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Application of Attribute Information of Voxel-Based 3D Data Format FAV for Metamaterials Structure Design

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Abstract

A FAV is novel voxel-based 3D data format in which the voxels can hold attribute information such as materials, colors, modeling parameters, or physical values. FAV is expected to be used for various kinds of simulations or for modifying the design of the object based on the results of measurement data from various sensors. We applied the attribute information for designing metamaterials structure for the first time. Attribute information is registered in each voxel of 3D data by specified directional penetrate projection of two-dimensional raster data or overlaying of three-dimensional raster data. Locally modified metamaterials structure is embedded into 3D data by using a 3D threshold value matrix which represents the shape of unit of metamaterial element and digital halftone screening technology. The 3D threshold value matrix is generated for any type of metamaterials based on the existence probability of voxel arrangement of the unit of metamaterial element. With the technologies, three-dimensional physical property values' distributions can be easily converted to locally modulated metamaterials structure, which can be expected various industrial use.

Introduction

We are developing and standardizing a novel voxel-based 3D data format "FAV" [1-3]. FAV stands for fabricatable voxel, and represents 3D model by arranging of three-dimensional volume cells (voxels) in a similar way to images consisting of arranging two-dimensional picture cells (pixels). The FAV can express complex structures of 3D model including internal structures. Figure 1 shows configuration of comparison with conventional mesh model data and voxel model data with holding attribute information.

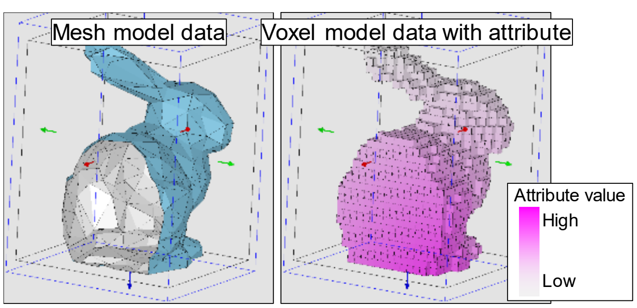

Figure 1. *Configuration of comparison with conventional mesh model data and voxel model data with holding attribute information.*

Another feature of the FAV is that each voxel can hold various attribute information such as materials, colors, modeling parameters, or physical values with the overall shape of the object. Therefore, voxel-based data can be used for various kinds of simulations or for modifying the design of the object based on the results of measurement data from various sensors. Figure 1 schematically shows the concept of FAV.

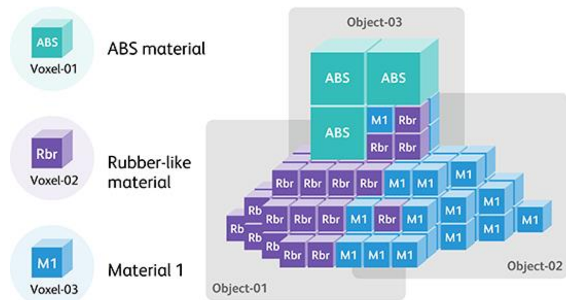

Figure 2. *Conceptual diagram showing voxels arranged three-dimensionally.*

On the other hand, metamaterial, which is micro-structured object so as to control or generate specific physical properties that is hard to achieve with a single material, are widely investigated. It is suitable for forming metamaterial structures by 3D printer, and they are assumed to use in several applications such as elastic porous materials [4], heat dissipation materials [5-6], sound insulation materials [7], negative refractive materials [8], etc. Generally, 3D printable materials are limited, metamaterial is expected to break through the limitation. For example, there are some papers on the methods to modify elasticity of 3D printed object by changing metamaterials structure [9-12]. However, they were only able to make restrictive modifying such as in units of metamaterial element (mm order) or based on specific theoretical formula.

With the FAV, continuous local control of physical properties becomes possible by changing the shape of metamaterials structure referring to the attribute information in voxels, which makes to control the performance locally by using single material. Therefore, mass-customized products can be easily manufactured to optimize not only the shape, but also the several physical features individually.

