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COLOR VISUALIZATION OF 3D-MODELS FOR ENHANCED PREPARATION OF ADDITIVE MANUFACTURING PROCESSES

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Abstract. *The main aspects of color visualization of triangulated models of industrial products are presented. The implementation of visualization capabilities is based on RGB and HSV color models. The structure and key features of the software implementation of color visualization and the export of the displayed image in PLY, and AMF formats are discussed. Methods for transformations between RGB and HSV color models are described, as well as an algorithm for coloring the triangular faces of the model based on specified color ranges. The developed algorithms allow for a sufficiently informative representation of the desired areas of the product's surfaces by significantly altering one color component while minimally changing the other two. This is achieved by directing the assignment of functional dependencies and value ranges for each component of the color model. Examples of various methods for color shading of vertices and/or edges and/or faces of the model are provided. The visualization subsystem enables the analysis of the geometric characteristics of the polygonal model during the preparation phase of additive manufacturing processes. Significant advantages of these approaches to color visualization are evident when adapting the product design to technological requirements (design preparation) and when solving optimization tasks in technological preparation. The developed software is integrated into the technological preparation system for manufacturing enterprises in the machine engineering sector. This research was developed at the Department of "Integrated Technologies of Mechanical Engineering" named after M. Semko of NTU "KhPI".*
Keywords: *technology planning; additive manufacturing; triangulated model; color model; RGB; HSV.*

1. Introduction

There is a problem of the low efficiency of additive technologies, especially in the mass production of a group of 3D-models of complex products. Each technology has its rational scope of application, which is determined by the design features of the product [1]. Automation of determining the design features of the product by its triangulation model creates the basis for a rational choice of manufacturing strategy and increases the efficiency of additive manufacturing [2]. An additional aspect of the problem is the visual verification of 3D-models of industrial products at the preliminary stage of technological planning of processes.

Geometric models in CAD systems are based on a specific data structure that ensures the topological integrity of the model. In order to unify the representation of information about the surfaces of 3D-models for their subsequent additive manufacturing, a transition is made from CAD-models to triangulation models. The triangulation representation of the product model (STL format) is approximate. The accuracy of the approximation of the triangulation model to the original CAD-model is ensured by a sufficient number of triangular faces (polygons) within the specified limits of the permissible error.

2. Review of the literature

Color visualization of triangulated models plays an important role in preparation for additive manufacturing. Colors can be used to represent different properties of the model, such as surface curvature, wall thickness, or material stress. This helps to identify potential problem areas before printing.

The RGB and HSV color models are widely used in computer graphics and image processing. The HSV model is considered more user-friendly for human perception due to its intuitive separation into hue, saturation, and brightness. Conversions between RGB and HSV are actively investigated for computational optimization [3].

Exporting triangulated models to PLY, OBJ, OFF, and AMF formats is necessary for data exchange between different CAD and analytical systems. Much work has been done to develop efficient methods for transforming and simplifying polygonal meshes [4].

The use of color to encode geometric and physical properties of models helps in visual analysis and defect detection [5]. Various shading techniques have been developed that take into account curvature, slope, wall thickness, etc. [6, 7].

In general, color visualization is an important tool for the preparation and optimization of additive manufacturing processes, which is confirmed by numerous studies in this field [7-9].

The work aims to determine recommendations for color visualization of polygonal model elements when analyzing both topological indicators and design features of the product, affecting the implementation of technological preparation tasks for additive manufacturing processes.

3. Materials and methods

When visualizing triangulation models, two approaches can be used to highlight the colors of the studied topological and geometric features: discrete assignment of colors according to given conditions or the use of color scales for the interval of change of the studied feature.

Primary analysis of product models manufactured by layered building shows that to solve color visualization tasks, it is sufficient to use the RGB, and HSV color models and their combination [10, 11].

