# Computer Aided Design and Manufacturing (DI05019031)

## Complete Lecture Deck

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# Course Agenda VI

# Course Agenda VII

# Introduction to Computer Aided Design

- Welcome to CAD/CAM
- Fundamentals of CAD systems

# Agenda

- What is CAD?
- History and Evolution of CAD
- Hardware Components of CAD
- Software Architecture of CAD
- Benefits of CAD Systems

# What is CAD?

- CAD (Computer-Aided Design) involves using computers to aid in the creation, modification, analysis, or optimization of a design.
- It replaces manual drafting with an automated process, significantly increasing productivity and precision.
- Output is often in the form of electronic files for print, machining, or other manufacturing operations.

# Evolution of CAD Systems

- 1960s: PRONTO, the first commercial NC programming system.
- 1970s: 2D drafting systems emerged, running on mainframe computers.
- 1980s: Advent of UNIX workstations and 3D wireframe modeling.
- 1990s and beyond: Parametric solid modeling (e.g., Pro/ENGINEER) revolutionized product design.

# Hardware for CAD Systems

- Processing Unit: High-performance CPUs and GPUs are required for complex 3D rendering.
- Input Devices: Mouse, digitizers, 3D space mice, and touch pads allow precise coordinate entry.
- Output Devices: High-resolution monitors, plotters, and 3D printers bring designs to life.

# Basic CAD System Architecture

- User -¿ Interface -¿ Core Modeling Engine -¿ Database
- Graphics module renders the geometry for display.
- Application modules handle specific tasks like finite element analysis or kinematics.

# Types of Geometric Modeling

- Wireframe Modeling: Represents objects by their edges and vertices. Simple but ambiguous.
- Surface Modeling: Represents the outer shell of an object. Useful for complex curves (aerospace, automotive).
- Solid Modeling: Contains complete mathematical representation of a volume. Enables mass properties calculation.

# Parametric vs Direct Modeling

- Parametric Modeling: Driven by constraints and dimensions. Changes update dynamically based on relations.
- Direct Modeling: Push-and-pull interaction with geometry without a history tree. Flexible for rapid conceptualization.

# Example: Mechanical Part Design

- Consider an engine block. In CAD, it begins as a 2D sketch of the base profile.
- The sketch is extruded into a 3D solid.
- Holes for cylinders are created using cut operations with circular profiles.
- Fillets and chamfers are applied to reduce stress concentrations.

# Benefits of Using CAD

- Increased productivity of the designer by automating repetitive tasks.
- Improved quality of design through thorough engineering analysis and fewer drafting errors.
- Enhanced communication through standardized documentation and realistic visualizations.
- Creation of a manufacturing database used by CAM systems downstream.

# Standard CAD File Formats

- Native formats (e.g., .sldprt for SolidWorks, .ipt for Inventor) retain complete history.
- Neutral formats allow data exchange between different CAD systems.
- IGES (Initial Graphics Exchange Specification) primarily for wireframe and surfaces.
- STEP (Standard for the Exchange of Product model data) represents complete 3D solid data.

# Summary of CAD Overview

- CAD is essential for modern engineering design, moving beyond drafting to full digital representation.
- Modern systems rely on solid modeling and parametric constraints.
- Hardware and software must work seamlessly to handle complex geometric computations.

# Next Lecture Preview

- In the next lecture, we will explore Computer-Aided Manufacturing (CAM).
- We will discuss how CAD data is translated into machine instructions (G-code).
- We will also cover the integration of CAD and CAM systems into a unified workflow.

# CAM Overview and CAD/CAM Integration

- From Design to Physical Product
- Understanding CAM and Integration

# Agenda

- What is CAM?
- Role of CNC Machines
- Toolpath Generation
- What is CAD/CAM Integration?
- Benefits of an Integrated System

# What is Computer-Aided Manufacturing (CAM)?

- CAM is the use of software and computer-controlled machinery to automate a manufacturing process.
- It takes the digital model created in CAD and translates it into a language machines can understand.
- Primary goal: create faster production processes and components with more precise dimensions and material consistency.

# Computer Numerical Control (CNC)

- CNC machines are electro-mechanical devices that manipulate machine shop tools using computer programming inputs.
- Types of CNC machines include mills, lathes, routers, plasma cutters, and waterjet cutters.
- CAM software acts as the critical bridge, generating the CNC code from the 3D model.

# The CAM Process: Toolpath Generation

- A toolpath is the coordinate route that a machine tool follows to machine a part.
- Roughing: Rapidly removes large amounts of material, ignoring exact surface finish.
- Finishing: Moves slower to leave a highly accurate, smooth surface on the final part.
- The software calculates paths to avoid collisions between the tool, the part, and fixtures.

# Post-Processing Workflow

- CAD Model -¿ CAM Software -¿ Toolpath (CL Data) -¿ Post Processor -¿ NC Code (G-Code) -¿ CNC Machine
- The Post Processor translates generic toolpaths into machine-specific syntax.

# Understanding G-Code and M-Code

- G-Code (Preparatory codes): Commands that tell the machine where to move and how (e.g., G00 for rapid positioning, G01 for linear interpolation).
- M-Code (Miscellaneous codes): Commands that control machine hardware (e.g., M03 for spindle on, M08 for coolant on).

# What is CAD/CAM Integration?

- Historically, CAD and CAM were separate standalone systems. Data transfer was tedious and error-prone.
- Integration implies a single database or seamless data transfer where CAD and CAM modules reside within the same software environment.
- Any change in the CAD model automatically updates the CAM toolpaths.

# Computer-Integrated Manufacturing (CIM)

- CIM is the manufacturing approach of using computers to control the entire production process.
- It extends CAD/CAM integration to include business functions: purchasing, inventory control, cost accounting, and scheduling.
- The goal is a unified, automated, and highly efficient manufacturing enterprise.

# Example: Associative Updating in CAD/CAM

- An engineer designs a bracket in CAD and generates machining toolpaths in the integrated CAM module.
- A late design change requires a hole diameter to increase from 10mm to 12mm.
- Because of integration, the CAM software detects the change and recalculates the drilling toolpath automatically.
- This eliminates the need to restart the programming process from scratch.

# Benefits of CAD/CAM Integration

- Reduced Cycle Times: Faster transition from design to physical prototype.
- Fewer Errors: Eliminates data translation issues between separate systems.
- Design for Manufacturability (DFM): Designers can easily simulate machining to verify if a part can be cost-effectively manufactured.

# Summary

- CAM translates 3D models into machine instructions for automated manufacturing.
- CNC machines rely on precise toolpaths (G-code) generated by CAM.
- Integrating CAD and CAM shortens development time, reduces errors, and enables associative design changes.

# Next Lecture Preview

- Next, we will discuss the Digital Manufacturing Concept.
- We will explore how digital twins and virtual factory simulations allow us to test entire production lines before building them physically.

# The Digital Manufacturing Concept

- Bridging the Virtual and Physical Worlds
- Industry 4.0 and Smart Factories

# Agenda

- Introduction to Digital Manufacturing
- Core Elements: Simulation and 3D Modeling
- Product Lifecycle Management (PLM)
- The Digital Twin Concept
- Virtual Commissioning

# What is Digital Manufacturing?

- Digital manufacturing is the application of computer systems to manufacturing services, supply chains, products, and processes.
- It links systems across different departments and processes in a unified digital platform.
- It serves as a key component of Industry 4.0, integrating IoT, cloud computing, and advanced analytics.

# Key Drivers for Digital Manufacturing

- Need for rapid product innovation and shorter time-to-market.
- Demand for mass customization and flexible manufacturing systems.
- Requirement to reduce operational costs and improve resource efficiency.
- Increasing complexity of products requiring multidisciplinary engineering.

# Product Lifecycle Management (PLM)

- PLM is an information management system that can integrate data, processes, business systems, and people in an extended enterprise.
- It manages a product from its initial conception, through design and manufacturing, to service and disposal.
- Digital manufacturing acts as the execution engine for the strategies defined in the PLM system.

# Factory Simulation and Modeling

- Before laying a single brick, modern factories are built in a digital environment.
- 3D simulation software is used to design production lines, optimize robot placement, and analyze worker ergonomics.
- Discrete event simulation models material flow to identify bottlenecks and optimize throughput.

# The Digital Thread

- Concept (Requirements) -¿ Design (CAD) -¿ Engineering (CAE/Simulation) -¿ Manufacturing (CAM/CMM) -¿ Operation (IoT)
- The Digital Thread represents the seamless flow of data across the product lifecycle.

# The Digital Twin Concept

- A digital twin is a virtual representation of a physical product or process, used to understand and predict its performance characteristics.
- It continuously updates itself from multiple sources to represent its near real-time status, working condition, or position.
- Applications include predictive maintenance, process optimization, and remote diagnostics.

# Example: Digital Twin of a Wind Turbine

- Sensors on a physical wind turbine collect data on wind speed, vibration, and temperature.
- This data feeds into a digital twin running physics-based simulations in the cloud.
- The twin predicts that a bearing will fail in two weeks due to excess vibration.
- Maintenance is scheduled proactively, preventing catastrophic failure and minimizing downtime.

# Virtual Commissioning

- Virtual commissioning involves testing the control software (PLCs) against a virtual model of the automated manufacturing system.
- Traditionally, PLC code could only be tested when the physical machine was built.
- Virtual commissioning detects software bugs early, reducing physical startup time by up to 70%.

# Industrial Internet of Things (IIoT)

- IIoT refers to interconnected sensors, instruments, and other devices networked together with computers' industrial applications.
- It provides the real-time data necessary to fuel digital manufacturing and digital twins.
- Enables shop-floor transparency and real-time Overall Equipment Effectiveness (OEE) tracking.

# Summary

- Digital manufacturing uses a unified data platform to optimize production before physical execution.
- PLM and the digital thread ensure data continuity from design to end-of-life.
- Digital twins and virtual commissioning drastically reduce risk, downtime, and launch costs.

# Next Lecture Preview

- In the final lecture of this unit, we will look at real-world applications.
- We will explore how the concepts of CAD, CAM, and Digital Manufacturing are applied across the automotive, aerospace, and medical industries.

# CAD/CAM and Digital Manufacturing in Industry

- Real-World Applications
- How Industries Leverage Advanced Technology

# Agenda

- Automotive Industry Applications
- Aerospace and Defense Applications
- Biomedical and Healthcare Applications
- Consumer Electronics
- Emerging Trends in Applications

# Automotive Industry Applications

- Surface Modeling: Achieving aerodynamic and aesthetically pleasing car body panels (Class A surfaces).
- Assembly Simulation: Ensuring thousands of parts fit together without interference before physical prototyping.
- Crash Simulation: Using FEA (Finite Element Analysis) via CAD data to simulate impacts, saving millions in physical crash tests.

# Aerospace and Defense

- Lightweighting: Topology optimization algorithms in CAD help design parts that are lighter but structurally sound.
- Complex Machining: Jet engine turbine blades require 5-axis CNC machining, relying heavily on advanced CAM toolpaths.
- Digital Twins: Monitoring the health of aircraft engines in flight to predict maintenance needs globally.

# Biomedical and Healthcare

- Custom Implants: Using CT scans to generate 3D CAD models of a patient's bone, then designing custom titanium implants.
- Prosthetics: Rapidly designing and 3D printing custom-fit prosthetic limbs for amputees.
- Surgical Planning: Surgeons use virtual 3D models to plan complex surgeries before entering the operating room.

# Example: Custom Dental Aligners

- An intraoral scanner captures the current geometry of a patient's teeth.
- CAD software is used to design a sequence of aligners that progressively shift the teeth.
- CAM drives 3D printers to manufacture the molds for each aligner in the sequence.
- This is a prime example of mass customization made possible by CAD/CAM.

# Consumer Goods and Electronics

- Ergonomic Design: Designing products like gaming controllers and power tools to comfortably fit the human hand.
- Mold Design: Rapid design of injection molds for plastic casings using automated CAD drafting tools.
- PCB Integration: Integrating Mechanical CAD (MCAD) with Electrical CAD (ECAD) to ensure circuit boards fit within confined electronic enclosures.

# Reverse Engineering Workflow

- Physical Part -¿ 3D Laser Scanning -¿ Point Cloud Data -¿ Surface Reconstruction (CAD) -¿ Modified Design -¿ CAM -¿ New Part
- Used when original drawings are lost, or for analyzing competitor products.

# Integration with Additive Manufacturing

- Additive Manufacturing (3D Printing) relies entirely on 3D CAD models.
- Specialized CAM slicer software converts the solid model into 2D layers and generates G-code for the printer.
- Enables designs with internal complexities (like conformal cooling channels in molds) that are impossible to machine conventionally.

# Robotics and Automation

- CAD is used to design the robotic effectors and the work cells.
- Offline Programming (OLP) uses CAM-like logic to program robotic welding or painting paths in a virtual environment.
- Avoids taking the physical robot out of production to teach it new paths.

# Impact on the Global Supply Chain

- Digital manufacturing allows a design created in Germany to be instantly transmitted and manufactured in a facility in India.
- Standardized CAD formats (STEP, IGES) ensure that suppliers using different software can still manufacture the parts accurately.
- Cloud-based CAD/CAM platforms are enabling real-time collaboration among global teams.

# Unit 1 Summary

- CAD/CAM systems are the backbone of modern product development and production.
- Digital manufacturing concepts like digital twins and PLM are driving the Industry 4.0 revolution.
- The applications of these technologies are vast, touching every sector from aerospace to customized healthcare.

# End of Unit 1

- This concludes Unit 1: CAD/CAM overview and integration.
- Review the concepts of modeling, toolpaths, integration, and digital twins.
- Prepare for the upcoming quiz and assignments on these introductory concepts.

- Lecture 5: Introduction to Feature-Based Modeling

# Agenda

- What is Feature-Based Modeling?
- Historical Context of CAD
- Parametric vs Non-Parametric Modeling
- Basic Features: Extrude and Revolve
- Feature Tree and History
- Summary and Next Steps

# What is a Feature in CAD?

- A feature is a basic geometric shape or operation used to build a part.
- Unlike primitive solids (blocks, cylinders), features are operation-based.
- Examples: Extrusion, Revolve, Sweep, Loft, Fillet, Hole.
- Features contain parametric information that defines their shape and size.

# Feature-Based Modeling Concept

- Models are created by adding and modifying sequential features.
- Each feature represents a specific manufacturing operation or geometric detail.
- This approach allows designers to capture the 'design intent'.
- Modifications are easier because individual features can be edited at any time.

# Feature Creation Workflow

# Parametric Modeling Integration

- Feature-based modeling is almost always parametric.
- Parameters (dimensions, angles) drive the geometry.
- Changing a parameter automatically updates the feature and any dependent features.
- Establishes relationships between different parts of the design.

# Base Features: Sketch-Based

- The first feature of any part is the 'base feature'.
- Usually created from a 2D profile (sketch).
- Requires selecting a reference plane (Top, Front, Right).
- The sketch must be fully defined for a stable model.

# The Extrude Feature

- Extrusion adds material by projecting a 2D sketch along a linear path.
- Most common base feature.
- Parameters include: Blind depth, Through All, Up to Next, Mid Plane.
- Can also be used to remove material (Extrude Cut).

# Example: Extruded Bracket

- A standard L-bracket is created by sketching an L-shape and extruding it to a specific thickness. This single feature replaces the need for boolean operations on multiple blocks.

# The Revolve Feature

- Revolve creates features by rotating a 2D sketch around an axis.
- Ideal for axisymmetric parts like shafts, pulleys, and cylinders.
- Axis of revolution must be clearly defined (can be a sketch line or reference axis).
- Angle of revolution can be 360 degrees or less.

# Example: Turned Shaft

- A stepped shaft is modeled by sketching its half-profile and revolving it 360 degrees around the centerline. This perfectly mimics the lathe turning process.

# Lecture Summary

- Features are the building blocks of modern 3D CAD models.
- Feature-based modeling captures design intent and manufacturing logic.
- Extrude and Revolve are the primary sketch-based features.
- Parametric controls allow for rapid design changes.

# Next Lecture

- Advanced Feature-Based Modeling
- Sweeps and Lofts
- Applied Features: Fillets, Chamfers, and Holes

- Lecture 6: Advanced Feature-Based Modeling

# Agenda

- Applied vs Sketch-Based Features
- Fillets and Chamfers
- Hole Wizards and Standard Holes
- Patterning and Mirroring
- Sweeps and Lofts
- Summary

# Applied Features

- Applied features do not require a 2D sketch.
- They are applied directly to existing 3D geometry (edges, faces).
- Examples: Fillets, Chamfers, Shells, Drafts.
- Typically added later in the feature tree to refine the model.

