MFG219635
Understanding 5-Axis Machining Concepts

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Learning Objectives

- Understand 3+2 programming concepts
- Understand the differences between traditional work offset versus dynamic versus incline plane
- Understand 5-axis programming methods of RTCP versus Inverse Time and how to improve surface finishes
- Gain confidence in 5-axis programming, and discover how certain codes can improve processes and help you select a machine tool

Description

As more multi-axis machine tools are adopted into production, there is sometimes a disconnect between what is happening in the CAM software and the G-code results and how that affects machine behavior. This session is designed to provide clarity in understanding various programming concepts that not only make programming more simplified, but, more importantly, demystify the resultant code produced from CAM software—whether the application is a 4- or 5-axis milling machine, a multifunction lathe with live tooling, or even Swiss-style machines. These concepts can be applied to any CNC-controlled application. Having a better understanding of these concepts not only will help avoid potentially damaging collisions of the machine tool, it will also help select a machine tool and control combination when purchasing new equipment.

Speaker

Like many people I started on AutoCAD and after being in Industry for a few years I transitioned to the CAD/CAM service side of the Industry, having an opportunity to bring a new product to market in 1996, which was SolidWorks. Having a successful partnership with SolidWorks for over 10 years becoming certified as a trainer and support technician. The primary focus for my customers was really manufacturing having provided services and consulting for the manufacturing segment. In 1998 I was fortunate to be introduced to what was Delcam. Who was already an established respected UNIX product for manufacturing. Delcam was transitioning its technology to the Windows platform, so it was an exciting time to have new products with a rich legacy of robust technology. In recent years I eventually was reunited with Autodesk as part of the Delcam acquisition.

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General Terminology

Right Hand Rule

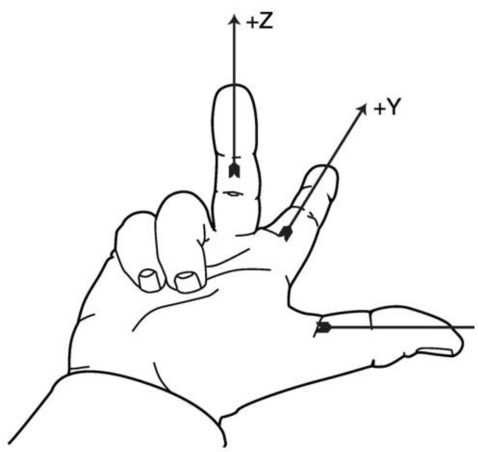


Image courtesy of https://www.instructables.com

For **right-handed** linear coordinates,

The positive **X** Axis is represented by the direction of your right **thumb**

The positive **Y** Axis is represented by the direction of your right **index finger**

The positive **Z** Axis is represented by the direction of your right **middle finger**

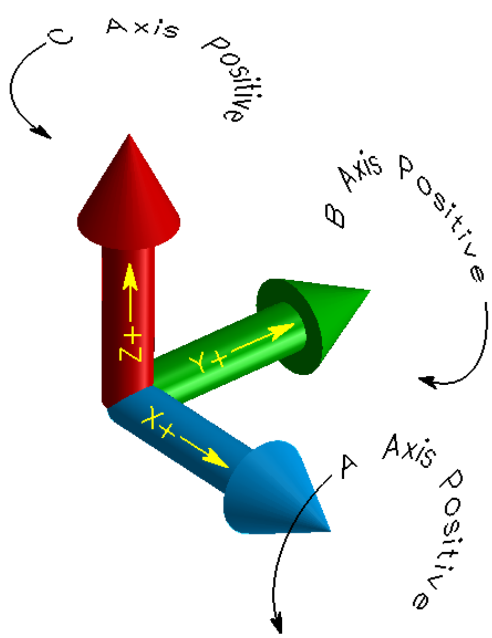


Image courtesy of ttp://www.cnc-toolkit.com/support.html

For **right-handed** Rotational Axis,

The **A** Axis rotates around the **X** Axis.
The **B** Axis rotates around the **Y** Axis.
The **C** Axis rotates around the **Z** Axis.

