ON-MACHINE DIMENSIONAL VERIFICATION

W. Rendulic

Published August 1993

Final Report
W. Rendulic, Project Leader

Project Team:
R. L. Clewell
R. W. Huff
R. C. Moreno, Jr.
G. C. Rice
R. J. Russell

Technical Communications
Kansas City Division

JP

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Abstract

General technology for automating in-process verification of machined products has been studied and implemented on a variety of machines and products at AlliedSignal Inc., Kansas City Division (KCD). Tests have been performed to establish system accuracy and probe reliability on two numerically controlled machining centers. Commercial software has been revised, and new cycles such as skew check and skew machining, have been developed to enhance and expand probing capabilities. Probe benefits have been demonstrated in the area of setup, cycle time, part quality, tooling cost, and product sampling.

Summary

General technology for automating in-process verification of machined products has been implemented at AlliedSignal Inc., Kansas City Division (KCD). Although the development efforts focused on Monarch VMC 75/150 machining centers, the basic techniques developed on these machines can be applied to other probe-equipped machines.

In the traditional machining process, the operator monitors the manufacturing process with data gathered by manual equipment using his own senses on manual attribute gages. The automated in-process verification system, with the capability to perform dimensional measurement, identify trends, make automatic compensations, and communicate to an operator, is making significant contributions in verification of setup, geometric relationship, and part alignment. The major benefits from determining and controlling these parameters are shorter setup time, fewer defective products, and shorter cycle time. Several products that were previously inspected 100% have been reduced to sampling as a result of the probe's demonstrated ability to reduce variation by measuring, comparing, and compensating

before making a final cut, all without removing the part from the fixture.

A standard test to evaluate machine/probe accuracy has been developed using a calibrated ball plate, a Moore bar, and a step gage. Other tests have been made to evaluate the system's accuracy as a function of probing parameters. The use of calibrated metrology equipment proved to be the most reliable alternative.

By isolating the probe from the machine, the test results show that the machine contributes up to 90% of total error. To improve machining and probing accuracy, KCD has initiated a machine characterization study. KCD has also contracted with Purdue University to study machine errors. The study developed a computer model and made recommendations based on the laboratory study.

Commercial software routines have been modified to standardize the use of probing variables. A new user-friendly program has been developed to assist operators in performing machine setup functions. On some routines, like referencing rotary axes,

the use of the probe has reduced the setup time by 75%.

KCD has broadly expanded the potential for using a probe by developing programs for measuring and compensating for skewed surfaces. These programs were first developed to measure the skew of cast surfaces on the EMR Shield. The ability of the program to compensate and machine relative to a skewed surface made it possible to combine three machining operations, reduce flowtime, and improve the quality of machined features.

During the first two years, probing was installed on 24 machines, and 57 different operations were using probe in production. Initial efforts have demonstrated up to 35% productivity gains in reducing setup and cycle time. In addition to gains in productivity, dimensional quality of products has improved. Although this project represents just an initial step towards automatically generating, compensating, and verifying product with minimum human intervention, the technical knowledge will be instrumental in resolving technological and administrative issues associated with automated product machining and acceptance in a flexible manufacturing system and in a computer integrated manufacturing environment.

Discussion

Scope and Purpose

The objective of this project was to develop and implement the general technology for automating in-process verification of machined products produced on milling and turning machines. Automated in-process verification required the integration of available commercial and in-house expertise to identify, characterize, and implement sensor and software technology.

The KCD had purchased one of the first commercially available machining centers equipped with a touch-probe system. Once the basic operating principles and capabilities became known, efforts were initiated to characterize the process, evaluate the system's accuracy and reliability, incorporate measurement techniques on product, define methods for broadening the system's capability, and investigate the feasibility of using in-process results for final product acceptance.

This report describes major components of the On-Machine Verification (OMV) System, the software developments, and the incorporation of probing into production processes on the EMR Shield and the Solenoid Housing. Discussions of the system's accuracy, guidelines for minimizing errors, and potential future applications are included.

