Development of Software for the Implementation of an Adaptive Approach to the Generation of Internal Filling of a 3D Model in Additive Manufacturing

A A Kholodilov¹, E V Faleeva¹, M V Kholodilova²

¹Department of "Computer Science and Computer Graphics", Far Eastern State Transport University, Serysheva st. 47, Khabarovsk 680021, Russia
²Computing Center of the Far Eastern Branch Russian Academy of Sciences, Kim Yoo Jong st. 65, Khabarovsk 680000, Russia

E-mail: kholodilovsapr@gmail.com

Abstract. The article describes the technology of software development for the implementation of an adaptive approach to generating the external and internal structure of a 3D model in preparation for 3D printing when transferring from * .stl format to * .gcode format. The main stages of software design, the principles of mathematical modeling underlying the development are considered, the practical significance of the developed software complex-slicer is shown with a description of the functionality and conceptual development.

1. Introduction
In the field of additive manufacturing, including Fused Deposition Modeling (FDM) technology, the actual stage in the process of preparing a model for 3D printing is the task of converting a 3D model from * .Stl format to * .Gcode format. This problem is solved by a slicer program, which translates the geometric parameters of the three-dimensional model and the parameters of its internal filling into the control code.

The slicer program at the program level sets the parameters of three-dimensional printing for the model, including the structure of the inner filling, the parameters of the thickness of one layer, the percentage of the inner filling and others, as well as parameters affecting the physical process of the device - parameters of the print head temperature, table temperature, movement speed extruder, extrusion speed and volume of extruded plastic.

An analysis of the existing methods for translating a 3D model into a control program showed that in the existing slicer programs on the market, there are no software tools for automatic or automated increase in both the speed of products and improve their quality.

Thus, to solve the problems posed in the additive production of structures of complex shapes, thin-walled shells, models with complex topology, in addition to manually adjusting the layer thickness, it is possible to create a slicer program code for creating objects with a generated and automatically recalculated layer thickness in three-dimensional print.

Here are the requirements for the implementation of such an algorithm for generating * .Gcode: the algorithm must be applicable for three-dimensional models with complex topology; infill created in
the interior of the model must have an adjustable density so that the infill network closer to the walls of the model or in narrow spaces is denser and penetrates wider areas with greater sparseness.

2. Principles underlying the development
In the course of work on a software package - a slicer, the so-called "Exhaustion Algorithm" proposed by R. Lohner was chosen as an algorithm for implementing the principle of mesh thickening, and its three-dimensional version was developed by Professor of the University of Hong Kong S.Kh. Lo, as well as Shcheglov I.A., IMP them. M.V. Keldysh RAS [1,2]. The algorithm is intended for the programmatic construction of equal-dimensional grids in arbitrary areas.

This algorithm allows you to programatically implement the construction of grids of equal size, including in arbitrarily specified areas.

The mesh of the internal filling, built by this exhaustion method, has the required accuracy, and subsequent optimization, possible optimization of the nodes, gives an additional increase in quality.

The exhaustion method is most effective if the triangulation of the area boundary is initially specified. Based on this fact, the principle of analyzing the outer contour with the subsequent recalculation of the parameters of the inner filling on each layer depending on the geometric shape of the outer contour was put into the development of the program code when writing the program complex. Subsequent optimization of the nodes gives an additional increase to the quality of the generated mesh.

An example of the operation of the algorithm for implementing a mesh of internal filling with condensation at the break point is shown in Figure 1.

![Figure 1. Creation of a mesh of internal filling with condensation in the place of a probable break.](image)

As part of the work, a functional has been developed to perform the following tasks using iterative methods using Delaunay triangulation, it is necessary to implement the following functionality of the slicer program: Drawing a working three-dimensional scene; The ability to manipulate the camera inside this scene; Rendering a loaded 3D model; The ability to rotate the model; Generation of points of internal filling of the model [3].

3. Development of a slicer program with adaptive fill generation
The development is a software package that works on the basis of a modular design, for the implementation of an adaptive approach to the generation of the outer contour and the inner filling of a three-dimensional model in preparation for three-dimensional printing.

The application work is based on the OpenGL specification based on the C ++ programming language and the Qt Creator development environment, for working with two-dimensional and three-dimensional graphics, implementing a user interface and a working three-dimensional scene [4, 5].
The implementation of the functionality was carried out through a set of classes shown in the Uml diagram (Figure 2), Widget and GtWidge, to plan the interaction between widgets, and implement all the necessary methods of software classes, observing all the principles of Solid [6].

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Figure 2. Class diagram of the developed slicer program.

