

St. Petersburg Federal Research Center of the Russian Academy of Sciences

Rule-Based Approach to Detect Modifications on Layers of 3D Products

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Relevance

- **Increasing use of 3D-printed products** across various industries where product **reliability and integrity are critical**, for example, in the aerospace, automotive, and medical sectors.

- **The most dangerous attack**: layer-by-layer modification of the internal structure (changing the infill percentage or the number of internal reinforcing contours) while keeping the external contour intact.

- Variations in attack implementation – the insertion of malicious code (software backdoors) into the printer's firmware, or compromising the channel used to transmit 3D models to the 3D printer.

- **Attack characteristics**:
  - It is not visually detectable, yet it reduces structural strength and can lead to premature failure.
  - In composite products, such an attack can be concealed by offsetting the print time and material consumption through adjustments to adjacent parts.
  - Existing methods require large amounts of labeled data and lack interpretability.

Related works

- **ML-based approaches:** require large volumes of labeled data for training; model predictions are not always explainable.

- **LLM-based approaches:** offer high accuracy but demand significant computational resources and access to proprietary models.

- **Methods utilizing auxiliary devices (sensors, cameras, acoustic data):** require expensive hardware for real-time monitoring.

Gaps:

- The existing literature does not address the task of **detecting modifications in products composed of multiple parts**.

- There is a lack of research that combines **reference-free G-code analysis, clustering for part segmentation, and computer vision** for extracting geometric features and ensuring full **interpretability of the results**.

Aim and distinctive features

• **Aim:** to develop an approach for detecting modifications to the internal structure of multi-component products based on G-code analysis, which does not require a reference file and ensures interpretability.

Distinctive features of work:

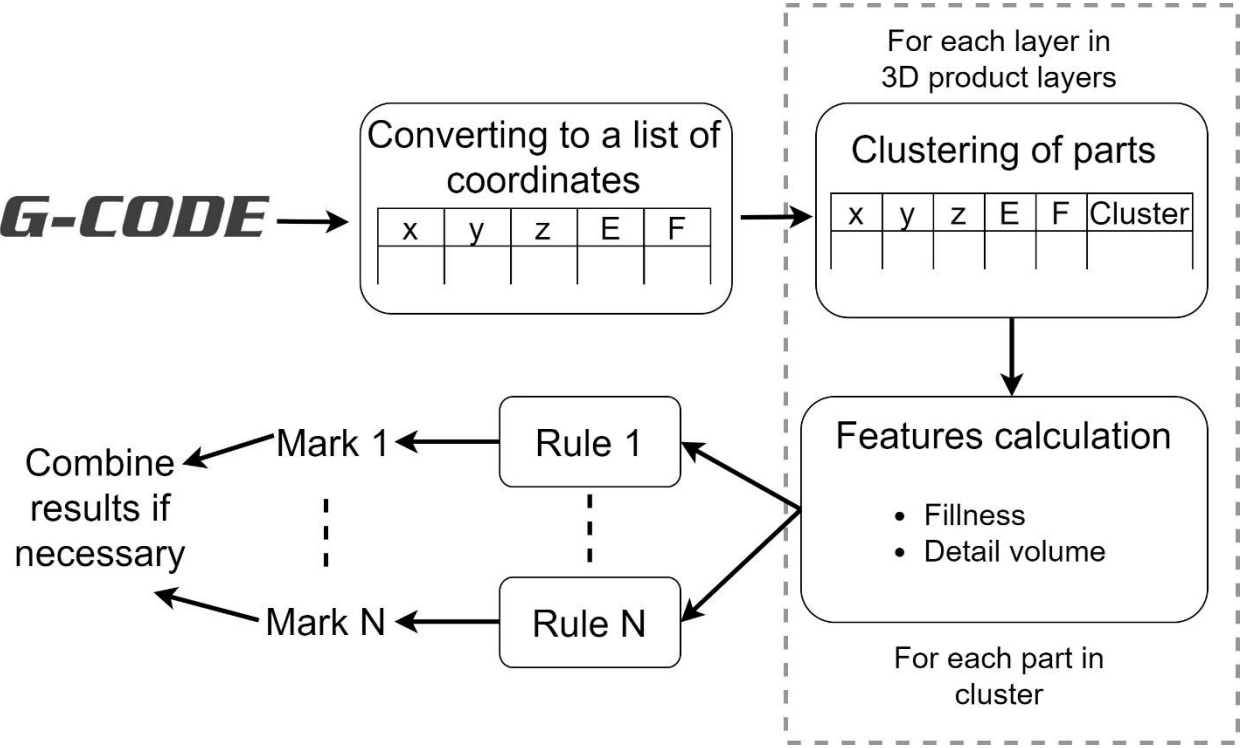
• Moving away from machine learning in favor of interpretable rules.

