ANALYSIS OF DATA SYNCHRONIZATION METHODS AND FRAMEWORK IN WIRE ARC ADDITIVE MANUFACTURING (WAAM)

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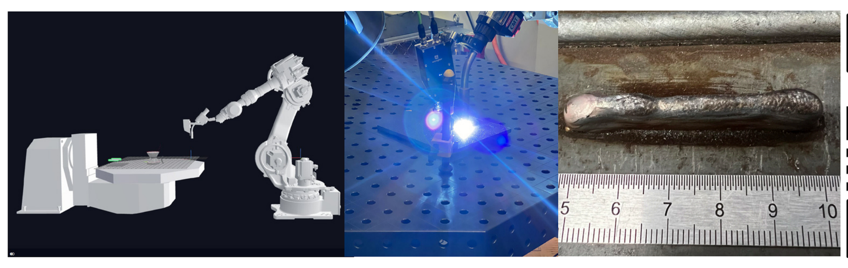


Author: **Sergejs Kopils**
Study Programme: **Data Analytics and Artificial Intelligence**
Supervisor: Professor, Dr. sc. ing. **Mihails Savrasovs**
Consultant: Invited lecturer, Mg. sc. ing. **Arsenii Kisarev**

SERGEJS KOPILS
+371 2914 5182
sergejs.kopils@gmail.com
www.linkedin.com/in/sergejs-kopils

Background

In Wire Arc Additive Manufacturing (WAAM), synchronizing multiple asynchronous data streams—3D scans data, process data, and initial data—is vital for quality control, anomaly detection, and process optimization.

Research Question

- Which synchronization method provides the most reliable alignment between scan and process data in the absence of timestamps?
- How effective is geometric segmentation compared to clustering-based approaches in detecting deposition layers?
- Can rule-based anomaly detection reliably identify irregularities in the WAAM process based solely on geometric data?

Objectives

- Analyze synchronization methods for WAAM
- Develop a modular synchronization and visualization framework
- Compare segmentation techniques for layer detection
- Implement rule-based anomaly detection
- Visualize anomalies and layer data in 3D

Methodology

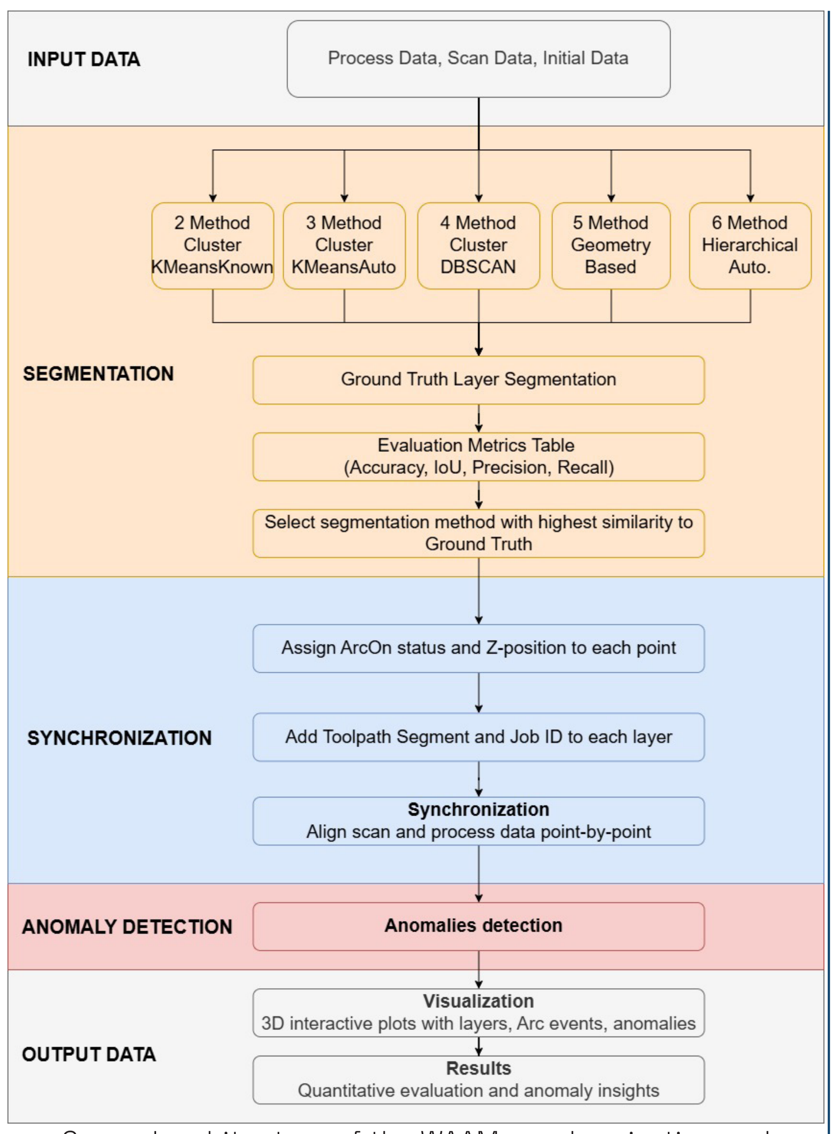
Study Design: Experimental evaluation using WAAM dataset (Initial Data, Process Data and Scan Data).

