

Introduction

- WAAM challenges:** Wire Arc Additive Manufacturing (WAAM) offers high material deposition rate but suffers from significant process uncertainty, leading to defects such as porosity (gas entrapment) and humping (surface irregularities).



Porosity Defect

Hump Defect

- Limitations of existing monitoring systems:** Most monitoring solutions rely on centralized computer servers, introducing latency, and cybersecurity risks.
- Lack of human interaction:** Current systems does not allow for human-in-loop decision-making.
- Need for local, distributed intelligence:** There is a clear need for on-device, distributed intelligence that leverages local knowledge, enabling secure, low-latency, real-time defect detection and human-interactive mitigation in WAAM processes.

Research Objective

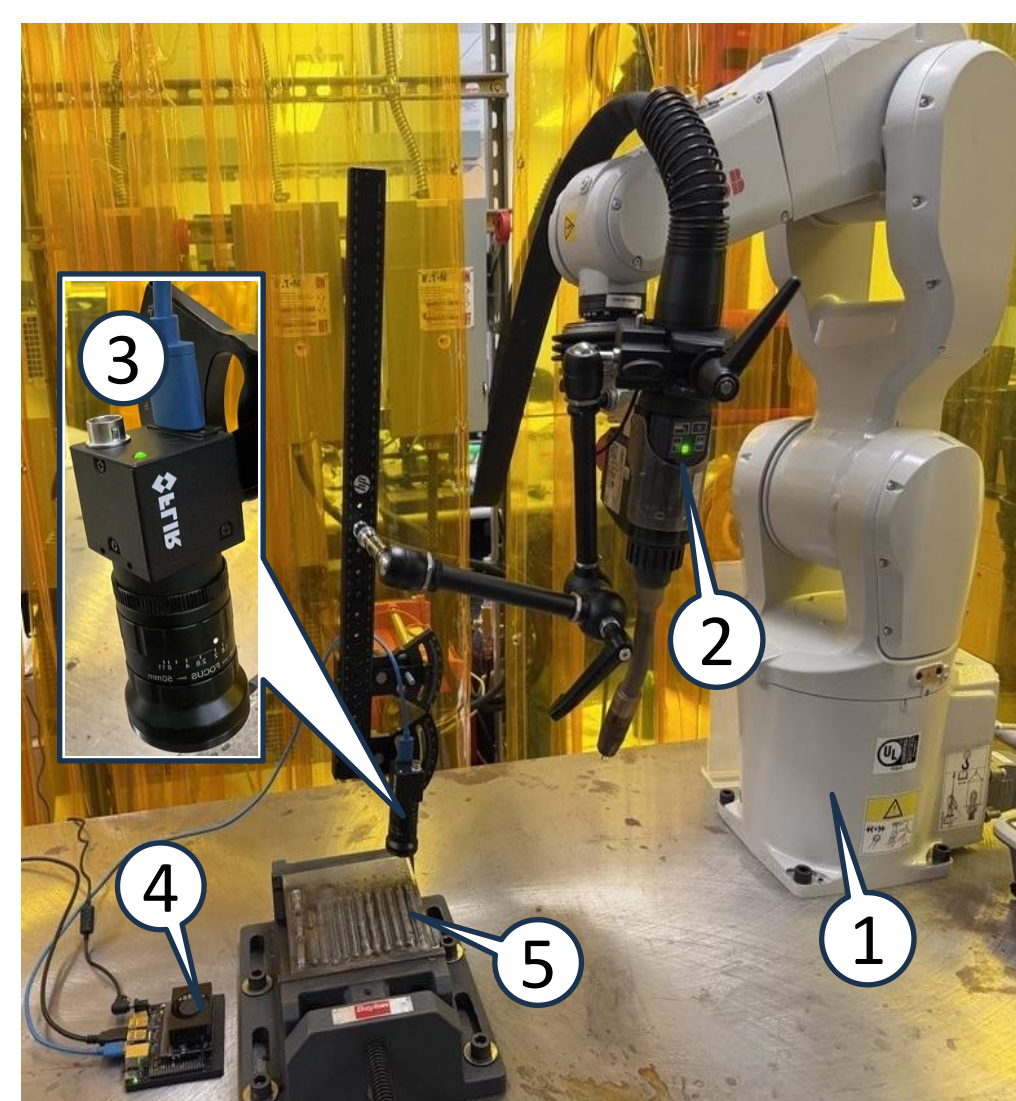
This project aims to develop a framework comprising -

