Visual Servoing of a Conventional CNC Machine Using an External Axis Controller

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Abstract

This paper presents the implementation of an external axis control system on a conventional CNC machine so that the machine can be actively controlled in response to sensors such as vision and force. The controller that runs on an external computer has direct access to the CNC controller for machine position sensing. The control signals to the machine are sent through purpose built circuitry via the machine's manual pulse generator (MPG) inputs. To demonstrate the accuracy and performance of the control system, it was used to visually track the profile of a mandrel used for shear spinning. The implemented system eliminates the parallax error and the need to use an accurate pixel resolution. The raw tracking data is processed by a curvature detection algorithm that detects linear and circular segments and segment transitions. The results show that the visual tracking system provides accurate tracking results that are well within the tolerances used in the industry.

Keyword: Visual profile tracking, active control, shear spinning

1 Introduction

First, this paper presents the design and implementation of an axis control system that allows the real-time control of a commercial CNC machine. Then it demonstrates its use by visually servoing one axis of the CNC machine so that a profile is automatically scanned. The axis control system presented enables the machine to be actively controlled. An active system has the ability to respond to inputs from sensors such as force and vision. A CNC machine that is equipped with an active axis control system can be utilized to carry out various tasks such as force control and visual profile tracking. Commercially, CNC machines are not equipped with active axis control systems. They utilize part programs which are run in block execution mode. Part programs do not respond to sensor signals.

A number of studies have been carried out in the recent years in an attempt to bring the CNC machines under low level control [1], [2]. The work described in [1] reports the use of a PC-based controller for a CNC machine. By using the external PC to generate actuating signals, they retain the monitoring and safety aspects of the CNC machine. Whereas the work described in [2] is aimed at optimizing drilling using an external PC. The work presented in [3] is able to control feed rate of a CNC machine. Their work detects the tool-workpiece contact on-line and adjust the feed rate from rapid traverse when 'not cutting' to cutting feed rates when the tool is in contact with the workpiece. Their work however does not actively control the tool path.

The method presented in this paper uses trains of pulses generated by an external controller to actuate the axes of the machine. These pulses replace the pulses generated by MPGs. To close the position feedback loop the external controller requires the machine position. Most CNC machines have some means of reading their current position. If such a system is not readily available, the machine encoders or resolvers can be accessed directly from outside. A special purpose High Speed Serial Bus (HSSB) was available to the machine used in this study to read the machine position. The external axis controller is then converted into an active axis control system by closing a visual feedback loop. Using the active control system, a camera mounted in the tool magazine is traversed in an automated fashion to track a profile.

The ability to accurately detect the edges of the acquired images plays a very important role. There are a number of methods presented in literature. A method of enhancing object resolution and detecting edge curvatures by observing gradual changes of grey levels of a pixel is presented in [5]. Improving the image contrast [7] has made edge detection more resilient. In other studies [8] presents a statistical method to enhance the luminance of grey levels of pixels around the edge. The comparison of performances of edge detectors and criteria for optimizing edge detectors are presented in [9]. Many other edge detection techniques are available, however the use of differential operator [4], [6] is of particular interest. The edge detection technique presented in [4] introduces a filter called Infinite Symmetrical Exponential Filter (ISEF). In this study, the method described in [4] is used to accurately detect the edges.

The devised system was used to track the profile of a mandrel mounted on a CNC lathe for shear spinning. Two sets of experimental results are presented; the first showing the tracking accuracy and the second showing the dimensional accuracy of spun components.

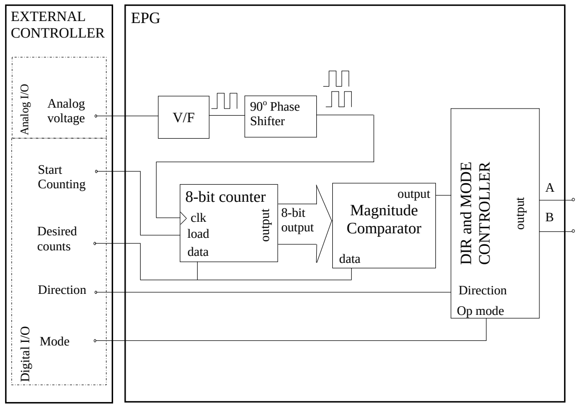

Figure 2: The EPG system

2 System Components

2.1 Active Axis Control System

The purpose of the active axis control system is to automatically track the contour of a profile. The tracking system must operate in such a manner that the axis of the camera is able to accurately follow the profile. The active axis control system consists of a position sensing system, a machine actuating system and the controllers.