Activity

Approach

The best ways to describe the automated On-Machine Verification (OMV) System are to see how it fits into the machining

process and to compare it to a traditional in-process verification and control system.

In a traditional machining process (Figure 1), an operator is a focal point in every element of part orientation, tool data interpretation, machine operation, work instruction interpretation, and part measurement. The operator normally starts with a work instruction, commonly known at KCD as a production traveler. From traveler instructions, an operator selects a machine, from the family of machines stated on the traveler, to which he adds tooling and raw material. If the machine is numerically controlled, the operator loads the part program and tool information into the machine control. After the part is machined, the operator performs an in-process verification by either using manual attribute gages to measure the part on the machine (Figure 2) or by unloading the part and verifying it using a custom designed gage (Figure 3). He records part measurements on paper, compares them to work instructions, manually performs calculations, and adjusts the tool path (Figure 4) based on the difference between the actual and the desired part dimensions. Each one of these steps is time-consuming and offers an opportunity for error.

The objectives of this project were to reduce total cycle time and to assist the operator in the measuring and decision-making processes. This has been accomplished by automating the on-machine verification and control process (Figure 5). As in a traditional approach, raw material and tooling are added to the machine. However, with the automated system, the tool sensor automatically measures and adjusts for tool length. After

Figure 1. Traditional In-Process Verification and Control

a part is machined, a probe is automatically loaded into the spindle and measures the part while on the machine (Figure 6). Process verification control compares the probe results to desired dimensions and automatically adjusts the tool path to compensate for the difference.

Equipment and Operation

The major components of OMV, shown in Figure 7, include the machine, control, probe, receiver, tool length indicator, and a printer. The Monarch VMC 75 with a Bendix System 5CM control and a Valeron probe was one of the first OMV systems available at KCD. Later, other systems with a different machine, probe, or control were installed (Table 1).

The probe is a battery-powered wireless transmitter (Figure 8). It can be fitted with a variety of styli, as illustrated in the

Appendix of this report, and different adapters are commercially available to fit any standard spindle. At KCD, probes (Figure 9) are commonly used on machining centers. Basically, probes differ in size, type of battery, and the way they are activated. The major difference is in the way they transmit the signal. The three probes on the right of Figure 9 use an optical signal, while the one on the left uses an inductive signal.

The basic operating principle of an optical probe is shown in Figure 10. The probe is positioned near the expected location and the machine is commanded to move along any of the three linear axes. The instant the probe makes contact, it transmits an infrared signal that is picked up by the receiver located a few feet away. The signal instructs the control to capture and record the axis position. With knowledge of the location of probed surfaces or points, custom developed subroutines can

Figure 2. Part Verification On-Machine Using Standard Manual Gage

be used to calculate the size and location of various geometric relationships. Some systems can make compensations, identify trends, make comparisons, and print the results.

These same capabilities exist with an inductive probe. The main difference is that an inductive system has a primary coil located on the probe and a secondary coil located on the spindle (Figure 11). The two coils monitor the difference in signal frequency between deflected and non-deflected stylus conditions. In contrast to an optical signal, this approach minimizes the possibility of picking up a false signal. However, some machines cannot be retrofitted with an inductive probe because not all spindles have enough space to locate the secondary coil.

A tool length indicator is a tool sensor used to measure and store tool length offsets (Figure 12). The first tool is used to

establish the relationship between the reference surface and the tool length indicator. The operator enters the number of tools that will be measured. Software routines automatically present subsequent tools to the tool length indicator which measures each tool and records the offsets (Figure 13).

Accuracy

Once the equipment and principles of operation became known and the process was determined feasible, efforts to determine the accuracy and reliability were initiated.

