

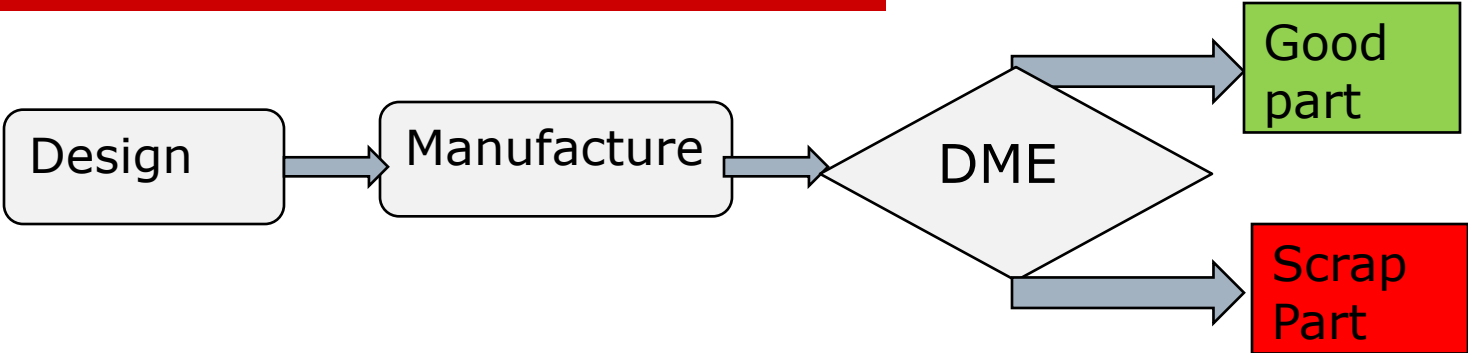
Innovations in Machine Tool In-Process Measurement & Feedback



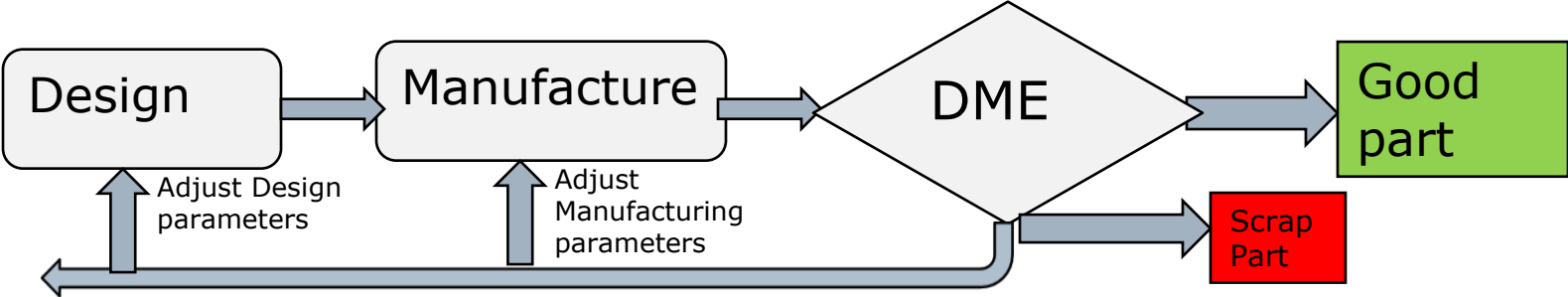
Ray Karadayi
President, AAT

www.aat3d.com

Evolution of Measurement Process

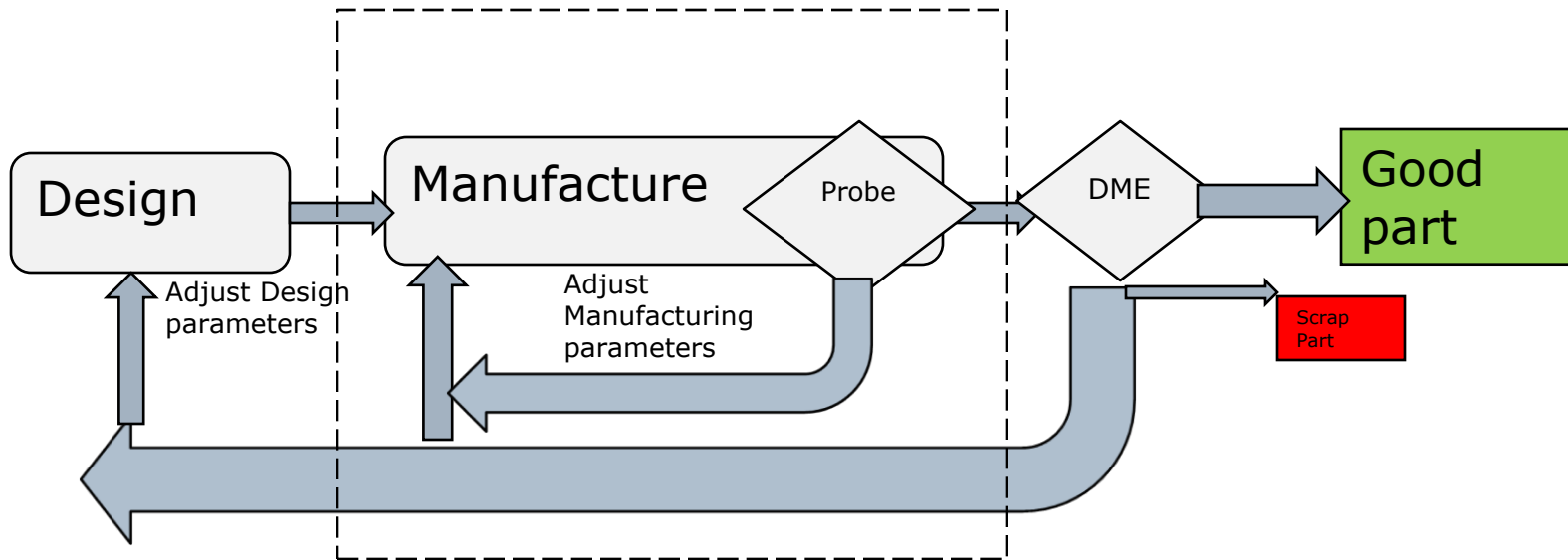


Open Loop Quality Control



Closed Loop Quality Control

In process Measurement



Inner loop provides
faster feedback to
manufacturing

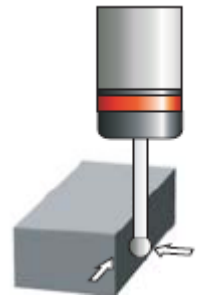
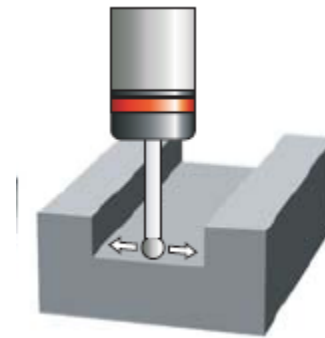
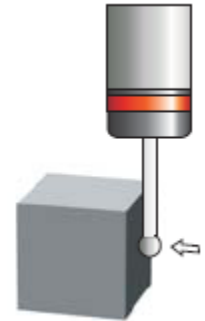
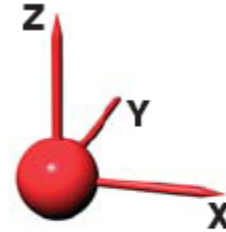
Current State: Machine tool probing programs

