DISTRIBUTED RESILIENT AND EMERGENT INTELLIGENCE-BASED ADDITIVE MANUFACTURING

NSF E-RISE RII Award #OIA-2417062

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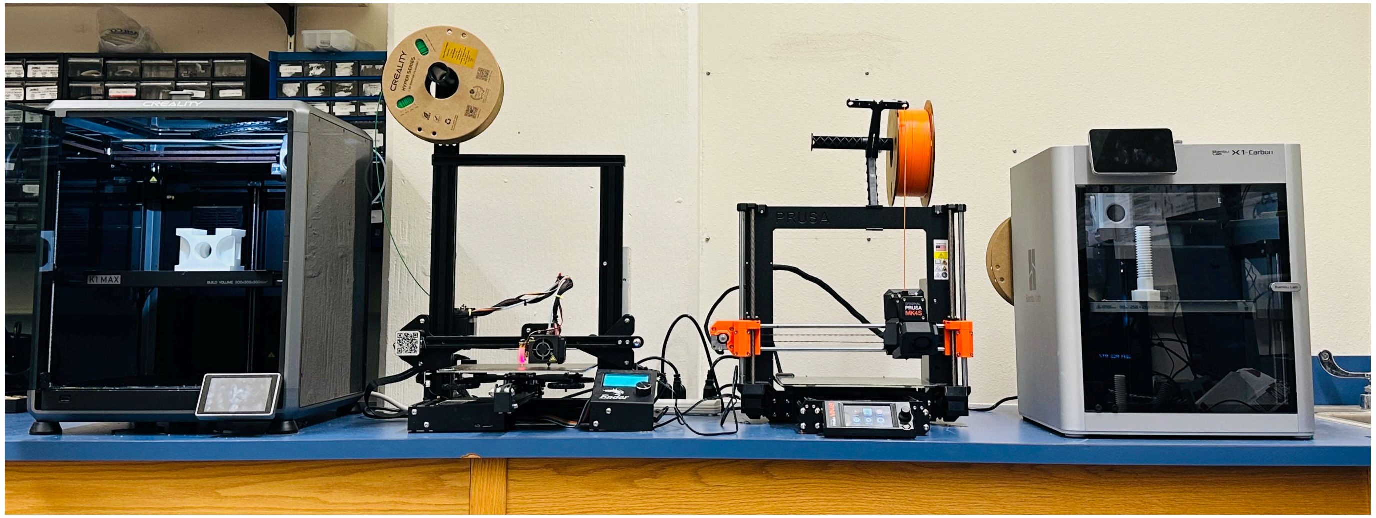
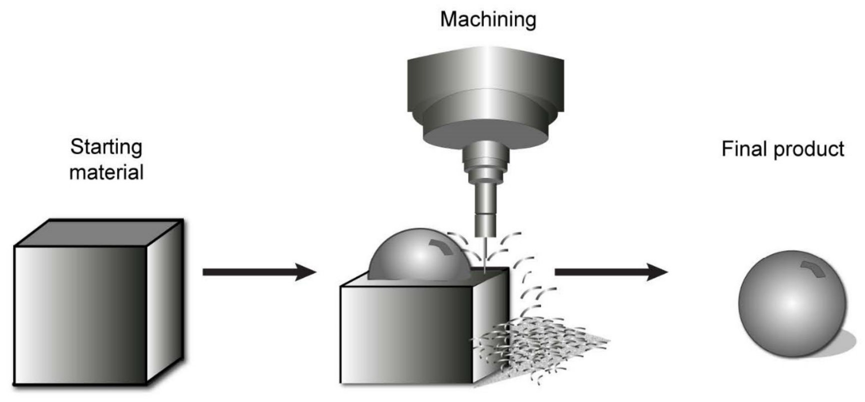
Overview of Operational DREAM Center Acquired 3D Printers

Krishna Roy and Chaitanya Mahajan

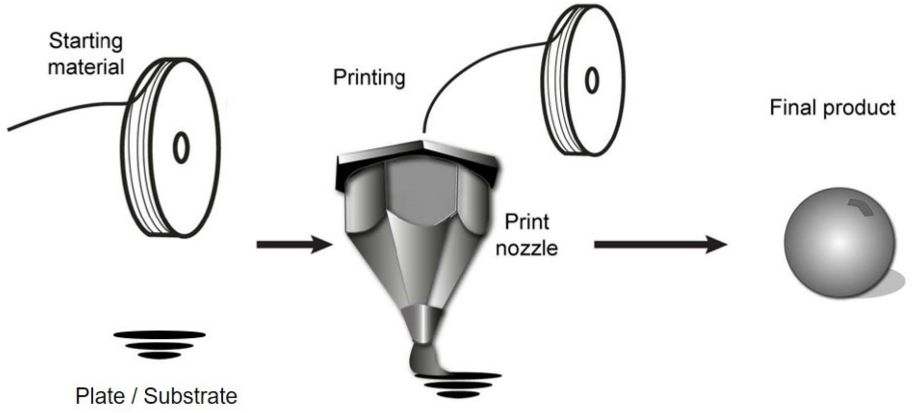


Subtractive vs Additive Manufacturing

Subtractive

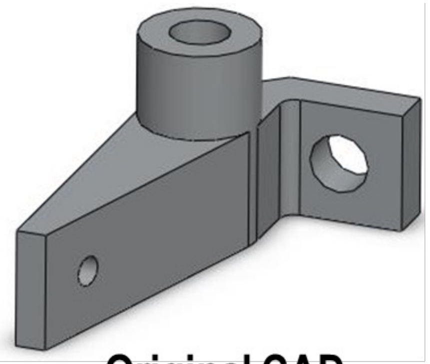


Additive

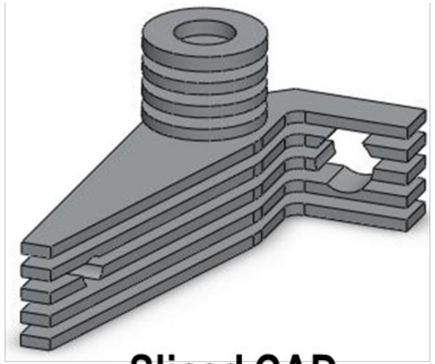


Additive Manufacturing (AM)

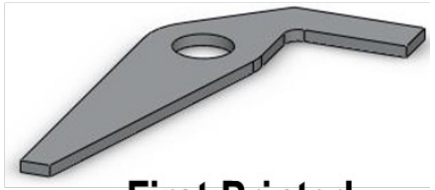
- 3D printing, additive manufacturing, solid freeform fabrication, digital printing, rapid prototyping, etc.
- 2.5D, 3D, and 4D printing
- Layer-by-layer printing