The effect of different levels of five parameters on the measuring accuracy of the machine/probe system were statistically evaluated on the Monarch VMC 150. The five parameters were geometry, size, stylus length, stylus offset, and

Figure 3. Part Verification Off-Machine Using Custom Designed Gage

probing feed rate. A modified version of Latin square experimental design was drawn by KCD statisticians. The design was composed of 81 combinations of the parameters, with two repeats per combination. Statistical analysis was performed on the equality of the mean and standard deviation of the X, Y, and size deviations between the different levels of the parameters.

Three probes were used during the tests. One probe was equipped with a 55 mm, one with a 75 mm, and one with a 100 mm long stylus. Because of the difficulty in setting the exact stylus offset, three offset ranges were selected: small, medium, and large. The small offset ranged from 0 to 0.003, the medium from 0.003 to 0.005, and the large from 0.005 to 0.010 inches. The features were arranged on the work table of the machine as shown in Figure 14.

An evaluation of the results indicated that the system can measure the size of hole, slot, and sphere within 0.0003 inch. The location of these features varied up to 0.0007 inch. Certified gages were used to measure the size of all features, while the location was determined by an operator using machine coordinates and an indicator. Inconsistencies in data indicate that this manual method of locating features on the machine contributed to total error. The team members recommend that a feature plate similar to the one shown in Figure 15 be used for more accurate evaluation of the probe's ability to locate various features.

To obtain a more reliable indication of the system's accuracy, a decision was made to use calibrated metrology equipment. The objective was to evaluate the linear accuracy of each axis, the volumetric

Figure 4. Operator Makes Manual Calculation and Tool Compensation

Figure 5. Automated On-Machine Verification and Control

Figure 6. Probe Locating a Surface

accuracy, and the accuracy of the probe when isolated from the machine.

Single Axis Test

The single axis test was performed to evaluate the positioning accuracy of the machine while traveling along a single axis and probing in one direction. The Moore Bar, an 18 inch long step standard shown in Figure 16, was used as a reference. It was placed on the work table of the Monarch VMC 150 machining center and aligned longitudinally parallel to the X-axis. The Valeron touch probe was used to locate each of the 19 faces on the bar.

The bar was rotated 90 degrees and aligned parallel to the Y-axis of the machine. The Y-axis was evaluated in a similar manner. The Z-axis was evaluated using a series of gage blocks that ranged in length from 1 to 4 inches. The probe measured the distance from the reference surface to the top surface of each block. In all cases, the sequence was run three times.

The data reduction was performed on each axis individually. The evaluation converts the 19 locations that describe the position of each face of the Moore Bar into values of length. The number of different length

Figure 7. Probing Hardware (probe in spindle and tool length setter on machine table)

Table 1. Probing Systems at KCD

Machine	Type of Check	Instrument	Uncertainty (inch)
Monarch VMC150	X-Y Plane	Ball Plate	0.00096
Monarch VMC150	Volume, 28x18x6	Ball Plate	0.00100
Monarch VMC45	Volume, 7x7x5	Ball Plate	0.00060

combinations resulting from 19 positions taken 2 at a time is 171. The deviation between the measured value and the

reference length was calculated and a prediction of precision and uncertainty was made.

Figure 8. Probe Components

The variance was calculated for each of the 171 lengths by using the three individual measurements of a given length obtained by making three separate runs. The values were summed and their mean value was calculated. The estimate of the process standard deviation was obtained by taking the square root of this mean. The precision was defined as two times the value of the standard deviation. The Z-axis had only 10 combinations of length, but it was evaluated in an identical manner.

The mean deviation for a given axis was calculated from the 3 x 171 values of deviation. This value was taken as an estimate of the bias or systematic error of the measurement process along this axis.

The measuring uncertainty for a given axis when measuring in one direction was obtained by adding the bias value to the

value of precision. The results for each axis are shown in Table 2.

The random and systematic errors associated with the calibration values assigned to the reference lengths are insignificant to this test and were neglected.