In this report, we describe the methods to register the attribute information in voxels, and to modify locally the volume and/or pitch of various metamaterials structure by comparing a 3D threshold value matrix with the attribute information in FAV.

Key Methods

A design flow of metamaterials structure

In this section, we would like to talk about outline of the developed technologies. Figure 3 shows a design flow of metamaterials structure applying the technologies. First of all, attribute information is registered in voxels of prepared 3D shape data by using raster data (image or CSV). In next step, metamaterials structure is embedded into the 3D shape data by Boolean operations (AND). At this time, by digital halftone screening technology, the volume and/or pitch of metamaterials structure is locally modified by comparing the attribute information in FAV and 3D threshold value matrix which is prepared.

The following sections describe each technology in detail.

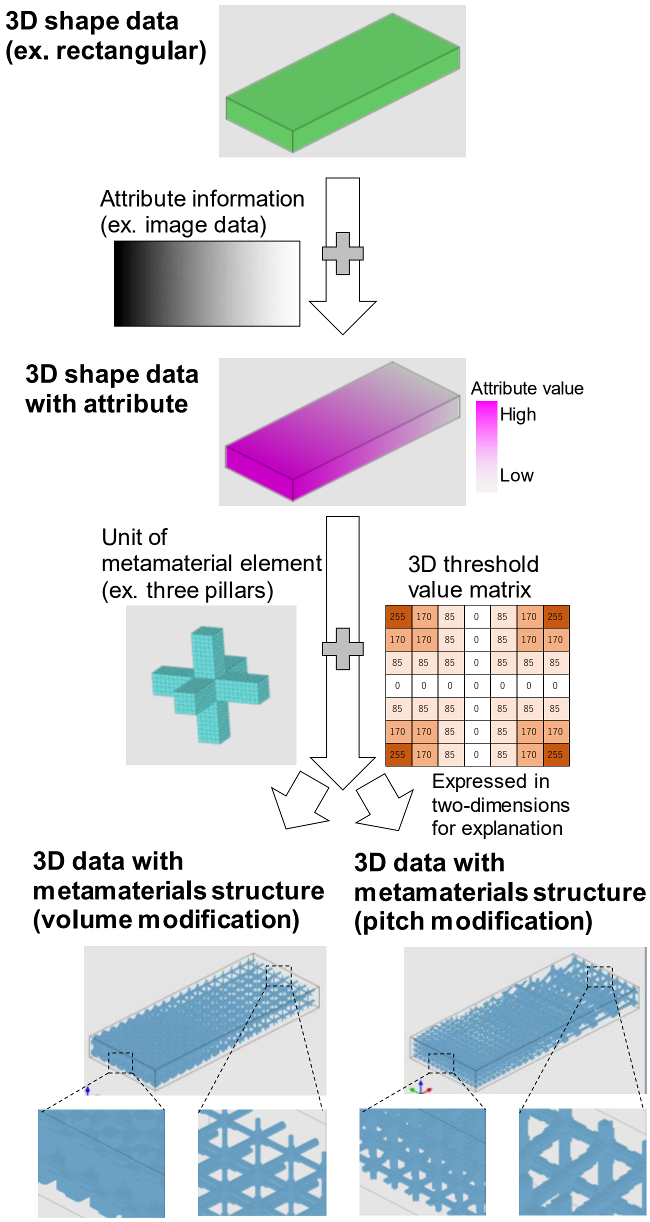

Figure 3. *A design flow of metamaterials structure applying the technologies.*

Method to Register Attribute Information in Voxels

We adopted two ways to register attribute information in voxels, the first is specified directional penetrate projection of two-dimensional raster data, and the second is overlaying three-dimensional raster data provided in CSV format. The procedure is described below;

1). Prepare voxel model data for which you want to register attribute information.
2). Read original data that to be attribute information as two-dimensional raster data (image or CSV) or three-dimensional raster data (CSV).
3). Adjust position and size by moving / rotating / scaling the raster data relate to the voxel model data.
4). Register the attribute information to the voxel model data by penetrate projection in a specified direction of two-dimensional raster data or overlaying of three-dimensional raster data.