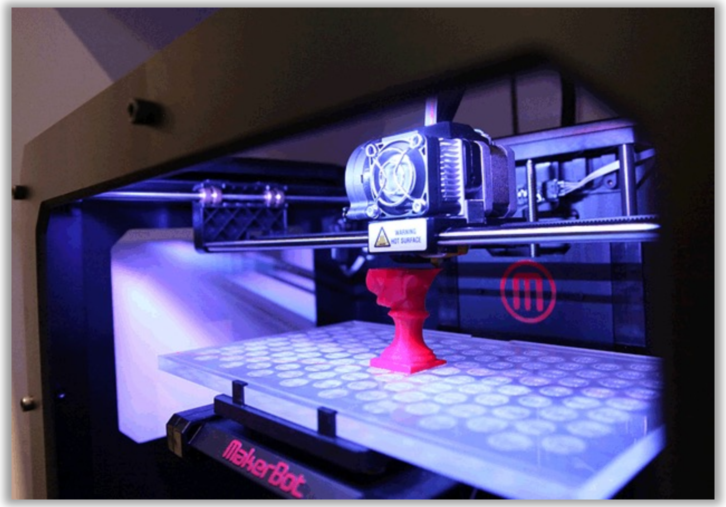
Original CAD Model

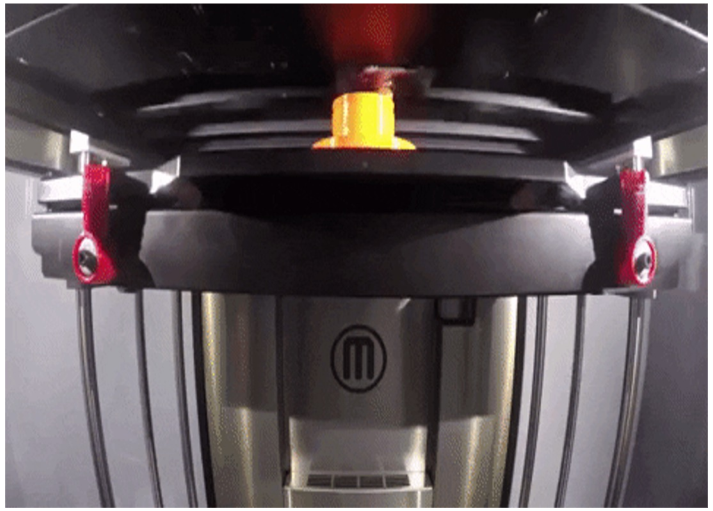


Sliced CAD Model

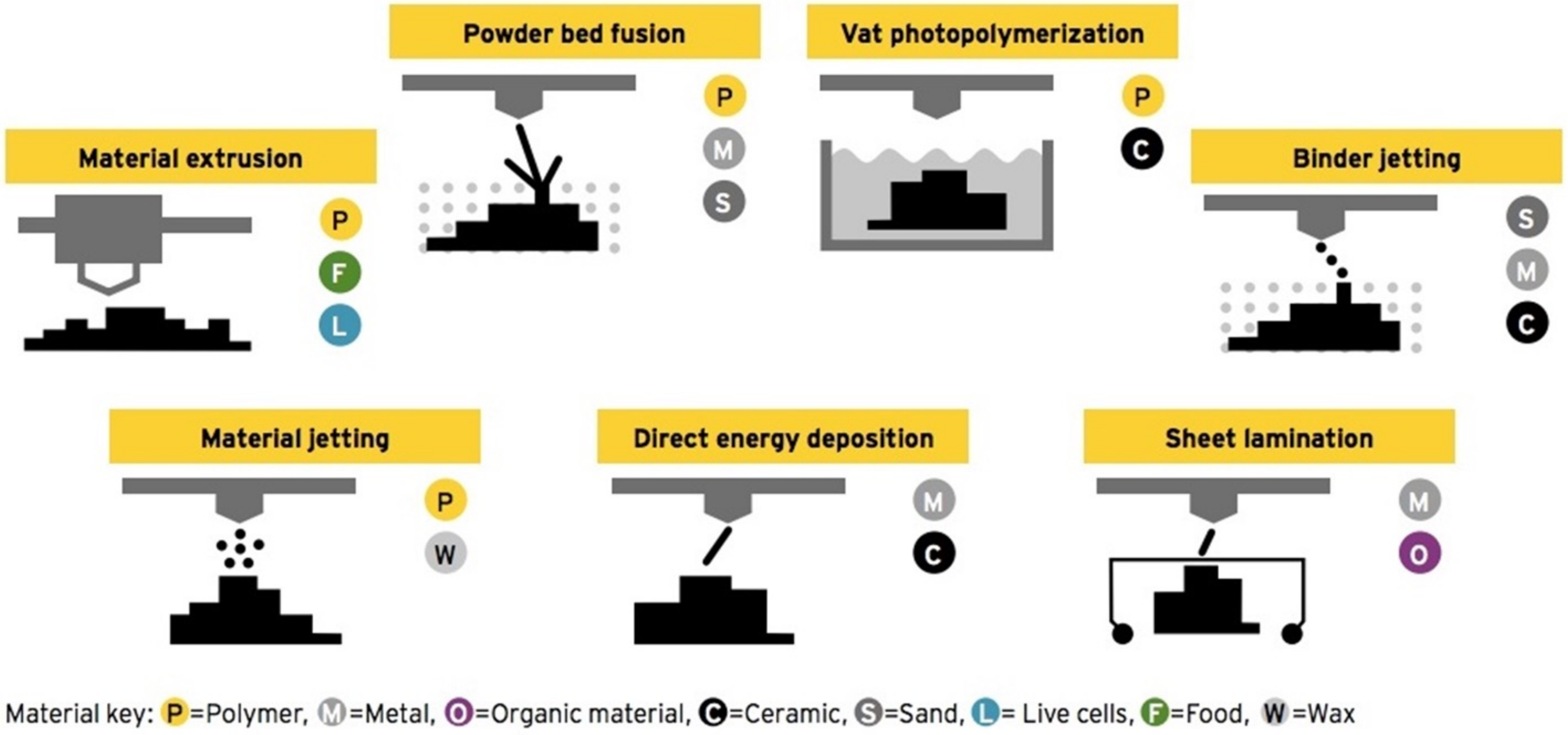


First Printed Layer



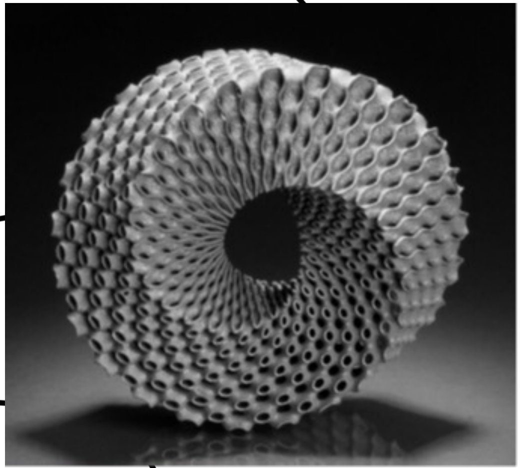


Different AM Processes



https://www.sculpteo.com/blog/2017/05/23/metal-3d-printing-which-technologies-for-which-applications/

Complex Geometry



Art piece by AM
From http://www.3ders.org/

Prosthesis

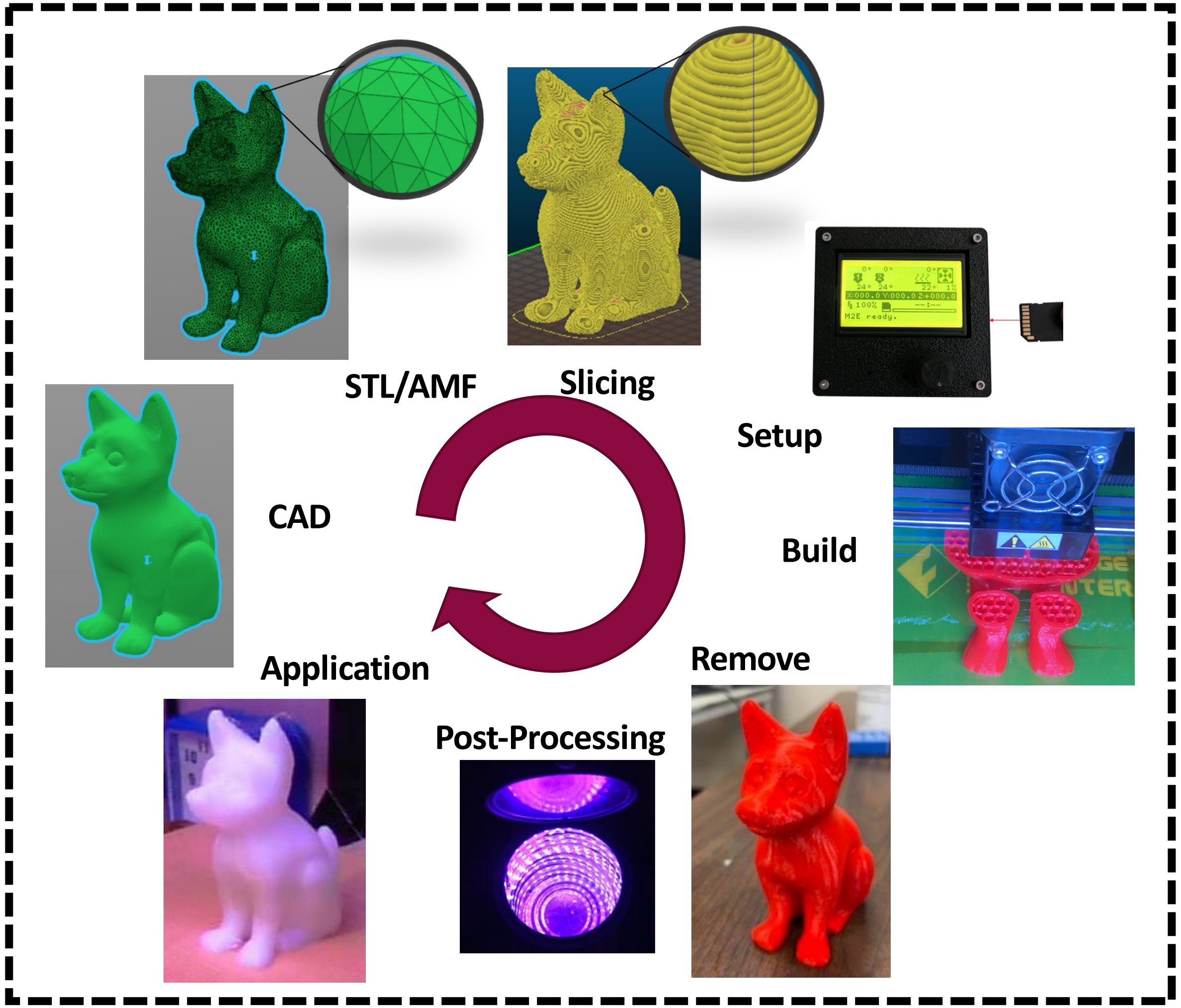
Teeth Aligner
From https://www.invisalign.com

hearing aid bud
From https://envisiontec.com

fuel nozzle 25% lighter, 5x stronger
From http://www.gereports.com/

Airbus A320 nacelle bracket 30% lighter
From http://www.altairhyperworks.com/

AM Production Cycle

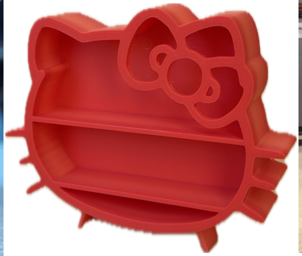


Additive Manufacturing Process Flow: CAD → STL/AMF → Slicing → Setup → Build (Print) → Remove → Post-Processing → Application

Challenges to Adopt AM

- Quality of AM parts
- Anomaly identification
- Data safety
- Teaching and workforce

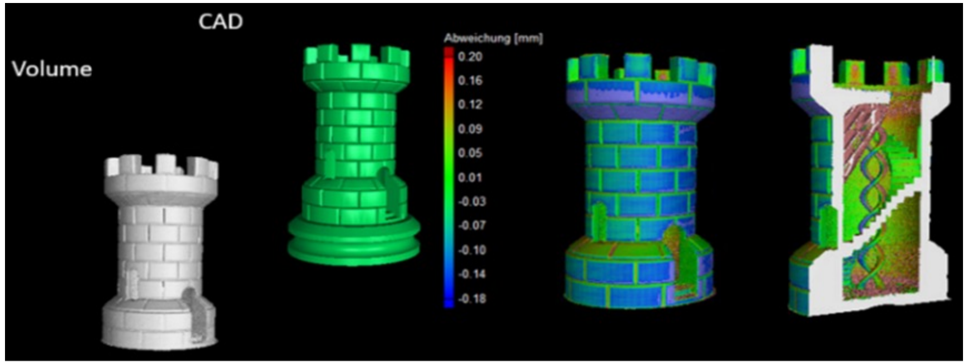
Workshop: K-12 Teachers



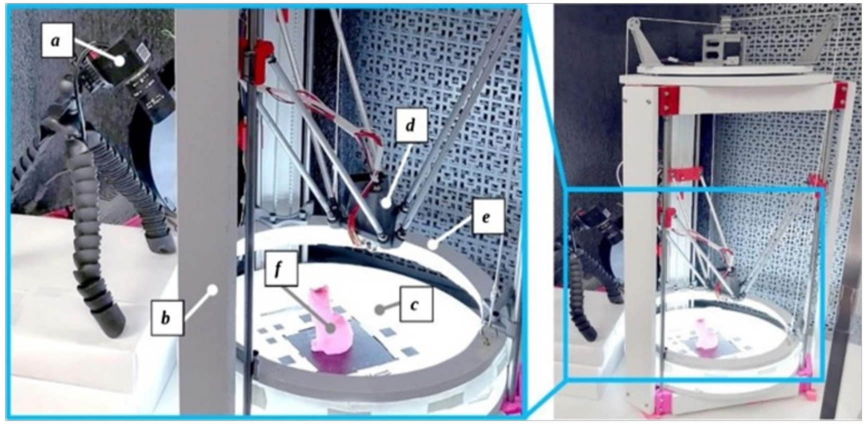
Additive Manufacturing Quality Control

- Quality control within Additive Manufacturing (AM)
  - Non-destructive testing
  - Computer vision

- Benefits of utilizing a computer vision-based quality control:
  - Cost efficiency in optical lenses
  - Applicable across different AM processes
  - Visually interpretable data and results
  - <u>*in-situ* process monitoring/inspection</u>



