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Paper

6 AXIS ROBOTIC ABRASIVEJET ADVANCEMENTS IN ACCURACY FOR QUALITY AND PRODUCTION

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ABSTRACT

Presentation by Flow Applications Group (division of Flow International), an integrator and manufacturer of more than 1,000 specialized automated 6 axis systems utilizing Ultra High Pressure waterjets for trimming of various products in the aerospace, automotive and consumer product industry. Topic of this discussion to include 6 Axis Robotic trimming characteristics and techniques for calibrating the work envelope to enable accurate cutting using standard offline programming software. These include using waterjet and abrasive waterjet work cells for state-of-the-art industrial production lines.

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1.0 INTRODUCTION

Today, thousands of 6 axis robotic trimming cells are deployed worldwide in a vast array of high production environments; manufacturing standard and customized components, prototype designs, low volume-mass production (albeit with many option changes) and including service parts for OEM and aftermarket sectors. In other words, a lot of flexibility is required and these systems must work with continuously changing demands!!

Processing a work piece in an automated trimming system requires, first of all, the understanding and control of variables. These variables can stack up and result in parts being processed out of tolerance. Recognizing, and therefore, compensating for the idiosyncrasies of the material, such as shrinkage, warping etc. and considering the machine challenges, such as part location, cutter / tool wear, etc. will ensure the success of the trimming operation.
An additional variable is the robot unit itself, which is a complex machine, an assembly of a series of interconnected links, gears, gear trains, servo drives, harmonic drives and even belt drives. This paper deals with quantifying and thus minimizing the robot variances with a state-of-the-art mechanical hardware solution and an imbedded (proprietary) mathematical software solution.

2.0 ROBOTS AND CALIBRATION

Robots are mass produced machines (Fig. 1) and although highly repeatable, they are not accurate until they are mastered. Robots are typically manually taught by eye from a teach pendant (Fig. 2) using a ‘point-to-point’ format. The programmer may choose to use a custom pointer as the simulated Tool Center Point (TCP) or a non contact optical pointing device, aimed at the target zone, or they may simply guess and cut a part, measure the deviations and correct it with another pass and so on. During this somewhat tedious procedure the operator will program the path, consisting of lines and circles (Fig. 3) and also define speeds, corner positioning etc and assign any I-O (inputs and outputs) to control or monitor external functions. These external devices can be the nozzle, vacuum system, clamps etc. The robot can also be oriented in a variety of positions to suit the work environment. (Fig. 4) Moving forward from this manual procedure to an offline programming environment will enable elimination of the teach pendant programming (sometimes referred to as point “touch-up”) and allow the use of standard offline programming software which will then utilize a custom post processor, enabling a download of a complete program of instructions to any standard industrial robot. In order to do this, the robot, the end effector TCP and the work holding fixture must be identified and defined in the real world, in other words “you must know where all of your zeroes are!!”

2.1 Calibration

The robot calibration procedure is used to fine-tune the accuracy of the robot for offline position compensation from *virtual* to *real* world location points. A calibration process is first required to establish the exact Tool Center Point (TCP) of the robot nozzle tip to the "real world", as well as identification of the actual robot parameters (joint offsets, link lengths, twist angles, compliances, etc.). This calibration process will also establish the relationship between the robot and the fixture/workpiece (i.e. Alignment). This process is a "calibration" routine using fixed base remote encoder(s), or a laser tracker and track ball to collect measurements from the Robot-Cell. These units use a tensile wire from an encoder tracker, or attaching a track ball for a laser tracker to the robot's TCP and running a series of stop/start moves within the robot work envelope to compare and identify these coordinates to the real world.

2.1.1 Identifying and Filtering

The complete process of calibration actually consists of two phases: (1) the Identification phase, and (2) the Compensation phase. "Identification" is the process of accurately *determining* the actual parameters of the Robot-Cell (i.e. the robot, the end-effector, and the fixture or positioner), whereas "Compensation" is the process of utilizing these identified parameters to *correct* for the inaccuracies in the complete robot-cell.

