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Automatic Tool Path Generation for Finish Machining*

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Abstract

A system for automatic tool path generation was developed at Sandia National Laboratories for finish machining operations. The system consists of a commercially available 5-axis milling machine controlled by Sandia developed software. This system was used to remove overspray on cast turbine blades. A laser-based, structured-light sensor, mounted on a tool holder, is used to collect 3D data points around the surface of the turbine blade. Using the digitized model of the blade, a tool path is generated which will drive a 0.375" CBN grinding pin around the tip of the blade. A fuzzified digital filter was developed to properly eliminate false sensor readings caused by burrs, holes and overspray. The digital filter was found to successfully generate the correct tool path for a blade with intentionally scanned holes and defects. The fuzzified filter improved the computation efficiency by a factor of 25. For application to general parts, an adaptive scanning algorithm was developed and presented with simulation results. A right pyramid and an ellipsoid were scanned successfully with the adaptive algorithm.

1 Introduction

There are many applications where machining and finishing operations are required on complex surfaces. The fabrication of stamping dies, for example, is an iterative process where the initial die shape is first defined in a CAD system. Tool paths are then computed and the shape is created with a CNC machining center. Initial stampings reveal areas where the shape must be changed either by removing existing material or adding material where it is deficient. These finishing operations are performed manually today by a skilled craftsman because no system exists which can measure the error in the stamping and automatically define the process parameters to adjust the shape of the die.

Manufacturing machines are traditionally designed for large volume production capabilities and are time consuming and tedious to retool for different tasks. Production machines that are easily reprogrammed, heuristic by design, intelligent, and highly adaptable for a variety of manufacturing tasks are needed in the agile manufacturing technologies area. The emphases on these machines are the flexibility and ability to make rapid design and product changes based on market demands. Sandia has developed robotics and automation techniques that make use of sensors, CAD information, and intelligent algorithms to improve manufacturing processes. Consequently, we applied fuzzy logic techniques to the tool path generation processing in this research. Specifically we have employed fuzzy selection criteria in processing the data collected by the structured light sensor, and in the scan step-size selection of the adaptive scanning algorithm.

Zadeh [1] introduced fuzzy logic to describe systems that are "too complex or too ill-defined to admit of precise mathematical analysis." Its major features are the use of linguistic rather than numerical variables and the characterization of relations between variables by "fuzzy" conditional statements. Mamdani and Assilian [2], recognizing that fuzzy logic provided a means of dealing with uncertainty, extended the concept to industrial process control in the expectation that it would be applied to systems for which precise measurements of the state variables could not be obtained. Processes to which the fuzzy, rule-based approach has been applied include cement kilns, wood pulp grinders, and sewage treatment plants [3]. Fuzzy logic was used in this research for data smoothing and in the adaptive algorithm for intelligent scanning of unknown parts.

This paper describes research conducted in the Intelligent Systems and Robotics Center (ISRC) of Sandia National Laboratories (SNL) to further develop sensor-directed, automated surface and edge finishing operations on cast and machined parts. As an example application, this technology was applied to Sprayed Abrasive Tip (SAT) overspray removal on cast turbine blades.

2 Turbine Blade Finishing Operation

Many manufacturing operations utilize processes such as investment casting to fabricate metal parts with complex shapes. Alternate fabrication techniques, such as machining, are either incapable of forming the required shapes or require too much effort, resulting in prohibitively expensive parts. Due to dimensional variations inherent with

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the casting process, cast parts typically require additional machining operations to create precision features. Since current automated machining technology is based on precise position knowledge of the part to be machined, automation on cast parts is frequently impossible because of the dimensional uncertainties resulting from the casting process.

Just as the piston rings improve compression and efficiency in automobile engines, one measure of combustion efficiency in jet engines is how small the gap between the tips of the turbine blades and the inside of the engine case (shroud) can be made. Too big a gap results in leakage, too small a gap and differential thermal expansion (as the engine operating conditions are changed) could drive the blades right into the shroud. The latter is actually preferred if the blades are designed to handle the interference and grind out the inside of the shroud. This is exactly what's being done with the Sprayed Abrasive Tip blades in the jet engine manufacturing industry.

After the blades are formed by investment casting, a silicon carbide grit is applied to the tips of the blades and bonded in place by plasma spraying a nickel alloy which extends the metal matrix of the blades up around the grit. The plasma spraying operation, however, leaves excess material extending 0.05" to 0.10" down the sides of the blades. This excess material must be ground off to recreate the blade's airfoil shape, a process that must be tightly controlled both for the aerodynamic efficiency of the airfoil as well as ensuring there are no disjoint surfaces (stress risers) which would lead to failure when the blade is subjected to the high-temperature, high-stress environment of an operating jet engine.