[1] CT Scan comparison to CAD model

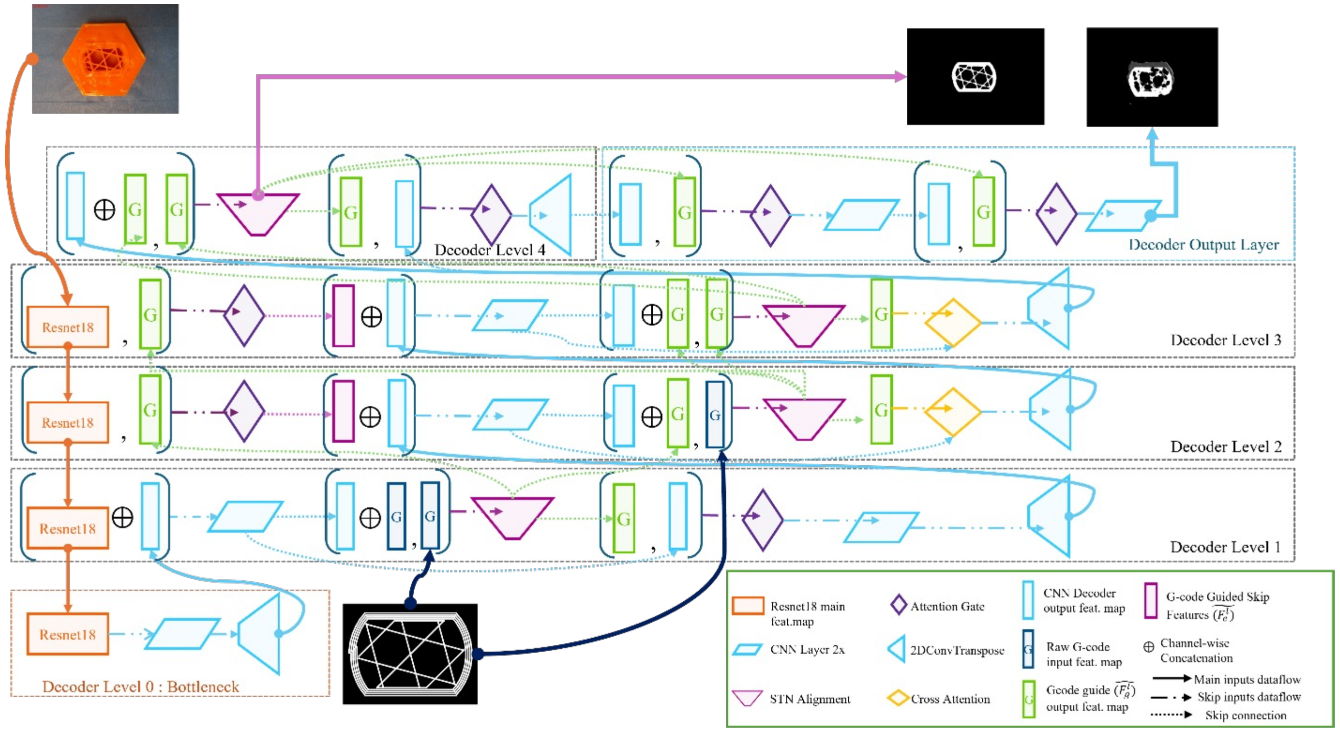


[2] Computer Vision in 3D Printing

G-code Gated U-Net (GG-Net)

- G-code Gated U-Net (GG-Net) integrates the encoder/decoder architecture of the standard U-Net

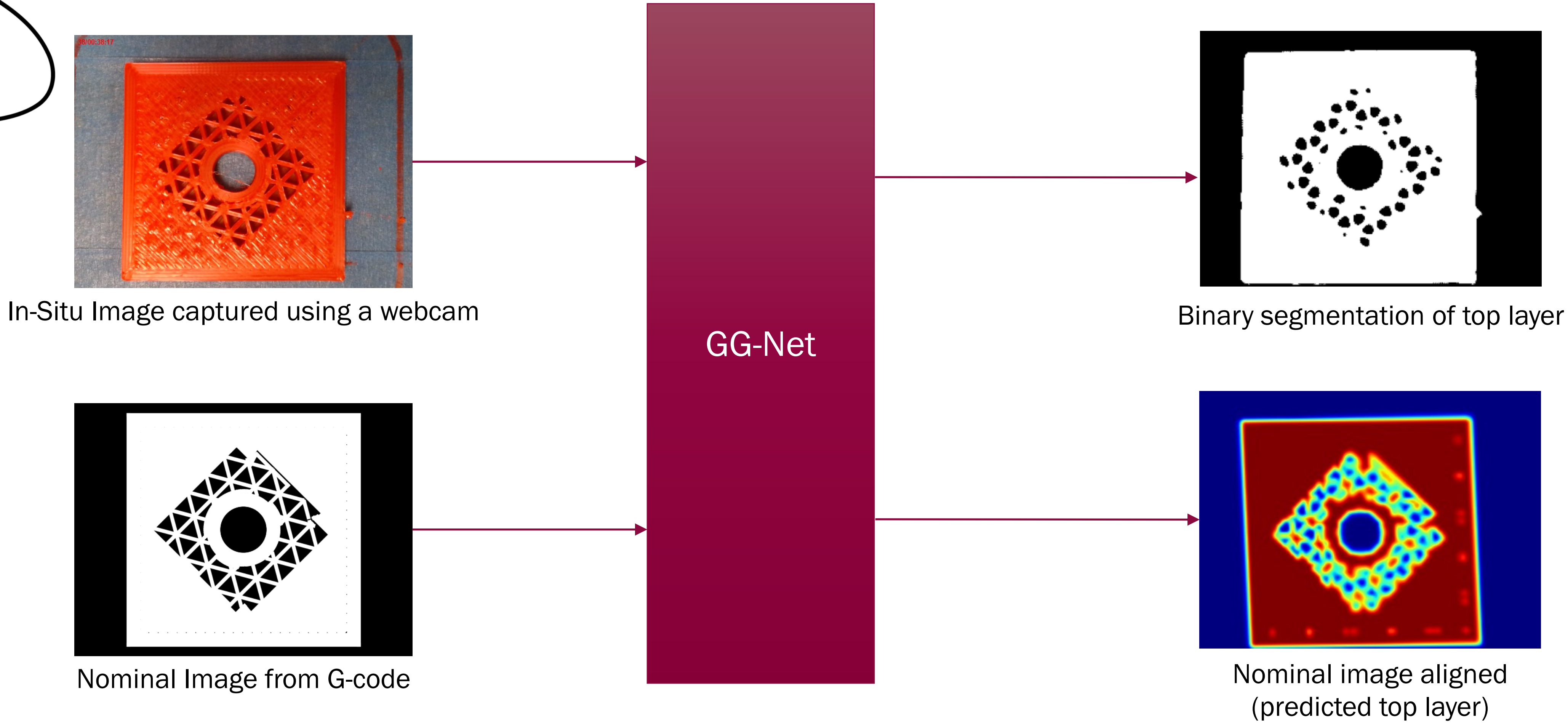
- <u>**GG-Net is designed for top-layer (TL) segmentation from images captured from a top-view perspective**</u>



GG-Net Architecture

Casey Wong Tran et al. "G-code gated U-Net (GG-Net) for real-time layer-wise in-situ quality control in additive manufacturing processes. (in prep)

G-code Gated U-Net (GG-Net)



