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VIRTUAL RAPID PROTOTYPING MACHINE

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ABSTRACT

Conventional design techniques do not allow full testing of a device as complex as numerically controlled machine, before physical prototype is created. Doing so requires investing time and money. If designed machine realizes a new process, it is almost impossible to test it and tune its parameters without physical prototype. Paper presents possibilities of using virtual reality to create fully functional virtual prototype of machine for additive manufacturing. The machine itself is a new, innovative device for producing physical prototypes of parts with multidirectional Fused Deposition Modeling process. Basing on CAD model of the 5-axis FDM machine, virtual prototype was created, along with virtual additive manufacturing process. Virtual machine is operated using NC code, prepared basing on product CAD model. Virtual machine can be used to preview the process and to check how various process parameters affect the part quality. Therefore, optimal process parameters can be determined without the physical prototype of the machine. Furthermore, various design aspects can be tested using virtual machine, allowing design verification, also without investing resources into physical prototype.

KEYWORDS

Additive Manufacturing, Rapid Prototyping, Fused Deposition Modeling, Virtual Prototyping,

1. INTRODUCTION

Rapid prototyping and manufacturing using additive manufacturing technologies (AMTs) allows creating physical prototype of an object basing on 3D CAD (Computer Aided Design) model, with no need for special tooling. AMTs have found their place among other manufacturing technologies – they are invaluable when there is a need for quick production of physical prototype of designed part. (Górski et al, 2010)

Constant development of additive technologies results in creating new and improved methods, giving consideration to increasing requirements that must be fulfilled by these methods and prototypes manufactured using them. Promising trend of development is multidirectional additive prototype manufacturing, currently studied in many research centers across the world. Multidirectional manufacturing breaks with an approach traditional for AMTs – unidirectional division of manufactured object.

Research on multidirectional prototype manufacturing using one of the most popular methods – Fused Deposition Modeling (FDM) is also conducted in Laboratory of Rapid Prototyping, located in the Institute of Mechanical Technology, in the Faculty of Mechanical Engineering of Poznan University of Technology. Current result of these work is a design of the device for multidirectional material deposition.

Full testing of such device using conventional design techniques (CAD systems only) would not be possible without creating its physical prototype. This is when modern techniques of product development become useful, especially one of them – Virtual Reality (VR). VR techniques expand the range of application of model created in CAD system, allowing to place it in virtual environment of any form, in presence of other objects. Essence of virtual environment is representation of mutual interactions between objects and their behavior in response to actions taken by user. Prototyping using virtual reality techniques (Virtual Prototyping, VP) enables presentation, testing and analysis of 3D CAD models without need of producing a physical prototype. Virtual models allow for manufacturing, assembly, operation and recycling of the product and influence of these processes on its costs. Using virtual prototypes, especially in early phases of product development allows making appropriate decisions taking time and costs into account. (Weiss et al, 2005)

Presented paper shows possibilities of virtual reality in field of creating virtual prototype of production machines. Basing on research regarding multidirectional prototype manufacturing (among others basing on the design of device manufacturing prototypes with 5-axis FDM method), a virtual version of rapid manufacturing process and virtual prototype of machine realizing it were created. Prepared virtual reality applications allow to eliminate wrong assumptions and determine appropriate limits of process parameters variation on very early stage of development work. Verification and optimization of device design is also possible.

Work on creating virtual prototype of the machine and virtual additive manufacturing process were carried out using EON Studio environment – authoring tool for making virtual reality applications.

2. MULTIDIRECTIONAL FUSED DEPOSITION MODELING PROCESS

2.1. BASICS OF 5-AXIS FDM PROCESS

Manufacturing models with FDM technology consists in layered deposition of plastified build and support material in thread form, by an extrusion head with two nozzles. Numerically controlled machine deposits build and support material on the model table, basing on subsequent horizontal cross-sections prepared from digital 3D model. ABS material is the most frequently used in this method. Obtained models are characterized with acceptable strength and durability and they can be put to further processing, like machining, gluing, painting to acquire sufficient surface quality. Produced part faithfully represents the digital model and after removing support material is almost immediately ready for use. FDM method, according to Wohler report belongs to one of the most popular additive manufacturing technologies worldwide.

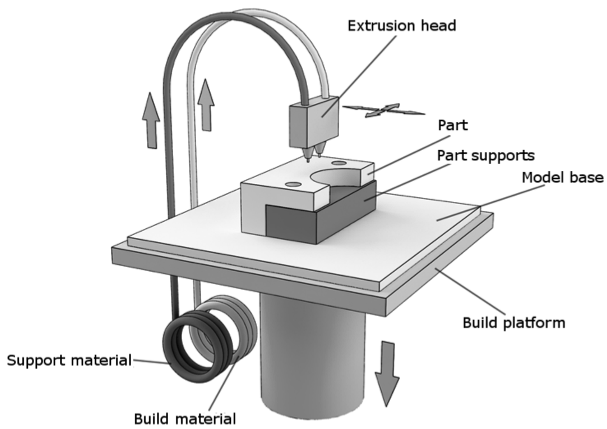

Figure 1 – FDM technology scheme

Almost each additive manufacturing method (and all the prevalent ones) consists in producing models layer by layer. In consequence of layered structure, volume errors are generated. In general, volume errors are differences between volume of material used for manufacturing and volume resulting from digital representation. Volume errors can be of various forms (Weiss et al, 2010) and they can influence many characteristics of the model – surface quality, dimensional and shape accuracy or mechanical properties.

