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Voxel-based modelling in additive manufacturing

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Bachelor’s thesis

Author(s):
Aaron Vänskä

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Turku

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Voxel-based modelling is a method to represent a three-dimensional model with tiny cubes, which are called voxels. This thesis explores the construction of voxel models, their advantages in additive manufacturing and their various applications. Voxel models can be generated using different algorithms, though the most common approach is voxelizing where an existing 3D model is converted into a voxel-based form. Compared to other modelling methods, voxel models provide numerous benefits, some of which are unique to voxels. These advantages include volumetric data representation, usage of multimaterials, and the ability to modify material properties. Additionally, voxels are used for simulation purposes particularly in 4D printing. Despite these advantages, computational and memory demands are increased due to high resolution of voxel models. Applications of voxel models are utilized in various fields, including medicine, aerospace and automotive industries. The future of voxel models is promising, as additive manufacturing continues to evolve and models with additional data are needed to meet growing industry demands.

Vokselipohjainen mallinnus on tapa ilmaista kolmiulotteinen malli pienten kuutioiden eli vokselien avulla. Tämä tutkielma tarkastelee miten vokselimalli rakennetaan sekä mitä hyötyjä ja käyttökohteita vokselipohjaisella mallinnuksella on lisäävässä valmistuksessa. Vokselimalli voidaan luoda erilaisten algoritmien avulla, mutta suosituin tapa on vokseloida jo olemassa oleva 3D-malli vokselimuotoon. Muihin mallinnusmenetelmiin verrattuna vokseleilla on lukuisia etuja, joista osa on vokseleille ainutlaatuisia. Esimerkkejä näistä ominaisuuksista ovat tieto kappaleen tilavuudesta, monimateriaalien käyttö sekä materiaaliominaisuuksien muokkaaminen. Lisäksi vokseleita käytetään simulointitarkoitukseen erityisesti neliulotteisessa tulostuksessa. Hyödyistä huolimatta laskennalliset- ja muistikustannukset ovat suuria vokselimallien korkean resoluution vuoksi. Vokselimalleja hyödynnetään useilla eri aloilla, kuten lääketieteessä, ilmailu- ja autoteollisuudessa. Vokselimallien tulevaisuus on lupaava, sillä lisäävä valmistus kasvaa entisestään ja lisätietoa sisältäviä malleja tarvitaan vastaamaan alan kasvaviin vaatimuksiin.

Key words: voxel, voxel-based modelling, voxelization, computer aided design, multimaterial, additive manufacturing, 3D printing, 4D printing

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1 Introduction

Additive manufacturing (AM), also recognized as 3D printing, is a method to produce an item by adding material in layers. This technology has made it possible to produce complex 3D models effortlessly. Manufacturing is done based on data from a three-dimensional model made with Computer Aided Design (CAD) software. CAD is a tool utilized to create, design, modify, analyse and optimize a part. The advantages of using CAD include efficiency, easy implementation of changes, and the ability to create simulations and prototypes of the model [1]. Examples of traditional three-dimensional models include implicit surface, boundary representation and polygon mesh.

A novel approach to conventional 3D models is voxel-based model. They provide unique features, such as the ability to represent multi-materials through volumetric information. Additionally, they simplify the production of complex geometries and make Boolean operations effortlessly [2]. These attributes make voxel models useful in certain applications, such as the design of complex structures as lattices or in medicine, aerospace, and automotive industries. This thesis investigates the options, possibilities and limitations voxel models have in additive manufacturing.

1.1 Voxels

A voxel, or a volume pixel, is a pixel that has volume. Similarly as 2D pictures are made of pixels, 3D images are made of voxels [3]. Voxels can be represented using binary numbers, where ‘one’ is considered as a solid voxel and ‘zero’ as a void voxel. To illustrate this, the same group of pixels/voxels are represented as 2D and 3D models are shown in Figure 1 [4].