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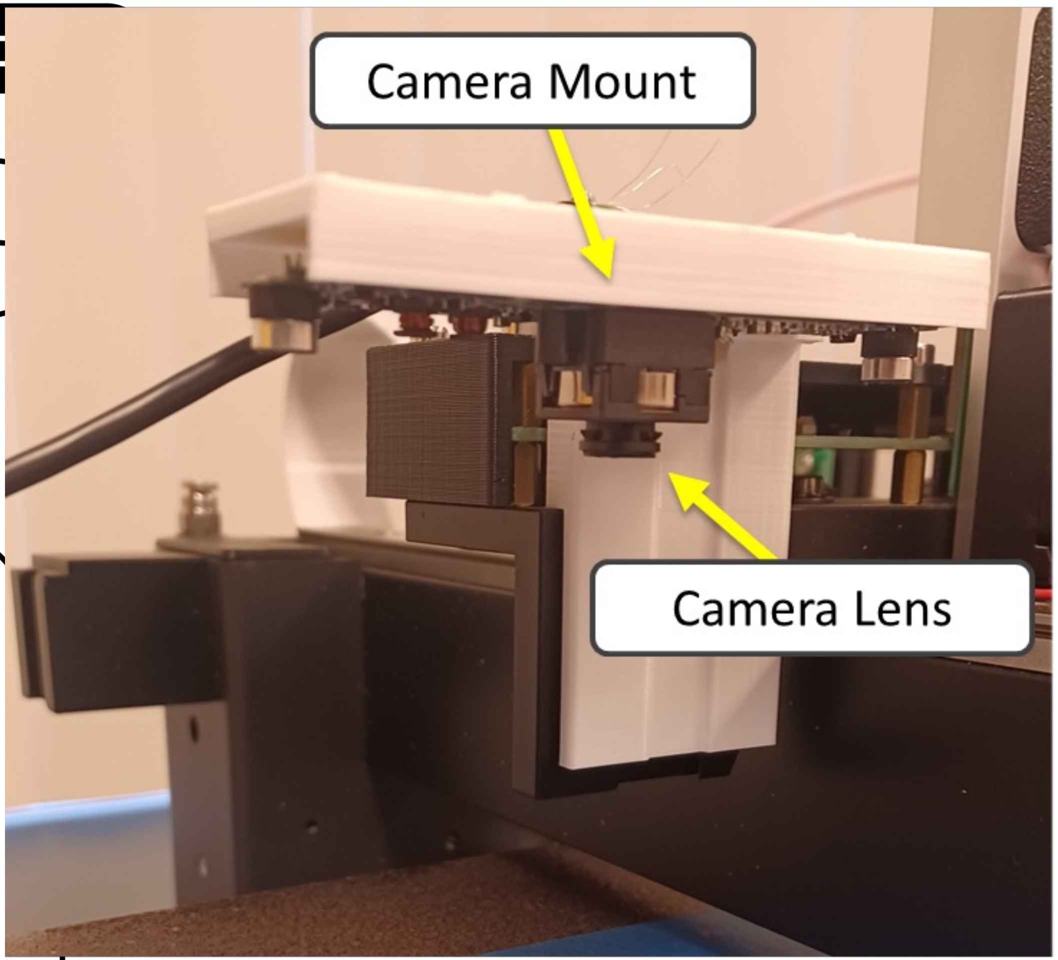
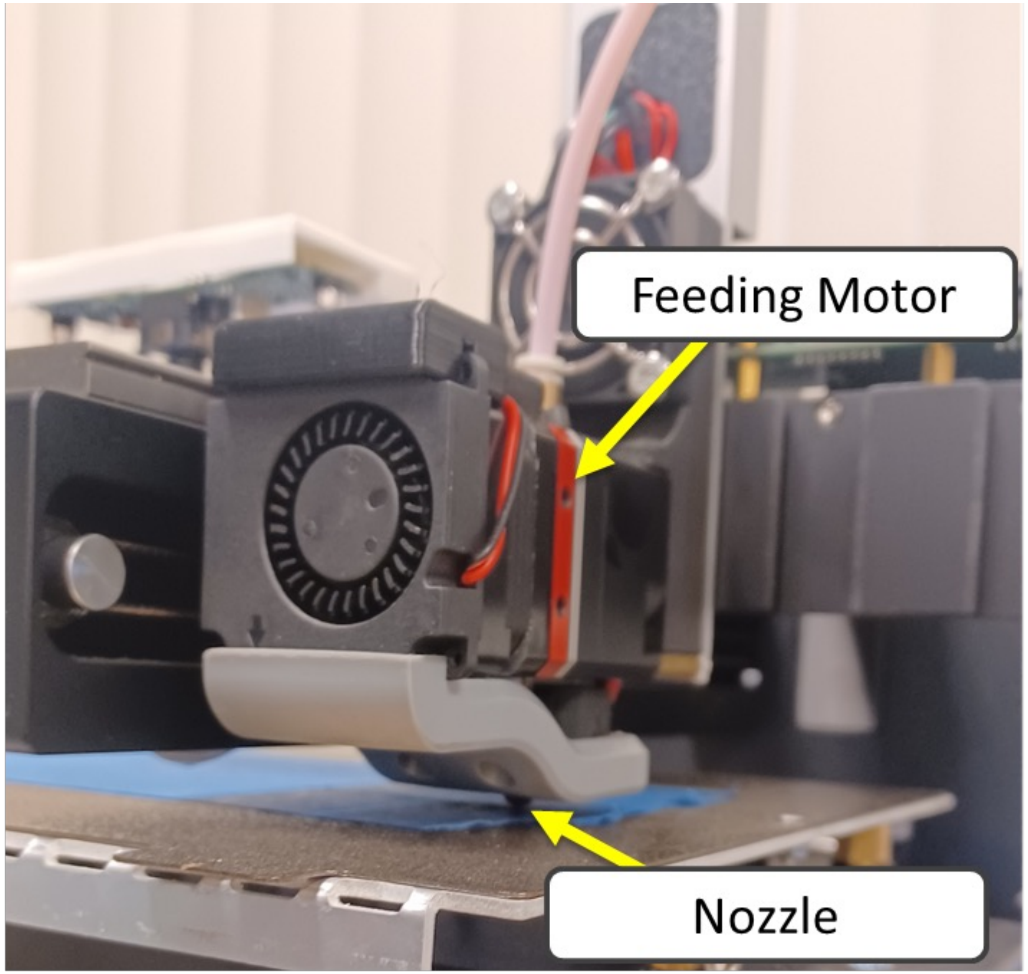
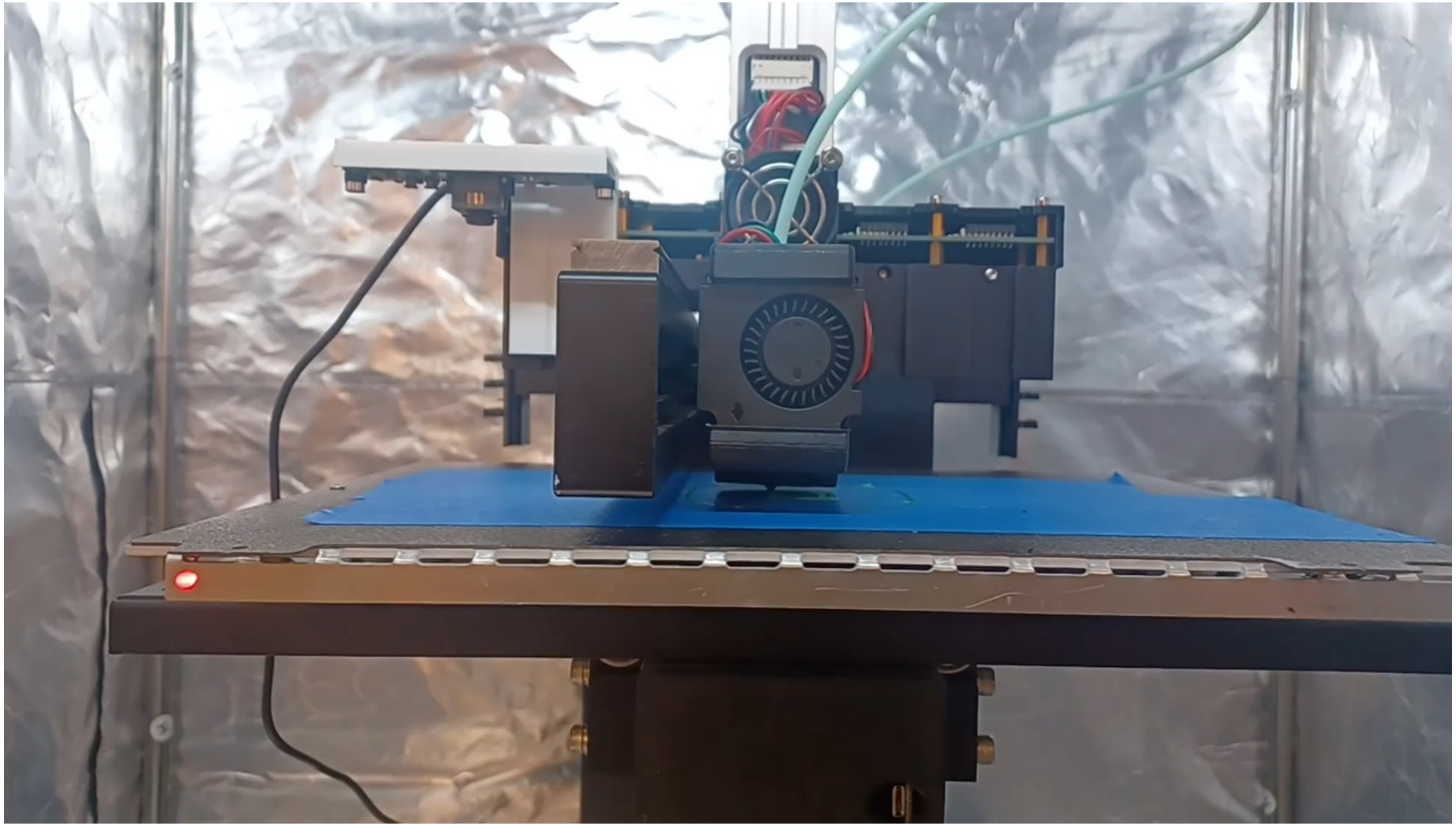


Camera



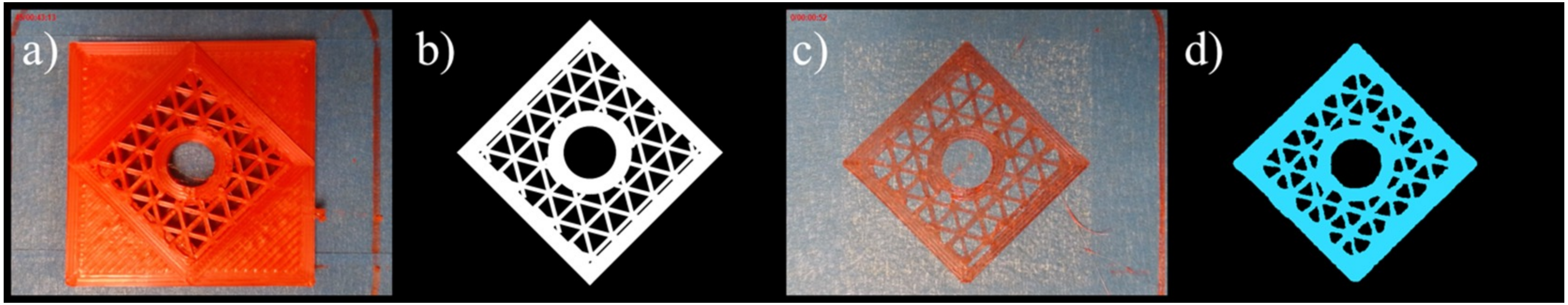
FH2-260 Extruder



Casey Wong Tran et al. "G-code gated U-Net (GG-Net) for real-time layer-wise in-situ quality control in additive manufacturing processes. (in prep)

Labeling Training Data

- Once raw images were gathered, training masks were developed through human labeling on custom software
  - capture images pertaining to the isolated layer's extrusion at the same camera offset and conditions as its training counterpart
  - segment the captured images of individual layers into generated mask labels
  - match the mask labels to the training dataset.