Analysis of the additive manufacturing process in FDM method shows that magnitude of volume error is mostly dependent on orientation of the model in working chamber (layer deposition direction). Volume error influences parameters like surface quality and part accuracy. Consumption of support material and manufacturing time is highly dependent on model orientation itself – so it can be said that this one parameter has influence on all key aspect of additive manufacturing process. This subject is studied by many research centers worldwide and conducted research aim at preparing methodology of finding optimal orientation to make the prototype reach desired characteristics (Daekeon et al, 2005, Thrimurthulu et al., 2003, Pandey et al, 2006).

Selection of optimal model orientation during additive manufacturing process is a difficult and time consuming problem, because it is dependent on many, frequently opposing factors like time and surface quality or strength. Analysis of different researches in field of selection of optimal orientation is a starting point for developing the technology of multidirectional layer deposition of plastic materials. Multidirectional layer deposition is characterized with varying direction of material deposition, frequently obtained by changing orientation of model in working chamber. This approach has a number of advantages, like possibility of reaching better parameters of final product or possibility of significant reduction of consumed support material (Yang et al, 2003).

Technology of multidirectional deposition of layers of plastic for additive manufacturing requires different process planning than in conventional, widespread unidirectional material deposition technologies. It becomes necessary to develop algorithms of division of model into smaller parts/solids/elements produced in various directions, which results in hierarchical structure of the object (Figure-2).

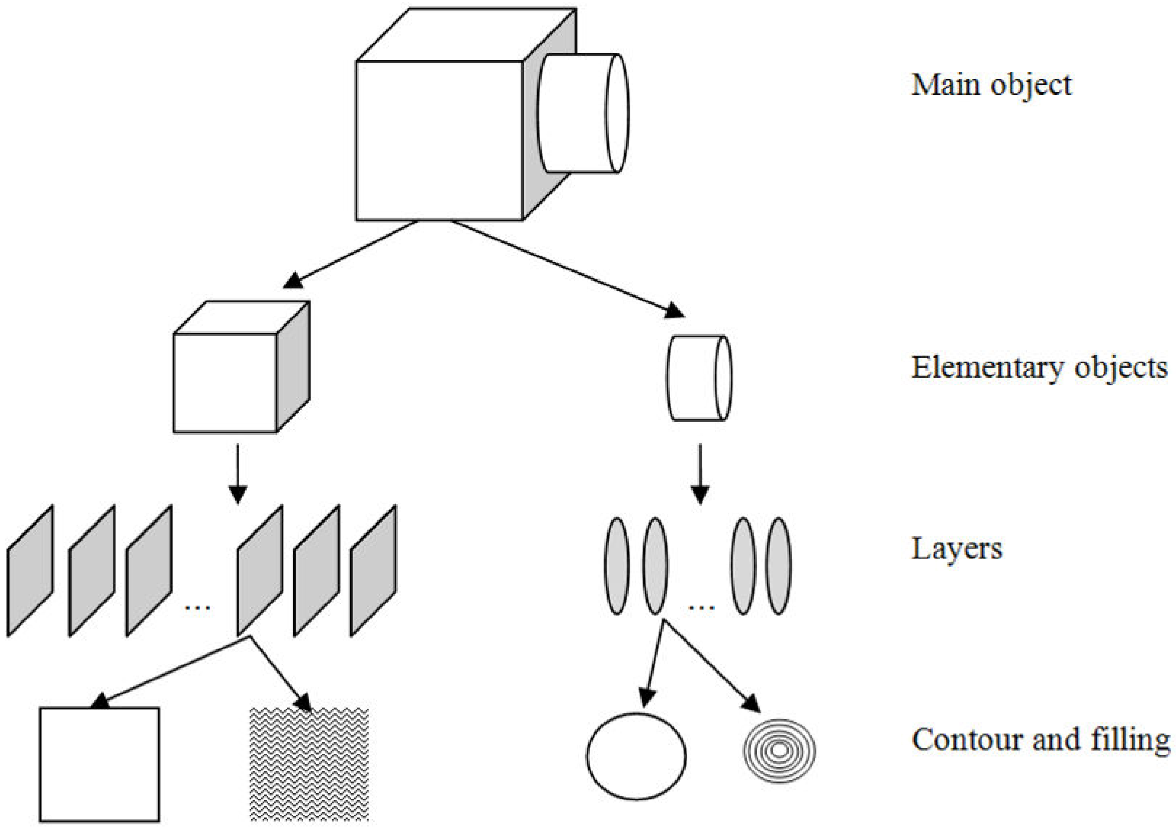

Figure 2 – Hierarchical structure of model for multidirectional additive manufacturing process

2.2. DESIGN AND FUNCTIONS OF 5-AXIS FDM MACHINE

The development of multidirectional plastic layer deposition technology is related with a problem of designing mechanism for manufactured part orientation change. The mechanism has to ensure the extrusion head the possibility to deposit layers from different directions.