# Fillets and Rounds

- Fillet: Adding material to an internal corner to reduce stress concentration.
- Round: Removing material from an external corner for safety or aesthetics.
- Can be constant radius, variable radius, or face-based.
- Crucial for manufacturability (e.g., casting and molding).

# Chamfers

- A chamfer is a beveled edge connecting two surfaces.
- Defined by distance-distance or angle-distance parameters.
- Used for easing assembly (lead-ins) and deburring edges.
- Computationally lighter than fillets.

# Fillet vs Chamfer

# Hole Features and Standards

- While holes can be made with 'Extrude Cut', dedicated Hole features are preferred.
- Hole tools include standard libraries (ISO, ANSI, DIN).
- Types: Simple, Counterbore, Countersink, Tapped (Threaded).
- Automatically call out correct dimensions in 2D drawings.

# Example: Counterbore Hole

- A counterbore hole allows a socket-head cap screw to sit flush with the surface. The Hole Wizard ensures the bore diameter, depth, and drill point match standard hardware sizes.

# Patterning Features

- Patterns duplicate existing features in a specific arrangement.
- Linear Pattern: Duplicates along one or two directions.
- Circular Pattern: Duplicates around an axis.
- Saves time and ensures design consistency.
- Updates automatically if the source feature changes.

# Mirroring

- Mirroring duplicates a feature, face, or body symmetrically across a plane.
- Essential for symmetric parts (e.g., automotive brackets).
- Reduces modeling time by 50% for perfectly symmetric designs.

# Sweep Features

- Requires two sketches: a Profile and a Path.
- The profile is translated along the path to create a solid.
- Used for tubing, wiring, springs, and complex brackets.
- Guide curves can be used to vary the profile along the path.

# Loft Features

- Creates a transitional shape between two or more different profiles.
- Example: A square duct transitioning into a round pipe.
- Profiles are placed on offset planes.
- Guide curves control the transition shape between the profiles.

# Lecture Summary

- Applied features like fillets and chamfers refine base geometry.
- Hole tools ensure standardization and integration with drawings.
- Patterns and Mirrors drastically reduce modeling time for repetitive features.
- Sweeps and Lofts enable the creation of complex, organic solid shapes.

# Next Lecture

- Introduction to Surface Modeling
- Wireframe vs Surface Representation
- NURBS and Bezier Curves

- Lecture 7: Introduction to Surface Modeling

# Agenda

- Solid vs Surface Modeling
- Wireframe Modeling Limitations
- What is a Surface?
- Parametric Curves (Bezier, B-Spline, NURBS)
- Basic Surfacing Operations
- Summary

# Solid vs Surface Modeling

- Solid Modeling: Represents the complete volume of an object. Has mass properties (volume, center of gravity).
- Surface Modeling: Represents only the outer boundary (skin) of an object. Zero thickness.
- Surfaces are used when complex, organic shapes cannot be achieved with standard solid features.
- Often used in automotive and aerospace design.

# Evolution: Wireframe Modeling

- Earliest form of 3D CAD.
- Models consist only of points, lines, and curves representing edges.
- Ambiguous: Cannot determine inside from outside.
- Cannot perform boolean operations or calculate volume.
- Paved the way for surface and solid modeling.

# Wireframe vs Surface vs Solid

# Mathematical Representation of Curves

- Surfaces are generated from curves.
- Analytic curves: Lines, circles, ellipses (simple math equations).
- Synthetic curves: Used for free-form shapes.
- Synthetic curves are defined by control points.

# Bezier Curves

- Developed by Paul de Casteljau and Pierre Bezier (Renault).
- Curve passes through the first and last control points.
- Interior points pull the curve towards them but the curve does not pass through them.
- Global control: Moving one point affects the entire curve.

# B-Splines (Basis Splines)

- Improvement over Bezier curves.
- Offers local control: Moving a control point only affects a segment of the curve.
- Made of piecewise polynomial segments connected with a specified continuity.
- Can handle more complex shapes with fewer points.

# NURBS (Non-Uniform Rational B-Splines)

- Industry standard for modern CAD systems.
- 'Non-Uniform': Spacing between knots can vary, allowing sharp corners.
- 'Rational': Uses weights for control points, allowing exact representation of conic sections (circles, ellipses).
- Provides a unified mathematical model for both analytic and free-form shapes.

# NURBS in Action

- When designing a car fender, a designer uses NURBS curves. By adjusting the weight of a specific control point, they can sharpen or soften a character line on the fender without adding extra points.

# Basic Surface Creation

- Planar Surface: Created from a closed 2D sketch.
- Extruded Surface: Extruding a 2D or 3D curve in a linear direction (results in an open tube).
- Revolved Surface: Revolving a curve around an axis.
- These are the surface equivalents of base solid features.

# Continuity (C0, C1, C2)

- C0 (Positional Continuity): Surfaces touch at a boundary (sharp edge).
- C1 (Tangency Continuity): Surfaces share a tangent plane at the boundary (smooth transition).
- C2 (Curvature Continuity): Rate of curvature is equal across the boundary (Class A surfacing).

# Lecture Summary

- Surface modeling is essential for complex, ergonomic, and aesthetic designs.
- NURBS provide the mathematical foundation for representing both exact geometry and free-form curves.
- Understanding curve continuity is critical for high-quality surfaces.

# Next Lecture

- Advanced Surface Modeling
- Trimming and Knitting
- Converting Surfaces to Solids

- Lecture 8: Advanced Surface Modeling

# Agenda

- Advanced Surface Creation (Sweeps, Lofts, Fills)
- Surface Modification Tools
- Trimming and Extending Surfaces
- Knitting/Stitching Surfaces
- Hybrid Modeling (Surfaces to Solids)
- Summary

# Swept and Lofted Surfaces

- Swept Surface: Sweeps a profile curve along a path curve. Used for complex ducting or wire routing.
- Lofted Surface: Blends multiple profiles together. Guide curves dictate the boundary shapes.
- Boundary Surface: High-quality surface defined by curves in two directions (U and V directions).
- Allows for extremely precise control over surface tension and continuity.

# Filled Surfaces (Surface Fill)

- Creates a surface patch within a closed boundary defined by existing model edges or sketches.
- Useful for patching holes in imported geometry.
- Can match tangency (C1) or curvature (C2) with surrounding faces.
- Essential tool for reverse engineering and fixing broken imports.

# The U-V Grid System

# Trimming Surfaces

- Surfaces often need to be cut to achieve a specific shape.
- Trim Tool: Uses a sketch, plane, or another surface to cut away portions of a target surface.
- Mutual Trim: Trims two intersecting surfaces against each other simultaneously.
- Unlike solids, trimming is an everyday operation in surface modeling.

# Example: Designing a Computer Mouse

- The top shell of a mouse is created by lofting a large, smooth surface. To create the button cutouts, a 2D sketch of the buttons is projected onto the surface and used to trim away the gaps.

# Extending and Untrimming

- Extend Surface: Lengthens a surface along its natural curvature or tangency.
- Useful when a surface falls short of an intersection point.
- Untrim Surface: Restores a surface back to its original mathematical boundaries before it was trimmed.
- Crucial for recovering lost geometry during complex edits.

# Knitting (Stitching) Surfaces

- Individual surface patches must be joined together.
- Knit Surface tool combines two or more adjacent, intersecting surfaces into a single surface body.
- Gap tolerance settings allow knitting of slightly imperfect edges.
- A fully enclosed knitted surface can be automatically converted into a solid body.

# Hybrid Modeling Workflow

- Combines the best of solid and surface modeling.
- Process: 1) Build complex outer skins with surfaces. 2) Knit into a solid. 3) Add mechanical details (bosses, ribs, holes) using solid features.
- Thicken Tool: Adds thickness to a single surface to create a solid sheet part.
- Cut with Surface: Uses a surface to slice a solid body.

# Surface Analysis Tools

- Zebra Stripes: Projects black and white stripes to visually check surface continuity and defects.
- Curvature Combs: Displays the magnitude and direction of curvature along a curve or surface edge.
- Draft Analysis: Checks if the surface can be successfully ejected from a mold.

# Lecture Summary

- Advanced surfacing relies on lofts, boundary surfaces, and fills.
- Trimming and knitting are the core operations for manipulating surface patches.
- Hybrid modeling leverages surfaces for aesthetics and solids for mechanical details.

# Next Lecture

- Advanced Assembly Concepts
- Top-Down vs Bottom-Up Design
- Degrees of Freedom

- Lecture 9: Advanced Assembly - Part 1

# Agenda

- Introduction to Assemblies
- Degrees of Freedom (DOF)
- Assembly Modeling Strategies
- Bottom-Up Design
- Top-Down Design
- Standard Mates and Constraints
- Summary

# What is an Assembly?

- An assembly is a collection of individual parts (components) positioned relative to each other.
- Simulates how parts fit and function together in the real world.
- Maintains references to the original part files; if a part is updated, the assembly updates automatically.
- Allows for interference checking and motion analysis.

# Degrees of Freedom (DOF)

- A rigid body in 3D space has 6 Degrees of Freedom.
- 3 Translational: Movement along X, Y, and Z axes.
- 3 Rotational: Rotation around X, Y, and Z axes.
- When a part is brought into an assembly, it is 'floating' (6 DOF).
- Applying constraints/mates removes DOF to position the part.

# Degrees of Freedom Visualization

# The Base Component

- The first component placed in an assembly is typically 'Fixed'.
- Fixed means it has 0 DOF; it cannot move.
- Serves as the foundation for positioning all other components.
- Often the chassis, frame, or main housing of the product.

# Bottom-Up Assembly Design

- The traditional method of assembly modeling.
- Workflow: 1) Design all parts individually. 2) Insert them into an assembly file. 3) Apply mates to position them.
- Pros: Easy to manage, components can be reused in other projects.
- Cons: Harder to ensure parts fit perfectly if designed in isolation without references.

# Top-Down Assembly Design

- Parts are designed *in the context* of the assembly.
- Workflow: 1) Create a layout or skeleton sketch. 2) Create new parts within the assembly. 3) Reference edges and faces of other parts to define geometry.
- Pros: Guarantees perfect fit; changes to the overall design automatically update all parts.
- Cons: Creates complex file interdependencies; can be fragile if references are broken.

# Example: Top-Down Design

- Designing a custom lid for a box. Instead of measuring the box and designing the lid separately, the lid is created in the assembly by projecting the inner edges of the box. If the box changes size, the lid updates instantly.

# Mates / Assembly Constraints

- Mates define the geometric relationships between components.
- They remove DOF by locking faces, edges, or planes together.
- Standard Mates: Coincident, Parallel, Perpendicular, Tangent, Concentric.
- Applying mates mimics physical assembly logic.

# Common Standard Mates

- Coincident: Makes two planar faces flush or touches a point to a line.
- Concentric: Aligns the center axes of two cylindrical faces (e.g., a pin in a hole).
- Distance: Maintains a specific numerical gap between two entities.
- Angle: Locks two faces at a specific angle.

# Fully Defined vs Under Defined Components

- Under Defined: A component still has some DOF. It can be dragged/moved in the workspace.
- Fully Defined: All 6 DOF are removed. The component is locked in place.
- Over Defined: Conflicting mates are applied (e.g., locking a part parallel and perpendicular to the same face simultaneously). Causes errors.

# Lecture Summary

- Assemblies bring individual parts together using mates.
- Managing the 6 Degrees of Freedom is the core concept of assembly.
- Bottom-up is best for standard parts; Top-down is best for custom, integrated designs.

# Next Lecture

- Advanced Mates (Mechanical, Limit)
- Interference Detection
- Exploded Views

- Lecture 10: Advanced Assembly - Part 2

# Agenda

- Advanced and Mechanical Mates
- Interference Detection
- Collision Detection and Kinematics
- Exploded Views
- Bill of Materials (BOM)
- Summary

# Advanced Mates

- Go beyond simple geometric alignment.
- Profile Center / Width: Automatically centers a part within a slot or between two faces.
- Symmetric: Forces two components to remain symmetric about a plane.
- Limit Mates: Allows movement within a specific range (e.g., a drawer that slides open 200mm but no further).

# Mechanical Mates

- Simulate actual mechanical relationships and motion.
- Gear Mate: Forces two cylindrical components to rotate relative to each other based on a ratio.
- Rack and Pinion: Translates rotational motion into linear motion.
- Screw: Translates rotation into linear motion based on a defined pitch.
- Cam and Follower: Keeps a cylinder (follower) tangent to a continuous non-circular surface (cam).

# Example: Simulating a Gearbox

- By applying a Gear Mate between two gears with a 2:1 ratio, turning the input shaft in the CAD software will cause the output shaft to rotate at exactly half the speed. This allows for visual validation of the mechanism.

# Interference Detection

- A critical tool for validating digital prototypes.
- Analyzes the assembly for any overlapping volumes between components.
- Highlights clashes in red and calculates the volume of interference.
- Essential for ensuring parts will actually fit together during physical assembly.
- Ignores intentional interferences like press fits or threaded fasteners (if configured).

# Interference Detection Display

# Collision Detection and Physical Dynamics

- Allows users to drag components and see how they interact physically.
- Collision Detection: Stops motion when one part hits another.
- Physical Dynamics: Pushes other parts out of the way based on their mass and constraints.
- Useful for testing linkages, clearances, and range of motion.

# Exploded Views

- A representation of the assembly with its components separated by distance.
- Shows how the parts fit together and the order of assembly.
- Created by translating components along specific axes (Explode Steps).
- Explode lines can be added to trace the assembly path.

# Uses of Exploded Views

- Crucial for creating Assembly Manuals and Service Instructions.
- Used heavily in 2D engineering drawings.
- Can be animated to create digital assembly/disassembly videos for training.

# Bill of Materials (BOM)

- A tabular list of all components required to build the assembly.
- Automatically generated from the assembly data.
- Includes Item Number, Part Name, Quantity, and custom properties (Material, Vendor).
- Linked directly to the 3D model; adding a part updates the BOM instantly.

# BOM Numbering and Balloons

- In 2D drawings, balloons with item numbers are attached to parts.
- These balloons link directly to the BOM table.
- Ensures manufacturing and procurement teams order the correct parts.

# Lecture Summary

- Mechanical mates simulate real-world mechanisms like gears and cams.
- Interference and collision detection save money by finding errors before manufacturing.
- Exploded views and BOMs are the primary outputs for manufacturing documentation.

# Next Lecture

- Design Intent and Constraints
- Dimensional vs Geometric Constraints
- Parametric Equations

- Lecture 11: Design Intent & Constraints - Part 1

# Agenda

- Understanding Design Intent
- The Role of Constraints
- Geometric Constraints
- Dimensional Constraints
- Fully Defining Sketches
- Summary

# What is Design Intent?

- Design intent is how your model behaves when dimensions are modified.
- It is the 'intelligence' built into the model by the designer.
- A well-planned design intent ensures that modifications produce predictable and desirable results.
- Poor design intent leads to models breaking or distorting when changed.

# Example: Hole Placement Intent

- If a hole must always be in the center of a plate, dimensioning it 50mm from the edge works only if the plate is 100mm wide. If the plate changes to 150mm, the hole is off-center. A better intent is using a geometric constraint to lock the hole to the midpoint of the plate.

# The Role of Constraints

- Constraints are logical rules applied to geometry.
- They restrict degrees of freedom in a 2D sketch or 3D assembly.
- They define relationships rather than absolute sizes.
- Two main types: Geometric and Dimensional.

# Geometric Constraints

- Define relationships between geometric entities (lines, arcs, points).
- Do not involve numerical values.
- Examples: Horizontal, Vertical, Collinear, Perpendicular, Parallel.
- Applying these early makes sketches robust and reduces the need for dimensions.

# Common Geometric Constraints

- Tangent: Makes a line touch an arc at exactly one point smoothly.
- Concentric: Forces two circles or arcs to share the same center point.
- Equal: Forces two lines to have the same length, or two circles to have the same radius.
- Midpoint: Locks a point to the exact center of a line.

# Applying Constraints

# Dimensional Constraints

- Define the exact size or distance using numerical values.
- Also known as Smart Dimensions or Driving Dimensions.
- Linear Dimensions: Length, width, distance between points.
- Radial/Diametric: Size of circles and arcs.
- Angular: Angle between two lines.

