Computer Numerical Control (Part-6)

6ME4-02: Computer Integrated Manufacturing Systems

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Adaptive Control (AC) Machining Systems

- Definition: A control system that measures certain output process variables and uses these to control speed and/or feed.
- Process variables: Spindle deflection or force, torque, cutting temperature, vibration amplitude and horsepower.
- AC determines the proper speeds and/or feeds during machining as a function of variations.
- AC is try to operate the process more efficient
- The typical measures of performance in machining have been metal removal rate (MRR) and cost per volume of metal removed.

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Adaptive Control (AC) Machining Systems

Where AC is appropriate?

- When cutter is engaged more than 40% of the time on the machine,
- For variability in the job by the means of feed and/or speed,
- The cost of operating the machine tool is high,
- The typical jobs and hard materials like steel, titanium and high strength alloys.

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Adaptive Control (AC) Machining Systems

Sources of variability in machining

- Variable geometry of cut in the form of changing depth of cut,
- Variable workpiece hardness and variable machinability
- Variable workpiece rigidity
- Tool wear increases as the cutting force increases
- Air gaps during cutting

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Function of Adaptive Control (AC) Machining Systems

The three functions of adaptive control are:

1. Identification function,
2. Decision function,
3. Modification function.

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Identification Functions

- This involves determining the current performance of the process or system. Normally, the performance quality of the system is defined by some relevant index of performance.
- The identification function is concerned with determining the current value of this performance measure by making use of the feedback data from the process.

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Identification Functions (cont…)

- Since the environment will change overtime, the performance of the system will also change.
- Accordingly the identification is one that must proceed over time or less continuously.
- Identification of the system may involve a number of possible measurements activities.

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Decision function

- Once the system performance is determined, the next function is to decide how the control mechanism should be adjusted to improve process performance.
- The decision procedure is carried out by means of a pre-programmed logic provided by the designer.
- Depending upon the logic the decision may be to change one or more of the controllable process.

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Modification function

- The third AC function is to implement the decision.
- While the decision function is a logic function, modification is concerned with a physical or mechanical change in the system.
- It is a hardware function rather than a software function.
- The modification involves changing the system parameters or variables so as to drive the process towards a more optimal state.

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Modification function

- The process is assumed to be influenced by some time varying environment.
- The adaptive system first identifies the current performance by taking measurements of inputs and outputs.
- Depending on current performance, a decision procedure is carried out to determine what changes are needed to improve system performance.
- Actual changes to the system are made in the modification function.

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Adaptive Control (AC): Types

1. Adaptive control optimization (ACO)
2. Adaptive control constraint (ACC)

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Adaptive Control Optimization (ACO) Machining Systems

- Based on Index of Performance (IP)

$$\text{Index of performanc e} = \frac{\text{Metal Removal Rate (MRR)}}{\text{Tool Wear Rate (TWR)}}$$

- The IP is a measure of overall process performance such as production rate or cost per volume of metal removed
- Adaptive control (AC) is optimize the IP by manipulating speed and/or feed of tool,
- Drawback: TWR measured by sensor and it may not be so accurate.

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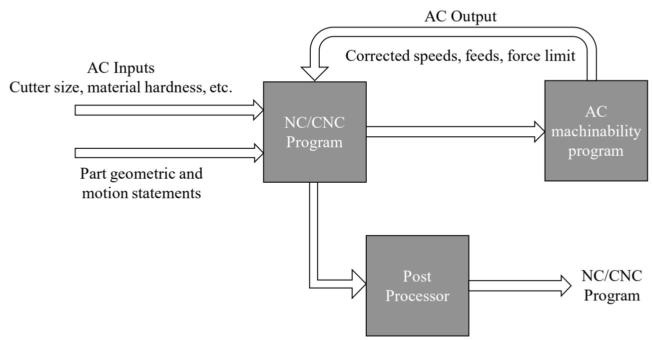
Adaptive Control Constraint (ACC) Machining Systems



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Adaptive Control Constraint (ACC) Machining Systems

- Less sophisticated than the ACO systems,
- Utilize constraint limits imposed on certain measured process variables,
- To manipulate feed and/ or speed so that these measured process variables are maintained at or below their constraint values,
- The most useful constraints in practical ACC systems are the cutting force F, the cutting power P, and the torque T,

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Adaptive Control Constraint (ACC) Machining Systems

The adaptive controller is fed by signals of two sensors:

A. Spindle torque sensor:

The spindle torque is measured by strain-gauges mounted on the machine spindle.