The **positive** direction of rotation is **counter-clockwise** when looking down the positive direction of the respective Axis

Unit Vectors

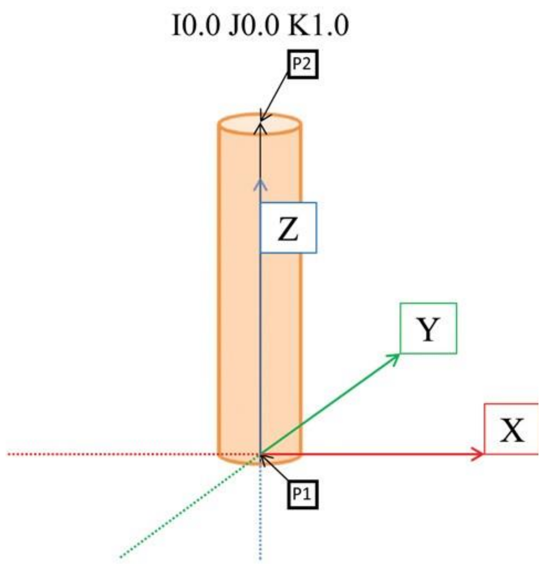


Image courtesy of https://www.mmsonline.com

Tool Vectors consist of two points

P1 represents the tool tip in **XYZ**

P2 represents the tool direction in **IJK** incremental from **P1** tool tip

Vectors are expressed in 1 unit in length. So **IJK** values are always 1 unit or less in value.

When Tool is Vertical like the *(left image)* the vector is
I0.0 J0.0 K1.0

IJK is incremental respective to **XYZ**

I = X J = Y K = Z

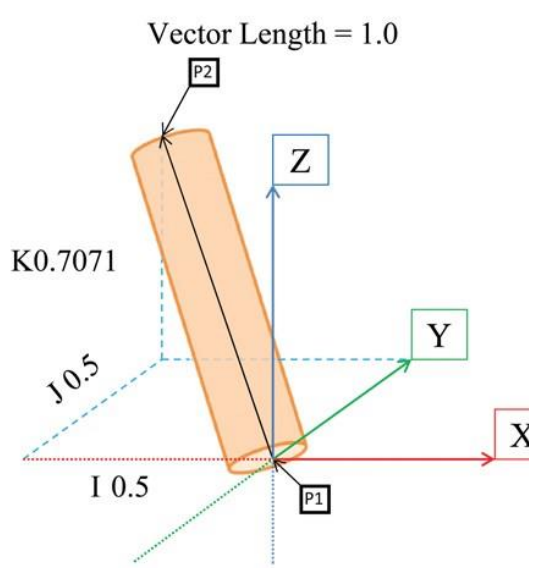


Image courtesy of https://www.mmsonline.com

When Tool is tilted *(left image)* the vector is
I0.5 J0.5 K0.7071

This works out to be angles
Rotated about **X -39.236466°**
Rotated about **Y +24.095487°**
Rotated about **Z -18.438410°**

Or expressed as

Elevation of **44.995674** degrees
Azimuth of **45.0** degrees

Azimuth & Elevation

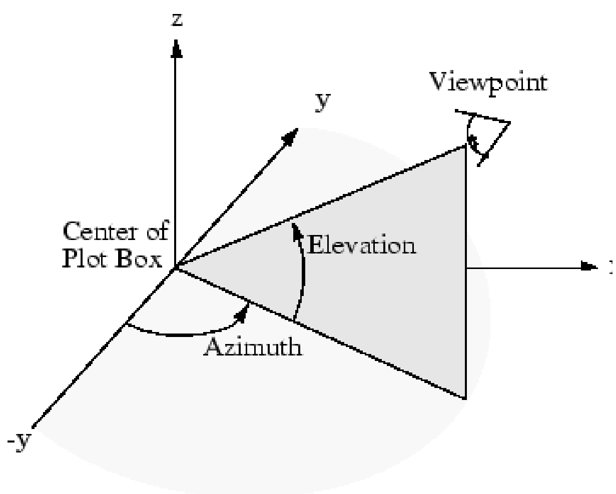


Image courtesy of https://www.mathworks.com

Azimuth & Elevation are common terms to define a direction is space. In the mechanical world

