COMPUTER NUMERICAL CONTROL OF MACHINE TOOLS

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Chapter 16:
5-Axis Machining

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Objectives of Chapter 16

- Understand the **capabilities and limitations** of **5-axis machines**
- Describe the **different configurations** of **5-axis machines**
- Understand the **differences and applications** for continuous **5-axis**, **4+1**, and **3+2 machining**

5-Axis Machining

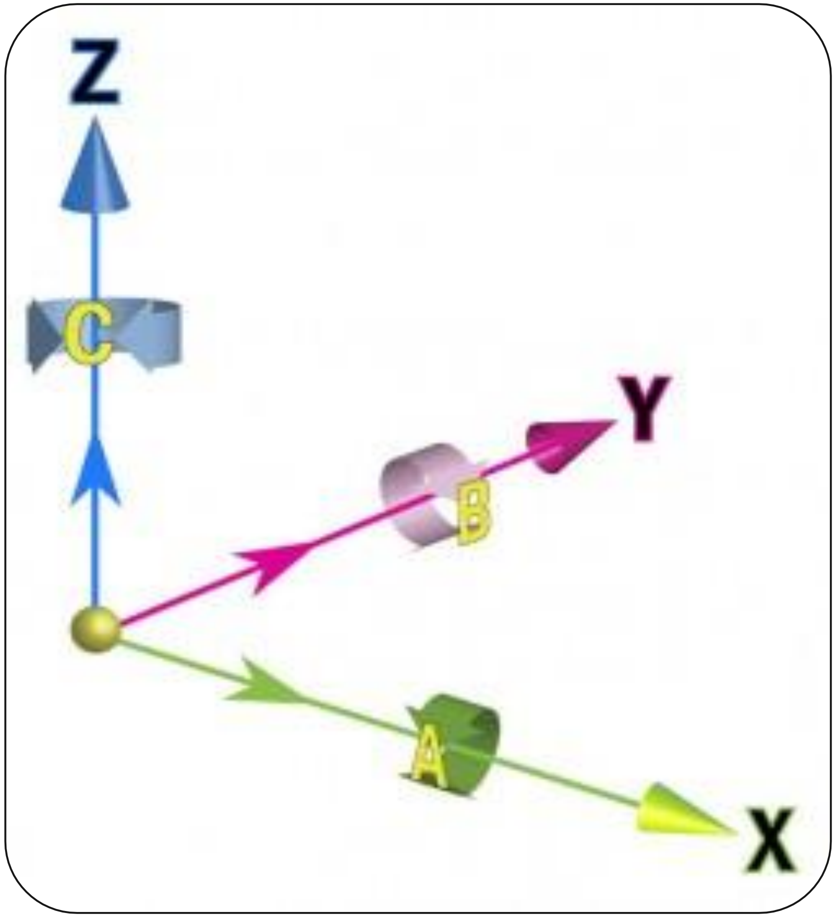
What is 5-axis machining?

- Standard machines have **linear motion** along the **X**, **Y** and **Z axes**
- **5-axis machines** have **two additional axes of rotation**
- Most machine tool builders identify their rotary axes according to the ISO standard, which is that:
  - The **A axis** rotates around **X**
  - The **B axis** rotates around **Y**
  - The **C axis** rotates around **Z**

NOTE Some machine tool builders may use a **different naming convention**, but the principle is the same

5-Axis Machining

What is 5-axis machining?



- In **5-axis machining** the additional rotary axes will rotate about two of those three primary axes

Figure 1: X ,Y and Z axis with the Z axis being parallel to the tool spindle

5-Axis Machining

What is 5-axis machining?

- In Figure 2, the machine is equipped with a rotary table mounted on a trunnion table
  - The trunnion uses **A axis** movement to tilt the part around the **X axis**
  - The rotary table rotates around **Z** for **C-axis** motion

- **By tilting and turning the part**, the tool can reach virtually any surface

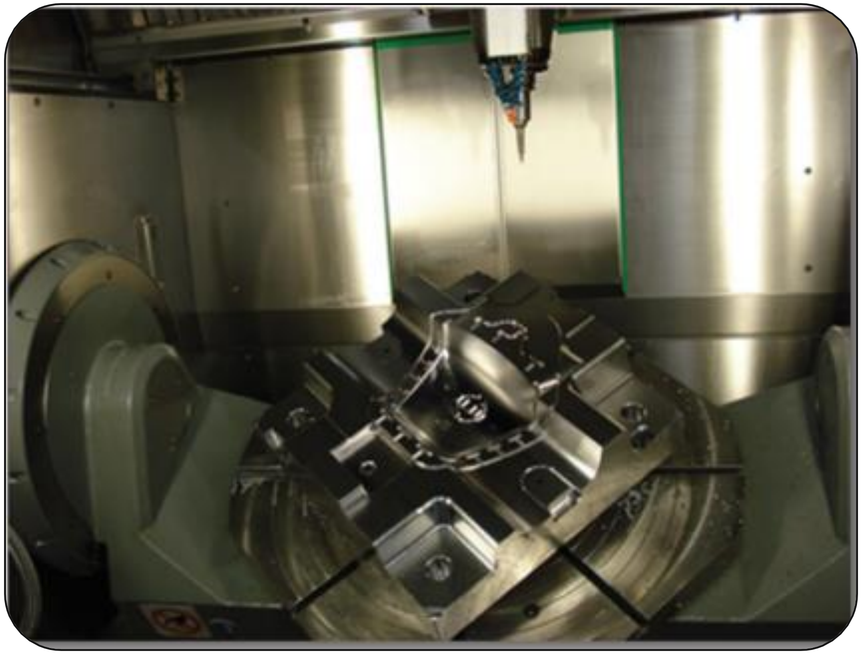


Figure 2: Machine equipped with rotary table

5-Axis Machining

How is 5-axis used?

- Even though **5-axis machining** is associated with **complex geometries**, it is much more common that 5-axis machines are used for five-sided machining to :

✓ **Reduce setup time**

✓ **Eliminate the typical flipping of parts required on three-axis machining centers**

- This way the **profit margin per part is increased**; plus **accuracy is increased** when switching from moving parts around on standard mills to mounting them once on a five-axis machining center and machining all sides

5-Axis Machining

Advantages of 5-Axis machining

Machine parts with one setup

- ✓ Improved productivity, reduced set up time and cost
- ✓ Improved accuracy
- ✓ Reduced risk of operator error

Easy to optimize tool orientation

- ✓ Use flat end mills instead of ball mills to finish angled faces
- ✓ Best finish and improved cycle time
- ✓ NC code is easier to understand

Efficiently machine hard-to-reach features

- ✓ Undercuts, complex contoured faces, etc.
- ✓ Shorter cutting tools can be used since head gets closer to work piece
- ✓ Improved cutting conditions = better finishes, increased tool life

Disadvantages of 5-Axis machining

- **Reduced machine rigidity**
- **Reduced working envelope**
- **Reduced feed rate**
- **Overall accuracy depends heavily on the machine axis accuracy** and mathematical rotary compensations on the control
- **Fixture setup can be more complex**
- **Higher initial investment**

Figure 3:Overall accuracy depends heavily on the machine axis accuracy

5-axis Machine Configurations

- **5-Axis milling centers have 3 linear axes, 2 rotary axes that are usually configured one of two ways:**
  - **Tilting table**
    - Tool moves linearly
    - Both rotary axes are on the table
  - **Tilting head**
    - Tool rotates
    - Milling headstock has at least one rotary axis
- **5-axis Mill Turn**
  - Usually one rotary axis on the milling head and the second rotary axis is the spindle

NOTE

The 'best' machine configuration depends greatly on the part(s) that are being cut