Materials and Tools:
- Industrial robot (Yaskawa),
- Welding power source (Fronius),
- Laser scanner (Wenglor).
- Python, Dash, Plotly

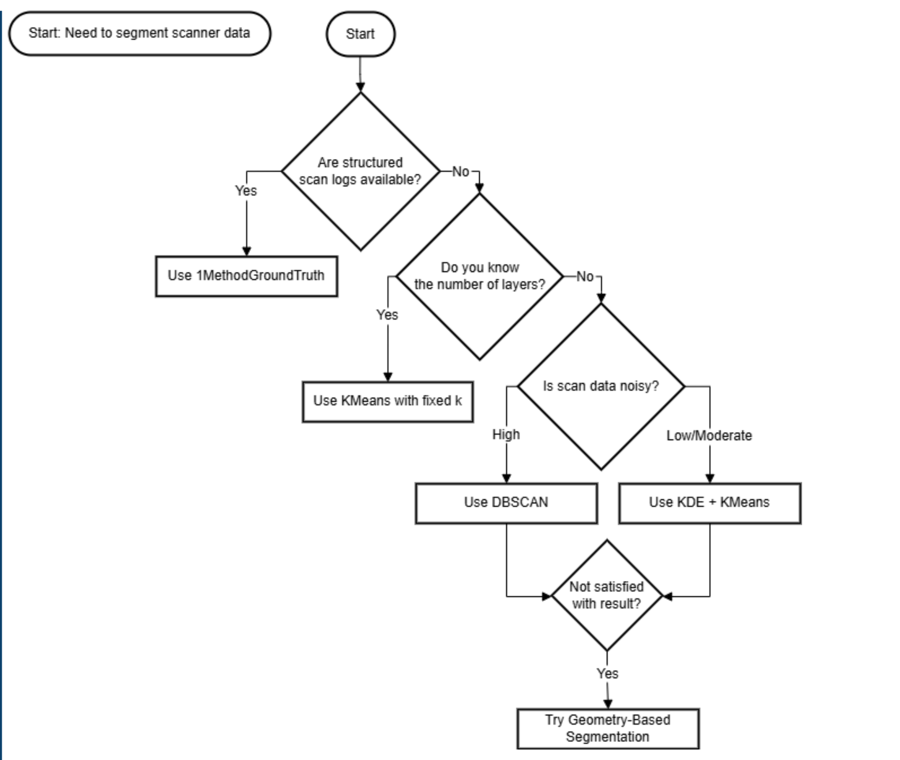
Data Collection & Data Analysis:
- Post-layer 3D scans
- Process logs (Arc On/Off, robot path, TS, WFS)
- Segmentation: 6 methods (KMeans, DBSCAN, Geometry-based, etc
- Accuracy metrics (Precision, Accuracy %, Recall, F1-score, IoU)
- Rule-based anomaly logic
- Interactive 3D dashboard

