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Increasing Machine Accuracy by Spatially Compensating Large Scale Machines for Use in Constructing Aerospace Structures

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ABSTRACT

Starting in 2003 Electroimpact began development on a comprehensive kinematic and compensation software package for machines with large envelopes. The software was first implemented on Electroimpact's Automatic Fiber Placement (AFP) equipment. Implementation became almost universal by 2005. By systematically collecting tracker measurements at various machine poses and then using this software to optimize the kinematic parameters of the machine, we are able to reliably achieve machine positional accuracy of approximately 2x the uncertainty of the measurements themselves.

The goal of this paper is to document some of the features of this system and show the results of compensation in the hope that this method of machine compensation or similar versions will become mainstream.

INTRODUCTION

Since automatic machine tools are used to assemble and manufacture twin-aisled commercial aircraft parts, extremely large envelope machines are often required and appropriate. Traditional methods of machine compensation for accuracy are not ideal for these large structures. Additionally, machine accuracy specifications do not consider the needs of the part being manufactured nor do the prescribed tests give a full picture of the machine accuracy in the machining envelope. Electroimpact tackles these problems by carefully measuring the effect of each axis' motion at the point of application (the tool-tip) and quantifying the six-degree-of-freedom machine accuracy results at the tool-point. In this paper, we will describe how we use a serial link kinematic chain to carefully account for each axis' characteristics and how the metrology data is collected and why. Finally, this paper will discuss ideas for more appropriate specifications pertaining to machine accuracy and performance of large envelope machine tools. Included in this paper is a case study of the section 41 AFP machines in Wichita, KS (Figure 1).

TRADITIONAL MACHINE COMPENSATION

Typical machine compensation is accomplished by exercising an individual axis and applying a compensation amount that attempts to constrain the axis' motion along a desired axis. The compensation (comp) table will have values for X, Y, and Z offsets. This compensation table will encompass the extent of the axis' travel and have offsets on even intervals; so for each table entry there is a value indicating the axis' position along its length of travel and its associated dX, dY, dZ compensation amount. The machine will insert this compensation on top of the commanded position, moving all three primary prismatic axes so that motion along an axis, the X-axis for instance, is constrained to only the prescribed X-axis. This compensation is "invisible" to the NC programmer and machine operator. This method is well documented by Freeman et. al [2]. As Freeman points out there are shortcomings to this method. First, this method leaves out the possibility of compensating the tool-point motion for machines that are not prismatic, such as four and five axis mills, articulated arms and other unique kinematic arrangements. As Freeman points out, the methods for attaining the required data can be very time consuming resulting in machine downtime in excess of a week. Additionally this method does not accurately account for the tool-point orientation as only linear offsets are applied to the model even though we know that most linear displacements are due to angular deflections multiplied by an arm. For rotary axes, the machine manufacturer is left with a solution that could ensure the axis move extremely precisely in one dimension, but no way to account for the other five degrees of freedom (2 axis orientation and the XYZ Cartesian offset). Because of this it was important to ensure that the revolute axis was physically orthogonal to the base coordinate system and the links prior to it and that it moved extremely precisely in its envelope without compensation. This involved the assembly, measurement, disassembly, grinding of custom spacers and repeat until satisfied of the revolute axis in question. Kinematic link offsets are not accounted for in this system and NC programs typically command machine axis positions and not part coordinates.

TOOL-POINT, TOOL-CENTER-POINT (TCP) AND TOOL-TIP

The tool-point or tool-center-point, refers to CNC machine systems where the program for the part is specified in an arbitrary coordinate system that is convenient for the NC programmer. Instead of the NC program directly commanding physical axis positions, the NC program commands values of X,Y,Z,A,B,C or, for five axis machines, X,Y,Z,I,J,K that are relative to the coordinate system of their choice. A series of transforms and inverse kinematics equations calculate the necessary machine axis positions to ensure that the machine follows the path desired. These calculations are performed real-time on the CNC during part program execution. All Electroimpact equipment since in 1996 has been tool-point controlled. Therefore, Electroimpact equipment has always had a kinematic chain of sorts and a back solution to match. What we lacked was a comprehensive kinematic chain that included compensation and a software tool to “solve” for the kinematic parameters.

An additional advantage of tool-tip NC programing is that since these machines account for their individual peculiarities of construction, a single NC program can be run across a line of machines without change. For multi-machine cells and for a company with more than one of a type of machine making a given part, this allows a common data set for the part-program regardless of the number of machines that may be used to manufacture it. In the multi-machine cell, this allows a program originally intended to be run on one machine to be run on another machine in the cell when required without any modification to the part program. In section 41 we have a left and a right hand machine, one on each side of the part. The part programs are completely interchangeable between the two machines.

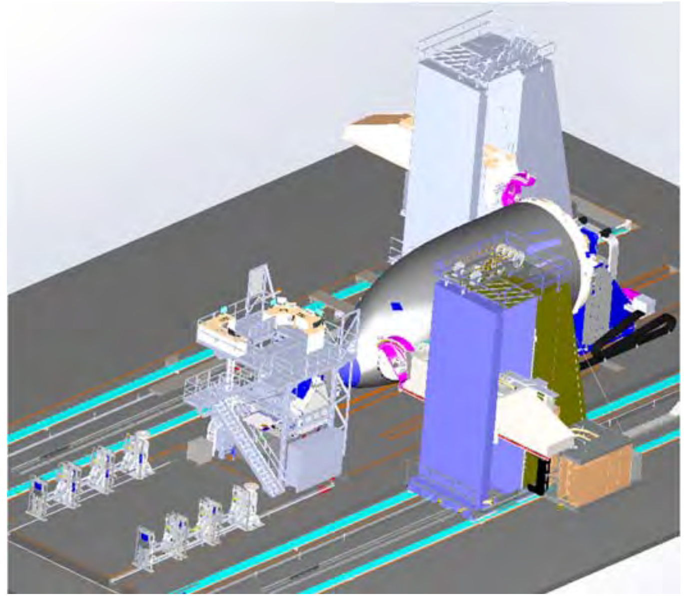

Figure 1– section 41 machine in Wichita KS. Between the two machines is the first 40’ of the Boeing 787. The near machine is a left-handed machine and the far machine is a right-handed machine. Both machines can run the same part-program unedited because they handle their own peculiarities of construction in their kinematic chains on-the-fly. The part program’s origin is chosen by the NC programmer to suit his needs. The machines share a common origin & not only run the same part programs, they use the same part to machine transform (the machine is established in a Fixed-Reference-System [FRS] detailed later).

AN INTEGRATED APPROACH TO KINEMATICS AND COMPENSATION

In 2001, after suffering through a few machine setups, even one that involved a 5 axis machine that drove along an “X” axis that was comprised of straight and curved rail sections, it became apparent that an integrated method of machine kinematics and compensation would give our company a distinct advantage during machine setup. The system needed to achieve the following goals:

1) Fully account for all possible machine axis arrangements, accounting for the position and orientation of one axis to the next organized into a single readable .xml file.