- Edge AI for real-time defect detection:** We customized YOLOv8s on a Jetson Orin Nano which enables low-latency for immediate WAAM defect detection.
- Local LLM-enabled human-interactive intelligence:** We devised a locally grounded RAG-based LLM that converts sensor data into research article-backed, optimized parameters, supporting human-in-the-loop decisions while ensuring on-device data security.

WAAM System Setup

The WAAM system comprises a Fronius CMT welding machine, an ABB robotic arm, a machine camera, and an edge computer.

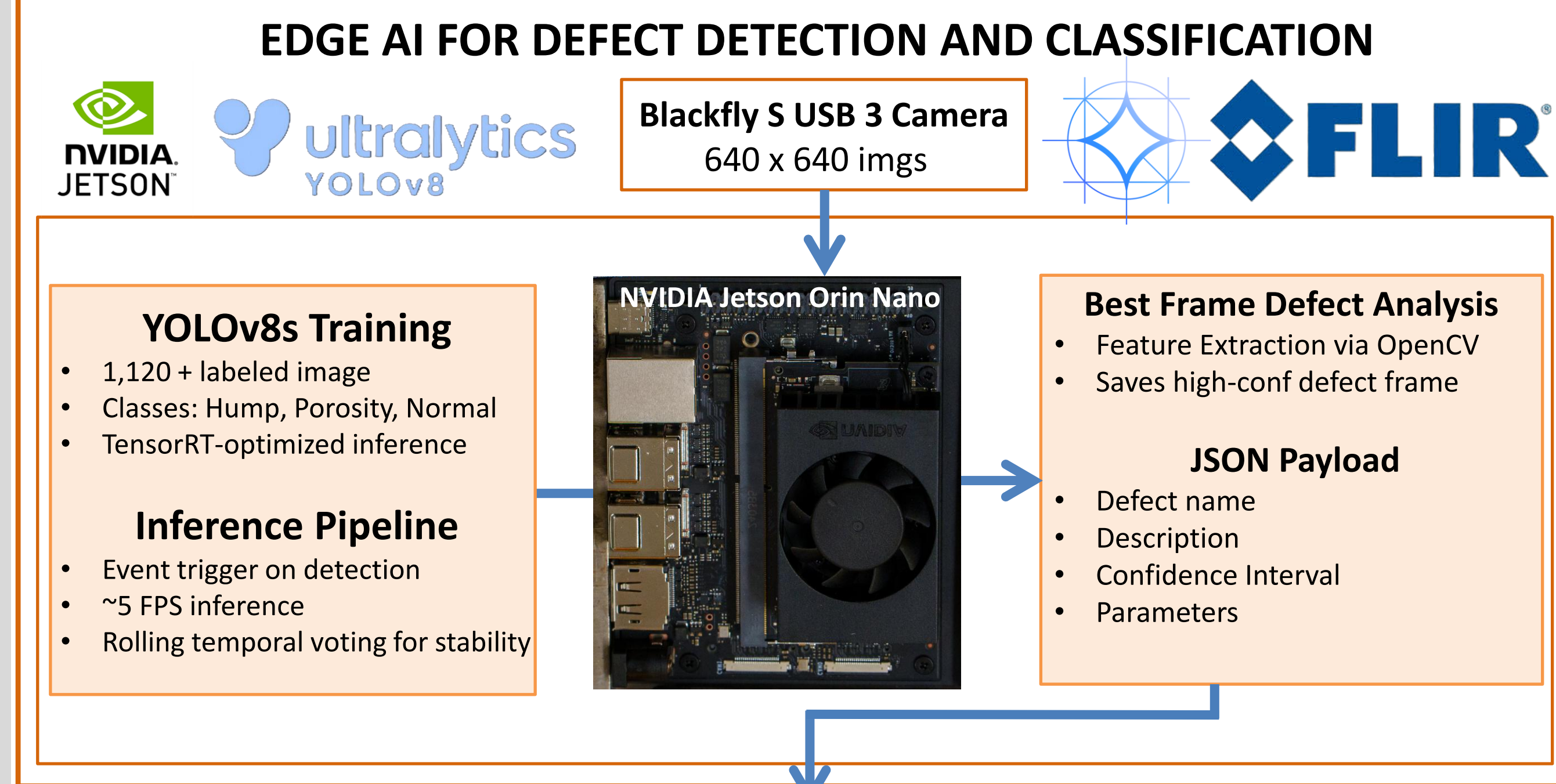
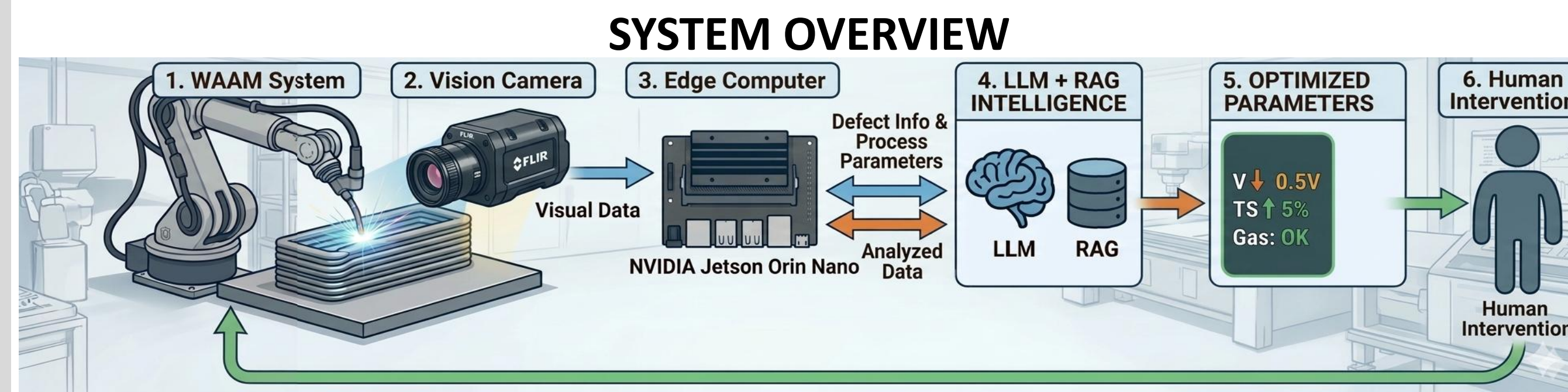
- ABB IRB 1200 robot arm
- CMT Welder Drive Unit
- FLIR Blackfly S USB 3, 1.6MP, 226 FPS
- Jetson Orin Nano
- WAAM Substrate