# Driving vs Driven Dimensions

- Driving Dimensions: Control the geometry. Changing the number changes the shape.
- Driven (Reference) Dimensions: Controlled by the geometry. They display a value based on other constraints but cannot be directly edited.
- Attempting to add a driving dimension to fully defined geometry creates an over-defined error.

# Fully Defining Sketches

- A sketch is 'Fully Defined' when all degrees of freedom are removed.
- Usually indicated by color (e.g., lines turn from Blue to Black).
- Requires both Geometric and Dimensional constraints, tied to the Origin.
- Best Practice: NEVER leave a sketch under-defined in a production model.

# Tying to the Origin

- The Origin (0,0,0) is the anchor of the part.
- A sketch can have perfect internal constraints, but if it's not locked to the origin, it can still float in space.
- Always start your first sketch by snapping to the origin.

# Lecture Summary

- Design intent dictates how a model reacts to change.
- Geometric constraints establish shape logic and relationships.
- Dimensional constraints establish exact sizes.
- A robust model relies on fully defined, origin-anchored sketches.

# Next Lecture

- Capturing Design Intent via Equations
- Global Variables
- Design Tables and Configurations

# Unit 2: Geometric Modeling

- Lecture 12: Advanced Design Intent and Equations

# Agenda

- Parametric Equations
- Global Variables
- Best Practices for Stable Models
- Configurations
- Design Tables
- Summary of Unit 2

# Parametric Equations

- Allow dimensions to be driven by mathematical formulas rather than static numbers.
- Links dimensions to each other to capture advanced design intent.
- Syntax examples: ‘D1@Sketch1 = D2@Sketch1 * 2‘
- If D2 changes, D1 updates automatically to maintain the ratio.

# Example: Using Equations

- Designing a tank where the volume must remain proportional. You can set an equation so that the height is always exactly 1.5 times the radius. Updating the radius dimension updates the entire tank accurately.

# Global Variables

- Named constants that can be used across multiple sketches and features.
- Instead of entering '10mm' for wall thickness 50 times, create a Global Variable 'Wall_Thick = 10mm'.
- Link dimensions to the variable.
- Changing 'Wall_Thick' in the equation manager updates the entire model instantly.

# Best Practices for Stable Models

- 1. Plan ahead: Determine critical dimensions before sketching.
- 2. Prioritize geometric constraints over dimensions (they calculate faster and are more robust).
- 3. Avoid long chains of references. Base features off primary planes.
- 4. Keep sketches simple; use multiple simple features rather than one incredibly complex sketch.

# Feature Tree Management

# Configurations

- Allows multiple variations of a part or assembly within a single file.
- Can suppress/unsuppress features, change dimensions, or swap components.
- Example: A single bolt file containing configurations for M6, M8, M10, and M12 sizes.
- Reduces file clutter and makes assemblies lighter.

# Design Tables (Spreadsheet Driven Design)

- Uses embedded spreadsheets (like Excel) to drive configurations.
- Columns represent dimensions or feature suppression states.
- Rows represent different configurations.
- Extremely powerful for generating large families of standard parts (e.g., structural steel profiles).

# Design Intent in Assemblies

- Design intent isn't just for parts; it applies to mates.
- Use reference planes for mating instead of faces when possible (faces can be deleted, planes are permanent).
- Group related mates in folders.
- Use sub-assemblies to organize large projects logically.

# Unit 2 Review: Core Concepts

- Feature-Based Modeling uses history-based operations.
- Surface Modeling provides tools for organic, complex boundaries.
- Assemblies use mates to remove DOF and simulate real-world interaction.
- Design Intent and Constraints ensure models are robust, editable, and intelligent.

# Lecture Summary

- Equations and global variables automate design updates.
- Configurations and Design Tables efficiently manage part families.
- Adhering to best practices ensures models do not crash when modified.

# Next Unit

- Unit 3: Computer Aided Manufacturing (CAM)
- CNC Machine Basics
- G-Code and M-Code Generation

# CNC Architecture - Basics and Components

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Introduction to CNC Architecture
- Core Components of CNC Systems
- Machine Control Unit (MCU)
- Data Processing Unit (DPU)
- Control Loops Control Unit (CLCU)

# What is CNC Architecture?

- CNC (Computer Numerical Control) architecture refers to the internal structure and hardware layout that enable automated machine control.
- It integrates computer hardware with mechanical components to perform precise manufacturing tasks.
- The architecture bridges the gap between digital CAD/CAM data and physical machine movements.

# General CNC System Block Diagram

- Part Program -¿ MCU -¿ Driving System -¿ Machine Tool
- Feedback System -¿ MCU

# Major Components of CNC

- 1. Input Device (Keyboard, USB, Network)
- 2. Machine Control Unit (MCU)
- 3. Machine Tool
- 4. Driving System
- 5. Feedback Devices
- 6. Display Unit

# Input Devices in CNC

- Used to enter part programs into the CNC memory.
- Traditional: Punched tape readers, magnetic tapes (obsolete).
- Modern: USB flash drives, Ethernet connections, serial ports (RS-232), and direct DNC links.
- Manual Data Input (MDI) via the control panel keyboard.

# Machine Control Unit (MCU)

- The 'brain' of the CNC machine.
- Reads the part program and interprets instructions.
- Generates axis motion commands.
- Monitors feedback signals to ensure positional accuracy.
- Controls auxiliary functions (coolant on/off, spindle speed, tool change).

# MCU Internal Structure

- Input Buffer -¿ DPU (Data Processing Unit)
- DPU -¿ CLCU (Control Loop Control Unit) -¿ Interpolator -¿ Axis Drives

# Data Processing Unit (DPU)

- Responsible for reading and decoding part programs.
- Calculates the required positions and feed rates based on the program blocks.
- Passes the decoded information to the CLCU.
- Handles tool radius compensation and machine offsets.

# Control Loop Control Unit (CLCU)

- Takes position and speed data from the DPU.
- Continuously compares the commanded position with actual feedback from encoders.
- Generates control signals for the servo drives.
- Performs interpolation (linear and circular) to ensure smooth tool paths.

# Machine Tool Mechanics

- The physical mechanical system that performs the cutting operations.
- Includes the machine bed, guideways, spindle, and axes (X, Y, Z).
- Designed for high rigidity, low friction, and thermal stability to maintain accuracy under CNC control.

# Display Unit (HMI)

- Human Machine Interface (HMI) screen.
- Displays current machine position, active program, alarms, and tool data.
- Allows the operator to interact with the MCU, edit programs, and configure setup offsets.

# Example: MCU Processing a G-Code

- Block: N10 G01 X50 Y50 F200
- DPU decodes: Linear move to X50, Y50 at 200 mm/min.
- Interpolator calculates intermediate points.
- CLCU sends voltage signals to X and Y servo drives.
- Feedback loop ensures X and Y arrive at exactly 50.000 mm.

# Summary

- CNC architecture relies on the seamless integration of digital controllers and mechanical hardware.
- The MCU consists of the DPU and CLCU, working together to interpret programs and control motion.
- Modern CNCs use sophisticated input methods and advanced HMIs for operator interaction.

# Next Lecture

- We will dive deeper into advanced MCU structures, PLCs, and specific hardware architectures.

# CNC Architecture - PLC and Control Configurations

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Programmable Logic Controller (PLC) in CNC
- PLC vs CNC Control
- Hardware Architecture (DNC vs CNC)
- Open Architecture Control (OAC)
- Real-time Operating Systems in CNC

# Role of PLC in CNC Systems

- A PLC (Programmable Logic Controller) is often integrated into the CNC MCU.
- While the CNC handles continuous path control (axes), the PLC handles discrete logic operations.
- Also known as a Programmable Machine Control (PMC).

# PLC Functions in CNC

- Spindle start, stop, and direction control.
- Coolant pump control (M08, M09).
- Automatic Tool Changer (ATC) sequencing.
- Safety interlocks (door switches, emergency stops).
- Turret indexing logic on lathes.

# CNC vs PLC Tasks

- CNC Tasks: Interpolation, G-code decoding, Axis Servo Control, Tool Compensation.
- PLC Tasks: Relays, Solenoids, Limit Switches, M-codes, Hyd/Pneu Systems.

# Hardware Architecture Types

- 1. Centralized Control: A single high-performance processor handles both CNC and PLC tasks.
- 2. Distributed Control: Multiple microprocessors communicate over a high-speed bus; one for GUI, one for CNC interpolation, one for PLC.

# Direct Numerical Control (DNC)

- DNC involves a central computer managing multiple CNC machines.
- Part programs are stored centrally and 'drip-fed' to the CNCs as needed.
- Benefits: Eliminates local storage limits, centralizes revision control, collects real-time production data.

# Distributed Numerical Control (Modern DNC)

- Modern DNC networks CNC machines via Ethernet.
- Instead of drip-feeding, entire programs are downloaded to the CNC's hard drive or RAM.
- Facilitates remote monitoring (OEE tracking) and Industry 4.0 integration.

# Open Architecture Control (OAC)

- Traditional CNCs used proprietary hardware and software (closed architecture).
- OAC uses standard PC hardware (Intel processors, Windows/Linux OS).
- Allows easy integration of third-party software, sensors, and customized HMIs.

# Advantages of PC-Based CNC

- Lower hardware costs due to commercial off-the-shelf (COTS) components.
- Vast storage capacity for complex CAM files (e.g., 3D surfacing).
- Easy networking and IT integration.
- Familiar user interface (Windows/Linux environment).

# Real-Time Operating Systems (RTOS)

- CNC requires deterministic execution (tasks must finish within strict time limits).
- Standard Windows is not real-time. PC-based CNCs use an RTOS extension.
- The RTOS guarantees servo loops run exactly every millisecond without interruption from GUI or networking tasks.

# Example: Tool Change Sequence

- 1. CNC reads M06 T02.
- 2. CNC tells PLC: 'Perform tool change to Tool 2'.
- 3. PLC executes logic: Orient spindle -¿ Z-axis to tool change pos -¿ Open door -¿ Rotate ATC -¿ Swap tool -¿ Close door.
- 4. PLC signals CNC: 'Done'. CNC resumes cutting.

# Summary

- Modern CNC architectures separate path control (CNC) from discrete logic (PLC).
- PC-based Open Architecture Control provides flexibility, large storage, and easy IT integration.
- RTOS ensures deterministic performance required for high-speed machining.

# Next Lecture

- We will explore Drives and Feedback Systems, specifically Stepper and Servo motors used for axis movement.

# Drives and Feedback Systems - Drive Motors

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Introduction to Axis Drives
- Types of Drive Motors
- Stepper Motors: Working and Types
- Servo Motors: DC vs AC
- Linear Motors

# Introduction to Axis Drives

- Axis drives provide the motive power to move the machine tool tables and spindle.
- They convert electrical signals from the MCU into precise mechanical rotary or linear motion.
- Must provide high torque, rapid acceleration, and precise positioning.

# Requirements of CNC Drives

- 1. Fast response time.
- 2. High stiffness and holding torque.
- 3. Smooth rotation at very low and very high speeds.
- 4. High reliability and low maintenance.
- 5. Excellent thermal dissipation.

# Types of Drive Motors

- 1. Stepper Motors (Used in low-cost, open-loop systems)
- 2. DC Servo Motors (Older technology, reliable but require brush maintenance)
- 3. AC Servo Motors (Modern standard, brushless, highly efficient)
- 4. Linear Motors (Direct linear motion, ultra-high speed)

# Stepper Motor Concept

- Stator Coils energized in sequence -¿ Rotor aligns with magnetic field -¿ Rotates by one 'Step Angle'

# Stepper Motors

- Operates by receiving discrete electrical pulses.
- Each pulse rotates the motor shaft by a specific angle (e.g., 1.8 degrees for a 200-step motor).
- No feedback required for positioning (inherently open-loop).
- Prone to 'missed steps' if overloaded.

# Servo Motors (Overview)

- Servo motors operate in a closed-loop control system.
- They use a continuous electrical signal and rely on encoders/resolvers for position feedback.
- MCU constantly adjusts the power to eliminate the error between desired and actual position.

# DC Servo Motors

- Uses permanent magnets on the stator and wound coils on the rotor.
- Current is supplied via brushes and a commutator.
- Pros: Simple control, excellent low-speed torque.
- Cons: Brushes wear out, generate spark/heat, limited top speed.

# AC Servo Motors (Brushless)

- Permanent magnets are on the rotor, wound coils on the stator.
- Electronic commutation replaces physical brushes.
- Pros: Maintenance-free (no brushes), higher speed capabilities, better heat dissipation (stator is on the outside).
- Cons: Complex control electronics required.

# Linear Motors

- Essentially an AC servo motor rolled out flat.
- Provides direct linear motion without ballscrews or gears.
- Eliminates backlash and mechanical friction.
- Capable of extreme acceleration (up to 5G) and very high traverse speeds (120+ m/min).

# Stepper vs Servo Example

- Stepper: Sending 1000 pulses requests 1000 steps. If the cutting force is too high, it might only move 990 steps, causing a permanent 10-step error.
- Servo: Controller requests a position. If resistance slows it down, the controller increases current until the encoder confirms arrival at the exact position.

# Summary

- Drives convert MCU signals into physical motion.
- Stepper motors are simple and open-loop, while servo motors use closed-loop feedback for high accuracy.
- AC Brushless Servos are the industry standard for modern CNCs.

# Next Lecture

- We will discuss how closed-loop systems actually work, focusing on Feedback Devices like Encoders and Resolvers.

# Drives and Feedback Systems - Feedback Devices

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Open-Loop vs Closed-Loop Control
- Role of Feedback Devices
- Optical Encoders (Incremental & Absolute)
- Resolvers
- Linear Scales (Glass Scales)

# Open-Loop Control Systems

- The MCU sends signals to the drive, but receives no confirmation of execution.
- Typically uses Stepper motors.
- Advantages: Cheap, simple electronics.
- Disadvantages: Cannot detect or correct errors (e.g., missed steps due to heavy cutting forces).

# Closed-Loop Control Systems

- Includes a feedback loop measuring actual position and/or velocity.
- MCU compares 'Commanded Position' with 'Actual Position' (Error Signal).
- If Error != 0, MCU adjusts drive output until Error = 0.
- Ensures high accuracy and repeatability.

# Closed-Loop Block Diagram

- MCU -¿ Error Amplifier -¿ Servo Drive -¿ Motor -¿ Leadscrew -¿ Table
- Table/Motor -¿ Feedback Device (Encoder) -¿ Feedback Signal -¿ MCU

# Types of Feedback Sensors

- Feedback devices measure displacement or velocity.
- 1. Rotary Encoders (attached to the motor shaft).
- 2. Resolvers (analog rotary sensors).
- 3. Linear Scales (attached directly to the machine table).

# Optical Rotary Encoders

- Uses a glass disk with fine opaque lines, a light source (LED), and a photodetector.
- As the motor turns, the lines interrupt the light, generating electrical pulses.
- Two types: Incremental and Absolute.

# Incremental Encoders

- Generates a series of pulses as it rotates.
- Only tracks *relative* movement. Does not know absolute position at startup.
- Requires a 'Homing' or 'Machine Zero' procedure every time the machine is turned on.
- Uses Phase A and Phase B channels to determine direction (Quadrature).

# Absolute Encoders

- Disk has multiple concentric tracks forming a unique binary/Gray code for every position.
- Knows exact position immediately upon power-up.
- No homing procedure required.
- More expensive and complex than incremental encoders.

# Resolvers

- Analog electro-mechanical device, functions like a rotary transformer.
- Primary winding on rotor, two secondary windings on stator at 90 degrees.
- Outputs sine and cosine voltage waves.
- Extremely robust, handles shock, vibration, and high temps better than optical encoders.

# Linear Scales (Direct Feedback)

- Rotary encoders on motors measure *indirect* position (ignores ballscrew thermal expansion or backlash).
- Linear glass scales are mounted directly on the moving table.
- Provide *direct* position feedback of the actual workpiece location.
- Highest accuracy, immune to mechanical slop in the drivetrain.

# Example: Thermal Expansion Issue

- A ballscrew heats up during operation and expands by 0.05 mm.
- With rotary encoder: The MCU thinks it moved 100mm, but it actually moved 100.05mm. Error!
- With linear scale: The scale reads exactly 100mm, forcing the motor to stop early to compensate for the expansion.

# Summary

- Closed-loop systems are vital for CNC precision.
- Incremental encoders require homing; absolute encoders do not.
- Linear scales offer the best accuracy by measuring actual table movement directly.