Results and Discussion

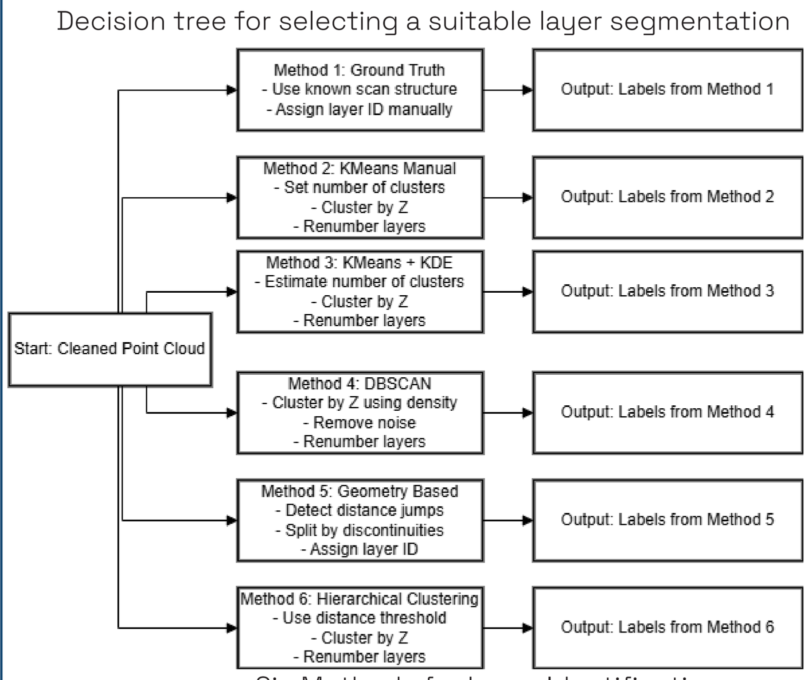
- Geometry-based segmentation (Method 5) had highest robustness without timestamps.
- KDE+KMeans method performed best under noisy scan data.
- Anomaly detection flagged Z-depressions, arc gaps.