Result of the research on the multidirectional additive prototyping technology, conducted in Laboratory of Rapid Prototyping, is design of the device for 5-axis manufacturing with Fused Deposition Modeling method. Multidirectivity was achieved by adding two extra rotational axes allowing to change the model orientation during manufacturing. Movement in these two axes is realized using rotary table with cradle. The important issue is proper programming of the extrusion head movement, to avoid collisions with material already deposited.

Because of appointed tasks and requirements of the FDM process, the device has the following features:

- Five controllable axes. The material deposition head makes movement in X and Y axes, while feed in Z axis is realized by the table, on which the model is manufactured. Rotation in two additional axes (A and C) is ensured by cradle and rotary table.

- Rigid frame based on welded steel sections.
- Possibility of heating the working chamber to the temperature necessary to provide right conditions for FDM process. The chamber has thermal insulation minimizing the heat losses.
- Extrusion head for material deposition with possibility of heating applied material to the temperature ensuring proper course of the process. The head has a feature of cutting the thread of material (for additional movements between material deposition movements), which is fed automatically from the spool. Head has possibility of working with various materials.
- Machine control realized with dedicated computer application, communicating with machine controller.

The machine consists of following subassemblies:

- Body – welded frame from steel sections.
- X and Y axis drive – realized with ball screws and servomotors (drive transmission with cogbelt)
- Z drive – realized like X and Y drives.
- A and C axis drive – rotary table with cradle allowing full turn in C axis and turn in A axis in range between -10° and +100°. Drive is possible to disassemble – possibility of working only with three axes.
- Head for material deposition.
- Material feeder – material in a form of wire unwound from the spool.
- Heating and insulation system.

Figure 3 contains the scheme of the machine with marked main subassemblies.