The Identification phase, consists of two major stages: (1) the measurement process itself, and (2) the parameter calculation process. During the measurement process, various positions and configurations of the robot are measured, using a specific type of measurement equipment (i.e. the DynaCal system utilizing an encoder device or Laser Tracker) and taking an array of measurements within the robot work envelope with accentuating TCP variations throughout (Fig. 5). These measurements are then used to calculate the "actual" parameters of the entire robot-cell. This digital routine of the calculation process registers positional data taken during the measurement process into a new set of actual parameters. This set of new parameters is based on the differences between the positions where the robot was externally measured to be and where the robot position was internally (i.e. from the nominal parameter set used by the robot controller) assumed to be. This new set of Robot-Cell parameter files are specifically, the robots' "signature" data file and enables a compensation '*filter*' through which the export file from the user's CAD system and post processor is sent before being loaded to the robot for execution.

The Compensation process uses the new calculated parameter file (containing the actual or "true" parameters defining the exact structure of the entire Robot-Cell) to correct for the inaccuracies in the robot-cell (Fig. 6). The purpose the Compensation process is to actually modify, or "Filter", each robot position (x,y,z and orientation) in any robot program, in order to compensate for the differences between the nominal parameters and the actual ones (stored in the parameter file). Therefore, while the robot is actually now *programmed* to go to various *Filtered* positions, it will in reality *physically be positioned* at their corresponding *CAD* (i.e. originally intended) positions (Fig. 7).

2.1.2 External Device Calibration

Note that the calibration process incorporates the entire Robot-Cell, this includes (as stated earlier) the actual parameters of the Robot, TCP, and Fixture. Calibration of multi-axis fixtures and other auxiliary axes are possible (including robot tracks). The Fixture calibration can include static fixtures/nests as well as ‘dynamic’ fixtures such as turntables or trunyon-style positioners. This allows an accurate “user frame” to be set and that all the “zeros” of the workcell are identified for offline programming success.

3.0 VERIFICATION

When all is said and done, how can we prove the unit is accurate and performing as specified? Another device, called the CompuGauge system, is used to measure the accuracy of the Robot-Cell.

3.1 ISO and ANSI/RIA Standards:

The CompuGauge system is an external audit unit, which also allows the operator to execute some specific performance analysis of the data according to two internationally recognized Standards: the *ISO 9283* “*Manipulating Industrial Robots – Performance Criteria and Related Test Methods*” and the *ANSI/RIA R15.05* “*American National Standard for the Evaluation of Performance Characteristics of Industrial Robots and Robot Systems*”. This device can track and trace the actual path movements of the robot’s TCP (Fig 9). This unit can trace the actual path (Fig. 10) and compare it to the CAD data path so you can see any variance in real time.

This monitoring device can measure static, as well as dynamic path, including vibration of the tool (Fig. 11) and cornering (Fig. 12). The CompuGauge System allows 3D measurement and performance analysis of robot position (both static and dynamic). The CompuGauge System monitors and processes measurement data and allows several robot performance tests on previously recorded measurements for the two different internationally recognized standards mentioned above. These Standards thus also define the mathematical formulas describing the particular performance characteristics being tested as a function of the recorded test data. The CompuGauge System software has included these several formulas, so that it is able to automatically perform the necessary calculations based on the appropriate measured data.

The CompuGauge System software provides functionality beyond accurate data acquisition (i.e. recording of static and dynamic measurements) and Visual Inspection of the recorded measurement. For example, the CompuGauge system allows the user to measure position/path accuracy and repeatability, cycle time, velocity, acceleration, vibration frequencies, events (I/O signals), etc.

3.2 CompuGauge System Specifications:

Resolution: <0.010mm Repeatability: <0.020mm
Accuracy: ± 0.150mm Sampling Frequency: from 25 to 1000Hz
Measurement Area: 1500mm x 1500mm x 1500mm Operating Temperature: 20°C ± 3°C
Maximum Operating Speed: 5m/s Maximum Operating Acceleration: 5G

4.0 CONCLUSION - THE NEXT GENERATION

Accuracy numbers are now at +/- 0.25mm for Abrasive Waterjet cells and this number is getting smaller as we advance. The calibration process allows the robot and the workcell to become “accurate”, by precisely defining the Actual or “true” kinematic model of the robot-cell, and offsetting and compensating for the differences to the CAD or “ideal” kinematic model. The differences between these two models are defined in a new parameter file and then corrected for using a compensation processes called a “Filter”.

Robot cell calibration will assure competent offline programming capability. Every robot program created in Simulation within the robot cell can be “Filtered” using the new kinematic parameters. Additionally, the calibration process can work in reverse to change some of the parameters within the offline-programming task such as the TCP or the location of the Fixture relative to the robot base frame, etc.