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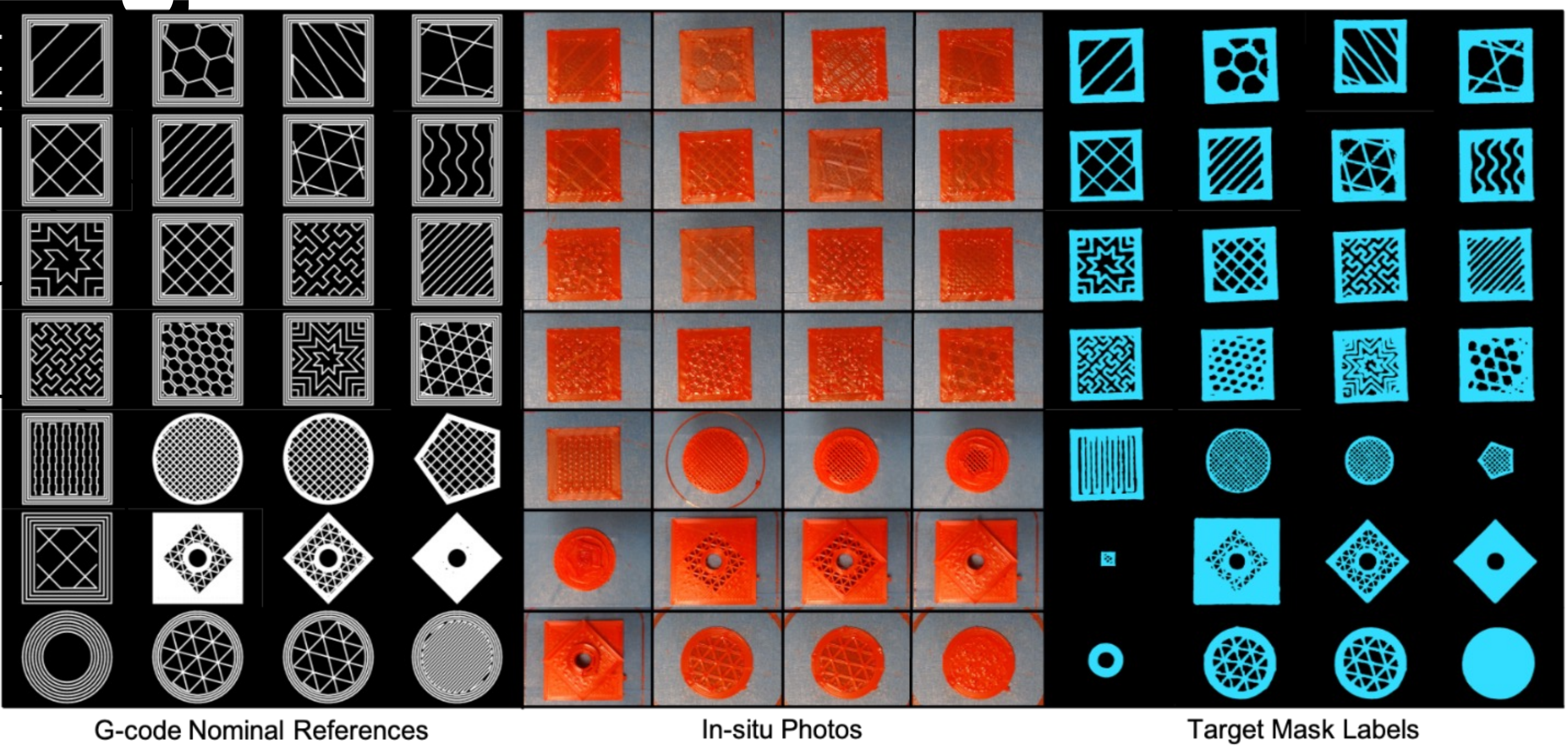
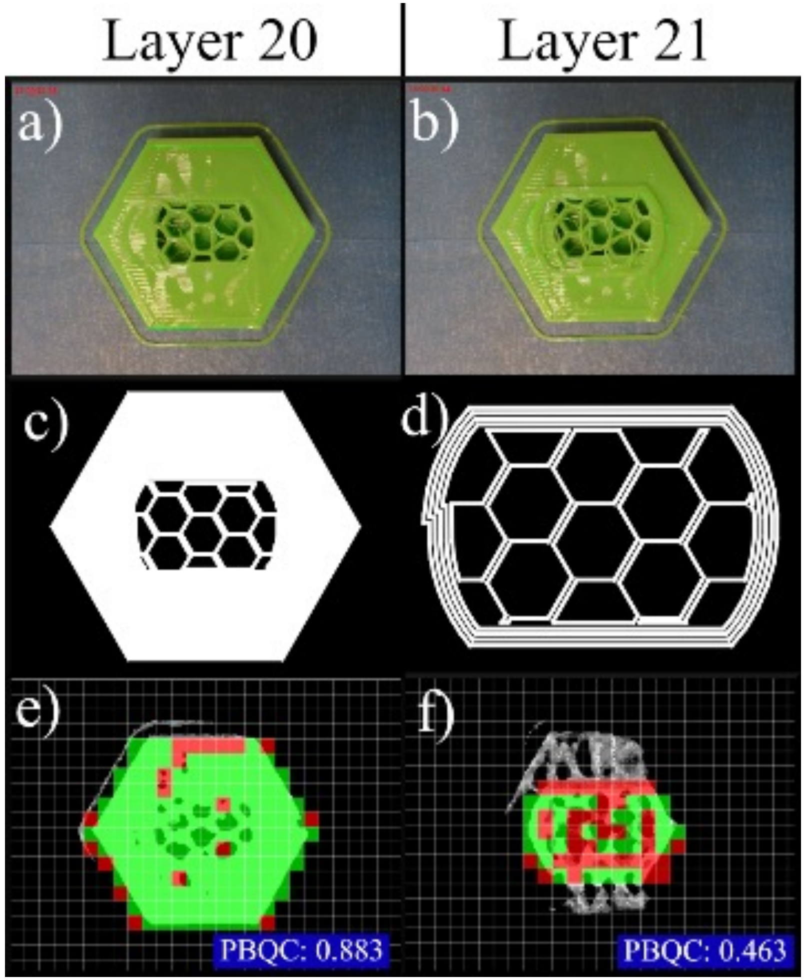


Casey Wong Tran et al. “G-code gated U-Net (GG-Net) for real-time layer-wise in-situ quality control in additive manufacturing processes. (in prep)

Patch Based Quality Characteristic (PBQC)

- Patch Based Quality Characteristic (PBQC) is the measuring characteristic used to evaluate GG-Net
- PBQC breaks the aligned nominal image and binary segmentation of the TL into 24x24 patches, each evaluated independently
- The final score is a ratio of compliant to total evaluated patches



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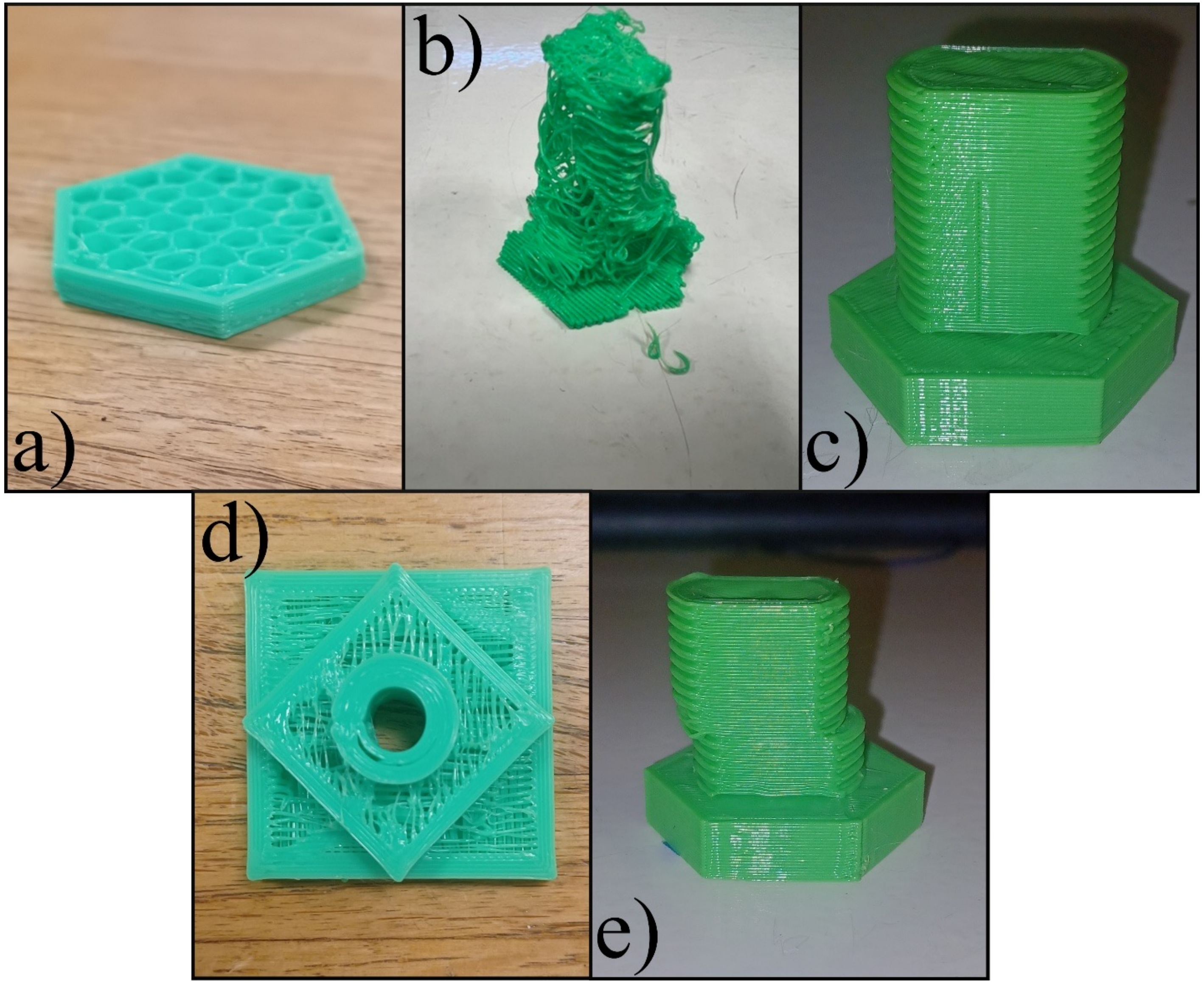
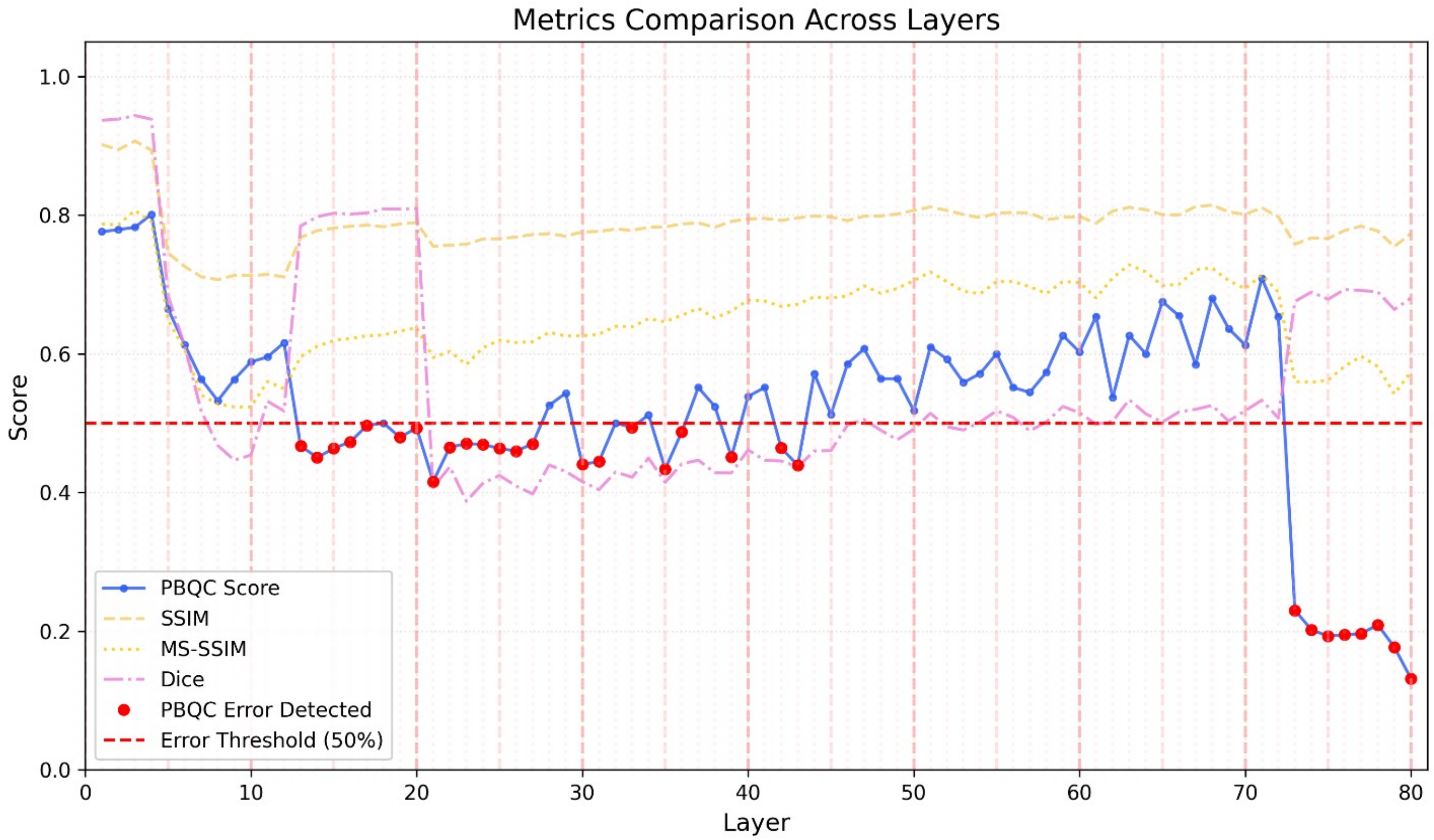
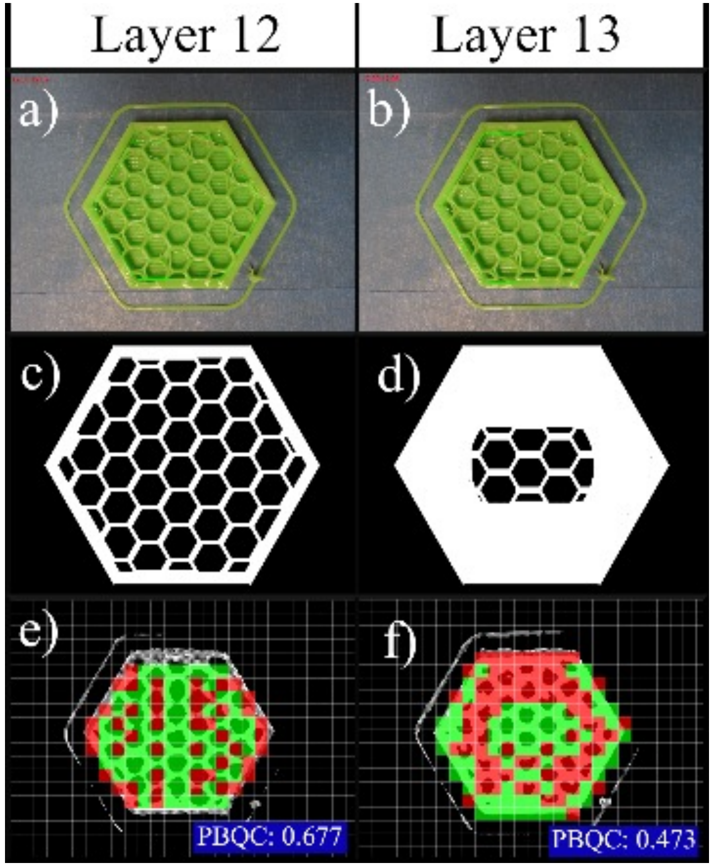