Tilting Table Example

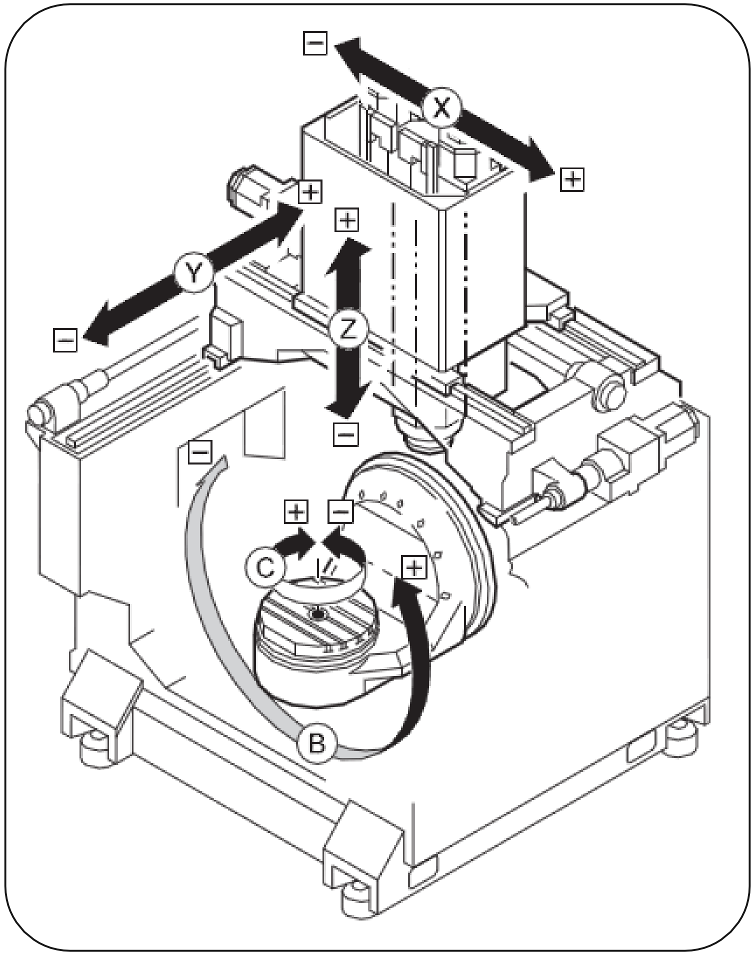


Figure 4: Mori Seiki NMV 5 Axis Vertical Machining center

Rotary Tables

Tilting Table Example

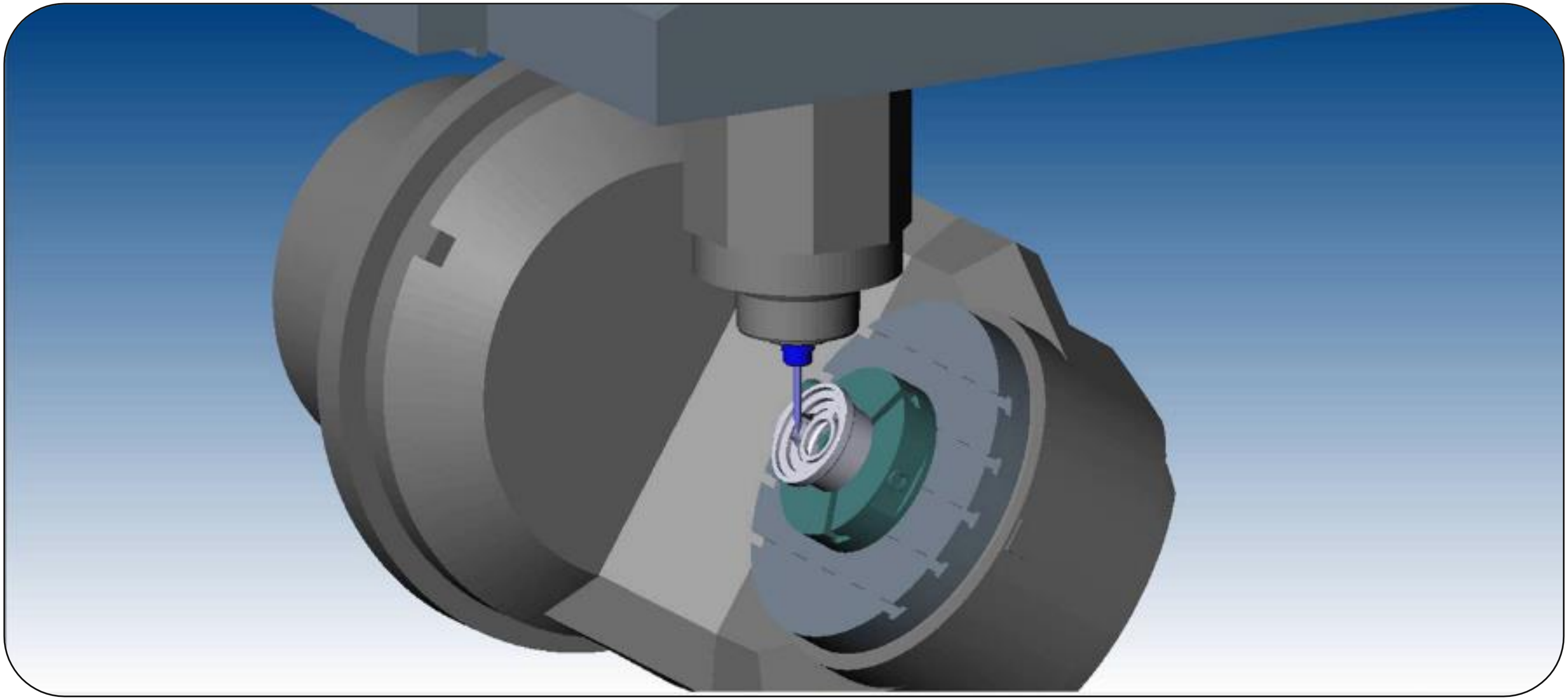


Figure 5 :Mori Seiki NMV Machining center table

Trunnion Table

Tilting Table Example

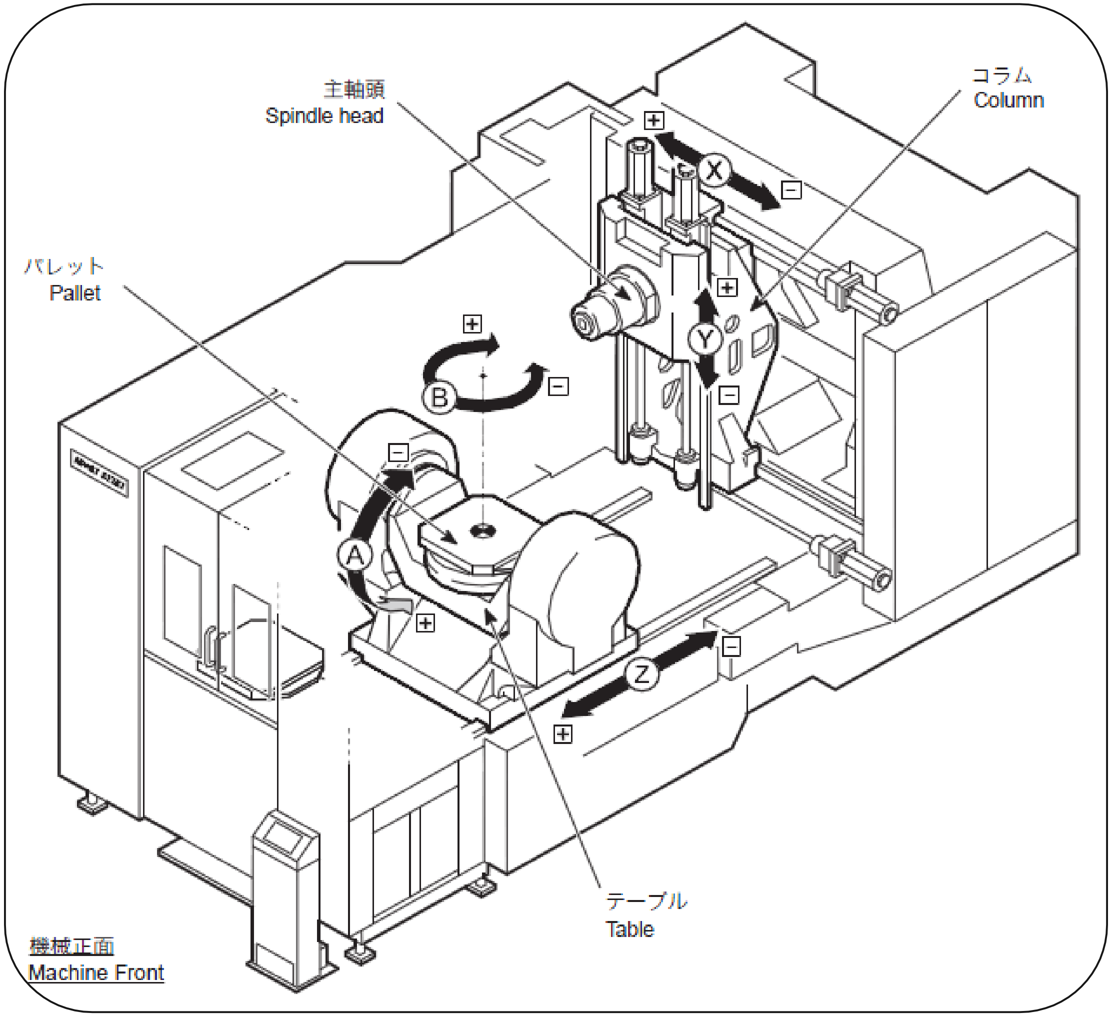
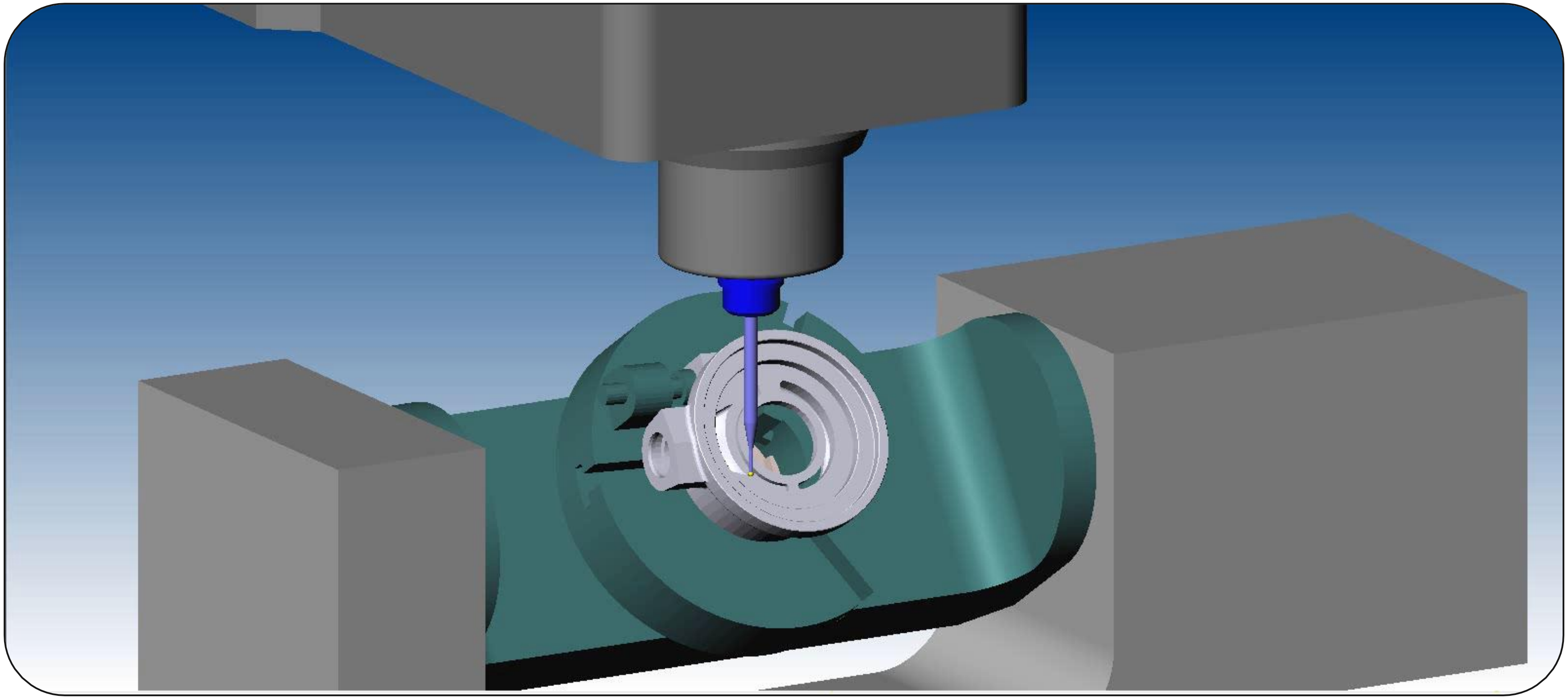


Figure 6 :Mori Seiki NMH Machining center

Trunnion Table

Tilting Table Example



Animation : Mori Seiki NMH Machining center Trunnion table

Tilting Table Machines

- **Rotary Tables**
  - Mori Seiki NMV
  - DMG DMU 50
- **Trunnion Table**
  - Mazak Variaxis
  - Okuma MU
  - Matsuura MX-520

Figure 7:Common Tilting Table Machines

Tilting Table Machines

Pros & Cons

Pros

- **Material rotates**, good for smaller parts
- **Large work envelope**
- **Large angular range of motion** around work piece
- **High rigidity** is good for heavy cuts and hard materials

Cons

- **Large parts cannot be rotated**
- Trunnion can make **work piece difficult to see and reach for operator**
- **Axis limits must be set** to prevent ‘flipping’ the work piece during the cut