Volumetric Measurement Capability

A ball plate was used to evaluate the volumetric measurement capability of the Monarch VMC150. The data were obtained in both the horizontal and tilted modes. Horizontal data were obtained by placing the base of the ball plate approximately parallel to the machine table (Figure 17). Tilted data were obtained by elevating one end of the ball plate in a way similar to raising a sine plate (Figure 18).

Figure 9. Typical Probes at KCD

Data Collection

The ball plate was placed on the table of the machining center in the selected mode with the plate nominally aligned to the machine axes. A line through balls 1 and 6 of the ball plate is aligned parallel to the X-axis of the machine. Ball 1 was selected as the reference ball or origin. The probe measured the X, Y, and Z locations of each ball in a prescribed sequence.

Data Reduction Method

Data from the ball plate were analyzed to obtain a quantitative estimate of machine precision and accuracy. The term "precision" expresses the degree of repeatability of the measuring process. It indicates how closely identical values were obtained when repeating the same measurement. The lack of agreement between these measurements is caused

by random errors inherent in the measurement process.

The term "accuracy" designates the degree of agreement between the measured size and its true magnitude. Because the true value can never be known, the uncertainty of the measurement estimates the magnitude of the range of possible errors.

The X, Y, Z coordinate of each ball was measured by the machine. These data were then transformed to a new set of X, Y, Z-axes established by three mutually perpendicular planes defined by four balls. This transformation was necessary because the reference coordinates assigned to the plate are also in the same coordinate system defined by the same four balls. By having both sets of data in the same coordinate system, the X, Y, Z components of the deviations between

Figure 10. On-Machine Operational Diagram, Optical Probe

measured and reference lengths can be obtained by a simple subtraction.

The evaluation was performed with the ball plate in both the horizontal and tilted modes. A summary of the complete analysis of data for the horizontal mode is given in Table 3 and for the tilted mode in Table 4. In these tables, the column headings of X, Y, Z and R refer to the X, Y, Z components of the deviations, and the radial or total deviation, respectively.

Probe Evaluation Using SIP Trioptic

The capabilities of the GTE Valeron Model 733 telemetry touch probe were evaluated when using an SIP Trioptic measuring machine (Figure 19). The evaluation was performed to provide a measuring capability estimate of the probe when isolated from the machining center. The SIP Trioptic was chosen to minimize the

contribution of error introduced by the machine. It is felt this contribution is negligible and it was ignored during this evaluation.

Sphere, External and Internal Cylinders

The location of five points was measured on the surface of a certified sphere. Ten determinations of the sphere's diameter and center location were made by applying a least squares criterion to each data set; the results are shown in Table 5.

Four measurements were made on the surface of a cylinder. Ten determinations of the cylinder's diameter and center location were made by applying a least squares circle fit criterion to each data set. The average, standard deviation, and range for the internal cylinder are reported in Table 6 and for the external cylinder in

Figure 11. Inductive Probe Circuitry

Table 7. The deviation of size for the three geometric shapes is shown in Table 8.

Repeatability in X, Y, or Z

The probe was checked for repeatability of locating an edge when motion is along a specific axis. The edge was a gage block that was aligned with its gaging face perpendicular to the axes of motion. Positive and negative direction were tested for X and Y. The average, standard deviation, and range of 10 readings of the location of this edge are shown in Table 9.

Probe Trigger Force Measurement

The force required to trigger the switch of the Valeron probe was measured with a Satham load cell. Each axis was tested independently. The results of the tests are shown in Table 10.

In summary, this evaluation shows that the VMC 150 with the Valeron probe can measure accurately within 0.001 inch in a 28 by 18 by 6 inch volume. By isolating the probe from the machine, it was determined that the probe contributes approximately 10% of the total error. This study clearly shows that the total accuracy of the machine/probe system is highly dependent on the machine.