2.1.1 Position sensing system

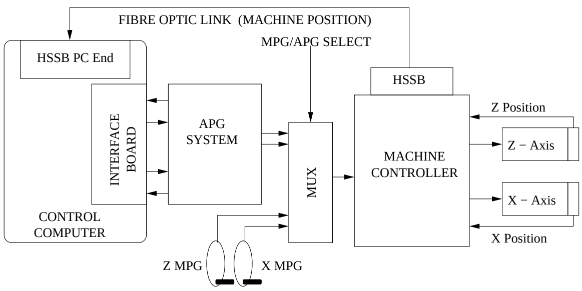

Figure 1: Schematic of the external axis control system

The HSSB shown in Figure 1, linking the CNC machine and the computer that runs the external axis controller, reads the machine position. These machine positions are used as the feedback signals for the external axis controller. The HSSB interface is also able to provide other information such as the speed of each axis and the modes of operation of the machine.

2.1.2 Machine actuating system

The CNC machines have manual pulse generators (MPGs) to enable the operator to manually move the tool to a desired position. The signals generated by the MPGs of the lathe machine are identical to quadrature signals generated by optical incremental encoders. In this study, the MPG inputs are used to interface the actuating signals to the machine. Custom built electronic hardware called the electronic pulse generators (EPGs) are used to generate quadrature signals that are multiplexed with the existing MPG signals. While the MPGs are manually operated, the EPGs are commanded by the control computer. When EPGs are chosen as the quadrature signal source, the machine moves in response to the commands from the control computer. The multiplexing of the MPGs and EPGs are shown in Figure 1.

A block diagram of the EPG system is given in Figure 2. The EPG circuit receives three primary commands from the control computer. First, it receives an analog voltage. In response, the EPG generates trains of quadrature pulses. The frequency of the pulse trains are proportional to the applied analog voltage. The feed rate of a particular axis depends on the frequency of pulses. Therefore the feed rate is proportional to the analog voltage applied. Thus in a contouring operation, it is necessary to appropriately adjust the analog voltages applied to both axes of the machine. Next the EPG circuit receives a direction command. This signal determines whether a particular axis must move forward or reverse. Finally, it receives the exact number of pulses to be issued to each axis. Apart from these primary signals, it also receives a secondary signal. This signal controls the mode of operation. The EPG circuit operates in two modes; the free running mode and the control mode. When the total number of counts by which the machine axis must move is greater than the maximum pulses permissible within the sampling interval, the EPG constantly output pulses to the machine at the rate determined by the applied analog voltage. This mode is called free-running. When the number of pulses fall below the maximum permissible for the next sampling time, the EPG switches to controlled mode. At the end of the appropriate number of pulses, the EPG will stop issuing pulses.

2.1.3 The Controllers

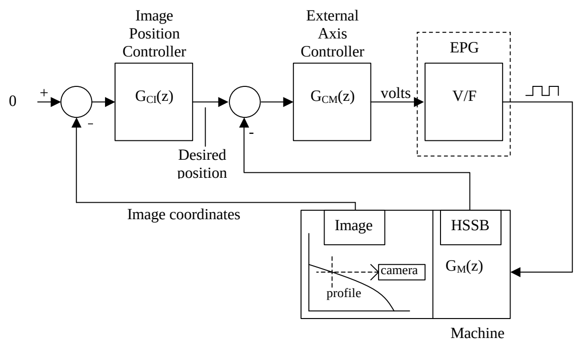

Figure 3: The active axis control system

As shown in Figure 3 the active control system consists of a number of controllers. They are the external axis controllers and the image position controller. To proceed with the design of the controller, the transfer function of the machine axes must be identified. Experimental system identification was used to obtain these transfer functions.

The transfer function of the machine axes control system must relate the pulse input (from EPGs) to the machine position. The transfer functions of the machine axes system in Z and X axes are as follow;

$$G_{M_Z}(z) = \frac{0.0764z + 0.0764}{z - 0.3887} \tag{1}$$

$$G_{M_X}(z) = \frac{0.0729z + 0.0729}{z - 0.4170} \tag{2}$$

Note that the DC gain of the above transfer functions is 0.25. This agrees with the fact that each MPG input requires 4 counts to produce 1 μm motion.