The 3rd party device, such as the CompuGauge system, to measure and therefore certify these work cells will enable the 6 axis robot cells (Fig. 13) to enter the machine tool arena at a significantly lower cost than CNC gantry systems.

The 6 axis systems also offer much more flexibility and require much less space (Fig. 14) than conventional “box frame” systems, allowing a whole new *Next Generation* of industrial machine tools to enter the market.

REFERENCES

Dynalog technical communication *“3D CompuGauge ™ Robot Performance and Analysis System”* Version 3.1 August 2001

Dynalog technical communication DynaCal™ (Version 5.0) Robot Cell Calibration System, June 2004

GRAPHICS

Figure 1. Robots being produced in mass production lines

Figure 2. Standard hand held robot Teach Pendant

Figure 3. Compound angle circle cutting

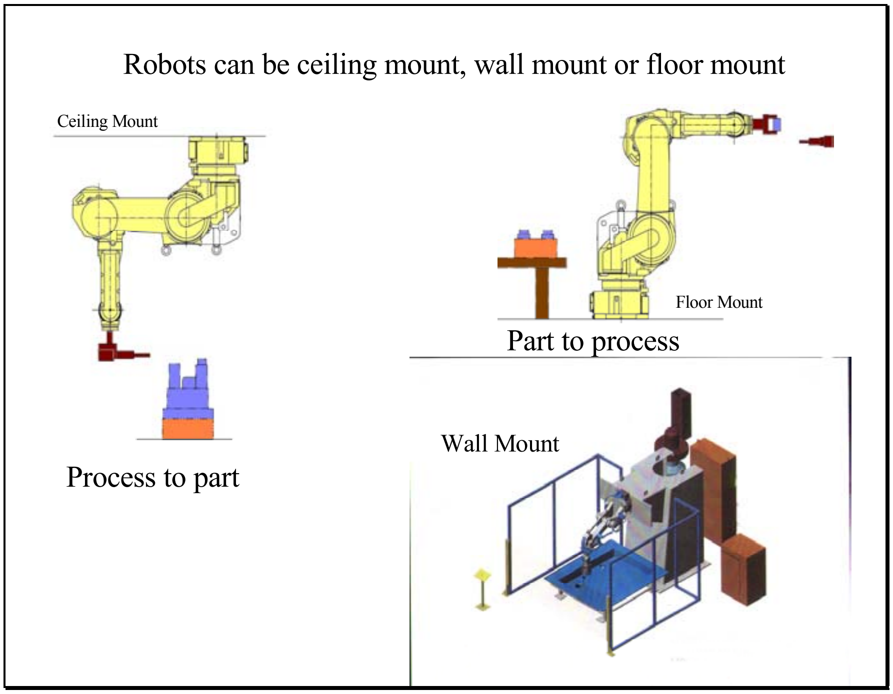


Figure 4. Various robot orientations

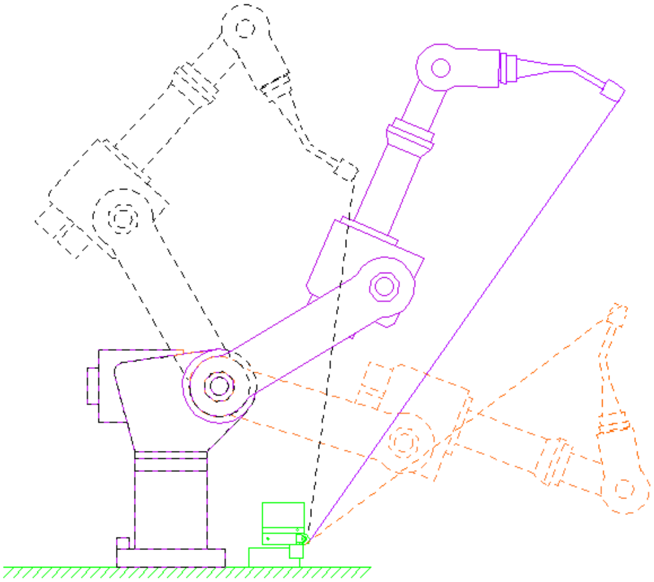


Figure 5. Variations of the Tool Center Point is essential for data input in the Identification phase of the calibration process.