Because it was understood that to improve the accuracy of the system it is necessary to reduce machine errors, KCD started investigating the ways to upgrade the existing machines. A literature search revealed that several universities are studying the effects of various machine variables on accuracy. Through theory and computer modeling, they have shown that custom-developed software can compensate for positioning error, backlash, and thermal growth. A contract

Figure 12. Tool Length Indicator

was placed with Purdue University to further study the feasibility of incorporating these developments on some of KCD's equipment. The results of the study have been reported.¹

Probing capabilities are being used in the miniature machining area to study the effects of machining parameters on accuracy. Mario Perez Wilson (MPW) methodology is being applied to characterize variables and to identify optimum parameters. The results of this study have been reported.²

Software Capabilities

Every machine tool builder supplies supporting software to operate the probe and accessories. The software varies depending on control. Some cycles are fixed and cannot be changed by the machine user. Others, like Bendix System 5, allow the user to revise supplied cycles or to custom write his own.

Numerical control programmers at KCD have revised most of the programs to provide more efficient use of variables and to make the programs more operator friendly. Several new application programs were developed for both probing and

Figure 13. Operation of Tool Length Indicator

ARRANGEMENT OF FEATURES
ON VMC 150 TABLE

FEATURE	SIZE	-X- LOC.	-Y- LOC.
HOLE 1	1.0001	0.0000	0.0000
HOLE 2	1.5037	-4.4600	5.9539
HOLE 3	0.5000	6.0294	5.9005
SPHERE 1	0.3750	-15.3908	6.9577
SPHERE 2	0.5000	-11.8532	4.0548
SPHERE 3	1.0000	6.6230	-2.9821
SLOT 1	0.5000	-11.7448	-2.8000
SLOT 2	1.0000	-12.6188	-2.8000
SLOT 3	2.0000	-8.1941	-2.8000

Figure 14. Arrangement of Features for Accuracy Check

Figure 15. Probe Feature Plate

machining. One of the most notable is a skew check and skew compensating program for machining. This program is further discussed below in relation to the EMR Shield.

The confidence level of the probing system is highly dependent on the datuming cycle. It is used to reference the stylus on the probe to the machine coordinate system (Figure 20). Before the probe can make accurate measurements, it must be datumed. Any error in datuming will directly affect measuring accuracy.

In addition to the datuming cycle, a setup program was made to aid operators in specific parts of the setup process. To make the program user-friendly, a menu was developed (Figure 21). The program

includes subroutines that allow the operator to datum the stylus, automatically align the rotary axis, set the probe tool length, indicate a bushing for program zero, and automatically set the tool lengths. The application of the probe and these subroutines resulted in a 30 to 75% reduction in setup time when compared to the conventional approach.

Incorporating Probe on Product

Throughout the plant, probe-equipped machines are receiving the benefits of probe capabilities at every setup. In addition to setup, probing has been incorporated into numerous production operations. Part alignment, size measurement, automatic compensation, and decision making are typical probe applications. During the first two years,

Figure 16. Moore Bar

Table 2. Single Axis Test, Monarch VMC 150

Axis	Feed Rate (in./min)	Stylus Length (mm)	Precision (inch)	Uncertainty (inch)
X	10	50	*	0.00030
X	50	50	0.00008	0.00030
X	25	50	0.00008	0.00027
Y	50	100	*	0.00035
Y	25	100	*	0.00033
Y	50	100	0.00008	0.00034
Z	50	100	*	0.00090

* Indicates 2 or less runs.

Figure 17. Ball Plate, Horizontal Mode

over 50 production operations included a probe as part of the cycle.

To further illustrate probing capability, two applications will be explained below in more detail.

EMR Shield

Initially, a probe was incorporated on this product to automate the process of locating casting datums (-E-, -F-, -H-, and -J-) before machining features relative to each of these datums (Figure 22). After loading on the fixture, the part is machined and probed using the steps shown in Table 11. Before the probing was available, all the steps involving a probe were performed manually.