2) Be flexible and simple so that any engineer could devise his own kinematic chain for any serial link kinematic arrangement he might desire.

3) Insert compensation into the kinematic chain where the deflection/anomaly occurred.

4) Precisely account for tool-point orientation. An often forgotten detail by many compensation methods.

5) Require as few observations (tracker measurements) as possible.

7) Optimization would be based on the forward kinematic solution with an off the shelf commercial optimizer eliminating the need for a custom solving solution for each iteration of a kinematic chain.

8) Lastly, once a method was developed for achieving the accuracy results we desired, a clear path would remain for re-qualifying the machine after some time had passed.

We will detail the implementation of a system that largely meets these goals below.

The Kinematic Chain

The file defining the kinematics for Electroimpact machines has the following main sections: Variables and Transforms. The variables are user defined, and are used as arguments later in the Transforms section. Variables can be either solved for by the Electroimpact Solver or used as axis arguments to set the position of a given axis to be used in the forward kinematics.

<u>Variables</u>

There are currently three types of variables: Static, Machine Axes and Comp Tables.

Static:

```xml
<static multiply="10000.0">
  <_Debug value="False" />
  <ymrxoff value="0.0000" />
  <ymrzoff value="0.0000" />
  <zmrxoff value="0.0000" />
  <zmryoff value="0.0000" />
  <c1rxoff value="0.0000" />
  <c1ryoff value="0.0000" />
  <c1rzoff value="0.0000" />
  <c1x value="0.0000" />
  <c1y value="0.0000" />
  <amrxoff value="0.0000" />
  <amryoff value="0.0000" />
  <amrzoff value="0.0000" />
  <lAy value="0.0000" />
  <lAz value="-147.5740" />
  <bmrxoff value="0.0000" />
  <bmryoff value="0.0000" />
  <bmrzoff value="0.0000" />
  <lBx value="0.0000" />
  <lBz value="287.2000" />
  <cmrxoff value="0.0000" />
  <cmryoff value="0.0000" />
  <cmrzoff value="0.0000" />
  <lCx value="0.0000" />
  <lCy value="0.0000" />
  <xmoff value="0.0000"
    note="homing offset for X axis" />
  <ymoff value="0.0000"
    note="homing offset for Y axis"  />
  <zmoff value="0.0000"
    note="homing offset for Z axis"  />
  <boff value="0.0000"
    note="this is the cg and mass and stiffness of B weldment" />
  <Zflex value = "0.000"
    note="this is not accoutned for in the CB yet" />
  <Aflex value = "0.000"
    note="this is not accoutned for in the CB yet" />
  <BaseShift X="15.4432" Y="-2.2318" Z="777.4374"
    rX="0.0000" rY="0.0000" rZ="0.0000" />
  <LHMachine value="-1.0000" Hide="true"
    note="Use 1.0 for right handed machine.
          Use -1.0 for left handed machine" />
  <lTHx value="0.0000" Hide="true" />
  <lTHy value="0.0000" Hide="true" />
  <lTHz value="0.0000" Hide="true" />
  <rTHz value="0.0000" Hide="true" />
  <TP1X value="-32.6101" Hide="true" />
  <TP1Y value="0.2979" Hide="true" />
  <TP1Z value="-779.4478" Hide="true" />
  <TP2X value="195.3946" Hide="true" />
  <TP2Y value="-213.327" Hide="true" />
  <TP2Z value="-661.7691" Hide="true" />
```

Figure 2

The static variables in Figure 2 are the simplest of all variable types. They define a name and a value. The static variables are comprised of two types: variables that have the keyword ‘Hide = “true”’ and those that don’t. If the variable is not hidden, it is a variable that can be modified during the optimizing stage. The variables with the ‘Hide=”true”’ are not intended to be modified during optimization, and in this specific case, these are used to define the various tool-point offsets of the probe head (Figure 14). Typically we measure up to four different locations on the probing head during parts of the data collection. We do this to establish orientation of the tool-tip with respect to the FRS (Figure 8). These variables have an established value and will not modified during the optimization process.

Machine Axes:

```
<machineaxes multiply="1000000.0">
  <Xm rotary="False" scalefactor="0.000000" />
  <Ym rotary="False" scalefactor="0.000000" />
  <Zm rotary="False" scalefactor="0.000000" />
  <Cpm rotary="True" scalefactor="0.000000" />
  <Am rotary="True" scalefactor="0.000000" />
  <Bm rotary="True" scalefactor="0.000000" />
  <Cm rotary="True" scalefactor="0.000000" rollover="true" />
  <TP rotary="False" scalefactor="0.000000" Hide="true" />
</machineaxes>
```

Figure 3

Machine axis variables are shown in Figure 3. These variables provide a way to define a machine axis. The variable name, or machine axis name, is user definable. We use Xm, Ym, Zm, Cpm, Am, Bm, Cm as our machine axis variable names. Prismatic axes are assumed. If the axis is rotary, then rotary = “true” is specified. If the axis rolls over continuously, rollover = “true” is necessary to avoid discontinuities in the compensation table at the rollover point. 1.0 is added to scalefactor and the raw machine axis position is multiplied by this scaler before returning a value in the transforms section described later (Figure 5 & Figure 6). The last axis in the list is called TP. This is used in the kinematic chain to determine which tool-point offset to use. Remember the offsets are defined in the Static Variable section above (TP2 for example has arguments TP2X, TP2Y, TP2Z).

Compensation Tables:

```
<table axis="Am">
  <station loc="-90" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="-75" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="-60" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="-45" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="-30" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="-15" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="0" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="15" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="30" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
  <station loc="45" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
</table>
```

Figure 4 – the A machine axis compensation table.

For every axis defined above, our software looks to see if a comp table (Figure 4) is defined for the axis. Here, the Am axis comp table is shown. Each station defines seven variables. The loc variable indicates the machine axis position where this set of X, Y, Z, rX, rY, rZ variables apply. When the machine axis is between stations, a linear interpolation occurs. To access any of these six variables in the transform chain, the following form is used:

For X, Y, and Z:

l<axisname>X, l<axisname>Y and l<axisname>Z…or in the case of Am: lAmx, lAmy, lAmz.

For rX, rY and rZ:

r<axisname>X, r<axisname>Y and r<axisname>Z…or in the case of Am: rAmx, rAmy, rAmz.

These comp table values can be used anywhere in the kinematic chain. Generally these variables are intended to define the orientation of the axis at this position along its travel and any translations that may have occurred at this location. Occasionally it makes sense to use a variable further up or down the chain. An example is in the case of a post mill with a cantilever Z axis. As the Z arm is extended the moment about the X axis will change. Often times, it is kinematically correct to place the rZmx (rotation due to the Z machine axis about the X axis) at the same location where we account for the Y axis orientation. This effectively models the kinematic effect of deflection about the X axis due to the changing moment that occurs due to Z axis motion where the center of rotation is near the origin of the Y axis. If the center of rotation is closer to the origin of the Z axis, then rZmx would be in its normal spot in the kinematic chain at the point where the Y axis “hangs-on” to the Z axis.