Azimuth is the rotation around the principal axis *(Usually Z)*

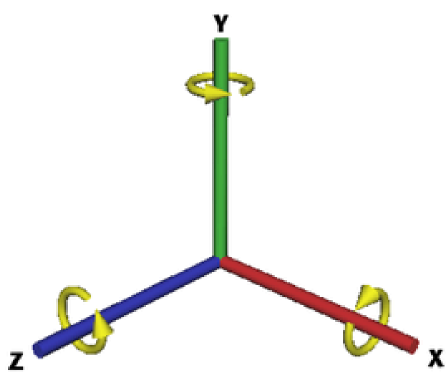
Elevation is the angle of Tilt from the product of that Axis *(Usually the XY plane)*

Thinking of a HEAD – HEAD style machine, **Azimuth** is similar of a C Axis (but not specifically) and **Elevation** would be the tilt of the Tool

Euler Angles

The **Euler angles** are three angles introduced by Leonhard Euler to describe the orientation of a rigid body with respect to a fixed coordinate_system.

Credit https://en.wikipedia.org/wiki/Euler_angles



Euler rotation interpolation

There many combinations of **Euler Conventions**

1. XYZ STATIC
2. XYX STATIC
3. XZY STATIC
4. XZX STATIC
5. YZX STATIC
6. YZY STATIC
7. YXZ STATIC
8. YXY STATIC
9. ZXY STATIC
10. ZXZ STATIC
11. ZYX STATIC
12. ZYZ STATIC

1. XYZ ROTATING
2. XYX ROTATING
3. XZY ROTATING
4. XZX ROTATING
5. YZX ROTATING
6. YZY ROTATING
7. YXZ ROTATING
8. YXY ROTATING
9. ZXY ROTATING
10. ZXZ ROTATING
11. ZYX ROTATING
12. ZYZ ROTATING

Any of these conventions are possible for any machine. Therefore, it is important that the actual convention used by the machine itself is known and understood.

Some machine controllers, the Euler convention is set by the machine builder. In other cases, the machine kinematic determines the convention. There are also some controls where the convention is stated within the G Code

Kinematics

Official definition of Kinematics

1: a branch of physics that deals with aspects of motion apart from considerations of mass and force

2: the properties and phenomena of an object or system in motion of interest to kinematics

https://www.merriam-webster.com/dictionary/kinematic

Practical definition of Kinematics

The axis composition of the machine tool and style of machine tool, specifically the rotary axis

(XYZAB) (XYZAC) (XYZBC)

Types of machine kinematics

4 Axis Table

- Includes **H**orizontal **M**achining **C**enters (**HMC**)
- Very common on **V**ertical **M**achining **C**enters **(VMC)**

4 Axis Table

Image courtesy of https://www.haascnc.com

Table – Table

- Most common 5 Axis machine style
- Typical with **VMC**
- Can be added to existing machine
- Cutting tool remains vertical

Table – Table

Image courtesy of https://www.haascnc.com

Head – Head

- Typical on gantry style machines
- Most common is 5 Axis routers
- Cutting tool must tilt
- C Axis limits are a major consideration
- Multiple solutions for a single position

HEAD - HEAD

Image courtesy of www.dmscncrouters.com/

Head – Table

- Common on task specific machines
- "Turn/Mill" machines fall into this category
- The "Chuck" would be considered a "Table"