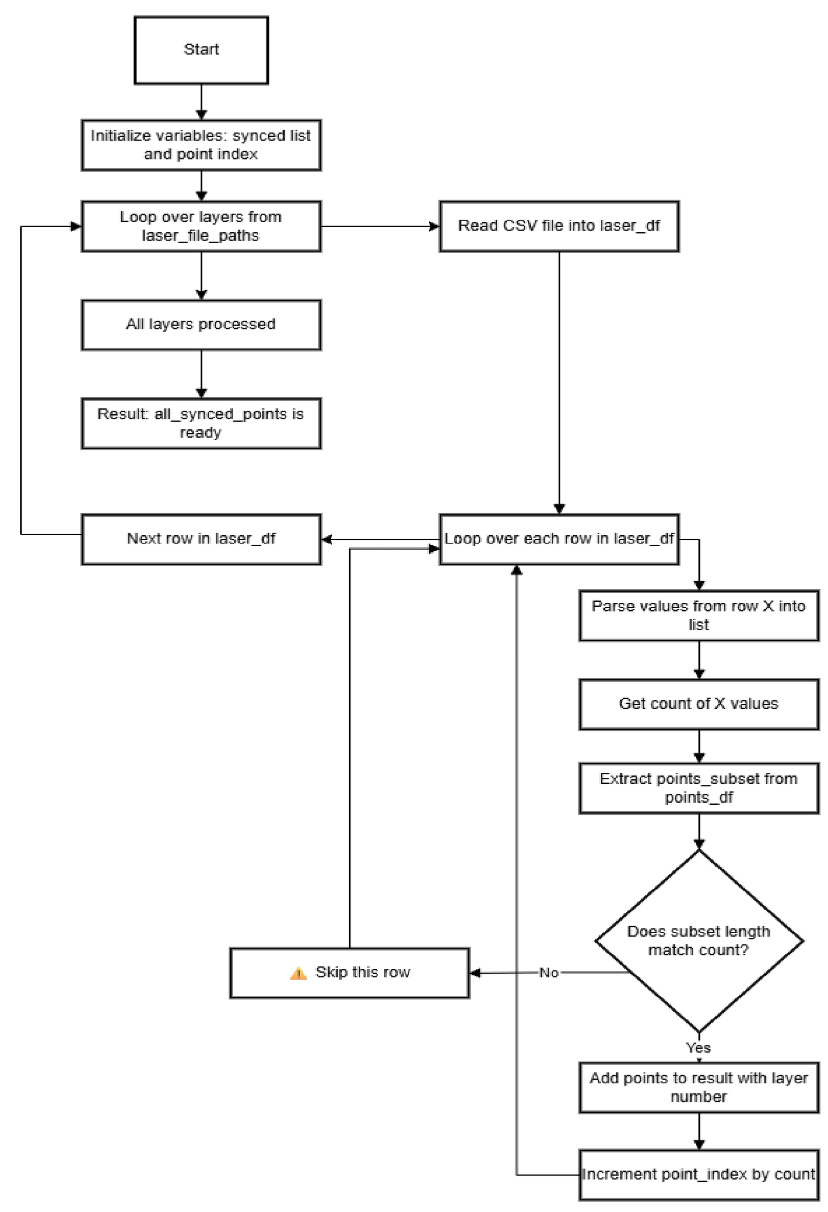
General architecture of the WAAM synchronization and anomaly detection framework.



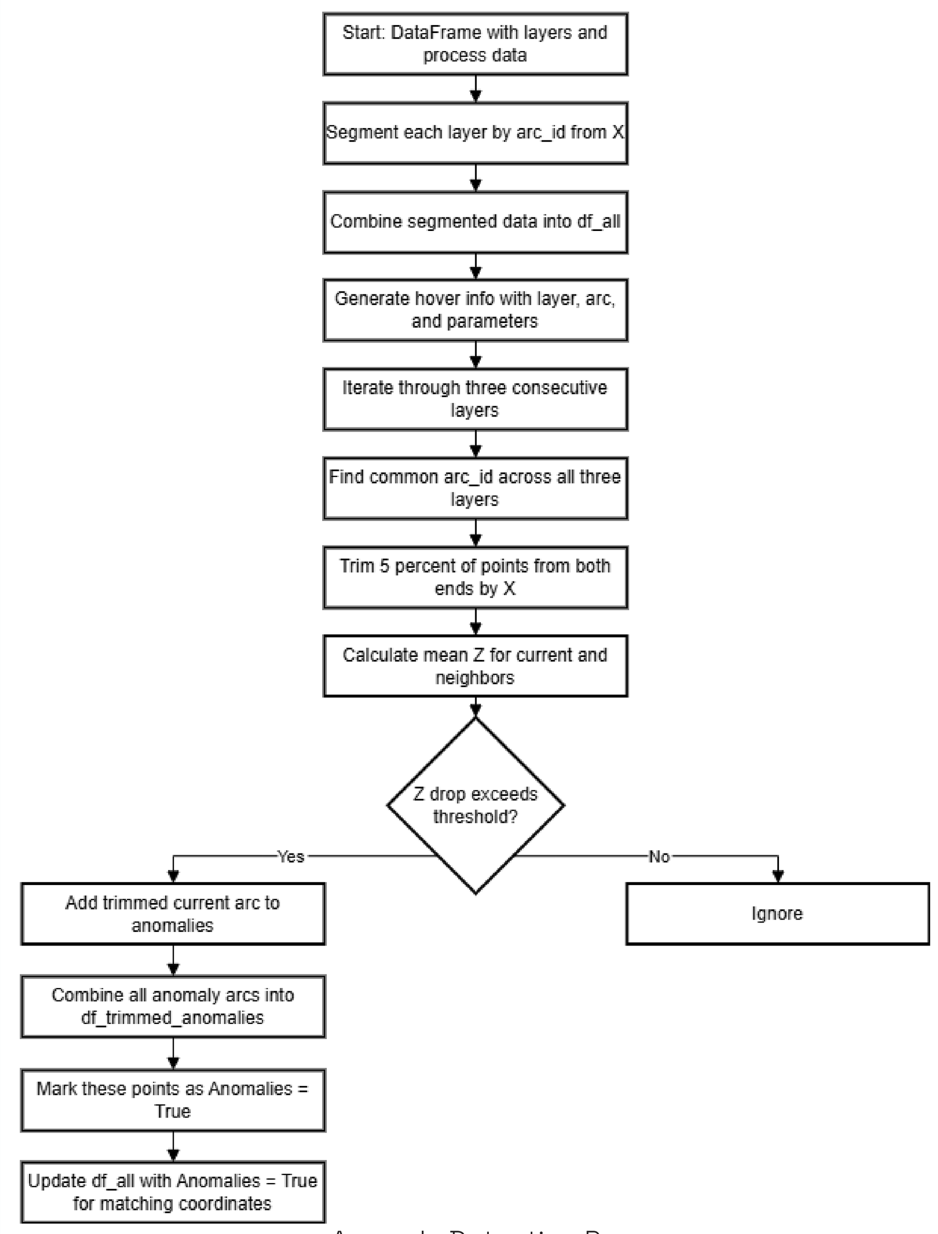
Decision tree for selecting a suitable layer segmentation