Casey Wong Tran et al. “G-code gated U-Net (GG-Net) for real-time layer-wise in-situ quality control in additive manufacturing processes. (in prep)

Evaluating GG-Net with Errors: Nozzle Clog

- Induced by continuously capturing images after the completion of the twelfth layer



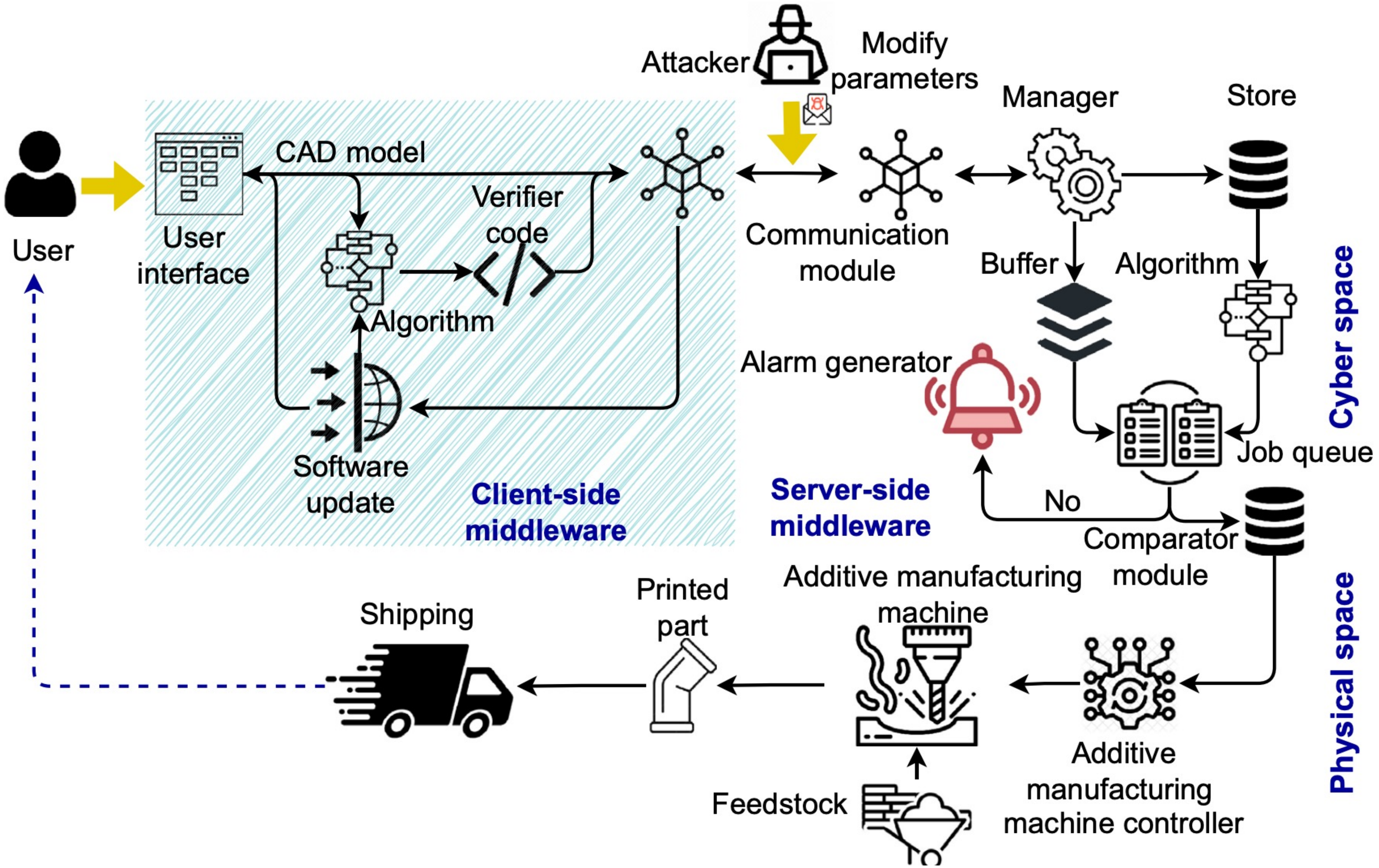


Casey Wong Tran et al. "G-code gated U-Net (GG-Net) for real-time layer-wise in-situ quality control in additive manufacturing processes. (in prep)

Current Status

- Expanding the training dataset to include more complex geometries and different printing parameters
- Evaluate zero-shot testing of our approach on complex geometries
- Describe current obstacles to networked/remote printing and quality assessment capabilities (with estimated timeline to solve each obstacle, if possible, to reference strategic plan)

AM Cyber and Physical Space

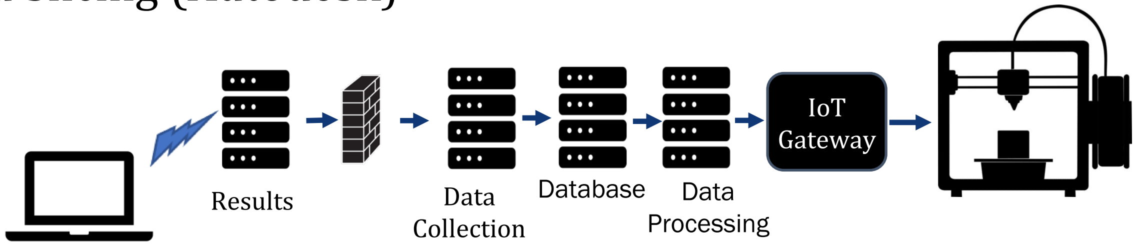


Mahmood, Muhammad Arif, Asad Waqar Malik, and Frank Liou. "A novel framework for identification of cyber-physical attacks in additive manufacturing." *Progress in Additive Manufacturing* 10.2 (2025): 1575-1586.

Network Architecture

Baseline

Printer ↔ OctoPrint/WebUI (WiFi/Eth) → Cloud Slicing (Autodesk)



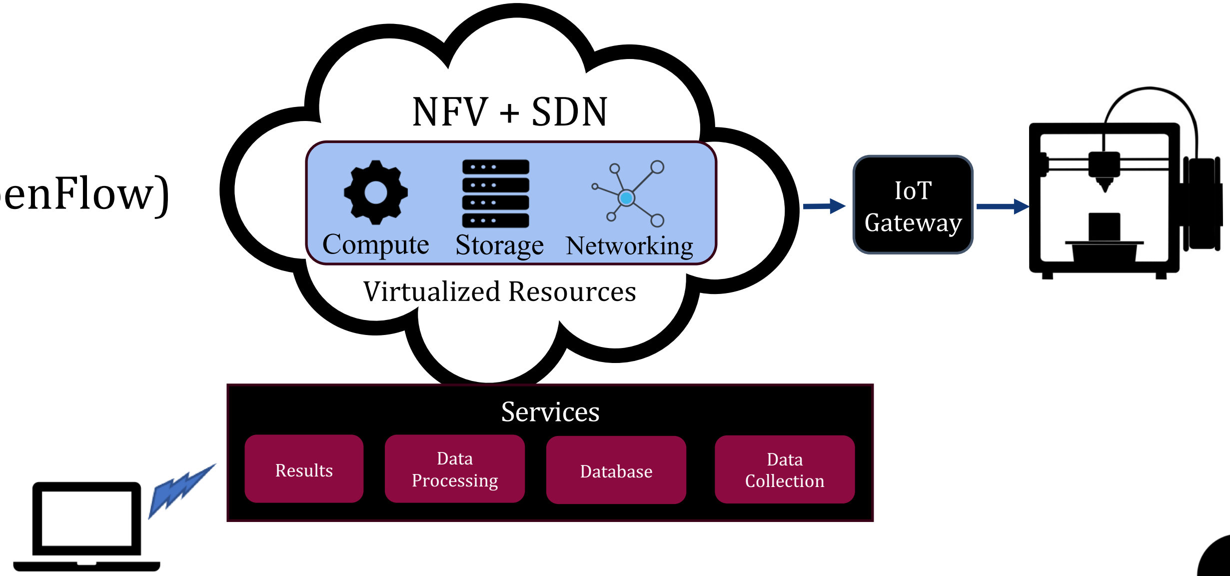
Advanced

SDN for IIoT orchestration

- Centralized control for printer fleets (OpenFlow)