HEAD – TABLE

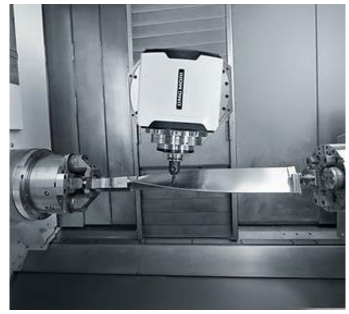


Image courtesy of dmgmori.com

Nutating Head

- Can be a HEAD only 4 Axis Machine
- Nutating HEAD-TABLE machines are also common
- Not as common, usually found on European machines
- More complex rotations as both rotaries need to move to achieve a simple 90° position

Nutating HEAD

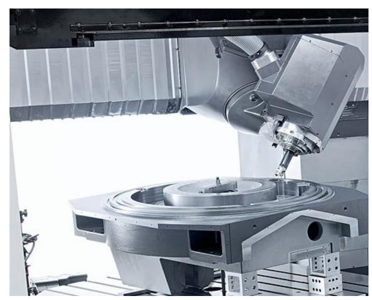


Image courtesy of dmgmori.com

Nutating Table

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Nutating TABLE

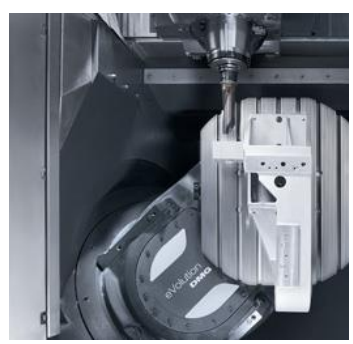


Image courtesy of dmgmori.com

CAM Software programming classifications

2 Axis "2+1"

- wireframe or some 2D profile or geometric feature
- Shape is offset in the XY plane then an incremental step occurs in the Z Axis then the shape offset is repeated

3 Axis "Surfacing"

- machining directly from surface or faces of a solid
- up to 3 linear Axis can be used
- faces are approximated by linear move segments
- typically, more calculation intensive

Indexing "3+1" / "3+2"

- sometimes referred to as positioning or "3+1" / "3+2"
- uses a fixed angle on the index axis
- consists of a 2 axis or 3 axis method with an included rotary axis
- single rotary Axis (3+1)
- two rotary Axis (3+2)
- most common application of "Multi-Axis" machining
- generally, a preferred strategy over simultaneous 4/5 axis programming

Simultaneous 4 and 5 Axis

- simplest method is wrapping a 2/3 Axis toolpath to a cylinder creating a 4 Axis program
- wrapping can be done at the control in some cases
- similar in calculation to 3-Axis where faces are approximated
- programming time tends to be more intensive
- ability of CAM software become more instrumental to success
- usually referred to as "5- Axis"
- can be limited to a single rotary axis "4-Axis"
- includes "wrapped" toolpaths
- machine tool needs to support full 4 or 5 Axis machining
- typically, VERY calculation intensive

Concepts for 4 & 5 Axis Indexing

Multiple Offsets

- uses separate work offsets for each rotational position or face
- typical of 4 Axis horizontal machines
- amount of work offsets available on the machine is a concern
- setup time can be considerably longer
- typically, acceptable for “tombstone” style indexing
- not recommended for accessing indexable positions within the workpiece. For example, a single part with many holes at different indexed positions would be difficult or impossible to use this concept

Center of Rotation

- single Program for all indexed positions
- straight forward output and programming. Nothing fancy!
- NO Part Tracking when part is rotated
- usually requires the part to be perfectly centered about the machine rotary axis
- single workoffset is used. Which would reduce how many times a part needs to be indicated, however placing the part on rotation center may be difficult and time consuming if even possible