Six Methods for Layer Identification



Segmentation logic for Method 1: GroundTruth



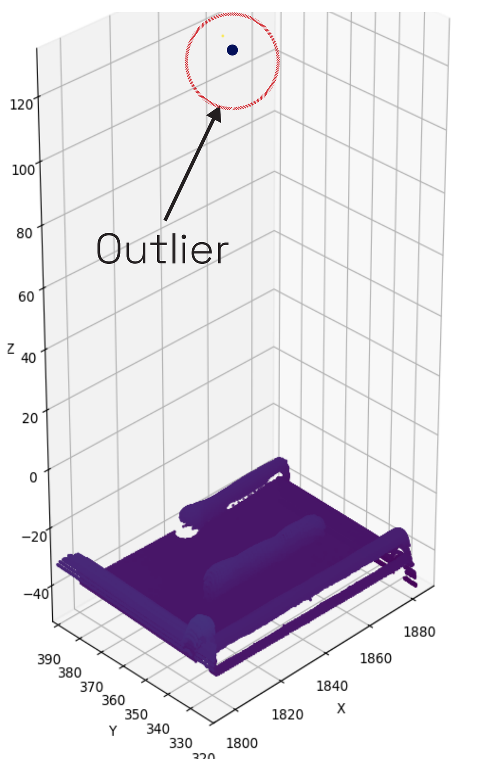
Anomaly Detection Process

Data preprocessing and cleaning:
Step 1: Raw data (no filtering)
Step 2: Z Outlier removal + ROI X/Y
Step 3: ROI X/Y/Z and substrate removal

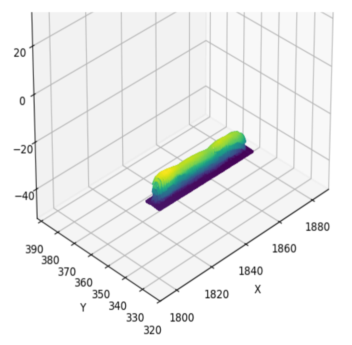
Stage	Points
Raw Data	694020
Cleaned Data	23340