Figure 4 shows configuration of steps of voxel attribute registration using two-dimensional raster data. It is also possible to use multiple raster data to register single attribute information. At that time, the attribute information between each raster data is registered by interpolation. Figure 5 shows configuration of voxel attribute registration using multiple two-dimensional raster data.

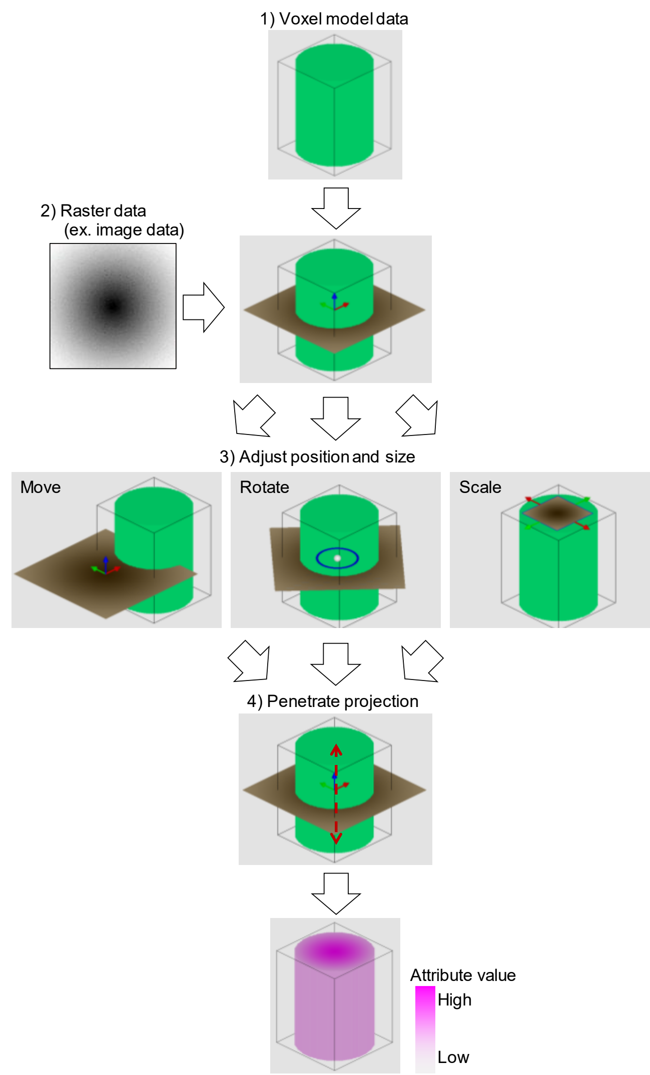

Figure 4. *Configuration of steps of voxel attribute registration using two-dimensional raster data.*

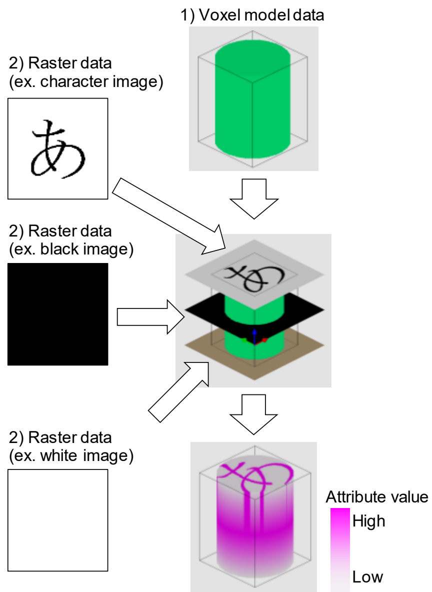

Figure 5. *Configuration of voxel attribute registration using multiple raster data.*

Method to Modify Locally of Metamaterials Structure

Locally modified metamaterials structure is embedded into the 3D shape data as follows;

1). Prepare a 3D threshold value matrix which represents the shape of unit of metamaterial element.