- Usually hard coded into machine language
- Copied with floppy disk or serial interface.
- Limited to simple feature measurements or one directional points
- Hard to use and understand. Require on machine editing and proving.
- Hard to edit or make changes.
- User prompts are cumbersome, need operator to make decisions and enter data
- Slow to start and execute.
- Simple reports or on screen display

```
G103P1
M19
G65P9360C#3
IF[#13EQ-1]AND[#7GT[#556*6]]THEN#33=1
IF[#13EQ-1]AND[#170GT[#556*6]]THEN#33=1
#180=#24
#183=#25
#22=0
#24=#5041
#25=#5042
#16=#5043-#5083
IF[#7LE0]THEN#3000=137(INVALID D)
IF[#18EQ#0]THEN#18=#5043-#5083
IF[#13EQ#0]THEN#13=#556*.2
IF[#1EQ#0]GOTO150
#22=#1
IF[#1EQ2]GOTO170
IF[#1NE1]THEN#3000=131(INVALID A)
N150#1=1
N170#3=#182
IF[#1EQ2]THEN#3=#3+2
IF[#19EQ1]GOTO230
IF[#19EQ2]GOTO210
IF[#19NE3]THEN#3000=149(INVALID S)
N210IF[#6NE#0]GOTO230
IF[#11EQ#0]THEN#3000=106(NO K)
G90G31Z[#16-#556/3]F[#556*10]
-- --
```

Machine Tool Probing Software: Current Methods

- Work offsets:
 - Simple feature location: Corner, Hole, Edge.
Data is displayed or set to a machine work offset.
- Size and location measurement
 - Measure feature location: Corner, Hole, Boss
 - Measure diameter or width of a slot.
- Measurements are for simple features
- Points are measured along one direction X Y Z
- Report is printed to serial port. Very slow and difficult to modify.



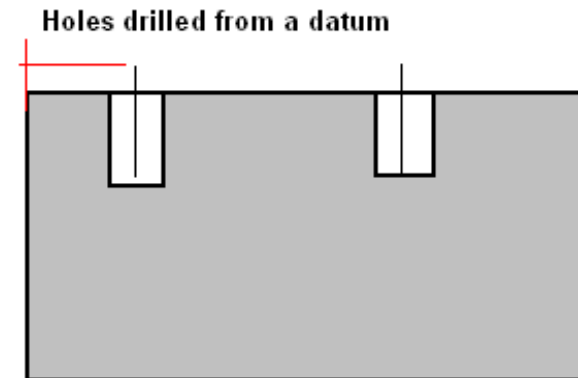
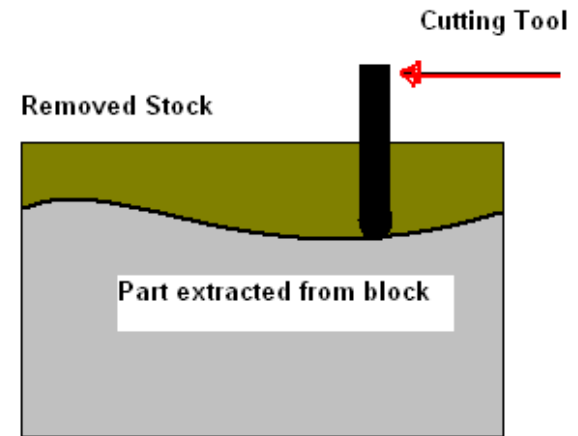
Types of part machining process

□ Single operation process:

- Extract part from a block:
- Die & Mould making process

□ Multi Operation process

- Extract features relative to the other features
- Machines have to be aligned to each other
- Might require expensive fixtures



Machine tool as a measuring device

Goals:

- ❑ Locate part before cutting: Create a 3D alignment of the part to adapt cutting program. Not just a origin transfer.
 - ❑ Create offsets for stock removal built in to cutting programs.
 - ❑ Detect part errors during cutting process to produce parts with no errors.
 - ❑ Automation: Provide closed loop manufacturing system that minimize cost while enhancing quality.
 - ❑ Avoid unnecessary CMM verification loops; Shorten overall part manufacturing time.
 - ❑ Improve manufacturing quality.
-

Machine tool as a measuring device

More goals:

- ❑ **Extend tool life**, use tools to their max life.
 - ❑ Avoid expensive hard gages, **provide flexible part inspection** environment.
 - ❑ **Automate manufacturing process**, achieve a flexible lights out factory environment.
 - ❑ **Achieve flexibility** in part program development, editing, verification.
 - ❑ Create **single programming and data collection environment** for multiple machine environment as well as CMMs.
 - ❑ Generate final measurement reports
 - ❑ Collect **statistical data** for production environment.
 - ❑ **Improve finished part quality**
 - ❑ **Minimize overall production cost**, Maximize Productivity, Quality.
-

Challenges to overcome

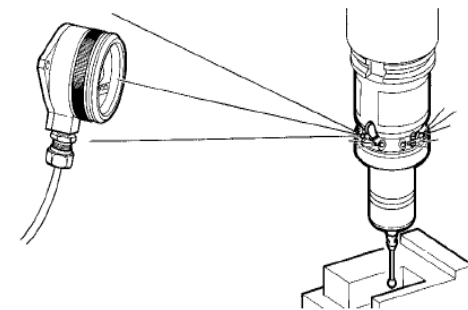
General concerns for machine tool measurement:

- ❑ Cannot measure on same machine that cuts part
 - ❑ Less time for machining process
 - ❑ Dirty messy environment to measure
 - ❑ Temperature issues, part expansion
 - ❑ Cannot measure complex parts
-

PROBE SYSTEMS

Probes

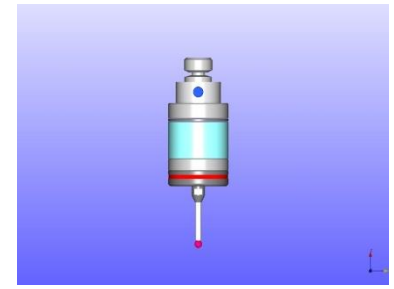
- Built for the harsh manufacturing environment.
- Durability ensured in all manufacturing situations; the probes are designed to minimize the effect of vibration, acceleration, coolant exposure and possible collisions.
- Are designed to be loaded automatically like a cutting tool. Can be held on the tool magazine
- Very good repeatability. Most probes have lobbing errors due to probe trigger kinematics.
- Some of the manufacturers are: Marposs, Renishaw, BLUM, M&H, Heidenhain



Transmission Systems

- [Hard-wired](#)
 - [HF \(high frequency\)](#)
 - [Optical \(infrared\)](#)
 - [Radiofrequency](#)
-

Calibration of Probes

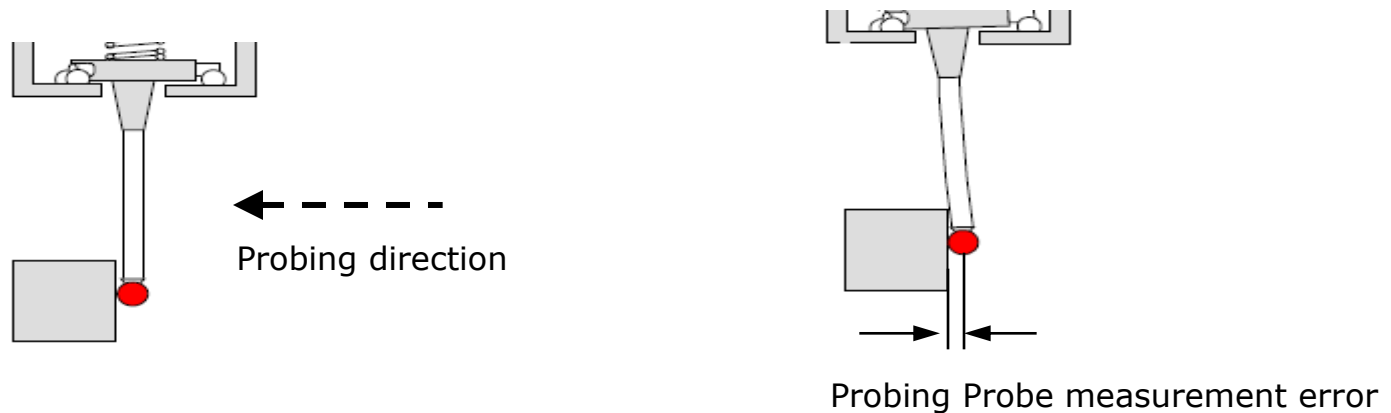


First step to achieve all the goals set: IMPROVE MEASUREMENT DATA

Probes are normally indicated like a tool using a pre-setter for its exact length and diameter. This is not flexible, forces to measure along one axis at a time.