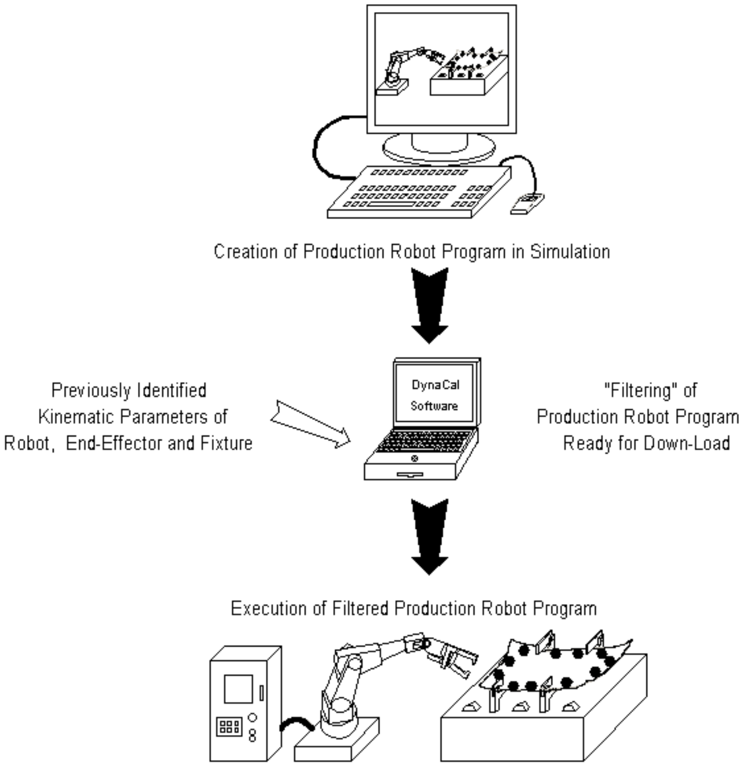
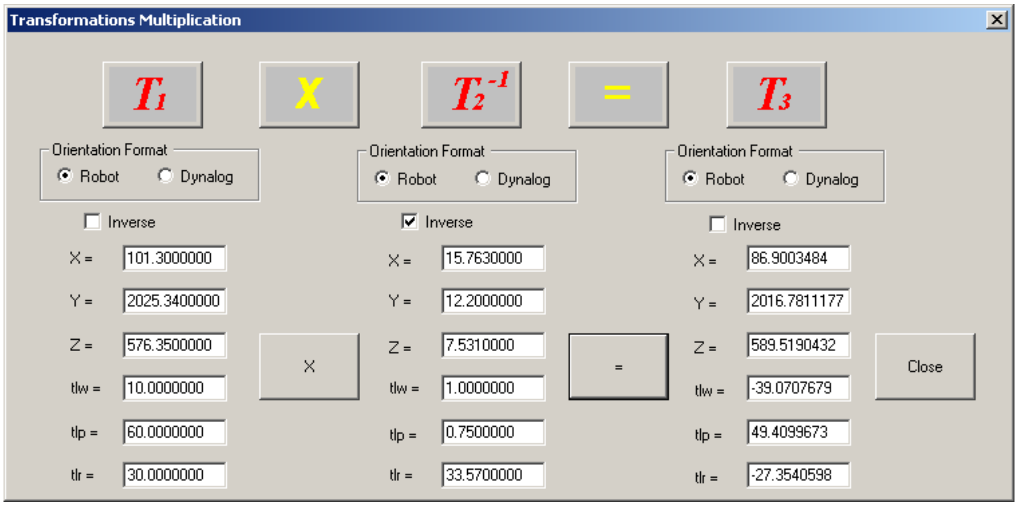


Figure 6. Process flow of the calibrated "filtered" program.


Transformations Multiplication

	T_1	T_2^{-1}	T_3
Orientation Format	● Robot ○ Dynalog	● Robot ○ Dynalog	● Robot ○ Dynalog
	☐ Inverse	☑ Inverse	☐ Inverse
X =	101.3000000	15.7630000	86.9003484
Y =	2025.3400000	12.2000000	2016.7811177
Z =	576.3500000	7.5310000	589.5190432
tlw =	10.0000000	1.0000000	-39.0707679
tlp =	60.0000000	0.7500000	49.4099673
tlr =	30.0000000	33.5700000	-27.3540598