# Next Lecture

- We will shift focus to Tooling and Workholding for CNC machines, starting with Automatic Tool Changers.

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Requirements for CNC Tooling
- Cutting Tool Materials
- Automatic Tool Changer (ATC)
- Tool Magazines
- Presetting Tools

# Requirements for CNC Tooling

- CNC machines remove metal faster and continuously compared to manual machines.
- Tools must have: High red hardness, wear resistance, toughness.
- Tool holders must provide high rigidity, concentricity, and quick-change capability.

# Cutting Tool Materials

- High-Speed Steel (HSS): Low cost, but slow. Rarely used in production CNC.
- Carbide (Tungsten Carbide): Industry standard. High speed, highly rigid.
- Ceramics: For high-speed machining of hard steels and cast iron.
- Cubic Boron Nitride (CBN) & Diamond: For ultra-hard materials and non-ferrous alloys.

# Insert Tooling

- Instead of solid tools, CNC uses indexable inserts.
- When a cutting edge dulls, the insert is unscrewed, rotated to a new edge, and tightened.
- Eliminates the need for tool regrinding.
- Available in various shapes: Rhombic, Square, Triangular, Round.

# Automatic Tool Changer (ATC)

- A mechanism that quickly swaps cutting tools in the spindle without operator intervention.
- Reduces non-cutting time dramatically.
- Controlled by PLC using M06 command.
- Uses a 'tool arm' to grab the old tool from the spindle and the new tool from the magazine simultaneously.

# ATC Cycle Diagram

- Spindle stops & orients -¿ Arm grabs both tools -¿ Drawbar releases -¿ Arm moves down -¿ Arm rotates 180 deg -¿ Arm moves up -¿ Drawbar clamps -¿ Arm returns

# Types of Tool Magazines

- 1. Carousel / Drum type: Simple, umbrella-shaped. Holds 10-30 tools. Tool goes back to its exact original pocket.
- 2. Chain type: For large capacities (40-120+ tools). Uses random access tool selection.
- 3. Turret (Lathes): Rotating block holding 8-12 tools, indexing directly into cutting position.

# Random Access Tooling

- In chain magazines, a tool does not return to its original pocket.
- It goes into whichever pocket the previous tool left empty.
- The MCU tracks where every tool is located in memory.
- Reduces tool search time.

# Tool Holders

- Interface between the machine spindle and the cutting tool.
- Common tapers: BT40, CAT40, HSK (Hollow Shank Tooling).
- HSK is used for high-speed machining (¿15,000 RPM) as centrifugal force actually tightens the grip.
- Use pull studs (retention knobs) to lock into the spindle drawbar.

# Tool Presetting

- To cut accurately, the CNC needs to know the exact length and diameter of the tool.
- Offline Presetting: Using a dedicated machine optical setter before loading into CNC.
- On-Machine Probing: A laser or physical probe in the CNC measures the tool automatically.

# Example: Tool Length Offset

- Tool 1 is 100mm long. Tool 2 is 120mm long.
- Without offsets, Tool 2 would crash 20mm into the part.
- By setting H-offsets, the CNC automatically adjusts the Z-axis zero point up by 20mm when Tool 2 is loaded.

# Summary

- Carbide indexable inserts are standard for CNC.
- ATCs and tool magazines minimize idle time.
- Accurate tool holders and presetting are critical for precision and avoiding crashes.

# Next Lecture

- We will discuss how we hold the raw material during machining: Workholding Devices (Chucks, Jigs, Fixtures).

# Tooling and Workholding - Workholding Devices

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Workholding Requirements
- Chucks and Collets (Turning)
- Vises, Clamps, and Tombstones (Milling)
- Jigs vs Fixtures
- Zero-Point Clamping Systems

# Workholding Requirements in CNC

- Must withstand high cutting forces and rapid feed rates without movement.
- High repeatability: Loading a new blank must locate it in the exact same spot.
- Fast actuation to minimize load/unload times.
- Clearance for the cutting tool (avoiding crashes).

# Lathe Workholding: Power Chucks

- Hydraulic or pneumatic chucks actuate jaws automatically (via foot pedal or M-code).
- 3-Jaw Universal: Self-centering, for round stock.
- Soft Jaws: Unhardened jaws that are machined perfectly to fit the specific shape of a complex part.

# Lathe Workholding: Collet Chucks

- Uses a slotted collar that squeezes the material when pulled into a taper.
- Excellent concentricity.
- Less crushing force than chucks, great for thin-walled parts.
- Ideal for automated bar-feeders.

# Milling Workholding: CNC Vises

- High-precision machine vises.
- Often use 'pull-down' jaws to prevent the part from lifting when clamped.
- Can be mounted side-by-side on the table to run multiple parts per cycle.

# Tombstones for Horizontal Mills

- A large vertical block (usually square or cross-shaped) mounted on a rotary pallet.
- Allows parts to be mounted on 4 sides.
- Maximizes the number of parts machined in one setup.
- Spindle accesses different sides by rotating the pallet (B-axis).

# Jig vs Fixture Concept

- Jig: Holds the part AND guides the cutting tool (e.g., drill bushing).
- Fixture: Only holds and locates the part. CNC relies on its own program for tool path.

# Jigs vs Fixtures in CNC

- Jigs are largely OBSOLETE in CNC.
- Because the CNC machine precisely controls the tool path, it doesn't need physical bushings to guide the drill.
- Fixtures are heavily used. A CNC fixture locates the part accurately relative to the machine zero.

# Modular Fixturing

- Uses standardized grid plates with alternating threaded and dowel holes.
- Clamps, locators, and stops can be bolted together like Lego to create temporary custom fixtures.
- Great for low-volume, high-mix production.

# Zero-Point Clamping Systems

- Uses quick-release pneumatic retention knobs.
- A complete fixture plate can be dropped onto the machine table and locked in seconds.
- Repeatability within 0.005mm.
- Allows fixtures to be loaded with parts OFF the machine, eliminating spindle downtime.

# Example: SMED (Single Minute Exchange of Die)

- Traditional: Unbolt vise, clean table, bolt new fixture, dial in with indicator (30 mins downtime).
- Zero-Point: Press button, lift old fixture, drop in new fixture, lock (30 seconds downtime). Machine starts immediately.

# Summary

- Workholding must be rigid, repeatable, and fast.
- Hydraulic chucks and collets dominate turning, while precision vises and tombstones dominate milling.
- Zero-point systems drastically reduce setup times.

# Next Lecture

- We will cover CNC Setup and Calibration, including Machine Zero, Work Zero, and Offsets.

# CNC Setup and Calibration

- Unit 3: CNC System Elements
- Computer Aided Design and Manufacturing

# Agenda

- Coordinate Systems in CNC
- Machine Zero vs Work Zero
- Setting Tool Offsets
- Work Coordinate System (WCS)
- Calibration and Machine Geometry Test

# Coordinate Systems

- CNC programming relies on the Cartesian coordinate system (X, Y, Z).
- To execute a program, the machine must know exactly where the part is located in physical space.
- This is achieved through referencing specific 'Zero' points.

# Machine Zero (Reference Point)

- A fixed point on the machine, defined by the manufacturer.
- Usually the extreme positive limits of X, Y, and Z axes.
- When a machine with incremental encoders boots up, it must be 'Homed' to find this point.
- G28 command sends axes to Machine Zero.

# Zero Points Diagram

- Machine Zero (Fixed at corner) —¿ Distance (G54 offset) —¿ Work Zero (On the part corner)

# Work Zero (Program Zero)

- The origin point (X0, Y0, Z0) used by the programmer when writing the G-code.
- Can be placed anywhere on the workpiece (e.g., top left corner, or center of a bore).
- Makes programming much easier than calculating distances from Machine Zero.

# Work Coordinate System (WCS)

- The CNC uses WCS offsets (G54 through G59) to link Machine Zero to Work Zero.
- The operator uses an edge finder or probe to find the part's corner.
- The distance from Machine Zero to that corner is stored in the G54 register.
- When the program calls G54 X0 Y0, it moves to the part's corner.

# Tool Length Offsets

- Tools have different lengths.
- The Z Work Zero is usually set using a reference tool or probe.
- For every other tool, the difference in length is stored in a Tool Offset Register (H code).
- G43 H02 tells the machine to apply the length offset for Tool 2.

# Cutter Radius Compensation

- The CAM system or MCU needs to account for the thickness of the milling cutter.
- If cutting a 100mm square with a 10mm endmill, the center of the tool must follow a 110mm square path.
- G41 (Left) and G42 (Right) shift the toolpath automatically based on the diameter stored in the D register.

# Machine Calibration (Pitch Error)

- Ballscrews are not perfectly manufactured; a requested 100mm move might actually be 99.98mm.
- Laser interferometers are used to measure these tiny errors across the entire axis travel.
- The MCU stores a 'Pitch Error Compensation Table' to automatically correct these physical imperfections.

# Backlash Compensation

- When an axis reverses direction, there is a tiny amount of slop before the nut engages the screw threads.
- This is called backlash.
- Measured using a dial indicator. The value is entered into a CNC parameter.
- Upon direction reversal, the motor adds an extra micro-move to eat up the backlash.

# Ballbar Testing

- A circularity test to evaluate overall machine geometry and servo tuning.
- The machine interpolates a circle. A high-precision telescoping ballbar measures the actual radius generated.
- Identifies issues like servo mismatch, squareness errors, and worn guideways.

# Example: Full Setup Sequence

- 1. Power on -¿ Home Machine (Find Machine Zero).
- 2. Load fixture and part.
- 3. Edge find part -¿ Store X/Y in G54 (Work Zero).
- 4. Touch off tools -¿ Store Z heights in H offsets.
- 5. Run program.

# Summary

- WCS (G54) connects the physical machine space to the programmed part space.
- Offsets (H and D) manage tool variations without altering the G-code.
- Calibration ensures mechanical inaccuracies are compensated via software.

# Unit Complete

- This concludes Unit 3. The next unit will cover Part Programming in detail, including G-codes, M-codes, and Canned Cycles.

# Advanced G & M Codes

- Introduction to Advanced CNC Programming

# Agenda

- - Review of Basic G-Codes - Need for Advanced Codes - Introduction to G04, G70, G71 - M-Codes beyond M03/M08 - Summary

# Review of Basic G-Codes

- Standard G-codes prepare the machine for motion. G00: Rapid traverse G01: Linear interpolation G02/G03: Circular interpolation These form the foundation of any CNC program.

# Why Advanced G-Codes?

- Basic codes require line-by-line programming for complex shapes. Advanced codes (canned cycles) condense repetitive tasks into fewer lines. Benefits: reduced program size, easier editing, fewer errors.

# G04: Dwell Command

- Used to pause axis movement while the spindle continues rotating. Syntax: G04 X[seconds] or G04 P[milliseconds] Example: G04 X2.0 (pauses for 2 seconds to clear chips at bottom of a hole).

# G71: Rough Turning Cycle

- Automates roughing of stock in a turning operation. Uses parameters to define depth of cut, retract amount, and finishing allowances. Syntax typically involves two blocks in Fanuc controls.

# G71 Example

- G71 U2.0 R1.0; G71 P100 Q200 U0.5 W0.2 F0.25; U2.0 = Depth of cut R1.0 = Retract amount P/Q = Start and end block numbers of the profile.

# G70: Finishing Cycle

- Used in conjunction with G71, G72, or G73. Executes the profile defined in the roughing cycle using the finishing feed rate and speed. Syntax: G70 P100 Q200;

# Roughing vs Finishing

g pass

# Advanced M-Codes

- Machine codes control hardware functions. M19: Spindle orientation (locking spindle at specific angle for tool change). M98/M99: Subprogram call and return (covered in detail later).

# Coolant Control

- M08: Flood coolant ON M09: Coolant OFF Advanced machines may have M88/M89 for through-spindle coolant.

# Summary

- - Advanced G-codes simplify programming. - G04 pauses movement. - G71/G70 handle complex turning automatically. - M-codes manage machine hardware.

# Next Lecture

- In Lecture 21, we will explore specialized milling cycles and advanced drilling operations.

# Specialized Milling Codes

- Canned Cycles for Milling Operations

# Agenda

- - Introduction to Canned Cycles - G81 Standard Drilling - G83 Deep Hole Drilling - G84 Tapping Cycle - G80 Cycle Cancel - Examples

# Canned Cycles in Milling

- Canned cycles (G81-G89) simplify repetitive hole-making operations. They combine positioning, drilling, and retracting into a single block of code.

# Parameters of Canned Cycles

- X, Y: Hole position Z: Final hole depth R: Reference plane (retract height before feeding) F: Feed rate K/L: Number of repeats

# G81 Standard Drilling

- Used for center drilling or shallow holes where chip clearing isn't an issue. Syntax: G81 X... Y... Z... R... F...; Operation: Rapids to X,Y -¿ Rapids to R -¿ Feeds to Z -¿ Rapids to R.

# G83 Deep Hole (Peck) Drilling

- Used for deep holes to clear chips and prevent drill breakage. Introduces the 'Q' parameter for peck depth. Drill retracts fully to the R plane after each peck.

# G83 Example

- G83 X10 Y10 Z-50 R2 Q10 F150; Drills to Z-10, retracts to R2. Drills to Z-20, retracts to R2. Repeats until Z-50 is reached.

# G73 High-Speed Peck Drilling

- Similar to G83 but does not retract fully to the R plane. Retracts just enough (usually 0.5mm) to break the chip, reducing cycle time. Ideal for materials where stringy chips form.

# G84 Tapping Cycle

- Used for cutting internal threads. Spindle rotation must synchronize exactly with the Z-axis feed (Rigid Tapping). At the bottom (Z), the spindle reverses to retract the tap.

# G84 Example

- M29 S500 (Rigid tapping mode) G84 Z-20 R5 F750; Feed rate must equal Spindle Speed * Thread Pitch (500 * 1.5 = 750).

# G80 Canned Cycle Cancel

- Crucial command! Always cancel canned cycles when finished. If not canceled, the machine may attempt to drill a hole at the next X,Y coordinate given for a tool change. Syntax: G80;

# Retract Planes: G98 vs G99

- G98: Retract to initial Z level (safest for clearing clamps). G99: Retract to R plane (faster for multiple holes on a flat surface).

# Summary

- - G81 for standard holes. - G83/G73 for deep holes (pecking). - G84 for tapping. - Always use G80 to cancel.

# Next Lecture

- In Lecture 22, we will look at specialized turning codes like grooving and threading cycles.

# Specialized Turning Codes

- Advanced Operations on CNC Lathes

# Agenda

- - Review of Turning Principles - G72 Facing Cycle - G74 Peck Drilling/Grooving - G75 Radial Grooving - G76 Threading Cycle - Practical Application

# Turning Cycle Review

- We discussed G71 (axial roughing) in Lecture 20. Lathes often require operations in the radial direction (X-axis) like facing and grooving. Specialized cycles handle these efficiently.

# G72 Facing Cycle

- Used when the part requires more material removal from the face than the diameter. Functions like G71, but cuts along the X-axis and steps in along the Z-axis.

# G72 Parameters

- G72 W2.0 R1.0; G72 P100 Q200 U0.2 W0.2 F0.2; W = Depth of cut in Z R = Retract in Z Removes material face-by-face.

# G74 Axial Grooving / Drilling

- Used for face grooving or peck drilling on a lathe. Allows chip breaking by pecking along the Z-axis. Prevents tool breakage in deep holes on a lathe.

# G74 Example

- G74 R0.5; G74 X... Z-50 P... Q5000 F0.1; Q5000 means 5mm peck depth (in microns). R0.5 is retract amount.

# G75 Radial Grooving Cycle

- Used for cutting grooves on the outside diameter. Pecks along the X-axis to break chips. Can also step along Z to widen a groove.

# Grooving Geometry

otions

# G76 Threading Cycle

- The most powerful turning cycle. Cuts multi-pass threads automatically. Calculates depth of each pass to maintain constant chip load. Handles straight or tapered threads.

# G76 Block 1

- G76 P010060 Q100 R0.05; P01: 1 spring pass 00: Chamfer amount 60: Thread angle (60 deg for metric) Q: Minimum cut depth R: Finishing allowance

# G76 Block 2

- G76 X20.0 Z-30.0 P1226 Q300 F1.5; X, Z: End point of thread P: Thread depth (radial) Q: First pass depth F: Thread pitch (1.5mm)

# Summary

- - G72 for facing. - G74/G75 for grooving and pecking. - G76 simplifies complex threading calculations.