• Development of a specialized, robust method for isolating individual components within multi-component products.

• Application of computer vision tools (the OpenCV library) to extract geometric characteristics of products from G-code.

• Utilization of adjacent elements within a multi-component product as an internal reference.

Rule-based Approach



General scheme of the proposed approach

- **Input data:** G-codes for printing products.
- **Output:** a determination as to whether a modification is present in the product, accompanied by an explanation for this determination (based on the application of rules).
- At this stage of the research, the percentage of fillness for each component within a layer of the product and the volume of each component have been selected as the primary features, as they are the most representative.

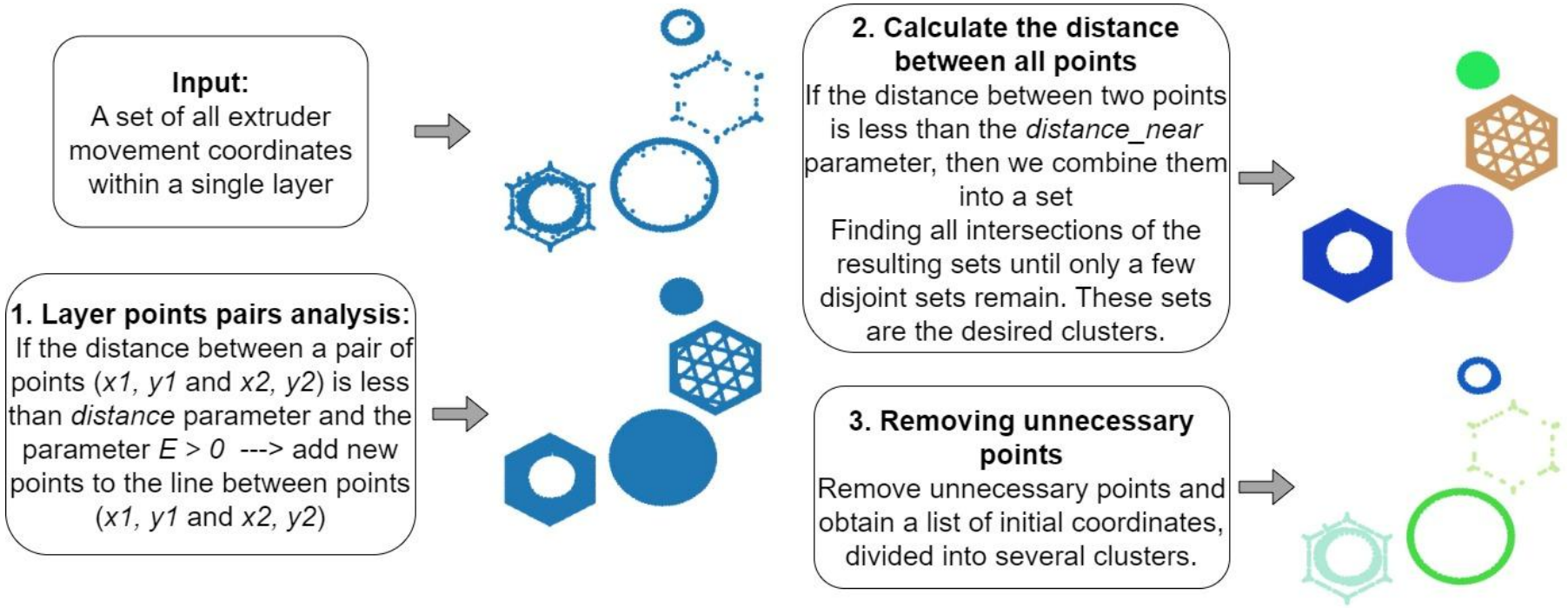
G-code Transformation

- Example of G-code transformation into a coordinate list
- Command – command code—in this case, G1—for linear movement
- x, y, z – coordinates of the extruder's movements during the printing of a single layer
- E – amount of material fed (millimeters)
- F – table or extruder feed speed (millimeters per second)

command	x	y	z	E	F
1.0	60.0	-3.0	0.2	9.0	1000.0
1.0	100.0	-3.0	0.2	12.5	1000.0
1.0	100.0	-3.0	0.2	-0.8	2100.0
1.0	100.0	-3.0	0.6	0.0	720.0
1.0	71.351	62.147	0.6	0.0	10800.0
1.0	71.351	62.147	0.2	0.0	720.0
1.0	71.351	62.147	0.2	0.8	2100.0
1.0	71.351	62.147	0.2	0.0	1200.0
1.0	77.729	56.562	0.2	0.26581	1200.0
1.0	78.395	56.164	0.2	0.02433	1200.0
1.0	78.822	56.003	0.2	0.01431	1200.0