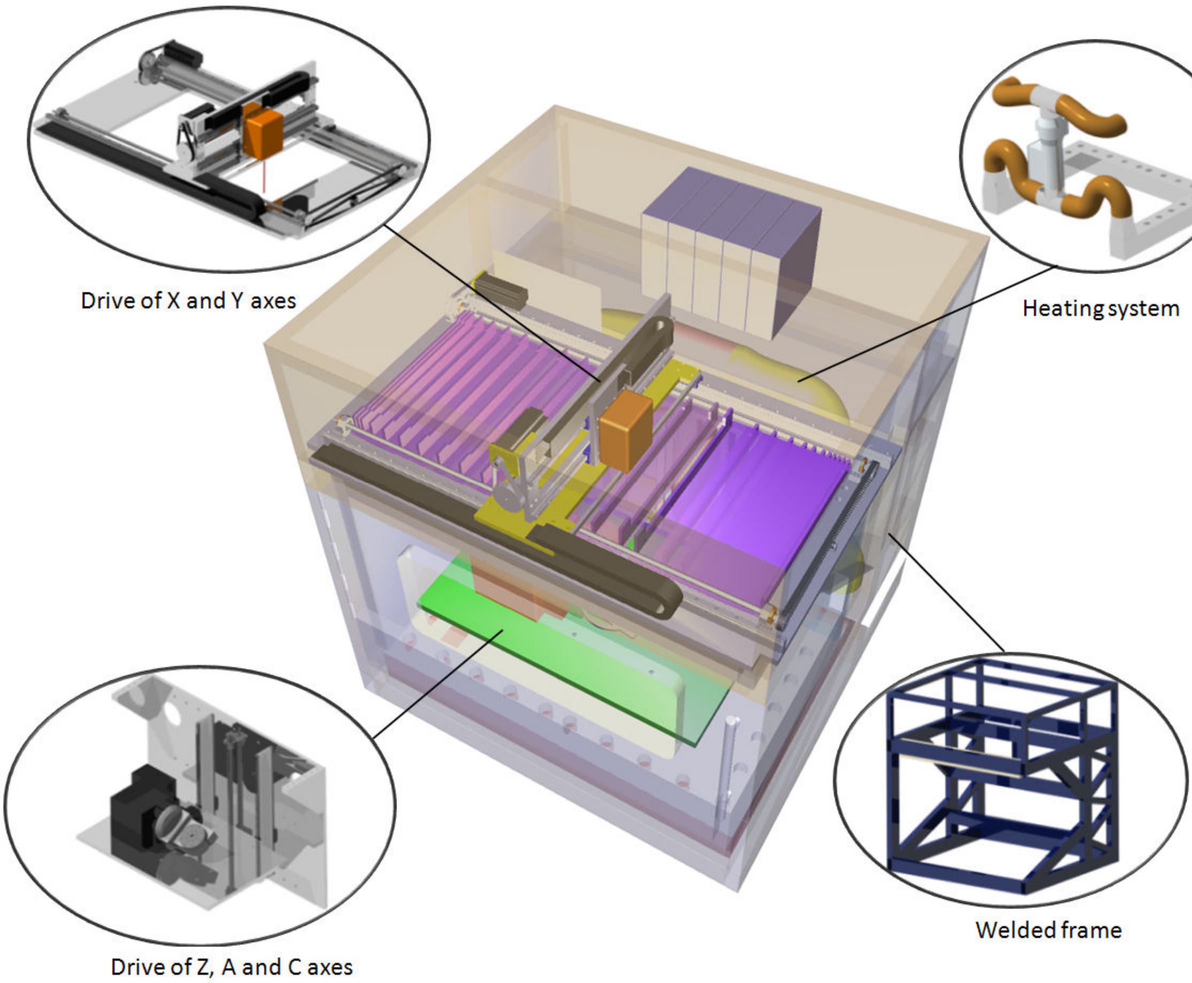

Figure 3 – 5-Axis FDM Machine and its main components

3. VIRTUAL RAPID PROTOTYPING MACHINE

3.1. PRINCIPLES AND TASKS OF VIRTUAL RP MACHINE

Virtual additive manufacturing machine is a computer application of virtual reality, with a main purpose of simulating the operation of designed innovative machine for 5-axis prototype manufacturing with FDM technology. Virtual Rapid Prototyping machine is therefore a virtual prototype of additive manufacturing device. Destination of the machine means that apart from standard functionality of virtual prototype, it is necessary to expand it with the virtual version of rapid manufacturing process of FDM in five axes.

Thus, functionalities can be divided in two groups, which are obviously related and blend with each other, but they can be considered entirely separately:

- representation of principles of operation of the machine,
- representation of the manufacturing process realized using the machine.

Results of trials and tests conducted on the virtual machine have on purpose the verification of machine construction and also examination of the limits and possibilities of using the innovative technology of 5-axis Fused Deposition Modeling. Detailed tasks of virtual machine are as following:

1. Visualization of prototype manufacturing process in five axes, possibility of visual checking of produced prototypes and identification of occuring volume errors.
2. Visualization of machine operation – movement of drives and other movable elements (in detail level necessary for construction verification), checking of collisions.
3. Representation of human-machine interaction – possibility of manual control of particular axes, adjustment of velocities and layer thickness, zeroing the machine coordinate system. Running the process basing on supplied NC code.

Functionality related with simulation of the manufacturing process in 5-axis FDM technology has been created in form of a separate module. Functionality contained in this module is also integrated with main application, necessity of creating the separate module is related with test procedure – machine operation is not always necessary, especially while testing important aspects of the 5-axis FDM process itself. Besides, presence of machine geometry in virtual environment and visualization of its kinematics significantly decrease the application performance, especially on computers with low processor capacity.

Virtual RP machine was created basing on three-dimensional geometrical model prepared in CAD system. This model was imported to virtual environment (created using EON Studio software) and was given proper visual traits. Then the behaviors and events related with machine operation in answer for user actions were designed and implemented. Application was provided with appropriate graphical user interface and possibility of running on any computer station.

3.2. VIRTUAL FDM PROCESS

Representation of FDM manufacturing process in virtual environment requires using the tools related with dynamical creation of geometry. Purpose of the application realizing the virtual process is an interpretation of the supplied NC code, prepared in earlier stage. Basing on the code, the additive process of model manufacturing is being re-created.

Functionality of virtual process is possible as integral part of virtual RP machine and also in separate module, for supportive visualizations and process study. This module functions entirely separately, as individual application of EON Studio software.

Basic task of the module is visualization of the manufacturing process of 5-axis FDM method and visualization of the model which results from the process. This functionality is realized based on supplied NC code, prepared for the machine. This code is prepared using CAD/CAM based application, from the CAD model of manufactured part. The code contains mostly instructions regarding tool and object movement.

Code destined for virtual reality application is submitted to the conversion process, to simplify the procedures of its later reading and interpretation. The conversion is conducted in additional application created by authors especially for this purpose (Figure-4).

Ready NC code in form of text file can be loaded into the virtual reality application. Interpretation of the code consists in translating the information connected with tool and object kinematics to the form compatible with nodes realizing the kinematics in EON Studio software.