The controllers for the two machine axes, designed using direct analytical design method, are given in Eq. 3 and Eq. 4.

$$G_{CM_Z}(z) = \frac{1.1126(z^4 - 0.8887z^3 + 0.1943z^2)}{z^4 - 0.8748z^3 - 0.07954^2 - 0.04339z - 0.002152} \tag{3}$$

$$G_{CM_Z}(x) = \frac{1.1439(z^4 - 0.9170z^3 + 0.2085z^2)}{z^4 - 0.8799z^3 - 0.08136z^2 - 0.03836z - 0.00038} \tag{4}$$

To maintain simplicity, the image position controller chosen in this study is a proportional controller. The pixel resolution of 312 counts/pixel is used as the controller constant.

2.2 Visual Tracking System

The visual scanning system must not be susceptible to parallax error. When images of objects of significant depth are acquired, parallax error may cause the acquired image to be inaccurate. This is especially true when imaging cylindrical objects of large diameters. The surface of the cylinder itself will cover the area of the cylinder that actually shows its full diameter. Therefore a single image of the entire object will not deliver the desired result. Furthermore, the processing will be image based. In such a situation, it is necessary to transform the image coordinates into machine coordinates. In addition, due to the spherical abberation of the lens, the image resolution changes as a function of the pixel location with respect to the line of sight of the camera. This requires the maintenance of a pre calibrated accurate set of pixel-resolution data. However, these data are susceptible to errors in the distance between the camera and the object. Even when the spherical abberation has been eliminated, the parallax error cannot be avoided. Therefore the only image information that can be trusted is at the center of the image plane. The scanning method suggested in this paper avoids parallax error, spherical abberation and transformation from image coordinate system to machine coordinate system.

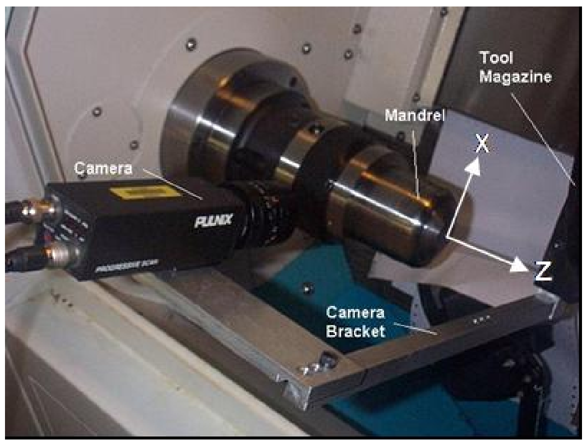

Figure 4: Tool magazine mounted camera

To implement the visual scanning system, shown in Figure 4 the camera was mounted on the tool magazine. Of the two axes Z and X, only the X axis was actively controlled with visual feedback. The Z axis was incrementally moved until the entire profile is scanned. The visual feedback signal for the X axis was generated as follows.

Using back light, an image of the silhouette of the profile is first acquired. The area imaged is specifically chosen so that the profile will be within the image. Since only the center of the image plane contains trusted information, only the center vertical line of pixels are analyzed. The method described in [4] is then implemented.The differential operator [4] is applied twice to the filtered grey levels to obtain the sub-pixel coordinate of the profile edge. This sub-pixel value is used as the visual feedback signal for the active control system.

The desired sub-pixel value is zero, i.e. the active axis control system requires the camera to be actively moved in the vertical direction until the image of the profile edge passes through the camera center. When this has been achieved, the possibility of parallax error is completely eliminated. At this moment, the machine position is also recorded. The image resolution was used only as a constant in the active controller and as such need not be known accurately. It only affects the stability and speed of response of the active control system. Also note that the machine position was directly recorded and therefore the transformation from image plane to the real world coordinates is not necessary.

2.3 Curvature Detection Algorithm

The shapes of the profiles used in this study contained only straight line and circle segments. The curvature detection algorithm described in this section can be used to identify straight line segments, circle segments and transition points in the set of raw data obtained by recording the machine position during scanning. The algorithm is described below.

First, a series of curvatures along the extracted profile is calculated using narrow bands of tolerances. Recall that the curvature of a curve $x = x(z)$ is

$$\kappa(z) = \frac{x''(z)}{(1 + x'(z)^2)^{\frac{3}{2}}}.$$

In this case $x(z)$ is represented in a discrete way by the ordered set of scanned values $\{x_i = x(i\Delta z)\}$ with $0 \le i \le n+1$. The central first derivative $x'_i = (x_{i+1} - x_{i-1})/(2\Delta z)$ and backward second derivative $x''_i = (x'_i - x'_{i-1})/\Delta z$ were used to calculate the series of curvatures

$$\kappa_i = \frac{8(x_{i-1} - 2x_i + x_{i+1})}{\Delta z^2 \left(4 + \Delta z^2 (x_{i+1} - x_{i-1})^2\right)^{3/2}},$$

where $1 \le i \le n$.