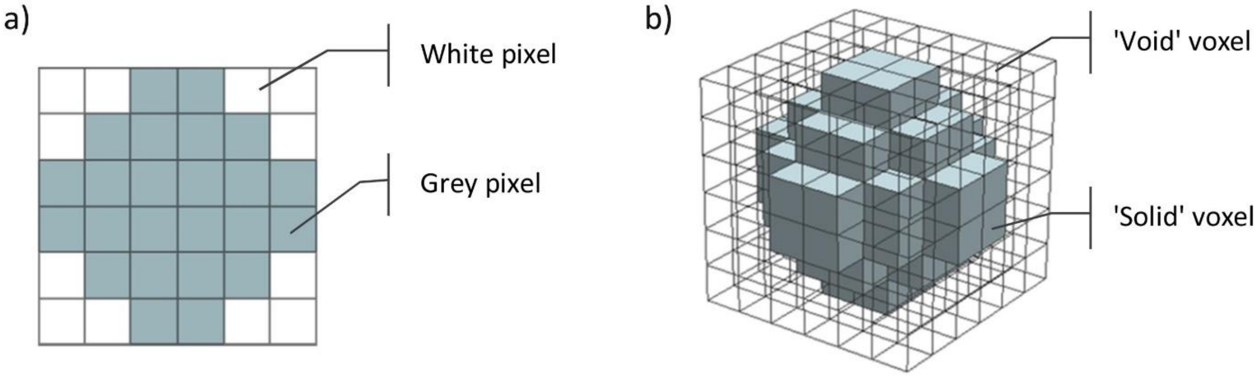

Figure 1. Presenting a sphere using a) pixels and b) voxels [4]. © 2016 Elsevier

2 Design process

Every additive manufacturing process begins with a 3D model of the desired product. The model should describe the external shape of the part [1]. Besides creating the 3D model, the design process additionally involves potential voxelization and preparing data for manufacturing.

2.1 3D model representation methods

There are various methods to express a three-dimensional model. Traditional approaches include implicit surface, boundary representation and polygon mesh. A more recent method involves voxel-based modelling.

2.1.1 Implicit surface

Implicit surface modelling is a mathematical method for expressing objects using equations to define curves and surfaces. Implicit surface in three-dimensional space describes the different solutions to an equation that has no more than three variables x, y and z. For instance, the function of a unit sphere is described in Equation 1 [5].

$$x^2 + y^2 + z^2 - 1 = 0 \tag{1}$$

2.1.2 Boundary representation

Boundary representation (BREP) is a method to describe a solid model by the surface surrounding it. The surface consists of multiple faces that are connected to each other using edges. Vertices are the corners where various faces meet [6].

2.1.3 Polygon mesh

Polygon mesh is a set of faces, edges and vertices. The faces are generally triangles, however, sometimes other type of polygons may be used depending on the requirements and application of the product [7].

2.1.4 Voxel-based model

Voxel-based model represents an object with a rectilinear three-dimensional grid made of multiple voxels. Each voxel contains scalar values that describe the information of the solid geometry [8]. A voxel model is fundamentally a 3D matrix, where voxels represent each unit of the matrix [4]. In general, a pre-existing CAD model is voxelized to create a voxel model.

2.2 Voxelization

Voxelization is the process of converting a three-dimensional model, usually made of surface information, into a voxel-based model. Voxelizing with different resolutions allows to create more precise models. As seen in Figure 2, a geometric three-dimensional model of a Stanford Bunny is voxelized with different resolutions to demonstrate the process. As the resolution increases, the voxels decrease in size, resulting in a more detailed model [7], [9]. There are multiple different approaches to complete voxelization, such as signed distance field, surface voxelization, solid voxelization and the Marching Cubes algorithm.

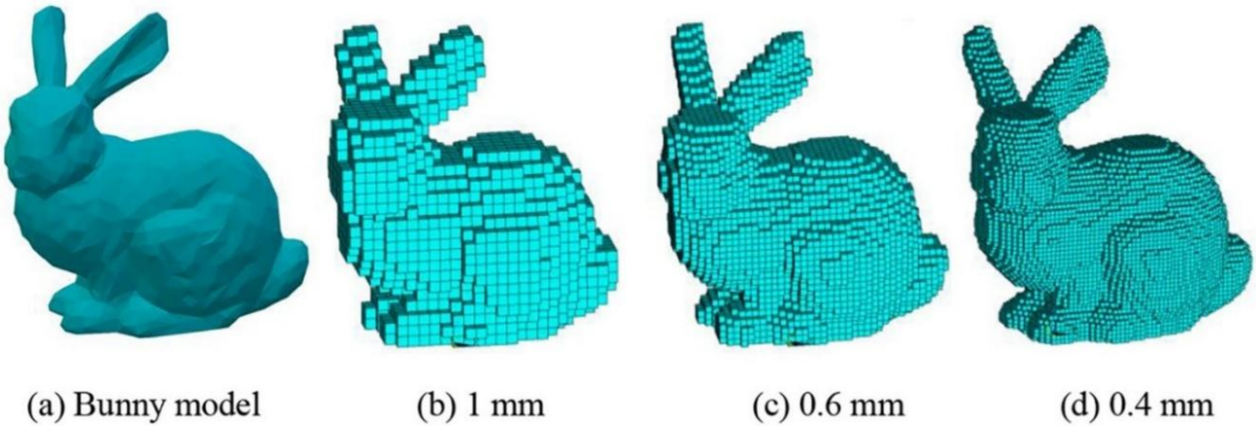

Figure 2. A Stanford Bunny model (a) voxelized with different resolutions (b, c, d) [9]. © 2019 Elsevier

2.2.1 Signed distance field

Signed distance field, also referred to as signed distance function (SDF), tells the distance between a single point and the surface of a body. The sign tells whether the point is inside or outside of the body. The negative sign shows that the point lies inside the body, while positive sign indicates that the point is outside. With the value being zero, the point is right on the surface of the body [3]. Traditional voxelizing methods may lose the finest details and results in rough surface representation. However, utilizing SDF leads to smooth surfaces and volumes due to an accuracy level of subvoxels, which are smaller units within a single voxel. SDF allows to represent implicit surfaces as a volumetric grid. In Figure 3, the same model with binary and SDF representation is shown [10].