Transform Chain

Several of Electroimpact’s AFP machines share the same kinematic chain. This is Linear, Linear, Linear, Rotary, Rotary, Rotary, Rotary. The axis names are Xm, Ym, Zm, Cpm, Am, Bm, Cm. In one case, Cpm, Am, Bm and Cm are not orthogonal to each other, however, the kinematic chain is still valid for this machine.

Electroimpact’s software accepts two types of transforms. One is called sixdof (six-degree-of-freedom) and the other DH (Dennavit-Hartenberg).

Sixdof:

```
<TransForms>
  <sixdof n="1" X="0" Y="0" Z="0"
    rX="rXmx" rY="rXmy" rZ="rXmz" />
  <sixdof n="2" X="Xm+lXmx+xmoff" Y="lXmy" Z="lXmz"
    rX="rYmx+ymrxoff" rY="rYmy" rZ="rYmz+ymrzoff" />
  <sixdof n="3" X="lYmx" Y="Ym+lYmy+ymoff" Z="lYmz"
    rX="rZmx+zmrxoff+Zm*.0001*Zflex" rY="rZmy+zmryoff" rZ="rZmz" />
  <sixdof n="4" X="lZmx" Y="lZmy" Z="Zm+lZmz+zmoff"
    rX="rCpmx+c1rxoff" rY="rCpmy+c1ryoff" rZ="Cpm+rCpmz+c1rzoff" />
  <sixdof n="5" X="lCpmx+c1x" Y="lCpmy+c1y" Z="lCpmz"
    rX="rAmx+amrxoff" rY="rAmy+amryoff" rZ="Am+amrzoff+rAmz+cos(Am)*Aflex*0.0001" />
  <sixdof n="6" X="lAmx+lAx" Y="lAmy+lAy" Z="lAmz"
    rX="rBmx+bmrxoff" rY="rBmy+bmryoff" rZ="Bm+rBmz+bmrzoff+sin(Am)*sin(Bm)*Bflex*0.0001" />
  <sixdof n="7" X="lBmx+lBx" Y="lBmy+lBy" Z="lBmz"
    rX="rCmx+cmrxoff" rY="rCmy+cmryoff" rZ="Cm+rCmz+cmrzoff" />
  <sixdof n="8"
    X="lCmx+lCx+lTHx+TP2X*(TP=2)+TP5X*(TP=5)+TP3X*(TP=3)+TP10X*(TP=10)"
    Y="lCmy+lCy+LHMachine*(lTHy+TP2Y*(TP=2)+TP5Y*(TP=5)+TP3Y*(TP=3)+TP10Y*(TP=10))"
    Z="lCmz+lTHz+TP2Z*(TP=2)+TP5Z*(TP=5)+TP3Z*(TP=3)+TP10Z*(TP=10)"
    rX="0" rY="0" rZ="rTHz" />
</TransForms>
```

Figure 5

The transform chain above is built from the sixdof transform. The sixdof transform has six arguments. In a single transform we can define a three axis translation and a three axis orientation. The following matrix in Equation 1 defines the sixdof you see above. It has arguments X, Y, Z, rX, rY, and rZ:

$$
\begin{pmatrix}
\cos(rY)\cdot\cos(rZ) & -\cos(rY)\cdot\sin(rZ) & \sin(rY) & X \\
\cos(rX)\cdot\sin(rZ) + \cos(rZ)\cdot\sin(rX)\cdot\sin(rY) & \cos(rX)\cdot\cos(rZ) - \sin(rX)\cdot\sin(rY)\cdot\sin(rZ) & -\cos(rY)\cdot\sin(rX) & Y \\
\sin(rX)\cdot\sin(rZ) - \cos(rX)\cdot\cos(rZ)\cdot\sin(rY) & \cos(rZ)\cdot\sin(rX) + \cos(rX)\cdot\sin(rY)\cdot\sin(rZ) & \cos(rX)\cdot\cos(rY) & Z \\
0 & 0 & 0 & 1
\end{pmatrix}
$$

Equation 1

This transform performs first a translation and then an orientation. So if you look carefully at Figure 5 you will see that first a link is orientated in one transform and then translated in the next transform. If you look specifically at transforms n1 and n2 from Figure 5:

```
<sixdof n="1" X="0" Y="0" Z="0"
  rX="rXmx" rY="rXmy" rZ="rXmz" />
<sixdof n="2" X="Xm+lXmx+xmoff" Y="lXmy" Z="lXmz"
  rX="rYmx+ymrxoff" rY="rYmy" rZ="rYmz+ymrzoff" />
```

Figure 6 – The first two transforms. Note that in transform 1, we orient the Xm axis. In transform 2, we then translate the Xm axis and then orient the next axis (Ym). This pattern repeats.

Dennavit-Hartenberg:

Besides the sixdof, the software also supports the DH transform matrix notation. Below is the same chain represented in DH form:

```
<Transforms>
  <DH n="1" theta="0" d="0" a="Xm+lXmx+xmoff" alpha="rXmx" />
  <DH n="2" theta="rXmz+ymrzoff+rYmz" d="lXmz" a="0" alpha="-90+ymrxoff+rYmx" />
  <DH n="3" theta="rXmy+rYmy+rZmy+zmryoff" d="Ym+lXmy+lYmy+ymoff"
    a="lYmx" alpha="90+rZmx+zmrxoff+Zm*.0001*Zflex" />
  <DH n="4" theta="0" d="lYmz+lZmz+Zm+zmoff" a="lZmx" alpha="-90" />
  <DH n="5" theta="clryoff+rCpmy" d="lZmy" a="0" alpha="90+clrxoff+rCpmx" />
  <DH n="6" theta="Cpm+rCpmz+clrzoff" d="lCpmz" a="lCpmx+clx" alpha="-90" />
  <DH n="7" theta="-90+rAmy+amryoff" d="lCpmy+cly" a="0" alpha="-90+rAmz+amrzoff" />
  <DH n="8" theta="-90+Am+amrxoff+rAmx+Sin(Am)*.001*Aflex" d="lAmx" a="lAmy+lAy" alpha="-90" />
  <DH n="9" theta="90+rBmz+bmrzoff" d="lAmz+lAz" a="0" alpha="90+bmrxoff+rBmx" />
  <DH n="10" theta="90+Bm+rBmy+bmryoff+Sin(Am)*Sin(Bm)*boff*0.0001" d="lBmy" a="lBmz+lBz" alpha="-90" />
  <DH n="11" theta="-90+cmrxoff+rCmx" d="lBmx+lBx" a="0" alpha="-90+cmryoff+rCmy" />
  <DH n="12" theta="Cm+cmrzoff+rCmz+rTHz" d="lCmz+lTHz+TP2Z*(TP=2)+TP3Z*(TP=3)+TP4Z*(TP=4)+TP10Z*(TP=10)"
    a="lCmy+lCy+LHMachine*(lTHy+TP2Y*(TP=2)+TP3Y*(TP=3)+TP4Y*(TP=4)+TP10Y*(TP=10))" alpha="0" />
  <DH n="13" theta="-90" d="0"
    a="lCmx+lCx+lTHx+TP2X*(TP=2)+TP3X*(TP=3)+TP4X*(TP=4)+TP10X*(TP=10)" alpha="0" />
</Transforms>
```