The curvatures are then grouped into sets of approximate constant curvatures. Among these, zero curvatures represent straight lines and non-zero curvatures represent circular segments. Clockwise and anti-clockwise circular interpolated regions can be determined using the sign of the curvature. A transition between circular segments is detected by a change in curvature. This method will also identify a transition between two segments with identical curvatures (for example two straight segments with different slopes), as the discontinuity of the derivative at the transition point will generate high curvature. For all segments with non-zero curvatures, radii will be worked out so that if necessary, they can be used in the CNC program. End points of any segment play an important role as they maintain continuity between segments. Therefore, despite the possibility of being affected by noise, all raw boundary points of each segment are kept. Knowing the radii and boundary points, for each segment a CNC part program can be generated.

The maximum allowable deviation of curvature is denote by ε. Initially, set $i = 0$ to be the index of the first point of the segment and $j = i+1$ to be the index of the last segment. Then, j is repeatedly incremented until

$$\max_{i<k<j+1} \kappa_k - \min_{i<k<j+1} \kappa_k > \varepsilon.$$

At this stage the end points of the segment are determined to be $(i\Delta z, x_i)$ and $(j\Delta z, x_j)$. If the segment has only two points, i.e. $j - i$=1, or if

$$\bar{\kappa} = \operatorname*{average}_{i<k<j} \kappa_k$$

is less then $1/R$, where R is the maximum allowable radius for a segment, then the segment is approximated by a straight line. Otherwise the segment is circular with radius equal to $|\bar{\kappa}|$ and interpolation is clockwise if $\bar{\kappa} < 0$ or counter clockwise if $\bar{\kappa} > 0$. At this stage i is assigned the value of j and the process is repeated for the next segment. By assembling all extracted segments sequentially, a complete CNC part program can be generated.

3 Experimental Setup

The CNC machine used in this study is a Colchester Tornado A-50 lathe. It is equipped with two simultaneously controllable MPGs. The machine has a minimum incremental motion of $1\mu m$. As described earlier, an HSSB is available for an external computer to read the machine position.

The vision system consists of a Data Translation DT-3162 Frame Grabber and a Pulnix TM-6CN camera. In order to enhance the contrast between the background and foreground, back lighting was used. The back lighting will provide an image of the silhouette of the mandrel with uniform low grey levels in all covered areas.

4 Results

The results presented below relates to a shear spinning exercise. Shear spinning [10] requires a mandrel - a thick chunk of steel of a certain shape, mounted on the lathe. The visual tracking system developed was used to scan the profile of the mandrel. The first set of results demonstrate the visual tracking accuracy. The second set of results demonstrate the dimensional accuracy of a component spun using data obtained through visual tracking.

