Classification of Simulation Methods in Machining on Multi-axis Machines

K. Bouhadja, M. Bey

Abstract—**The simulation techniques development for multi-axis machining is key to the evolution of productivity and quality in the manufacture of mechanical parts with complex shapes (aerodynamic shapes, molds, etc.). The machining simulation representing accurately the cutting phenomenon is indispensable. However, this technique is penalized by the lack of knowledge of the cut. This field is wide and deals with various aspects. In this paper, the main machining simulation techniques are classified by category (geometrical and physical), by scale (multi-scale approach) and Part-Tool-Machine (dynamic and geometric) system. In the end, particular attention is given to geometric simulation techniques at macroscale.**

Key Words—**Machining simulation, Multi-axis machining, NC verification, Virtual workpiece, Geometric modeling.**

I. INTRODUCTION

Mechanical parts with free form surfaces used in various industries (molds, automotive, aerospace, etc...) are machined on multi-axis CNC milling machines because of their highly complex geometric shapes. Toolpaths for obtaining these parts are generated by taking into account several parameters (cutting conditions, tools shapes, surfaces models, etc...). The final shape of the part is obtained in three operations: roughing, semi-finishing and finishing. Before real machining, it is essential to simulate virtually the machining to verify the geometry of the finished part and to predict physical factors that are necessary to optimize the cutting parameters. Several researches have been conducted to deal with various problems related to the machining simulation of freeform surfaces on multi-axis machines. The objective of this work is to propose criteria for classification of these studies. The different proposed classifications are by category (geometrical and physical), by scale (human, macroscopic and microscopic) and by model of the Part-Tool-Machine system (dynamic model and geometric model). In the end, special attention is given to the geometric simulation at the macroscale.

II. CLASSIFICATION BY CATEGORIES

The machining simulation is divided into geometric and physical simulations (Fig. 1).

A. *Geometric Simulation*

The geometric simulation is used for verifying graphically the absence of interferences and collisions and the respect of tolerances imposed by the designer. In addition, it can provide geometric information necessary to the physical simulation.

B. *Physical Simulation*

The physical simulation of a machining process aims to reveal the physical aspects of a machining process such as cutting forces, vibrations, surface roughness, machining temperature and tool wear. It is based on the geometric simulation and on the choice of the cutting tool material [1].

III. CLASSIFICATION BY SCALES

The study of the machining is often dealt with by using multi-scale approach to separate difficulties by limiting the number of phenomenon to be considered and the size of the model at a given scale. Three levels of analysis can be distinguished: human, macroscopic and microscopic.

A. *Human Scale*

It is a global simulation of the machining environment where the objective is to predict the behavior of production means to prepare the machining process by considering axes movements, workpiece position on the table and space of the working area (Fig. 2). This step is necessary when the means of production are complex and the movements of the workpiece relative to the tool are difficult to anticipate (multi-axis machine, machining robot, etc.). It allows the detection of possible collisions during machining.

B. *Macroscopic Scale*

In an industrial approach, it is very important to look closely to the part in order to visualize the removal of the material. The purpose of the simulation is to determine the volume of the material removed for each tool movement during part machining (Fig. 3).

At this scale, simulation techniques allow to visualize and to anticipate surface defects totally related to the programmed strategy or to the machine kinematics.

In the literature referenced, different kinds of work are cited. Some considered the representation of the workpiece to machine [3-4]. Other works, considered the generation of the tool swept volume [5-7]. The difficulty at this level is related to the kinematics of the 05-axis machine where the tool translates and rotates simultaneously. For a higher precision, other works used the theory of multi-body systems kinematics [8-10].