B. Tool vibration sensor:

The tool vibration is measured by two accelerometers mounted on the machining spindle housing.

- The sensor data are fed to the adaptive control unit which calculates new feed and speed to optimize metal removal rate within the limits of a set of constraints.

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Adaptive Control Constraint (ACC): Constraints

The constraints are:

1. Maximum permissible spindle speed in rpm. This limit can be imposed either by the machine capability or from metal cutting considerations.
2. Minimum spindle speed. It takes into account limitations of the spindle drive.
3. Maximum allowed torque. This limit is prescribed by cutter radius and length as well as by depth of cut and finish requirements.
4. Maximum allowed chip load in /rev. the chip load is actually the feed per tooth. The number of teeth on the cutter should fed to the control by the operator.
5. Minimum chip load in /rev. This constraint is required to prevent slow feeds.

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Adaptive Control Constraint (ACC): Constraints

6. Maximum permitted feed-rate in rpm. This constraint takes into account the cutter radius and length, spindle material, accuracy and finish requirement.
7. Maximum allowed vibration, measured as a percentage of the acceptable operating range. The zero point is used to indicate air gap.
8. Impact chip load, in in/rev. This limit is the maximum cutter feed per spindle revolution that would be allowed in traveling through unprogrammed air gaps. This limits the feed of the tools when entering in to the work piece.

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Benefits of Adaptive Control (AC) Machining Systems

- Increase production rates
- Increased tool life
- Greater part protection
- Less operator intervention
- Easier part programming

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VIRTUAL MACHINING

- Verification of NC programs through trial machining is risky, slow and costly.
- Virtual machining using software tools can overcome this difficulty.
- Optimization of cutting parameters achieved through this cuts down machining time and improves quality and tool life.
- But existing virtual machining methods are all inexact.

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Needs of Virtual Machining

- The sources of errors in NC programs are many and varied. They range from relatively trivial syntax errors to subtle interactions with work-holding fixtures.
- Debugging NC programs on the shop floor is expensive, time consuming and sometimes dangerous.
- CAD/CAM/CAE packages available today offer for modeling, visualization, analysis and manufacturing.
- Almost all CAM modules can generate efficient NC cutter paths with minimal user interactions.
- However, the correctness of the NC programs generated by these packages cannot be guaranteed until a component is produced on a CNC machine using these programs and inspected.

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Needs of Virtual Machining

- An unproved NC program may have movements that may cause collisions with the fixture elements, dig into the component, create undercuts, leave excess material.
- An erroneous NC program may also produce out of tolerance dimensions, poor surface finish or have wasteful movements.
- The task of ascertaining the correctness of the NC programs of a component is called NC Verification or Tape Proving.

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Needs of Virtual Machining

The physical tape proving methods have the following drawbacks:

- They are slow and tedious.
- The machine tool is utilized less efficiently during tape proving.
- The programmer and operator are underutilized and fatigued.
- These methods may be dangerous for the operator and can cause damage to the machine and cutting tools.

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Computer Automated/Aided Part Programming (CAPP)

- Can produce error-free NC programs,
- Require 'updated' vast knowledgebase (KB) and database (DB) related to machining,
- To obtain a 'zero-defect' NC program of a practical component.