NFV virtual slicers in Industry 4.0 CPS

- Cloud-orchestrated slicing



Slicer & Print-Server Ecosystem

Printer	Default Slicer	Print Server / Control Interface	Cloud Integration	Notes
Creality K1 Max	Creality Print (uses Cura engine)	Fluidd / Mainsail / Creality OS UI via Moonraker	Optional Creality Cloud	Rooted unit can use Klipper APIs & custom scripts
Creality Ender 3	Ultimaker Cura / Prusa Slicer / Orca Slicer	OctoPrint / Mainsail / Fluidd (when Klipper installed)	None by default	Highly modular and open-source
Prusa MK4s	Prusa Slicer	Prusa Connect / OctoPrint(Via Raspberry Pi)	Prusa Cloud (optional)	Native integration with Prusa ecosystem
Bambu X1 Carbon	Bambu Studio (closed)	Bambu Handy App / Bambu Cloud	Mandatory Cloud for updates & monitoring	Encrypted .3mf container with G-code and metadata

Networking and AM Data Flow

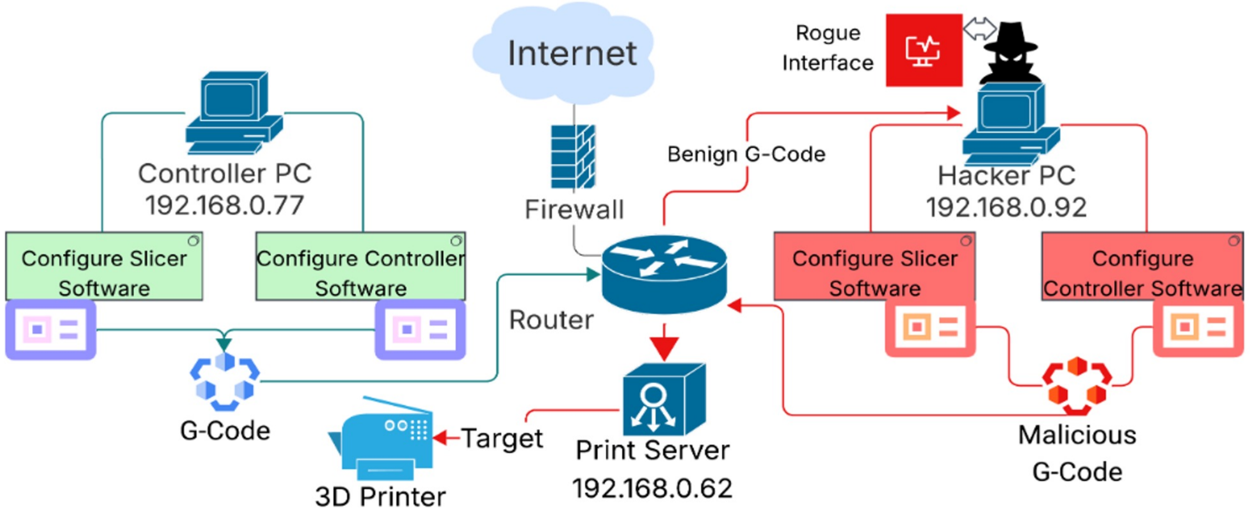
1	2	3	4	5	6	7
Parameters Materials Tolerances	Rich Package (Mesh + Metadata)	Toolpaths/ Temps / Speed Profile	Motion & Temp Commands	Controller/ Firmware	RGB/ IR/ AE/ Power/ Encoders	Telemetry Hashes/ Signatures
Validate Schematic	Sign Package	Pin Slice Version	Hash Output	Attest Firmware	Sync Sensors	Store Provenance
CAD/Design →	AMF/3MF →	Slicer →	G-code →	Printer →	Monitoring →	Logs & Provenance

Physical/Operational Vulnerabilities

1. **Unsigned/ Unverified** — Firmware
2. **USB/ CD** — G-Code Media
3. **Cameras/ APIs** — Sensors/ Add-ons
4. **Environment** — Materials
5. **QA Routines** — Calibration

- Unverified Firmware: debug ports (UART/JTAG), OTA downgrades
- USB/SD Removable Media (malicious G-code, autorun macros)
- Material/Environment: filament swaps, powder contamination, humidity/temp drift
- Sensor Tampering: camera occlusion, IR/light injection, AE masking
- Side-channels: optical/acoustic/power leakage of IP/toolpaths
- Power/EMI events; physical access to controllers and storage

Network Vulnerabilities



- Rogue AP / Wi-Fi spoof → MitM (API keys, tokens, job tamper)
- Weak TLS (no pinning), cookie/session hijack, CSRF on controllers
- Insecure protocols & config: HTTP/MQTT, OPC UA with anonymous creds
- LAN/VLAN gaps: client-to-client access, missing egress control
- TSN/PTP timing abuse → micro-jitter impacts process quality
- Remote access/VPN misuse; exposed admin interfaces

Literature Demonstrated Attacks

Attacker Model	Access	Example Attack	Success Rate (8 Printers)
AC1	Pre-exec inject	M928 IP theft	100%
AC2	Slicer config	Over-extrude (M200)	87.5%
AC3	On-fly inject	Voids (M28)	75%

Attack vectors causing physical damage

- **G1 Z-1:** Nozzle crash into bed
- **M907:** Motor current overload — leads to burnout.
- **dr0wned (WOOT 2017)**: Cyber-induced **internal voids** cause **fatigue failure** under load

1. Rossel, Jost, Vladislav Mladenov, Nico Wördenweber, and Juraj Somorovsky. "Security Implications of Malicious {G-Codes} in 3D Printing." In 34th USENIX Security Symposium (USENIX Security 25), pp. 1867-1885. 2025.
2. Belikovetsky, Sofia, Mark Yampolskiy, Jinghui Toh, Jacob Gatlin, and Yuval Elovici. "dr0wned–{Cyber-Physical} attack with additive manufacturing." In 11th USENIX workshop on offensive technologies (WOOT 17). 2017.

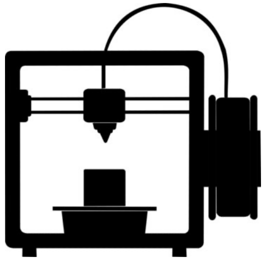
Anomaly Detection Baselines

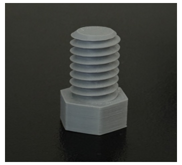
Attack Landscape

- **STL file or Toolpath attack**
  Wireshark, etc.
- **Firmware attack**
  Remove Firmware Update, etc.
- **Network attack**
  Rogue AP / Wi-Fi spoof, etc.

...

Design File





Printed Product

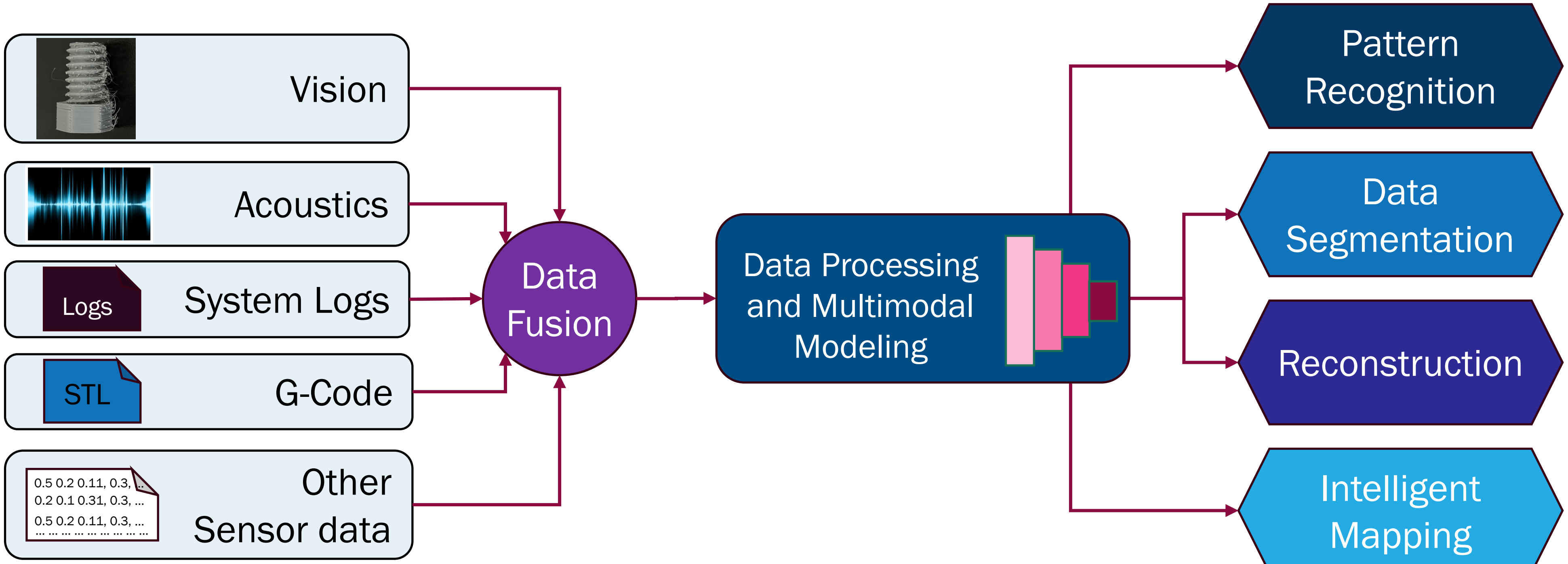
Detection Landscape

- **Pre-process validation**
  Signature-based detection, anomaly-based detection, etc.
- **In-process inspection**
  Vision, acoustic, etc.
- **Post-process inspection**
  Vision, laser, ultrasonics, weighting, etc.

...