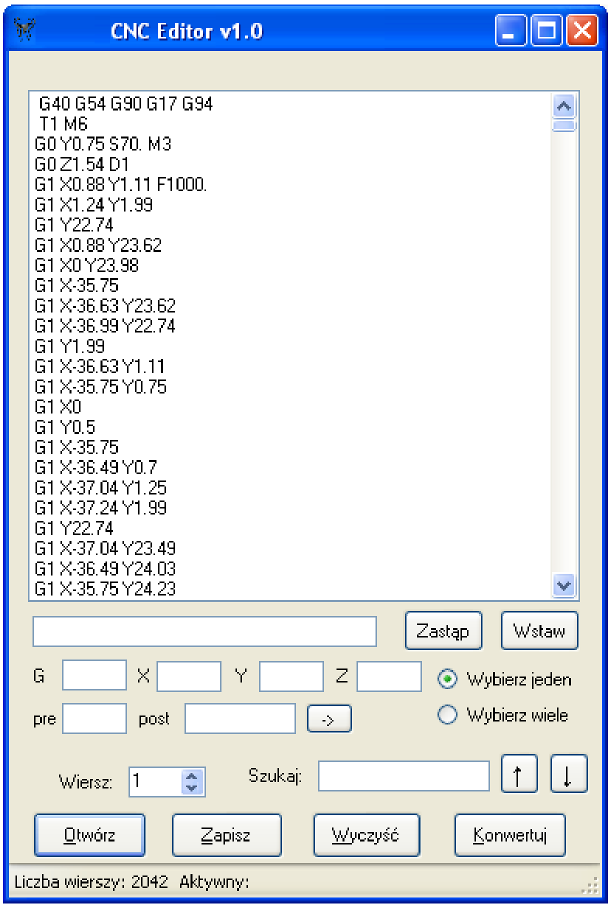

Figure 4 – CNC Editor for code conversion and edition

The loading and interpretation process consists of the following stages:

1. Submitting the name of the file with code and target path by the user.
2. Checking the file correctness.
3. Loading the single line from the file. Division of the line into separate words, interpretation of first word for command identification (movement with material deposition, dead movement in Z axis – next layer, movement in fourth and fifth axis – next elementary object)
4. Creation of position vector for the tool basing on the rest of the line, containing coordinates in appropriate axes. According to the rules in standard NC code (so-called G-code), if command does not contain information for all axes, coordinates from previous command are adopted.
5. Adding the position vector to the tool movement table.
6. In case of going to the next layer or object – marking the fact by writing a value in appropriate table.
7. Repetition of points 3-6 until the end of file.

The end effect of loading the code are the tables containing data of subsequent positions of the tool. For simplification, in module realizing virtual FDM process, all movements are performed by the tool. This solution provides effect identical with real one, when displacement values in object-related axes will have opposite signs – which is realized during sending the information about single movement to node responsible for tool kinematics.

After loading and interpreting the code, it is possible to begin the course of virtual manufacturing process in FDM technology. This process is realized in following steps:

1. Zeroing the counter containing ordinal numbers of subsequent movements.
2. Taking the information from movement table (created during code interpretation). Index of taken information is equal to the value of mentioned counter (zeroed in first step).
3. Taking the information from object table and layer table. Basing on this information, it is determined if the movement will or will not be related with deposition of thread of material. Place (index) of shifting to next object/layer is marked.
4. Sending the displacement vector to the node realizing the kinematics. Movement of the tool.
5. In case of movement with material deposition – sending the information about previous and current position of the head to the object representing the single thread of material (geometrical prototype of cylinder).
6. After the movement – automatic incrementing of the counter. Repetition of steps 2-5 in loop until the end of movement table.