- New Calibration methods are developed:
 - Removes all probe lobbing (triggering) errors in order to measure points along 3D vector.
 - Create dedicated calibration routines for programs to achieve maximum accuracy. Create compensation data for each point at its measuring velocity.
 - Calculate probe offsets and runouts instead of forcing probes to be perfectly straight.
 - Create perfect relationships between probes and any cutting tools in order to provide feedback for tool error detections.
-

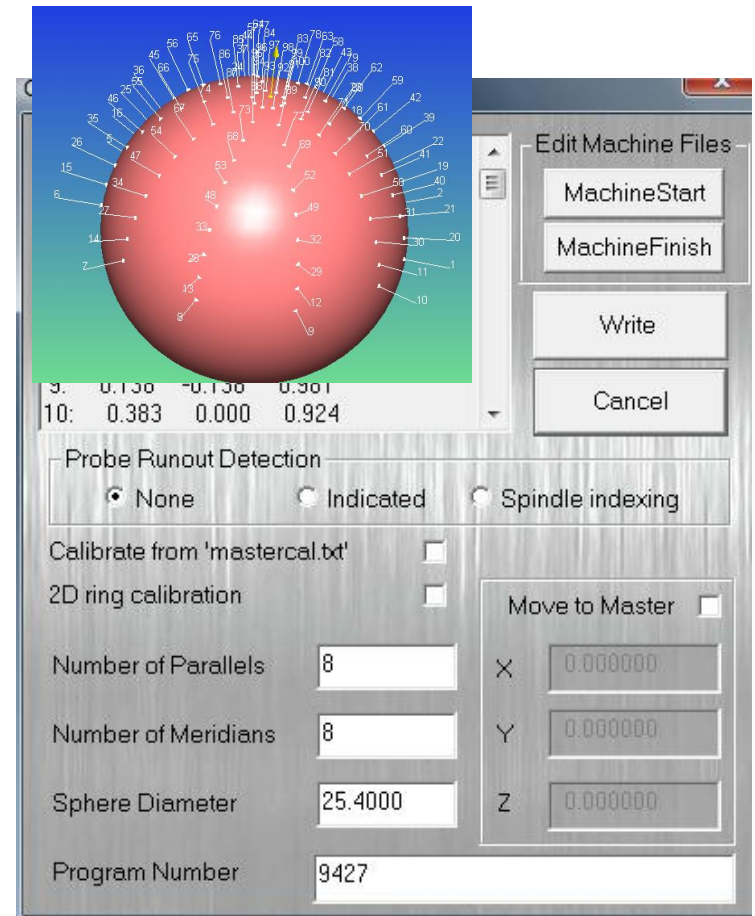
Probe Trigger Error



- ❑ Probing error depends on direction of approach
 - ❑ Error is larger at higher measuring velocities
 - ❑ Error is very repeatable
-

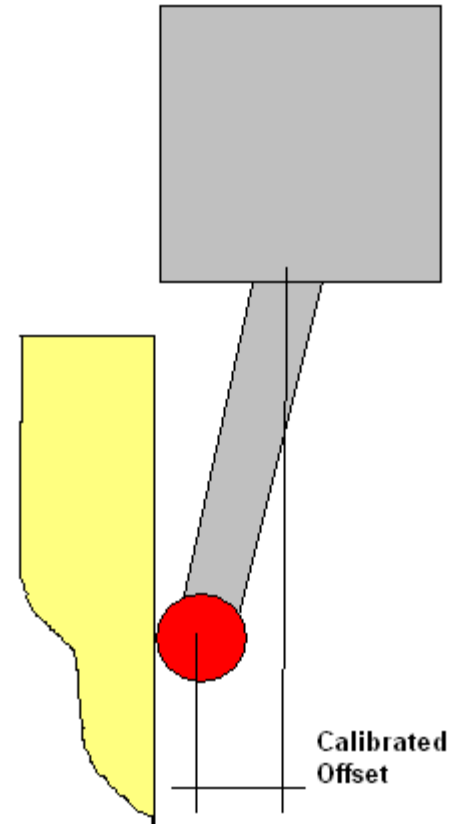
Probe error compensations

- ❑ Locate calibration ball
- ❑ Measure points on calibration ball at pre-designated vectors
- ❑ Vectors are decided from the measurement program or on a grid
- ❑ Calculate probe trigger errors at the speed of measurement for each vector
- ❑ Use these errors for compensating actual measurement data while executing programs



Calibration of probe to other tools

- Traditional systems require probe to be perfectly aligned with no DX DY deviations
- CappsNC can calculate exact probe offsets to the machine tool
 - Calibrate offsets by way of indicating
 - By way of measuring a cut specimen



Probe implementation

- All probe measurement errors must be removed in the software
- Probes offsets are calculated to other tools for perfect relationship
- Real time data interface allows compensation of every point in order to achieve highest accuracy.
- Probe head alignment is calculated and applied to probing vectors for 5 axis head configurations

Calibration Options

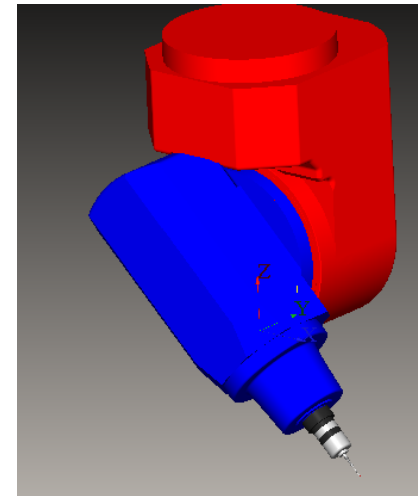
Create Calibration File

CNC Cal. Prog. name:

Max Angle between calibrated vectors:

Sphere Diameter

Move to Master Spindle Indexing



Review of manufacturing errors

- So far we created a perfect tool to measure by means of probe calibrations
 - Next: Review possible sources of manufacturing errors to measure and detect them by using our probe
-

Sources of Manufacturing Errors

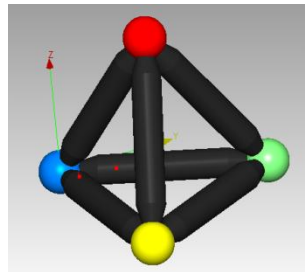
ERRORS Inherent to each machining center:

- Errors due to Machine Geometry
- Errors due to Part offsets
- Error due to Part flexibility
- Errors due to Part offsets from one machine to other
- Errors due to tool flexibility
- Errors due to tool wear
- Errors due to thermal effects

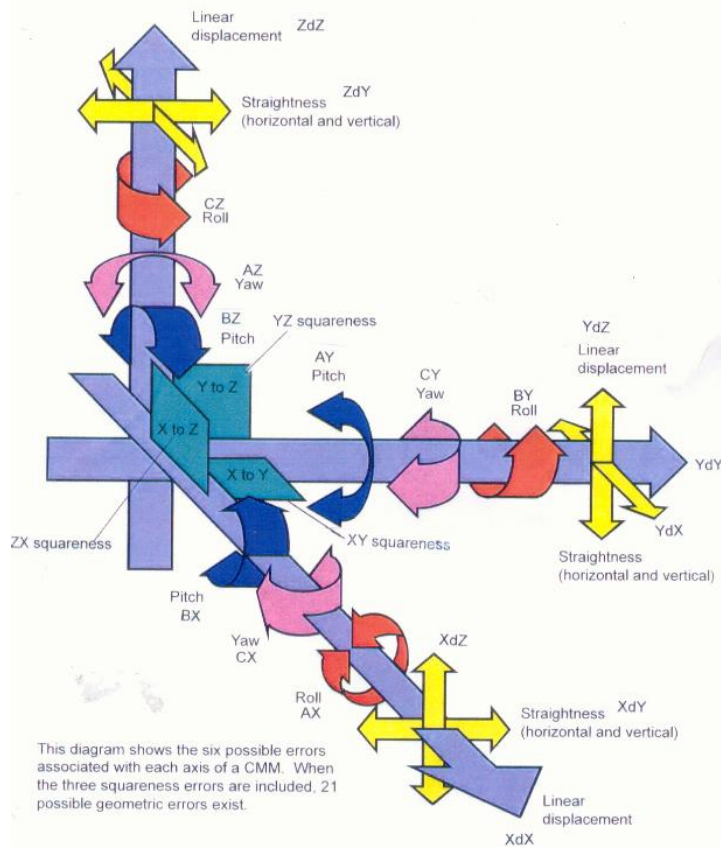
Additional Errors in multi operation systems due to misalignment of machines to each other.