While grinding the overspray off the complex contours of the blade tips to less than 0.001" tolerance is difficult enough, it's made impossible for conventional CNC machines since, as castings, each blade is unique. Investment casting can produce intricate shapes, such as the cooling passages inside these hollow blades, but cannot yield identical parts. During solidification, the blades tend to shrink and warp, producing variances of ±0.030" in the location of the tip from blade to blade. Consequently, a unique tool path to grind off the overspray is needed for each blade. Figure 1 illustrates typical variations among the design blade and two actual blades.

3 Tool Path Generation Method

A system capable of grinding the overspray off the blades has been developed. The system is an integration of commercially available equipment, controlled by Sandia developed software. To process a blade, the blade is fixtured in a 5-axis milling machine. A laser-based, structured-light sensor, mounted on a tool holder, is used to collect 3D data points around the surface of the blade tip, adjacent to the overspray.
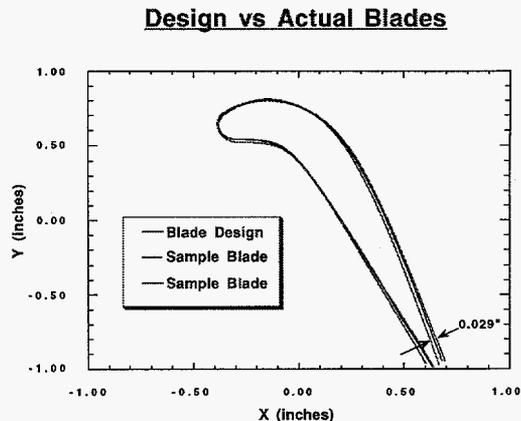
Design vs Actual Blades

Figure 1 Design Vs Actual Blades.

Figure 2 shows a schematic diagram of the structured light system setup. Based on tensor product surfaces, the data points are analyzed to produce a CAD file in the format of cross-sections at various heights along the blade. Typically, 4 bicubic splines are used to describe each cross-section. Using this digitized model of the blade, a tool path is generated which will drive a 0.375" CBN grinding pin around the tip of the blade.
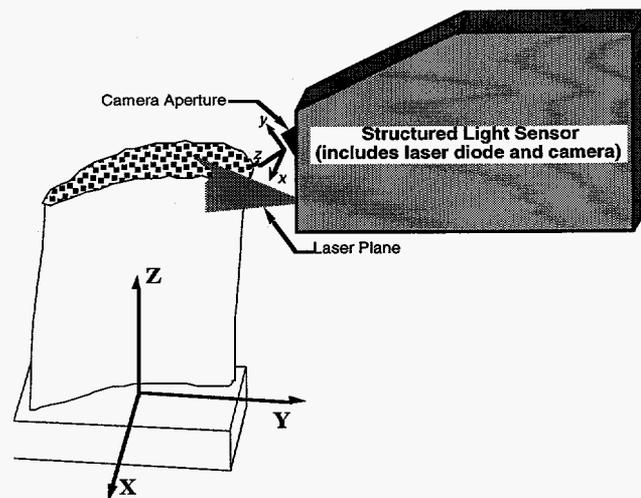

Figure 2 Laser-based Structured Light-Sensor Setup.

Figure 3 shows the generated tool path, and Figure 4 shows the tilt-angle, Alpha, of the blade for the machining operation based on the design blade. A low-pass filter is deployed for the smoothing performed on the tilt-angles in Figure 4.

This path is downloaded to the milling machine, which now holds a high speed spindle and the grinding pin as a

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Tool Path from Design Data
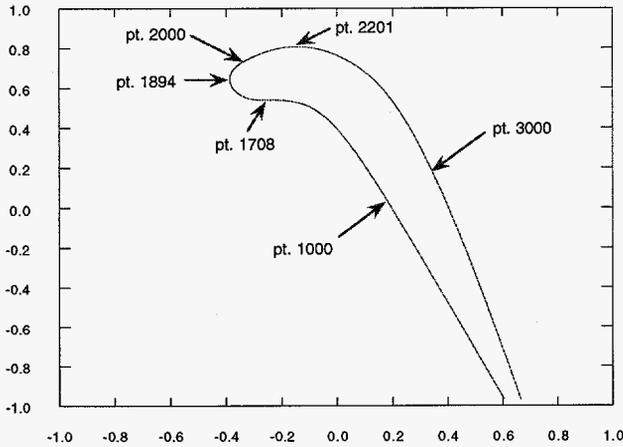computed same way as with digitized data