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About Virtual Machining (VM)

- One starts with the virtual model of the work piece and as machining progresses, the geometry of the work piece gets updated by subtracting the volume swept by the cutter during each motion.
- It is possible to model even the machine tool and fixture elements so that even collisions can be detected.
- The VM systems can depict the material removal also,
- Provides a realistic visual feel of the machining process,
- Automatically do the verification both to ascertain the safety of machining (detection of collision etc.) and geometric conformance to design.
- Also possible to optimize the technological parameters (spindle speed and feed rate) from the geometric characteristics of the material removal process.

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Classification of NC Verification Systems

	On-line	Off-line
Physical	Z-neglect machining Scaled-down machining Dry-run machining Alternate-material machining	Desktop manufacture
Virtual	Kinematic NC simulation Volumetric NC simulation	Graphical Software base

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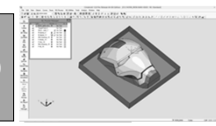
Graphics-based or virtual NC simulation

Kinematic NC Simulation (KinSim)

Volumetric NC Simulation (VolSim)



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Kinematic NC Simulation (KinSim)

- KinSim is very popular among CAM packages because of its low computational complexity.
- As the cutter moves, it is drawn at the end of each position.
- The cutter may be depicted simply by its tip or axis or it may be drawn fully in 2D or 3D.
- KinSim can depict only motions and not material removal.
- Therefore, physical NC verification may be necessary before releasing the NC program for regular production.

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Volumetric NC Simulation (VolSim)

- VolSim, in addition to motions, depicts material removal.
- Therefore, it helps in better visualization of machining.
- As the current shape of the work piece at any time is available in VolSim, the NC programmer will know the regions yet to be machined; Programmer can also evaluate alternate machining strategies.
- As programmer can see the scallops on the machined surfaces, this helps in arriving at an optimal step over increment during area clearing or pocket milling

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Volumetric NC Simulation (VolSim)

- The programmer can also correct for undercuts, gouging, collisions etc. which are not easy to visualize in KinSim.
- The intermediate shapes of blank geometry can be preserved as part of the NC documentation for use in the shop floor.
- In other words, VolSim is a software that emulates the CNC machine. Therefore, we shall refer to VolSim as Virtual Machining (VM).

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Virtual Simulation

The primary uses of VM are:

- NC Verification,
- Optimization of NC program.

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Virtual Machining Systems

- Virtual machining is nothing but the subtraction of the swept volume of the cutter from the instantaneous shape of the blank.
- Any CAD package with functions for
  - Solid representation of the entities in the machining environment such as cutter, work piece, tool holder, fixture and machine elements,
  - Calculating the swept volume of the cutter,
  - Boolean subtraction operation and
  - Appropriate API is good enough to develop a VM system.

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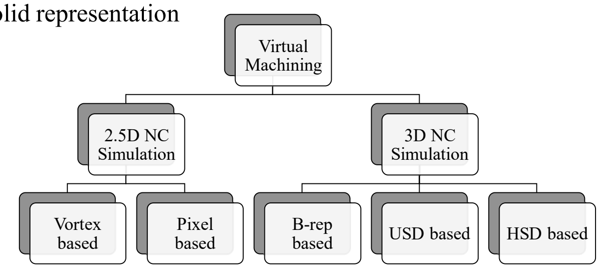
Virtual Machining Systems: Classification

- The classification of virtual machining systems based on the method of solid representation



Boundary Representation (BRep); Uniform Space Decomposition (USD); Hierarchical Space Decomposition (HSD)

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Virtual Machining Systems: Classification

- 3D NC simulation is also known as object-space volumetric NC simulation and 2.5D NC simulation is known as image-space volumetric NC simulation.
- In 3D NC simulation, the display resolution is same in all directions whereas in 2.5D NC simulation, it is the best in only the chosen direction.
- Obviously, 3D simulation is better but costs more in space and time.