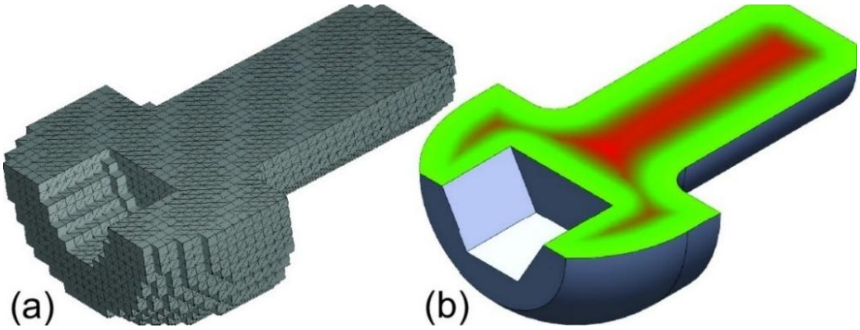

Figure 3. A cross-sectional model of a bolt in a) binary representation and b) SDF representation [10]. © 2023 Oxford University Press

2.2.2 Surface voxelization

In surface voxelization, only the surface of the model is voxelized and the interior remains hollow. Voxelization is performed by setting a criterion stating that all voxels overlapping a triangle, whether fully or partially touching, are placed [11].

2.2.3 Solid voxelization

Solid voxelization means that the whole model, including the surface and interior, is voxelized. All voxels whose centre is inside the object are placed, which results in a closed, watertight object. Additional surface voxelization might be done afterwards to secure the finest details. Moreover, solid voxelization can be done utilizing an octree, which is a tree data structure with eight children. The octree-based method reduces memory consumption with focusing on high-resolution surface voxels, leaving the interior voxels lower in resolution [11].

2.2.4 Marching Cubes algorithm

The Marching Cubes (MC) algorithm is mainly used to visualise an implicit surface. MC is based on a voxel-based data structure. There are three stages of the algorithm: separating the bounding box, surface sampling and surface polygonization. The algorithm begins by dividing a box into cubes, which are processed one at a time. After one cube is complete, the algorithm ‘marches’ to the next cube [5].

However, with modifications to the Marching Cubes algorithm, it can perform voxelization. First, the surface geometry of a 3D model is imported, and its minimum bounding box is calculated. The size of the voxel is determined by dividing the maximum dimension of the bounding region by a selected voxel resolution. Afterwards, the surface 3D model is sliced into multiple layers depending on the chosen voxel size, and boundaries for every slice are determined. For every slice, a minimum bounding box of voxel grids is defined. This allows the computer to determine whether a voxel grid is occupied (‘1’) or empty (‘0’). To calculate whether the voxel element is inside or outside of the boundary, the signed distance is used. With this technique, a voxel model of a 3D surface geometry can be generated [12].

3 Manufacturing process

To manufacture the designed model, various methods are available. This chapter focuses on additive manufacturing, specifically in 3D and 4D printing. These techniques have their own advantages compared to conventional manufacturing methods such as machining or casting. For instance, 3D printing enables the manufacturing of complex shapes, while 4D printing allows objects to transform over time. Additionally, voxel models add their own unique benefits to additive manufacturing. Before manufacturing can begin, the 3D model data must be processed to a suitable format.

3.1 Processing 3D model data for manufacturing

To successfully manufacture a 3D model, its data must be converted into a format that the manufacturing machine can read and understand. The data of a model can be converted either into a polygon mesh form or a CLI file.

3.1.1 Polygon mesh

The most common type of file format used for additive manufacturing is polygon mesh. It describes the model’s external, closed surfaces using triangles. Polygon mesh forms the basis for calculating the slices, which determine how the material will be added to form the part [1]. The size of the triangles depends on the resolution: smaller triangles indicate higher resolution. To be printable, the model must be manifold, have measurable volume and be watertight. Different types of polygon mesh files include STL, OBJ, 3MF and AMF. The oldest and most favoured format is STL file, and it has data only about the surface geometry of the model. Furthermore, with modern file formats (OBJ, 3MF and AMF) additional information, such as units, colour, material type or other properties can be preserved [13].

Instead of using CAD, polygon mesh file can be created by reverse engineering (RE). RE forms a model based on capturing a set of data points from a surface of another object. However, the set of data points may not be enough to create an ideal object. Scanning helps to minimize the possible imperfections of the object. Different scanning techniques include laser and touch probe scanning besides CT scan for complicated internal structures [1].

3.1.2 CLI file

A CLI (Common Layer Interface) file is a vector-based file that is used for planar geometric data in additive manufacturing. It is based on a 2.5-dimensional layer representation, which makes it suitable for non-extrusion additive manufacturing processes such as powder bed fusion. The file consists of 2D layers stacked on top of each other. The layer thickness forms the third dimension, which can be determined by the layer height. While CLI files lose the volumetric information of voxel-based models, they are suitable for defining precise grid lines in a model. This is practical in terms of transferring data between two different file formats since there will be no loss of accuracy or detail [13], [14].