2). Compare the attribute information of voxel with the 3D threshold value matrix, then the greater part and the lesser part are separated into different type of voxels.

Volume modification which means modification of thickness of the metamaterials structure is possible by preparing 3D threshold value matrix having graded threshold field. Pitch modification of metamaterials structure is also possible by changing geometric scale of 3D threshold value matrix space and that of voxel model data space based on the attribute information.

For comparing the attribute information of voxel with the 3D threshold value matrix, following equation are applied.

$$V(i,j,k)=\begin{cases} n_a, At(i,j,k) < Mt(l,m,n) \\ n_b, At(i,j,k) \geq Mt(l,m,n), \end{cases} \tag{1}$$

where

$$\begin{cases} l = MOD\left(A_x * i, \dfrac{M_x}{v_x}\right) \\ m = MOD\left(A_y * j, \dfrac{M_y}{v_y}\right) \\ n = MOD\left(A_z * k, \dfrac{M_z}{v_z}\right), \end{cases} \tag{2}$$

$$\begin{cases} A_x = \dfrac{A_{x0}-100}{100} * \dfrac{At(i,j,k)}{At_{\max}} + 1, A_{x0} \geq 100 \\ A_y = \dfrac{A_{y0}-100}{100} * \dfrac{At(i,j,k)}{At_{\max}} + 1, A_{y0} \geq 100 \\ A_z = \dfrac{A_{z0}-100}{100} * \dfrac{At(i,j,k)}{At_{\max}} + 1, A_{z0} \geq 100. \end{cases} \tag{3}$$

Here, $V(i, j, k)$ is the voxel identification at position (i, j, k) of the voxel model data (ex: n_a = absence of voxel, n_b = present voxel), $At(i, j, k)$ is the attribute value of the voxel at position (i, j, k) of the voxel model data, At_{max} is the maximum of the attribute value, $Mt(l, m, n)$ is the threshold value at position (l, m, n) of the 3D threshold value matrix, M_x, M_y, and M_z are the overall numbers of grid of the 3D threshold value matrix for each of the axes: x, y, and z, v_x, v_y, and v_z are the unit sizes of the voxel of the voxel model data for each of the axes: x, y, and z, A_x, A_y, and A_z are the scale factors for changing geometric scale of the 3D threshold value matrix space, and A_{x0}, A_{y0}, and A_{z0} are the scale factor changing rates that specify the changing rate of the scale factors for each of the axes: x, y, and z.

It is also possible to superimpose both volume and pitch modification of metamaterials structure by applying these equations. In case of modifying only the volume of metamaterials structure, it is possible by substituting 100 to A_{x0}, A_{y0}, A_{z0} of the equation (3). To modify only the pitch of metamaterials structure, it is possible by binarizing $Mt(l, m, n)$ of the equation (1). Figure 6 shows configuration of modification of metamaterials structure by comparison operation between the attribute information of voxel with the 3D threshold value matrix.

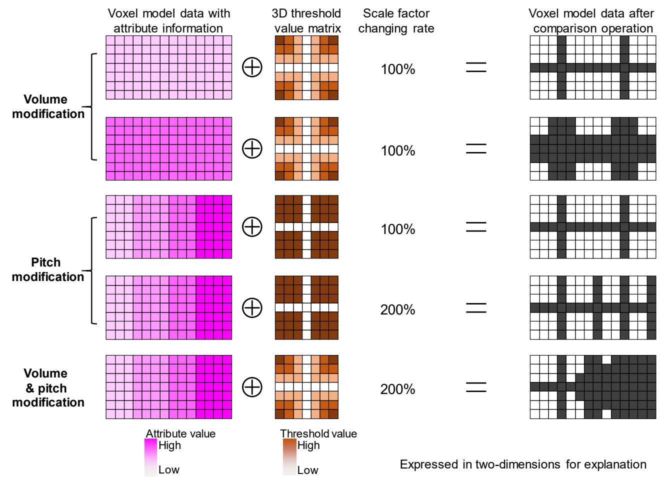

Figure 6. Configuration of modification of metamaterials structure by comparison operation between the attribute information of voxel with the 3D threshold value matrix.