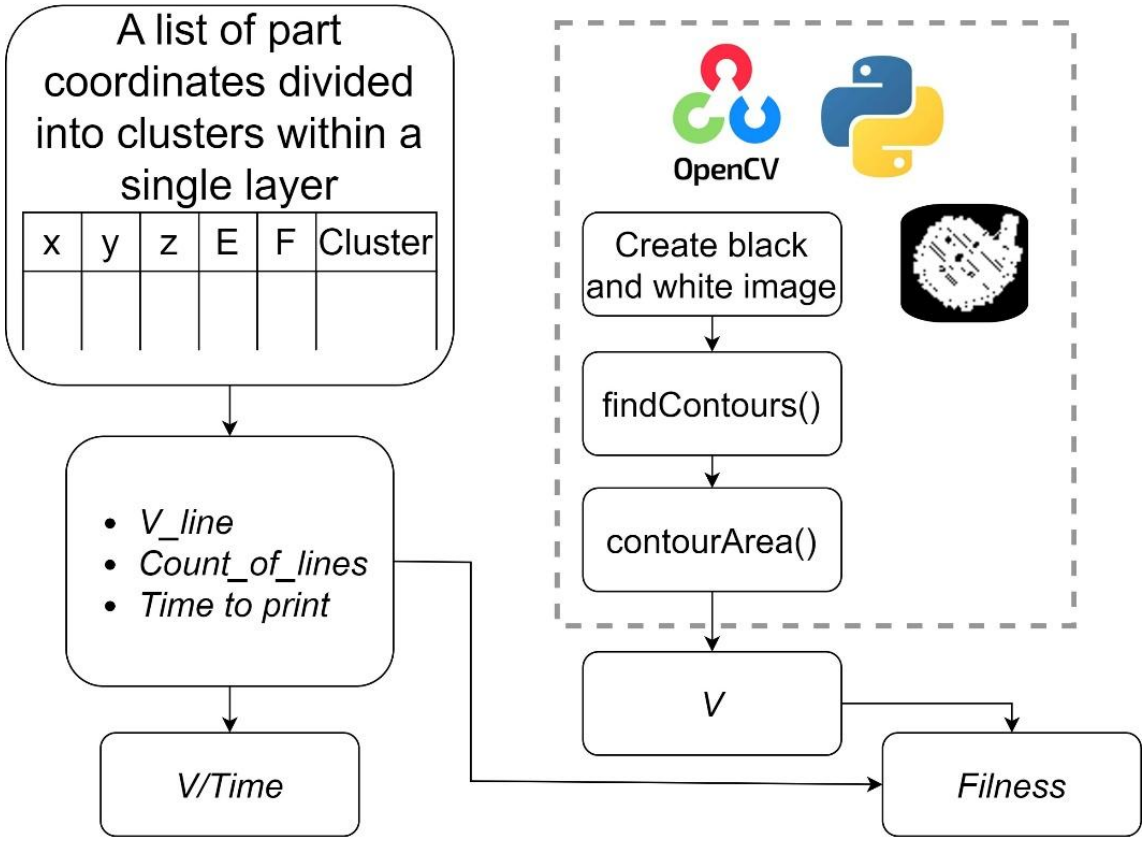
Part Clustering

Scheme of the clustering algorithm for product parts within a single layer



- **Input data:** coordinates of the extruder's movement during the printing of a layer.
- The algorithm is based on calculating the *Euclidean distance* between print coordinates.
- **Configurable parameters:** "*distance*" and "*distance_near*". The first is used when adding points between two coordinates, while the latter is used for partitioning into distinct sets (clusters).

Calculation of Derived Features



Scheme of the feature calculation method using OpenCV

- **Input data:** a list of coordinates for product components, divided into clusters.
- **The following features are calculated:**
  - geometric volume of the part within a layer.
  - layer fill percentage (the ratio of the area actually filled to the area within the contour).
  - ratio of volume to extrusion length (or print time).
  - number of contours and print time for the part.
- **Limitations:** rounding errors may occur during rasterization, which affects accuracy for complex geometries.