A datum -B- boss was rough machined. The operator would then measure the remaining height, compensate the tool

length, and finish machine the boss. The operator also manually located datums -E- and -F- by using a locating device and an indicator. A similar approach was used to locate datums -H- and -J- prior to machining the 12-hole pattern and the O-ring groove. Incorporation of the probe minimized operator involvement and reduced the cycle time by 30%.

The above method compensated only for variation of datums along the X and Y locations. However, one shipment of raw material showed that casting datums could also be skewed up to 1/2 degree (Figure 23). This condition translates to 0.032 inch mislocation of holes, almost three times the allowable tolerance. The amount and direction of skew were not consistent. This presented a challenge to engineers and NC programmers to develop a method to measure and compensate for both the location and rotation of datum surfaces. Programs for measuring, calculating, and

Figure 18. Ball Plate, Tilt Mode

Table 3. Volumetric Test, Ball Plate in Horizontal Mode

	X (inch)	Y (inch)	Z (inch)	R (inch)
Average Deviation	0.000354	0.000110	0.000041	0.000389
Range of Deviations	0.001333	0.001152	0.001771	0.001449
Standard Deviation	0.000282	0.000231	0.000260	0.000279
Avg. + Two Std. Dev.	0.000918	0.000573	0.000561	0.000947
Avg. - Two Std. Dev.	-0.000211	-0.000353	-0.000480	-0.000169
Average Drift	-0.000007	0.000013	0.000033	
Maximum Drift	0.000200	0.000100	0.000200	
Total Uncertainty				0.000959

machining relative to skewed surfaces were developed, and parts were machined within product specifications. One of the more challenging tasks was developing a

program to machine an O-ring groove with variable starting, ending, and center points on each radius. The initial benefits were quick turnaround and a reduction in cycle

Table 4. Volumetric Test, Ball Plate Tilted

	X (inch)	Y (inch)	Z (inch)	R (inch)
Average Deviation	0.000416	0.000012	-0.000097	0.000289
Range of Deviations	0.003310	0.002196	0.009492	0.001991
Standard Deviation	0.000487	0.000333	0.001238	0.000354
Avg. + Two Std. Dev.	0.001389	0.000677	0.002378	0.000997
Avg. - Two Std. Dev.	-0.000557	-0.000653	-0.002573	-0.000418
Average Drift	-0.000067	-0.000013	-0.000033	
Maximum Drift	0.000900	0.000300	0.000300	
Total Uncertainty				0.000999

Figure 19. Accuracy Evaluation Using Trioptic

time, setup time, tooling cost, rework, and scrap cost. However, the success of this

project was a major step in advancing the probing application and expanding the use

Table 5. Probe Accuracy Off-Machine, Sphere Measurement

Parameter	X (inch)	Y (inch)	Z (inch)	Radial (inch)
Mean	-7.397483	-1.147724	-0.995953	0.375036
Std. Dev.	0.000038	0.000081	0.000088	0.000084
Range	0.000141	0.000282	0.000224	0.000211
Precision	0.000076	0.000162	0.000176	0.000168

Table 6. Probe Accuracy Off-Machine, Internal Cylinder

Parameter	X (inch)	Y (inch)	Radial (inch)
Mean	-4.288834	0.250897	0.375924
Std. Dev.	0.000085	0.000102	0.000081
Range	0.000251	0.000341	0.000268

Table 7. Probe Accuracy Off-Machine, Outside Cylinder

Parameter	X (inch)	Y (inch)	Radial (inch)
Mean	2.820448	0.661923	0.374977
Std. Dev.	0.000069	0.000077	0.000025
Range	0.000236	0.000243	0.000120

Table 8. Probe Accuracy Off-Machine, Size Measurement

Type of Feature	Deviation From Ref. Size (inch)
Sphere	0.000197
Internal Cylinder	0.000154
External Cylinder	0.000056

Table 9. Repeatability of Probe Along Each Axis (Inch)

Axis	Average	Standard Deviation	Range
Pos. X	3.873320	0.000025	0.000098
Neg. X	4.702143	0.000006	0.000016
Pos. Y	-0.904589	0.000003	0.000009
Neg. Y	-0.069436	0.000006	0.000018
Pos. Z	0.576963	0.000004	0.000013

Table 10. Trigger Force

Stylus Length (mm)	X Direction (grams)	Y Direction (grams)	Z Direction (grams)
50	84.0	84.0	82.0
75	80.0	77.0	82.0
100	55.4	65.7	81.0

of customer-programmed cycles to machining.