Figure 3 Generated Tool Path.

tool, and the overspray is removed in a one-pass, creep-feed grinding operation. In preliminary tests, the overspray was completely removed from a test blade leaving a mismatch of less than 0.001".
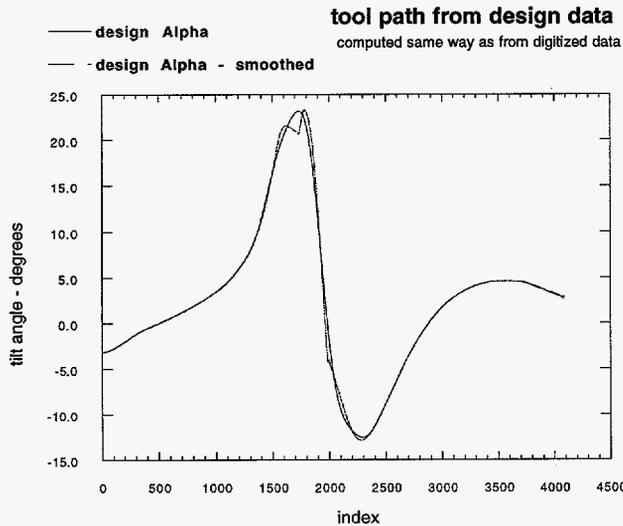
tool path from design data
computed same way as from digitized data

Figure 4 Tilt-angle of the Blade during Machining.

4 Digital Filtering

The tool path generation method described above works for most blades that have smooth finishes with relatively few flaws and defects on the surface where the scan plane lies. However, when the scan surface contains burrs, holes or overspray, the structured light sensor would mistakenly average the burr, hole or overspray to the actual surface and would, therefore, produce an incorrect profile to be used in generating the tool path. This would render the blade to be unacceptable following the finishing operation. A digital filter was developed to avoid this problem.

The digital filter developed for this application is a fuzzified lowess (locally-weighted scatterplot smoother) filter [4][5]. The fuzzified parameter is the smoothness parameter f, which is a number between 0 and 1. As f increases, the smooth curve becomes smoother, but computational requirements increase exponentially. The goal is to choose f to be as large as possible to get as much smoothness as possible without distorting the underlying pattern in the data, and not too large so that the computations can be completed within a reasonable time. Fuzzy rules are used in choosing the f value during execution. If the scanned curvature of the surface is large, f is chosen to be small. If the curvature is small, f is chosen to be large [5]. Fuzzy logic is an ideal choice for solving this kind of optimization problem.

In the lowess procedure, the program first chooses f, which is approximately the fraction of points to be used in the computation of each fitted value. First, let q be fn rounded to the nearest integer, where n is the number of data points to be smoothed. Second, let d_i be the distance from x_i to its qth nearest neighbor along the x axis. (x_i is counted as a neighbor of itself.) Let $T(u)$ be the tricubic weight function:

$$T(u) = \begin{cases} (1 - |u|^3)^3 & for \ |u| < 1 \\ 0 & otherwise \end{cases}$$

Then the weight given to the point (x_k, y_k) when computing a smoothed value at x_i is defined to be

$$t_i(x_k) = T\left[\frac{x_i - x_k}{d_i}\right]$$

To compute a fitted value at x_i in the first stage of lowess, a line (or constant if $d_i = 0$) is fitted to the points of the scatter plot using weighted least squares with weight $t_i(x_k)$ at the point (x_k, y_k). That is, values of a and b are found which minimize

$$\sum_{k=1}^{n} t_i(x_k)(y_k - a - bx_k)^2$$

If $\hat{a}$ and $\hat{b}$ are the values that achieve the minimum, then the initial fitted value at x_i is defined to be

$$\hat{y}_i = \hat{a} + \hat{b}x_i$$

Following the computation of initial fitted values for all x_i, residuals are computed,

$$r_i = y_i - \hat{y}_i$$

and robustness weights are computed from them. Let $B(u)$ be the bisquare weight function:

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$$B(u) = \begin{cases} (1 - |u|^2)^2 & for \ |u| < 1 \\ 0 & otherwise \end{cases}$$

Let m be the median of the absolute values of the residuals, that is,

$$m = median \, |r_k|$$

The robustness weight for the point (x_k, y_k) is defined to be

$$w(x_k) = B\left[\frac{r_k}{6m}\right]$$

The median absolute residual, m, is a measure of how spread out the residuals are. If a residual is small compared with $6m$, the corresponding robustness weight will be close to 1. If a residual is greater than $6m$, the corresponding weight is 0.