Dynamic Workoffset

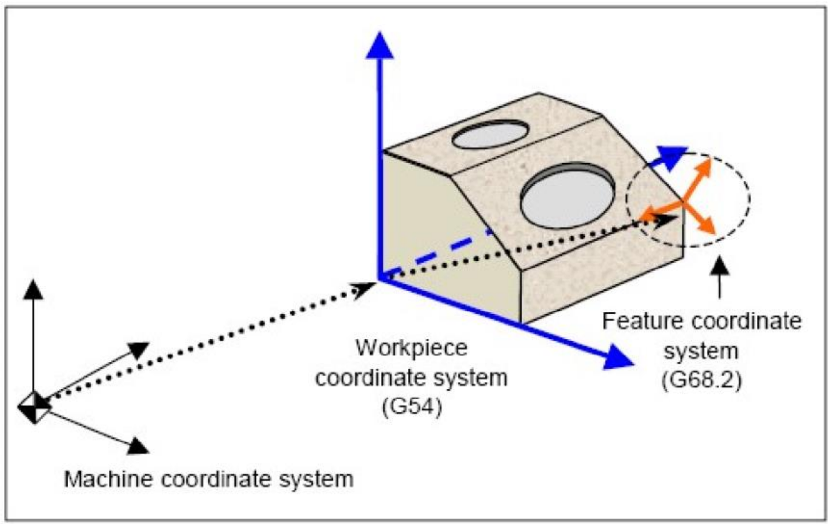
- DWO *(Dynamic Workoffset)*
- output is very similar to center of rotation
- allows the part to be placed anywhere on the table
- CNC controller compensates for any offsets in the machine kinematic or the location of the part on the table of the machine
- only works on Table -Table style machines

Incline Plane or tilted working plane

- most sophisticated robust method for positional programming
- includes all the benefits of ‘Dynamic Workoffset”
- works on any style machine
- mimics the functionality of the “workplane” used in the CAM software during programming
- it is imperative that Euler Angles are known and understood
- post development and testing should be considered as it is more complicated to ensure things are correct, and testing may become difficult if the concept is not fully understood

Incline Plane in Detail

Incline Plane is defined by a translation or offset from the WPCS (workpiece coordinate system) this is expressed as an XYZ value *(typically)*. It is also defined by three rotational values. These rotations are controlled by the Euler Convention either defined by the machine or by the cycle. These are expresses as an IJK *(typically)*



The axis rotations defined determine what the axis directions are for the actual machine

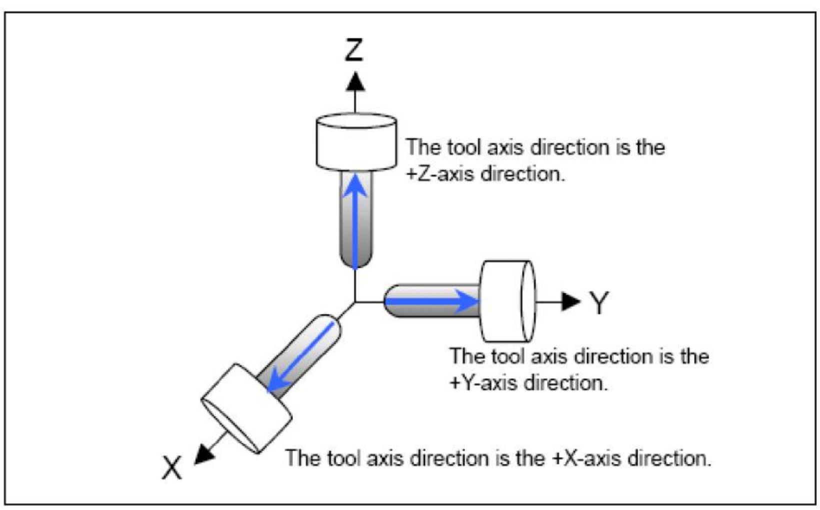


Image courtesy of www.fanucamerica.com

The axis rotations defined determine what the axis directions are for the actual machine. In many cases once the plane is defined a second code is required to invoke the new coordinate systems axis as updated axis of the control