Figure 7

The following matrix (Equation 2) defines the DH you see above. It has arguments d, Θ, α and "a" and executed in the following order d – a translation along the Z axis, Θ – a rotation about the z axis, α – a rotation about the X axis and finally "a" – a translation along the X axis:

$$
A(\theta, d, a, \alpha) := \begin{pmatrix}
\cos(\theta) & -\cos(\alpha)\cdot\sin(\theta) & \sin(\alpha)\ \sin(\theta) & a\cdot\cos(\theta) \\
\sin(\theta) & \cos(\alpha)\cdot\cos(\theta) & \sin(\alpha)\cdot -\cos(\theta) & a\cdot\sin(\theta) \\
0 & \sin(\alpha) & \cos(\alpha) & d \\
0 & 0 & 0 & 1
\end{pmatrix}
$$

Equation 2

---

[1] John J Craig, *Introduction to Robotics Mechanics and Control Third Edition* (Pearson Education, Inc, 2004), Appendix B defines the 24 angle-set conventions. [1]

Each of the kinematic chains above essentially define the same kinematic chain. The arguments in the chain are defined in the various sections above. The static variables, the axis variable and the comp tables are all represented in these kinematic chains.

In both the sixdof transform method and the DH method, as many arguments as possible are packed into each transform resulting in fewer total transforms and reducing the number of matrix products required to achieve a forward solution.

State Matrix

The 4x4 matrix resulting in multiplying the above series of transforms together is often referred to as the state matrix. In this matrix, the full 6-DOF (six-degree-of-freedom) representation of the machine's tool-point state is defined. The upper left 3x3 defines the orientation of the tool-tip and upper three elements of the far right column represent the tool-tip's position (X,Y,Z).

In the Euler angle set where rX, rY, rZ is the specified order of operations with displacement X, Y, Z we have the following matrix:

$$
\begin{pmatrix}
\cos(rY)\cdot\cos(rZ) & -\cos(rY)\cdot\sin(rZ) & \sin(rY) & X \\
\cos(rX)\cdot\sin(rZ) + \cos(rZ)\cdot\sin(rX)\cdot\sin(rY) & \cos(rX)\cdot\cos(rZ) - \sin(rX)\cdot\sin(rY)\cdot\sin(rZ) & -\cos(rY)\cdot\sin(rX) & Y \\
\sin(rX)\cdot\sin(rZ) - \cos(rX)\cdot\cos(rZ)\cdot\sin(rY) & \cos(rZ)\cdot\sin(rX) + \cos(rX)\cdot\sin(rY)\cdot\sin(rZ) & \cos(rX)\cdot\cos(rY) & Z \\
0 & 0 & 0 & 1
\end{pmatrix}
$$

Equation 3

Any value in the fixed reference system (FRS – Figure 8) can be fully represented by this matrix. Typically our customers chose to define a point in the part program as X, Y, Z, A, B, C, where A, B, C are the Euler angle set[1] such that A is a rotation about the X axis, B about the rotated Y axis and C about the rotated Z axis. The arguments in a Gcode line are formed into the above state matrix. In most cases, an additional 6-DOF transform is used to correlate the part-program to the fixed reference system. This is known as a rigid body transform.

MEASUREMENT METHOD

FRS – Fixed Reference System

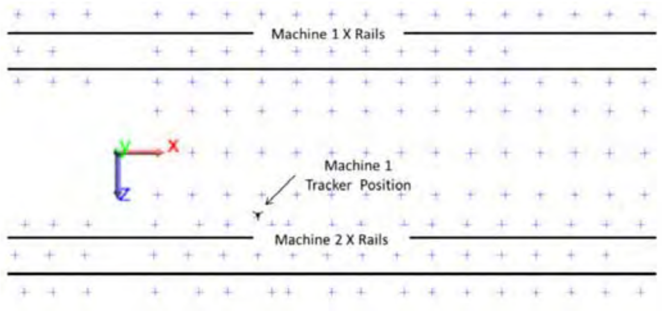

Figure 8 – Fixed Reference System (FRS). The FRS is embededed into the the concrete floor and is used as the base coordinate system.

A series of SMR (Spherical Mounted Retro-reflector) nests is embedded into the concrete floor. These nests are positioned approximately in a 1 meter grid. A convenient coordinate system is established and each of the SMR nests is given a value relative to this system. Any time a tracker is used, it will be located relative to the FRS. Furthermore, all machine kinematics will have a forward solution into the FRS and a back solution from the FRS to the required machine axis positions. This is our common coordinate system. All devices in the cell will share this base reference system (An example is the laser projectors used for inspection and part locating [3]).

Probehead, laser tracker, active target:

Figure 9 – A linear-linear-linear-rotary-rotary-rotary AFP machine equipped with a probe head. Note that the rotary axes are extremely non-orthogonal.

The machine shown in Figure 9 has a removable AFP head. During machine compensation the AFP head is removed in favor of a probe head similar to the one shown. This probe head has a similar weight and CG as the AFP head. The tool-point offset to the active target is very nearly the same as the application point (or nip point) of the AFP head. Arrayed around the active target is a series of SMR nests. These nests are valued relative to the tool changer datum surface. When tracking, we use the active target to capture values for the tool-point and four of the other nests to establish orientation.

Tracker Trigger

Besides causing less machine cell interruption, it is imperative to collect tracker data quickly to ensure a clean data set. Electroimpact has developed an integrated tracker trigger for this purpose. The tracker trigger software relays messages from the CNC to Spatial Analyzer and from Spatial Analyzer back to the CNC. Therefore the CNC can indicate to Spatial Analyzer that it is time to take a point and Spatial Analyzer can relay the fact that the point was taken to the CNC. This software works over TCP-IP and is a closed loop system. The tracker trigger records machine axis positions from the CNC and the associated tracker measurement. This allows for extremely consistent data collection that takes the least amount of time possible, eliminating many of the errors that can occur during tracking.