3.2 Direct voxel model printing

Voxel models can be directly printed without any file manipulation. As shown in Figure 4b, the multi-level voxel representation consists of coarse and fine voxels. Utilizing two types of voxels results in better accuracy and quality of the model. Manufacturing relies on G-code instructions, which are determined by the layer heights. With this method, slicing operations are not needed since built-in information of layers exists. Slicing typically affects the surface quality, manufacturing time and mechanical properties of the model. Other advantages compared to polygon mesh files include volumetric information and the possibility to produce models directly from medical data such as MRI and CT scan. Direct voxel model printing is suitable method for various manufacturing processes, which makes it a diverse option. [8].

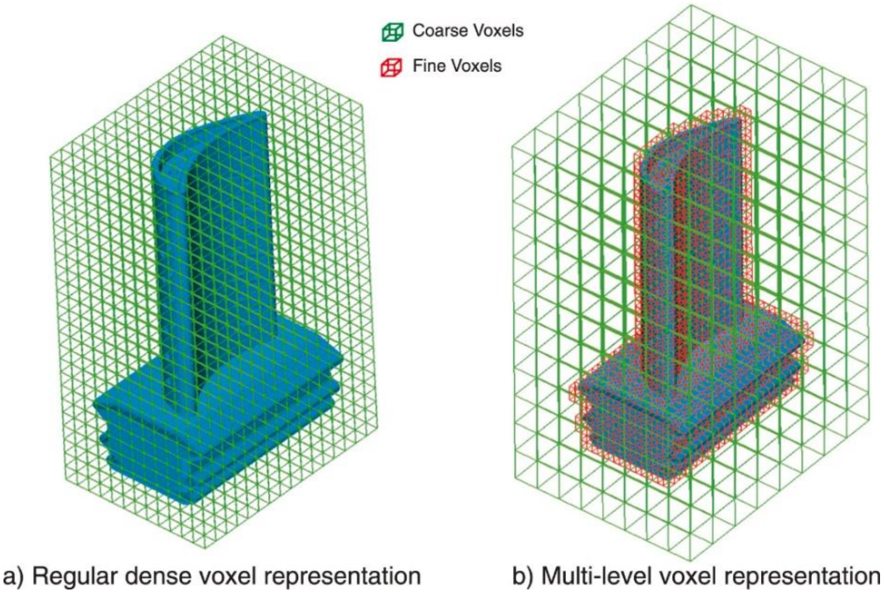

Figure 4. A model of a turbine with a grid of voxels in regular dense voxel representation (a) and multi-level voxel representation (b) [8]. © 2021 Elsevier

3.3 3D printing

The generic 3D printing process consists of transferring geometric data of the part into the machine, setting up the machine and checking parameters, building the part, removing the part and possible post-processing such as cleaning or removing support structures. There are multiple different types of 3D printing processes. Choosing the most suitable process depends on the desired outcome of the product. Some factors are, for example, material, size, manufacturing speed, appearance of the product and post-processing. Seven generic AM processes are described in Table 1 [1].

Table 1: Additive manufacturing processes [1].

Process	**Description**
Binder jetting (BJT)	A part is done by fusing powdered material with a print head.
Directed energy deposition (DED)	A material is simultaneously melted and deposited layer-by-layer.
Material extrusion (MEX)	Using pressure, a semisolid material is forced through a nozzle Added material solidifies and bonds to already extruded material.
Material jetting (MJT)	Droplets of material are dispensed from a print head. Works similarly to a 2D printer.
Powder bed fusion (PBF)	Powder particles are fused together with a help of heat source, usually lasers. After a single layer is complete, the platform is lowered, allowing the next layer to be formed
Sheet lamination (SHL)	Sheets of desired material are cut, stacked and bonded until a product is formed.
Vat photopolymerization (VPP)	Uses liquid polymers that become solid after radiation, usually ultraviolet light.

3.3.1 Capabilities of voxel models

Using voxel-based modelling in additive manufacturing comes with multiple benefits. Voxel models have all the benefits from traditional 3D modelling representations and more. The importance of utilizing voxel models arises from their volumetric information, which allows modifications to the material properties and use of multimaterials. Additionally, Boolean operations are easy to complete with voxels [8]. Moreover, the high resolution and precision of voxel models enable design and manufacturing of complex structures [4]. These attributes make voxel models closer to real-world objects compared to other 3D representation methods, which lack the necessary information. Furthermore, processing time of a part can be reduced with certain methods by directly outputting the slice file, avoiding general file processing [2].

Despite the benefits of voxel models, there are some challenges as well. For the voxel model to be precise enough, a high resolution is a must. For the finest details, numerous voxels of around one billion are required. This results in increased computational and memory costs [8]. Moreover, fine details of the model are lost in voxelization if the resolution is too low, which results in imprecise objects. However, these challenges are negligible compared to the numerous advantages voxel models offer.