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Image-space Virtual Machining: 2.5D NC Simulation: Vortex based

- A direction of simulation is chosen and the blank is split into sticks called voxels of equal cross-section with their lengths along the chosen direction.
- The cross-section of these voxels could be square, cylindrical etc.
- The simulation direction is Z axis and the voxels are cuboids.
- The cross-sectional size of these voxels decides the resolution of simulation.
- The length of the voxel will also be represented in discrete domain but to a coarser resolution.
- Whenever a cutter makes a movement, the volume it sweeps will be calculated as shown in Figure and then converted into voxels

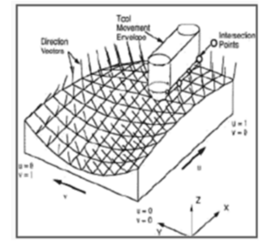

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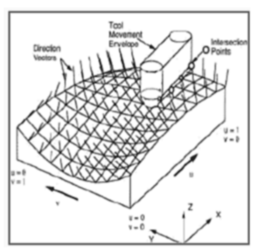
Image-space Virtual Machining: 2.5D NC Simulation

- The discrete domains of the blank and cutter will have to match.
- One can easily subtract the voxels of the cutter from the corresponding voxels of the blank to update the blank geometry due to machining.
- As the voxels are of uniform cross-section, it is enough to store its corner or center and its Z values.
- The Z values of a voxel will always occur in pairs; a voxel may have more than one pair of Z value as it may be split into more pieces during machining.
- From the bounding square of the object and the resolution perpendicular to the simulation direction, one can calculate the number of voxels, say m and n, along X and Y directions.



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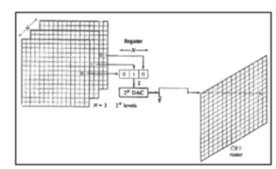
Pixel-based Virtual Machining: 2.5D NC Simulation

- A special case of voxel-based NC simulation in which the size of the voxel is same as that of the pixel of the display screen.
- Choosing pixel size as voxel size has very interesting effects on space and time complexity since the geometric information of the voxels no longer require to be stored explicit memory as it can make use of the video memory of the computer called frame buffer.
- This is organized in the form of bit-planes such that it has one bit for each pixel.
- For instance, if the frame buffer contains 8 bits, it can store any number from 0 to 255 for each pixel.
- Frame buffers of PCs today have as much as 32 bit/64-bit-planes. This memory location is normally used to store the color of the pixel.



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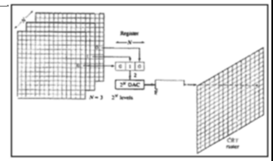
Pixel-based Virtual Machining: 2.5D NC Simulation



- In a pixel-based system, it stores the Z values of the sticks associated with the pixel.
- Therefore, in the context of image-space representation, the frame buffer is called Z-buffer.
- When machining proceeds, the lengths of these sticks are modified by changing the Z values in Z-buffer.
- As the geometric data is stored in the frame buffer itself and generation of display from the Z-buffer is trivial, pixel-based VMs are the fastest till date.
- Due to this, pixel based VMs are the most popular one among the commercial VolSim packages.

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BRep-based Virtual Machining: 3D NC Simulation

- Boundary Representation (BRep) is a solid representation in which an object is represented in terms of the surface patches defining its boundary.
- Most CAD/CAM packages such as Creo, UG and CATIA make use of Non-Uniform Rational BSpline (NURBS) - based BRep.
- When BRep is used For NC Simulation, one uses its inexact form called triangular polyhedral BRep. In other words, the object boundary will be a collection of triangles rather than NURBS patches.
- However, when BRep is used, the memory required to store the blank increases as simulation progresses. Therefore, it is useful only for few thousand motions.

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BRep-based Virtual Machining: 3D NC Simulation

- Boundary Representation (BRep) is a solid representation in which an object i… its bounda…
- Most C… ake use of Non-…
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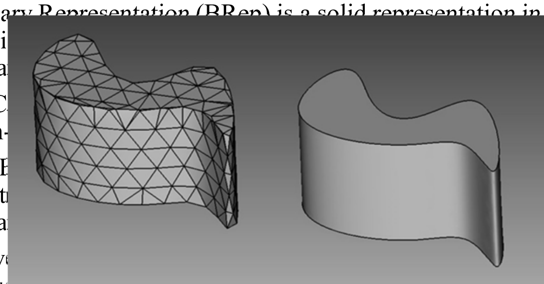
- Howev… the blank increas… y for few thousand motions.