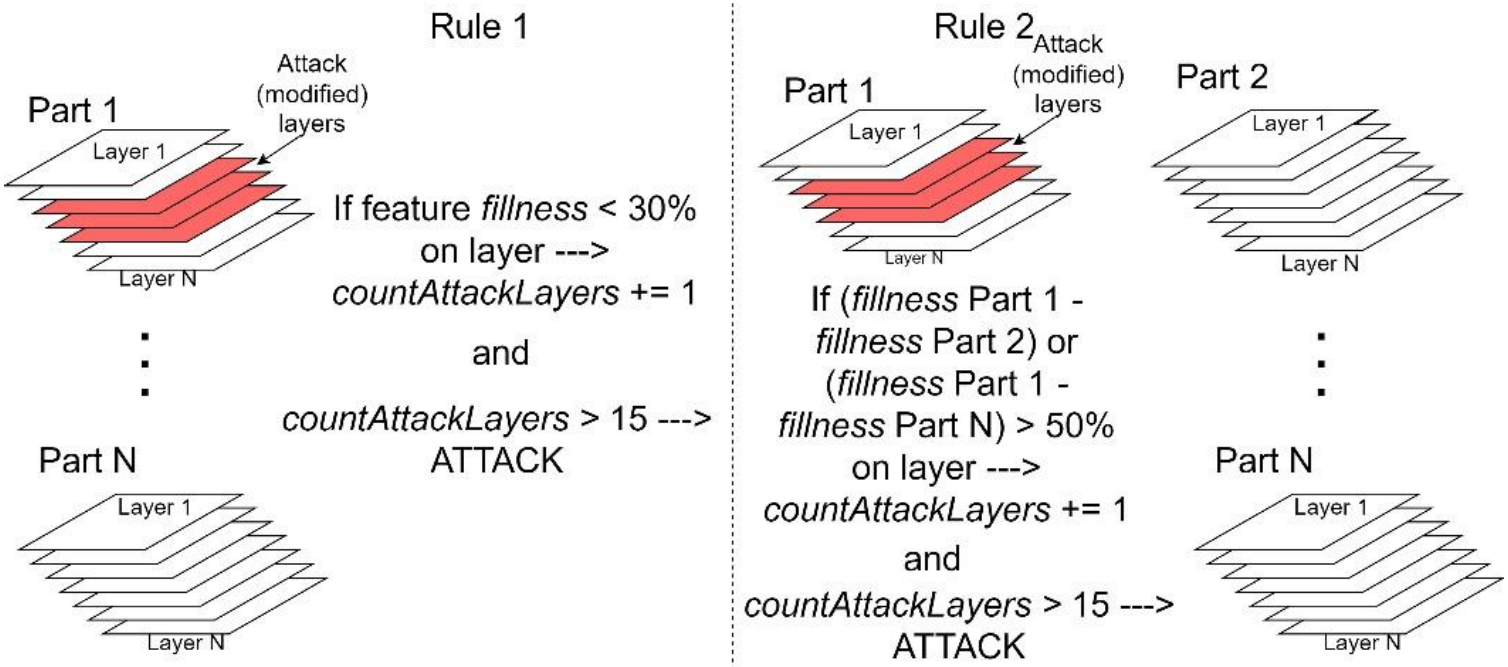
Detection Rules

Rule 1:

• If the fillness of one of the parts is less than 30% and this persists for more than 15 consecutive layers, the file is considered modified.

Rule 2:

• If the difference in fillness between two or more parts within a single layer exceeds 50%, and there are more than 15 such layers, the file is considered modified.



Scheme of the feature calculation method using OpenCV

Combined strategy: the decision to attack is made according to Rule 2, while the decision not to attack is made according to Rule 1.

Experiment (data)

- Dataset: 208 G-code files.
  - 104 unmodified parts (Fillness for each component > 70%).
  - 104 modified parts (Fillness for one or more components reduced below 70%; infill for the remaining components slightly increased to compensate for print time and material consumption).

- All items consist of multiple components—several parts are printed in a single print cycle.
- The modification affected the internal infill; the external contours remained unchanged.

Experiment (results)

Detection results using Rule 1 and Rule 2

Rule 1 result				Rule 2 result			
Mark	precision	recall	F-score	precision	recall	F-score	support
normal	0.66	0.78	**0.71**	0.73	0.47	0.57	104
attack	0.73	0.60	0.66	0.61	0.83	**0.70**	104
weighted avg	0.69	0.69	0.68	0.67	0.65	0.64	208

Results of combined detection using Rule 1 and Rule 2

Mark	precision	recall	F-score	support
normal	0.82	0.78	**0.80**	104
attack	0.79	0.83	**0.81**	104
weighted avg	0.80	0.80	0.80	208

Discussion

- Combining rules makes it possible to achieve an **F1 score of 0.81** for the attack class, which is significantly higher than what can be attained with individual rules (the best result being *0.70*).
- The approach **requires no training** and works "out of the box."

Key advantages

+ Interpretability: every rule trigger has a clear physical meaning; it is possible to identify the specific part and layer involved.
+ No reference G-code required (neighboring parts are used as an internal reference).
+ Robustness to changes in print configurations (thresholds can be readjusted).
+ Processing time per G-code file: 2–5 minutes per script (acceptable, given the speed of the printing process).

Limitations

× OpenCV errors occur when calculating features for parts with complex geometry.

× Only two rules have been implemented, both utilizing a single feature (Fillness).

× Threshold values (30%, 50%, 15 layers) were determined empirically and will require adjustment for other manufacturing environments.

Conclusion and future work

- An approach for detecting layer-by-layer modifications to an internal structure, based on G-code analysis, is proposed.
- **Key elements** include a novel clustering algorithm, feature extraction using computer vision (OpenCV), and a set of two threshold-based rules.
- An **F1-score of 0.81** was achieved for the attack class, confirming the practical applicability of the approach.
- The decisions regarding attack detection are fully interpretable.

Future work:

- Improving the algorithm for calculating derived features
- Expanding the set of features and constructing multifactor rules.



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Thank you for your attention

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