In equation (3), the scale factors A_x, A_y, and A_z are calculated as 100% (which performs no pitch modification) when the attribute information of the voxel *At(i, j, k)* is minimum. While, following equation (4) is applied instead of equation (3) in case of the scale factors A_x, A_y, and A_z need to be calculated as 100% when the attribute information is median. Equations (3) and (4) can be selected depending on cases.

$$\begin{cases} A_x = \left(\dfrac{A_{x0}}{100}\right)^\wedge \left(2 * \dfrac{At(i,j,k)}{At_{\max}} - 1\right), A_{x0} \geq 100 \\ A_y = \left(\dfrac{A_{y0}}{100}\right)^\wedge \left(2 * \dfrac{At(i,j,k)}{At_{\max}} - 1\right), A_{y0} \geq 100 \\ A_z = \left(\dfrac{A_{z0}}{100}\right)^\wedge \left(2 * \dfrac{At(i,j,k)}{At_{\max}} - 1\right), A_{z0} \geq 100. \end{cases} \tag{4}$$

Method to Generate 3D Threshold Value Matrix

To modify continuously without separation or overlapping between each elements of metamaterials structure, the 3D threshold value matrix should be designed appropriately for each metamaterial. We developed a procedure to generate 3D threshold value matrix from any type of metamaterials described below;

1). Prepare voxel arrangement (whether a voxel is present or not at each three-dimensional position) of a unit of metamaterial element, where the dimension and the unit size set to be equal to that of the 3D threshold value matrix to be generated.

2). For each position in the voxel arrangement, calculate accumulate number of present voxels weighted by the distance from the target position, which represents the existence probability of voxel at each position.

3). Normalize the accumulated number of present voxels as the threshold value according to the attribute information to be compared, which makes it possible to generate the 3D threshold value matrix based on the existence probability of voxel arrangement of prepared unit of metamaterial element.

The accumulated number of present voxels is calculated by following equation (5).

$$N(l,m,n) = \sum_{x=1}^{M_x} \sum_{y=1}^{M_y} \sum_{z=1}^{M_z} V(x,y,z) * 2^{-d} \tag{5}$$

Here, *N(l, m, n)* is the accumulated number of present voxels at the target position *(l, m, n)* of the voxel arrangement of the unit of metamaterial element, M_x, M_y, and M_z are the overall numbers of grid of the 3D threshold value matrix for each of the axes: x, y, and z, *V(x, y, z)* is binarized value of voxel presence at position *(x, y, z)* of the voxel arrangement of the unit of metamaterial element (0 = absence of voxel, 1 = present of voxel), and *d* is the minimum distance between the target position *(l, m, n)* and the position *(x, y, z)* in the metamaterials structure.

In addition, multiple units of metamaterial element can be used for applying the method, and it can be realized modification of metamaterials structure further controlled as desired. Furthermore, in case of modifying the metamaterials structure regardless of the attribute information in FAV, it is possible by setting the threshold value which exceeds the maximum or the minimum value of the attribute information to be compared.

In figure 7, in case of using "three pillars" and "gyroid" as the unit of metamaterial element, it schematically shows to design 3D threshold value matrix by abovementioned method.