Data Collected for Solving

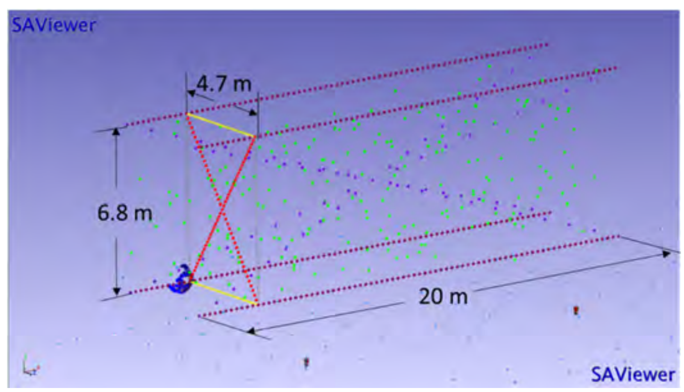

Figure 10 – As promised, the machine envelope is extremely large.

Figure 10 shows the data we use to compensate this particular 6 axis machine (used to build the first 40' of the Boeing 787 fuselage – Figure 1). This machine has a machining envelope of 20 m in X, 6.8 m in Y, 4.7 m in Z, 135° in A, 180° in B, and 360° continuous in C. It is important to collect data that represents the machining envelope and, when the variables of kinematics are optimized, the new kinematic model works on randomly selected machine positions that are not included in the solved data set.

The data set that we find works well is organized into four types: linear axis station data, rotary axis station data, random data and check data.

Linear Axis Station Data:

Linear axis station data (Figure 11) is taken on every station defined in the comp table. We will solve for the specific X, Y, Z, rX, rY, rZ of each axis at these “stations”. As stated earlier, typically the rX, rY, rZ comp table elements (Figure 12) are used to orient the machine axis and the X, Y, Z elements are used to account for any linear offsets that occur. Data is collected in a way to ensure that we get strong indications of how the individual axis’ motion affects the position and orientation of the tool-point and on how the variables in the kinematic chain can be optimized to account this effect.

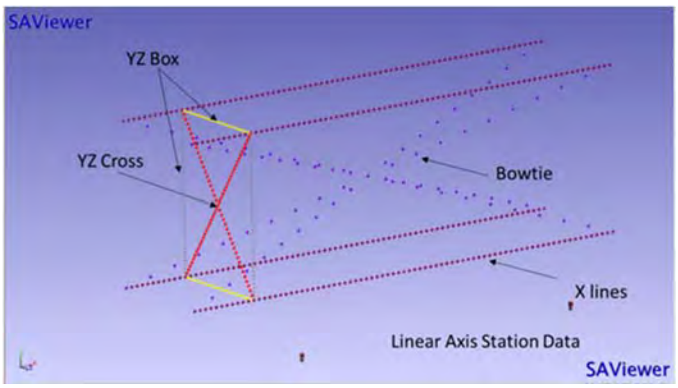

Figure 11 – Compensation data used to capture the linear axis characteristics

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  <station loc="3000" X="0" Y="0" Z="0" rX="0" rY="0" rZ="0" />
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Figure 12 - Partial X axis compensation table. loc (location) is a position along Xm. X, Y, Z, rX, rY, rZ are the six degrees of freedom arguments corresponding to this specific location.

Rotary Axis Station Data:

Similar to the linear axis station data, the rotary axis station data is taken only on the specific stations indicated in the axis’ compensation table. The rotary axis station data differs from the linear axis station data by its inability to get strong indications of the axis orientation by taking data from a single location on the probe head.

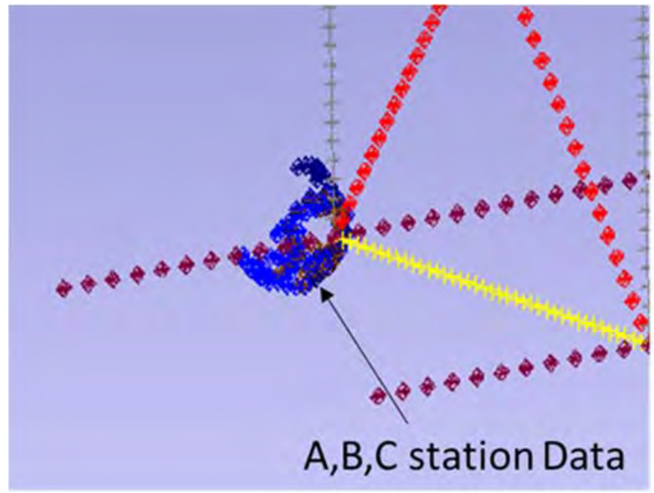

Figure 13 – ABC data, measured at least three times from three different nests on the probe head.

The A, B, C station data is taken at least three times. For each run an SMR is located in a different SMR nest on the probe head (Figure 14). The geometry of the SMR nests is sufficient to ensure an orientation measurement uncertainty of approximately 0.014°. Remember that this is measured in the three primary angles (rX, rY, rZ) at the tool-point. 0.014° ensures a deviation of less than .002” across an 8” tool.

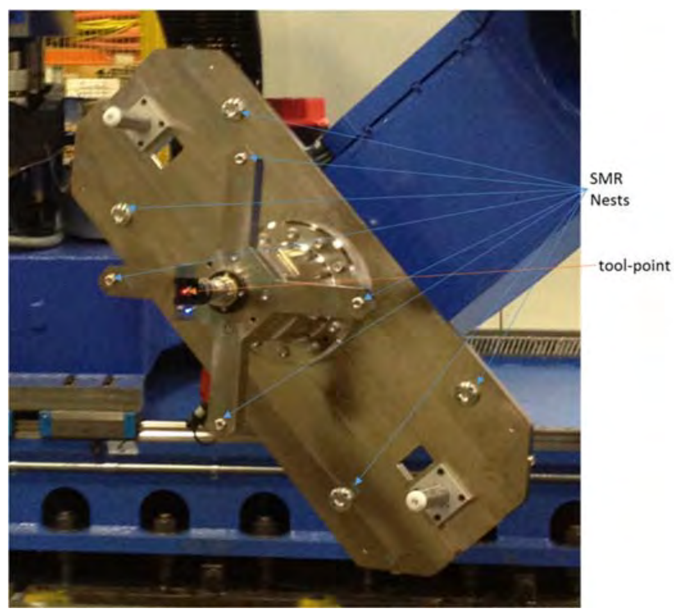

Figure 14 – Probe head used during the tracking of an Electroimpact AFP machine

Random Data:

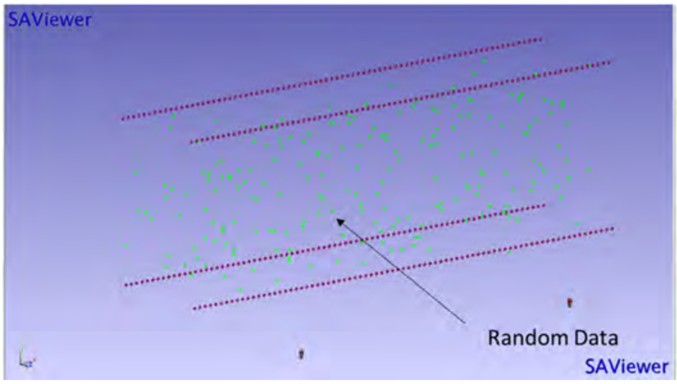

Figure 15 – Six-degree-of-freedom random data

Shown in Figure 15, the large sample of completely random data represents the machining envelope of the machine in both position and orientation.