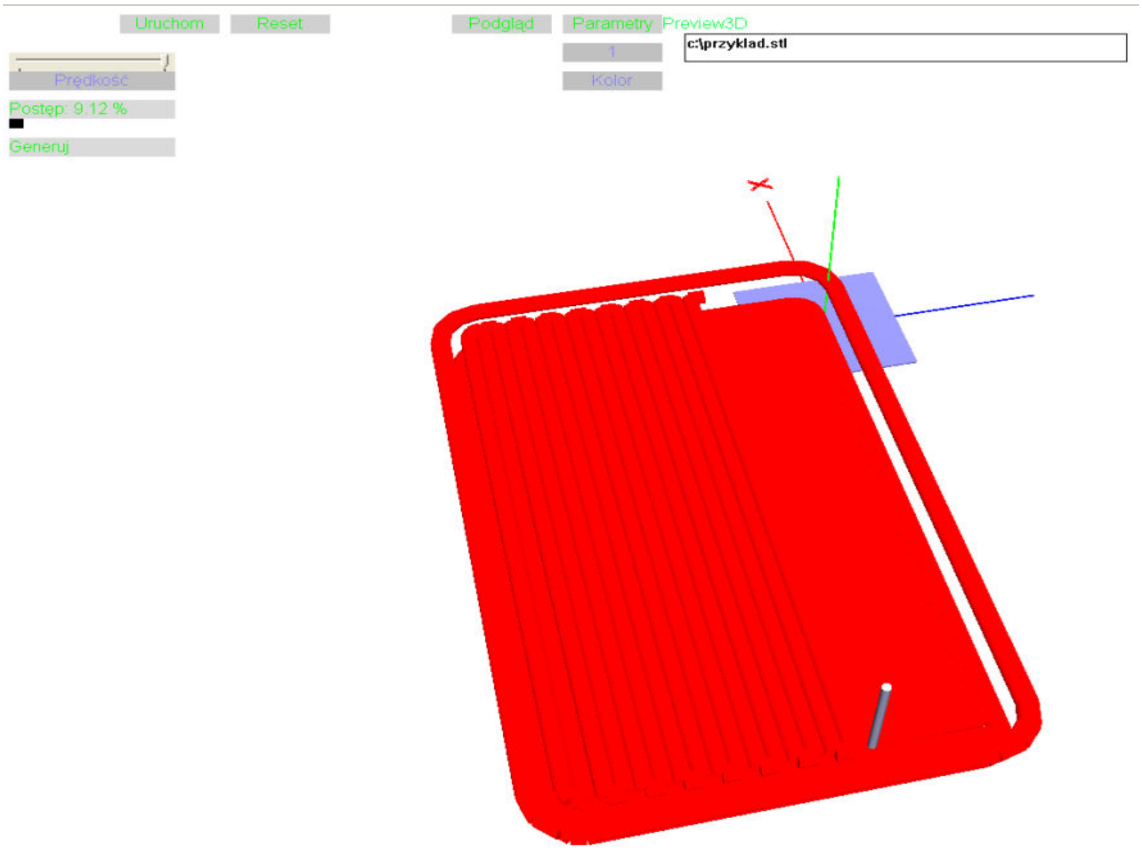

Figure 5 – Virtual FDM process preview

The process is realized in continuous loop, stopping is possible using the "Reset" button in graphical user interface. The progress of the process is displayed as a percentage and is also visualized in form of progress bar. If there is no need of visualizing the whole process, it can be turned off by using the button "Preview" ("Podglad"). Turning off the visualization accelerates the process of virtual model generation.

The end result of virtual process is the ready prototype. Writing the information about shifting between layers and objects allows selective visualization of individual elementary objects or layers. Application allows saving the information about current state of all objects representing the threads of material, for later quick re-creation of object visualization.

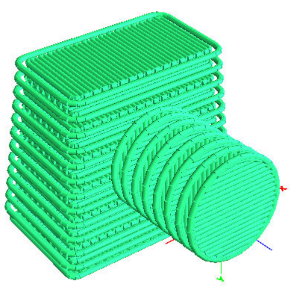

Figure 6 – Virtual model resulting from virtual FDM process

Application contains functions allowing model verification – volume of used material can be calculated (by calculating the volume of all used material threads) and visual verification can be performed – preview of STL file (standard file format for Rapid Prototyping) containing original geometry is also a feature of application.

Applied method of representation of the FDM process has some disadvantages. The main issue is high need for processor capacity, because of high number of geometrical objects (material threads). This need can be partially decreased, by realizing the visualization of layer contours only (the external model "shell" will remain for visualization), but the possibility of calculating the volume of end model will be then unavailable, not allowing to evaluate the total volume error.

3.3. VIRTUAL MACHINE – FUNCTIONALITY AND OPERATION

Virtual 5-axis additive manufacturing machine was created on the basis of CAD model prepared in CATIA v5 environment. The model was converted to the form recognized by EON Studio virtual reality software and imported to the virtual environment. Then, its visual features were adjusted along with object hierarchy. Next step was modeling of the machine kinematics (displacement in five axes) and programming the methods of operation (manual control, NC code interpretation) and additional functionalities. The last stage was an integration of formerly created module realizing virtual FDM process with main application and making the application available for general tests.

Created virtual reality application has the following functionalities:

1. Control of movement in all five axes. Control can be realized manually, there is a possibility of reaching specific, submitted coordinates. Velocity adjustment for each axis separately is also implemented.
2. Selection of working mode – classic 3-axis or 5-axis. In 3-axis mode, rotary table with cradle is removed and all possibilities of movement in two rotary axes are blocked.
3. Adjustment of the coordinate system (zero point). There are two predefined zero points, for 3-axis and 5-axis configuration. Any zero point can be defined by setting the tool and the table in desired position and using the right option to mark the position as new zero.
4. Loading and interpretation of the program in form of NC code. A choice of realization mode is possible – first mode simulates material deposition (for process testing) and second simulates only kinematics of the machine (without material deposition).
5. Set of functions related with visual aspects of the application – hiding and showing the elements of the machine body and casing for better visibility, additional camera placed on the FDM head (simultaneous process preview from different positions), predefined positions of main camera.

Application is provided with graphical user interface (Figure-7), which consists of buttons, labels, text boxes, pop-up menu (allowing to turn on and off almost all elements of the interface) and sliders. Part of the commands have keyboard shortcuts, for actions performed manually in reality (opening the doors, removing the material cassettes or finished models), mouse can be used, there is a possibility of implementation of special VR devices (gloves, tracking systems). Virtual control panel has not been implemented, because machine design assumes control of all the functions through computer application.