Errors due to Machine Geometry

- ❑ There could be errors due to machine geometry. Machines are periodically calibrated for accuracy. 21 degree of machine errors can also be incorporated to the measuring software.
- ❑ An error map can be created for all or only significant machine errors.
- ❑ **Software will compensate** measurement data by using error map.
- ❑ Machine errors can be periodically checked using a simple gauge such as the TETRA-CHECK which can also update machine error parameters.
- ❑ Periodic check of datum features are built in to measurement programs to detect changes in the machine.



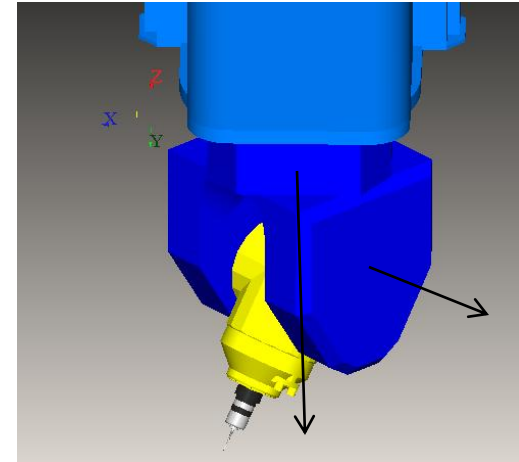
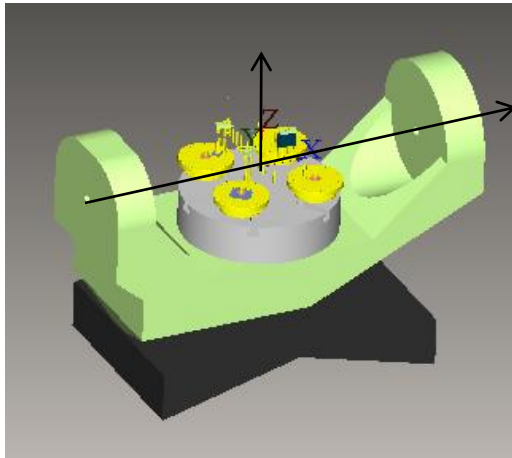
21 Degree of geometric errors



- Each axis has 6 degree of freedom errors.
 - Linearity
 - Straightness's to 2 other axis
 - Roll, Yaw, Pitch
 - Squareness of 3 axis
 - Very expensive to measure these errors
 - Overloads can change these errors
- Measuring software can
 - Verify these errors periodically to assure accuracy
 - Independently calculate and correct for these errors.
 - Quick verification and calculation for major errors can be performed.

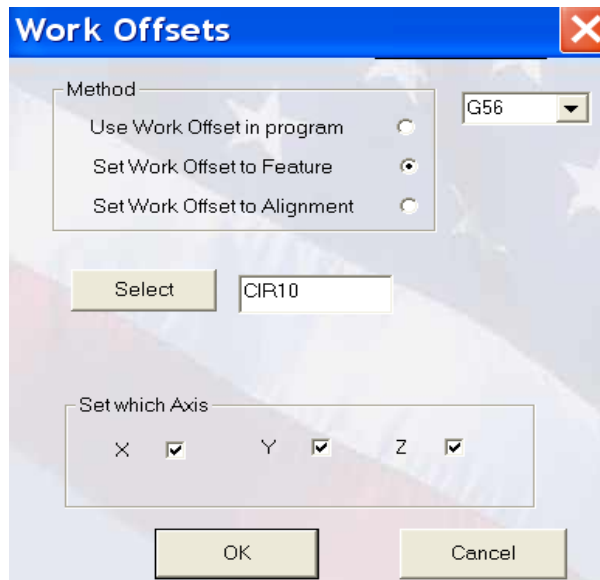
Errors due to 5 Axis Geometry

- ❑ 5 Axis heads with spindle indexing could have errors due to head alignment
- ❑ Rotary table or 5 axis index able tables have errors in table location, offsets and direction of rotations.
- ❑ All actual configurations can be calculated by the measuring software independently to assure accuracy.
- ❑ Simple test programs can be written for periodic verifications.



Errors due to Part Offsets

- ❑ Parts does not have to be located by expensive fixtures in order to achieve perfect locations.
- ❑ An 3D alignment program is created from the CAD model and parts exact location is calculated.
- ❑ Calculated data can be used as work offset and updated into controller variable.
- ❑ Cutting program can be adapted to parts exact shape to achieve perfect cut.

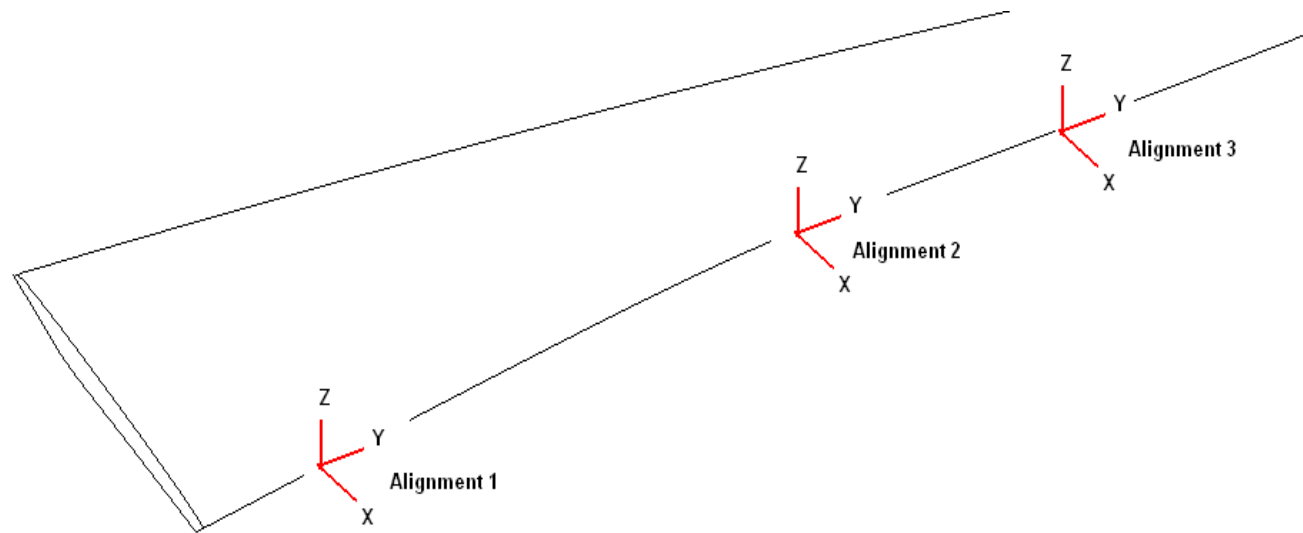


Work offset GUI for measurement program

CAPPS/WRKOFF,SET,G56,FA(CIR10),X,Y,Z

Adapting cutting program to a large part

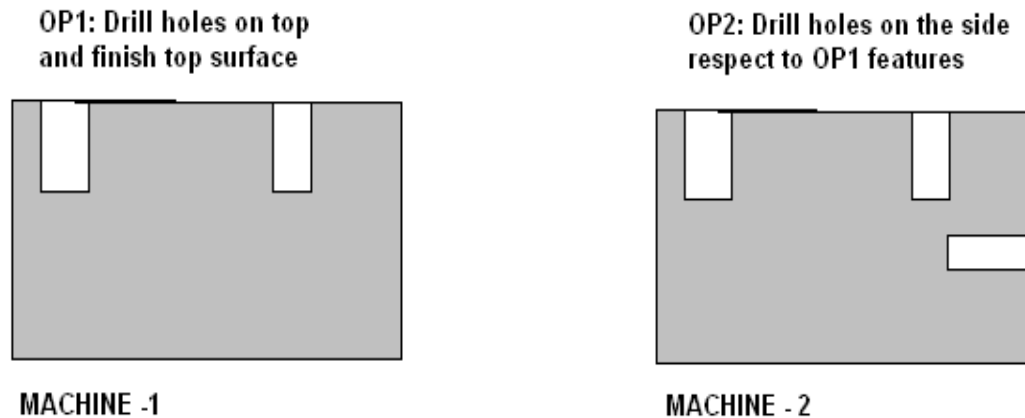
- ❑ Multiple 3D alignments can be calculated by probing datum features.
- ❑ Cutting program is adapted by using these alignments.