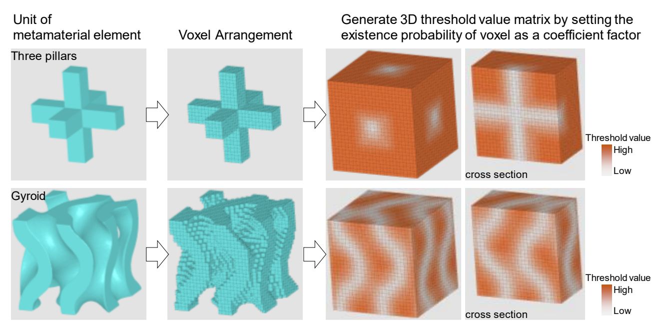

Figure 7. Configuration of Method to Design 3D Threshold Value Matrix.

Results

Based on the methods, various attribute information can be registered for each voxel of 3D data, and also the volume and/or pitch of various metamaterials structure can be locally modified based on the attribute information of each voxel. As an example of the results, figure 8 shows the example 3D objects based on the methods.

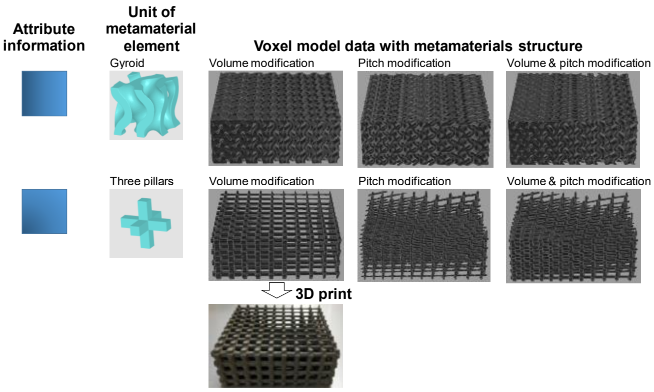

***Figure 8**. The example 3D objects based on the methods.*

Impacts

With these technologies, three-dimensional physical property values' distributions can be easily converted to locally modified metamaterials structure, which can be expected various industrial use. For example, in an insole of shoe, comfortable fit can be provided by increasing shock absorption of particularly high pressure area. Figure 9 shows insole of shoe in which the low volume gyroid structure is embedded at the high pressure area based on the attribute information that is the pressure measurement data of the foot.

Further, in a propeller, both high durability and weight reduction are able to achieve by keeping rigidity only the necessary part based on a result of simulation. Figure 10 shows propeller in which high volume and high pitch three pillars structure is embedded at the high stressed area near the axis, and the volume and the pitch of the structure is lowered toward the low stressed tip area, based on the attribute information that is simulated result of the stress to the propeller in flight.

Conclusion

The method to register the attribute information in each voxel of 3D data by specified directional penetrate projection of two-dimensional raster data or overlaying of three-dimensional raster data was developed. In addition to the development of the method to modify locally the volume and/or pitch of various metamaterials structure by comparing the 3D threshold value matrix with the attribute information in FAV, the method to generate 3D threshold value matrix for any type of metamaterials based on the existence probability of voxel arrangement of the unit of metamaterial element was also developed.

In the future, we will study new modeling method to design several metamaterials structure using many attribute information of FAV effectively to create valuable use for both academically and industrially. And we will work on enhancing FAV handling software to utilize FAV and expanding FAV specification.