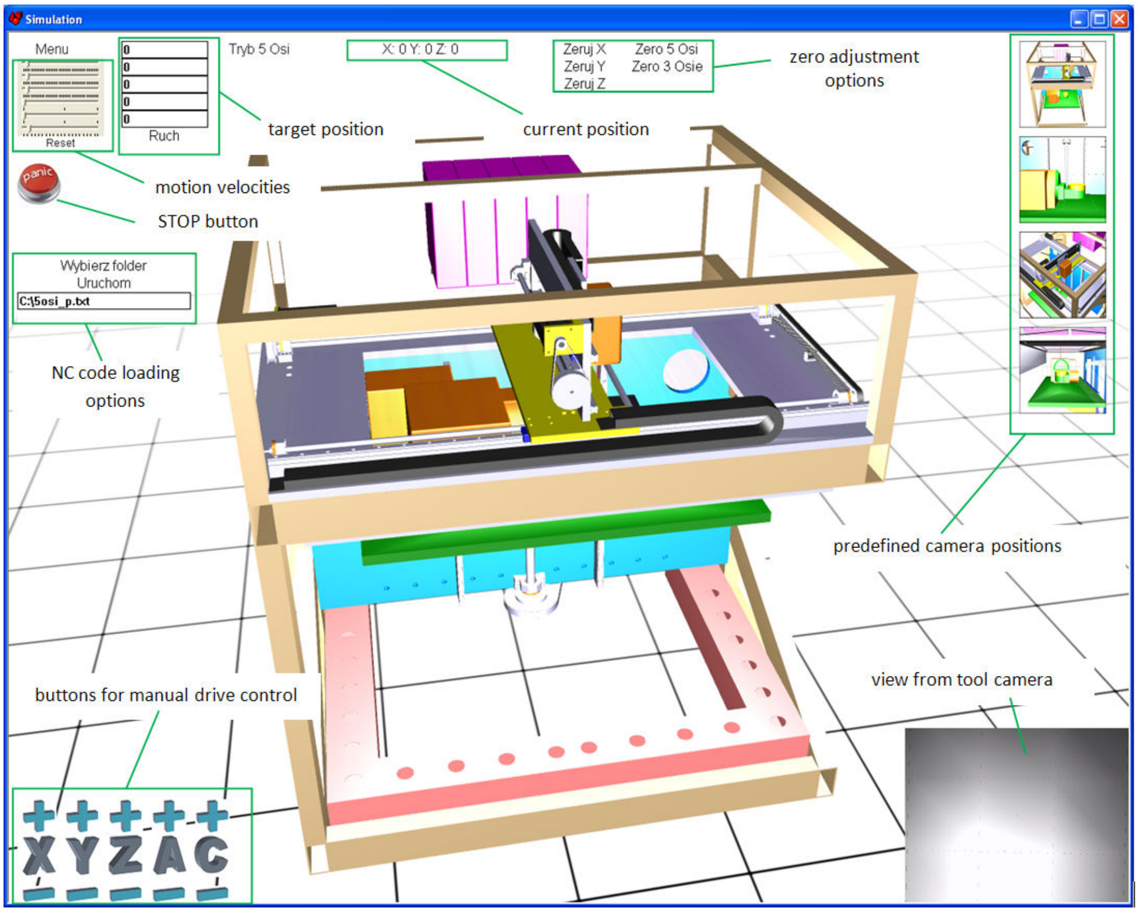

Figure 7 – Graphical user interface of virtual RP machine

Realization of the main machine functionality, which is the movement of material deposition head (in X and Y axes) and table containing manufactured model (in Z axis and two rotary axes – A and C) required changing the mutual dependencies of objects and introducing auxiliary nodes, to allow zeroing of the positions and limiting the field of movement.

For each axis, kinematic nodes were introduced (for X, Y and Z axis it was a linear motion, for A and C – rotary motion). Activity of these nodes was connected with interface elements – keyboard buttons and text buttons. The velocities were made dependent on the value of the sliders, also controlled by user. User is also informed about current position in each axis by a text communicate, constantly displayed on the screen.

Separate problem is the realization of movement into desired location. Earlier defined kinematic nodes are not used for this purpose. Instead, special logical nodes ensuring smooth transition between two given values in provided time interval are implemented. Each axis is assigned with one such node, values sent to this node are taken from text box filled by user with demanded coordinates. Time of movement is calculated as ratio of distance (calculated as difference between current and demanded position) and velocity from the sliders.

The most important functionality is however the possibility of loading and executing the NC code, contained in text file. Algorithm of reading and interpretation of the code is practically identical with an algorithm applied for virtual FDM process. The only difference is in instant realization – tables of movement are not created, subsequent lines of code are interpreted on the fly and sent to the nodes realizing the movement. Currently performed line of code is visible in main application window.