WAAM System Setup

Sensing: After each bead deposition, images are captured and sent to the edge computer.

METHODOLOGY



DEFECT INTERPRETATION USING A LARGE LANGUAGE MODEL (LLM)

LLM (Gemma3 – 27B Params)

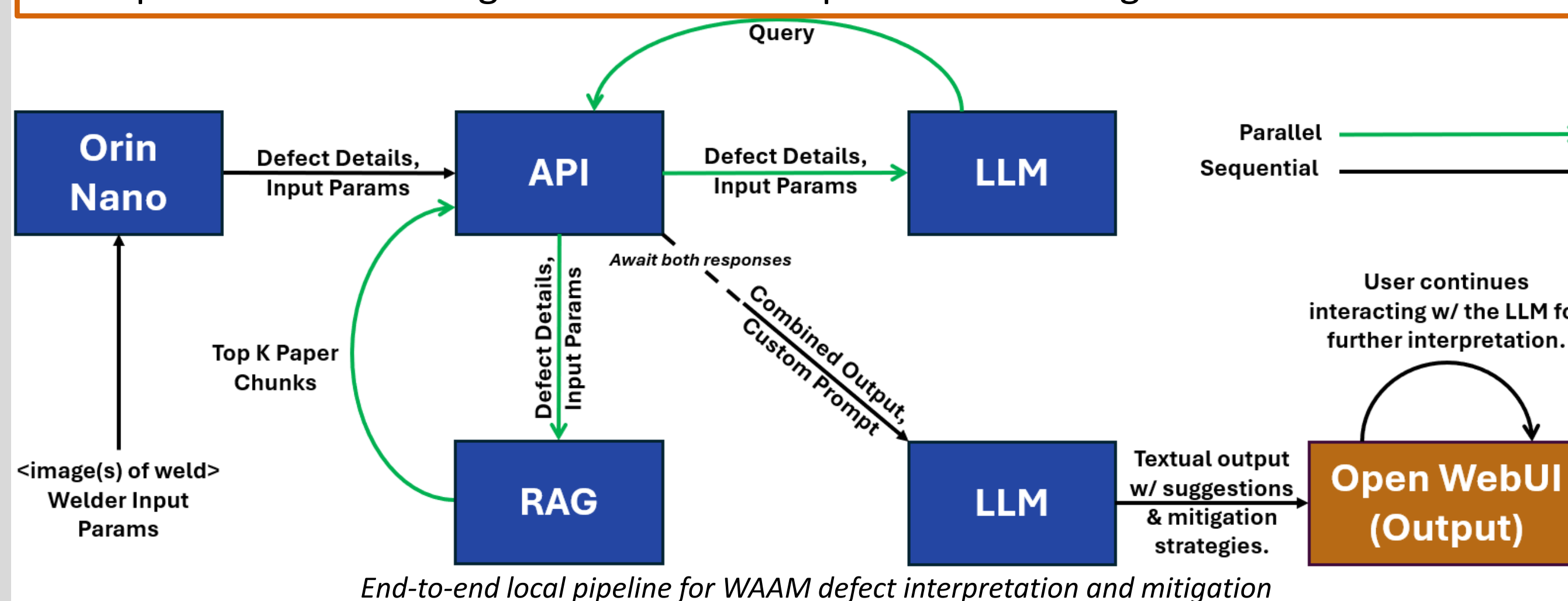
Generates a query using the received defect description, and process parameters.

```
{
  "status": "completed",
  "defect_name": "hump defects and porosity",
  "query_summary": "Defect query for porosity augmented with process parameters.",
  "evidence_count": 5,
  "extracted_evidence_count": 5,
  "forwarded_to_open_webui": true,
  "final_question": "Given the observed hump defects and porosity (91.0% confidence) in a Carbon Steel WAAM process using cold metal transfer with current at 95.0, voltage at 20.0, travel speed at 5.0, and shielding gas flow rate at 18.0, what specific adjustments to these process parameters are recommended to mitigate this defect, with a clear explanation - supported by citations from the provided literature - of how each adjustment is expected to reduce both the humping and porosity in this scenario?"
}
```

Retrieval-Augmented Generation (RAG)

- Converts defect inputs into queries.
 - Retrieves candidate WAAM literature chunks using hybrid dense & BM25 search from the knowledge base.
 - These rankings are combined with Reciprocal Rank Fusion, reranked using defect relevance & evidence directness
- The top-k chunks are then assembled into a context-pack for the LLM.

- Finally, the LLM is invoked with a custom prompt using outputs from prior layers.
- It analyzes the aggregated defect context, process parameters, and retrieved literature to generate evidence-based mitigation recommendations.
- The system also supports interactive follow-up analysis, allowing users to clarify responses and enabling human-in-the-loop decision making.