Tilting Head Example

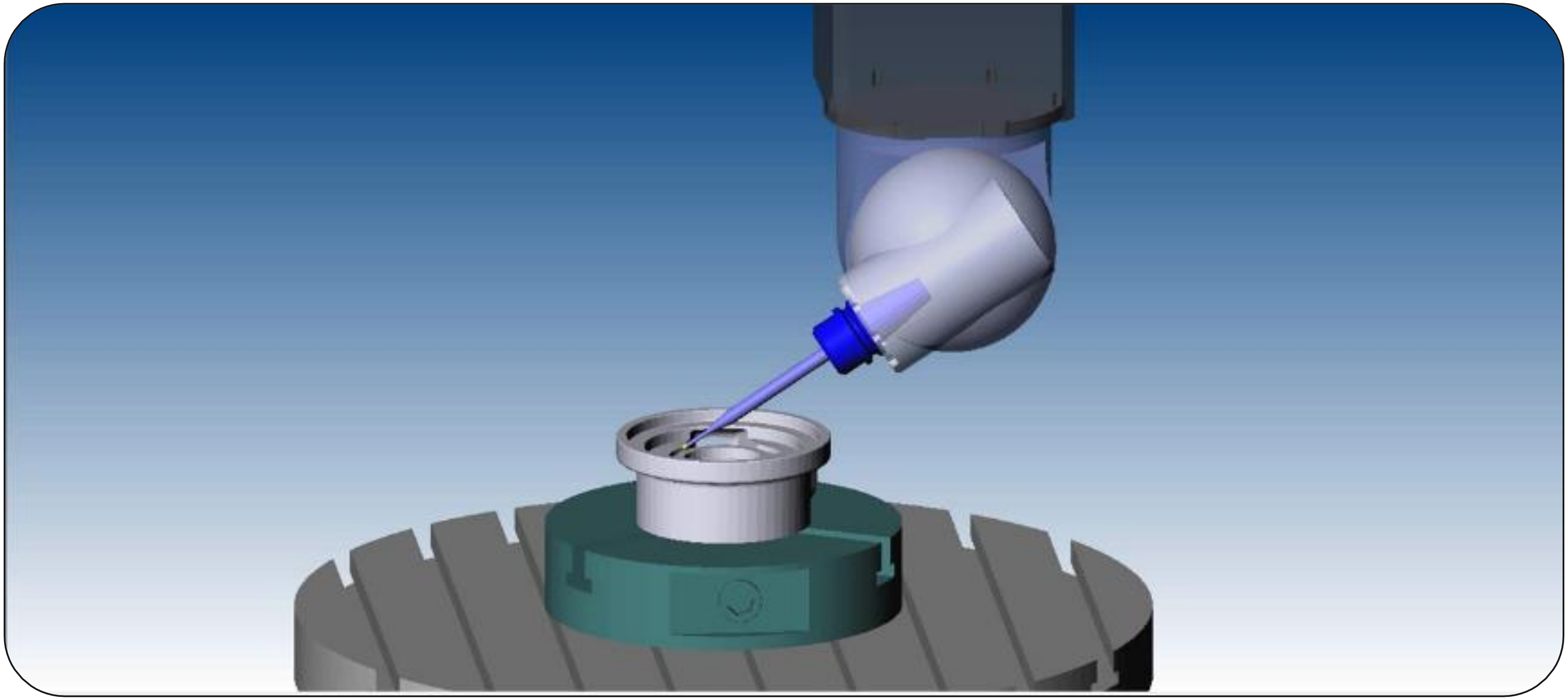


Figure 8:Tilting Head Example

Tilting Head with Rotary Table Example

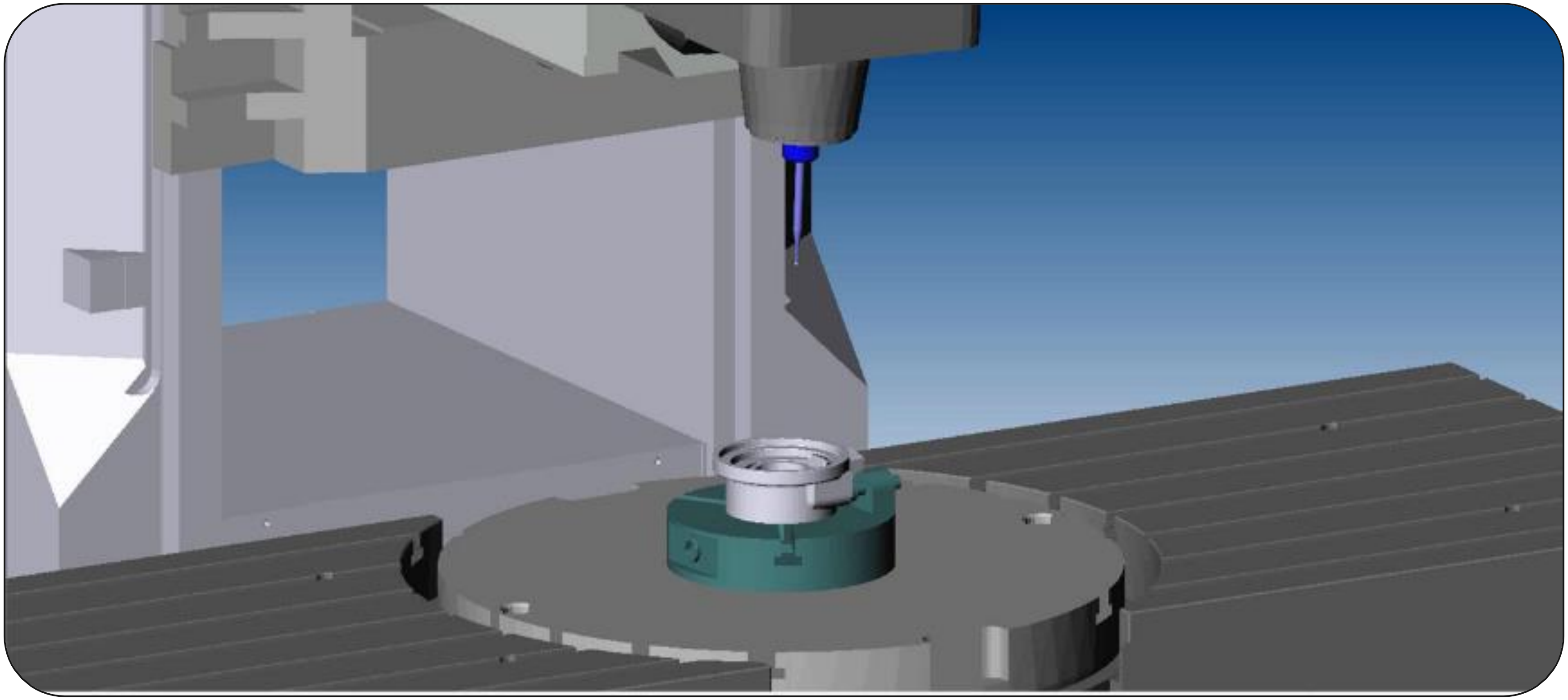


Figure 9:Tilting Head with Rotary Table Example

Tilting Head Machines

Tilting Head

- Mazak Vortex

Tilting Head with Rotary Table

- DMG DMU MonoBlock

Figure 10:Common Tilting Head Machines

Pros and Cons of Tilted Head Machines

Pros

- **Material moves less**, makes it possible to machine large parts
- **Work piece is more accessible** to operator

Cons

- **Lighter cuts** due to low rigidity
- **Large clearances required to move head around work piece**

Multi-Axis Lathe Example

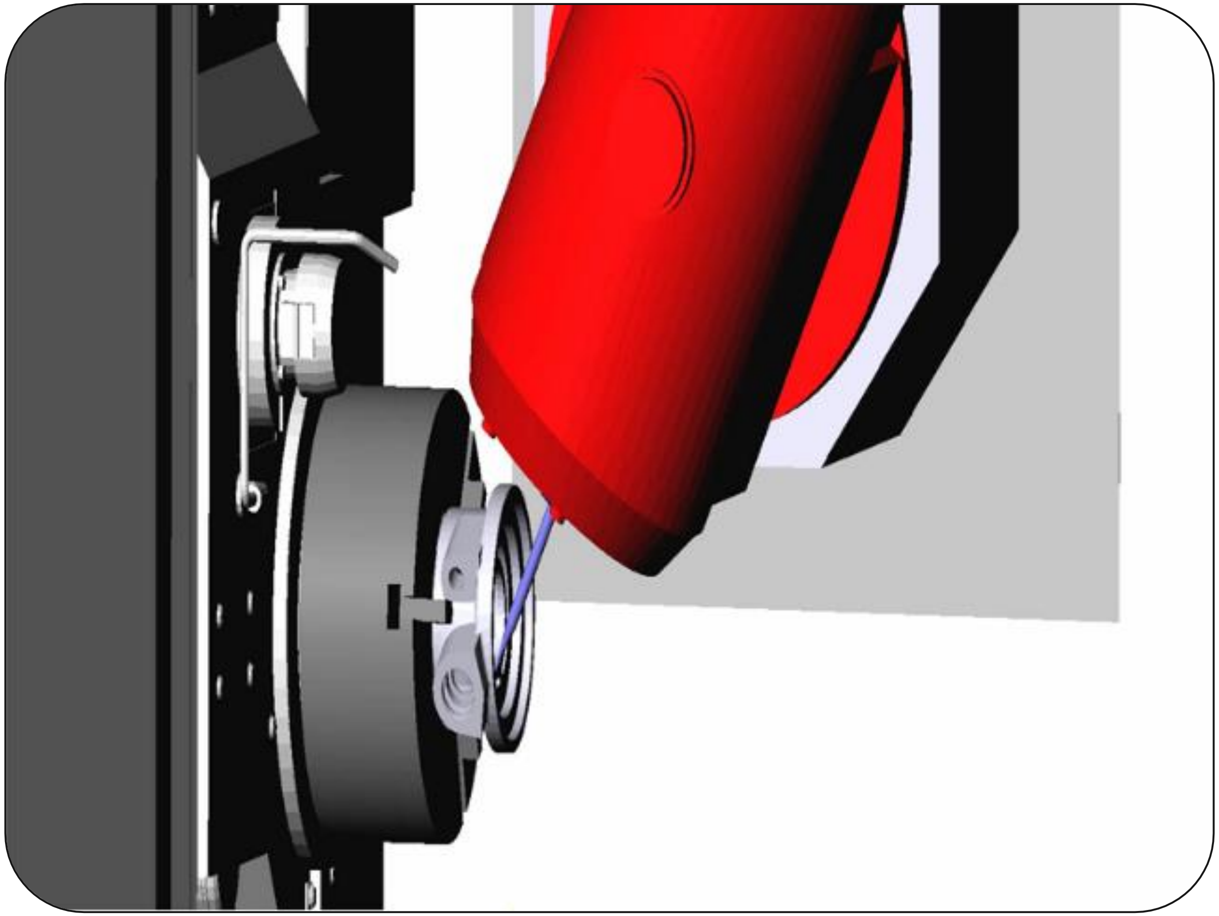


Figure 11:Multi-Axis Lathe Example

Multi-Axis Lathe Machines

1. Mori Seiki NT
2. DMG CTX
3. Mazak Integrex
4. Okuma Multus

Figure 12:Common Multi-Axis Lathe Machines

Pros and Cons of Multi-Axis Lathe Machines

Pros

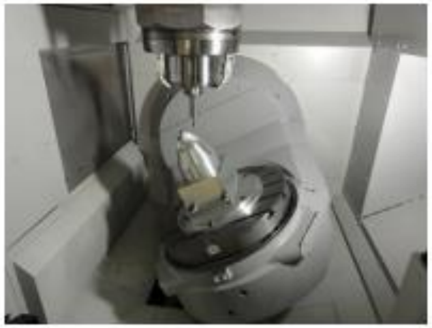
- **Very versatile** – can program many types of parts
- **Lathe operations** can be used for **efficient roughing**
- **Easy to reach all sides of a part**
- **Ideal for long parts**