RGB color model. The RGB model is based on the combination of three main colors (components): red, green, and blue. Each of these colors has a range of discrete brightness values of 0÷255. The required color is achieved by adding three basic colors with given intensity levels (additive model). The RGB model is the basic one for computer devices and color visualization programs. The maximum number of reproducible color shades is 256×256×256 ≅ 16.7 million colors [12].

The disadvantage of the RGB model is the impossibility of constructing color scales for visualizing changes in the studied features since it is difficult to predict the consequences of even small changes in the color components R, G, B [10, 11].

HSV color model. The HSV model is based on the assumption that color can be described by a single monochromatic wave – color tone (hue) H with an additional assignment of saturation S and lightness V [10]. The parameters of this color model are as follows:

H (Hue) – color tone, one of the main characteristics of color that determines its shade, varies within 0°÷360°;

S (Saturation) – saturation, characterizes the quality of the purity of the chromatic color tone, the closer this parameter to zero, the lighter the selected color, varies within 0÷255 (0÷1 or 0÷100);

V (Value) – brightness, the closer this parameter to zero, the darker the selected color, varies within 0÷255 (0÷1 or 0÷100).

In computer graphics, the parameters S and V are usually represented as an integer from 0 to 255.

The main advantage of the HSV model is the ability to construct color scales to visualize the features being studied.

The color scale displays the change in the studied feature using color shades for a given color model (S = S_{base}, V = V_{base}). The color scale is defined by the range from the initial value H = H_{Top} to the final value H = H_{End}, which contains all the shades corresponding to the spectrum. For the original HSV model, the values H_{Top} = 0°, H_{End} = 360° ($H_{Top} < H_{End}$), which provides a smooth transition between the six primary colors: red ⇒ yellow ⇒ green ⇒ blue ⇒ dark blue ⇒ purple [11]. When creating special color scales, the range of color shades can be reduced (H_{Left} > 0°

and/or, H_{Right} <360°) or the order of shades can be reversed ($H_{Left} > H_{Right}$). In color visualization of computer models, $S_{Base} = V_{Base} = 255$ is usually taken, i.e. the maximum possible values of saturation and brightness (prismatic colors) [11, 12].

Color visualization taking into account the values of the studied feature X ($x_{min} \le x \le x_{max}$) is performed in two stages:

1. transition $x \Rightarrow H = f(x;\, x_{min},\, x_{max},\, H_{Left},\, H_{Right})$;
2. transition HSV ⇒ RGB: R, G, B = $f(H;\, S_{Base},\, V_{Base})$.

Transition *x* ⇒ *H*. The transition from the current x value visualized by color to the H color value of the HSV scale for linear scales is performed according to the following dependencies (proportion problem taking into account special cases):

- $H = H_{Left}$, if ($x = x_{min}$ and $H_{Left} \le H_{Right}$) or ($x = x_{max}$ and $H_{Left} \ge H_{Right}$);
- $H = H_{Right}$, if ($x = x_{max}$ and $H_{Left} \le H_{Right}$) or ($x = x_{min}$ и $H_{Left} \ge H_{Right}$);
- $H = [(x - x_{min}) / (x_{max} - x_{min})] \times (H_{Right} - H_{Left}) + H_{Left}$, if $H_{Left} < H_{Right}$;
- $H = [(x - x_{min}) / (x_{max} - x_{min})] \times (H_{Left} - H_{Right}) + H_{Right}$, if $H_{Left} > H_{Right}$,

where H_{Left}, H_{Right} – left and right values of the HSV color scale;

x_{min}, x_{max} - minimum and maximum possible values of x.

Transition HSV ⇒ RGB. The transition diagram is shown in Fig. 1. The transition functions for each of the RGB components are piecewise linear and shifted relative to each other by 120°.