At the beginning of a typical session of the software package, the following is carried out:

1. Loading a three-dimensional scene;
2. Loading a three-dimensional model and choosing from a set of operations for visual display of this three-dimensional model in the scene space, including the operations of rotation, reflection, shift;
3. Execution of the main functionality - the work of algorithms for statistical or dynamic division of a three-dimensional model into layers according to the parameters set before execution;
4. Generation of a mesh of internal filling according to the analysis of the structure of the generated set of contours;
5. Reflection of the result of dividing a three-dimensional model in the space of a three-dimensional scene;
6. Export of the final file of the control program in *.code format to the Export.gcode file, with saving the result of the program on the user's personal computer.

After the completion of the program, it is possible to check the generated control code using third-party services and programs (in the future, it is planned to develop this functionality within the framework of the software package) [7].

A typical session of the developed software consists in the phased implementation of the functionality: launching the application; selection of a file for display and selection of display parameters; task of parameters of contour generation and automated generation of internal filling; unloading the g-code file according to the generated file.

The step-by-step procedure for the application is shown in Figure 3. The full code of the program is presented in the accompanying materials to the certificate of state registration of the computer.
program Rospatent No. 2021614444 "Computer program for implementing an adaptive approach to generating the internal structure of a model in 3D printing" with output data.

Figure 3. Application work step by step.

The operating principle of the developed program - slicer "Computer program for the implementation of an adaptive approach to generating the internal structure of a model in three-dimensional printing" consists in converting the model loaded into the program at the input in *.Stl format into a program code in *.code format. In this case, the loaded model is divided into layers with a certain step equal to the thickness of one layer, which is specified by the user during FDM printing in the range from 0.4 to 0.05 mm, depending on the model of the 3D printer and the installed nozzle.

Figure 4 shows a sequence diagram of the process of loading a *.Stl file of a model and receiving a Gcode of a given model for subsequent sending it to print. The first item is Widget. It handles all events of user interaction with the interface and calls methods for working with the 3D model. The GIWidget widget is responsible for working with the model. Both of these widgets interact with each other through the slots described in the Widget. An activity diagram describes the dynamic behavior of a system (Figure 5).

Figure 4. Application sequence diagram.  Figure 5. Application activity diagram.
The program, by working with the graphical user interface, implements an adaptive approach to the specified layer thickness and to the internal filling, with a decrease in time consumption, through the use of mathematical modeling capabilities and Voronoi's triangulation mesh [8]. The program processes three-dimensional models, analyzing the outer contour and the inner filling of the structure, with the refinement of the mesh in the places of the presence of thin-walled structures by applying the Voronoi mesh, with the generation of g-code from the array of contours [9].

At the same time, to implement the g-code on each of the generated contour layers, a grid of internal filling is generated, with the recalculation of the parameters of this internal filling.

The resulting developed user interface is shown in Figure 6.

![Graphical user interface](image)

**Figure 6.** Graphical user interface.

### 4. Research findings

Thus, in the study of the problem area, a software package was developed, which is a slicer program designed to prepare a 3D model for the 3D printing process by translating a 3D model in *.Stl format into *.Gcode format, with an engineering analysis of the created model, to increase the strength characteristics of the printed model by changing the structure of the outer contour of the model and internal filling (using algorithms for modeling the Voronoi mesh), by reducing the printing time by using an adaptive approach to the layer thickness when bypassing the outer contour and generating the inner filling.

To achieve the goal of developing a slicer program, mathematical modeling was chosen as a research method. For the numerical study of the process of dividing a three-dimensional model into layers and generating its internal structure, the method of irregular triangulation networks (TIN) is used, with the construction of a Delaunay triangulation for a given set of points [10].

The choice is due to the versatility of the implementation, both from the point of view of the consumed computing power, and because of the possible use for triangulation of regions and structures of an arbitrary type. The study used the node placement method, which is based on the principle of boundary correction [11].

The principle of analyzing the outer contour with the subsequent recalculation of the parameters of the inner filling on each layer, depending on the geometric shape of the outer contour, was put into the development of the program code when writing the software package [12].

For the software implementation of the software package for modeling the technology of dividing a three-dimensional model in additive manufacturing, methods of linear, object-oriented, functional
programming with the use of iterative triangulation methods and the use of the following technologies were used: the OpenGL specification, the QtOpenGL and QDir libraries of the C++ language, the Qt interface development tool Design Studio and Qt Designer. The use of these libraries and development tools made it possible to render the scene and divide the three-dimensional model.

The implementation of the author's algorithm is carried out using a set of Widget and GlWidget classes to plan the interaction between widgets and implement all the necessary methods of software classes [13].

The difference from existing slicer programs for translating a three-dimensional model into control code (such as Cura, 3D Slash, MeshLab, Simplify3D, CraftWare, Repetier, SketchUp, TinkerCAD, Slic3r, Meshmixer) is the possibility of automated selection of internal filling parameters, the presence of analysis software internal structure.

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