Cons

- **Cannot machine very large work pieces**
- **Ideal only for concentric** (or nearly concentric) **work pieces**
- **Long tools cause clearance issues**
- **Collisions are more common**
- **Less effective work piece holding can result in lighter milling cuts**

5-axis Machine Configurations

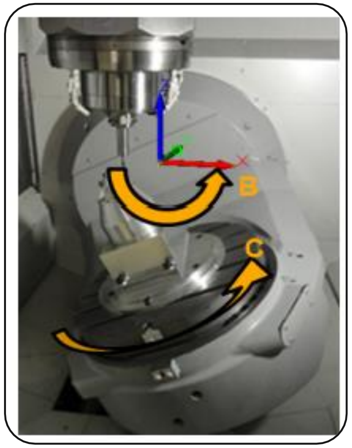
Common machine configurations

Table/Table	Table/Tool	Table/Tool (mill-turn)	Tool/Tool
Both rotary axes are in the table	One rotary axis is in the table, the other axis is in the tool	One rotary axis is in the turning spindle, the other axis in the tool	Both rotary axes are in the tool
			

5-axis Machine Configurations

Table/table

- In the first category, **the two rotary axes are located in the table**. The **B axis tilts** and the **C axis rotates the part**. Linear motion is handled by the milling head



Table/tool

- In the second one, the **table still rotates** in **C axis** but now the **tilt is in the tool**

Figure 13:Table/table and table/tool machine configurations

5-axis Machine Configurations

Table/tool (mill-turn)

- Looking at a table/tool combination on a mill-turn, the turning spindle becomes the **C-axis** to **rotate the part** and **the tilt of the tool is controlled by the B-axis**

- The linear axes are located differently on a lathe, with the **Z axis** positioned horizontally along the spindle axis instead of vertically along the tool axis

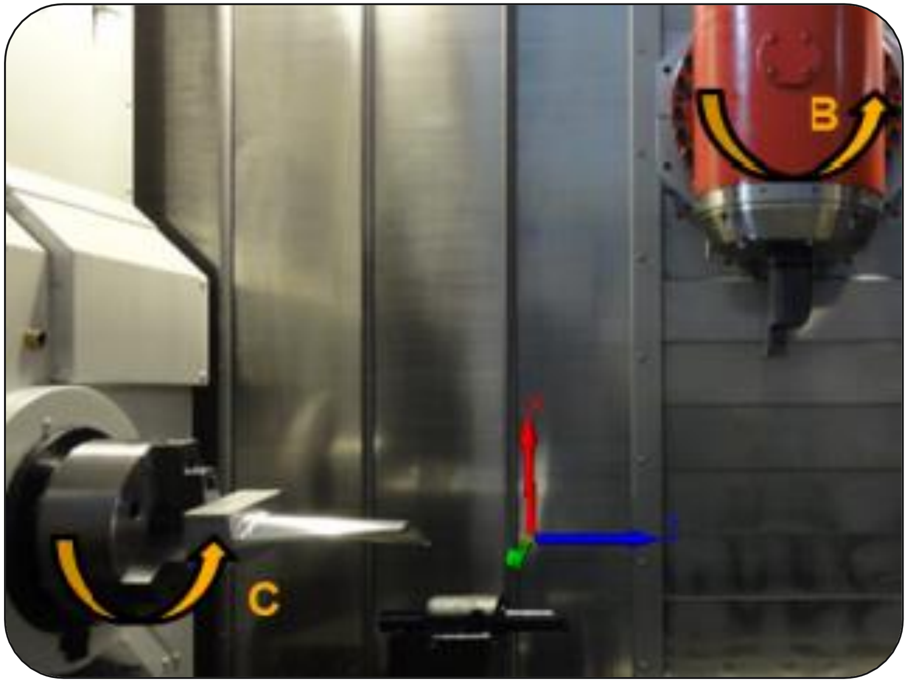


Figure 14:Table/tool (mill-turn)configuration

5-axis Machine Configurations

Tool/tool

- In the last category, the **two rotary axes are located in the milling head to rotate and tilt the tool** into any position

Figure 15: Tool/tool configuration

Different Ways to Utilize 5 Axes

I. Continuous 5-Axis tool motion

- all 5 axes moving simultaneously

II. 4 + 1 tool motion

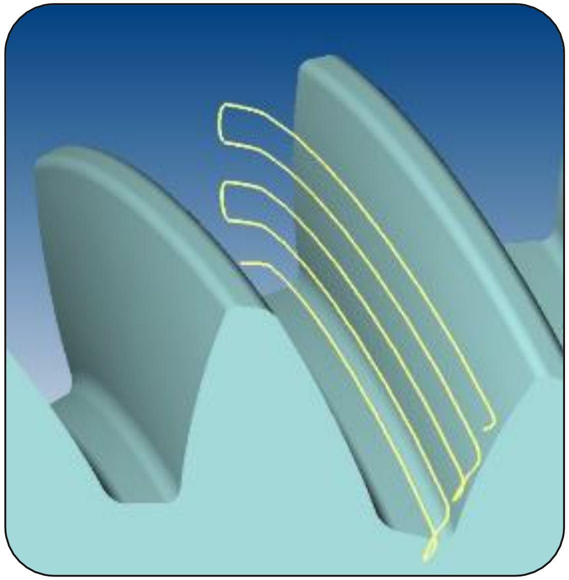
- 4 axis moving simultaneously while 1 axis is fixed

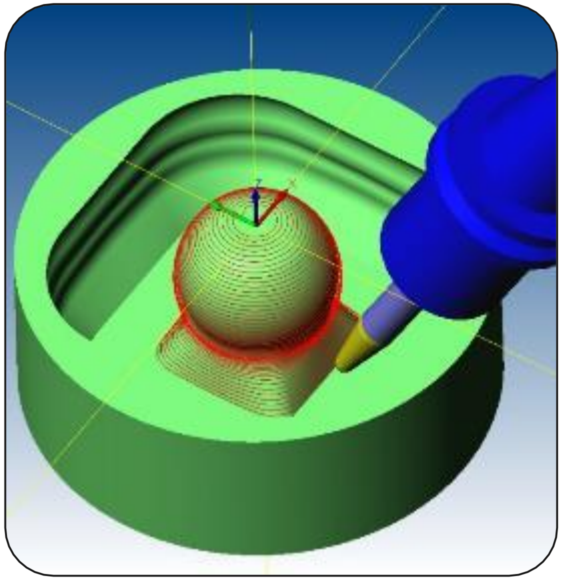
III. 3+2 tool motion

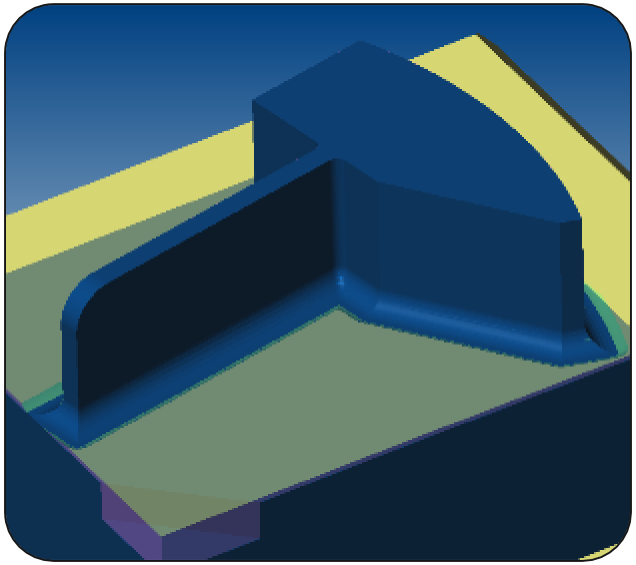
- 2 rotary axes are fixed at a position, three linear axes are used to move the tool

Applications for Continuous 5-Axis Machining

- **Finishing complex contours** with consistent tool engagement
- **Reaching into deep cavities** with short tools
- **Parts** that would otherwise **require multiple setups**







Example of Continuous 5-Axis Machining

- In this example of a blade, the **rotary axes move continuously** during the cut

Figure 16:Example of blade machining

Applications for 4+1 Machining

- **Rotary finishing** and **surface machining**
- **Fixed B-Axis option** rather then full B on the machine
- **Lock fifth axis when not needed** to minimize tool movement

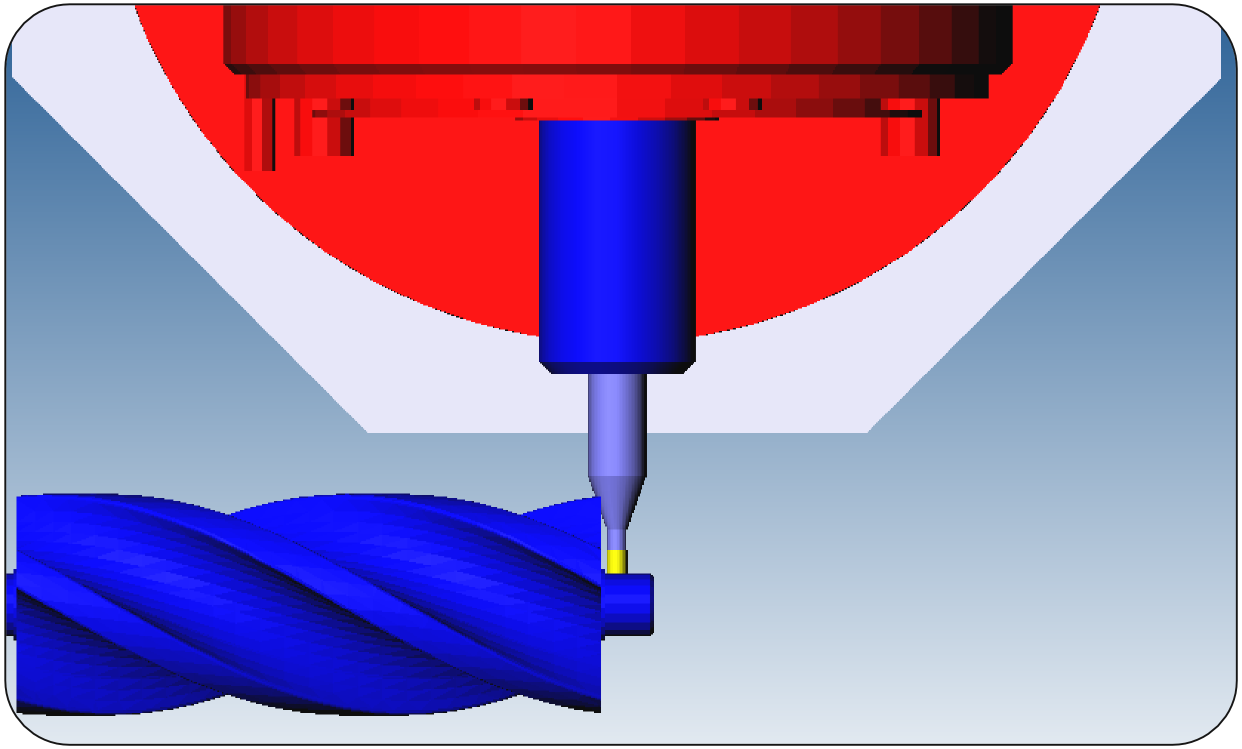


Figure 17:Application of 4+1 Machining

Applications for 4+1 Machining

- In this case, the **B-axis** on a mill-turn is tilted and locked into position while still allowing the part to rotate during the cut
- The **B-axis** spindle is more rigid when used in this configuration

