Development of a methodology for eliminating failures of an FDM 3D printer using a “failure tree” and FMEA analysis

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Abstract. The article presents a functional structural analysis of the design and software of an FDM 3D printer. On the basis of functional and structural analysis, a “failure tree” of the design of a 3D printer was built. An FMEA analysis was carried out to identify the reasons for the design failures of the 3D printer and develop recommendations for their elimination. The result of the FMEA analysis was the development of a method for eliminating design failures in FDM 3D printers.

1. Introduction
With the advent of new materials for 3D printing, such as composite materials, high-temperature polymeric materials, metal powders from various stainless, titanium and aluminum alloys, additive technologies are used more actively in various industries every year. It is especially necessary to note the aerospace industry, for which 3D printing allows the production of parts and assemblies of almost any geometric shape without loss of strength characteristics. Such well-known manufacturing companies as Boeing, Airbus, SpaceX, Blue Origin, Rocket Lab and others are increasing the number of 3D-printed parts in their product designs every year [1].

At the same time, additive equipment operators, especially novice operators, are faced with various types of design and software failures, which lead to defects in 3D printing, and in some cases, the failure of all equipment. There is a need to develop at enterprises that use additive equipment in the production of their products, such techniques and instructions that would allow operators to quickly eliminate design and software failures, and subsequently avoid defects in 3D printing.

Analysis of articles [2-9] shows that most of the research is devoted to the analysis of failures of parts and assemblies obtained using additive technologies, or the possibilities of additive technologies in the aerospace industry. At the same time, little research is devoted to the analysis of design and software failures of additive equipment, because the quality of products is largely determined by the parameters and equipment failures. In connection with the above, using the example of FDM (Fused deposition modeling) 3D printing, work was carried out to analyze the design and software failures of an FDM 3D printer and to analyze the causes of these failures by building a “failure tree” and conducting FMEA analysis (Failure Mode and Effects Analysis). The result of the work was the development of a methodology for eliminating FDM equipment failures using the indicated methods.

It should be noted that this work is a logical continuation of our work [10], where we carried out work to improve the quality of FDM 3D printing by parametric changes in the FDM equipment software. In [10], we presented a classification of defects in parts obtained by FDM 3D printing technology. For
the functional and structural analysis of the factors that cause defects in parts obtained by the FDM 3D printing technology, a fault tree was built. The result of work [10] was the development of a method for eliminating defects in parts obtained by FDM 3D printing technology, based on parametric changes in the software (figure 1).

| No | Defect type | Cause of the defect | Solution using 3D printer SOFTWARE | Solution by changing the G-code | Solution using a slicer program |
|----|-------------|---------------------|----------------------------------|---------------------------------|-------------------------------|
| 1  | First layer of the part does not stick to the 3D printer desktop | 1) overlay the first layer with high print speed; 2) incorrect table heating setting; 3) incorrect height of the first layer; 4) the desktop is not aligned. | 1. #define AUTO_BED_LEVELING_POINT 2. #define AUTO_BED_LEVELING_LINEAR 3. #define AUTO_BED_LEVELING_RILINEAR 4. #define AUTO_BED_LEVELING_UVL (if there is a sensor) 5. #define MESH_BED_LEVELING_UVL (if there is no sensor) | 1. M51 Z0 (setting zero Z offset) 2. G28 (Parking, reset with zero Z offset) 3. G29 (calibration after setting the desired calibration mode) | 1. Lower the print speed 2. Set a different table temperature 3. Change the layer height |
| 2  | Polymer material not extruded enough | 1) low extrusion ratio; 2) mismatch of the polymer thread diameter. | 1. #define DEFAULT_NOMINAL_FILAMENT_DIA 3. 0.00 | 1. M200 DN (to set the filament diameter N) 2. M220 S80 (Set the feed rate to 80%) 3. G10 S1 (Requires FWRETRACT) | 1. Set the thread diameter 2. To increase the value of the flow |
| 3  | Hairlines formation | 1) the distance of extruder; 2) extruder speed; 3) high temperature of the extruder. | 1. #define RETRACT_LENGTH 3 2. #define RETRACT_FEEDRATE 45 3. #define HEATER_0_MAXTEMP 5 4. #define HEATER_0_MAXTEMP 285 5. #define BED_MAXTEMP 130 | 1. G1 Enn (Set the retraction value mm/min) 2. G6 Enn (Set the feed rate to mm/min) 3. M104 en M109 | 1. Set the "retraction distance" parameter 2. Set the "retraction speed" parameter |

Figure 1. Fragment of a table from the method of improving the quality of FDM 3D printing [10].