Multiple alignment correction applied to an airplane wing

Datum errors between different operations

- ❑ Many parts are created through multiple operations
- ❑ Any misalignment between machines will cause error in the final manufactured part.
- ❑ Calibrating and maintaining machines to each other is expensive and time consuming.



- Flexible, adaptive measurement with built in probing scheme overcomes this problem.
- Offset relations are calculated between each machine tools.
- Alignment is calculated and applied to the cutting program for each OP.
- Measurement data are merged in a single database for total quality control.

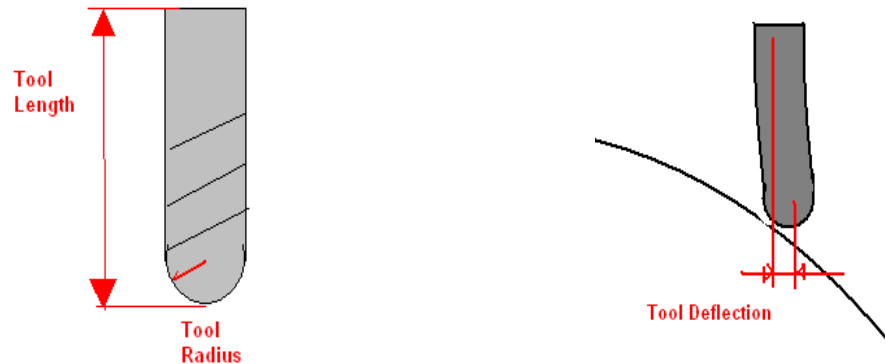
Cutting tool wear and deflection

- Most part manufacturing errors can be attributed to tool wear.
- Cutting tools will erode during cutting process resulting in
 - Shorter tool length
 - Smaller diameter

An intelligent compensation scheme can be developed in to manufacturing process with selective compensation and real time feedback

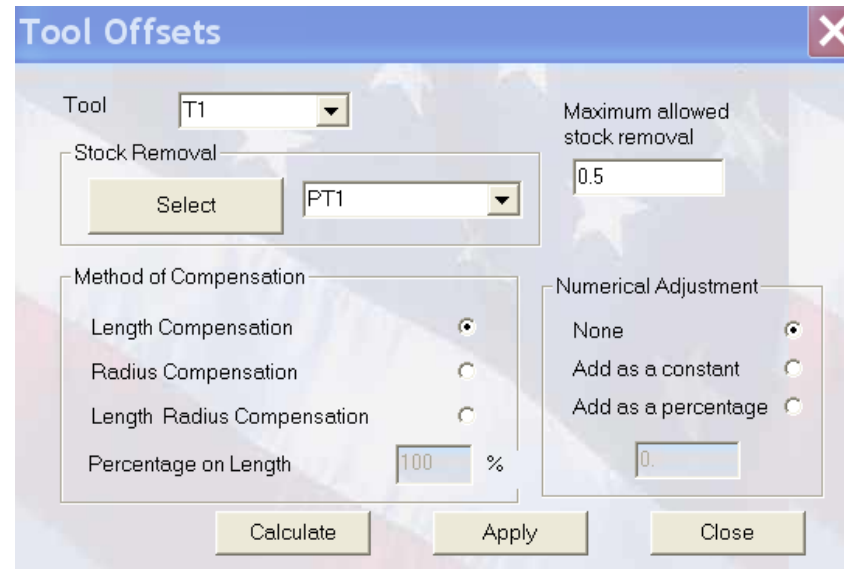
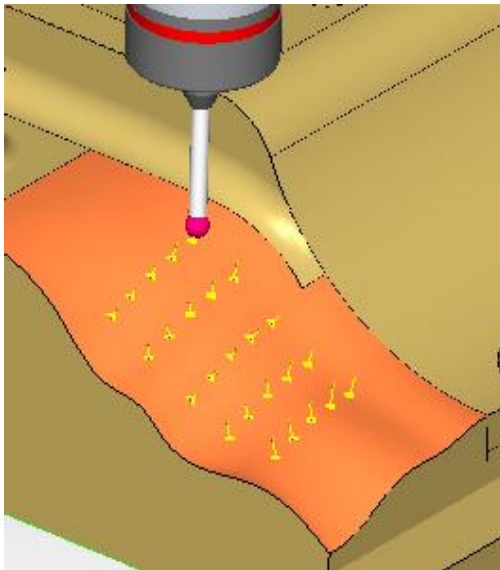
Tool can also deflect creating errors on part

Real time probing built in to manufacturing process will minimize errors from these sources



- Real time compensation utilizes all of useful cutting tool extending tool life.
- As tool errors are compensated within the manufacturing process, parts are always made at correct dimensions increasing quality.

Tool Compensation



CAPPS/TLCOMP,TL(T1),FA(PTRN),0,2,100.000,0.500

A different method of compensation can be incorporated though out a single program.

Thermal Effects

- ❑ Part and machine will expand due to excessive heat in the manufacturing cell.
- ❑ Measuring system can apply compensation for thermal effects in real time or as an average as a expansion factor.

Temperature Compensation

Apply Temperature Compensation

Sensor1	Disconnected
Sensor2	Disconnected
Sensor3	Disconnected
Sensor4	Disconnected
Sensor5	Disconnected
Sensor6	Disconnected
Sensor7	Disconnected
Sensor8	Disconnected

Nominal Temperature: 20.00

Ambient Temperature: 20.00

Unit: Celcius

Refresh

Material Type: Aluminium

Material Thermal Expn Coefficient: 0.000024

XAxis Thermal Expn Coefficient: 0.000000

YAxis Thermal Expn Coefficient: 0.000000

ZAxis Thermal Expn Coefficient: 0.000000

Manual Temperature Entry

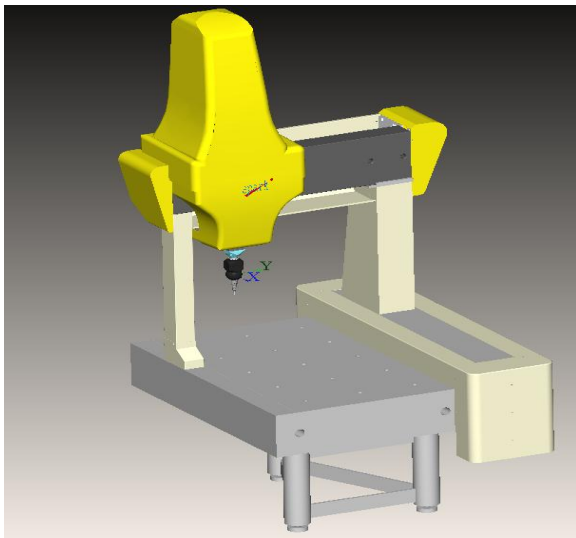
Shrink Factor		Shrink Center	
X	1	X	0
Y	1	Y	0
Z	1	Z	0