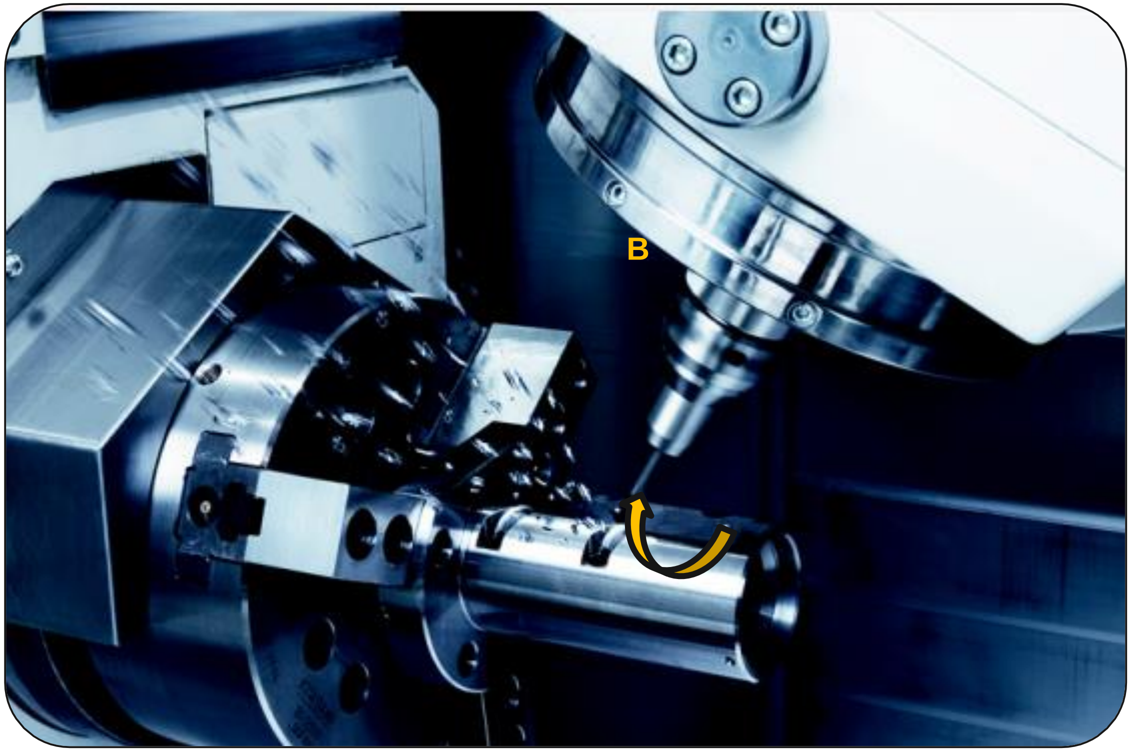


Figure 18: Part rotating while B axis is tilted and locked

Applications for 3+2 Machining

- Making **2** and **3 axis cuts in multiple planes**
- **Roughing** large amounts of material
- **Parts** that would normally require **multiple operations/fixtures**

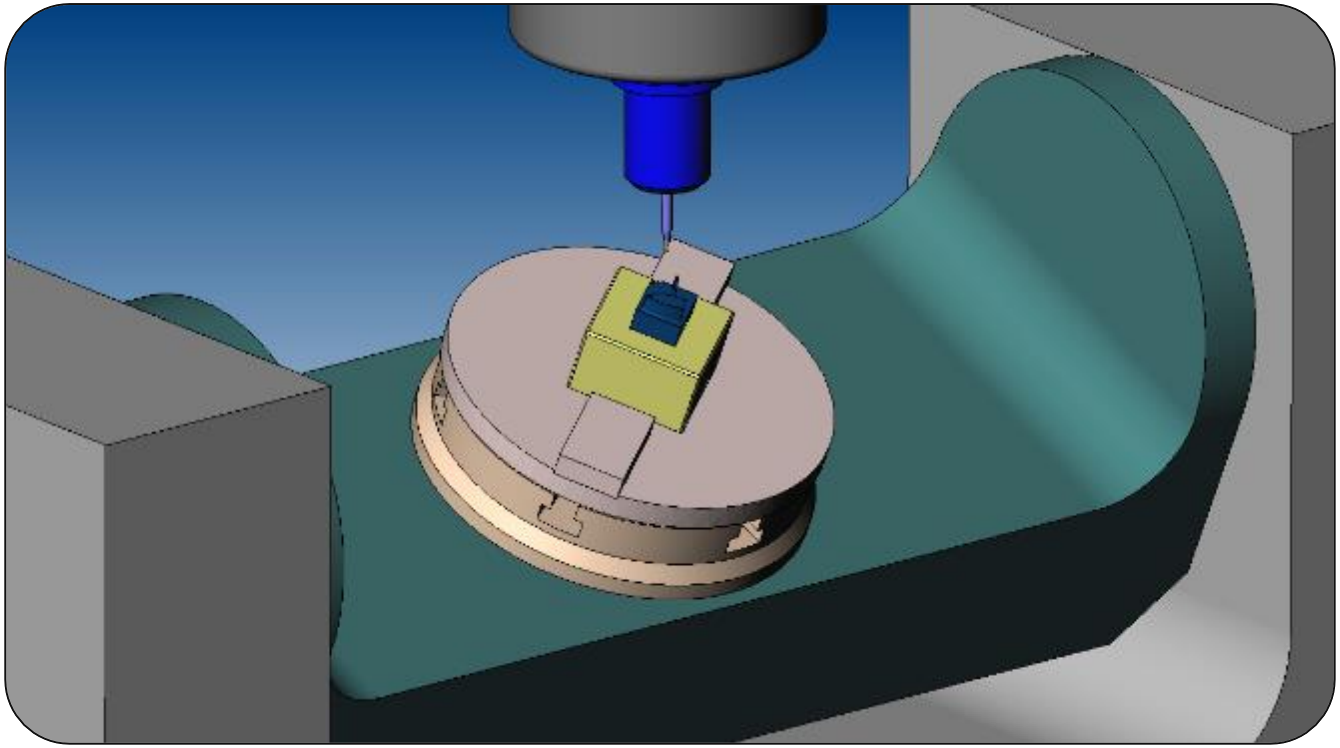


Figure 19: 3+2 machining on a part that would normally require multiple operations

Applications for 3+2 Machining

- The part is rotated into position before the start of each cut and then a standard 3-axis tool-path is run
- This makes programming easy since rotary motion only occurs between operations

Figure 20: Part of complex geometry

Exploiting the Capabilities of 5-axis

- Along with the benefits of 5-axis machines is the **challenge to generate CNC programs that fully exploit the capabilities of these machines**

- The first step is to **rethink current manufacturing processes**, which includes the design process as well as the machining process

- If **multiple steps and multiple processes** have traditionally been used to machine and assemble components, you may be able to **combine them into a single component** that was previously too complex to machine

- The next challenge is to **understand all the combinations of motion** that are not only possible but practical

- If you ask two programmers to machine the exact same part, it is guaranteed that the two programs will be different because **each person will attack the part from different directions**

Exploiting the Capabilities of 5-axis

- But remember that both programs will ultimately produce the same part, so the primary goal is to use the machine motion as efficiently as possible

A critical challenge is to **avoid collisions** between moving components

- The **smallest programming error can generate costly damages** because the materials, high precision tools, and accessories for these advanced machine tools can be quite expensive

- And finally you need **to stay within the limits of the machine**

- There are physical limits on how far each axis can travel and there are limits on just how fast those axes can move in relation to one another

- **Linear motion** is always **faster and more accurate than rotary motion**, so you need **to control acceleration to prevent backlash** when an axis moves too fast

How can a CAM system help?

- A **CAM system** can make the **programming process easier** by examining how the best machinists go about their work and then embedding that logic into the software
- Using the same logic as machinists lets the system provide guidance along the way for new programmers and provides a familiar environment for experienced programmers
- But guidance must never be used to impose limitations 5-axis programming can be compared to the artistic process of sculpting , which means that programmers must have creative freedom when deciding how to cut a part
- **CAM systems** also provide a risk-free proving ground for watching every movement of the machine
- Every machine component, every movement can be defined in the **CAM system** and then run in real-time on the computer
- The advantage is that there are no doors or coolant to impede the view and you are not taking up valuable machine time

How can a CAM system help?