Multimodal Data Modeling

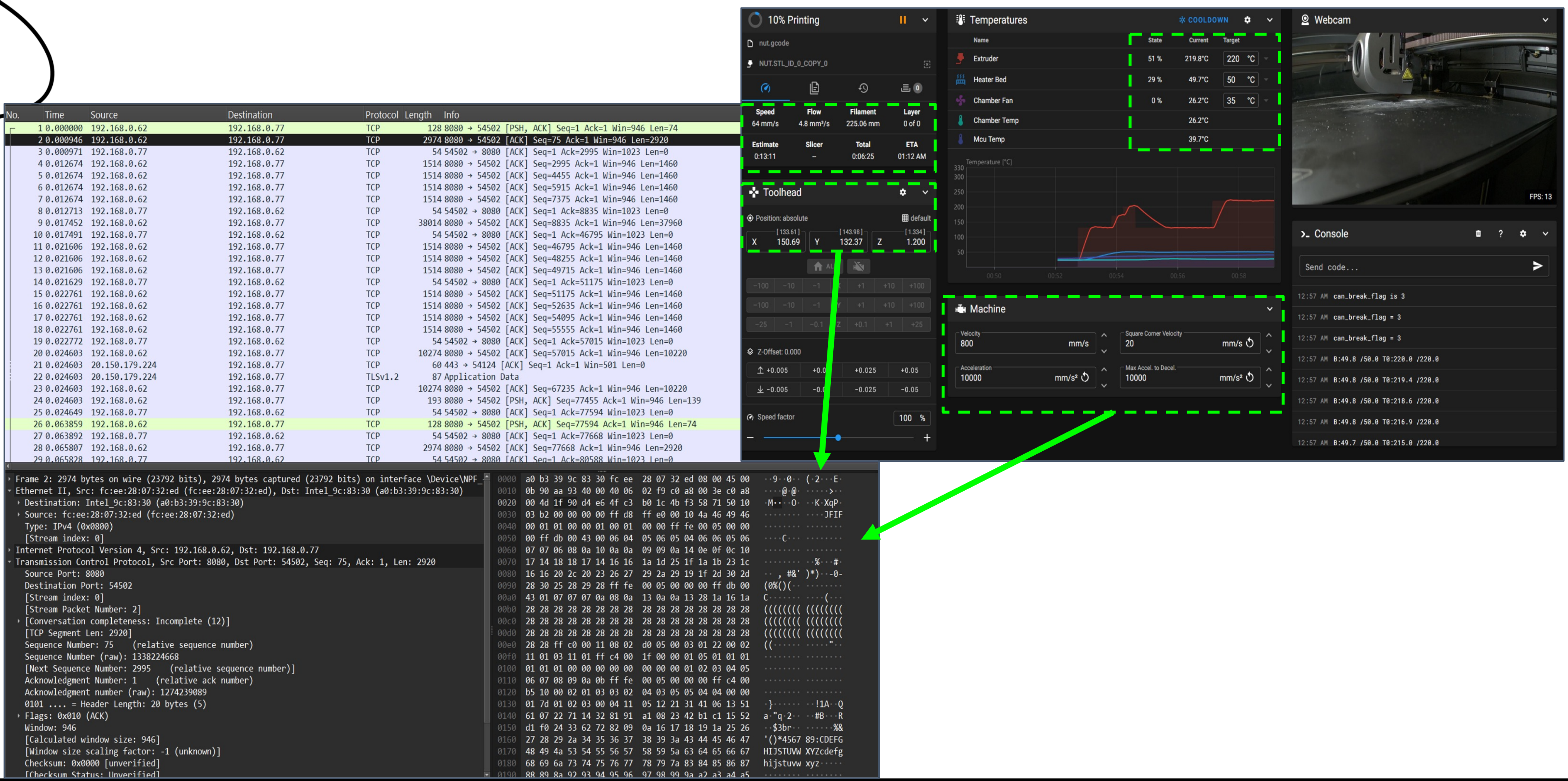
- Network and host logs and data provenance
- Print Progression Videos
- Acoustic or vibration signatures
- G-code etc.



Anomaly Detection Baselines

1. RGB/ IR/ AE/ Power/ Logs — Sensors
2. Optical/ Thermal and Spatial Temporal Features — Feature Extractors
3. Synchronization/ Sampling/ fusion/ Graph — Sync & Fusion
4. Reconstruction/ Diffusion/ Flow — Data Modeling
5. Thresholds, Alarms, Human-in-the-Loop — Decision

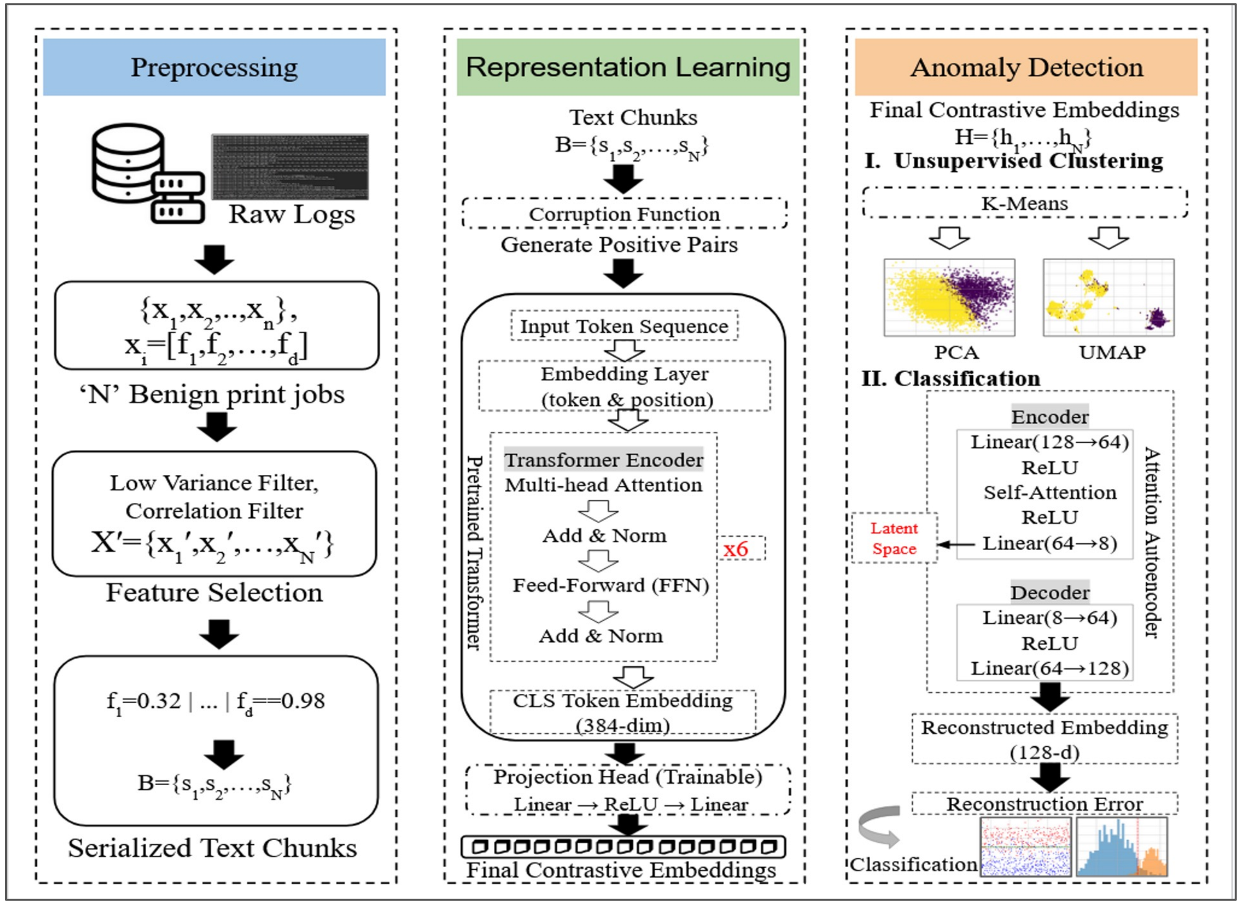
Anomaly Detection from System Logs



Anomaly Detection from System Logs

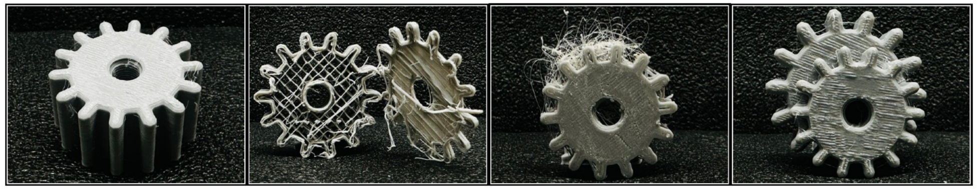
- Under-extrusion / Over-extrusion (extrusion multiplier changes)
- Noisy G-code injection (random hops / travel inserts)
- Dimensionality change (scale / offset edits)
- Internal cavity insertion (insert internal void prints)

Class Type	Attack Category	Samples
Benign	-	98,720
Attack	Under-extrusion	10120
	Over-extrusion	9950
	Noise Injection	15456
	Dimensional Change	9324
	Cavity Insertion	10521

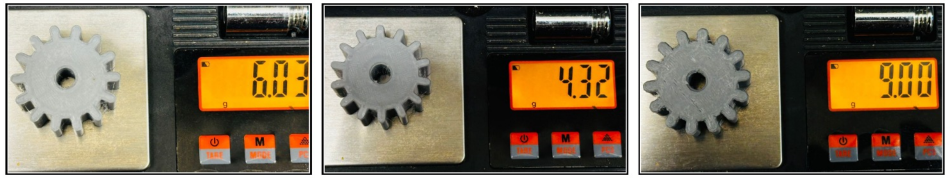


Anomaly Detection Performance

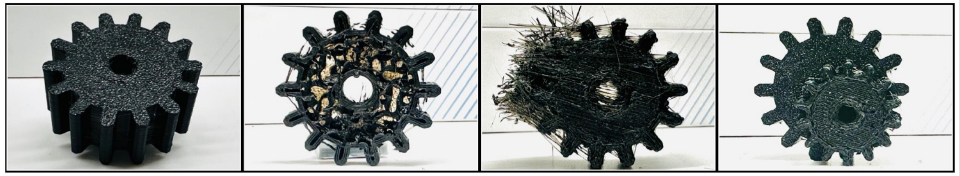
Metric	Benign		Attack	
	Value	(%)	Value	(%)
Precision	0.9801	98.01%	0.9055	90.55%
Recall	0.9499	94.99%	0.9614	96.14%
F1-score	0.9648	96.48%	0.9326	93.26%
Overall Accuracy	0.9537 (95.37%)			
Macro Avg F1-score	0.9487 (94.87%)			
Weighted Avg F1-score	0.9541 (95.41%)			
AUROC (AUC)	0.9870 (98.70%)			
Threshold (MSE)	0.0019			



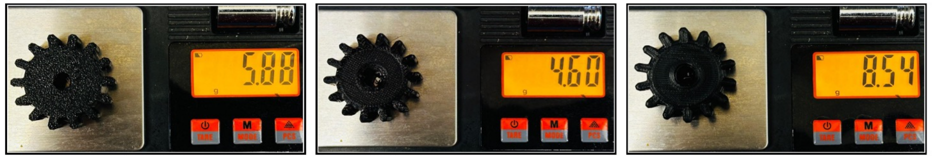
(a) Benign. (b) Cavity Ins. (c) Noise Inj. (d) Dimension Inj.



(e) Benign Extrusion (f) Under-Extrusion (g) Over-Extrusion



(a) Benign. (b) Cavity Ins. (c) Noise Inj. (d) Dimension Inj.



(e) Benign Extrusion (f) Under-Extrusion (g) Over-Extrusion

CONCLUSION

- Quality of AM parts → RG4
- Anomaly identification → RG2
- Data safety → RG2 and RG3
- Teaching and workforce → EWD1 and EWD2