate the Z coordinate.

To inspect the influence of surface angle of object to be measured, other experiments were done with rotary index and flat plate. The small flat plate was set on the center axis of rotary index, laser beam was emitted just across the rotational axis of rotary index, and the laser spot on flat plate was monitored by TV camera. Fig. 12 shows the influence of surface angle on the measuring accuracy. One is the experimental result from the direction which is perpendicular to the plane involving the laser beam and center axis of TV camera, and another is in parallel with it. From these results, an accuracy of spot detection is about 0.5 mm and the influence of surface angle on measuring accuracy is about 0.7 mm for the angle range from $-60°$ to $+60°$ and the ranging distance 100 mm. Thus the influence of surface angle on the measuring accuracy is not so clear.

And also in order to inspect the measuring accuracy of the laser ranging system, we do the measuring experiment for a half-ball body. Fig. 13 shows the results of measuring a half-ball, which is represented by micro-computer (Apple II) screen plotting. And Fig. 14 also shows the measuring results of laser ranging system on sectional plane of half-ball body. The solid line is the actual data and small circles are the data taken by the ranging system. The error is less than 0.7 mm for 100 mm ranging distance.

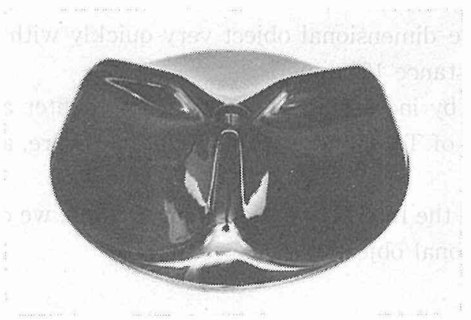

**Fig. 15** Example of curved object.

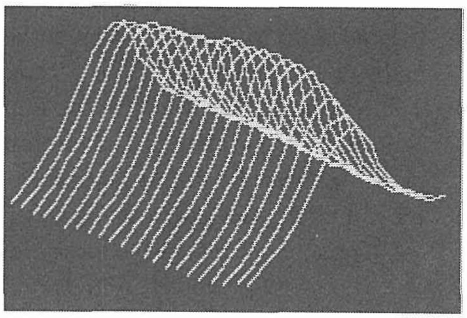

**Fig. 16** Measuring result of pulsator.

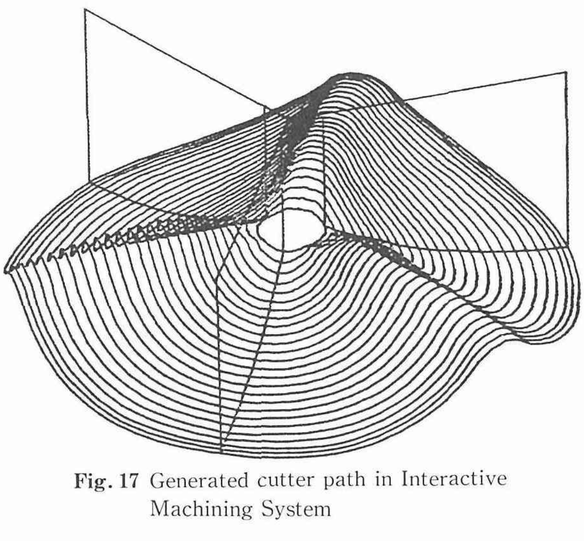

**Fig. 17** Generated cutter path in Interactive Machining System

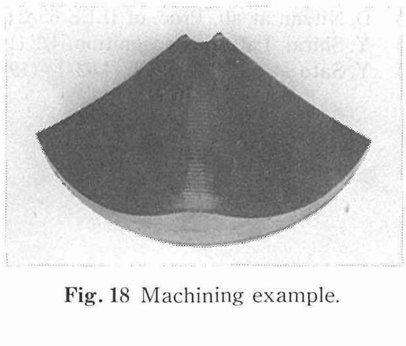

**Fig. 18** Machining example.

### 4-2 Measuring and Machining Results of a Curved Object

On the development of some new functional parts (for instance, shape of turbine blade, pulsator of washing machine, car body and etc.), some plot-typed models were required for inspection of shapes. In this case, the primary model was made by hand work and sometimes copied to metal material using tracer controlled machine tools.

If we can make a plot-typed model by using non-contact measuring technique and N/C machine tool, the primary model can be made from more softer material (for example, wax and etc.), and it is possible to save the required time of developement. In order to do so, we developed a laser ranging system with combined Interactive Machining System. And we applied it to measuring and machining of a pulsator of a washing machine as a curved three-dimensional object (see Fig. 15).

Fig. 16 shows the measuring results of the part of pulsator which is given by the developed laser ranging system. This data is sent to the Interactive Machining System to machine the shape of the pulsator. Fig. 17 shows the generated cutter path in the Interactive Machining System and Fig. 18 shows the machining example of the pulsator.

## 5. Conclusion

In this paper, we have proposed an effective non-contact measuring system which is combined with the Interactive Machining System for measuring and machining of curved three-dimensional objects. The features of this system are as follows:

1) It is possible to measure some curved three-dimensional object very quickly with an error of less than 0.5 mm for a ranging distance 100 mm.
2) The measuring accuracy can be improved by increasing the capacity of counter and controlling the stability of saw tooth wave of TV camera with special hardware, and by decreasing the size of laser spot.
3) By combining the laser ranging system and the Interactive Machining System, we can easily machine some curved three-dimensional objects.

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