Thermal compensation as a static expansion/shrinkage factor

Real time thermal comp. setting

Alternatives to On Machine Tool Measuring

Measuring with CMMs, and portable measuring machines

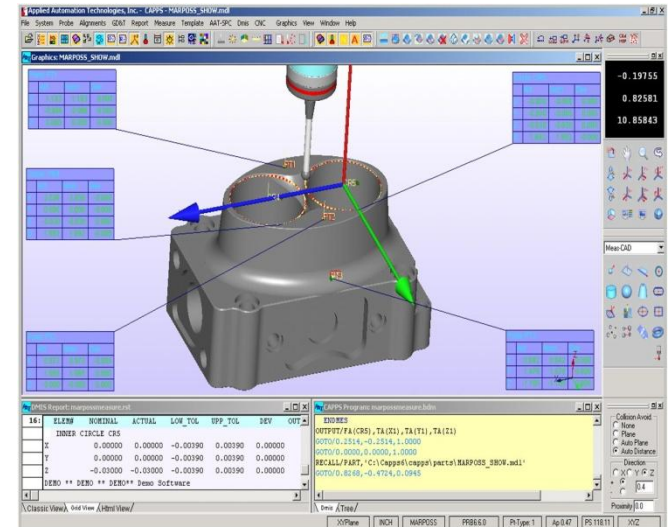


Measuring with Dedicated gages



Machine tool measurement vs CMM measurement

- **CMM:** Usually measure a finished part manufactured by multiple machines.
 - Part has to be removed from machine tool and moved to CMM
 - Sometimes, parts have to be moved several times and machine tool has to wait for results.
 - Parts are usually sampled and programs could be long for 100% verification
- **Machine Tool:** Measure features manufactured by one machine.
 - Machine tool probing is NOT to eliminate CMM part verification
 - Machine tool probing is to improve manufacturing process
 - Programs can be short, measuring and immediately correcting for critical errors.
 - Proper implementation will minimize many loops with CMMs
 - In some cases it could be impossible or very expensive to move parts to a CMM as for large die & mould. Machine tool probing can enhance quality control.



Machine tool measurement vs dedicated gages

- ❑ **Dedicated gauges** are not flexible
- ❑ New gauge must be made for part modifications
- ❑ Hard gauges are expensive
- ❑ Needs Calibration by a master part.

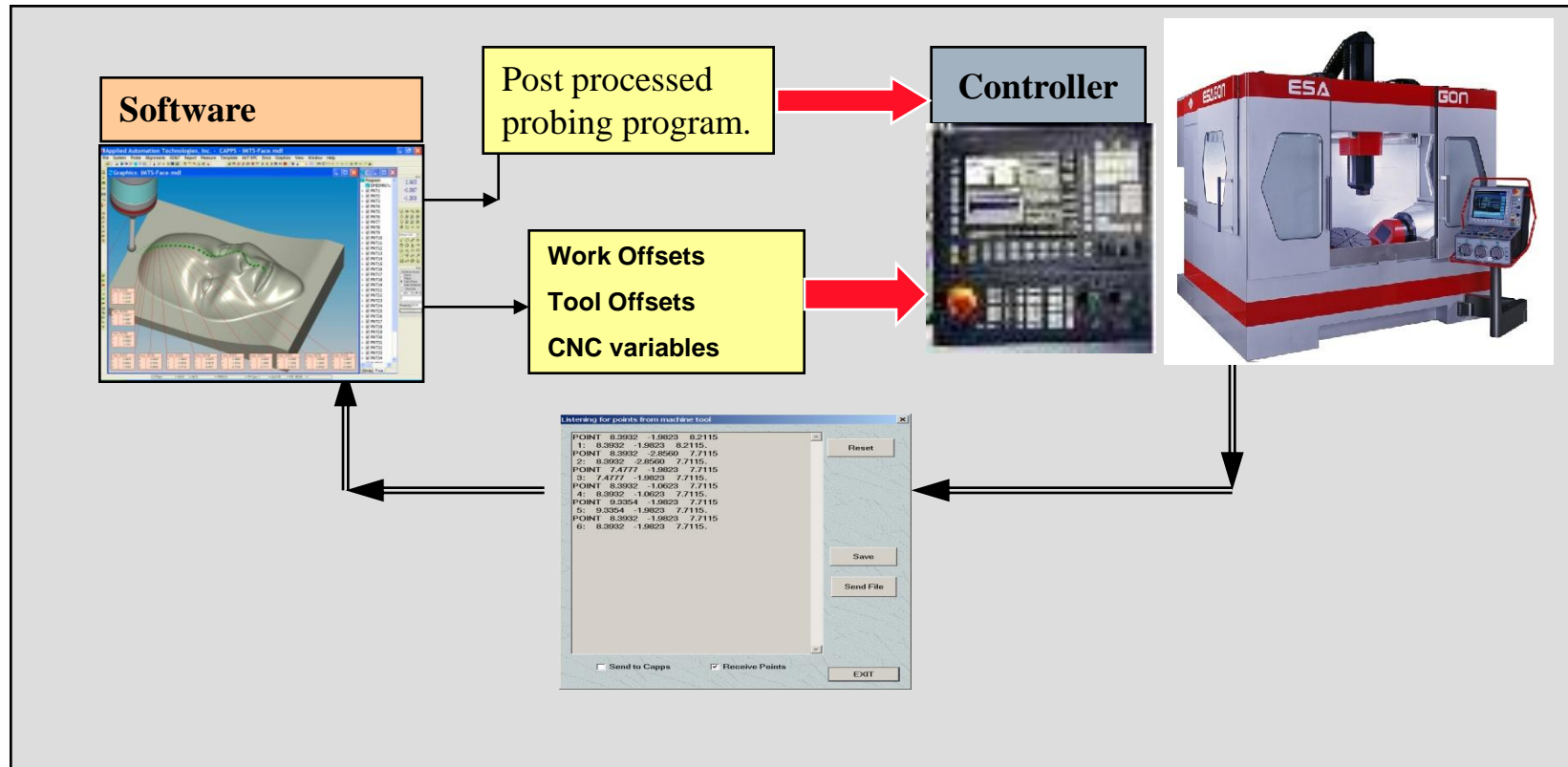
- ❑ **Machine tool probing** is a SOFT GAUGE process
- ❑ Data is compared to nominal CAD model. Not a master.
- ❑ Flexible, easy to modify adapt to changes in the part design.



Machine tool measurement process

- ❑ **Programs developed offline using a CAD model.**
 - ❑ Programs and measurement data are kept in PC environment. Standards such as DMIS, CAD or Excel are used.
 - ❑ A **virtual machine environment** is created in the software for total simulation and collision detection.
 - ❑ Developed measuring programs post process to machine code
 - ❑ Probing programs are included in the manufacturing process or run by the operator
 - ❑ **Real time data interface allows calculation of control parameters** and immediate display of results
 - ❑ Automatic feedback of part locations or tool offsets will allow final process to create a perfect part.
 - ❑ Any feature relationships, Geometric Dimensioning, and Tolerancing reports are generated automatically by the DMIS program.
-

Interface with CNC Machining Centers



Machine tool Interface methods

Method \ Function	Post Processed file upload	Data collection	Program execution & Report Calculation	Controller data update: Work, tool offsets, registers
File Interface	Manual Using files	Manual using files	Offline after program calculation	Manual using files
RS232	From CappsNC/3D SI Data I/O	Real Time	Real Time or after NC program execution	Secondary process after program is completed.
TCP/IP Ethernet	From CappsNC/3D SI Data I/O	Real Time	Real Time or after NC program execution	Can be done in real time during program run
Direct Link	File saved into NC folder directly	Real Time	Real Time or after NC program execution	Can be done in real time during program run

Part offset detection and compensation

- ❑ Create datums on a measured feature
 - ❑ Develop alignments similar to a CMM process using multiple features
 - ❑ 3D Bestfit alignments for surfaced parts
 - ❑ Create work offsets for translation and rotations
 - ❑ Modify work offsets for automatic adaptation of the cutting program to exact part location
 - ❑ Update 3D alignment matrix for inspection program during program execution
-