Thus, the purpose of this work is a functional structural analysis of the design and software of an FDM 3D printer by constructing a "failure tree", conducting an FMEA analysis to analyze the causes of these failures, and developing a technique for eliminating 3D printer failures.

2. Methods and equipment

In this work, as noted above, to develop a technique for eliminating the failures of additive equipment, the failures tree analysis method and FMEA analysis were used. The following are definitions of these methods and examples of their application.

2.1. Failure tree analysis method
Failure tree analysis method is a technique for identifying and analyzing factors that may contribute to the onset of some adverse event. The failure tree can be used for qualitative analysis – identification of potential causes and pathways of failure, defects, or for quantitative analysis – calculating the probability of a vertex event in the presence of information about the probabilities of factor events [11].

As an example of the application of the "failure tree" analysis method for qualitative analysis, we can cite work [12], which demonstrates the development of operator work instructions for the productivity of production processes using this method. The work describes the sequence of development of work instructions for the process of making upholstery of the luggage compartment of a car: studying the process, analyzing the elements of the operation, highlighting periodic and cyclic work, timing, extraneous maps of balanced work, identifying and explaining key points. The most important part of developing an instruction is to identify and explain the key points that, if not followed, could result in lost productivity, defects, increased hazard, and complexity. To identify and explain the key points in the work, a “failure tree” is proposed and demonstrated (figure 2).
As an example of the application of the “failure tree” analysis method for quantitative analysis, we can cite work [13], where the study of the reliability of gravitational separators using this method is demonstrated. The work revealed causal relationships between events leading to the failure of gravitational separators, and, subsequently, to emergency situations at work; the results of calculations of the occurrence of these events are presented. A detailed description of the application of the “failure tree” analysis method is given in [14].

2.2. Failure mode and effects analysis (FMEA)
The method for failure mode and effects analysis FMEA is used as a preventive measure for the systematic detection of the causes of possible consequences, as well as for planning corrective actions [15]. There are DFMEA analysis – an analysis of the types and consequences of potential design inconsistencies, PFMEA analysis – an analysis of the types and consequences of potential nonconformities in processes and MFMEA analysis – an analysis of the types and consequences of potential equipment failures.

The joint use of DFMEA analysis and PFMEA analysis is given in [16], where the improvement of the process of calibrating heat flow sensors for thermal vacuum testing of spacecraft is presented. In this work, a PFMEA analysis of the process of calibrating heat flow sensors was carried out, which resulted in a recommendation to change the design of special technological equipment to reduce the temperature spread on the thermostating plate. Next, a DFMEA analysis of the design of the specified equipment was carried out. The result of DFMEA analysis was a new tooling design (figure 3).
Figure 3. Thermostatic plate with pressure plates: original design (a); improved design (b):  
1 – sheet; 2 – pipeline; 3 – fitting; 4 – pressure plate [16].

The new design with a "serpentine" arrangement of the pipeline made it possible to reduce the temperature spread and, which is important, to reduce the labor intensity for its manufacture.  
A detailed description of the application of FMEA analysis is given in [17].

2.3. Additive equipment
An FDM 3D printer of the Flying Bear Tornado 2 PRO brand was used as additive equipment for failure analysis (figure 4).

Figure 4. FDM 3D printer from Flying Bear Tornado 2 PRO.

The Flying Bear Tornado 2 PRO FDM 3D printer is of the Cartesian type, that is, the extruder moves in the X and Y axes, while the desktop moves in the Z axis. Cartesian 3D printers are the most common in the aerospace industry due to their simplicity design and low cost of their maintenance. The Flying Bear Tornado 2 PRO FDM 3D printer uses open source Marlin T2ProD_V7.1 software.
3. Building a “failure tree” for the design of an FDM 3D printer

To build a “failure tree” it is necessary to know the structure of the FDM 3D printer and the functions of the components of the structure. The design of an FDM 3D printer consists of units and mechanisms that ensure the operation of the 3D printer (heating and melting of the filament, movement of the extruder and desktop, etc.) and software (software) that provides control and automatic operation of the 3D printer. A detailed description of the parts and assemblies of the FDM 3D printer and their functions are given in [17]. The vast majority of FDM 3D printers use open source Marlin software as software.

Failures in the design of an FDM 3D printer can occur both in parts and assemblies of a 3D printer, as well as in the software code. Figure 5 shows a fragment of the “fault tree” of the FDM 3D printer design.

![Diagram](image)

**Figure 5.** Fragment of the “failure tree” of the FDM 3D printer design.

As can be seen from the figure 5, the same types of failures can occur both due to a failure in the software code, and due to defects or malfunctions in the parts and components of the 3D printer. Therefore, there is a need to know the causes of failures and how to eliminate them.