Check Data:

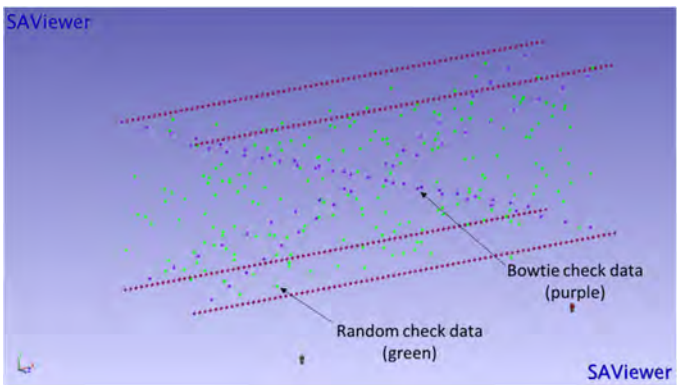

Figure 16 – Distribution of random check data and bowtie check data

Check data includes both a randomly generated bowtie, as seen in Figure 9, which does not change the orientation of the probe head. This bowtie allows us to isolate linear axis motion from rotary axis motion. The random data is full six-degree-of-freedom data that truly represents the six-degree-of-freedom machining envelope.

RESULTS

Before getting too excited about the results of this machine, it is important to first take a look at the accuracy capability of the measuring stick. In this case to collect the tool-point position data for this data set, an API (Automated Precision Inc.) Radian tracker was used. In ideal conditions the expected measurement uncertainty is just over 0.004” for a volume this size. When we collect a good clean data set we usually stop trying to improve the solved solution at about 2x this uncertainty. So, using 0.004” as the measurement uncertainty, one should expect the ability to position the machine randomly in the envelope at about 0.008” uncertainty. In nearly all cases we are able to meet this criteria. The example that follows is no exception. In the following figures in this section, we show how the kinematic chain develops as we solve for different kinematic variables. Finally, at the end we show the results in our check data. Remember that check data is comprised of randomly selected points in the machining envelope that were not evaluated during the optimization process.

Solve Status after Adjusting Basic Parameters

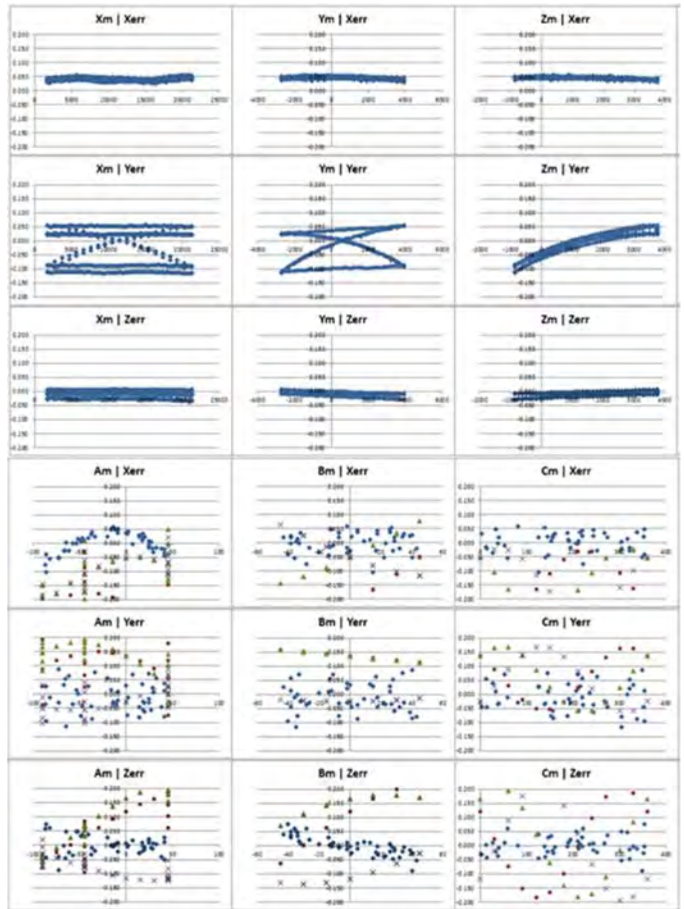

*Figure 17 – After solving for axis scaling, rotary axis link lengths and calculating the base shift we have these results. **NOTE: Scale is ±0.200”**.*

The chart titles in Figure 17 may be a little difficult to comprehend immediately, but they are easily decipherable. Xm | Xerr is the X error plotted vs Xm (or X machine) position. For all charts, the error is in inches unless otherwise noted. The Axis position is in mm (prismatic) or degrees (revolute), unless otherwise noted.

It is clear from this data that a rotation about the X axis prior to the Y axis results as the moment about X changes due to Z motion. This is evidenced by the X shaped plot in Xm | Yerr and Ym | Yerr and by the slanted line in the Zm | Yerr graphs. Since the Am to Bm and Cm to tool-point link lengths are optimized and the charts remain very messy, it is evident that the rotary axes are not particularly orthogonal. The charts in Figure 18 show the results after solving for parameters accounting for the orientation of each axis and also account for the moment about the X axis due to Zm motion. Here we see an order of magnitude improvement in the uncertainty of position amplitude.