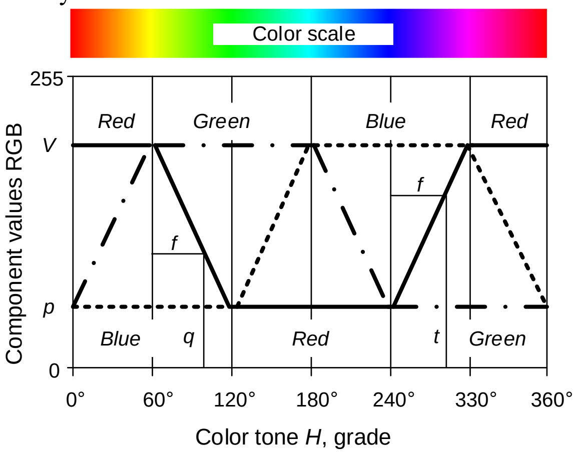

Figure 1 – Scheme of transition from HSV to RGB color model

The general algorithm for the HSV ⇒ RGB transition is presented in [12]. For the case of H = 0÷360°; S, V, R, G, B = 0÷255, the calculation is performed according to the following dependencies in two stages (definition of auxiliary variables and directly the RGB components).

Definition of auxiliary variables:

- integer part of the expression $H / 60 \Rightarrow H_i$;
- fractional part of the expression $H / 60 \Rightarrow f$;
- maximum possible value $R/G/B \Rightarrow V$;
- minimum possible value $R/G/B \Rightarrow p$: $p = V (1 – S / 255)$;

amplitude (interval of change) of values R/G/B $\Rightarrow A$: $A = V - p = V$ S / 255;

R/G/B value for downlink $\Rightarrow t$: $q = A (V – f) = V (1 – f S / 255)$;

R/G/B value for uplink $\Rightarrow t$: $t = p + f\ A = V [1 - (1 - f) S / 255]$.

Determining the values RGB components:

• if $H_i = 0$ or 6,	then	$R = V$,	$G = t$,	$B = p$;
• if $H_i = 1$,	then	$R = q$,	$G = V$,	$B = p$;
• if $H_i = 2$,	then	$R = p$,	$G = V$,	$B = t$;
• if $H_i = 3$,	then	$R = p$,	$G = q$,	$B = V$;
• if $H_i = 4$,	then	$R = t$,	$G = p$,	$B = V$;
• if $H_i = 5$,	then	$R = V$,	$G = p$,	$B = q$.

4. Implementation of developments in the morphological analysis system

The considered approaches to color visualization are implemented in the system of analysis of triangulation 3D models of products which was developed at the Department of "Integrated Technologies of Mechanical Engineering" named after M. Semko of NTU "KhPI" [13].

Color visualization of individual elements of triangulation models can be performed using discrete color assignment (RGB and/or HSV) or the HSV color scale (Fig. 2). The choice of color visualization strategy is determined by the features of the topological or design-technological analysis in the context of the production or educational task being solved.

The color of the model is assigned based on the data obtained during the morphological analysis of the components of the triangulation model surface. The subsystem allows coloring the following elements of the triangulation model: vertices, faces, or edges. Visual perception of the topological features of the model is achieved by comparing the specified color scale with the feature being studied.

For further work with the model, it is exported to formats that support color: PLY, AMF (new format for additive manufacturing), or XLS (analysis results). Vertex coloring during viewing is implemented as a gradient coloring of triangular faces by the color of adjacent vertices.