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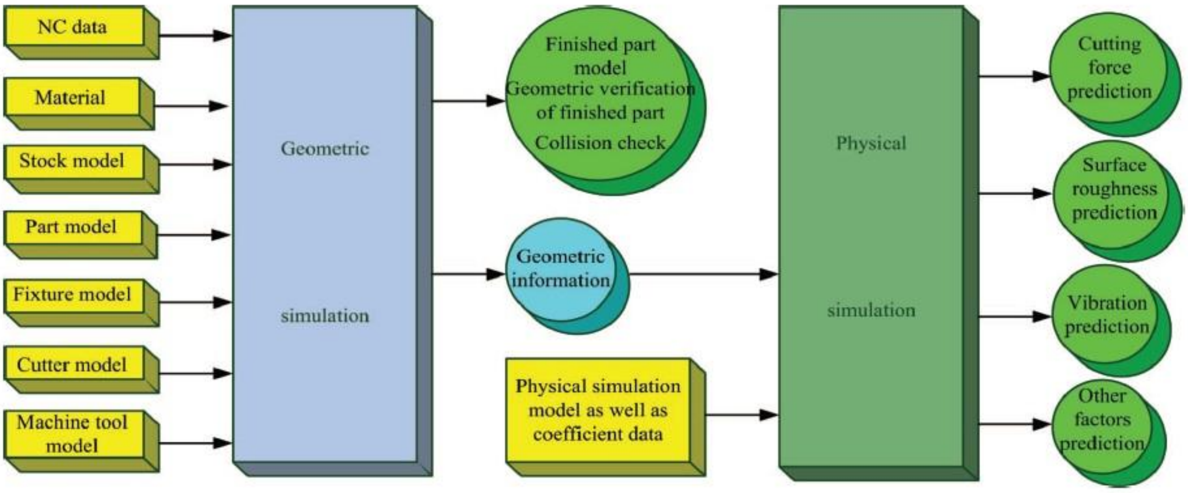


Fig. 1. General architecture of machining simulation [1]

Other mechanical phenomena have an impact on the surface quality such as the chattering phenomenon where the appearance conditions are difficult to predict. This phenomenon degrades the machined surface quality and accelerates the wear of certain sensitive parts of the production means such as cutting tools and spindle. Discontinuous and periodic nature of the cut in milling is also the cause of systematic vibrations of the system constituted by Part-Tool-Machine. Other investigations are related to the prediction of the cutting forces to optimize the cutting conditions [11]. Artificial intelligence is used to avoid collisions for multi-axis machines [12].

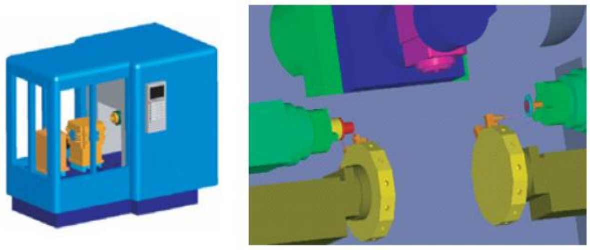
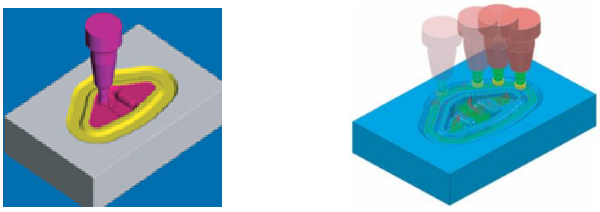


Fig. 2 Machine tool simulation [2]



a. Material removal simulation. b. Toolpath simulation.

Fig. 3. Macroscopic scale machining simulation [2]

C. *Microscopic Scale*

The simulation in this scale is related to the study of materials. It deals with the deduction of some properties from the material structure. Among these properties is the behavior law of the used material. The Mesoscopic scale is found at a larger scale than the microscopic scale. At this scale, the chip formation is studied. Based on a thermo-mechanical description involving physical and metallurgical phenomena, but in a scale of the continuum mechanics, the simulation is often dealt by the finite element method [13].

IV. CLASSIFICATION ACCORDING TO THE MODEL SYSTEM (PART-TOOL-MACHINE)

To simulate the current phenomena in the Part-Tool-Machine system dynamics at the macroscale, dynamic model and geometric model are introduced.

A. *Dynamic Model*

The used dynamic model of Part-Tool-Machine system can be a simple spring-mass model or a complex finite element model. The finite element modeling allows a much finer and a more flexible spatial discretization. It allows also the obtaining of more realistic vibration modes and to address the case where the workpiece and/or the tool are deformable in the working area.