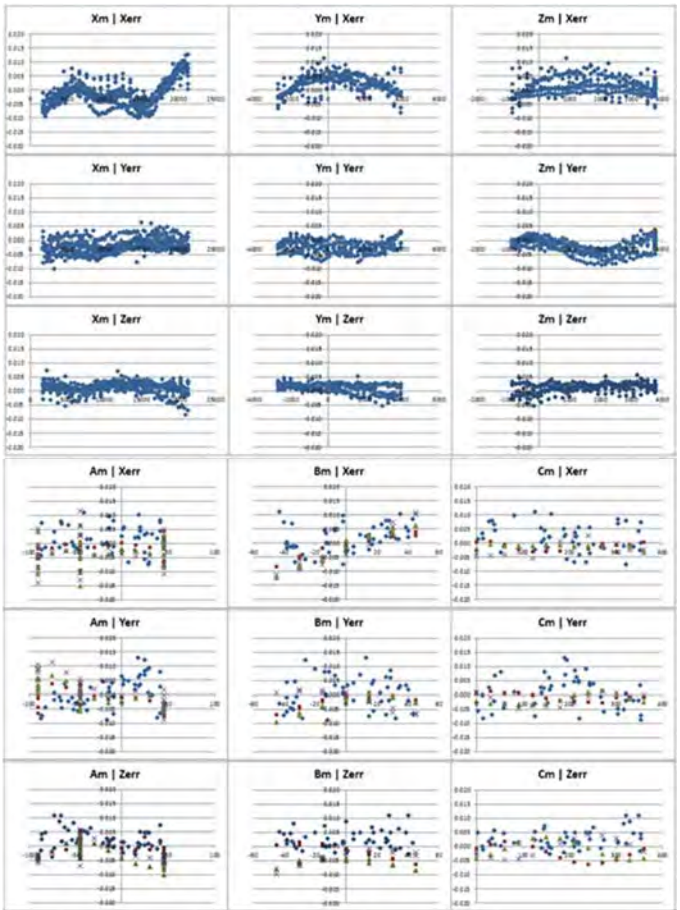

Figure 18 – After solving for axis scaling, rotary axis link lengths, axis-to-axis orientation and accounting for the rX moment due to Z motion and calculating the base shift we have these results. ***IMPORTANT NOTE: Scale is ±0.020" a full order of magnitude less than the last result shown in Figure 17.***

Solve Status after Applying Full Compensation

The charts in Figure 19 show the result of optimization of all kinematic parameters, including link offsets, axis to axis orientation, axis scaling and finally compensation tables:

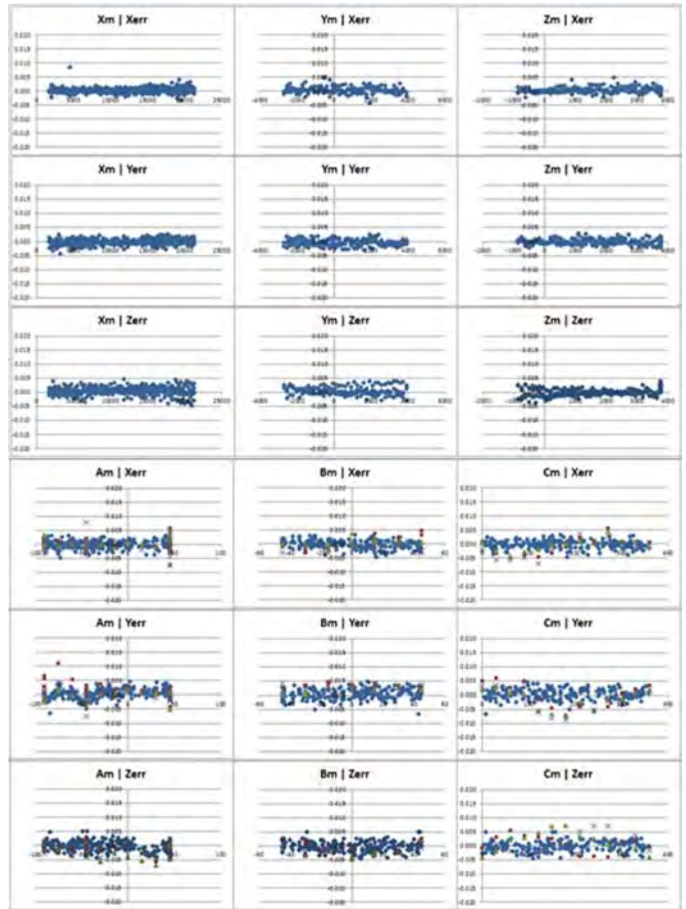

Figure 19 – Final results. The fit of the kinematic model to the data taken for compensation. ***NOTE: Scale is ±0.020".***

Check data results

Unlike the data taken for compensation, the data in Figure 20 and Figure 21 is not used during the optimization of kinematic parameters. This data represents the ability of the machine to perform throughout the machining envelope.

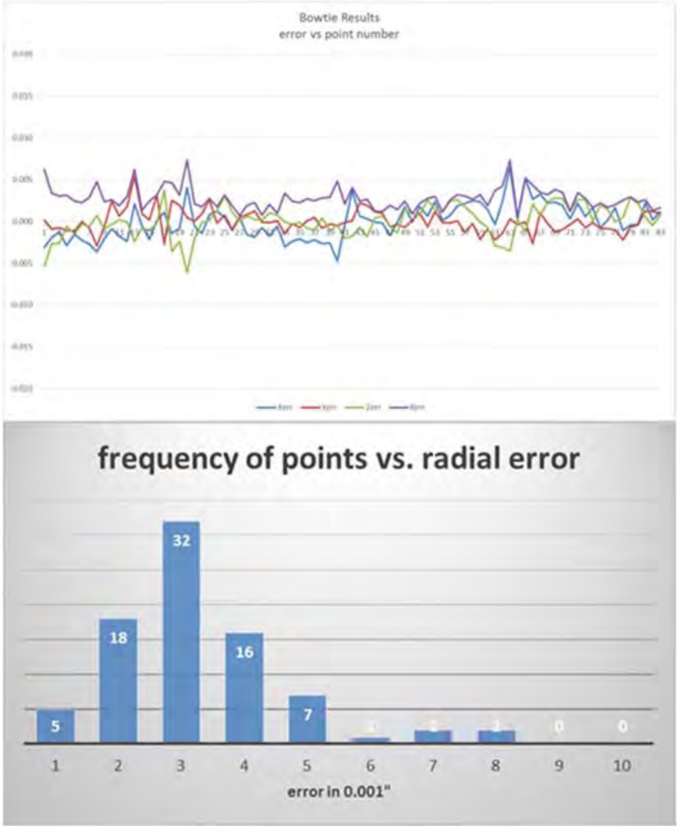

Figure 20 - Bowtie test results (check data)

As we eluded to earlier, we are able to optimize parameters such that the forward solution results in an accuracy of 2x the measurement uncertainty, or in this case .008".

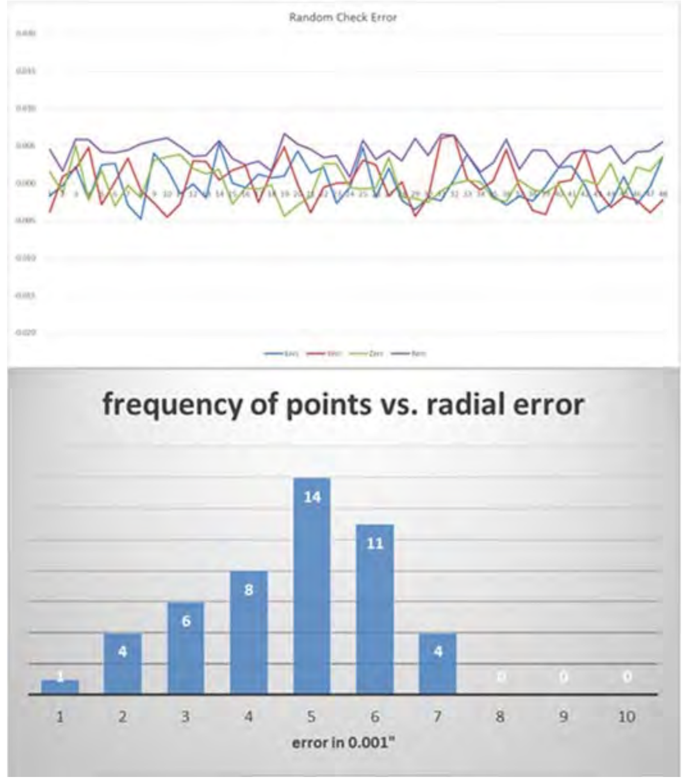

Figure 21 - Random test results (check data)

Again, even when moving the machine randomly in position and orientation, we are able to achieve tool-point uncertainty of approximately .008". In this case we have no error data greater than .007".