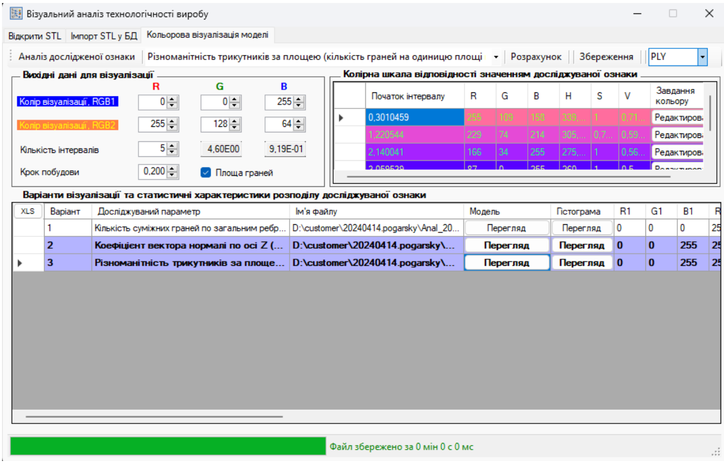

Figure 2 – Screen form of the color visualization subsystem

To view and edit the created files in the educational process, Materialise Magics program is used with a sufficient set of tools and is free, which is important for scientific research.

5. Examples of color visualization of triangulation models. Discussion

Let's consider several examples of color visualization of triangulation model elements.

• Color visualization of vertices by the value of adjacency of faces (Fig. 3). Vertices are assigned one of three specified colors. For example, if the adjacency of faces at a vertex is $A_{Vert} < 3$, then the color RGB 1 (red) is assigned, if $A_{Vert} = 3 \Rightarrow$ RGB 2 (green), $A_{Vert} > 3 \Rightarrow$ RGB 3 (gray). This allows us to visually identify missing edges that disrupt the closed nature of the model surface and lead to failure of the layer-by-layer materialization installations.

• Color visualization of faces (Fig. 4) relative to the x, y, z axes, where the orientation of the faces is determined by the direction cosines of the normal (HSV model).

• Color visualization of faces depending on the area value of triangles (HSV model). The studied feature that determines the color tone in this case is the area value of the face. The left border of the color scale of the color tone implies the

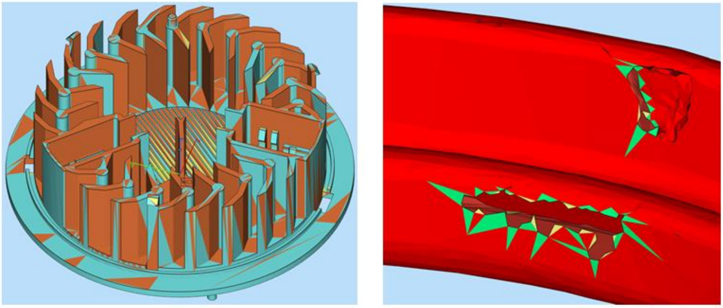

Figure 3 – Adjacency of faces

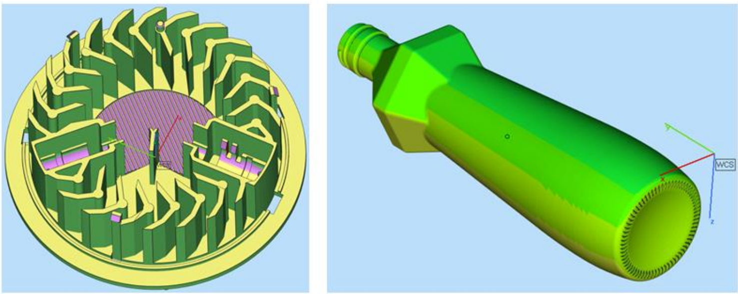

Figure 4 – Orientation of faces

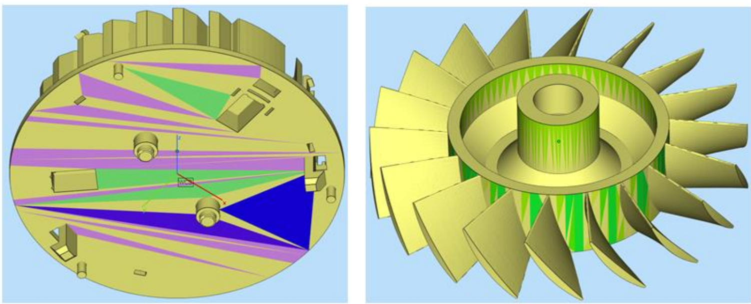

Figure 5 – Face area

largest value of the faces area, and the right one - the smallest (Fig. 5). Thus, the color scale gives a visual representation of the sizes of the triangles.