B. *Geometric Model*

The used geometric models can range from the simplest one, a series of points [14], to the most complex one, facetised surface description or representation using Z-buffer or Dexel [15].

Geometric Model of the Workpiece

Three families of geometric representations are distinguished.

--The boundary of the volume can be represented by a list of points projected on a plane.

--The boundary of the volume can be represented by surfaces (B-Rep model) [16].

--The geometric model can also be a solid model using Voxels [17], Dexels [18] (Fig. 4) or Triple-Nailboard (Fig. 5) [19].

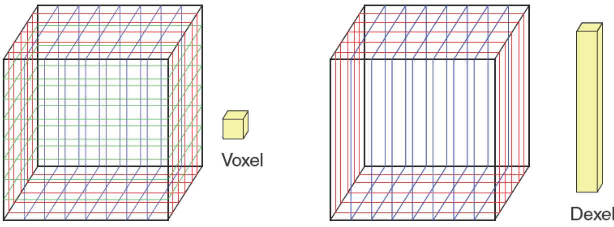


Fig. 4. Voxels and Dexels models [13]

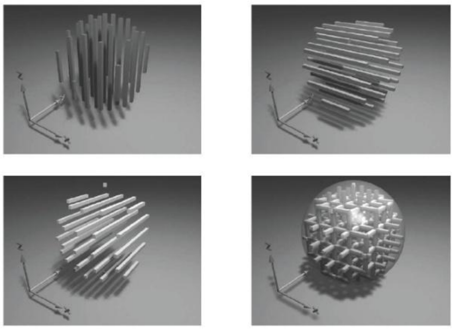


Fig. 5. Three-Nailboard model [19]

Geometric Model of the Tool

The geometric modeling of the tool permits to generate the machined surface and to calculate the geometric properties used in the cutting law. Several studies have been performed to improve the modeling starting from the consideration of the complex tool geometry. This problematic is complex because modeling requires a law model for cutting forces and a geometric description of the tool. The response was found in the modifications developed in the calculus of the static cutting forces. Simulations dedicated to milling profile operations were inspired from cutting forces model dealing with complex tools geometries as a sum of basic tools (Fig. 6) [20].

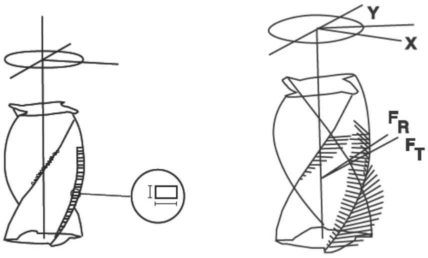
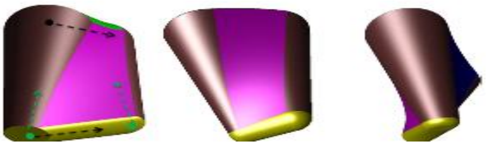


Fig. 6. Cutting tool decomposition [13]

Geometric Model of Swept Volume

The modeling of the tool swept volume is based on the CSG representation (Constructive Solid Geometry) of the solid envelope of the tool path for 03-axis machining. The recent works are focused on the generation of the tool swept volume for 05-axis machining [5-7] where the difficulty is increased by the kinematics of the machine since the tool translates and rotates simultaneously (Fig. 7).

a. Swept-volume envelope for 03-axis



b. Swept-volume enveloppe for 05-axis

Figure 7: Swept-volume envelope of a conical tool [3]

V. GEOMETRIC SIMULATION AT THE MACROSCALE

The literature shows that there are different ways for classifying the geometric representation in simulation at the macroscale. The used methods are classified as follows: wireframe-based, solid based, object space-based, image space-based and web-based simulation system [1]. In this study, the web-based simulation is not considered.

A. Wireframe-based

In wireframe-based simulation, the trajectory and the shape of the machined workpiece are displayed under shape of wire. This model has a simple and fast data structure. It has been applied extensively in the beginning of the machining simulation. This model remains applicable to parts of simple geometry.