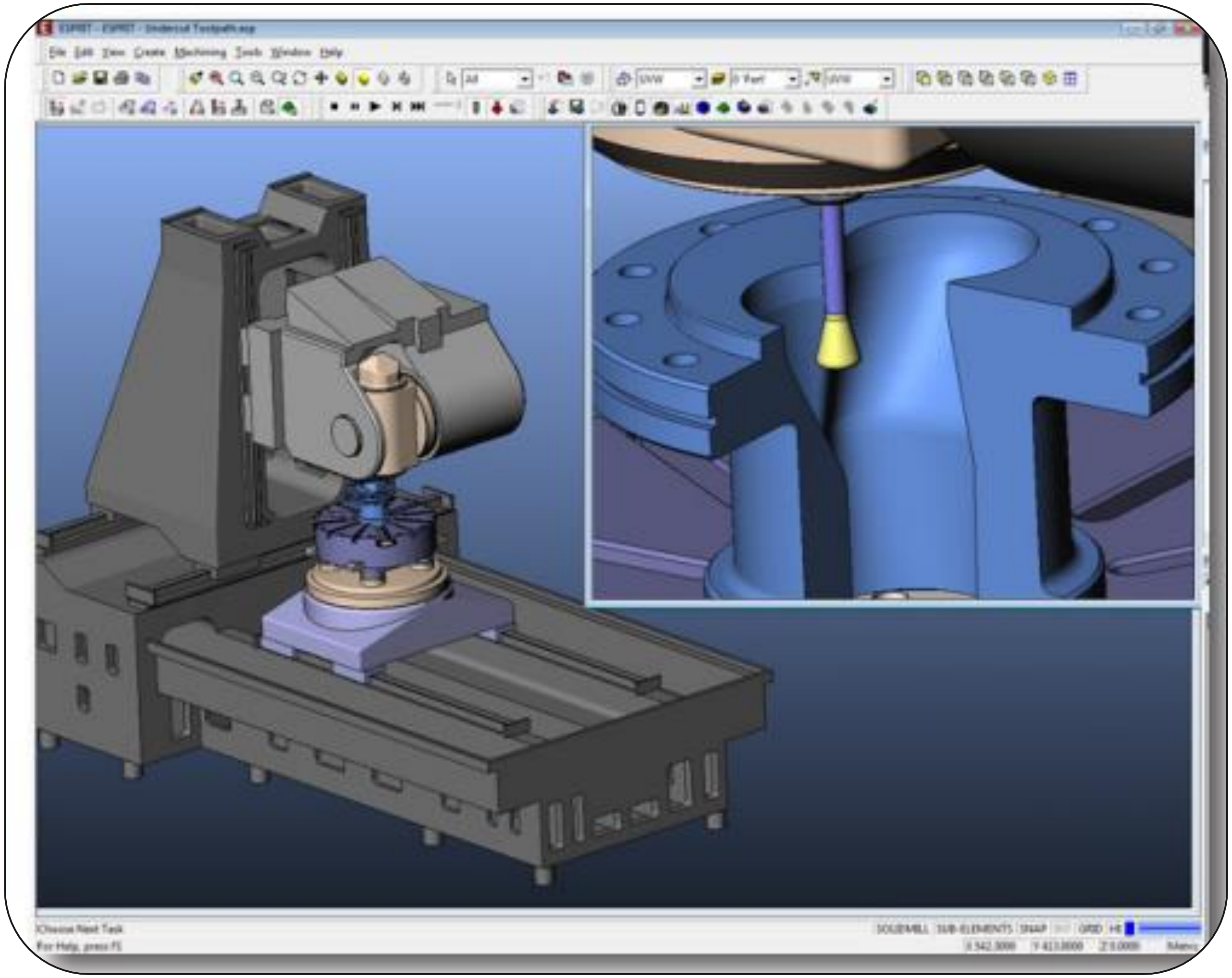


Figure 21: ESPRIT CAM software

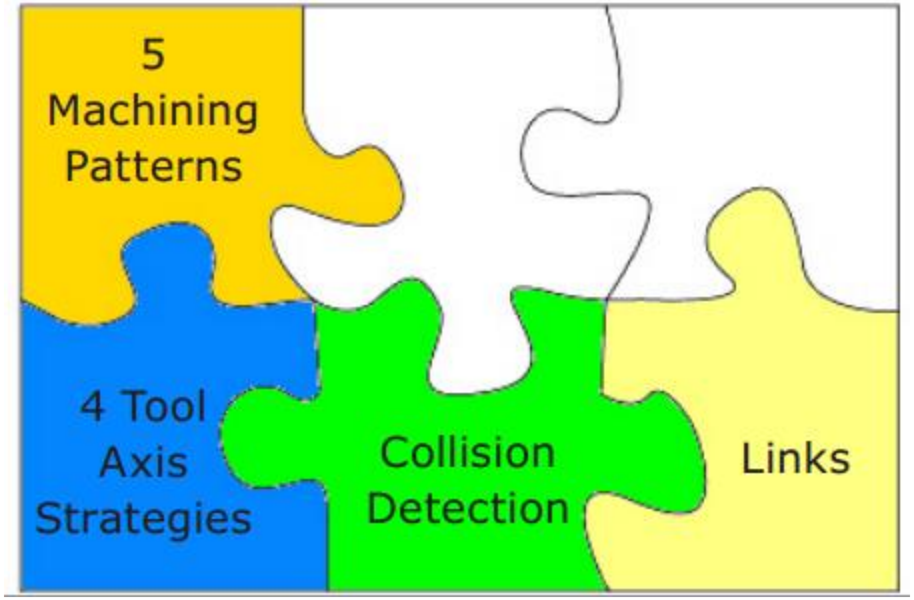
A Simplified Approach

- The key to creating an elegant solution is to start by throwing away the idea that each type of 5-axis work needs a specialized function. That approach is confusing and unnecessary

- A simpler approach is to create a single function that meets the needs of the majority of 5-axis work

A Simplified Approach

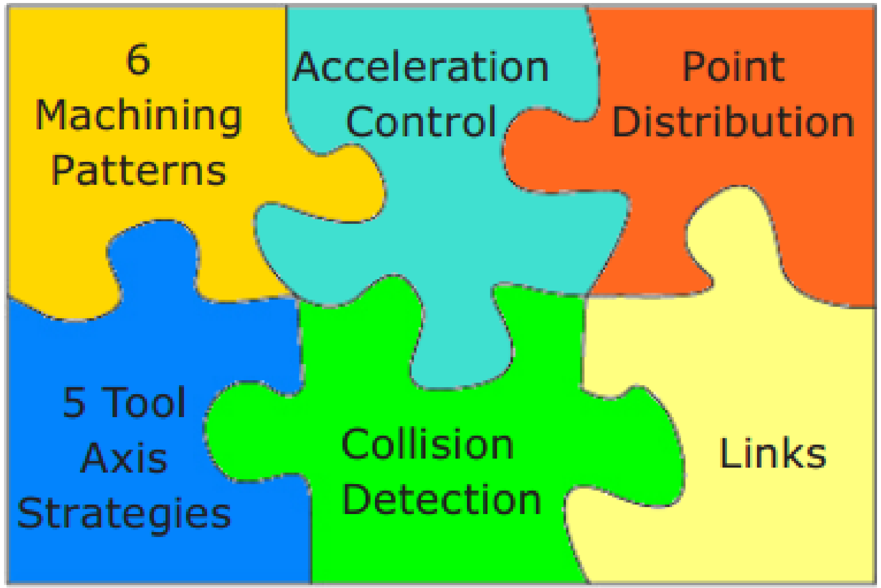
- To simplify software development, the Composite function is composed of a set of interlocking modules, somewhat like building blocks



- Each module is designed to perform well separately and together

A Simplified Approach

- The modular design of the software allows for easy testing and expansion when technology changes in the future
- This type of software development is not only faster to implement, it results in a more reliable software



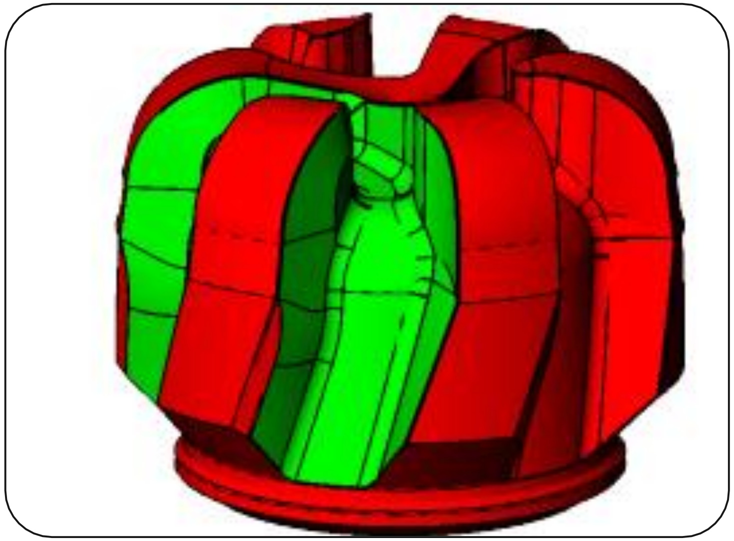
- Another way to simplify the software is to design an interface that responds intelligently to the choices being made
- The interface should be designed to only display options that apply to the current work situation

Simplified CAM for 5-axis

- To keep things simple, the Composite function follows 4 steps that are based on the standard workflow for any type of machining, whether it's 2-axis or 5-axis, lathe or mill

- It just makes sense to align the technology with the same logic that machinists already use

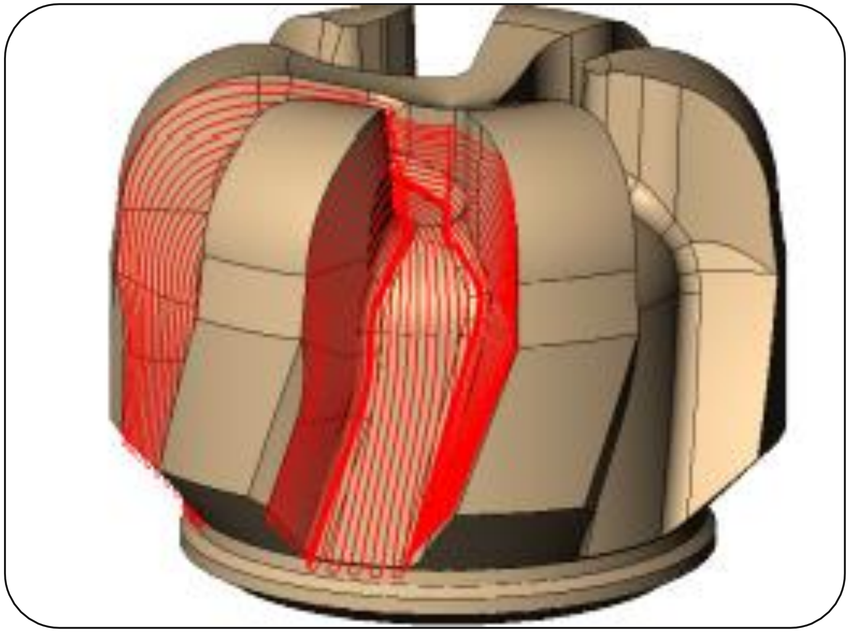
1. The first step is to **define the areas to machine** and the areas to avoid



- In this picture, the surfaces in the green area are selected for machining and the red zone indicates the surfaces that will be avoided