Orientation Considerations

When we take data for the rotary axes, we measure at least three positions on the probe head. This ensures that we account for the pointing ability of the machine. The geometry of these positions on the probe head is designed so that given an uncertainty of 0.004" we can establish tool-tip orientation uncertainty of less than 0.014 degrees. The system described in this paper directly measures the orientation of the tool tip as a result of machine motion including all six (or more) axes as they exist in the physical kinematic chain instead of measuring each individual rotational axis and not knowing the actual orientation of the tool tip. Because our mathematical kinematic chain accounts for six degree of freedom physical axes' position, they need not be physically orthogonal and we will still achieve excellent six degree of freedom tool tip accuracy. If you examine Appendix 2, you will find that none of the physical machine axes are particularly orthogonal to each other or the FRS. It is an extreme amount of work to make them "perfectly" orthogonal and a huge waste of time. In fact, in one case our rotary axes are purposely not orthogonal. For this machine the included angle between axes is approximately 50 degrees. This configuration proves to be just as accurate as machines with more “ideal” kinematic arrangements. Since the   Often times, we see machine specifications that call out rotary axis accuracy of 10 arc-seconds. These specifications are missing the point. An axis that can rotate precisely about an arbitrary axis does not necessarily create a machine that has excellent tool-tip orientation. There are many other factors that affect the actual tool-tip accuracy in both linear position and orientation. It is much more effective to quantify the orientation capability (and the linear for that matter) of the machine at the tool-tip…the ultimate point of application.

In the case of automated-fiber-placement, it is critical that the orientation of the tool-point is accurate or unwanted puckers and steering in the carbon fiber tow will occur. The author has seen the resulting layups on complex multi-curvature geometry completed by equipment where tool-tip orientation was not carefully considered during the machine accuracy phase and in these cases much greater puckering and steering in the layup was easily observed with the naked eye when compared to layups created by machines calibrated with the system we developed for this purpose.

SUMMARY/CONCLUSIONS

Although the machining volume of the Section 41 machine is extreme in both 3 axis Cartesian coordinates and 3 axis orientation, Electroimpact engineers can quickly collect the data necessary to find the kinematic parameters required to achieve exceptional machine accuracy. By understanding the limitations of the measurement device being used, in this case a tracker, our engineers know when good enough is good enough. In the example described in this paper, the tracker uncertainty was a little greater than 0.004” and the worst case positional error collected in check data as measured at the tool-tip was less than or equal to 0.008” effectively achieving a machine positional uncertainty of less than two times that of the metrology device used to measure the machine’s accuracy. Furthermore, since a good amount of the data taken was observed from three or more points on the probe-head, we are able to achieve an orientation (the other three degrees of freedom in the six-dof world) uncertainty of less than 0.025 degrees.

It is the author’s hope that future machine accuracy specifications and testing focus on a machine’s ability to deliver accurate performance at the point of action and that all six degrees of freedom are given their due consideration.

The author has seen many examples where machine accuracy specifications are impossible to achieve. Typically these specifications were originally written for three axis machines with machining envelopes of a meter or less cube. These same specifications often require machine uncertainty less than that of the device used to measure them.

Finally, I would like to thank my able colleagues Scott Smith, Justin Neilson, Rick Calawa, Josh Cemenska and Russ DeVlieg for their many valuable inputs along the way. Working on a parallel path, Russ DeVlieg has taken 6-axis articulated arm robot compensation to a level that rivals the accuracy of purpose built drilling machines [9]. If you find this paper useful, then it is because of their contributions to my understanding over my past 20 years at Electroimpact.

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NOMENCLATURE

Tool-tip, Tool-Center-Point, Tool-Point: the point of contact of a machine and the part it is creating.

6dof: six degree of freedom transform describing the Cartesian X, Y, Z position and the three Euler angles defining orientation.

Serial Kinematic Chain: A series of transforms that when multiplied together define the state matrix of a machine.

State matrix: the 4x4 transform that in column 4 describes the X, Y, Z Cartesian position of a tool-point and the 3x3 upper left matrix describes the orientation of the tool-tip. Typically NC programmers will program in the rX, rY, rZ Euler angle set. Another set commonly used is the rZ, rX, rZ. In the case of milling machines only two angles are required.

Back Solution: The mathematical solution for the machine axes to achieve a given state matrix. Typically fully compensated machines have mathematically impossible back-solutions so a simplified machine model is used to estimate the back-solution. Iteration on the forward solution is used to find the positions required.

Forward Solution: The kinematic chain that describes the state matrix of a machine's tool-tip given the machine axis positions.

Orientation: The upper 3x3 of a state matrix. This defines the vector along which the machine is pointing. Often times the first column is known as the i vector. The second column j and the third column k.

I, J, K programming: A dated way of representing the orientation of the tool-tip in a five axis machine. I, J, K are actually the elements of the unit vector k.

Active Target: A product developed by API. This device is effectively an SMR that points back at the laser tracker beam. This device is extremely useful when tracking large envelope machines with large orientation envelopes. Shown in Figure 22 is the Electroimpact Active Target.

Figure 22 – Justin Nielson, active target before the API active target. Armed with cowboy boots and a harness, Justin was sport enough to ride this crazy huge machine and turn the tracker ball toward the laser tracker and his batteries never ran out! Although we got good results with this method, the API active target is a much better instrument for this purpose. Luckily, Justin makes a much better engineer than the active target ever could. We have come a long way in the past 10 years!

APPENDIX

Appendix 1: Complete machine kinematic file before optimization


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Z="lCmz+lTHz+TP2Z*(TP=2)+TP4Z*(TP=4)+TP3Z*(TP=3)+TP10Z*(TP=10)" rX="0" rY="0"
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</EITransform>
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Appendix 2: Complete machine kinematic file after optimization


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<lAy value="0.0915" />
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<bmrzoff value="0.2123" />
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<Bflex value="-897.6837" note="this is the cg and mass and stiffness of B weldment" />
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PSPad