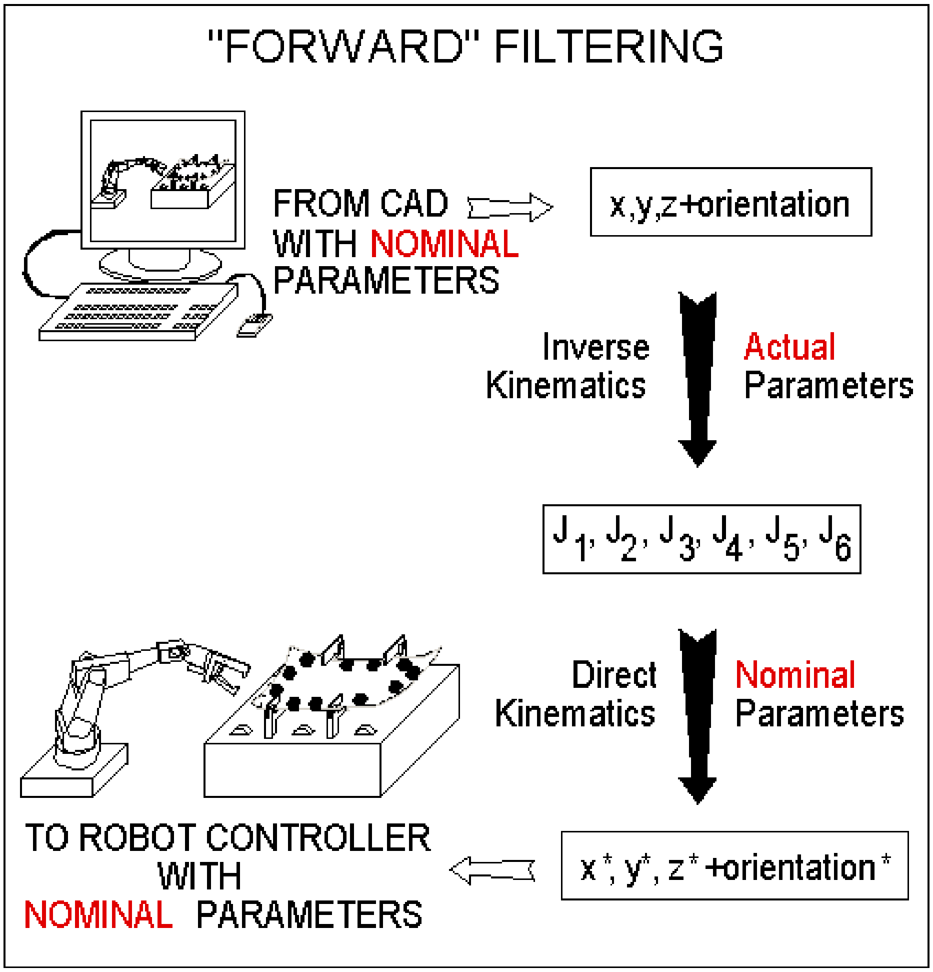
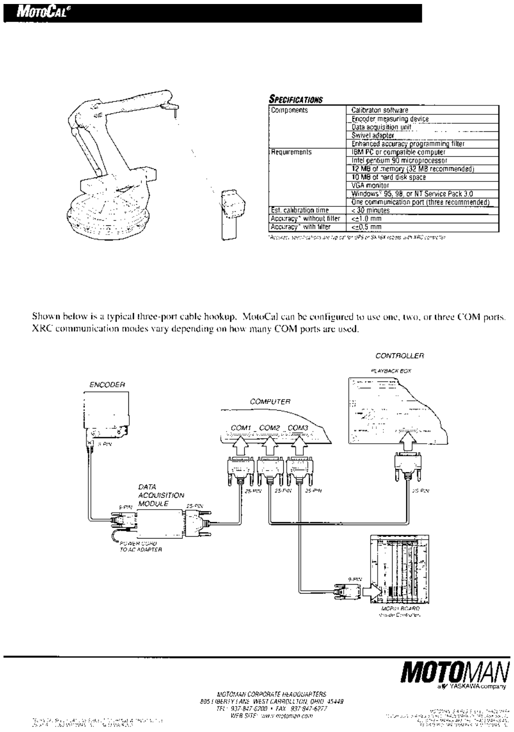


Figure 7. Sample of the transformations multiplication screen.



MotoCal®

SPECIFICATIONS

Components	Calibraton software Encoder measuring device Data acquisition unit Swivel adapter Enhanced accuracy programming filter
Requirements	IBM PC or compatible computer Intel pentium 90 microprocessor 12 MB of memory (32 MB recommended) 10 MB of hard disk space VGA monitor Windows® 95, 98, or NT Service Pack 3.0 One communication port (three recommended)
Est. calibration time	< 30 minutes
Accuracy* without filter	<±1.0 mm
Accuracy* with filter	<±0.5 mm

*Accuracy specifications are typical for UP6 or SK16X robots with XRC controller

Shown below is a typical three-port cable hookup. MotoCal can be configured to use one, two, or three COM ports. XRC communication modes vary depending on how many COM ports are used.