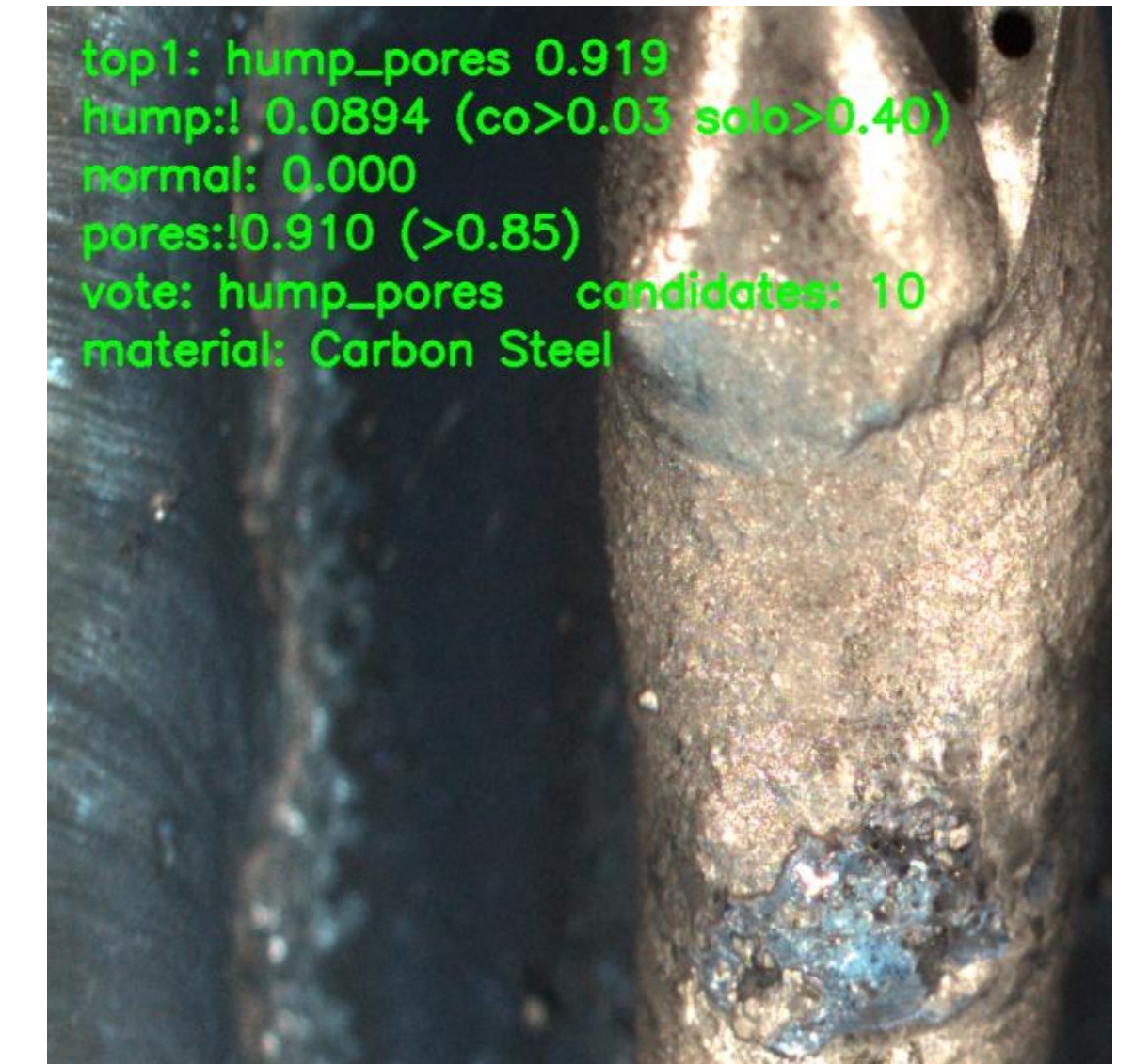
Results

Model Performance -

Model was able to demonstrate reliable real-time defect classification:

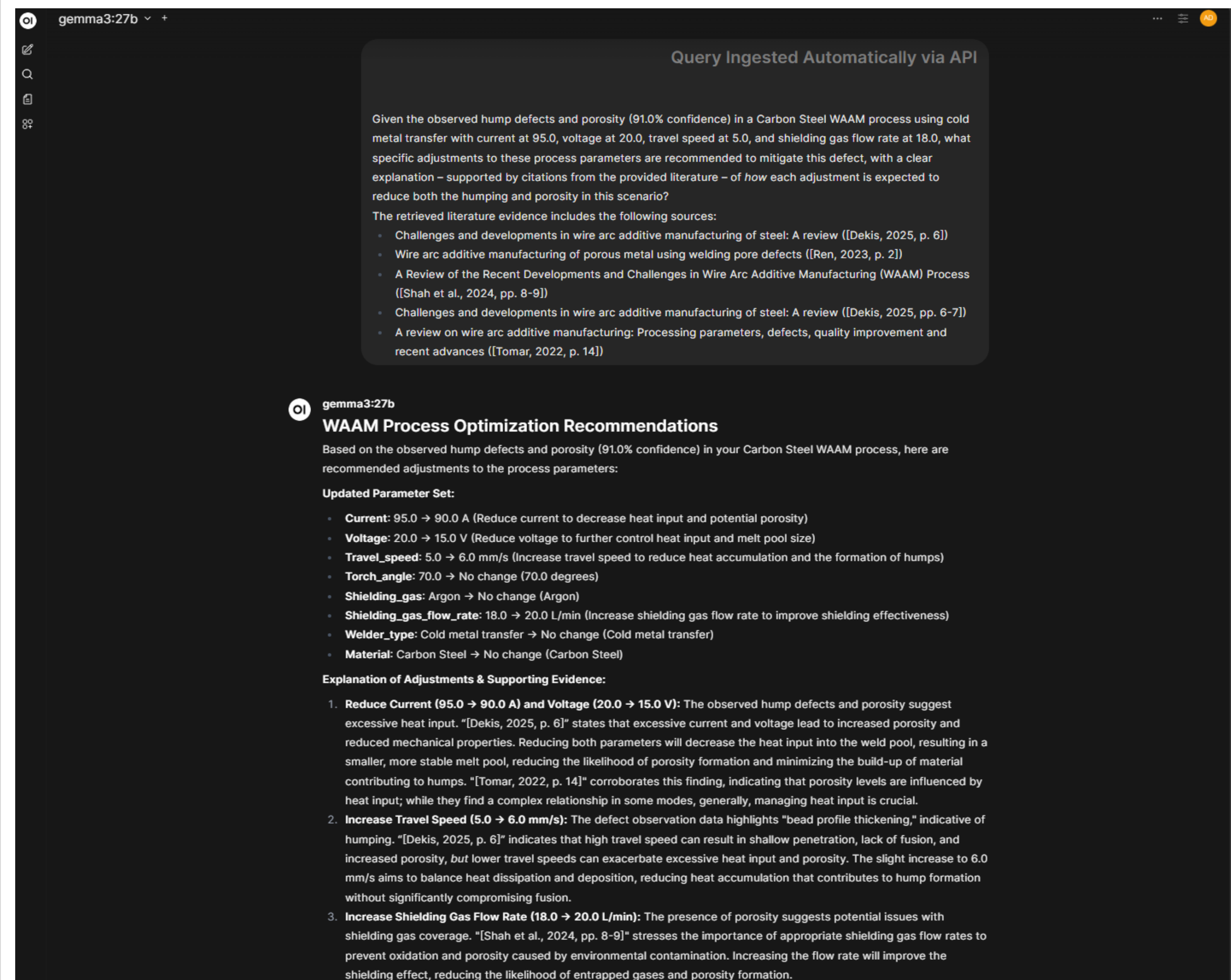
- Final Classification Accuracy:** 93.4 %
- Top-1 Accuracy:** ~94 %
- Best Performance :** Normal and Pores
- Main Confusion:** Hump vs Pores
- Edge AI example output:**

“Combined hump and porosity defects are visible, with cavity-like porosity and bead profile thickening.”



Example Model Prediction (Hump and Porosity)

LLM Output for Human Operators -



Conclusions and Discussions

- We successfully deployed Edge-AI for defect detection and classification.
- The RAG successfully retrieved relevant research papers based on the identified defect(s) and the LLM was able to cite them as evidence to provide justified mitigation strategies.
- The LLM facilitated interactive interpretation and enabled users to perform follow-up analysis through the Open WebUI interface.

References

- X. Liu et al., "Efficient defect detection method for wire and arc additive manufacturing based on modified YOLOv8 model," *Journal of Manufacturing Processes*, 2024. [Online]. Available: ResearchGate.
- M. Dekis, M. Tawfik, M. Egiza, and M. Dewidar, "Challenges and developments in wire arc additive manufacturing of steel: A review," *Results in Engineering*, vol. 26, p. 104657, 2025, doi: 10.1016/j.rineng.2025.104657.
- A. Thien, K. M. Kelly, C. E. Massey, and C. J. Saldana, "On process stability in WAAM-CMT of aluminum alloys," in *Proceedings of the 34th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference*, 2023, pp. 1528–1540.