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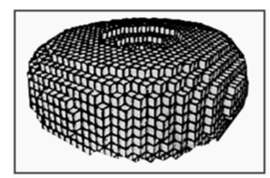
HSD-based Virtual Machining: 3D NC Simulation

- Uniform Space Decomposition (USD)
- The part is a collection of cubes or spheres or any such cell of same size.
- However, this is a very expensive way of representing solids and is limited to a few applications such as medical imaging.
- Obviously this is not practicable.
- Therefore, methods to represent an object as a collection of cells of varying sizes were developed.
- These are called Hierarchical Space Decomposition (HSD) representations.



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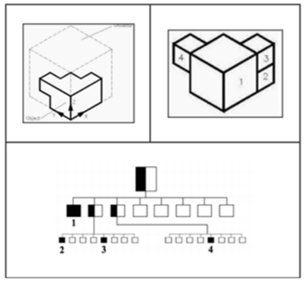
HSD-based Virtual Machining: 3D NC Simulation

- Octree is a HSD representation in which an object is represented by a set of cubes of varying sizes.
- This reduces the memory requirement considerably.
- Bintree and Polytree also are HSD models.
- In an Octree representation the universe (a cube that contains the object) is subdivided into 8 parts by introducing mid planes along width, depth, and height respectively.
- Each cube is one-eighth of its parent cube in size and is called an octant.
- All the octants can be visualized as the nodes of a tree in which every node has eight branches.



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HSD-based Virtual Machining: 3D NC Simulation

The other desirable features of octree are:

- All computations are based on integer arithmetic, which means that the analysis algorithms are fast
- Octree algorithms are readily parallel-processes.
- Memory required by Octree representation is independent of the number of primitives and operations. For a given resolution, memory required depends only on the surface area of the object.
- Boolean operations, rendering display in isometric view, scaling up/down in powers of 2, orthogonal rotations etc. are trivially simple since these operations require only tree traversal with simple exchange of terms.

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HSD-based Virtual Machining: 3D NC Simulation

The other desirable features of octree are:

- User is free to choose any desired accuracy (at the cost of speed and memory).
- Coarse modeling is a facility unique to HSD. A coarse model of a solid can be produced and processed quickly to get an order of magnitude estimate of the results. If these are found favorable, a more accurate model can be produced.
- All octree representations of solids are always valid and unambiguous.
- Octrees can inherently handle non-manifold and self-intersecting objects.

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Comparison of Representation Schemes for Virtual Machining

Features	Representation Scheme		
	Image-space	BRep	HSD
Model size as simulation proceeds	(+) remains constant	(-) linearly increases	(+) remains constant (significantly less than voxel-rep)
Simulation time per NC block as simulation proceeds	(+) remains constant	(-) factorially increases	(+) remains constant
Resolution selection	(-) The required resolution value cannot be directly specified; it is decided by the viewing conditions.	(+) The required resolution value can be directly specified.	(+) The required resolution value can be directly specified.
Accuracy	(-) Poorer in directions other than the simulation direction	(+) Same in all directions.	(+) Same in all directions.
Isotropy	(-) not isotrpic	(+) not isotrpic	(+) not isotrpic

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VM: Conclusions

- After verifying the NC programs using a Virtual Machining system, the NC programmer can confidently hand them over to the operator for machining.
- This also makes global manufacturing possible – model in one place, prepare cutter path in another place and machine it in yet another place.
- VM systems are too few compared to the CAM packages due to its high computational complexity.
- However, with the availability of powerful low cost computer hardware and software, VM systems are emerging.
- VM can also be used for machine tool simulation as well as optimization of spindle speed and feed rate.
- Standardization of NC procedures and documentation and careful customization of VM system will improve its effectiveness

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