# Next Lecture

- We will transition to Section 4.2 and look at complete Turning and Milling programs.

# Turning Programs

- Structuring a complete CNC Lathe Program

# Agenda

- - Program Header - Tool Selection & Setup - Main Machining Sequence - Program End - Full Example Program

# The Program Header

- Every program starts with a header to establish safe conditions. % (Program start flag) O1001 (Program number) G21 (Metric units) G99 (Feed per revolution)

# Spindle Setup

- Lathes often use Constant Surface Speed (CSS). G50 S2000 (Max spindle speed clamp) G96 S150 M03 (Constant surface speed 150m/min, spindle forward)

# Tool Selection

- T0101; T01 = Tool station 1 on the turret 01 = Offset register 1 (contains geometry and wear offsets) Always call tool at a safe home position (e.g., G28 U0 W0).

# Approach & Roughing

- G00 X52.0 Z2.0 (Rapid to start point) G71 U1.5 R0.5 (Roughing cycle) G71 P10 Q20 U0.5 W0.1 F0.25;

# Defining the Profile

- N10 G00 X0; G01 Z0 F0.1; X20.0 Z-10.0 (Chamfer) Z-30.0 X40.0 X50.0 Z-40.0 N20 Z-50.0;

# Finishing Pass

- After G71, change to finishing tool or use same tool. Optionally change speed/feed for finish. G70 P10 Q20 (Execute profile blocks N10 to N20 with finishing allowances).

# Program End Sequence

- Retract to safe position. Stop spindle and coolant. End program. G28 U0 W0 (Return to home) M09 (Coolant off) M05 (Spindle stop) M30 (End of program and rewind)

# Complete Program Review

- Reviewing O1001 line by line, explaining how the header, roughing, finishing, and footer tie together to create a safe, efficient part.

# Toolpath Visualization

green.

# Summary


- - Lathe programs use CSS (G96) and max speed clamp (G50). - Tools are called with T-codes. - G71/G70 combination is standard for profile turning. - Safe retracts are essential.

# Next Lecture

- We will apply similar structural concepts to CNC Milling programs.

# Milling Programs

- Structuring a complete CNC Mill Program

# Agenda

- - Milling Specifics vs Turning - Work Coordinate Systems (G54) - Tool Length Compensation (G43) - Full Profile Example - Safety Blocks

# Safety Block

- Milling programs start with a 'safety block' to cancel active modes. G40 G49 G80 G90 G21; G40 = Cutter comp cancel G49 = Tool length comp cancel G80 = Canned cycle cancel G90 = Absolute positioning

# Work Coordinate Systems (WCS)

- Unlike lathes, mills use G54 through G59 to define the part zero location on the table. G54 X0 Y0 is typically a corner or the center of the stock. Allows moving the program anywhere on the table.

# Spindle and Tool

- T1 M06 (Tool change to T1) G97 S3000 M03 (Direct RPM, Mills rarely use CSS) G54 G00 X-20. Y-20. (Rapid to WCS origin offset)

# Tool Length Compensation (TLC)

- CRITICAL MILLING CONCEPT. The machine must know how long the tool is to place the tip exactly at Z0. G43 Z10.0 H01; G43 activates TLC, H01 tells it to look at height offset register 1.

# Machining the Profile

- Drop to Z depth: G01 Z-5.0 F100; Mill the square profile: G01 X50. Y-20. F500; Y50.; X-20.; Y-20.;

# Retract and Tool Change

- G00 Z100. (Retract Z) Optionally cancel length comp: G49; M01 (Optional stop before next tool) T2 M06 (Load drill) G43 Z10. H02 (Apply new length comp for drill)

# Drilling Sequence

- G81 X10. Y10. Z-10. R2. F150; (First hole) X40. (Second hole) Y40. (Third hole) X10. (Fourth hole) G80; (Cancel cycle)

# Program End

- G91 G28 Z0; (Return Z to machine home safely in incremental mode) G28 X0 Y0; (Return table to home) M30;

# Milling Toolpath

X0 Y0

# Summary

- - Milling requires G54 for part zero. - Tool changes (M06) and Length Comp (G43/H) are mandatory. - Always cancel cycles (G80) and compensations (G40/G49) when done.

# Next Lecture

- We will dive deeper into Tool Compensation, focusing on Length and Radius.

# Tool Compensation

- Understanding Length and Radius Compensation

# Agenda

- - What is Tool Compensation? - Tool Length Compensation (TLC) - Cutter Radius Compensation (CRC) - G41 vs G42 - Lead-in / Lead-out Moves

# Why Tool Compensation?

- Tools wear down and break. Tools have different lengths and diameters. Without compensation, a program must be rewritten for every specific tool dimension. Compensation allows the program to define the *part geometry*, and the controller adjusts for the *tool geometry*.

# Tool Length Compensation (Review)

- G43 Hxx: Applies positive length offset. The offset register (e.g., H01) stores the physical length of the tool. Allows the programmer to just program Z depths as per the drawing (e.g., Z-10.0).

# Cutter Radius Compensation (CRC)

- Milling cutters have a radius (e.g., a 10mm endmill has a 5mm radius). If you program the tool center to travel exactly on the part line, the part will be undersized by the tool radius. CRC shifts the toolpath left or right by the tool's radius.

# CRC Shift

radius

# G41: Cutter Comp Left

- Used for Climb Milling (standard for CNC). The tool is shifted to the LEFT of the programmed path, looking in the direction of travel. G41 D01 (Activates CRC left, uses diameter offset register 1).

# G42: Cutter Comp Right

- Used for Conventional Milling. The tool is shifted to the RIGHT of the programmed path. G42 D01 (Activates CRC right).

# Turning on CRC (Lead-in)

- CRC cannot be turned on while cutting arcs or during Z-axis plunge. Must be activated during a linear move (G00 or G01) larger than the tool radius. This move is called a lead-in.

# Lead-in Example

- G00 X-20 Y-20 (Start point in space) G41 G01 X0 Y0 D01 F500 (Lead-in move turning on comp) Y50 (Mill part edge)

# G40: Cancel Cutter Comp

- CRC must be canceled when machining is finished, during a lead-out move away from the part. Failure to cancel can result in Gouging on the next move. G40 G01 X-20 Y-20;

# Summary

- - G43/H adjusts for Z length. - G41 (Left) / G42 (Right) adjusts for tool diameter/radius. - D register stores the radius value. - Always use lead-in/lead-out linear moves to activate/cancel CRC.

# Next Lecture

- We will look at Tool Wear offsets and how operators adjust for tool degradation.

# Tool Wear Compensation

- Managing Tool Life and Tolerances on the Machine

# Agenda

- - Geometry vs Wear Offsets - Adjusting for Tool Wear in Lathes - Adjusting for Tool Wear in Mills - Thermal Growth - Best Practices on the Shop Floor

# Geometry vs Wear Offsets

- CNC controls usually have two columns for tool data: Geometry and Wear. Geometry: The primary physical measurement of the tool (e.g., Length = 120.5mm, Radius = 5.0mm). Wear: Minor adjustments made by the operator to keep the part in tolerance (e.g., -0.02mm).

# Why use Wear Offsets?

- As a tool cuts, the cutting edge degrades. An insert on a lathe might wear down by 0.05mm. Instead of reprogramming or changing the master Geometry offset, the operator inputs -0.05 in the Wear column.

# Lathe Wear Adjustment (X-Axis)

- A lathe turns a diameter programmed as X50.0. Inspection shows the part is measuring 50.08mm (oversize). The operator inputs -0.08 in the X-axis Wear offset for that tool. The next part will cut perfectly at 50.00mm.

# Milling Wear Adjustment (Diameter)

- A mill cuts a pocket programmed as 100mm wide using G41. Part measures 99.9mm (undersize pocket - tool left too much material). This means the tool is effectively smaller than expected. Operator inputs a negative wear value (e.g. -0.05 radius wear).

# Thermal Growth

- As machines run, spindles and ball screws heat up and expand. A tool zeroed in the morning may cut 0.03mm deeper in the afternoon. Wear offsets are used to combat this thermal drift continuously throughout the shift.

# Offset Page Interface

and T

# Tool Nose Radius Compensation (TNRC)

- Lathe tool inserts have a radius at the tip (e.g., 0.4mm, 0.8mm). When cutting tapers or radii, this causes dimensional errors if not compensated. G41/G42 is used on lathes just like mills to compensate for the insert radius.

# TNRC Tip Direction

- Lathes require an extra parameter: Tip Direction (T parameter in the offset page). Tells the control how the tool is oriented relative to the workpiece (e.g., T3 for standard OD turning).

# Summary

- - Geometry = Main tool measurement. - Wear = Operator adjustments for degradation and temperature. - Minor adjustments keep production parts in strict tolerance without editing code.

# Next Lecture

- Introduction to Subprograms (M98/M99) to modularize CNC code.

# Subprograms

- Modular Programming using M98 and M99

# Agenda

- - What is a Subprogram? - M98 Subprogram Call - M99 Subprogram Return - Nesting Subprograms - Applications in Milling and Turning

# What is a Subprogram?

- A separate mini-program stored in the machine's memory. Can be called by the main program to execute repetitive tasks. Reduces main program length and makes editing easier.

# The Call: M98

- M98 P_ _ _ _ P specifies the program number to call. Example: M98 P1002 (Calls program O1002).

# The Return: M99

- Every subprogram must end with M99 instead of M30. M99 returns control to the line immediately following the M98 call in the main program.

# Looping Subprograms

- You can call a subprogram multiple times in a row using an L parameter. M98 P1002 L5; This runs program O1002 five times before returning to the main program.

# Program Flow Control

ogram

# Application: Grid of Features

- Milling 5 identical pockets on a plate. Instead of writing the pocket code 5 times, write it once in a subprogram. Main program positions to the first pocket, calls M98, moves to second pocket, calls M98...

# Incremental Subprograms

- Subprograms are highly effective when written in Incremental mode (G91). Main program: G90 G00 X10 Y10 (Absolute start) M98 P2000 Subprogram: G91 G01 Z-5 F100 (Plunges 5mm from current location)...

# Subprogram Nesting

- A subprogram can call another subprogram. Main -¿ Sub 1 -¿ Sub 2. Most controls allow up to 4 levels of nesting.

# Summary

- - M98 Calls, M99 Returns. - Subprograms save memory and simplify code. - L parameter allows looping. - Incremental mode maximizes subprogram reusability.

# Next Lecture

- We will introduce Custom Macros and variables to make programs truly dynamic.

# Macro Programming

- Introduction to Variables in CNC (Parametric Programming)

# Agenda

- - Subprograms vs Macros - What are Macro Variables? - Local, Common, and System Variables - Assigning Values - Basic Arithmetic

# Subprograms vs Macros

- Subprograms repeat fixed code. Macros are dynamic subprograms. They use variables instead of fixed numbers. Fanuc calls this 'Custom Macro B'. Haas calls it 'Advanced Math and Logic'.

# What is a Variable?

- A memory location that stores a number. Instead of writing G01 X50.0, you write G01 X#1. If $\#1 = 50.0$, the machine moves to X50.0. If you change #1 to 75.0, the same code moves to X75.0.

# Local Variables (#1 - #33)

- Used for passing arguments to a macro. Only exist during the execution of that specific macro program. Automatically cleared to 'null' when the macro finishes (M99).

# Common Variables (#100 - #199, #500 - #999)

- Shared across all programs in the machine. #100-#199 clear when power is turned off. #500-#999 remain in memory even after power off (Non-volatile).

# System Variables (#1000+)

- Read or write data directly to the machine's parameters. Read current tool position: #5021 (X-axis position). Change tool offset: #2001 (Tool 1 length offset).

# Assigning Variables

- #1 = 10.0 (Assigns 10.0 to variable #1) #2 = 20.0 G00 X#1 Y#2 (Machine rapids to X10.0 Y20.0)

# Arithmetic Operations

- Macros support math: +, -, *, /, SIN, COS, TAN, SQRT. #3 = #1 + #2 (Evaluates to 30.0) #4 = [ #1 * 2 ] (Brackets used for mathematical grouping, parentheses are for comments).

# Parametric Part Family

- Programming a family of washers. Define #1=OuterDia, #2=InnerDia, #3=Thickness. The entire program runs based on those 3 variables. Change the variables at the top to machine a different size washer instantly.

# Summary

- - Variables replace hardcoded numbers. - Local (#1-33), Common (#100+), System (#1000+). - Allows math operations. - Enables family-of-parts programming.

# Next Lecture

- Macro Control Structures: IF/THEN, WHILE loops, and G65 macro calls.

# Macro Control Structures

- Logic and Looping in Custom Macros

# Agenda

- - Unconditional Branching (GOTO) - Conditional Branching (IF) - Iteration (WHILE / DO) - The G65 Macro Call - Real-World Example

# Unconditional Branching: GOTO

- Forces the program to jump to a specific sequence number (N block). GOTO 100; ... N100 G00 X0 Y0;

# Conditional Branching: IF

- Executes a branch only if a condition is met. IF [ #1 EQ 10.0 ] GOTO 200; Operators: EQ (Equal), NE (Not Equal), GT (Greater Than), LT (Less Than), GE, LE.

# IF Example: Tool Breakage Checking

- (Check if tool offset was forgotten) IF [ #2001 EQ 0 ] GOTO 999; ... N999 #3000 = 1 (TOOL OFFSET IS ZERO); (This triggers a custom machine alarm).

# Iteration: WHILE [ ] DO

- Loops a section of code as long as a condition is true. WHILE [ #1 LT 10 ] DO 1; ... #1 = #1 + 1; END 1;

# WHILE Loop: Deep Pocketing

- #1 = 0 (Current Depth) WHILE [ #1 GT -20.0 ] DO 1; #1 = #1 - 2.0 (Step down 2mm) G01 Z#1 F100; (Pocket Milling Code Here) END 1;

# The G65 Macro Call

- Used to call a macro program and pass variables to it simultaneously. G65 P1010 A5.0 B10.0; Calls program O1010, and assigns A(5.0) to local variable #1, B(10.0) to local variable #2.

# Macro Flowchart

e Path

# Real-World Application: Probing

- Spindle probes use macros heavily. Probe touches part -¿ Updates System Variable with position -¿ Macro calculates center -¿ IF center is out of tolerance, GOTO Alarm, ELSE update Work Offset G54.

# Summary

- - IF and GOTO allow logical decision making. - WHILE/DO allows intelligent looping. - G65 passes variables like arguments to a function. - Macros elevate CNC from simple execution to intelligent automation.

# End of Unit 4

- This concludes Unit 4 on Advanced G & M codes, subprograms, and macros.

- Lecture 30: Introduction to CAM Workflow

# Agenda

# What is CAM?

- Computer Aided Manufacturing (CAM) refers to the use of software to control machine tools and related machinery in the manufacturing of workpieces. It bridges the gap between digital design (CAD) and physical production (CNC).

# Evolution of Manufacturing

- Historically, machinists interpreted blueprints manually to operate machines. CAM automates this by converting 3D models into precise geometric toolpaths, significantly reducing human error and production time.

# CAD/CAM Integration

# The CAM Workflow: Step 1

- Step 1: Import the CAD Model. The process begins by loading a 3D solid or surface model into the CAM system. Supported formats usually include STEP, IGES, Parasolid, or native CAD formats.

# The CAM Workflow: Step 2

- Step 2: Defining the Stock. Stock refers to the raw material block from which the final part will be machined. Defining accurate stock dimensions is critical for safe and efficient toolpath generation.

# The CAM Workflow: Step 3

- Step 3: Setup and Work Coordinate System (WCS). The WCS determines the origin point (X0, Y0, Z0) on the CNC machine. It must match exactly how the physical stock is clamped in the machine vise.

# The CAM Workflow: Step 4

- Step 4: Tool Selection. Choosing the right cutting tools (end mills, drills, face mills) from the tool library based on the material, operation type, and feature size.

# The CAM Workflow: Step 5

- Step 5: Creating Toolpaths. Applying specific machining operations (pocketing, contouring, drilling) to the 3D model features. The CAM software calculates the optimal path for the tool to follow.

# The CAM Workflow: Step 6

- Step 6: Simulation. Visually verifying the toolpaths on screen to detect collisions, gouges, or inefficiencies before sending the code to the real machine.