Simplified CAM for 5-axis

2. The next step is to define the shape of the path the tool will follow on the selected machining area

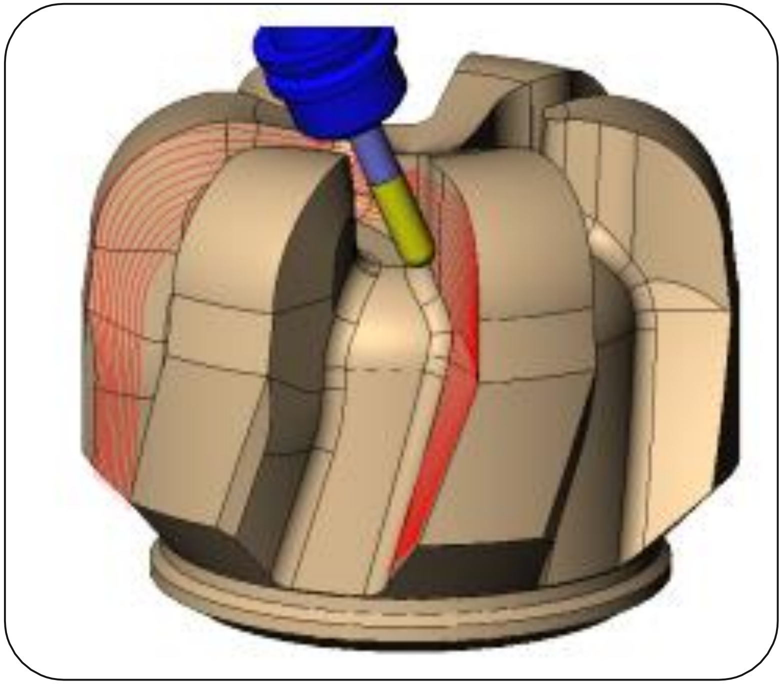


NOTE

This is also called the **machining pattern**

Simplified CAM for 5-axis

3. After the shape of the path is defined, the user can decide how the tool will be oriented as it travels along that path



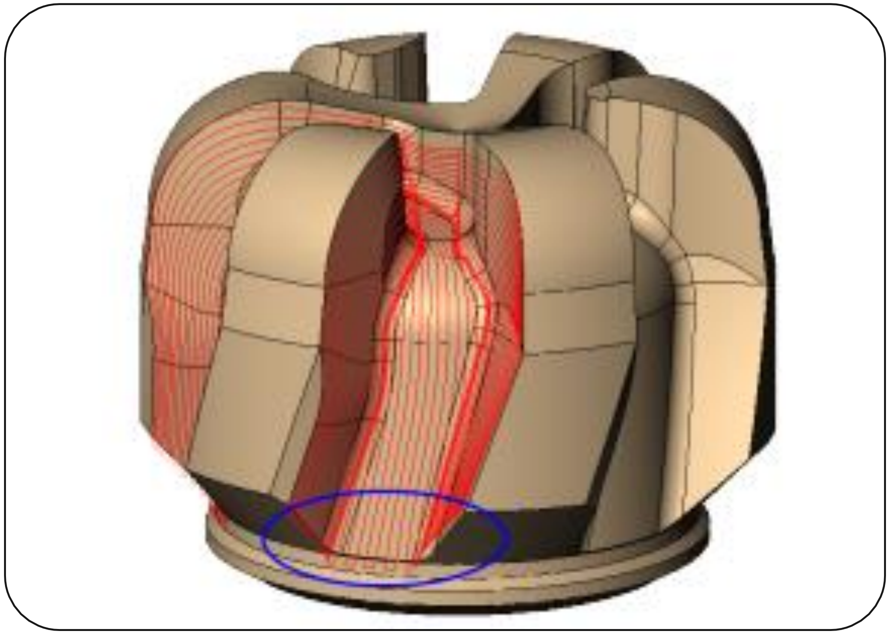
NOTE

As you've seen, a 5-axis machine offers a lot of **flexibility** in how to rotate the part or tool

Simplified CAM for 5-axis

4. The last step is to decide how the tool should transition, or link, between each cutting pass

   - Links apply to tool movement between cutting passes as well as non-cutting moves that control how the tool approaches the part at the beginning of the cut and movement between separate machining zones



The role of RTCP
(Rotate Tool Center Point)

Rotate Tool Center Point

- A major factor in **5-axis machining** is **controlling and optimizing tool motion**

- This lecture considers tool motion from the **aspect of the machine control** and how to **optimize tool motion during non-cutting moves**

- The role of **RTCP (Rotate Tool Center Point)** in 5-axis machining is explained in the next slides

What is RTCP?

- **RTCP** can be found on the General tab of 5-axis operations in ESPRIT CAM software

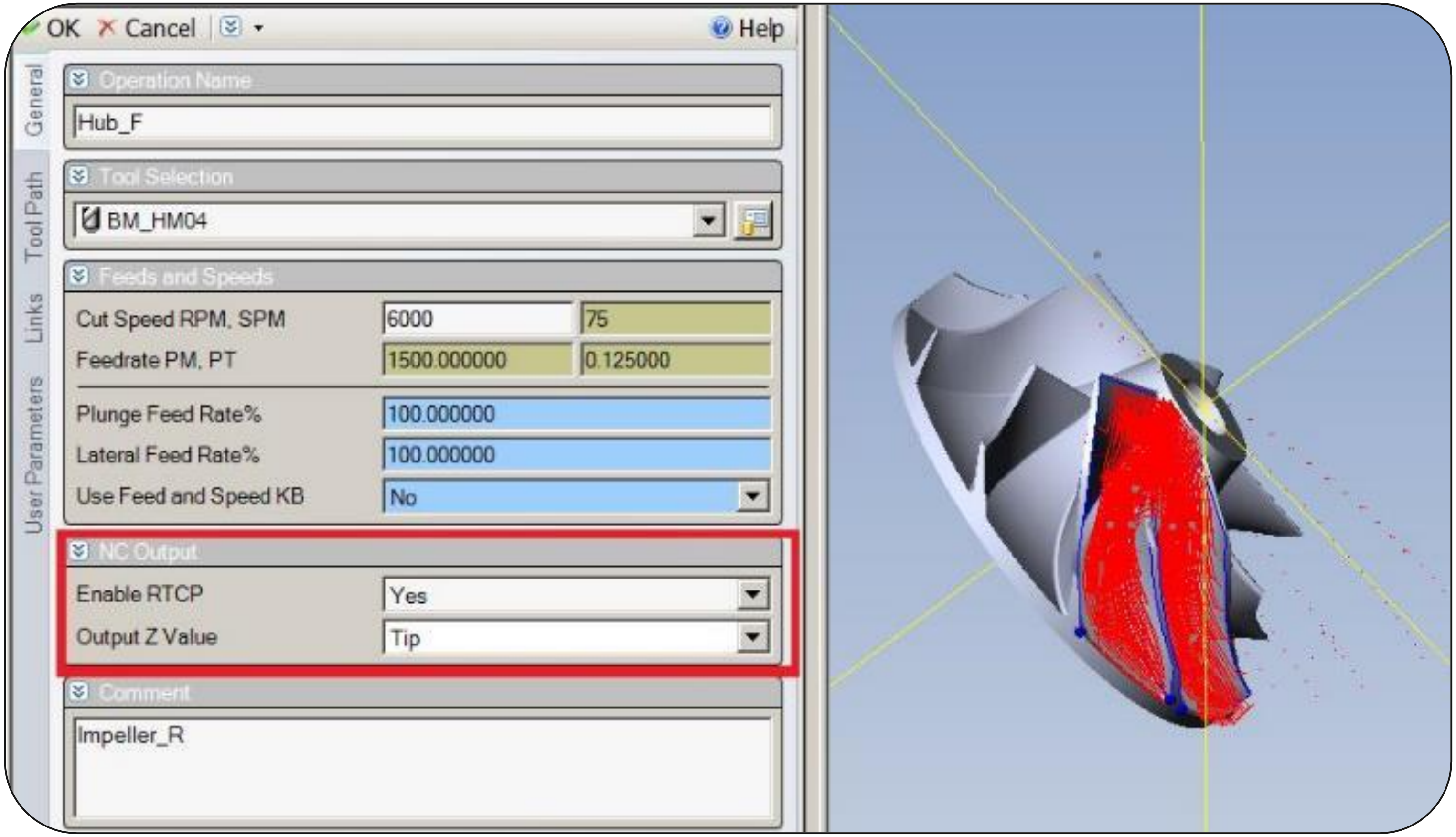


Figure 22 :RTCP mode on ESPRIT CAM software

What is RTCP?

- **Rotate Tool Center Point (RTCP)** is where the **center point of the tool tip is the rotation point for any rotary movements**
- The tool position is **output** relative to the work piece
- **RTCP** has three main advantages:

I. The tool orientation can change while keeping the tool on the programmed path

II. The NC code is independent of machine kinematics

III. Feed rates adjustments are automatically calculated

Following the Programmed Path

- In **3+2 milling** situations, softwares provide the control with XYZ and ABC positions to move to based on machine kinematics

- The **tool rotates about the center of rotation of the machine axes**
  - This causes the tool tip position to change
  - The tool must retract before rotation to avoid collisions

- In **RTCP** mode, the **control makes real time calculations to adjust the center of rotation to the center point of the tool tip**
  - Allows the machine to change tool orientation without moving tool tip
  - Tool can continue cutting while the relative tool orientation changes

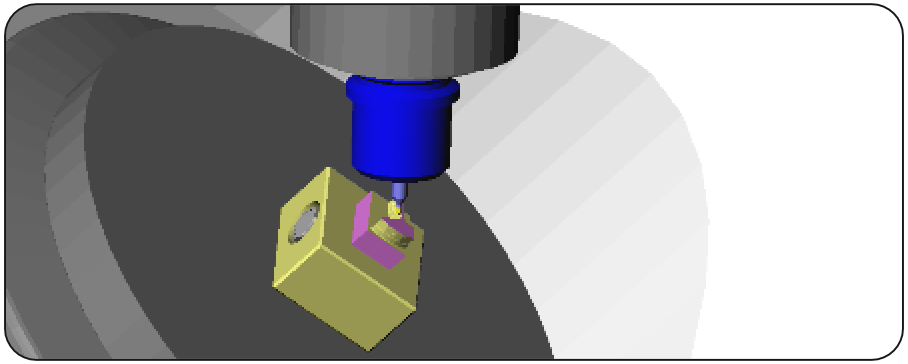


Figure 23:RTCP in CAM software

Center of Rotation

Machine Rotary Point vs. Tool Center Point (RTCP)