Solenoid Housing

The solenoid housing has six spiral surfaces on each end (Figure 24, with the spiral areas shaded). Spiral surfaces are dimensioned from datums A and B which revolve around the geometric center of the part and increase from a radius value of 0.352 inches at a rate of 0.0005 inch per degree. These spiral surfaces are difficult to machine and to measure to a required contour tolerance of 0.0018 inch. Using printed data from on-machine probing has proven to be beneficial in the production of this housing

The probe cycle establishes a reference on either datum A or B, depending on which end of the part is being machined. Once referenced, the probe can measure

any portion of any spiral surface, compare this measurement to a theoretical value, and print both values for all surfaces.

An operator can compare the values and make the necessary corrections before making a finish cut, without removing the housing from the fixture. No errors are introduced by removing and refixturing the part. A part repeatability of 0.0002 in. has been documented over a three-year period.

The quality history has led to reduced product inspection. A random sample is selected and inspected in the Precision Measurement department. The measurements are compared to the on-machine results supplied by Manufacturing. The entire lot is accepted if the two measurements correlate within 0.0001 inch.

Figure 20. Probe Datuming

(	)	()
(N10 IS DATUM THE PROBE	)	()
(N20 IS LEVEL -A- AXIS	)	()
(N30 IS SET PROBE TOOL LENGTH)	()	
(N40 IS INDICATE BUSHING	)	()
(50 IS SET TOOL LENGTH	)	()
()		
()		
()		

Figure 21. User-Friendly Setup Program

Prior to incorporating the probing techniques, a sensitive gage was used to verify spiral features. A part was removed from the fixture, verified, and refixtureed if additional machining was required.

Repositioning of the part in the fixture presented an extremely difficult task.

Prior to incorporating the probe, the scrap rate was as high as 60%. After the probing

Figure 22. EMR Shield

operation was perfected, the scrap rate was nearly eliminated. Only one housing was lost in approximately 10,000 spiral operations.

Benefits of On-Machine Probing

Setup and cycle time are reduced; the system• Minimizes the amount of high precision fixture alignment,

- Reduces individual part setup time, and
- Makes it possible to combine operations and eliminate multiple setups.

Quality and yield are improved. On-machine probing

- Accommodates the natural variations of key features on castings, forgings, and weldments,
- Provides immediate feedback of dimensions produced (corrections can be made before finish machining),
- Identifies and compensates for trends, and
- Provides bases for reduced final inspection.

Operator tool offset errors are eliminated. The system

- Reduces scrap on state-of-the-art tolerance parts, and
- Reduces rework of difficult features.

Tooling costs are minimized. The system

Table 11. Machining Sequence for the EMR Shield

Sequence	Description
	Load Part On Fixture
	Load Locating Detail on Datums E and F
Tool 1	C'Drill
Tool 2	Drill
Tool 3	Bore
Tool 4	Ream
Probe	Probe Locating Detail for Centerline of 5 Holes
Program Stop	Remove Locating Detail
Probe	Probe 5 Tabs for Location in -Z-
Tool 5	C'Drill and C'Sink
Tool 6	Drill
Tool 7	Tap
Probe	Probe Datums H and J
	Calculate Location and Skew
Tool 8	Mill Top Surface
Tool 9	Mill O-Ring Groove
Tool 10	C'Drill and C'Sink
Tool 11	Drill
Tool 12	Tap

- Reduces the complexity of fixtures, and
- Reduces the quantity of fixtures.