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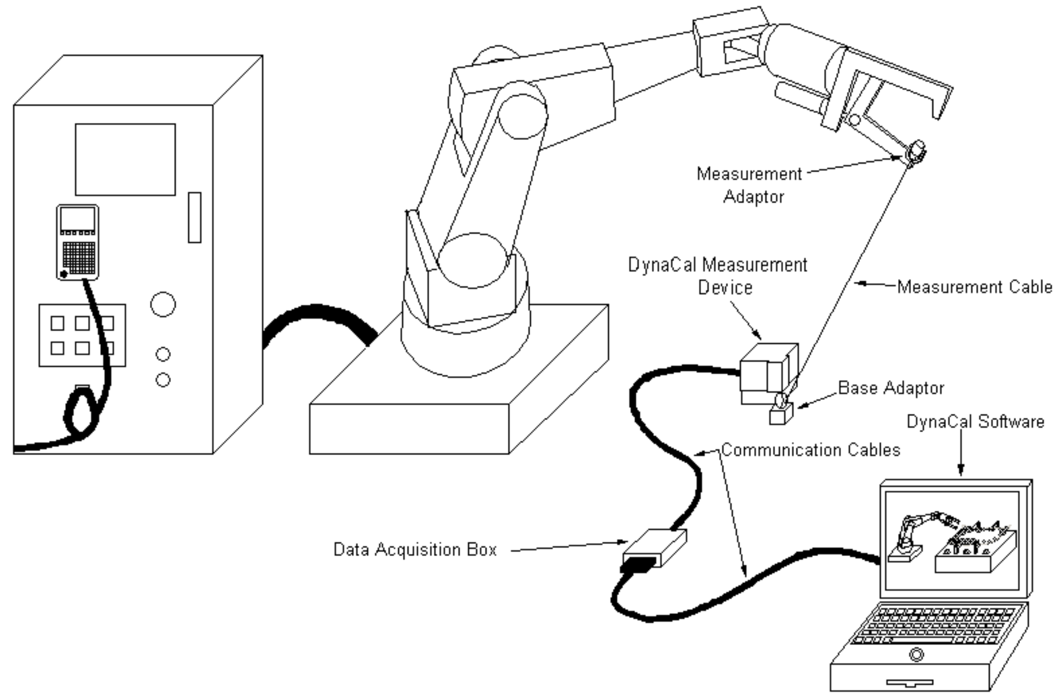


Figure 8. Sample overview of the calibration hardware with single encoder.