Column	Description
X, Y, Z	3D coordinates of the scan point
layer_id_*	Layer label from selected segmentation method
ArcON	Arc status at that point (1 or 0)
JobID	Job number from Initial Data
TS	Travel speed (mm/s)
anomaly_flag	Detected anomaly at point level (if any)

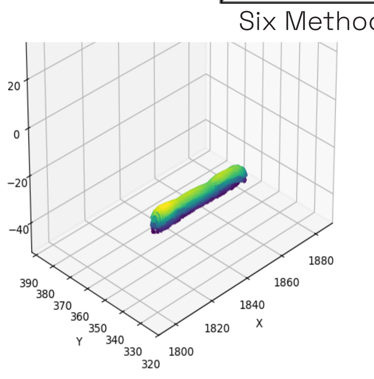
Structure of the DataFrame produced by the synchronization engine



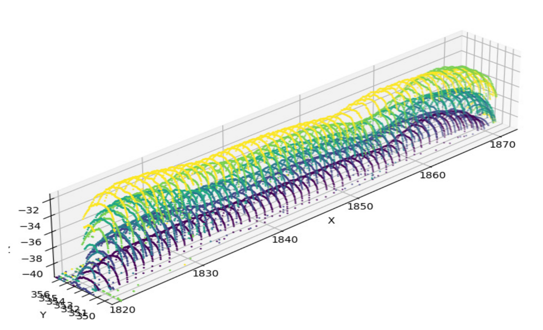
Step 1: Raw data (no filtering)