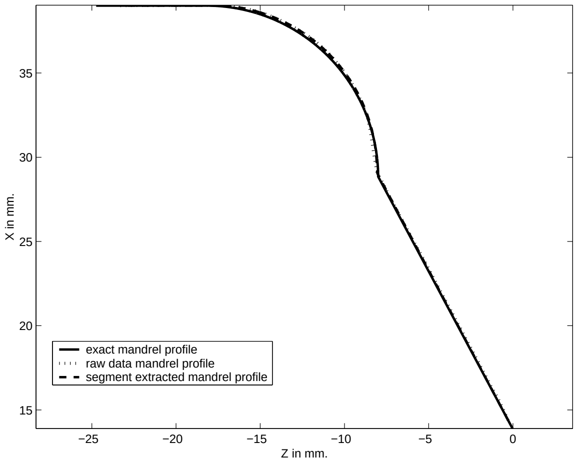

Figure 5: Actual, raw data and segment extracted mandrel profiles

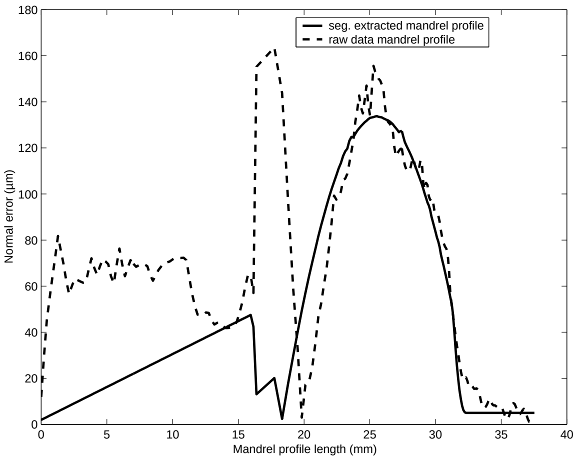

Figure 6: Error plot of Figure 5

4.1 Visual Tracking Results

The results obtained by visually tracking the mandrel profile is shown in Figure 5. Three sets of data are plotted. The raw tracking data were obtained by recording the machine position during active visual tracking. Each recorded point was joined by a straight line to its adjacent points. The segment extracted data were obtained by further processing the raw data by applying the segment extraction algorithm. Therefore, it contains straight line and circle segments. These two sets of data are compared with the actual mandrel profile. The actual mandrel profile was obtained from the CNC program used to machine the mandrel. The error plot of Figure 5 is shown in Figure 6. Note that in the error plot, the horizontal axis shows the length along the mandrel profile. The vertical axis shows the normal profile error with respect to the exact profile.

4.2 Dimensional Accuracy

Three components were spun using the three sets of data described in the last section. The spun component is shown in Figure 7. A hardened steel tool of nose radius 5 mm was used to spin the components out of 1 mm thick annealed aluminum discs. In each case the edge of the component was parted off using the same tool at the same machine position to avoid any adjustments during measurement using 3-D coordinate measuring machine.

Figure 7: Spun component

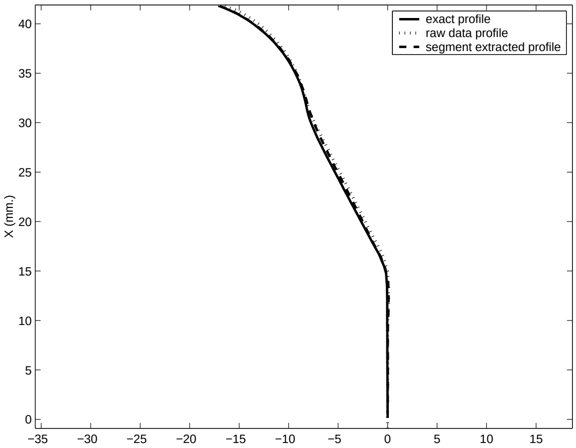

Figure 8: Comparison of spun profiles

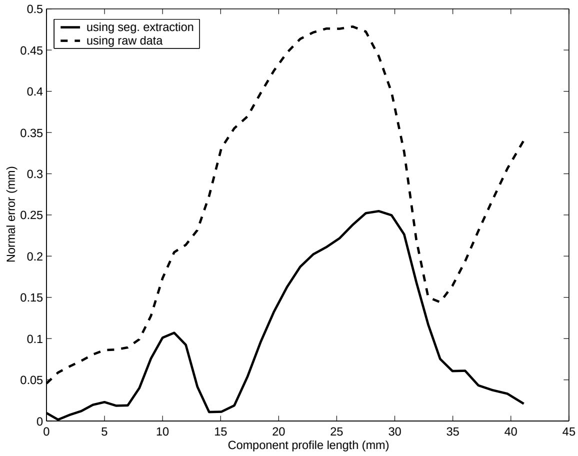

Figure 9: Error plot of Figure 8

The results from 3-D coordinate measuring machine is shown in Figure 8. The exact profile corresponds to the component spun using the same part program used to machine the mandrel. Appropriate tool offsets were used to account for the material thickness and the tool nose radius. When using raw-data to spin the component, linear interpolation was used to move from one point to another. In segment extracted profile, depending on whether the segment was a circle or a straight line, circular and linear interpolation was used. An error plot of Figure 8 is shown in Figure 9. In Figure 9 it is clearly shown that the error of the component produced using segment extracted profile is maintained below 250 μm. A significant factor that affects the dimensions of the spun component is 'spring back' effect due to elasticity. The spring back is significantly affected by the tool path. However there is not enough data available on the spring back effects of shear spinning.

5 Conclusion

This study demonstrated a method to implement an external axis control system that can be used in an active sense in real-time. The developed system was used to visually track a profile mounted on a CNC lathe machine. The scanning method eliminates the parallax error by actively aligning the line of sight of the camera with the point of interest. The inaccuracies of image resolution does not affect the accuracy of the data obtained through visual tracking. Although visual feedback is used, the system predominantly operates in the machine coordinate system. Thus the scanning data is directly available in machine coordinates - not in image coordinates. The axis control system can be used not only for visual scanning, but also for tactile scanning by replacing the vision system with a force sensor.

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