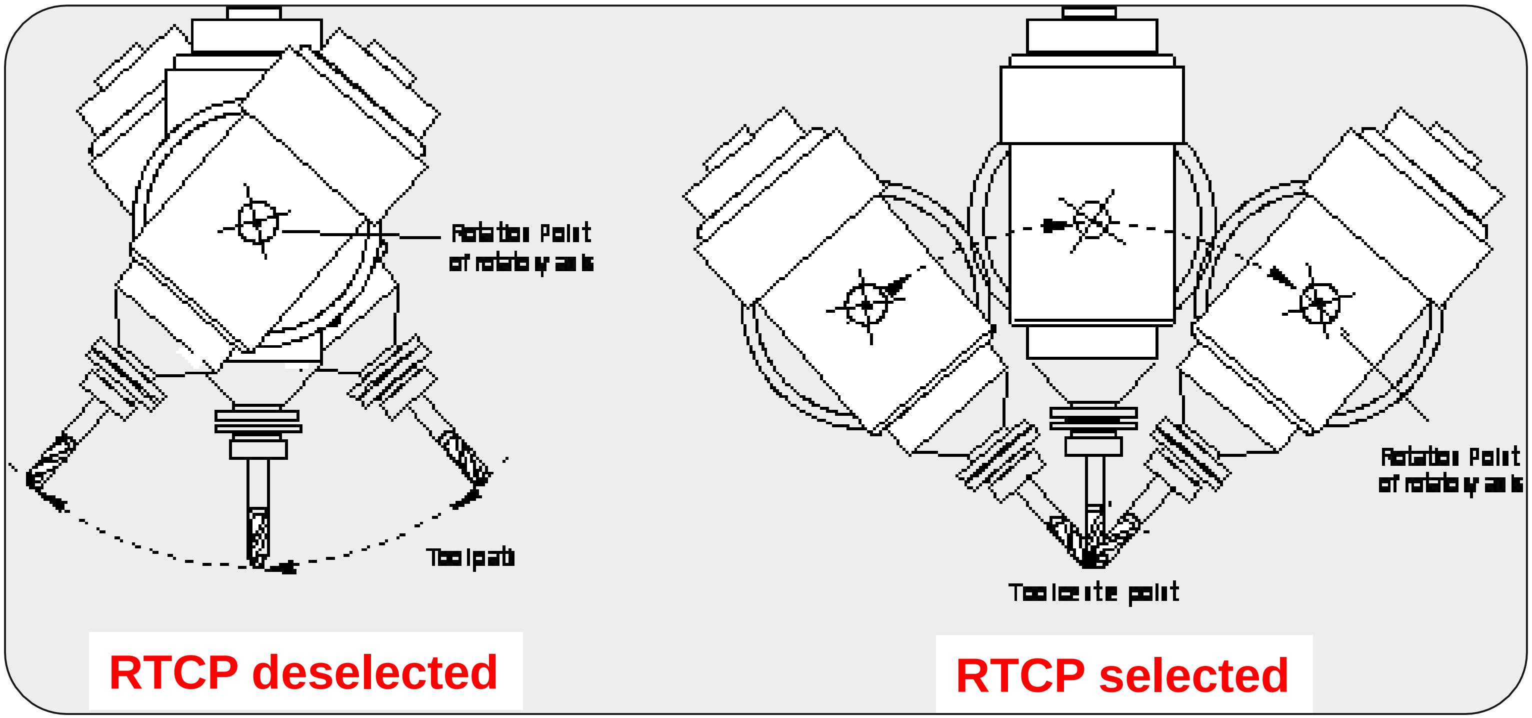


Figure 24:Rotary point when RTCP is selected and not selected

Machine Independence with RTCP

- In **RTCP** mode, **the control calculates how to move all the machine axes to keep the tool along the programmed path**

- The same programmed path (i.e. NC Code relative to the work piece) can go into any machine

  - **The controller knows how to adjust the motion based on its kinematics**

  - **Location** of the part in the machine **can be changed without reposting** (just adjust the work offset accordingly)

RTCP and Feed Rates

- There are **three typical feed rate methods** to run in a 5-axis simultaneous operation in:
  - **Feed per minute (G94)**
  - **Inverse time (G93)**
  - **RTCP mode (G43.4 / G43.5)**

- **The goal is to maintain constant relative velocity** (i.e. effective feed rate) **between tool and the work piece**
  - If the tool is moving at a constant speed, and the part is rotating 'into' the cut, **the relative velocity** – i.e. effective feed rate - **increases**

RTCP and Feed Rates

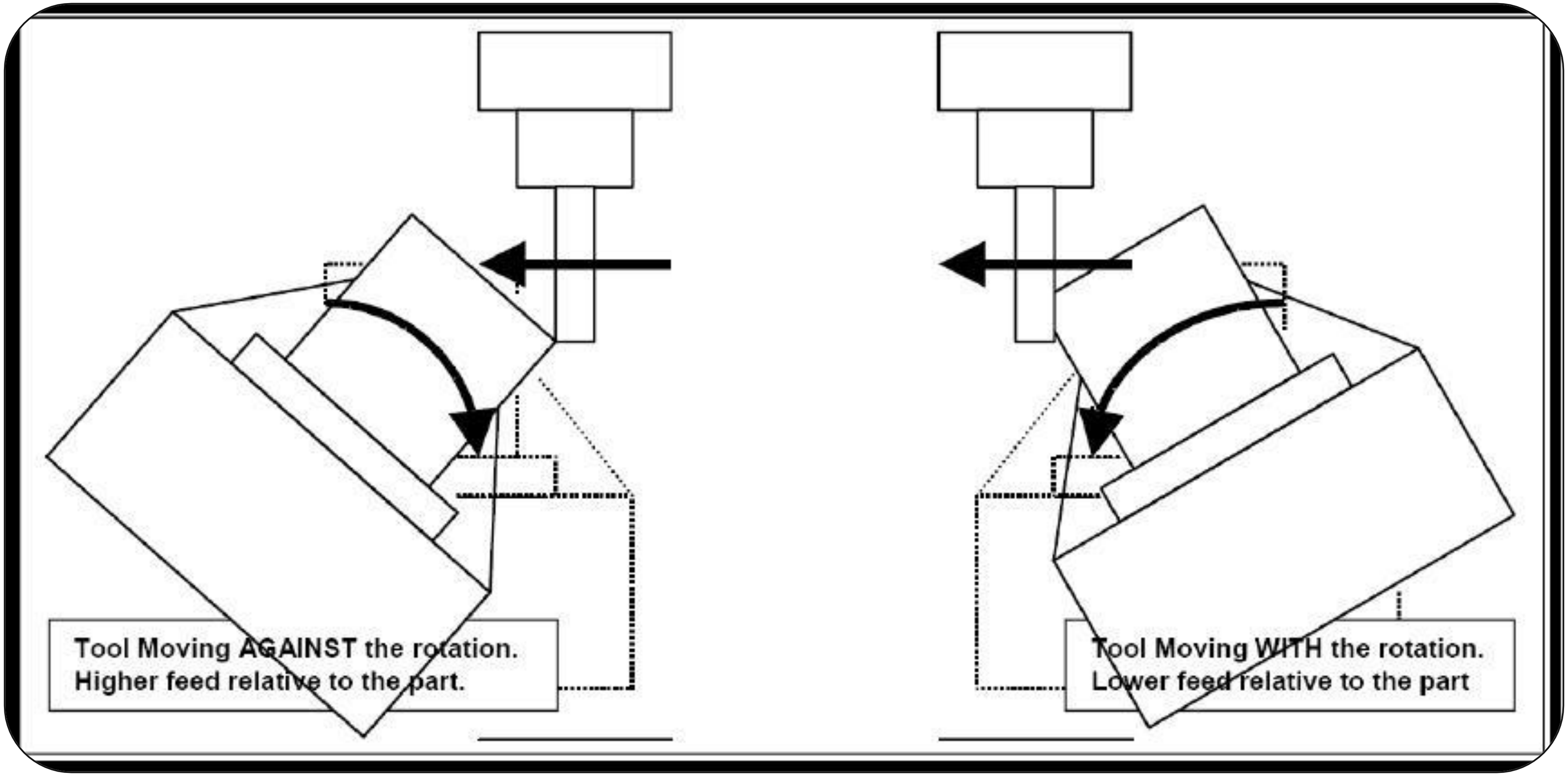


Figure 25: Cases when tool moves with or against the rotation

Feed per Minute Mode

- **Feed per minute (G94)** moves are **interpreted relative to the machine coordinate system**
- The machine expects to receive the **absolute axis positions**, both linear and rotary
- The control **cannot calculate the effective feed rate of the tool tip** relative to the machined area of the work piece
- **Post Processor** must **calculate all the additional linear movements necessary to keep the tool tip in contact with the work piece during the rotary movements**

How the Controller Interprets Feed Moves

- The controller calculates a **relative distance for the move (d)** that includes linear and rotary components

- The programmed **feed (F)** for the move is used to calculate a **time (t)**

- **This time is used to calculate the individual feed rate for each axis**

- The controller will then use these feeds to coordinate the motion of each axis **(F_x, F_y, F_z, F_A, F_B)**, **producing a linear motion relative to the part**

- This is called "**Linearization**"

$$d = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2 + \Delta A^2 + \Delta B^2} \Rightarrow t = \frac{d}{F}$$

$$F_X = \frac{\Delta X}{t} \quad F_Y = \frac{\Delta Y}{t} \quad F_Z = \frac{\Delta Z}{t} \quad F_A = \frac{\Delta A}{t} \quad F_B = \frac{\Delta B}{t}$$

Effects of Linearization of Feed Rates

- As the **delta A** and **delta B** values become larger, they will have a larger effect on the **d** calculation
- As **d** increases, so does **t**
- Since **F** is based on **1/t** the controller will slow down the move when there is a lot of rotation resulting in varying relative velocity

$$d = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2 + \Delta A^2 + \Delta B^2} \Rightarrow t = \frac{d}{F}$$

$$F_X = \frac{\Delta X}{t} \quad F_Y = \frac{\Delta Y}{t} \quad F_Z = \frac{\Delta Z}{t} \quad F_A = \frac{\Delta A}{t} \quad F_B = \frac{\Delta B}{t}$$

How to Maintain Constant Relative Velocity

Inverse Time feed rate mode (G93)

- When using **G93** you are telling the NC Controller to **ignore the changes in the 5 axes** during the time calculation, because **YOU** (or better, the Post Processor) are specifying the time to use
- The post will adjust the feed rate values (**1/t** since **t** is usually a very small number) to ***'trick'*** the machine into maintaining constant relative velocity
- This method helps, but is not usually perfect

RTCP mode (G43.4)

- In **RTCP** mode, we are giving the tool tip a **path to follow relative to the part** and the machine calculates how to adjust the axis to keep the tip along that path
- We also give the control **an effective feed rate** – the relative velocity between the tool tip and part – and the machine does the calculations to maintain that effective feed rate while following the programmed path

Summary

- **5-axis machining** is associated with **complex geometries**
- 5-axis machines are used for five-sided machining to :**reduce setup time and eliminate the typical flipping of parts required on three-axis machining centers**
- **5-axis common machine configurations are :**table/tool, table/table, tool/tool and table/tool(mill-turn)
- **Rotate Tool Center Point (RTCP)** is where the **center point of the tool tip is** the rotation point for any rotary movements
- There are **three typical feed rate methods** to run in a 5-axis simultaneous operation in: **Feed per minute (G94),Inverse time (G93),RTCP mode (G43.4 / G43.5)**
- When the controller uses calculated feeds to coordinate the motion of each axis (**Fx, Fy, Fz, FA, FB**), this is called "**Linearization**"

References

1. 5-Axis Basics, Alex Richard Applications Engineer, DP Technology, Esprit World Conference 2012

2. 5-Axis Essentials I: High Speed Machining , Alex Richard Applications Engineer, DP Technology, Esprit World Conference 2012

3. 5-Axis Essentials II: High Speed Machining Continued, Alex Richard Applications Engineer, DP Technology, Esprit World Conference 2012