Part verification and Measurement Reports

- All programming is done offline using CAD and DMIS environment
- Measurement process is very similar to CMM programming
- Real time data update allows single CNC program to do alignment and measurement

ELEM	NOMINAL	ACTUAL	LOW_TOL	UPP_TOL	DEV	OUT_TOL
28: POINT PT3						
X	77.226	77.226	-0.500	0.500	0.000	
Y	6.939	6.939	-0.010	0.010	0.000	
Z	27.675	27.675	-0.010	0.010	0.000	
Prof:	0.000		-0.010	0.010		
29: POINT PT4						
X	66.587	66.587	-0.500	0.500	0.000	
Y	6.922	6.922	-0.010	0.010	0.000	
Z	32.712	32.712	-0.010	0.010	0.000	
Prof:	0.000		-0.010	0.010		
30: POINT PT5						
X	57.019	57.019	-0.500	0.500	0.000	
Y	6.910	6.910	-0.010	0.010	0.000	
Z	39.640	39.640	-0.010	0.010	0.000	
Prof:	0.000		-0.010	0.010		
31: POINT PT6						
X	57.175	57.175	-0.500	0.500	0.000	
Y	10.761	10.761	-0.010	0.010	0.000	
Z	40.781	40.781	-0.010	0.010	0.000	
Prof:	0.000		-0.010	0.010		

Program
to DMIS

```

GOTO/0.0000,0.0000,53.4285
GOTO/101.1485,5.8891,53.4285
F(PT1)=FEAT/POINT,CART,100.
MEAS/POINT,F(PT1),1
PTMEAS/CART,100.11699,6.9
ENDMES
OUTPUT/FA(PT1),TA(X1),TA(Y1)
F(PT2)=FEAT/POINT,CART,88.2
MEAS/POINT,F(PT2),1
PTMEAS/CART,88.23221,6.95
ENDMES
OUTPUT/FA(PT2),TA(X1),TA(Y1)
F(PT3)=FEAT/POINT,CART,77.2
MEAS/POINT,F(PT3),1
PTMEAS/CART,77.22587,6.93
ENDMES
    
```