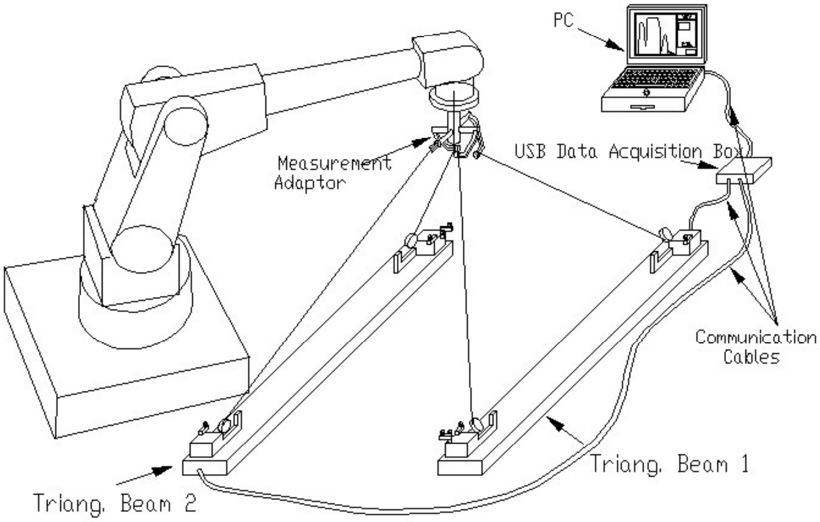


Figure 9. Sample of the CompuGage hardware with 4 encoders

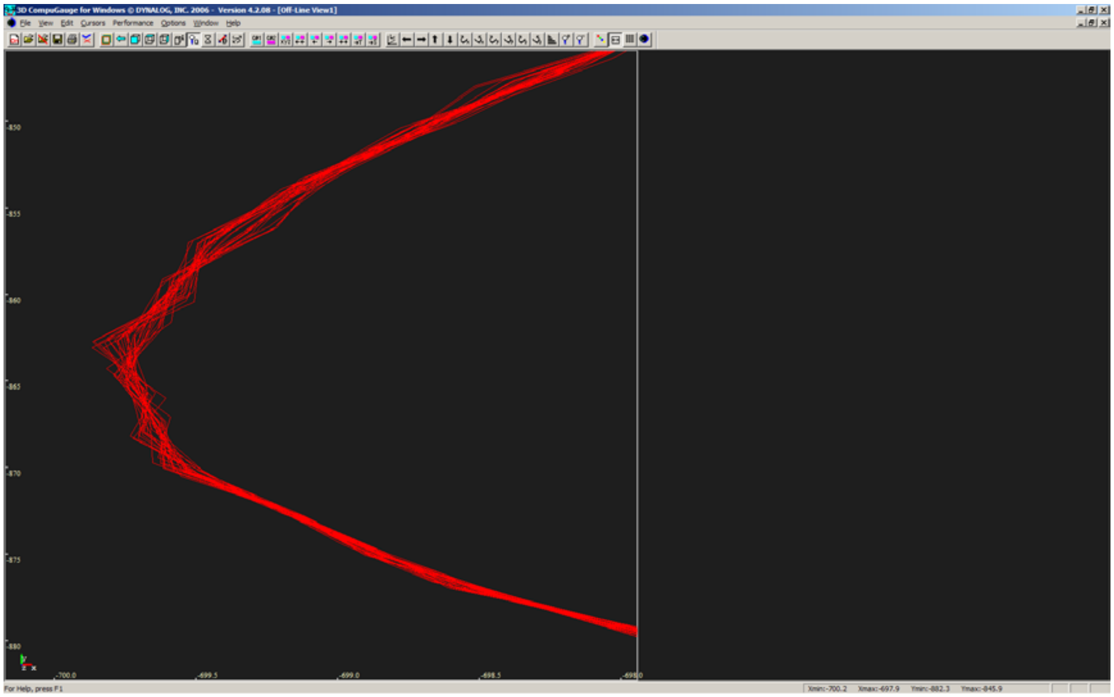
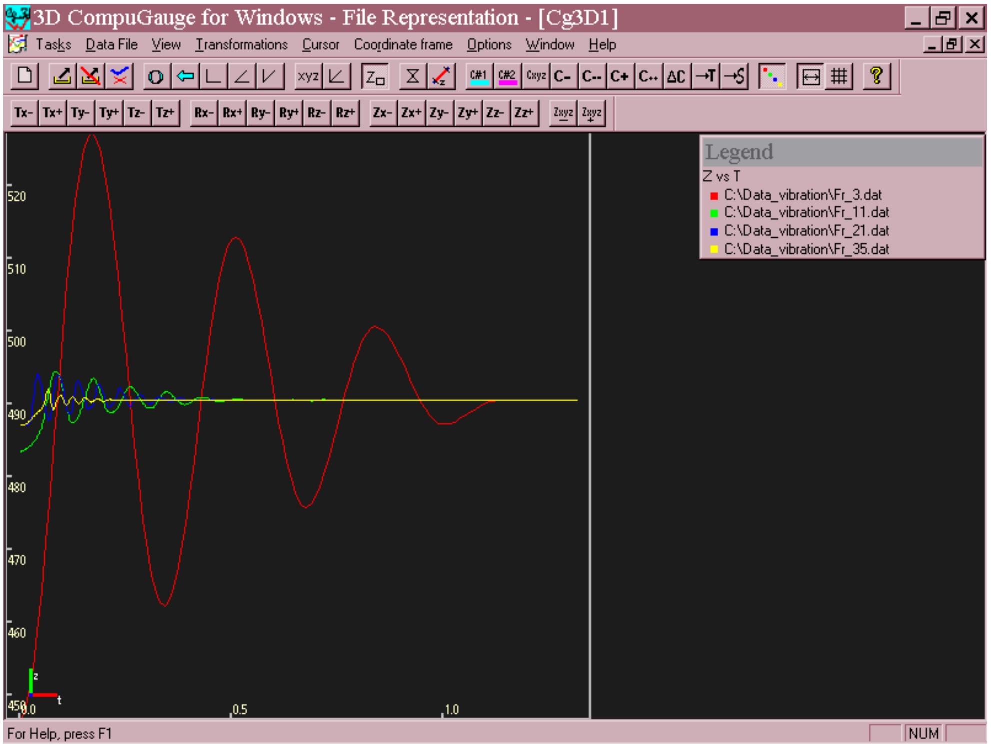