Voxel models can generally be manufactured utilizing any process that supports CAD models. However, since voxel models can capture fine geometric details and internal structures, processes with high precision are beneficial. Examples include material extrusion as well as material jetting [8], [15].

3.3.2 Materials, multimaterials and material properties

When it comes to materials in 3D printing, there is a large selection of materials available. For instance, metals, ceramics, polymers and composites are used and the material can be either liquid-, powder- or solid-based. Selecting the material depends on the chosen process. With some processes, a larger variety of materials can be dealt with [1]. Voxels are convenient in terms of utilizing multimaterials and modifying material properties.

Standard 3D model representations assume uniform density and homogenous material composition. Nevertheless, voxel models divide space into volume elements that each store distinct material properties [16]. With voxels, material distributions can be made on a micrometre scale accuracy. Each voxel can be considered as an individual unit that has information about different features such as material type, density and colour. This enables the creation of more complex and optimized structures, although it might add challenges to designing and manufacturing. Additionally, the printing process often requires support structures that are demanding to remove and can cause failures in the part [15].

The traditional way to customize material properties in 3D printing is through processing parameters, such as printing orientation, temperature, speed and void density. With voxels, material properties can already be modified in the design phase. This is practical when it comes to designing functional models with complicated geometries. Properties are then able to respond to the requirements for different applications [17].

For example, there is a case study about adjusting spatially varied thermomechanical properties by optimizing voxel size and inclusion content. In this study, digital materials are constructed by adding different portions of two materials, Vero and Tango, which are base photopolymers and share different mechanical properties. As seen in Figure 5a, utilizing lower amount of Vero results in decreased storage modulus, which represents the stiffness of a material. The change in storage modulus is directly proportional to the amount of Vero in the material. Meanwhile, Figure 5b shows that tan δ, or the capability to dissipate mechanical energy, varies unpredictably with different material depositions [17].

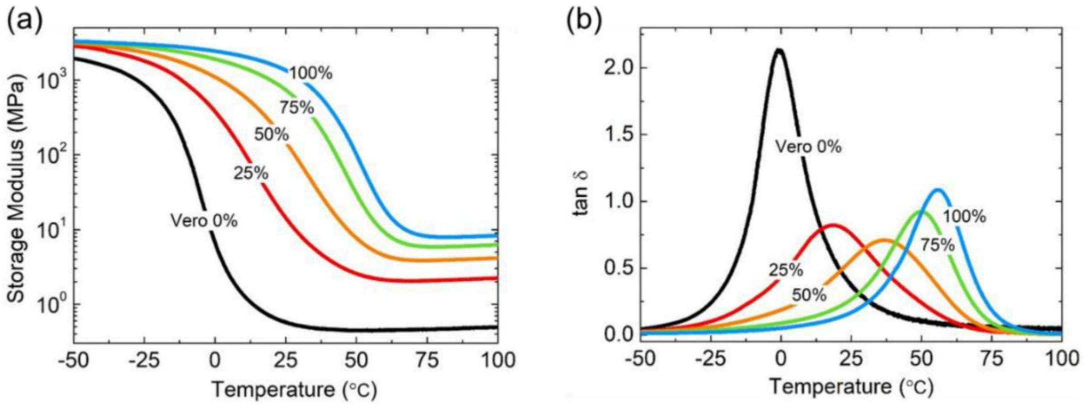

Figure 5. The change in thermomechanical properties with different material distribution [17].
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3.4 4D printing

4D printing (4DP) is based on 3D printing with addition of smart materials (SMs). Utilizing smart materials causes the object to change shape, properties, colour or functionality over time. This so called fourth dimension is activated with physical changes such as heat, light, humidity, magnetic fields, stress or pH [18]. Voxel models are practical in 4D printing when creating multimaterial objects, manufacturing high precision models and performing simulations.

3.4.1 Smart materials and multimaterials

Examples of smart materials utilized in 4D printing include hydrogels, shape memory polymers (SMPs), shape memory alloys (SMAs), liquid crystal elastomers (LCEs), hydrophilic materials and composites. Each material has its own specific characteristics, for example, SMPs and hydrogels respond to changes in temperature. The chosen printing method and application purposes have an impact on the material selection [18].

There has been some investigation of multimaterial voxel models in 4D printing. To utilize multimaterials in a part, material information is assigned in each voxel separately. As shown in Figure 6, soft and stiff materials are set to individual voxels in a beam [19]. To overcome issues in large and complicated structures, interlocking assemblies can be utilized. With this technique, different materials are separated to subassemblies constructed of voxels. These puzzle type assemblies can be made with either lattice or solid units [20].