B. Solid-based

The solid-based simulation is a 3D volumic representation. It is used for the geometric and the physical simulations. This model permits a very accurate geometric representation but expensive [1]. The two existing models for this case are CSG-based and B-Rep-based.

CSG-based

It defines the constructive form of a 3D model using primitive volumes such as cylinders, spheres ... etc. Although, the Boolean operations and the consistency check are simple, visualization or data analysis may require a transformation into another B-Rep model. The approximate cost of the simulation using CSG is O(n4) where n is the number of tool movements [21]. So, the simulation for machining freeform surfaces becomes intractable [22].

B-Rep-based

This model is suitable for viewing. Unlike the CSG model, the B-Rep model explicitly defines the volume by a list of surfaces, edges and vertices. The computational cost is high in terms of time, storage of data and complexity. For n tool movements, the cost of the simulation is estimated to O(n1.5) [23].

C. Object Space-base

In a machining simulation as object based space, the parts are represented by a set of discrete points with vectors or surfaces with vectors or some volume elements. There are three main decomposition methods for machining simulation patterns for object based space model.

Z-map Method

It consists in decomposing the model of the part in several 3D vectors (Figure 8). Each vector begins with the value of the height of the raw part. During the simulation process, 3D vectors heights are updated for each tool movement. In this case, the boolean operations have only one dimension and therefore the simulation is very fast. In [24], this method was used in the collision detection algorithm for 03-axis CNC milling machine. This method is not usable for 04-axis and 05-axis machining since the tool axis is not vertical. Later, many researchers have used different approaches to improve the Z-map model [25-28]

Vector Method

This method involves discretization of the surface according to specific methods to obtain a set of points. For each point, a vector is associated with limits between the nominal surface and the raw part. Its vectors can be oriented in two ways (Fig. 9):

-- According to the surface normal (accurate): in this case, each vector is linearly independent from the other vectors.

-- According to the Z-axis of the tool (simplified): in this case, all vectors are parallel to the Z-axis. This case is adapted to 03-axis machining.

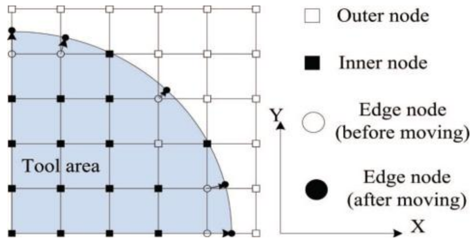
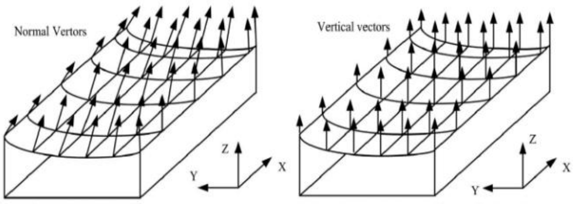


Fig. 8. Z-map method [29]



a. According to the normal. b. According to the vertical.

Fig. 9. Vectors orientations [1]

To simulate machining operations, the intersection of the vectors with the envelope of the tool swept volume must be calculated for each the tool displacement. The length and direction vectors are changed for each elementary tool movement. To detect non-machined areas, just check the direction and length of the vectors:

-- Positive direction: unmachined area;

-- Negative direction: machining under the nominal surface;

-- Length of vectors: if they are not in the machining tolerances, a correction is necessary.

Octree-based Method

This method represents the workpiece in a tree structure (Fig. 10). Each node is recursively subdivided into eight disjoint child nodes until satisfying the required accuracy. This representation on a hierarchical octree provides to the NC machining simulation simplicity of boolean operations calculation even when the local cutting area is complex. In [30], a machining simulation system is developed in which the part was represented by a traditional octree for the creation and modification of the model. Subsequently, it was represented in B –Rep model to animate the display, to verify and to optimize. The authors present the decomposition algorithm of the octree model into three quadtree models which store the geometry along the three main directions. Subsequently, this system was extended to the physical simulation for the prediction of the cutting forces based on the material removal rates [23]. For the optimization of the cutting parameters, Karunakaran et al. [11] found good results compared to the experimental. In [31-32], geometric and physical simulation were integrated to predict the cutting forces. Kawashima et al. [33] developed an extended octree called Graftree to represent more faithfully 3D objects in the geometric simulation (Fig. 11). For this case, each boundary cell has been described in the form of CSG with some restrictions. Kim et al. [34-35] used the super-sampling method to enhance the octree model.