The next stage is to get updated fitted values, by fitting the line again, but this time incorporating the robustness weights. In the weighted linear regression for refitting $\hat{y}_i$, the point (x_k, y_k) is given weight $w(x_k)t_i(x_k)$. If (x_k, y_k) is a peculiar point with a large residual, it will play a small role, or no role at all, in any of the fitted lines in this latter stage of the computation.

5 Adaptive Scanning Algorithm

In this section, we present an adaptive scanning algorithm for scanning surfaces that are unknown a priori. Figure 2 contains a schematic of the structured light scanning sensor. It produces an approximately 0.25 inch wide scan line over which about 400 simultaneous (x,y,z) position readings are taken. It has a 0.2 inch depth of field and a stand-off of 0.5 inches.

Clearly a collision-free scanning method will need the ability to adjust the orientation and position of the scanner with respect to the part whose surface in unknown a priori. The scanning algorithm proposed here first uses a digital contact probe to quickly and safely find, at a low z value, a maximum-radius point on the object. This can be done as follows:

Start the probe at a position (x,y,z) whose $r = \sqrt{x^2 + y^2}$ is $\geq$ an a priori-known bound on r.

Reduce r by Δr.

Let $r_{max} = r$

Let $r_{min} = 0$

While ($r_{max} - r_{min}$ > half the depth of field of the scanner)

Rotate part 360° about z (relative motion.)

if contact occurred over 360 degrees

$$r_{max} = r$$

else

$$r_{min} = r$$

endif

$$Let \ r = \max\left(r - \Delta r, \frac{r_{min} + r_{max}}{2}\right)$$

endwhile

Record (x,y,z) of the point at which contact first occurred in the last 360° rotation.

Let $(x_{start}, y_{start}, z_{start}) = (x, y, z)$.

The point just found will be used as the starting point for adaptive scanning with the structured light sensor.

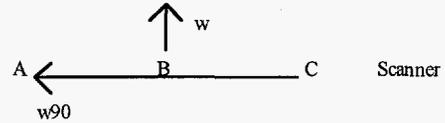Figure 5 below illustrates the notation that will be used in the algorithm description:

Figure 5: Schematic illustrating sensor notation

Point B is the center of depth of field along the central line of the scanner. A is the farthest point along this line and C is the closest. Vectors $\vec{w}$ and $\vec{w}_{90}$ denote unit vectors perpendicular and parallel, respectively, to the projection of $\overrightarrow{CA}$ onto the x-y plane.

Using the five degrees of freedom of a 5-axis CNC machine, we can specify the vector $\overrightarrow{CA}$, leaving spin of the scanner about this vector unspecified. However, for the type of parts that we will be considering, the line or curve of points formed by the scan line will still be essentially in the plane formed by the vector $\vec{w}_{90}$ and vector $\vec{k}$ (along the z-axis). Thus, the corresponding set of (x,y,z) points can be used to approximate a straight line which in turn gives us a vector $\vec{t}$ roughly tangent to the surface, thus enabling us to make an estimate of the elevation (angle) of the normal to the surface at that point.

We will let α denote the directed distance from B, along $\overrightarrow{BA}$, to the point at which the central line of laser light contacts the part surface. Also, point D will denote the corresponding surface point. An unacceptable scan occurs if no surface is detected within the depth of field here.

The scanner will initially be placed so that point $B=(x_{start}, y_{start}, z_{start})$ and so that $\overrightarrow{CA}$ is the inward normal to the radial curve passing through $(x_{start}, y_{start}, z_{start})$, and the scanner will be approximately parallel to the x-y plane. (In Figure 2, the sensor box is shown vertical just to enable visualization of its shape in the drawing.) Scans will be performed around constant-z perimeters, and between each perimeter scan will be a step upward in z-value. The vector $\vec{v}$ will denote the unit vector in the x-y plane along $\begin{pmatrix} x_D \\ y_D \end{pmatrix}_{k+1} - \begin{pmatrix} x_D \\ y_D \end{pmatrix}_k$, where k denotes an enumeration of successful scans, the (k+1)th one being the latest one.