Figure 10. Sample of the path trace variations

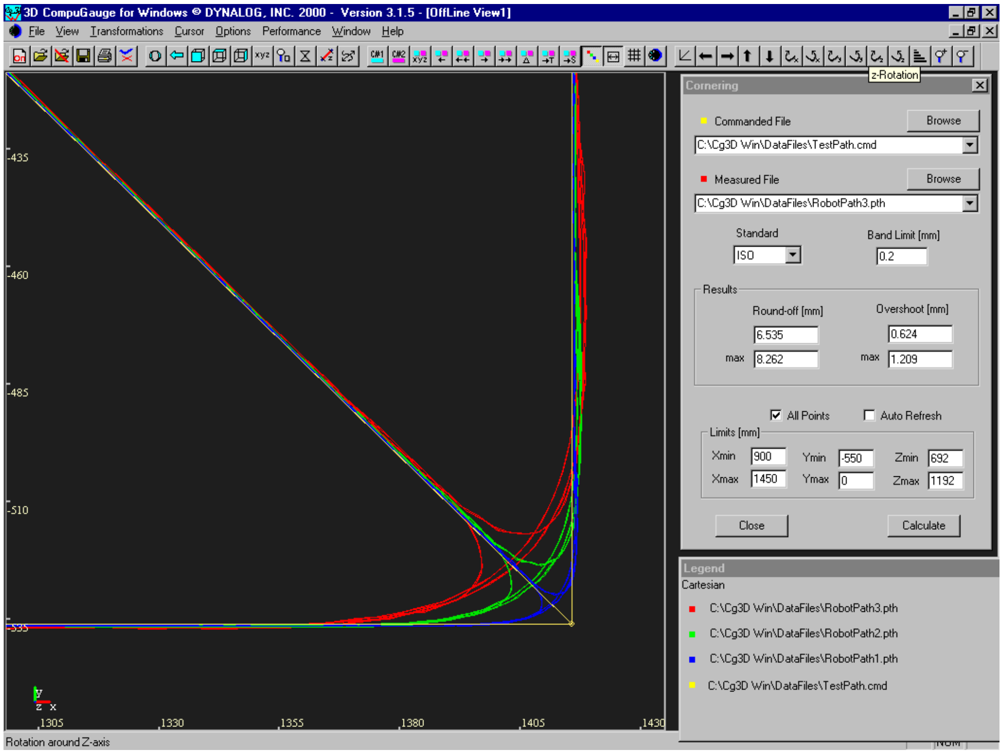


Legend

Z vs T

- 🟥 C:\Data_vibration\Fr_3.dat
- 🟩 C:\Data_vibration\Fr_11.dat
- 🟦 C:\Data_vibration\Fr_21.dat
- 🟨 C:\Data_vibration\Fr_35.dat

Figure 11 Sample of vibration analysis of the tool



Cornering

🟨 Commanded File Browse

C:\Cg3D Win\DataFiles\TestPath.cmd

🟥 Measured File Browse

C:\Cg3D Win\DataFiles\RobotPath3.pth

Standard: ISO

Band Limit [mm]: 0.2

Results

	Round-off [mm]	Overshoot [mm]
	6.535	0.624
max	8.262	1.209

☑ All Points ☐ Auto Refresh

Limits [mm]

Xmin	900	Ymin	-550	Zmin	692
Xmax	1450	Ymax	0	Zmax	1192

Close Calculate

Legend

Cartesian

- 🟥 C:\Cg3D Win\DataFiles\RobotPath3.pth
- 🟩 C:\Cg3D Win\DataFiles\RobotPath2.pth
- 🟦 C:\Cg3D Win\DataFiles\RobotPath1.pth
- 🟨 C:\Cg3D Win\DataFiles\TestPath.cmd

Figure 12 Sample of cornering analysis

Figure 13 Sample of a wall mounted 6 Axis robot over a 6' x 12' tank

Figure 14 Sample of a floor mounted 6 Axis Abrasive Waterjet robot