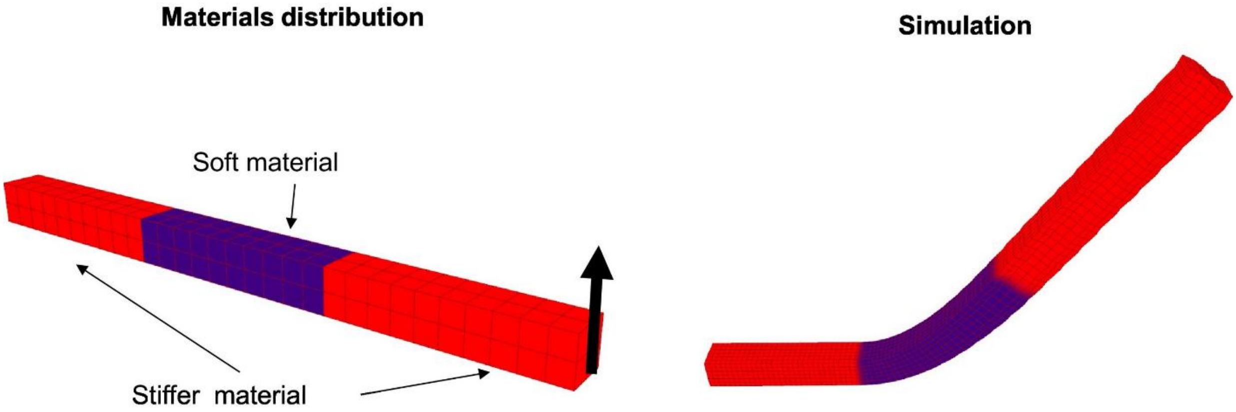

Figure 6. A multimaterial beam simulated to examine material behaviour under transformation [19]. © 2019 Elsevier

3.4.2 Simulation

When it comes to 4D printing with smart materials, it is beneficial to simulate the models before manufacturing them to see how changes apply with time. In Figure 6, a simulation is completed on a beam made of voxels to investigate how different materials behave under change. Voxel-based simulation allows rapid testing of a part and its material distribution under transformation before proceeding to more detailed design [19].

4 Voxel model applications

There are many different applications available for voxel models. Nevertheless, anything can be manufactured with voxels that can be made with other 3D representation methods. However, in some applications voxel models are more efficient compared to conventional 3D modelling methods. For example, medical applications as well as aerospace and automotive applications benefit from voxel-based models.

4.1 Medical applications

In medical applications, voxel models have certain advantages when compared to traditional modelling methods. Voxels are used in computed tomography (CT scan), which is a method used to photograph the inside of a human body. CT scan turns many 2D images into a single 3D image [3]. Voxels allow direct 3D printing from CT images, which is beneficial in terms of manufacturing custom implants like organs or bone scaffolds.

4.1.1 Modelling and manufacturing an organ

In medicine, individual parts like implants are created for patients using 3D images from CT scans and parametric surfaces, or triangle meshes. These traditional tissue modelling methods only represent surface topology, which leaves interior and volume of the object unknown. To ensure compatibility, the model is voxelized, which provides volume information and allows comparison with 3D images. To further improve tissue modelling, a voxel-based approach called Voxel Centric Processor (VCP) has been proposed. VCP utilizes CT-scans for creation of models, which allows objects to contain heterogeneous material properties inside and outside of the model. This method allows the assignment of different material features, such as colour or transparency. However, this approach comes with limitations as simulating essential physiological functions has not been possible. These challenges arise from the functionality of soft tissue materials. Figure 7 shows the process of manufacturing a full-scale model of a human liver [3], [21].

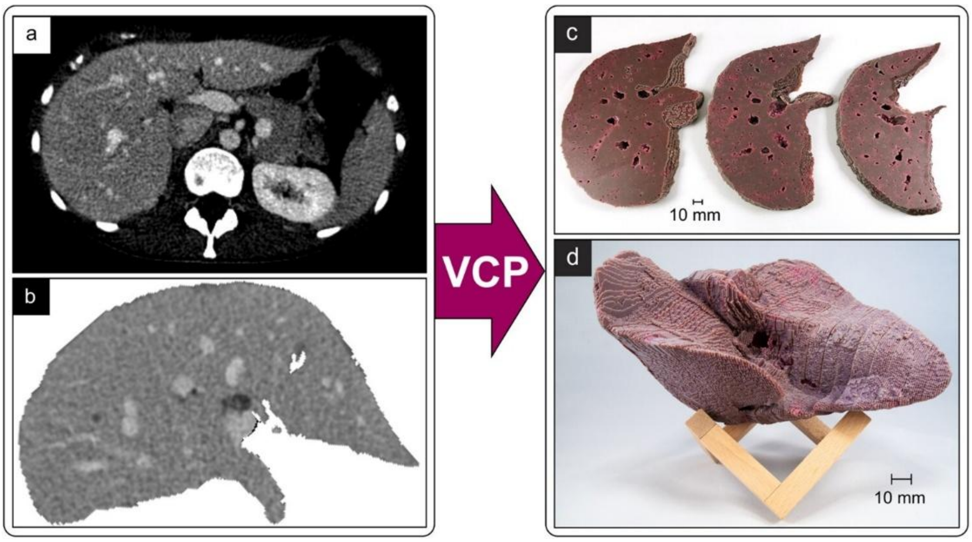

Figure 7. A patient CT-scan of a liver (a) isolated for segmentation (b). A cut-through picture shows the interior composition (c) of the 3D printed full-scale liver (d) [21]. © 2025 Taylor & Francis Group