Fuzzy adaptive step sizing is used in choosing the step size. If the estimated curvature of the surface is large, the step size is chosen small. If the curvature is small, the step size is chosen to be large [5].

With the above preliminaries and notations defined, we now discuss some features of the adaptive scanning algorithm. To add additional realism to the simulations, 0.003 inches of noise was added to each scan measurement. The details of the algorithm are presented in Reference [5] and are omitted here due to space limitations. However, we will discuss below a few of the approaches used in the algorithm.

In addition to the fuzzy rules for step-size adjustment based on estimated curvature (from the rate of change of the vector $\vec{v}$), the algorithm includes a special set of rules for detecting and navigating a corner. This enables the collision-free scanning of unknown surfaces that have sharp edges.

After each successful scan, a translation of length α is performed along the $\overrightarrow{CA}$ vector and a rotation about B performed to align vector w with the last chord vector $\vec{v}$. Then a translation along $\vec{v}$ is performed, and another scan attempt is made. If unsuccessful, the step is halved, while if successful, it is doubled, but limited to a maximum value deemed (a priori) to be the smallest feature size of the surface.

6 Results

Results from the generated tool path process without the fuzzified lowess filter produced blades to within 0.001". However, the blade will not pass the manufacturer's requirements without further improvement in the filtering routines for blades with burrs, holes, and overspray.

Figure 6 shows the result of using the fuzzified lowess filter on a scanned hole.

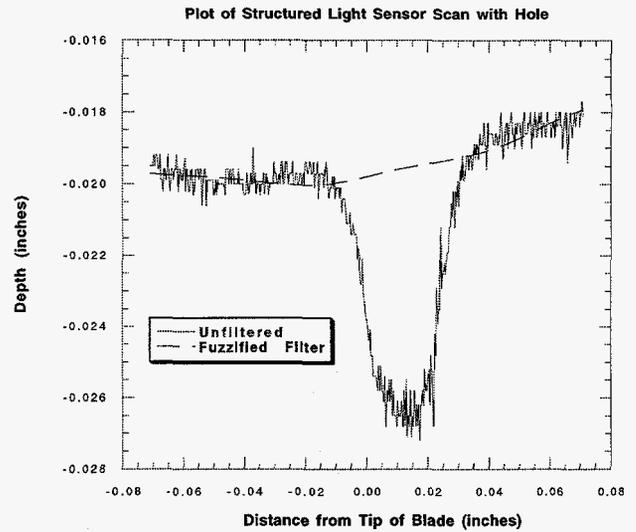**Plot of Structured Light Sensor Scan with Hole**

Figure 6: Result of Fuzzified Lowess Filter Applied to a Scanned Hole.

The unfiltered structured light output is extremely noisy and the filter successfully located the true surface for the tool path to be generated properly. This can be seen in Figure 7 where the unfiltered tool path is compared with the filtered one. The unfiltered tool path is unusable.

**Intentionally scanning holes -
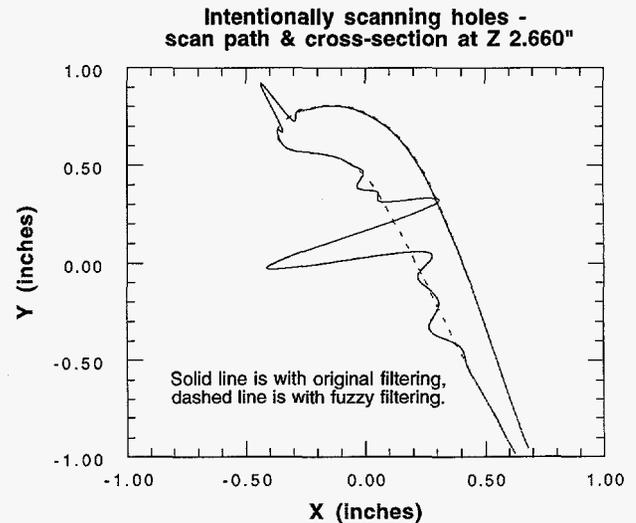scan path & cross-section at Z 2.660"**

Figure 7: Comparison of Tool Path Generated with and without the Fuzzified Lowess Filter.

Figure 8 shows the tilt-angle of the surface normal. It can be seen that the fuzzified lowess filter reduced the oscillation on the surface normal but did not eliminate it completely.