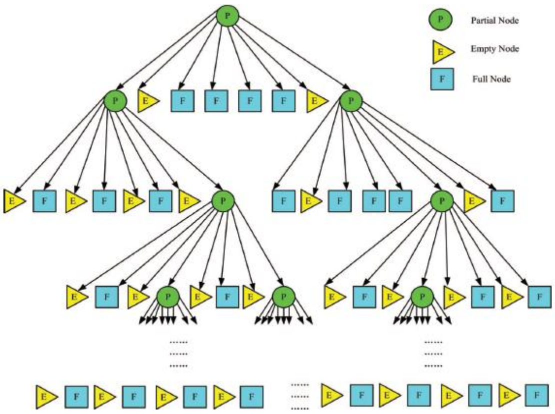


Fig. 10. Octree model [1]

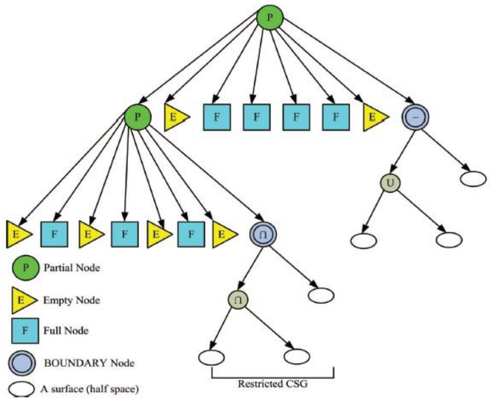
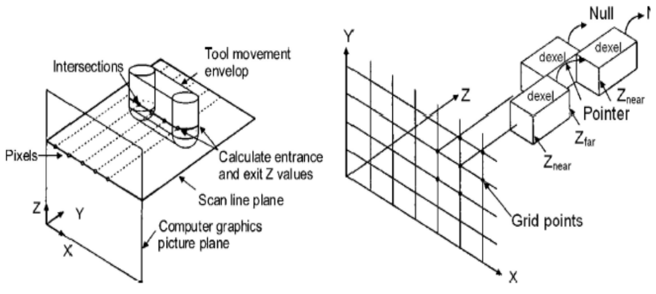


Fig. 11. Graftree model [33]

D. *Image Space-based*

In this model, parts are represented by the depths of the pixels (dexels). It is an extension of the Z-buffer. The basis of the method is the projection of a grid (or a screen) in a given direction on a surface according to a selected view (Fig. 12). It fits well for 03-axis machining simulation with the projection direction is the tool axis (Z-axis). The construction of the surface is obtained by the intersection between a set of straight parallel lines to the Z-axis and the swept volume envelope. The bijective surfaces are the most suitable ones. For a set of surfaces, it is not always possible to machine all surfaces. For each line, all intersections with all surfaces are calculated and the highest intersection belonging to the skin of the part is retained thereby allowing the machining the outer envelope of the part [1]. In [36-37], the model in dexels for milling with ball end mill tool is used with the integration of geometric and physical simulations to predict the cutting forces for 03-axis and 05-axis machining.



a. Intersection of Z-map of image with tool movement.

b. Extended Z-map as linked list of dexels

Fig. 12. Image space-based simulation [2]

VI. CONCLUSIONS

The machining simulation is a technique used to check the tool path, to detect collisions, to predict the surface roughness, to predict cutting forces for optimizing the cutting parameters. These objectives require an accurate modeling of the machining environment. This synthesis was carried out to clarify and separate the difficulties due to the complexity and the difficulty of this technique (Fig. 13). In perspective, the selection and the adoption of one or more simulation techniques for 05-axis machining will be consider