4.1.2 Bone scaffolds

Bone scaffolds are employed for bone repair and regeneration in case of bone loss or injury. Conventional design methods have limitations in designing composite scaffolds. Mimicking a natural, heterogeneous composition of bone tissue and constructing a functioning simulation model are challenging. However, bone scaffolds can be manufactured using a voxel-based method to satisfy biological and mechanical requirements. The ability of voxels to create complex and highly precise designs allows altering of pore shapes, sizes and mechanical properties in the scaffold. This method is beneficial when it comes to manufacturing individually tailored bone scaffolds for patients [22].

4.2 Aerospace and automotive applications

Aerospace applications benefit from components that are lightweight, can handle high temperature and have complicated geometries such as lattice or porous structures. Additionally, digital models of spare parts are useful in case of a broken component. As for automotive industry, the production volume is high thus additive manufacturing is less used for large-scale, mass-produced products. However, additive manufacturing is utilized to create prototypes and smaller-scale components [1]. Aerospace and automotive industries benefit from lattice and porous structures, topology optimization and simulation, which voxels can efficiently present.

4.2.1 Lattice structures

Lattice is formed of repeated trusses or plates that are connected to each other. With the help of lattices, special properties can be accomplished. However, the basic 3D representation methods, such as BREP or constructive solid geometry (CSG) do not represent lattices precisely. Expressing a lattice structure in its whole might exceed the abilities of conventional CAD systems. Additionally, there is a lack of information about interior regions of objects. Voxel representation method can be utilized to effectively represent lattice structures [4]. Building lattice structures is quick with voxels since only one model of an unit cell is made and copied to make a full model of a lattice [2].

4.2.2 Porous structures

Porous structures are components that have internal holes and tunnels, known as pores, which can vary in size, shape and arrangement. They can be used to perform computational fluid dynamics (CFD) simulation, which measures the flow of a fluid. In a case study, the flow simulation is done based on a CT image of a real-world object. This allows direct reconstruction of the model since CT images are made of voxels. Additionally, with this method, a CAD model is redundant. With suitable voxelization of the model, the attributes are relatable to the original data. However, if the resolution is not high enough, staircase effect will appear which leads to turbulence. This decreases the absorptiveness of the model and thus falsifies the results. Figure 8 shows a voxel-based porous structure [23].

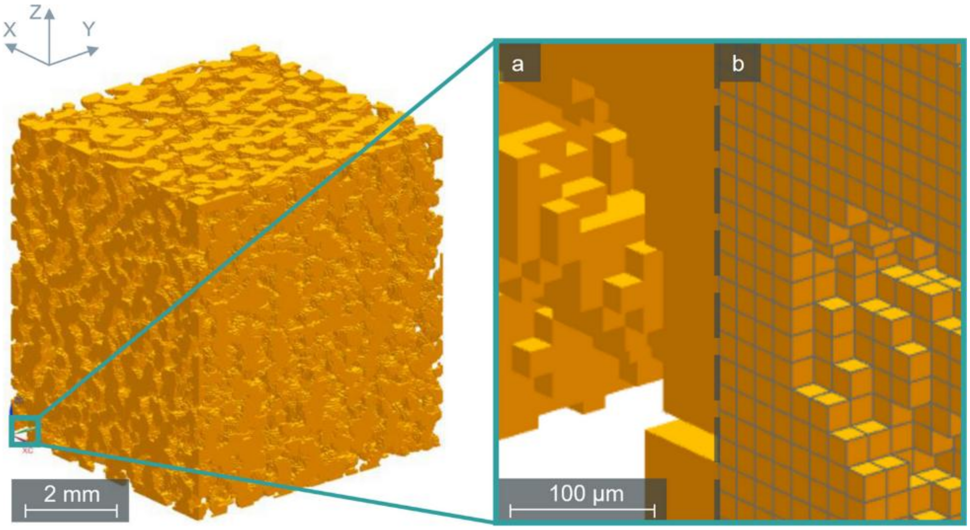

Figure 8. Voxel-based porous structure with a zoomed in view without (a) and with a grid (b) [23].

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4.2.3 Topology optimization

Topology optimization (TO) is a computational method for designing efficient and lightweight components. It is utilized in aerospace and automotive applications to improve performance and reduce costs, energy consumption and emissions. There has been developed a voxel-based TO method to optimize complex three-dimensional geometries efficiently. This method is based on an optimization algorithm, where a ray tracing voxelization is employed to convert 3D models into a voxel-based format. The procedure allows optimizing a model of any shape, which allows flexibility in design. Additionally, the algorithm recognizes and removes unnecessary voxels. Furthermore, it ensures the compatibility of the model in each iteration to avoid impractical designs for real-world applications [24].