Turnaround time on new parts is improved.
On-machine probing

- Minimizes lead time for complex parts, and

- Minimizes alteration time resulting from design change.

The system assists computer integrated manufacturing.

- Probing will play a vital role in the success of the Flexible Machining System and the Computer Integrated Manufacturing Environment.

Figure 23. Distorted EMR Shield

Figure 24. Solenoid Housing

Limitations

Probe-equipped machines provide many benefits and greatly expand the capability and flexibility of the machining process. However, on-machine probing does have limitations and drawbacks, if not used selectively. On most systems, probes can measure surfaces parallel to either the X-, Y-, or Z-axis. Surfaces that are oriented at an angle cannot be measured accurately unless the part is located on a rotary axis that can position the part surface parallel to one of the axes.

Probing can increase cycle time. To maximize benefits, all alternatives should be considered and a probe should be used

when it is determined to be the best overall approach. On most systems, formatting of printed results is very limited. This will have to improve in the future to expand the use of probing results.

Product Acceptance

One of the objectives of this project was to investigate the use of on-machine verification results for final product acceptance. The project team has addressed this subject and found that a broad range of issues would need to be resolved before 100% product acceptance based on probe results could take place. Some of the issues are machine calibration, probe calibration, labor classification, restrained versus free state condition, the effect of subsequent operations, and better methods of outputting and formatting the results. These issues will be addressed in the future as part of the Flexible Machining System (FMS) project where modern machines and more computing capabilities are available.

Even though products are not accepted 100% based on probe results, several

parts such as the Solenoid Housing are being accepted on a sample basis on probe results.

In these cases, it has been shown that probing has reduced process variability, therefore increasing the process capability index to where 100% final acceptance was not required.

Accomplishments

During the first two years, probing was installed on 24 machines, and 57 different operations were using probing capability in production.

The incorporation of automated on-machine verification has yielded a number of benefits for KCD. When compared to conventional methods, some machine setup functions have been reduced as much as 75%. Probing capabilities have allowed combining of operations, therefore reducing setup time, cycle time, and tooling cost. Part quality has improved by accommodating natural variations and by providing immediate feedback and automatic compensation prior to making a finish cut. Automated on-machine verification eliminates human error when measuring and applying tool offsets.

System accuracy and repeatability have been established for two families of N/C machining centers. Controller software has been enhanced, and initial correlations have been performed between in-process and final inspection. The close correlation of results and the ability of probing to control variance of process resulted in reducing the final inspection to a sample basis from previous 100% inspection.

Future Work

Current and future projects involve these elements:

- Expand capabilities to measure a wider range of geometric relationships;
- Further investigate the ways to improve machine accuracy and system reliability;
- Improve data collection, formatting, and automation of statistical quality control;
- Define the ways to use probes for machine monitoring;
- Define the products to accommodate on-machine probing; and
- Further investigate the issues associated with product acceptance

References

¹ G. L. Carnivale, *Machine Tool Error Analysis* (Final Report). Kansas City Division: KCP-613-5037, April 1993, Available from NTIS.

² L. W. Love, *Machine and Process Characterization* (Final Report). Kansas City Division: KCP-613-4971, December 1992, Available from NTIS.

Appendix A

NC Probe Styli

Figure A-1. N/C Probe Stylus 48601200

Figure A-2. N/C Probe Stylus 48601300

Figure A-4. N/C Probe Stylus 48601302

Figure A-5. N/C Probe Stylus 48601303

Figure A-6. N/C Probe Stylus 48601304

Figure A-7. N/C Probe Stylus 48601400

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Figure A-8. N/C Probe Stylus 48601401

Figure A-10. N/C Probe Stylus 48601403

Figure A-12. N/C Probe Stylus 48601405

Figure A-14. N/C Probe Stylus 48601407

END

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11 / 4 / 93