Update
CNC
Parameters

Post process to CNC

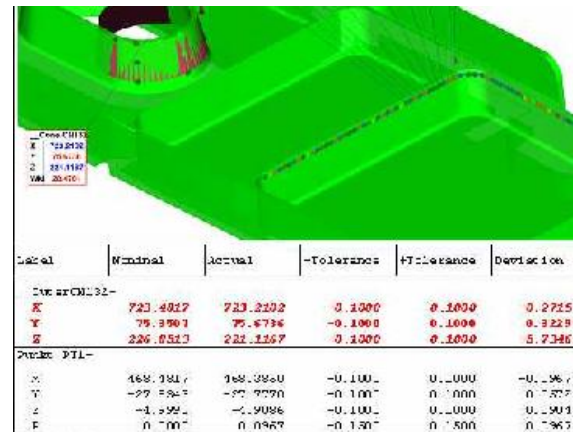
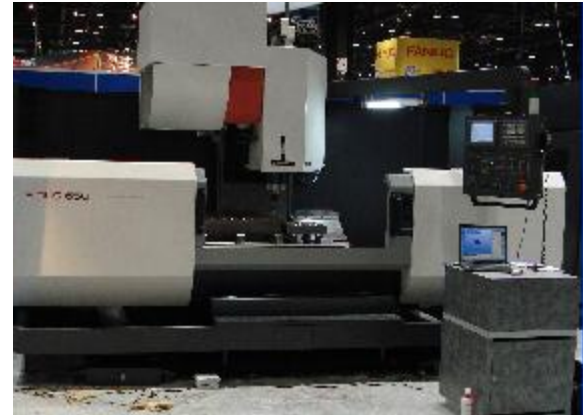
```

#101=1000.000 (POSITION :
G65 P9421 X[0.0000]Y[0.0000]
G65 P9421 X[101.1485]Y[5.8891]
G65 P9421 X[101.1485]Y[5.8891]
G65 P9420 X[100.5296]Y[6.939]
G65 P9421 X[88.3351]Y[5.8891]
G65 P9420 X[88.2734]Y[6.939]
Live data G65 P9421 X[80.4788]Y[5.8891]
feed      G65 P9420 X[78.5271]Y[6.939]
G65 P9421 X[68.0321]Y[4.0761]
G65 P9420 X[67.1648]Y[6.939]
G65 P9421 X[60.2070]Y[5.8891]
G65 P9420 X[58.2943]Y[6.939]
G65 P9421 X[60.0166]Y[9.4285]
G65 P9420 X[58.3113]Y[10.761]
G65 P9421 X[68.3740]Y[8.0761]
G65 P9420 X[67.5143]Y[6.939]
    
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Application Examples

Large die & mold manufacturing

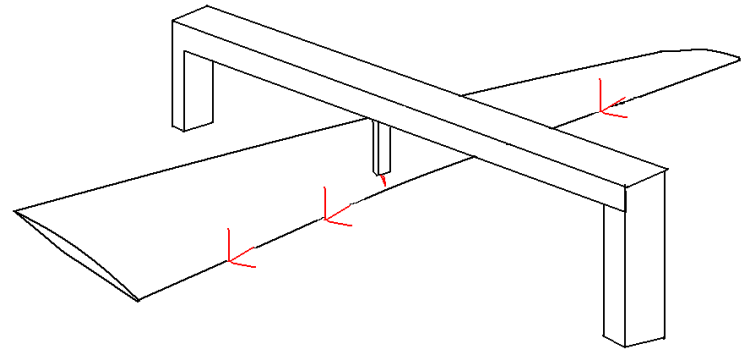
- ❑ Customer makes large dies
- ❑ Removing dies to be checked on the CMM is too expensive or impossible
- ❑ Customer can utilize CappsNC to solve the problem:
 - Program all die measurement offline with CAD
 - Measure die on the machine. Make corrections without having to move the part.
 - Make all measurement reports directly from machine.



Application Examples

Large part trimming & drilling

- Large flexible Parts are trimmed and drilled in relation to several datums
- Keeping profile and location is very important
- Customer can utilize CappsNC to solve the problem:
 - Program all measurements offline
 - Create a set of alignments along the part
 - Adapt cutting program to part location using these alignments
 - Final inspection is done using a measurement program



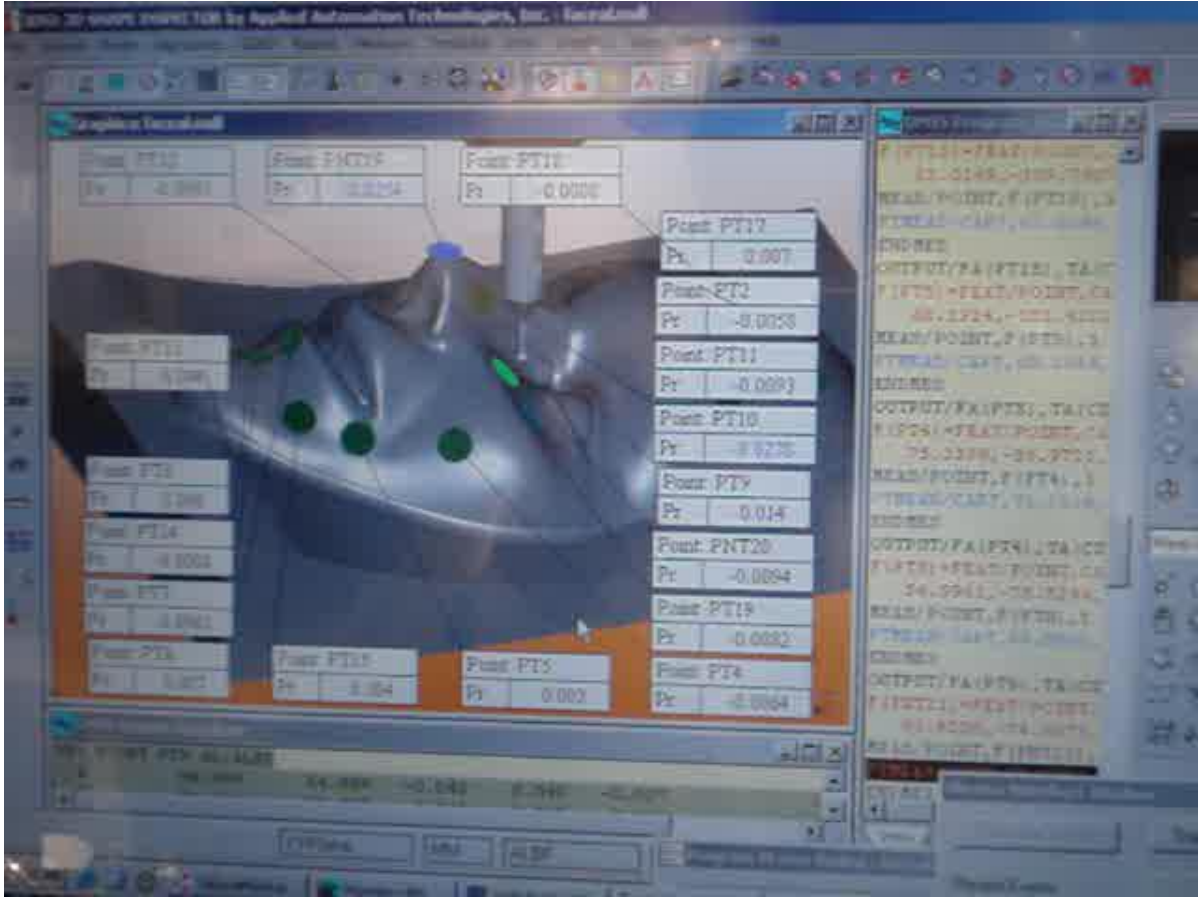
Application Examples

Automated multi OP manufacturing

- ❑ Parts are manufactured through an automated manufacturing system
- ❑ Standard dedicated gage are expensive and not flexible
- ❑ Historical data collection is important
- ❑ Customer can utilize CappsNC to solve the problem:
 - All 5 Axis probing programs created offline
 - Measured data collected in real time and fed back to SPC database
 - Measurement GD&T reports are generated and saved in server
 - Trend analysis allows scheduled maintenance and maximum tool life.



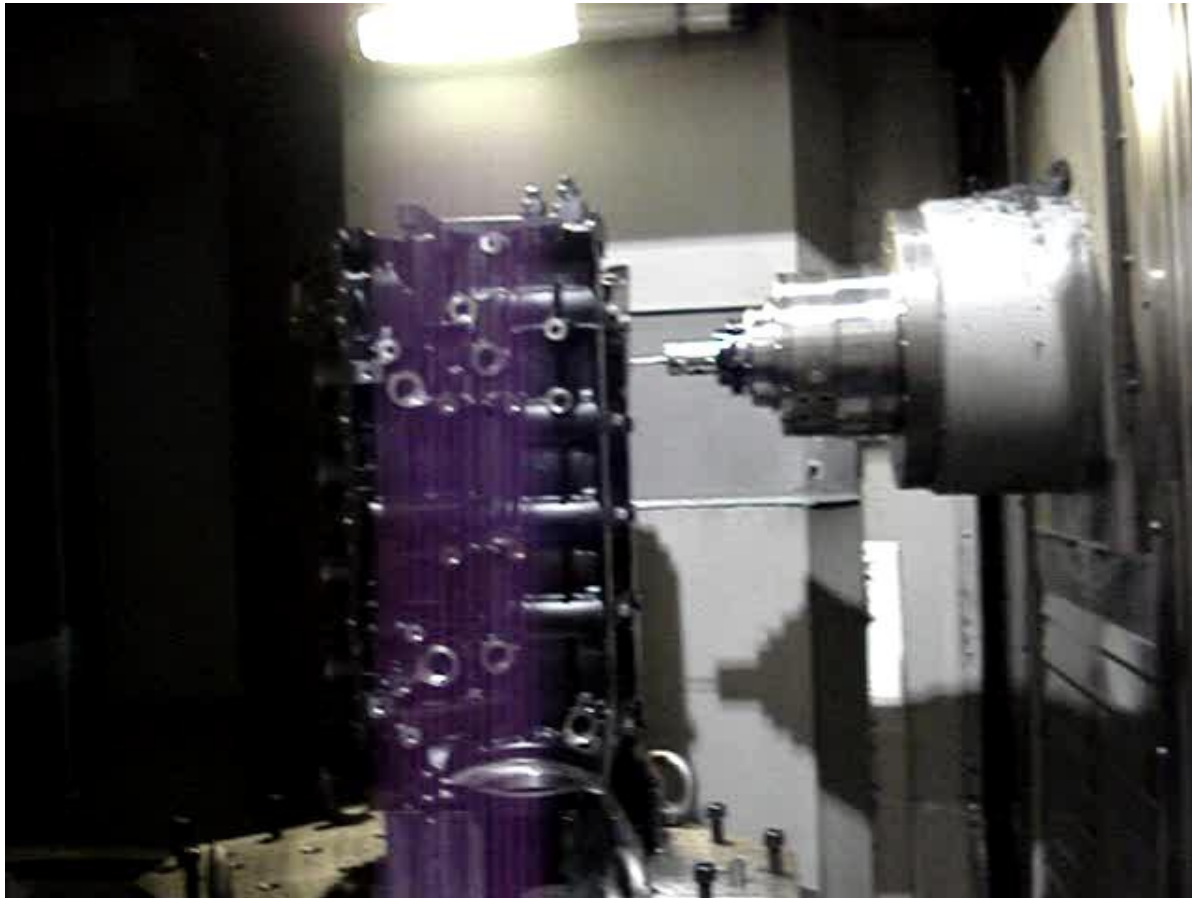
Examples: OKUMA



Examples: HAAS



Examples: 5 Axis



Thank You



Probing benefits

- ❑ Part set-up Eliminate the need for expensive fixtures and manual setting with dial indicators.
 - ❑ Extend tool life or detect tool errors
 - ❑ Automatic fixture, part alignment and rotary axis set-up
 - ❑ Elimination of manual setting errors
 - ❑ Increased productivity and batch size flexibility
 - ❑ Networking measurement data, collecting historical data
 - ❑ In process part measurement with automatic offset correction
 - ❑ Increased confidence in automated manufacturing
 - ❑ First-off inspection with automatic offset update
 - ❑ Reduced machine downtime from waiting CMM results
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AAT Background

- Established in 1987
 - Specializes in 3D metrology software for CMMs & Machine tools
 - R&D oriented software development
 - Developed many software products:
 - CappsDMIS for Cad based CMM software for all CMMs
 - CappsNC as online measuring and feedback software for machine tools.
 - Capps point cloud: for real time laser scanning, measurement and reverse engineering
 - RMI: Remote Machine Interface module available for all 3rd party software
 - Many other software for pipe & tube, airfoil & blade, and gear applications
 - Located in Michigan USA with offices in Italy, China and Turkey.
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Ray Karadayi

- President and founder of Applied Automation Technologies, Inc.
 - Has 25 years of experience with CAD/CAM and automation software development
 - 20 years of experience working with CMM software development and CMM controller interfaces
 - Developed many metrology software products
 - CAD based CMM software, off-line & online
 - DMIS translators and real time DMIS interfaces
 - Laser and vision based metrology
 - Machine Tool In process gauging and metrology
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Introduction to Machine Tool Probing

- Locate part position, calculate part origin
 - Set work offset location before cutting
 - Measure stock value
 - Adjust tool parameters for proper machining
 - Simple dimensional measurements
 - Verify what has been manufactured
 - Complex CMM like total measurement reports
 - Cutting Tool related
 - Tool geometry verification
 - Tool wear compensation
 - Tool offset determination
 - Tool breakage detection
 - Automatic correction of tool related errors
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