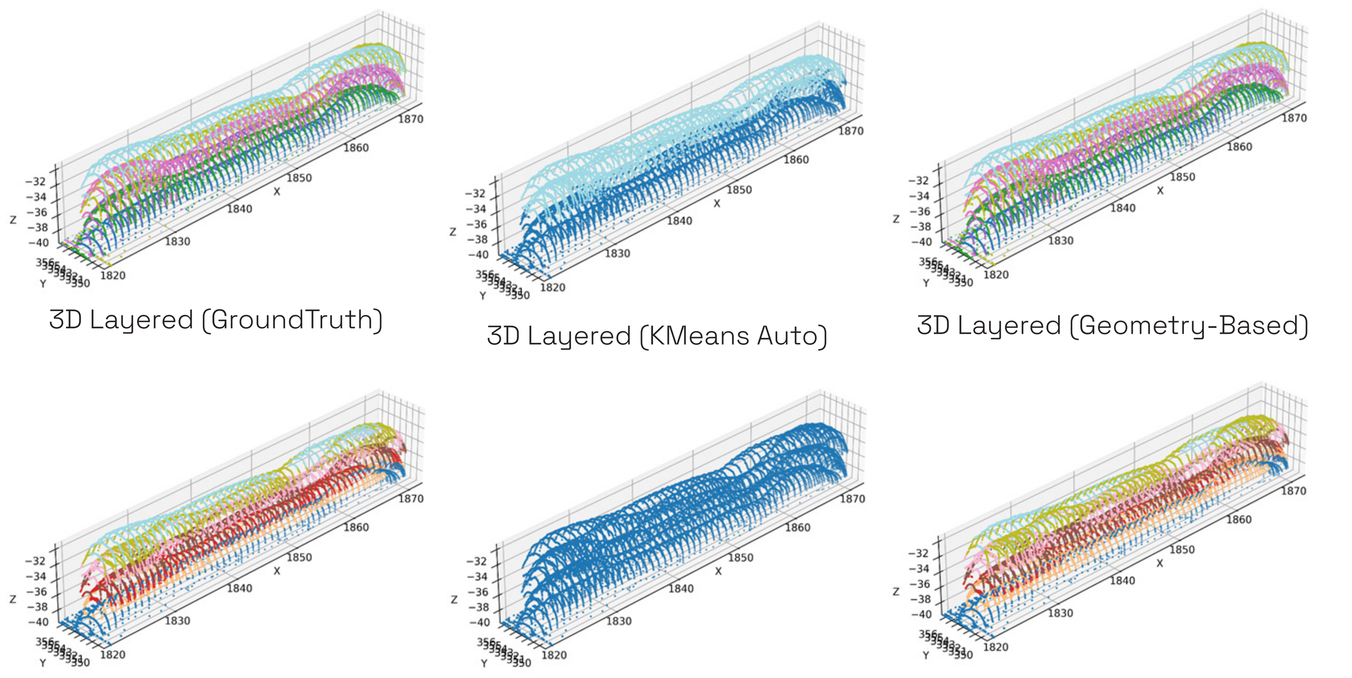
Step 2: Z Outlier removal + ROI X/Y



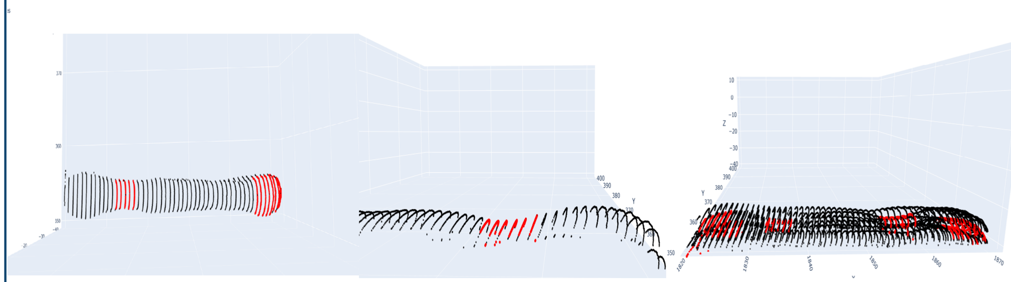
Step 3.1: ROI X/Y/Z and substrate removal