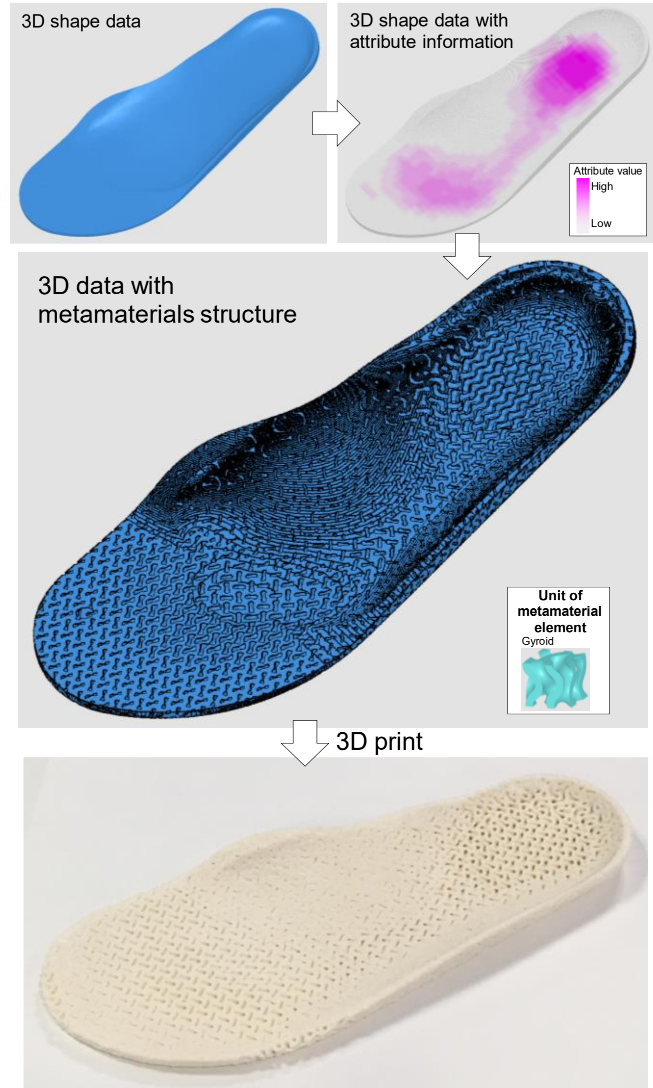

***Figure 9.** Insole of shoe in which the low volume gyroid structure is embedded at the high pressure area based on the attribute information that is the pressure measurement data of the foot.*

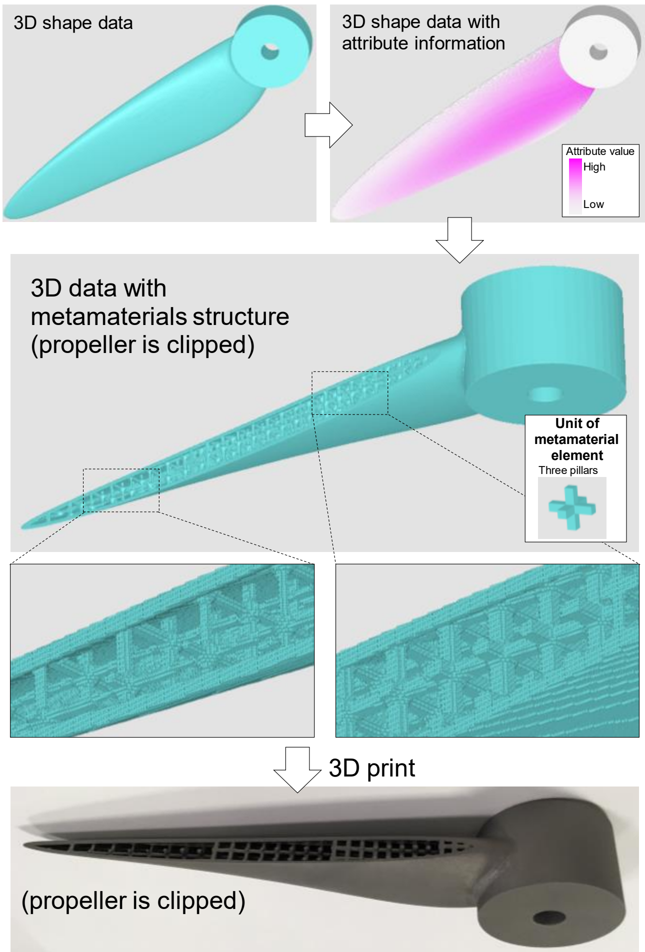

Figure 10. *Propeller in which high volume and pitch three pillars structure is embedded at the high stressed area near the axis, and the volume and pitch of the structure is lowered toward the low stressed tip area, based on the attribute information that is simulated result of the stress to the propeller in flight.*

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Author Biography

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