# The CAM Workflow: Step 7

- Step 7: Post-Processing. Translating the visual toolpaths into machine-specific G-code. Every CNC controller (Fanuc, Haas, Siemens) requires a specific post-processor to format the code correctly.

# Real-World Example

- Manufacturing an engine block: The CAD model is imported, stock (aluminum billet) is defined, roughing toolpaths remove bulk material, finishing paths create smooth cylinder walls, and the resulting G-code runs on a 5-axis mill.

# Summary

# Next Lecture Preview

- In Lecture 31, we will dive deeper into the specific setups and configurations required before generating toolpaths, including workholding considerations.

# Detailed CAM Setup

- Lecture 31: Stock, WCS, and Workholding

# Agenda

# The Foundation of Machining

- A perfect toolpath is useless if the initial setup is incorrect. Setup in CAM involves defining the starting conditions: what the material is, how big it is, and where it is located in machine space.

# Stock Definition Strategies

- Stock can be defined in several ways: a simple rectangular bounding box, a cylindrical tube, or a complex solid body representing a pre-cast or pre-forged part.

# Stock vs. Part Geometry

# Understanding the WCS

- The Work Coordinate System (WCS) is the bridge between the CAM software and the CNC machine. It establishes the X, Y, and Z axes orientations and the origin (0,0,0) point.

# Choosing a WCS Origin

- Common origin points include the top-left-front corner of the stock, or the top-center. The choice depends on how the machinist plans to probe or edge-find the part on the actual machine.

# Workholding in CAM

- Workholding refers to the devices used to secure the stock, such as vises, clamps, or chucks. Modeling these in CAM is crucial to avoid crashing the tool into them.

# Vise Setup Example

- When milling a bracket, the stock is held in a Kurt vise. By importing a 3D model of the vise into the CAM software and designating it as a 'fixture', the software will automatically warn if a toolpath comes too close.

# Multiple Setups

- Most parts cannot be machined from all sides in a single operation. This requires multiple setups (e.g., Setup 1 for the top, Setup 2 for the bottom). Each setup requires its own WCS and stock definition.

# Machine Zero vs. Part Zero

- Machine Zero is the fixed origin of the CNC machine. Part Zero is the WCS origin. The CNC controller uses work offsets (like G54, G55) to translate coordinates from Part Zero to Machine Zero.

# Safe Z and Clearance Planes

- During setup, clearance heights must be defined. The Safe Z plane is the height above the part where the tool can rapid traverse safely without hitting clamps or the part surface.

# Tolerances and Setup Accuracy

- The accuracy of the physical setup must match the CAM setup. If the CAM assumes the stock is perfectly square but the real stock is skewed, the resulting part will be out of tolerance.

# Summary

# Next Lecture Preview

- Now that our virtual part is set up, Lecture 32 will explore Toolpath Strategies, specifically focusing on Roughing operations to remove bulk material quickly.

# Toolpath Strategies

- Lecture 32: Roughing Operations

# Agenda

# The Purpose of Roughing

- Roughing operations are designed to remove the maximum amount of material in the shortest possible time. Surface finish and dimensional accuracy are secondary concerns at this stage.

# Key Characteristics of Roughing

- Roughing typically utilizes large diameter tools, deep depths of cut (axial), and significant stepovers (radial). It leaves a small layer of material ('stock to leave') for subsequent finishing passes.

# Facing Operations

- Facing is usually the first operation. A large face mill sweeps across the top of the stock to create a flat, true reference surface for all subsequent Z-depth calculations.

# 2D Pocketing

- Standard 2D pocketing involves clearing out an enclosed boundary. Traditional strategies offset the boundary inwards or outwards, which can cause sharp corners and spikes in tool load.

# Traditional vs. Dynamic Toolpaths

# High-Efficiency Milling (HEM)

- HEM (or dynamic/adaptive clearing) uses trochoidal motion. It maintains a constant radial engagement angle, preventing the tool from being buried in corners, allowing for full depth-of-cut machining.

# Benefits of Adaptive Clearing

- Because the tool load is strictly controlled, feeds and speeds can be dramatically increased. This reduces cycle times by up to 50% and significantly extends the life of the cutting tool.

# 3D Roughing

- For complex contoured surfaces (like molds), 3D roughing slices the CAD model into horizontal layers (Z-levels). The tool clears material layer by layer, creating a stair-step approximation of the final shape.

# Plunge Roughing

- An alternative strategy where material is removed by plunging the tool axially (like a drill) rather than feeding radially. Excellent for deep, rigid cuts on older machines that lack fast feed rates.

# Rest Roughing

- After a large tool completes initial roughing, it cannot fit into tight corners. 'Rest' (remaining stock) roughing uses a smaller tool to target only the areas the first tool could not reach, saving time.

# Aerospace Application

- Machining an aircraft wing rib from a solid block of titanium relies heavily on adaptive roughing. Removing 80% of the material efficiently is critical to keeping manufacturing costs viable.

# Summary

# Next Lecture Preview

- With the bulk of the material removed, Lecture 33 will focus on Finishing strategies to achieve the final dimensions and required surface quality.

# Toolpath Strategies

- Lecture 33: Finishing Operations

# Agenda

# The Purpose of Finishing

- Finishing operations remove the 'stock to leave' remaining after roughing. The primary goals are to hit exact dimensional tolerances and achieve the specified surface finish.

# Characteristics of Finishing

- Unlike roughing, finishing uses lighter depths of cut, smaller stepovers, and often higher spindle speeds. Deflection of the tool must be minimized to ensure accuracy.

# 2D Contour Profiling

- The most common 2D finishing path. The tool traces the outside perimeter or inside boundary of a part. Often involves multiple light passes ('spring passes') to compensate for tool deflection.

# 3D Finishing: Parallel (Lace)

- A common 3D strategy where the tool moves back and forth across the part in parallel lines. Excellent for shallow areas but leaves large scallops on steep walls.

# 3D Finishing: Waterline (Contour)

- Also known as Z-level finishing. The tool traces constant Z-elevations, stepping down for each pass. Excellent for steep walls, but leaves large scallops on shallow, flat areas.

# Scallop Height Illustration

# Scallop Height Control

- Scallop (or cusp) height is the theoretical ridge of material left between adjacent passes of a ball nose end mill. Smaller stepovers yield smaller scallops and a smoother finish, but drastically increase machining time.

# 3D Finishing: Scallop/Constant Stepover

- An advanced strategy that maintains a constant 3D distance between passes, regardless of the surface slope. This produces a uniform surface finish across the entire part geometry.

# Pencil Milling

- A specialized finishing toolpath where the tool traces along the internal intersections and fillets of a model. It cleans up sharp internal corners that larger finishing tools couldn't reach perfectly.

# Climb vs. Conventional Milling

- For finishing, climb milling is almost universally preferred on modern CNCs. It directs cutting forces into the part, reducing chatter and improving surface finish compared to conventional milling.

# Mold Making Application

- When manufacturing an injection mold for a plastic bottle, 3D scallop finishing with a tiny ball mill and a 0.1mm stepover might run for 20 hours to achieve a mirror-like finish that requires minimal manual polishing.

# Summary

# Next Lecture Preview

- Toolpaths are only as good as the tools executing them. Lecture 34 will cover Tool Selection Criteria and the geometry of cutting tools.

# Tool Selection Criteria

- Lecture 34: Choosing the Right Cutter

# Agenda

# Why Tool Selection Matters

- The cutting tool is the physical interface between the machine and the workpiece. Selecting the wrong tool can lead to poor surface finish, part inaccuracy, tool breakage, or damage to the spindle.

# Flat End Mills

- The workhorse of CNC milling. Used for 2D profiling, pocketing, and facing. They have flat bottoms and sharp corners, ideal for machining flat surfaces and 90-degree internal corners.

# Ball Nose End Mills

- Feature a fully radiused bottom. They are essential for 3D contouring and machining complex organic surfaces, as they leave a smooth scallop pattern rather than stair-steps.

# Bull Nose (Corner Radius) Mills

- A hybrid featuring a flat bottom with radiused corners. Much stronger than flat end mills (less prone to corner chipping) and great for roughing or machining fillets.

# Tool Selection Logic

# Flute Count

- Fewer flutes (2-3) provide more space for chip evacuation, ideal for softer materials like aluminum. More flutes (4-6+) provide a stronger core and better finishes, ideal for harder materials like steel.

# Tool Materials: HSS vs. Carbide

- High-Speed Steel (HSS) is cheaper and tougher but dulls quickly. Solid Carbide is much harder, handles extreme heat, and cuts faster, making it the standard for professional CNC machining.

# Tool Coatings

- Coatings like TiAlN (Titanium Aluminum Nitride) or Diamond increase surface hardness, reduce friction, and insulate the tool from heat, significantly extending tool life in tough materials.

# Tool Deflection

- Long, thin tools act like diving boards and deflect under cutting pressure. CAM programmers must choose the shortest possible tool that can reach the required depth to ensure rigidity.

# Building a CAM Tool Library

- In CAM software, every tool's physical dimensions (diameter, flute length, shoulder length) must be entered precisely. The software uses these dimensions for collision detection.

# Aluminum vs. Titanium

- For cutting aluminum, use a 3-flute uncoated carbide end mill with a high helix angle for chip clearing. For Titanium, use a 5-flute TiAIN coated end mill for strength and heat resistance.

# Summary

# Next Lecture Preview

- Once the tool is selected, how fast should it spin and move? Lecture 35 will cover Speeds, Feeds, and Cutting Parameters.

# Speeds and Feeds

- Lecture 35: Cutting Parameters and Optimization

# Agenda

# The Core Variables

- CAM software requires specific inputs for how fast the tool spins (Speed) and how fast it moves through the material (Feed). These parameters dictate the success of the cutting operation.

# Surface Speed (SFM/Vc)

- Surface speed (Surface Feet per Minute or cutting velocity in m/min) is the speed at which the tool's cutting edge travels through the material. It depends heavily on the material being cut (e.g., fast for aluminum, slow for steel).

# Calculating Spindle Speed (RPM)

- RPM is derived from the recommended Surface Speed and the Tool Diameter. A smaller tool must spin much faster than a large tool to achieve the same surface cutting speed.

# Chip Load (Feed per Tooth)

- Chip load (fz) is the physical thickness of the material removed by one cutting edge in a single revolution. Proper chip load carries heat away from the tool and into the chip.

# Calculating Feed Rate

- Feed Rate (inches per minute or mm/min) = Spindle RPM x Number of Flutes x Chip Load. This is the speed the CNC machine's axes will actually move.

# The Heat Dissipation Mechanism

# The Danger of Rubbing

- If the feed rate is too low, the chip load becomes microscopic. The tool 'rubs' rather than cuts, generating immense friction and heat, rapidly destroying the cutting edge.

# Axial Depth of Cut (Ap)

- How deeply the tool engages along its Z-axis. High-efficiency milling uses a very large axial depth (often the full flute length) to distribute wear evenly.

# Radial Depth of Cut (Ae) - Stepover

- How much the tool steps over in the X/Y plane for each pass. This dictates the width of the cut. Adaptive paths use small radial stepovers combined with deep axial cuts.

# Coolant and Lubrication

- Defining coolant usage (Flood, Mist, Through-Spindle, Air blast) in CAM is vital. It clears chips from the cutting zone and manages temperatures.

# Parameter Calculation

- Machining 1018 Steel with a 10mm 4-flute carbide endmill. Manufacturer recommends Vc = 120 m/min, Chip Load = 0.05mm. RPM = (120 x 1000)/(pi x 10) = 3820 RPM. Feed = 3820 x 4 x 0.05 = 764 mm/min.

# Summary

# Next Lecture Preview

- Before running the generated program on a $100,000 CNC machine, we must prove it is safe. Lecture 36 covers Simulation and Verification.

# Simulation & Verification

- Lecture 36: Proving the CAM Process

# Agenda

# The Cost of Mistakes

- A programming error in CAM can cause the machine spindle to crash into the vise at rapid speeds. This can destroy the tool, ruin the part, damage the spindle bearings, and cause thousands of dollars in downtime.

# Visual Backplotting

- The simplest form of verification. It draws colored lines representing the center of the toolpath over the CAD model. Good for checking general motion but ignores tool thickness and material.

# Solid Material Simulation

- The standard CAM simulation. It visually animates the 3D tool model removing material from the 3D stock model. It shows exactly what the part will look like at every stage of the process.

# Collision and Gouge Detection

- During solid simulation, the software mathematically checks for interferences. A 'gouge' occurs if the tool cuts into the finished part model. A 'collision' occurs if the tool shank or holder hits the stock or fixtures.

# Verification Feedback Loop

# Full Machine Simulation

- Advanced verification involves importing a complete 3D kinetic model of the actual CNC machine (table, trunnion, spindle head). Crucial for 5-axis machining to prevent the machine from crashing into itself.

# Analyzing Machining Time

- Simulation provides accurate estimates of cycle times. Programmers use this data to compare different strategies (e.g., trying a larger stepover) to optimize production efficiency.

# Post-Processing

- Once the simulation is flawless, the CAM paths are translated into G-code by the Post-Processor. The 'Post' acts like a language translator, formatting the generic CAM data into the specific dialect required by the machine's controller (e.g., Haas vs. Fanuc).

# G-Code Verification

- Some independent software (like Vericut) simulates the actual raw G-code rather than the CAM internal data. This provides the absolute highest level of security, catching errors introduced by a faulty post-processor.

# Avoiding a Crash

- During simulation, the programmer notices the tool holder (arbor) turning red. The simulation detected that while the cutting flutes were clear, the holder collided with the vise jaw during a deep pocketing routine. The tool length is adjusted before any metal is cut.

# Summary

# End of Unit 5

- This concludes Unit 5 on the CAM process. You are now familiar with the entire workflow from digital CAD model to simulated physical production.

- 'title': 'Computer Aided Design and Manufacturing', 'subtitle': 'Lecture 37: Model to Machining Workflow - Part 1', 'course_code': 'DI05019031', 'author': 'GTU Faculty'

# Agenda

- Introduction to CAM Workflow
- The CAD-CAM Link
- Geometric Modeling for Machining
- Setup and Coordinate Systems
- Tool Definition and Selection
- Summary

# Introduction to CAM Workflow

- Computer-Aided Manufacturing (CAM) uses software to control machine tools.
- The CAM workflow bridges the gap between digital design and physical production.
- It involves translating a 3D CAD model into precise instructions (toolpaths) for a CNC machine.
- A structured workflow ensures accuracy, efficiency, and safety in manufacturing.

# The CAD-CAM Link

- CAD (Computer-Aided Design) creates the digital representation of the part.
- CAM imports this CAD data directly or via neutral file formats like STEP or IGES.
- Modern systems integrate CAD and CAM (e.g., Fusion 360, Mastercam, NX), allowing associative updates.
- When the CAD model changes, the CAM toolpaths can automatically update, saving time.

# General Model to Machining Workflow

- 'description': 'Flowchart from CAD model to Machined Part', 'elements': ['1. 3D CAD Model Creation', '2. CAM Setup (Stock & Origin)', '3. Operation Selection & Tooling', '4. Toolpath Generation', '5. Simulation & Verification', '6. Post-processing (G-code)', '7. CNC Machining']

# Geometric Modeling for Machining

- Not all CAD features are relevant for machining; CAM requires specific geometry analysis.
- Surface topology, draft angles, and fillets are evaluated for machinability.
- Sometimes, manufacturing models require 'defeaturing' (removing non-machined holes or adding stock).
- The geometry dictates the type of machining operations required (2D, 3-axis, or 5-axis).

# CAM Setup: Defining the Stock

- The 'Stock' is the raw material block from which the final part will be machined.
- It can be defined as a rectangular block, a cylinder, or a custom casting shape.
- Accurate stock definition is critical for calculating material removal and avoiding tool collisions.
- Stock allowances must be considered for roughing and finishing operations.

# Setup and Coordinate Systems (WCS)

- Work Coordinate System (WCS) defines the origin (X0, Y0, Z0) on the CNC machine.
- In CAM, the user must align the digital WCS with how the stock will be clamped in the machine.
- Proper orientation ensures the tool approaches from the correct direction (e.g., Z-axis pointing up).
- Multiple setups may be required if the part needs to be flipped and machined from multiple sides.

# Example: WCS Placement

- Consider a rectangular block to be milled on a 3-axis VMC.
- The WCS origin is commonly placed at the top-left corner of the stock.
- Z0 is often set to the top surface of the stock to allow easy tool length offsets.
- This aligns the CAM software's coordinates with the machine operator's physical setup.