Step 4: Clean data

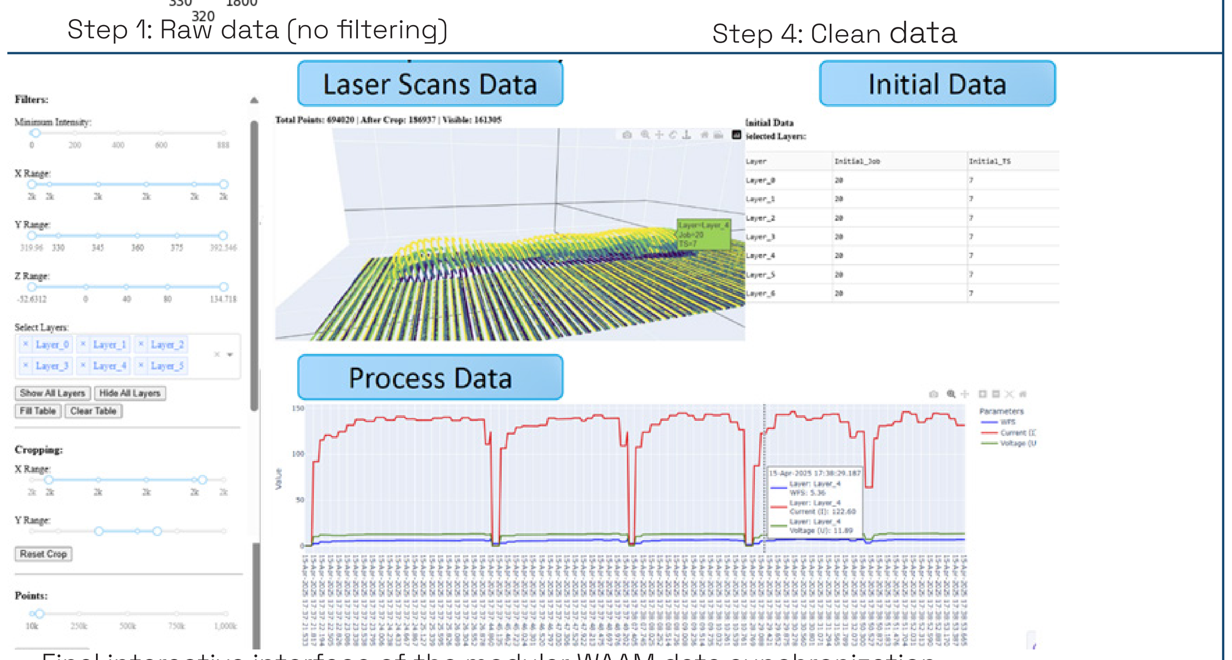


3D Layered (GroundTruth)
3D Layered (KMeans Auto)
3D Layered (Geometry-Based)
3D Layered (KMeans, Known N)
3D Layered (DBSCAN)
3D Layered (Hierarchical Auto)

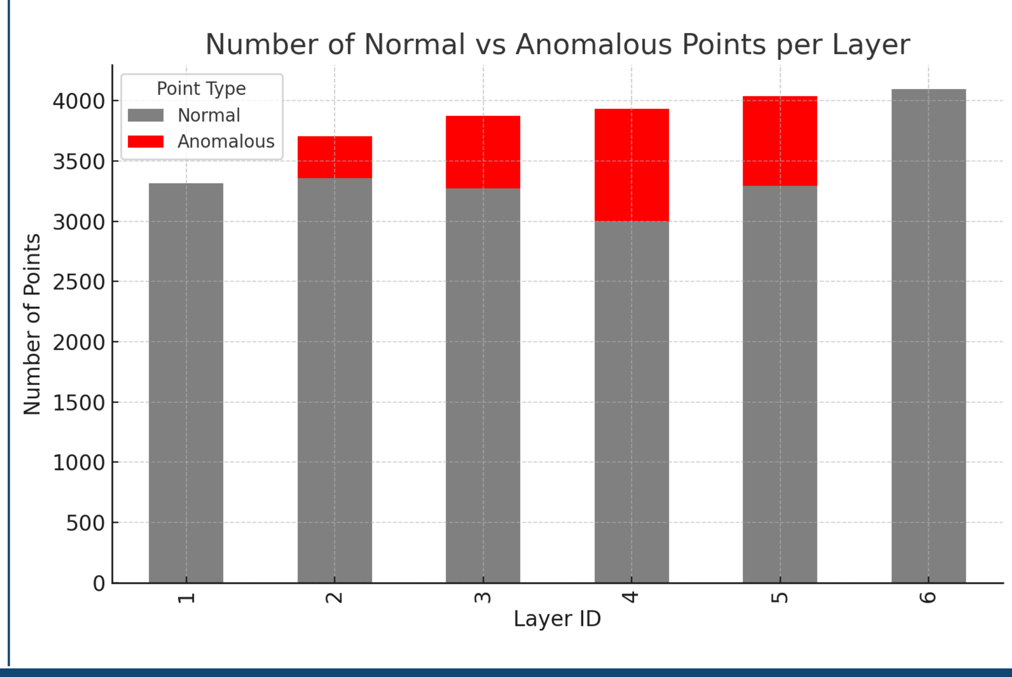


Visualizations of detected anomalies.

Method	Accuracy (%)	Precision	Recall	F1-score	IoU
Method 2: Cluster KMeans Known	57.1	53.9	49.3	51	36.7
Method 3: Cluster KMeans Auto	14.4	4.7	16.7	7.4	4.7
Method 4: Cluster DBSCAN Auto	14.4	2.4	16.7	4.2	2.4
Method 5: Geometry Based	100	100	100	100	100
Method 6: Hierarchical Auto	55.3	53.5	48	49.1	34.8



Final interactive interface of the modular WAAM data synchronization and anomaly detection framework.



Conclusions / Outcomes

Developed a modular, reusable synchronization framework for WAAM.
Proposed and benchmarked 5 segmentation methods + 1 ground truth.
Integrated anomaly detection logic and created a 3D analysis dashboard.

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