In order to extend the automatic tool path generation technology to general parts, the adaptive scanning algorithm

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**Intentionally scanned holes -
processed with fuzzy filtering**
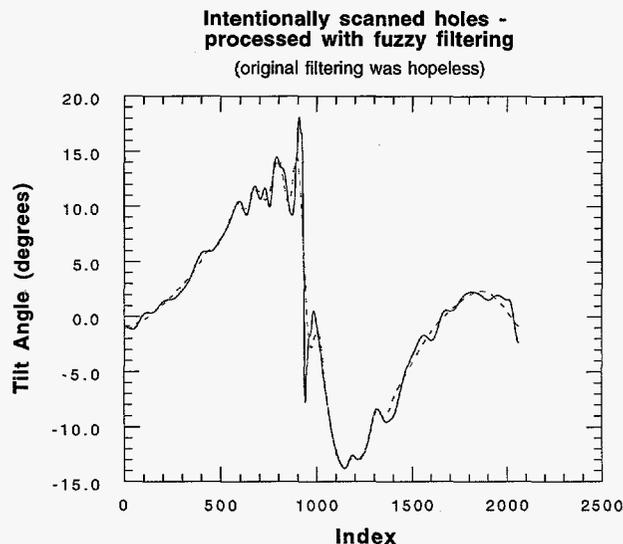(original filtering was hopeless)

Figure 8: Tilt-angles of the Generated Tool Path

was developed. The scanning algorithm was simulated on a right pyramid whose apex is at (0,0,2.5"). Figure 9 below shows the path of point B for this simulation. Reference [5] provides details of the simulation method.
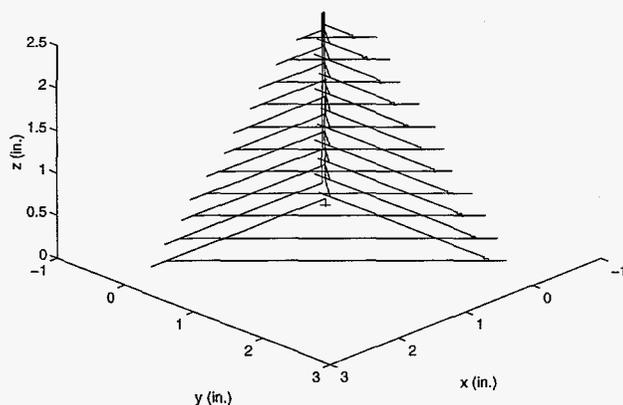
Figure 9: Simulated Scanner Path, Case of a Right Pyramid

Also, Figure 10 below illustrates a 2D portion of the scan path for the case of an ellipsoid.

7 Conclusions

The automatic tool path generation system was found to perform successfully for blades with relatively few flaws and defects. The fuzzified lowess digital filter allows the tool path generation system to function properly for blades with burrs, holes, and overspray. In summary, the fuzzified lowess filter improves the automatic tool path generation process so that:

1. higher resolution scanning data are passed to the surface analysis code which improves the curve fitting and CAD model generating process,
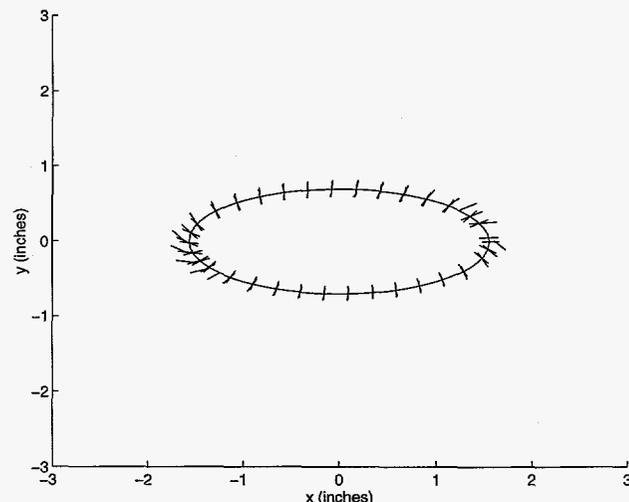2. the surface normals generated in the CAD file are "filtered" to reduce oscillation of the tool path.

Figure 10: Projection onto x-y Plane of a Constant-z Portion of Scanner Path of an Ellipsoid .

It is expected that these improvements will result in a process that meets the manufacturer's accuracy requirements. Optimization and automation of the individual process steps will be performed to minimize the total cycle time. Also for application to general parts, the adaptive scanning algorithm was developed and successfully scanned a right pyramid and an ellipsoid.

References

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