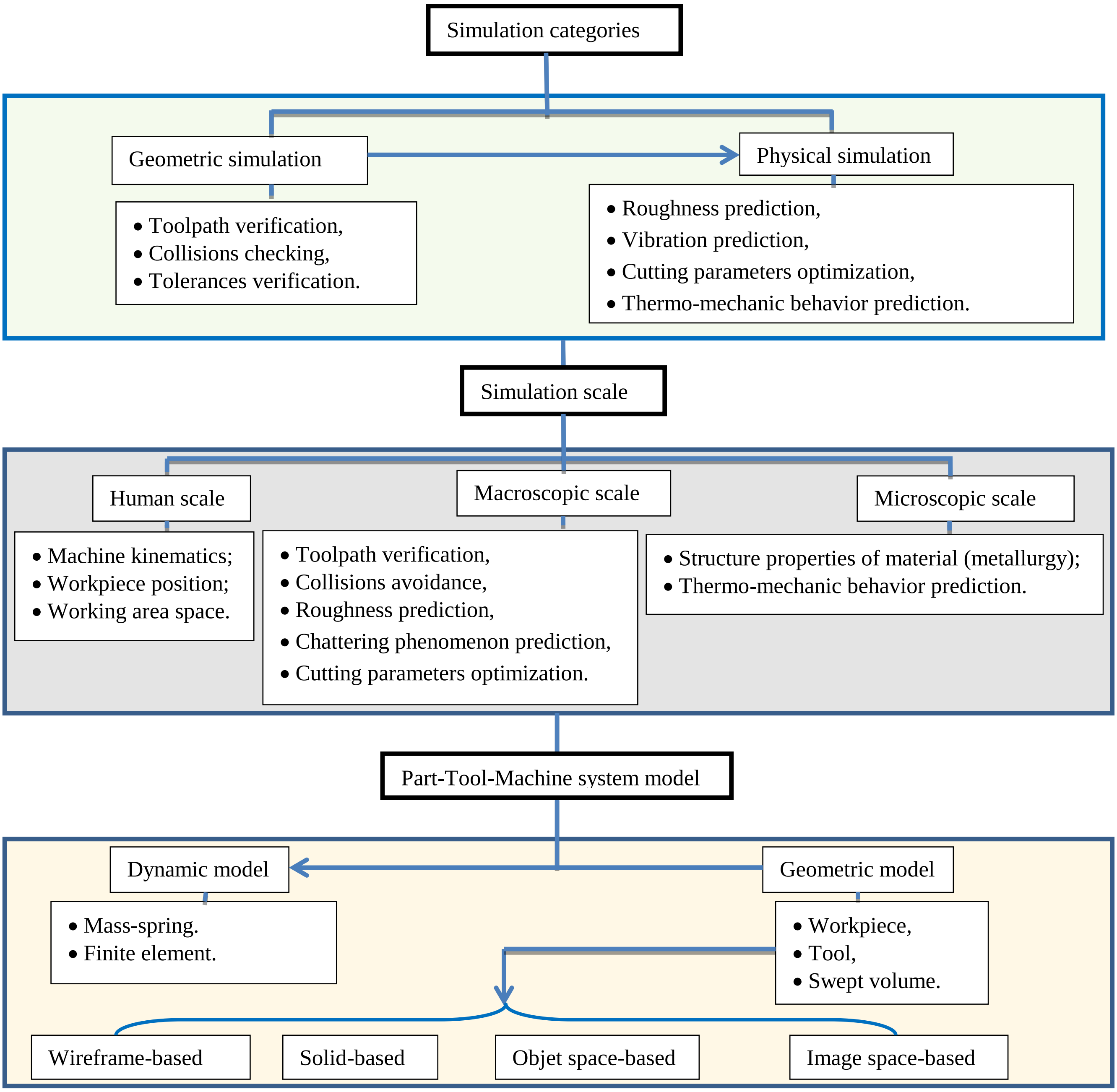


Fig. 13. Classification of simulation methods

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