4. Conducting DFMEA / MFMEA analysis

To manage the risk of failures, a DFMEA / MFMEA analysis of the FDM 3D printer design was carried out. Failures of additive equipment shown in the figure 5 were taken as potential inconsistencies. The result of the DFMEA / MFMEA analysis was the development of a method for eliminating design failures of FDM 3D printers. The basis of the technique is a table in the rows of which the types of failures are listed, arising from faults or defects in parts and assemblies or due to a failure in the 3D printer software code, and the columns list possible causes of failures, troubleshooting and remedies by changing the 3D printer software code or repairing or replacing parts.

Figure 6 shows a fragment of the table from the developed methodology. The developed method will allow operators in production, especially beginners, to quickly eliminate failures of additive equipment.

As mentioned above, the overwhelming majority of studies [2-9] are devoted to the analysis of failures of parts and assemblies obtained using additive technologies or the possibilities of additive technologies in the aerospace industry. In turn, our work is devoted to the analysis of design and software failures of additive equipment, because the quality of products is largely determined by the parameters and equipment failures. The result of the work was the development of a methodology for eliminating FDM equipment failures using the indicated methods. Further research will focus on improving the quality of FDM 3D printing by developing a 3D quality model that will demonstrate the relationship of equipment, material and product parameters.
Figure 6. Fragment of the table from the method of eliminating failures.

| № | Failure | Reason for failure | Fault detection | Elimination of failure in parts and assemblies of a 3D printer | Troubleshooting a 3D Printer Software failure |
|---|---------|--------------------|----------------|--------------------------------------------------|---------------------------------------------|
| 1 | Desktop does not boot 3D Printer | 1) defective thermistor; 2) the heater is faulty; 3) the wiring is faulty; 4) the control board is faulty; 5) non-core temperature setpoints. | 1. Incorrect temperature data on the display (minimum heating temperature at room temperature). 2. Check the thermistor with a multimeter. 3. Check the heater with a multimeter. 4. Check the wiring with a multimeter. 5. Check the multimeter on the motherboard. | 1. 3D Printer Software: 1. #define BED_MINTEMP <value>; 2. #define BED_MAXTEMP <value>. 2. G-code: 2. 1 M104 5sm (target temperature); 2. 2 M109 5sm (standby temperature). | 3. 3D Printer Software: 1. #define HEATER_0_MINTEMP <value>; 2. #define HEATER_0_MAXTEMP <value>. 2. G-code: 2. 1 M104 5sm (target temperature); 2. 2 M109 5sm (standby temperature); 3. Run (3D printing temperature). |
| 2 | Hot end is not heated | 1) defective thermistor; 2) the heater is faulty; 3) the wiring is faulty; 4) the control board is faulty; 5) non-core set temperature value; 6) blowing directly to the hot end. | 1. Incorrect temperature data on the display (minimum heating temperature at room temperature). 2. Check the thermistor with a multimeter. 3. Check the heater with a multimeter. 4. Check the wiring with a multimeter. 5. Check the motherboard with a multimeter. 6. Check the blowing direction of the fan. | 1. Replacement or repair of accessories; 2. Change the direction of the blowing of the fan. | |
| 3 | Overheating of the extruder motor | 1) insufficient cooling; 2) high printing speed; 3) poor quality of the motor; 4) a large number of retracts. | 1. Stop filament delivery when the axle motors are running. 2. The occurrence of corresponding printing defects. | Replacement or repair of accessories | 1. 3D Printer Software: 1. #define EXTRUDER_AUTO_FAN_TEMPERATURE <value>; 2. #define EXTRUDER_AUTO_FAN_SPEED <value>. 2. G-code: 2. 1 M106 5sm (set fan speed rpm 0 0 0 255); 2. 2 G0 FXY (set feed rate equal to N1 nms / min.). |

5. Conclusion

Thus, the classification of FDM 3D printer design failures using a "fault tree" is demonstrated. An FMEA analysis was carried out to identify the reasons for the design failures of the 3D printer and develop recommendations for their elimination. The result of the DFMEA / MFMEA analysis was the development of a method for eliminating the design failures of FDM 3D printers, which will allow production operators, especially beginners, to quickly eliminate additive equipment failures. In addition, using the example of FDM equipment, the combined application of the “failure tree” analysis method and FMEA analysis was demonstrated, which increases the expert assessment of the risks of failures of additive equipment and the 3D printing process [10]. Using the developed techniques in this study and in [10], it is possible to ensure and control the quality of parts and assemblies obtained using additive technologies, including in the aerospace industry. Further research will focus on improving the quality of FDM 3D printing using modern quality tools and robust design [18,19].

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