4.2.4 Simulation

In aerospace and automotive applications simulation is important whether testing the functionality of a space rocket or doing a car crash test. Voxel-based models are beneficial when presenting complicated geometries in CFD for simulating how a fluid would flow. For example, a CFD simulation of a Formula 1 car is shown in Figure 9. This helps to determine the aerodynamic performance of a car. With CFD, all kinds of attributes can be measured such as drag force, kinetic energy and voxel collision count. For achieving accurate simulation results, the voxel size must be small enough. Additionally, with trial and error, it is possible to enhance the outcome of the model [25].

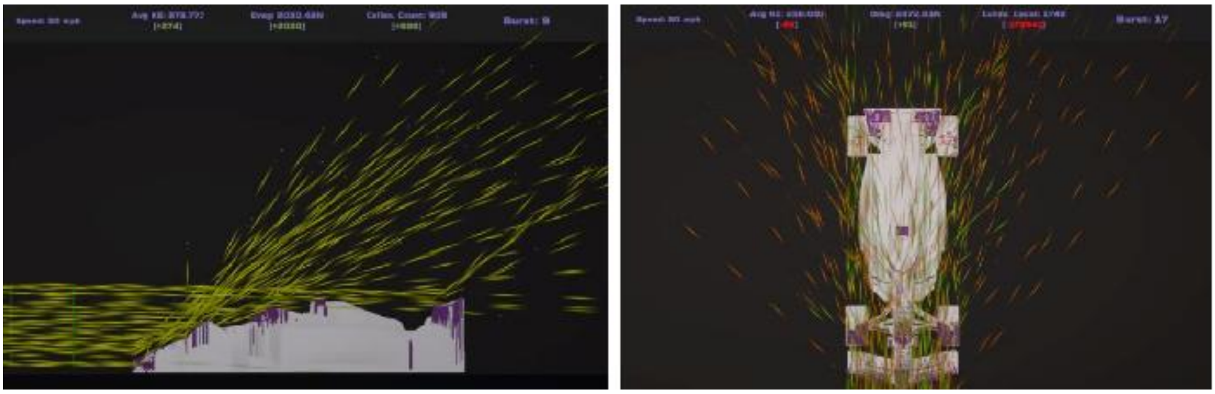

Figure 9. CFD simulation of a voxel-based Formula 1 car [25]. © 2024 IEEE

5 Future aspects

Additive manufacturing has developed rapidly in the last few decades and will continue to. Additionally, the possibilities of 4D printing are not fully discovered since the technique is novel. Some targets of development in voxel-based modelling could include manufacturing customized tissues and consumer products through scanning. Another step of progress is including artificial intelligence and machine learning in the design process.

5.1 Personalized medical and consumer products

Voxel-based models allow highly customized manufacturing in medicine and consumer products. Since voxel models can be created directly from a patient CT scan, personal organs, tissues, and implants are simple to manufacture. However, functionality is an issue when designing individual organs to patients. Besides the correct heterogeneous material properties and volume information of the model, functional artificial tissues are still under development [21]. Further studies on bioprinting and tissue modelling are crucial to succeed in this field.

Beyond medicine, other types of personalized items could be manufactured on request to fulfil customer needs. Products such as footwear or eyewear could be manufactured by scanning, which ensures a correct fit and size. Additionally, scanning allows direct manufacturing from the scan image.

5.2 Artificial intelligence and machine learning

At present, artificial intelligence (AI) has not been directly applied to voxel models. However, research has explored AI training using voxelized data, focusing on 3D AI learning. Compared to traditional 2D datasets, 3D AI learning is a less explored field. This technique can be implemented on fields such as product design [26]. Since AI is a growing field of study, the possibility of utilizing it with voxels in the future is high.

Machine learning (ML) is a subset of AI that employs various algorithms to analyse and adapt from provided data. Currently, no studies have utilized ML with voxel models. However, similarly to AI, machine learning shows significant potential for application with voxel models. Some examples of utilizing ML could include separating solid and void voxels from each other or optimizing material distribution in a desired way.

6 Conclusions

Voxel-based modelling offers multiple benefits among all other advantages of three-dimensional models. Compared to traditional modelling methods, voxels excel in providing volumetric information, which allows use of multi-materials effortlessly. Additionally, modifications to the material properties of the model can be made accurately. Other benefits include handling complex geometries, such as lattice structures, and providing easy Boolean operations between models. Furthermore, in 4D printing voxels are a great tool for accurate simulation and precise control of material distribution.

Combined with the abilities that arise from additive manufacturing, including 3D and 4D printing, voxels can be utilized in many applications for different purposes. Ranging from medical applications to aerospace and automotive industry, voxels are providing efficient and durable solutions to conventional modelling methods. However, due to high computational and memory costs of voxels, traditional modelling methods might be more practical for simple designs.

The future of voxel-based modelling is promising. By combining the advantages from voxels and additive manufacturing, special parts can be designed manufactured with high precision. As research progresses, fields such as medical applications and 4D printing will drive novel innovations and expand the possibilities of voxel-based design.

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