Important issue in code realization is the moment of transition to another line. Because there are five nodes realizing the movement separately for each axis, there is a need of gathering the signals about ending the current movement from them. Transition to next line of code is realized after making movements in all axes. Not implementing this solution could result in errors during code execution.

As mentioned, the machine can work in two modes, 5-axis and 3-axis. Switching to 3-axis mode is realized by removing the rotary table with cradle. Virtual machine allows free switching between modes – change of working mode results in hiding the elements realizing movement in additional axes. Possibility of changing the position in these axes, both manually and by the text box is also blocked.

The application allows zeroing the coordinate system, like on a real numerically controlled machine. Two standard zero points are defined as a base, one for 5-axis and other for 3-axis mode. At any moment, current position in selected axis can be marked as zero point (using the buttons of graphical interface). Current location of coordinate system can be checked at any moment, by clicking on one of the buttons “X”, “Y” or “Z”. The visual prototype of coordinate system will be displayed then, in a form of three colored lines with literal designation of particular axes.

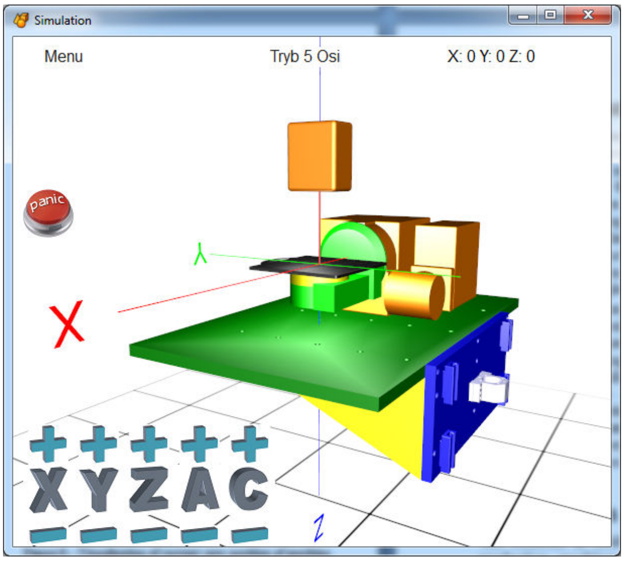

Figure 8 – Visualization of current zero position of machine coordinate system

To make the operation of virtual machine easier, a number of functions related with visual simulation aspects was implemented. Some of them are:

- hiding/showing of sheet metal casing and the doors,
- changing the transparency of machine body and folding covers,
- hiding every element of the machine except the FDM head and the table,
- hiding/showing the view from camera placed in the head
- predefined positions of main camera,
- showing/hiding the elements of graphical user interface.

Creating and programming of all relations between objects of virtual machine required connecting the techniques of visual programming with classic programming using script language. EON Studio software allows creating interaction solely using visual programming, but with complex object behavior (like in the case of virtual RP machine) it would be extremely difficult. Using the scripts written in available VBScript language allows to simplify many procedures and enables more efficient control of virtual environment.

4. FURTHER RESEARCH

Data about the construction of the model resulting from virtual FDM process (position and shape of particular threads of material) can be exported in form of vectors to the text file for later use. Additional application of this functionality is the possibility of building the standard CAD model basing on the vector data. This model, representing the method of manufacturing can be later used for many purposes, e.g. in strength calculations using Computer Aided Engineering software.

Virtual process can be further developed by implementing the simulation of physical laws and phenomena (e.g. material shrinkage and model deformations resulting from temperature shift). Virtual environment allows implementation of more advanced behaviors of objects and materials. Unfortunately, creating a full model taking dynamics and temperature-related phenomena into consideration is very labor consuming and additionally increases the need for processor capacity.

5. CONCLUSIONS

The solutions in field of virtual prototyping of production machines (especially realizing the processes of rapid additive manufacturing technologies) have very wide perspectives of development. Presently the main factor limiting the application of such virtual prototypes is the performance of computers – simulation of additive manufacturing process, even in case of less complicated model requires performing complex calculations and displaying the structure of model representing the method of its production (e.g. as a result of FDM process – out of the threads of plastified material) demands using graphical processors of very high efficiency. Connecting the virtual process with full functionality of virtual prototype (kinematics of the working elements, object collision detection, use of special VR devices to operate the virtual machine in a manner similar to the operation of real machine) requires further increase in computer performance level.

Virtual prototyping of objects as complex as production machines requires having detailed knowledge, from fields of mechanical technology, process engineering, ergonomics and also programming, creating 3D computer graphics and operating the special VR devices. However, virtual prototype created in an appropriate way allows to conduct the tests that would be otherwise possible only after building the physical, working prototype of the device. Results of tests performed on the virtual machine allow to draw some conclusions regarding optimization of the process realized on the machine and in consequence verification of the machine design. Savings of time and funds (which would be consumed on building and testing the physical prototype during conventional design process) are big enough to fully justify the application of virtual reality on this stage of development.

6. ACKNOWLEDGEMENTS

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