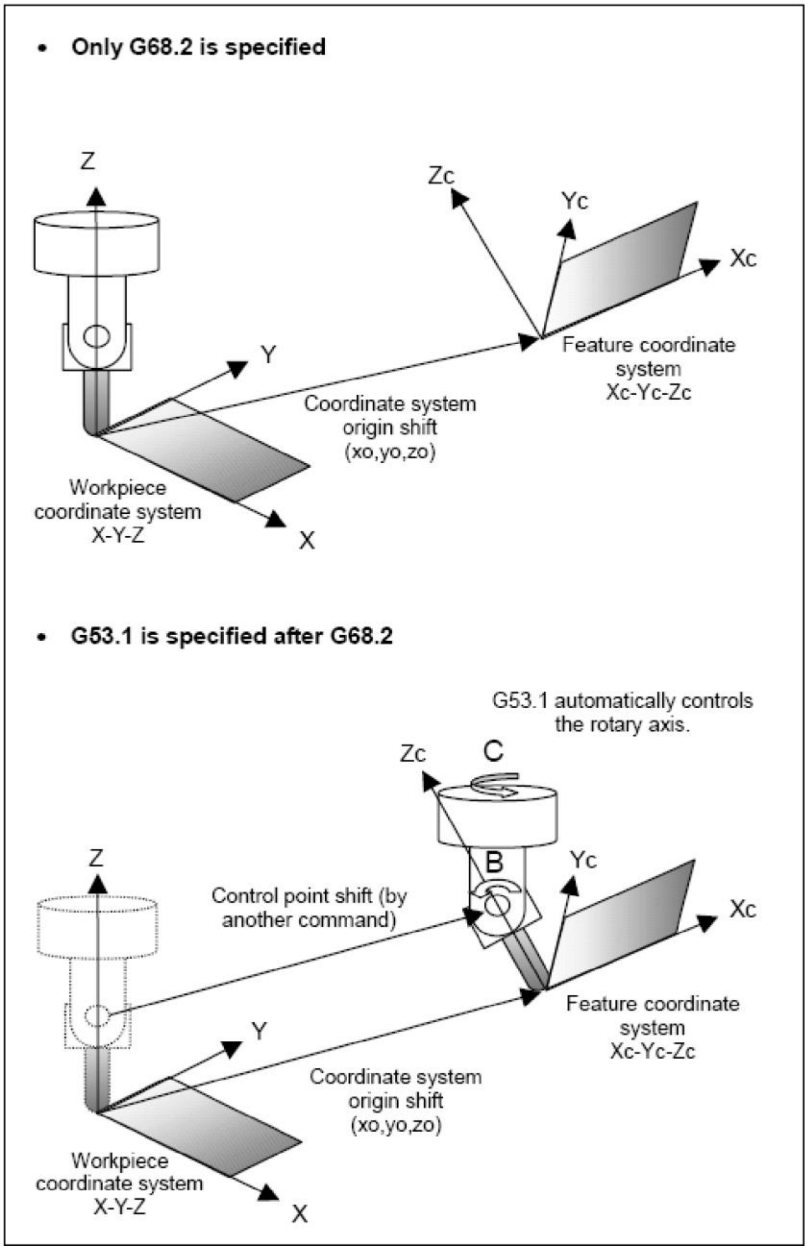


Image courtesy of www.fanucamerica.com

Concepts for Simultaneous Multi-Axis

Inverse Time

- Time Based feedrates versus linear speed
- Inverse Time is 1/Time
- available on most machines
- programmed with a single code G93 *(typically)*
- feedrates are required for every line of code
- values are difficult to interpret at the control (or edit)
- surface finish qualities are significantly improved

Center of rotation

- can be used with inverse time (G93)
- most common method for “legacy” machines
- programs may be machine specific as machine geometry variations between “identical” machines may be slightly different
- many problems arise from using center of rotation including part location factors