# Tool Definition and Selection

- Selecting the correct cutting tool is a fundamental step in the workflow.
- Tools are defined by parameters: type (end mill, drill), diameter, flute length, and material.
- Tool libraries in CAM software store these parameters along with recommended speeds and feeds.
- Using the correct tool geometry is vital for achieving the desired surface finish and dimensional accuracy.

# Speeds and Feeds Setup

- Spindle Speed (RPM) and Feed Rate (mm/min) must be calculated based on the tool and stock material.
- CAM software often calculates these automatically based on material libraries and tool manufacturer data.
- Optimizing speeds and feeds maximizes Material Removal Rate (MRR) while minimizing tool wear.
- Coolant options (flood, mist, air) are also defined at this stage.

# Workholding and Fixtures

- Workholding devices (vises, clamps, chucks) must be modeled or accounted for in CAM.
- Defining fixtures allows the CAM software to detect potential collisions between the tool and the clamps.
- Proper workholding ensures rigidity during machining, reducing vibration and chatter.
- It also determines the accessible areas of the part in a single setup.

# Summary

- The CAD-CAM workflow is a structured process to turn digital models into physical parts.
- It begins with importing the CAD model and defining the raw stock material.
- Setting the correct Work Coordinate System (WCS) is critical for machine alignment.
- Selecting appropriate tools and defining workholding setup the foundation for generating toolpaths.

# Next Lecture Preview

- In the next lecture, we will cover Part 2 of the Model to Machining Workflow.
- Topics will include Toolpath Generation strategies.
- We will explore Simulation, Verification, and Optimization of toolpaths.
- Understanding how to catch errors before sending code to the machine.

- 'title': 'Computer Aided Design and Manufacturing', 'subtitle': 'Lecture 38: Model to Machining Workflow - Part 2', 'course_code': 'DI05019031', 'author': 'GTU Faculty'

# Agenda

- Toolpath Generation
- Roughing vs. Finishing Strategies
- Toolpath Simulation
- Verification and Collision Detection
- Toolpath Optimization
- Summary

# Toolpath Generation Introduction

- Toolpath generation is the core function of CAM software.
- It involves calculating the specific trajectory the cutting tool will follow to remove material.
- Toolpaths are categorized into 2D (prismatic), 3D (surfacing), and multi-axis (4 or 5-axis) operations.
- The goal is to efficiently remove material while maintaining precision and surface finish.

# Roughing Strategies

- Roughing aims to remove the maximum amount of material as quickly as possible.
- Accuracy and surface finish are secondary concerns during this phase.
- Common strategies: Pocketing, Facing, and Adaptive Clearing (High-Efficiency Machining).
- Roughing leaves a small amount of 'stock allowance' for subsequent finishing operations.

# Example: Adaptive Clearing vs. Traditional Roughing

- Traditional Roughing uses stepovers based on tool diameter, often causing spikes in tool engagement load in corners.
- Adaptive Clearing maintains a constant tool engagement angle.
- It uses fluid, circular motions, allowing for deeper cuts and faster feed rates while extending tool life.

# Finishing Strategies

- Finishing operations remove the remaining stock left by roughing.
- The primary goal is to achieve the final dimensions, tolerances, and surface finish.
- Common 3D finishing strategies include Parallel, Scallop, Contour, and Pencil milling.
- Stepovers are very small to minimize the 'cusp height' (scallops left between tool passes).

# Toolpath Parameters

- Stepdown (Depth of Cut): The distance the tool moves down in the Z-axis for each pass.
- Stepover (Width of Cut): The distance the tool moves sideways between adjacent passes.
- Lead-in / Lead-out: How the tool enters and exits the material (e.g., arc, ramp, plunge).
- Proper parameter selection balances machining time and part quality.

# Toolpath Simulation

- Simulation provides a visual representation of the machining process on the computer screen.
- It animates the tool moving along the calculated path, showing material being removed from the stock.
- Allows programmers to verify that the tool is cutting the intended areas.
- It is the first line of defense against programming errors before actual machining.

# Simulation Workflow

- 'description': 'Simulation cycle in CAM', 'elements': ['Generate Toolpath', 'Run Visual Simulation', 'Analyze Material Removal', 'Check for Collisions', 'Modify Parameters if needed', 'Regenerate and Re-simulate']

# Verification and Collision Detection

- Verification goes beyond visual simulation by mathematically checking for interference.
- Collision detection ensures the tool holder, spindle, or machine components do not hit the part or fixtures.
- Gouge checking ensures the cutting tool does not cut into the final part model (overcutting).
- Advanced software simulates the entire machine kinematics (Machine Simulation).

# Toolpath Optimization

- Optimization involves refining toolpaths to reduce machining time and improve quality.
- Techniques include minimizing 'air cutting' (cutting where no material exists).
- Feed rate optimization automatically adjusts feeds based on material engagement.
- Smoothing arcs reduces sharp corners in the toolpath, allowing the CNC machine to run faster and smoother.

# Final Output of CAM Workflow

- Once toolpaths are generated, simulated, verified, and optimized, the CAM process is complete.
- The output is a set of generic location data, often called CL-Data (Cutter Location Data).
- This data must still be translated into the specific language understood by the CNC machine.
- This translation process is called Post-processing, which will be covered next.

# Summary

- Toolpath generation is divided into roughing for material removal and finishing for final dimensions.
- Simulation visualizes the cutting process to ensure correct programming.
- Verification and collision detection are critical for machine safety and preventing scrap parts.
- Optimization refines the process for efficiency before proceeding to post-processing.

# Next Lecture Preview

- In the next lecture, we will dive into Post-processing.
- We will understand what a post-processor is and why it is necessary.
- Topics include CL-Data and its translation into G-code.
- We will bridge the gap between CAM software and the physical CNC controller.

# Computer Aided Design and Manufacturing


- 'title': 'Computer Aided Design and Manufacturing', 'subtitle': 'Lecture 39: Post-processing - Part 1', 'course_code': 'DI05019031', 'author': 'GTU Faculty'

# Agenda

- Concept of Post-processing
- Why is Post-processing Required?
- Cutter Location Data (CL-Data)
- The Translation Process
- Introduction to G-code and M-code
- Summary

# Concept of Post-processing

- Post-processing is the final computational step in the CAM workflow.
- It acts as a 'translator' between the generic CAM software and the specific CNC machine.
- The CAM software calculates toolpaths independent of the machine tool.
- The post-processor converts these generic toolpaths into machine-specific NC (Numerical Control) code.

# Why is Post-processing Required?

- There is no universal, standardized language that every CNC machine understands exactly the same way.
- Different controller brands (Fanuc, Siemens, Haas, Heidenhain) have different syntax and formatting rules.
- Machines have different physical configurations (axis limits, rotary tables, tool changers).
- A post-processor tailors the code to match the exact requirements of the target machine.

# The Post-processing Flow

- 'description': 'Flow from CAM to Machine', 'elements': ['1. CAM Software (Toolpath calculation)', '2. CL-Data File (Generic format)', '3. Post-Processor Software (Translator)', '4. Machine Configurations / Kinematics', '5. G-code File (Machine specific)', '6. CNC Machine Controller']

# Cutter Location Data (CL-Data)

- When CAM software calculates a toolpath, it outputs an intermediate file known as CL-Data.
- CL-Data contains the generic coordinates (X, Y, Z, I, J, K) of the tool center point.
- It includes vectors for tool orientation in multi-axis machining.
- It is machine-independent; it knows the path but not how to command a specific machine to move there.

# Example: CL-Data vs. G-code

- CL-Data might specify: 'Move from Point A to Point B in a straight line at feed rate F'.
- A Fanuc Post-processor translates this to: 'G01 X50.0 Y20.0 F1500;'.
- A Heidenhain Post-processor might translate it to: 'L X+50 Y+20 F1500'.
- The post-processor bridges this linguistic gap.

# The Translation Process

- The post-processor reads the CL-Data sequentially.
- It applies coordinate transformations based on the machine's kinematics (e.g., pivot lengths).
- It formats the output into blocks (lines) of code.
- It adds necessary 'header' and 'footer' information (e.g., starting the spindle, ending the program).

# Introduction to G-code and M-code

- The resulting output is typically an alphanumeric program, commonly referred to as G-code.
- G-codes (Preparatory codes) prepare the machine for a specific type of motion (e.g., rapid traverse, linear feed).
- M-codes (Miscellaneous codes) control machine hardware functions (e.g., coolant on/off, spindle on/off).
- The combination of G, M, and coordinate data drives the machine.

# Components of a Post-processed Program

- Program Header: Program name, units setup (G20/G21), safety blocks.
- Tool Change Block: Calling the tool (T1 M06), setting tool length offsets.
- Motion Blocks: The actual cutting moves generated from CL-Data.
- Program Footer: Turning off coolant, stopping spindle, returning to home, end of program (M30).

# Errors in Post-processing

- Using the wrong post-processor can cause disastrous machine crashes.
- If the CAM software simulates perfectly but the post-processor is flawed, the machine will execute flawed code.
- Post-processors must handle machine limits; if a coordinate exceeds axis travel, it must generate an error.
- Thorough testing (cutting air or foam) is required when using a new post-processor.

# Standardization Attempts

- Historically, RS-274D was a standard for G-code, but variations proliferated.
- STEP-NC (ISO 14649) is an ongoing effort to eliminate G-code and post-processors.
- STEP-NC aims to send the actual CAD/CAM data directly to the CNC controller, making it 'smart'.
- However, traditional post-processing remains the industry standard today.

# Summary

- Post-processing translates generic CAM CL-Data into machine-specific NC code.
- It is essential because different CNC controllers have different programming languages and kinematics.
- The output is typically a G-code program structured with headers, tool changes, motion blocks, and footers.
- Accurate post-processing is critical for safe and correct CNC machine operation.

# Next Lecture Preview

- In the next lecture, we will explore Post-processing Part 2.
- We will discuss customizing post-processors for specific shop floor needs.
- We will look deeper into machine-specific codes and macro programming.
- Understanding how to tweak the 'translator' for optimal results.

# Computer Aided Design and Manufacturing

- 'title': 'Computer Aided Design and Manufacturing', 'subtitle': 'Lecture 40: Post-processing - Part 2', 'course_code': 'DI05019031', 'author': 'GTU Faculty'

# Agenda

- Customizing Post-processors
- Post-builder Software
- Handling Machine Kinematics
- Machine Specific Codes & Cycles
- Validating Post-processed Code
- Summary

# Customizing Post-processors

- Out-of-the-box generic post-processors rarely fit every machine perfectly.
- Customization is required to align the code with specific shop floor practices.
- Examples: Adding specific safe tool-change positions, customizing coolant M-codes, or adding operator messages.
- Customization ensures the machine operator doesn't have to manually edit the G-code every time.

# Post-builder Software

- CAM systems provide tools known as 'Post Builders' or 'Post Configurers'.
- These are development environments specifically for creating and editing post-processors.
- They use scripting languages (like JavaScript, TCL, or proprietary languages) to define translation rules.
- Users can define block templates, variable formats, and mathematical transformations.

# Example: Custom Scripting

- A user wants to ensure the machine always stops (M00) before tapping a hole to apply cutting fluid.
- In the post-builder, a script is added to the 'Tap Cycle' event.
- Script logic: 'If Tool_Type == Tap, then output block M00; before outputting G84;'.
- This automates a safety protocol directly into the generated code.

# Handling Machine Kinematics

- For 4-axis and 5-axis machines, the post-processor must calculate kinematics.
- It translates tool tip coordinates from the CAM system into physical rotary axis angles (A, B, or C).
- It must account for the pivot distance between the rotary center and the tool tip (RTCP - Rotary Tool Center Point).
- Errors in kinematic definitions lead to severe positional inaccuracies during multi-axis machining.

# Kinematic Transformation

- 'description': 'Transforming Tool Vector to Rotary Angles', 'elements': ['Tool Vector (I, J, K) from CL-Data', 'Machine Configuration (e.g., Trunnion AB)', 'Inverse Kinematics Calculation in Post', 'Output Rotary Angles (e.g., A45.0 B90.0)', 'Tool Center Point Control (TCPC) active']

# Machine Specific Canned Cycles

- Controllers have built-in 'Canned Cycles' (e.g., G81 for drilling, G83 for peck drilling) to simplify programming.
- The CAM system calculates point-to-point moves, but the post-processor optimizes this by calling the machine's canned cycle.
- This drastically reduces the file size of the G-code program.
- The post-processor maps CAM drilling parameters to the specific parameters expected by the controller's cycle.

# Handling Advanced Controller Features

- Modern controllers offer features like High-Speed Machining (HSM) modes (e.g., Fanuc G05.1 Q1).
- The post-processor must be configured to turn these modes on before complex 3D surfacing and off afterward.
- Probing cycles for automatic part setup are also generated via customized post-processor events.
- It unlocks the full potential of expensive CNC hardware.

# Validating Post-processed Code

- Just because a post-processor generates code doesn't mean it's safe.
- G-code verification software (e.g., VERICUT, NCSIMUL) is used to simulate the actual NC code.
- This differs from CAM simulation, which simulates the ideal CL-Data.
- Verification catches errors introduced by faulty post-processor logic before they reach the machine.

# The Role of the Application Engineer

- Developing robust 5-axis post-processors is a highly specialized skill.
- Application Engineers often spend weeks tuning a post-processor during a new machine installation.
- It requires deep knowledge of both the CAM software architecture and the specific CNC controller's manuals.
- A reliable post-processor is considered a highly valuable asset in a manufacturing facility.

# Summary

- Customizing post-processors aligns generated code with specific machine capabilities and shop standards.
- Post-builder software uses scripting to define translation rules and handle complex machine kinematics.
- Post-processors optimize code by utilizing machine-specific canned cycles and advanced features.
- Independent G-code verification is essential to validate custom post-processors and ensure safety.

# Next Lecture Preview

- In the next lecture, we will cover CNC Data Transfer (DNC).
- Once we have the perfect G-code file, how do we get it into the machine?
- We will explore RS-232, Ethernet, and Direct Numerical Control networks.
- Understanding modern shop-floor connectivity.

- 'title': 'Computer Aided Design and Manufacturing', 'subtitle': 'Lecture 41: CNC Data Transfer (DNC)', 'course_code': 'DI05019031', 'author': 'GTU Faculty'

# Agenda

- Introduction to Data Transfer
- Historical Methods (Punched Tape)
- Direct Numerical Control (DNC)
- RS-232 Serial Communication
- Modern Ethernet and Wireless Transfer
- Distributed Numerical Control
- Summary

# Introduction to CNC Data Transfer

- After post-processing, the NC program (G-code) exists as a digital file on a PC.
- This file must be transferred to the memory of the CNC machine's controller to be executed.
- The method of data transfer has evolved significantly from physical media to advanced networking.
- Efficient data transfer is crucial for minimizing machine downtime in a busy shop.

# Historical Methods

- Early NC machines used punched tape (paper or Mylar) to read instructions.
- The tape was physically carried to the machine and fed through a tape reader.
- Later, floppy disks and eventually USB flash drives became common for physical transfer ('sneakernet').
- While USB is still used today, physical transfer is inefficient for large-scale operations or frequent program updates.

# What is DNC?

- DNC stands for Direct Numerical Control (or Distributed Numerical Control).
- Originally, Direct Numerical Control meant a central mainframe computer directly controlling multiple machine tools without intermediate tape readers.
- The central computer sent blocks of code to the machine in real-time as it was cutting ('drip-feeding').
- This was necessary because early CNC controllers had very limited memory.

# Classic DNC Architecture

- 'description': 'Direct Numerical Control Layout', 'elements': ['Central DNC Server / PC', 'Communication Network (Serial RS-232 cables)', 'Machine 1 (Receiving drip-feed data)', 'Machine 2 (Receiving drip-feed data)', 'Machine 3 (Receiving drip-feed data)']

# Drip-feeding and Limited Memory

- Complex 3D surfacing programs can be tens of megabytes in size.
- Older controllers only had kilobytes of memory.
- Drip-feeding solves this: the PC sends a few lines of code via DNC, the machine executes them and deletes them, then the PC sends the next few lines.
- The machine is 'fed' continuously while cutting.

# RS-232 Serial Communication

- For decades, the standard hardware interface for DNC was the RS-232 serial port.
- It involves configuring baud rate (speed), parity, data bits, and stop bits to match the PC and the machine.
- RS-232 is notoriously slow and susceptible to electrical noise over long cable runs.
- However, its simplicity meant it was universally supported by controller manufacturers.