Color visualization will be especially advantageous in studying the physical and mechanical properties of products, as shown in [14].

6. Conclusions

The research presents a comprehensive approach to color visualization of triangulation models for additive manufacturing using RGB and HSV color models. Key findings include:

– the HSV color model offers significant advantages over RGB for visualization, enabling - intuitive color scale construction, smooth representation of feature changes, flexible color mapping for various topological and geometric characteristics;

– developed color visualization techniques allow for discrete color assignment; interval-based color scaling, and detailed analysis of model elements (vertices, faces, edges);

– practical implementation demonstrates the effectiveness of color visualization in identifying surface topology issues, analyzing face orientation, evaluating triangle areas, and detecting potential manufacturing challenges.

The proposed methodology provides a flexible tool for morphological analysis of 3D models, supporting both scientific research and educational applications.

The developed color visualization approach enhances the preparatory stages of additive manufacturing by enabling comprehensive visual analysis of geometric and topological model features.

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КОЛІРНА ВІЗУАЛІЗАЦІЯ 3D МОДЕЛЕЙ ДЛЯ УДОСКОНАЛЕННЯ ПІДГОТОВКИ ПРОЦЕСІВ АДИТИВНИХ ТЕХНОЛОГІЙ

Анотація. *Представлено комплексний підхід до кольорової візуалізації тріангульованих моделей промислових виробів для адитивного виробництва. Дослідження базується на використанні RGB та HSV кольорових моделей, що дозволяють створювати інформативні та наочні зображення геометричних характеристик виробів. Розроблено структуру та методологію програмної реалізації кольорової візуалізації з можливістю експорту в стандартні формати PLY, AMF. Детально висвітлено алгоритми перетворення між кольоровими моделями RGB та HSV, включаючи математичні залежності для перетворення значень кольорових компонент з урахуванням специфіки комп'ютерної графіки та вимог щодо виконання задач технологічної підготовки процесів адитивних технологій. Запропоновано новий підхід до розфарбовування трикутних граней 3D-моделі, який дозволяє цілеспрямовано змінювати кольорові відтінки для виділення специфічних геометричних особливостей. Ключова перевага розробленої методики – можливість інформативного відображення топологічних характеристик поверхонь шляхом контрольованої зміни кольорових компонент. Це реалізовано шляхом візуалізації кольорів з гнучким налаштуванням дискретності призначення кольору за наданими інтервалами шкали кольорів. Представлення шкали кольорів у вигляді таблиці дає розширені можливості. Таблиця шкали кольорів формується автоматично за налаштуваннями, але можлива зміна як окремо по кожній компоненті кольору або візуально на основі палети (стандартного набору) кольорів. Шкала кольорів визначається діапазонами компонент RGB моделі кольору, залежностями зміни, зсувом значень між компонентами та кількістю інтервалів. Реалізовано можливість зміни кольору вершин, ребер та граней залежно від їх геометричних параметрів або відносного розташування. Представлено практичні приклади застосування різних стратегій кольорової візуалізації. Розроблена підсистема візуалізації забезпечує ефективний аналіз геометричних характеристик полігональних 3D-моделей на етапі підготовки адитивного виробництва, надаючи розширені можливості для комплексної конструкторської та технологічної підготовки адитивного виробництва. Дослідження виконувалося з використанням системи "Технологічна підготовка матеріалізації складних виробів адитивними методами" розробленої на кафедрі «Інтегровані технології машинобудування» ім. М.Ф. Семка НТУ «ХПІ».*

Ключові слова: *технологічна підготовка; адитивні технології; тріангуляційна модель; колірна модель; RGB; HSV.*