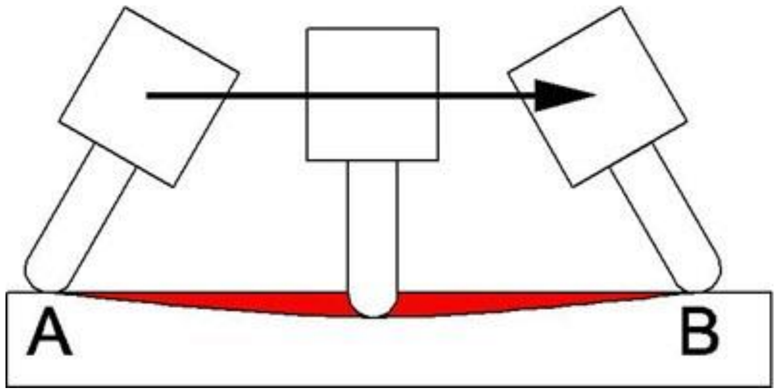
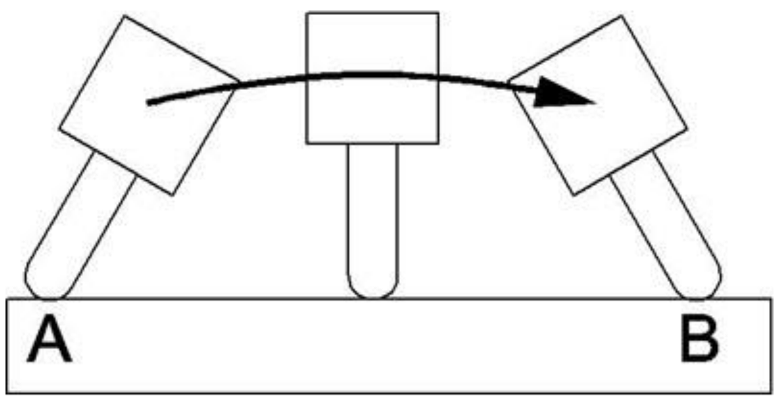
Vector Programming

- can be used with inverse time (G93)
- accepted by most “modern” controls
- easy to implement and develop post processor
- can be used to independent of the machines kinematic
- vector programming is difficult to read at the control
- hard for machine operators to understand which way the machine may move.

RTCP (TCPC) or Toolpath linearization

- RTCP *(Rotational Tool Compensation Point)*
- TCP *(Tool Center Point)*
- can be used with inverse time (G93)
- synchronizes all the axis including the rotational axis with the linear axis
- ensures tool tip motion follows the intended trajectory much more closely to what is in the CAM software
- usually easy to develop a post processor for, however transitional moves in between toolpaths may take some time to test properly. In most cases it is required to cancel RTCP in between toolpaths.

RTCP /TCP in detail

Without RTCP/TCP the tool simply rotates from the current position to the next commanded position. During this "swing" that occurs the tool tip travels through a position that can be deeper than expected as shown in the image below. Effectively rotations rotate around the machines rotary axis versus the tool tip.  Toolpath without TCP Images courtesy of www.fanucamerica.com
Machines with RTCP/TCPdynamically adjust the all the axis so the tool tip stays along the intended tip direct. With RTCP active the machine effectively rotates around the tool tip, versus rotating around the machine rotary centers.  Toolpath with TCP Images courtesy of www.fanucamerica.com

Conclusion

Even though multi-axis machining can be intimidating, understanding some fundamental terms and how multi-axis toolpaths are classified helps to understand difference is various software options and ensures you have the proper software to tackle work that you may try to perform or bid on. Nothing is more discouraging when a programmer sits down to work on their first multi-axis job and they realize they do not have the proper CAM software or machine control options to complete the task. Beyond programming workpieces, selecting the right machine tool is critical to success. Not just the brand but most importantly the kinematic of the machine. In many cases this choice may be obvious, but the when comparing Machine A to Machine B, all the usual considerations need to be factored in, however what is overlooked in many cases is the control options selected. Options like Dynamic Workoffset or RTCP are very critical to have success and being able to efficiently make parts at a competitive price.