# Example: RS-232 Handshaking

- Software Handshaking (XON/XOFF): The machine sends a stop signal (XOFF) to the PC when its buffer is full, and a start signal (XON) when it needs more code.
- Hardware Handshaking (RTS/CTS): Uses specific electrical pins in the cable to signal readiness to send/receive.
- Proper handshaking prevents data loss and machine crashes during drip-feeding.

# Distributed Numerical Control (Modern DNC)

- Today, DNC usually stands for Distributed Numerical Control.
- Modern controllers have gigabytes of memory, so drip-feeding is rarely needed.
- Modern DNC is a network system that manages, stores, and transfers NC programs to machines via local area networks (LAN).
- It ensures version control (ensuring the operator uses the latest program version) and data management.

# Modern Ethernet and Wireless Transfer

- Most modern CNC machines feature standard Ethernet (RJ45) ports or Wi-Fi capabilities.
- They connect to the factory network just like any standard office computer.
- Transfer speeds are incredibly fast compared to RS-232.
- Operators can often browse the factory server directly from the CNC controller screen to pull down the required programs.

# Industry 4.0 and Machine Monitoring

- Modern network connections do more than just send G-code to the machine.
- They allow data to flow back from the machine to the server (two-way communication).
- Protocols like MTConnect or OPC UA allow monitoring of machine status, spindle load, cycle times, and alarms.
- This data transfer is the foundation of smart manufacturing and predictive maintenance.

# Summary

- CNC Data Transfer has evolved from punched tapes to advanced Ethernet and wireless networks.
- Direct Numerical Control (DNC) was originally used to 'drip-feed' large programs to machines with limited memory via RS-232.
- Modern Distributed Numerical Control focuses on program management, version control, and rapid transfer via LAN.
- Modern connectivity enables Industry 4.0 data collection and real-time machine monitoring.

# Unit Conclusion

- This concludes Unit 6: CAM Workflows and Data Transfer.
- We have covered the complete digital thread from importing a CAD model, generating toolpaths, post-processing to G-code, and transferring it to the machine.
- You now understand the software processes required to drive modern CNC manufacturing.

- Lecture 42: Introduction to Industry 4.0

# Agenda

# Evolution of Industry

- The industrial revolution has gone through four distinct phases: 1. **Industry 1.0 (1784)**: Mechanization, water power, steam power. 2. **Industry 2.0 (1870)**: Mass production, assembly line, electrical energy. 3. **Industry 3.0 (1969)**: Automation, computers, and electronics. 4. **Industry 4.0 (Today)**: Cyber-physical systems, internet of things, networks.

# The Four Industrial Revolutions

# What is Industry 4.0?

- Industry 4.0 refers to the integration of intelligent digital technologies into manufacturing and industrial processes. * It encompasses a set of technologies that include industrial IoT networks, AI, Big Data, robotics, and automation. * The goal is to create a 'Smart Factory' where machines, systems, and humans communicate with each other seamlessly.

# Core Principles of Industry 4.0

- To implement Industry 4.0, a system must follow four design principles:
  1. **Interconnection**: The ability of machines, devices, sensors, and people to connect and communicate. 2. **Information Transparency**: Creating a virtual copy of the physical world through sensor data. 3. **Technical Assistance**: Systems supporting humans by visualizing data comprehensively and performing unsafe tasks. 4. **Decentralized Decisions**: Cyber-physical systems making simple decisions autonomously.

# Information Transparency

- Information transparency provides operators with vast amounts of useful information needed to make appropriate decisions. * **Digital Sensor Data**: Enriches physical models with context. * **Real-time Monitoring**: Identifying bottlenecks instantly. * **Predictive Maintenance**: Anticipating failures before they occur based on transparent operational data.

# Example: The Smart Factory

- In a Smart Factory, a CNC machine detects that its cutting tool is wearing out faster than expected.
  Instead of failing and stopping the line, it autonomously orders a replacement tool from the inventory system, adjusts its cutting speed to prevent immediate failure, and alerts maintenance staff to replace the tool during the next scheduled downtime.

# Cyber-Physical Systems (CPS)

- Cyber-Physical Systems are integrations of computation, networking, and physical processes.
  * **Embedded computers and networks** monitor and control the physical processes. * They form the basis of the Industrial Internet of Things (IIoT). * Examples include smart grids, autonomous automobile systems, and medical monitoring.

# Internet of Things in Manufacturing

- The Industrial Internet of Things (IIoT) is a critical component of Industry 4.0.
  * **Connectivity**: Connects industrial assets, such as machines and control systems, to information systems. * **Data Gathering**: Collects large volumes of data for analysis. * **Efficiency**: Improves efficiency, safety, and productivity.

# Cloud Computing & Big Data

- The massive data generated by IoT devices requires robust storage and analysis capabilities.
  * **Cloud Computing**: Provides scalable resources for data storage and complex computations. * **Big Data Analytics**: Analyzes patterns to optimize manufacturing processes and predict trends. * **AI/Machine Learning**: Uses data to learn and improve processes autonomously.

# Benefits of Industry 4.0

- Adopting Industry 4.0 brings significant advantages to manufacturing:
  * **Increased Productivity**: Optimized processes and reduced downtime. * **Flexibility**: Easier adaptation to changes in production requirements. * **Customization**: Cost-effective production of customized products (mass personalization). * **Resource Efficiency**: Optimized use of materials and energy.

# Challenges in Implementation

- Despite its benefits, Industry 4.0 faces several hurdles: * **Cybersecurity**: Increased connectivity raises vulnerability to cyber-attacks. * **High Initial Investment**: Significant costs for upgrading equipment and software. * **Skills Gap**: Need for a workforce skilled in IT, data analytics, and modern manufacturing. * **Standardization**: Lack of universal standards for interoperability.

# Key Takeaways

# Next Lecture

- In the next lecture, we will explore the concept of the **Digital Twin**, a virtual representation of a physical object or system, and its role in modern manufacturing.

# Unit 7: Recent Trends in Manufacturing

- Lecture 43: Digital Twin Technology

# Agenda

# Introduction to Digital Twin

- A Digital Twin is a highly complex virtual model that is the exact counterpart (or twin) of a physical thing.
  * It represents the physical asset in real-time. * The connection is established via sensors on the physical object collecting data. * This data is mapped onto the virtual model, allowing researchers to observe how the physical counterpart is performing.

# Why Digital Twin?

- Digital Twin technology is essential for modern product lifecycle management.
  * **Predictive Capability**: Allows predicting the future behavior and performance of the physical asset. * **Continuous Improvement**: Facilitates continuous optimization based on real-world operating conditions. * **Risk Reduction**: Testing scenarios virtually before applying them physically.

# Physical Space vs Virtual Space

# Key Components of Digital Twin

- A functioning Digital Twin requires three primary components: 1. **Physical Product**: The real-world object or system. 2. **Virtual Product**: The digital representation in a software environment. 3. **Connection**: Data and information that ties the physical and virtual products together in real-time.

# Sensors and Data Acquisition

- Sensors are the bridge between the physical and digital worlds. * **Types of Data**: Temperature, vibration, speed, pressure, position. * **IoT Integration**: Sensors communicate over industrial networks (IIoT). * **Fidelity**: High-fidelity sensors ensure the virtual model accurately reflects the physical state.

# Data Processing and Modeling

- Once data is collected, it must be processed and applied to the model.
  * **3D CAD Models**: Form the geometric baseline of the twin.
  * **Physics-based Models**: Simulate real-world physics (stress, heat, fluid dynamics). * **Data Analytics/AI**: Analyze historical and real-time data to find anomalies.

# Example: Digital Twin in Automotive Engine

- An automotive manufacturer creates a digital twin of an engine.
  As a customer drives the real car, sensors transmit data on RPM, temperature, and wear to the digital twin. The manufacturer uses this twin to identify that a specific driving habit causes premature wear on a component, allowing them to release a software update or recall the part before failure.

# Digital Twin vs Simulation

- While both use digital models, they have distinct differences: * **Simulation**: Typically studies one particular process, usually offline and without real-time data integration. * **Digital Twin**: Integrates real-time data and can run multiple simulations concurrently to study multiple processes simultaneously.

# Lifecycle Management with Digital Twin

- Digital Twins span the entire product lifecycle: * **Design**: Simulating performance before prototyping. * **Manufacturing**: Monitoring the production line and reducing defects. * **Operation**: Predictive maintenance and real-time monitoring. * **End-of-Life**: Planning for recycling or phase-out.

# Benefits in Manufacturing

- Implementing Digital Twins brings numerous benefits: * **Reduced Time to Market**: Faster prototyping and design validation. * **Lower Maintenance Costs**: Predictive maintenance avoids expensive breakdowns. * **Enhanced Productivity**: Process bottlenecks are easily identified virtually. * **Improved Quality**: Real-time adjustments keep parameters within tolerances.

# Challenges and Security

- Challenges in adopting Digital Twin technology:
  * **Data Security**: Transmitting sensitive operational data to cloud environments. * **Complexity**: Developing accurate physics-based models is computationally expensive. * **Integration**: Connecting legacy systems that lack modern sensor capabilities.

# Key Takeaways

# Next Lecture

- In our next lecture, we will dive into **Additive Manufacturing**, commonly known as 3D printing, and how it is revolutionizing the production of physical components.

- Lecture 44: Additive Manufacturing (3D Printing)

# Agenda

# Introduction to Additive Manufacturing

- Additive Manufacturing (AM), commonly known as 3D printing, is the process of joining materials to make objects from 3D model data.
  * Material is added layer upon layer. * It contrasts heavily with traditional subtractive manufacturing methodologies (like machining). * AM is used for rapid prototyping, tooling, and direct part manufacturing.

# Basic Principles of AM

- The fundamental principle of all AM processes involves taking a 3D digital model and slicing it into 2D cross-sections. * **Digital Foundation**: Every AM process starts with a CAD model. * **Slicing**: Software translates the 3D model into thin horizontal layers (G-code). * **Layer-by-Layer Building**: The printer reads the code and deposits/cures material one layer at a time.

# Additive Manufacturing Workflow

# Types of Additive Manufacturing

- AM processes are categorized based on how the layers are deposited and fused. ASTM classifies them into seven categories:
  1. Material Extrusion 2. Vat Photopolymerization 3. Powder Bed Fusion 4. Material Jetting 5. Binder Jetting 6. Directed Energy Deposition 7. Sheet Lamination

# Material Extrusion (FDM)

- Fused Deposition Modeling (FDM) is the most common AM technology.
  * **Mechanism**: A thermoplastic filament is heated to its melting point and extruded layer by layer. * **Materials**: PLA, ABS, PETG, Nylon. * **Applications**: Rapid prototyping, educational models, non-critical functional parts.

# Vat Photopolymerization (SLA)

- Stereolithography (SLA) uses a light source to cure liquid resin. * **Mechanism**: A UV laser or projector cures photosensitive liquid resin layer by layer. * **Characteristics**: Extremely high resolution and smooth surface finish. * **Applications**: Jewelry casting, dental models, highly detailed prototypes.

# Powder Bed Fusion (SLS & DMLS)

- Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) fuse powder.
  * **Mechanism**: A high-power laser sinters polymer or metal powder particles together. * **Self-Supporting**: Unfused powder supports the part, eliminating the need for support structures. * **Applications**: Strong, functional parts, aerospace components.

# Example: Medical Implants

- Additive manufacturing is revolutionizing custom healthcare. Using DMLS (Direct Metal Laser Sintering), a titanium hip replacement can be 3D printed based on a patient's CT scan. The implant fits the patient perfectly, and the print can include a porous surface structure that encourages bone growth into the implant, improving long-term success.

# AM vs Subtractive Manufacturing

- How does AM compare to CNC machining?
  * **Waste**: AM produces very little waste (additive); CNC cuts material away (subtractive, high waste). * **Complexity**: AM allows complex internal geometries impossible with CNC (complexity is 'free'). * **Speed/Volume**: CNC is much faster and cheaper for high-volume mass production.

# Advantages of Additive Manufacturing

- Key benefits that drive AM adoption:
  * **Design Freedom**: Ability to create organic shapes and internal channels. * **Rapid Prototyping**: Drastically reduces time from design to physical part. * **Customization**: Economical production of one-off custom parts. * **Lightweighting**: Designing parts using topology optimization and lattice structures.

# Limitations of AM

- Despite rapid growth, AM has limitations:
  * **Production Speed**: Slow process, not suited for mass manufacturing millions of parts. * **Material Properties**: Anisotropy (parts are weaker in the Z-axis due to layer lines).
  * **Post-Processing**: Often requires support removal, sanding, or heat treatment. * **Size Constraints**: Limited by the build volume of the 3D printer.

# Key Takeaways

# Next Lecture

- In our final lecture for this unit, we will discuss **Automation Integration**, exploring how these advanced technologies are connected and managed in a modern manufacturing environment.

- Lecture 45: Automation Integration

# Agenda

# What is Automation Integration?

- Automation integration is the process of connecting disparate manufacturing systems, software, and machinery into a single, cohesive unit.
  * It ensures that data flows seamlessly from the shop floor to the top-level management. * It moves a factory from isolated 'islands of automation' to a fully connected enterprise. * Fundamental for realizing Industry 4.0.

# The Automation Pyramid

# Field Level & Control Level

- The bottom layers of the automation pyramid interact directly with the physical world.
  * **Field Level (Level 0)**: Sensors, actuators, motors, and switches. They gather data and execute actions. * **Control Level (Level 1)**: PLCs (Programmable Logic Controllers) and CNCs. They receive sensor data, apply logic, and command actuators.

# Supervisory Level (SCADA)

- Level 2 involves Supervisory Control and Data Acquisition (SCADA).
  * **Function**: Monitors and controls multiple PLCs/systems across the factory floor. * **HMI (Human-Machine Interface)**: Provides visual dashboards for human operators to track machine status. * **Data Logging**: Records operational data and alarms for analysis.

# Planning Level (MES)

- Level 3 is the Manufacturing Execution System (MES). * **Function**: Manages and monitors work-in-progress on the factory floor. * **Tracking**: Tracks materials, labor, and machine time. * **Bridge**: Acts as the crucial bridge between business systems (ERP) and control systems (SCADA).

# Management Level (ERP)

- Level 4 is Enterprise Resource Planning (ERP).
  * **Function**: Top-level business management software. * **Scope**: Manages finance, HR, supply chain, and customer orders. * **Integration**: When an order is placed in ERP, integration ensures MES schedules it, SCADA monitors it, and PLCs execute it automatically.

# Example: Fully Integrated Assembly Line

- A customer orders a custom car online (ERP). The ERP system instantly checks inventory and sends the order to the MES.
  The MES schedules the production and commands the shop floor SCADA. As the car chassis arrives at a station, the PLC receives the specific robot program for that custom build. The robot welds the custom part, sensors confirm quality, and data flows back up to the ERP, notifying the customer their car is being built.

# Role of PLCs and CNCs in Integration

- Programmable Logic Controllers (PLCs) and Computer Numerical Control (CNC) machines are the workhorses. * Modern PLCs/CNCs must have advanced networking capabilities (Ethernet/IP, PROFINET). * They must be capable of transmitting state data (running, idle, fault) upward to MES/SCADA systems.

# Communication Protocols

- Integration relies on standardized communication languages to let machines talk.
  * **Fieldbus/Industrial Ethernet**: PROFINET, EtherCAT, Modbus TCP. * **OPC UA (Open Platform Communications Unified Architecture)**: The standard for industrial interoperability, allowing secure data exchange from sensors to IT systems.

# Benefits of Automation Integration

- Why invest in full integration?
  * **Real-time Visibility**: Management can see exact production metrics instantly. * **Error Reduction**: Eliminates manual data entry between systems. * **Agility**: Faster response to supply chain issues or changing customer demands. * **Traceability**: Complete tracking of every part and process step for quality control.

# Barriers to Integration

- Challenges faced during integration projects:
  * **Legacy Equipment**: Older machines lack networking capabilities and require retrofitting. * **Siloed Departments**: IT (Information Technology) and OT (Operational Technology) often have different goals and security practices.
  * **High Costs**: Upgrading software and infrastructure across an enterprise is expensive.

# Unit 7 Summary

# Course Conclusion

- This concludes Unit 7 and the course on Computer Aided Design and Manufacturing. The future of manufacturing relies on engineers who understand both traditional methods and these emerging digital technologies.