

Closed-Loop Control for Dual-Colour Rotational FDM Printing

Problem Space

Dual-colour FDM through a rotational nozzle can produce continuous colour gradients from a single two-colour filament meaning no purging, no extra hardware. But the deposited colour is a direct function of the nozzle's rotational angle, so small orientation errors become visible, uncorrectable colour misregistration. Running open-loop, the printer has no way of knowing what colour it is actually laying down.

Objective

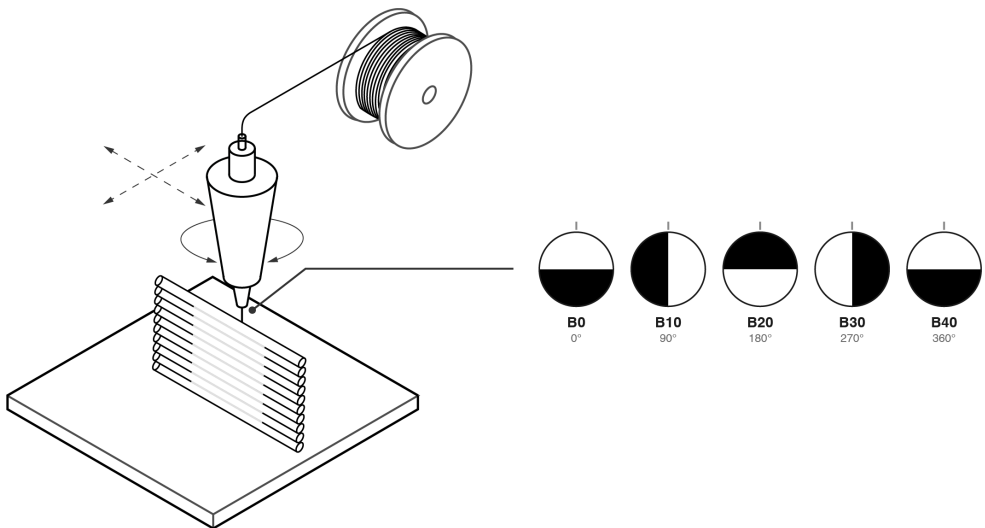
To what extent can computer vision and machine learning detect filament colour orientation in real time and use it to drive closed-loop correction of B-axis nozzle rotation? The work delivers three things: a working correction system, a CNN that estimates orientation from the nozzle's appearance, and validation across single-error, multi-error and full-range prints.

Methods

The dataset was collected by printing a 100-layer wall while sweeping all 41 B-axis orientations each layer, with orientation labels read deterministically from the G-code (no manual labelling). Frames were centre-cropped to 224×224 and augmented with colour jitter only. A ResNet-18 was then trained and validated through three progressive experiments: perception accuracy (reading orientation on seen and unseen prints), live monitoring (tracking orientation in real time during a print), and end-to-end closed-loop correction (injecting known errors mid-print to test detection and recovery).

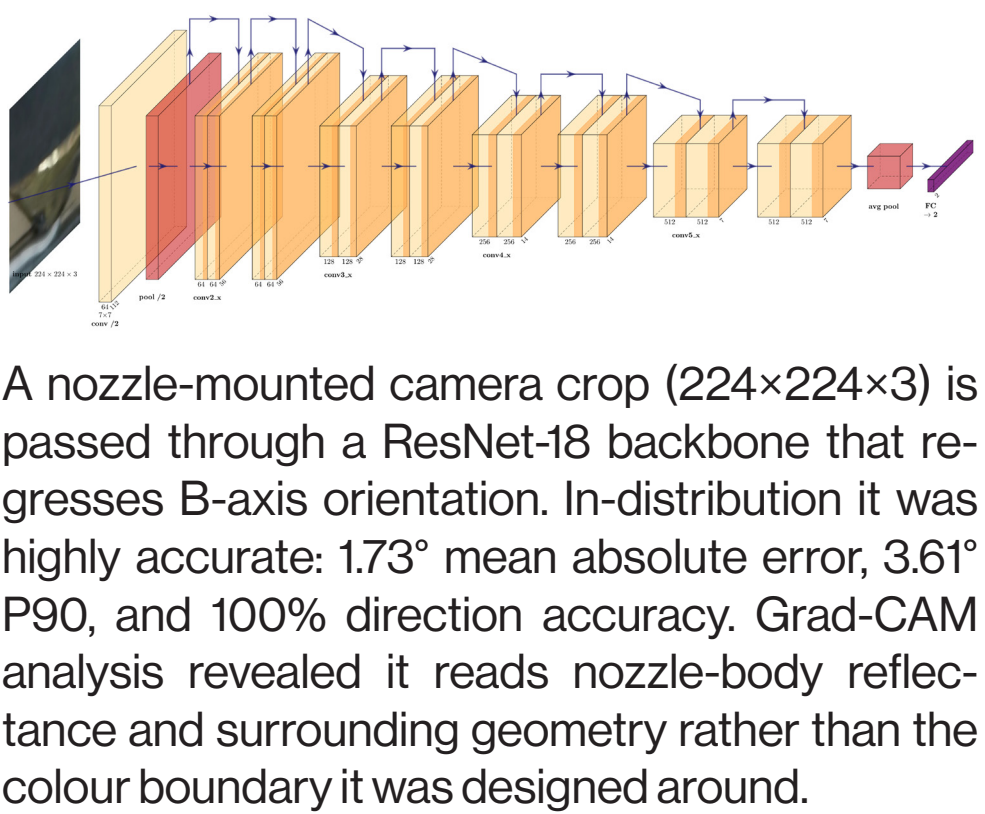
System

Rotational Nozzle



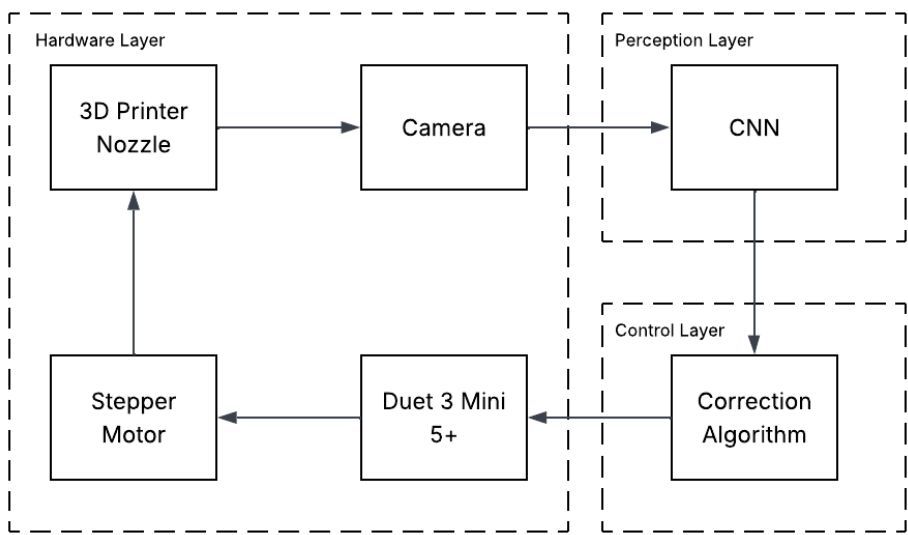
A single filament strand carrying two colours is fed through a nozzle that rotates about its vertical B-axis, sweeping the full 360° from B0 to B40 in 9° steps. As the cross-sections show (B0–B40), rotation continuously changes which colour faces the deposition path, turning orientation into a functional print parameter.

ML Model



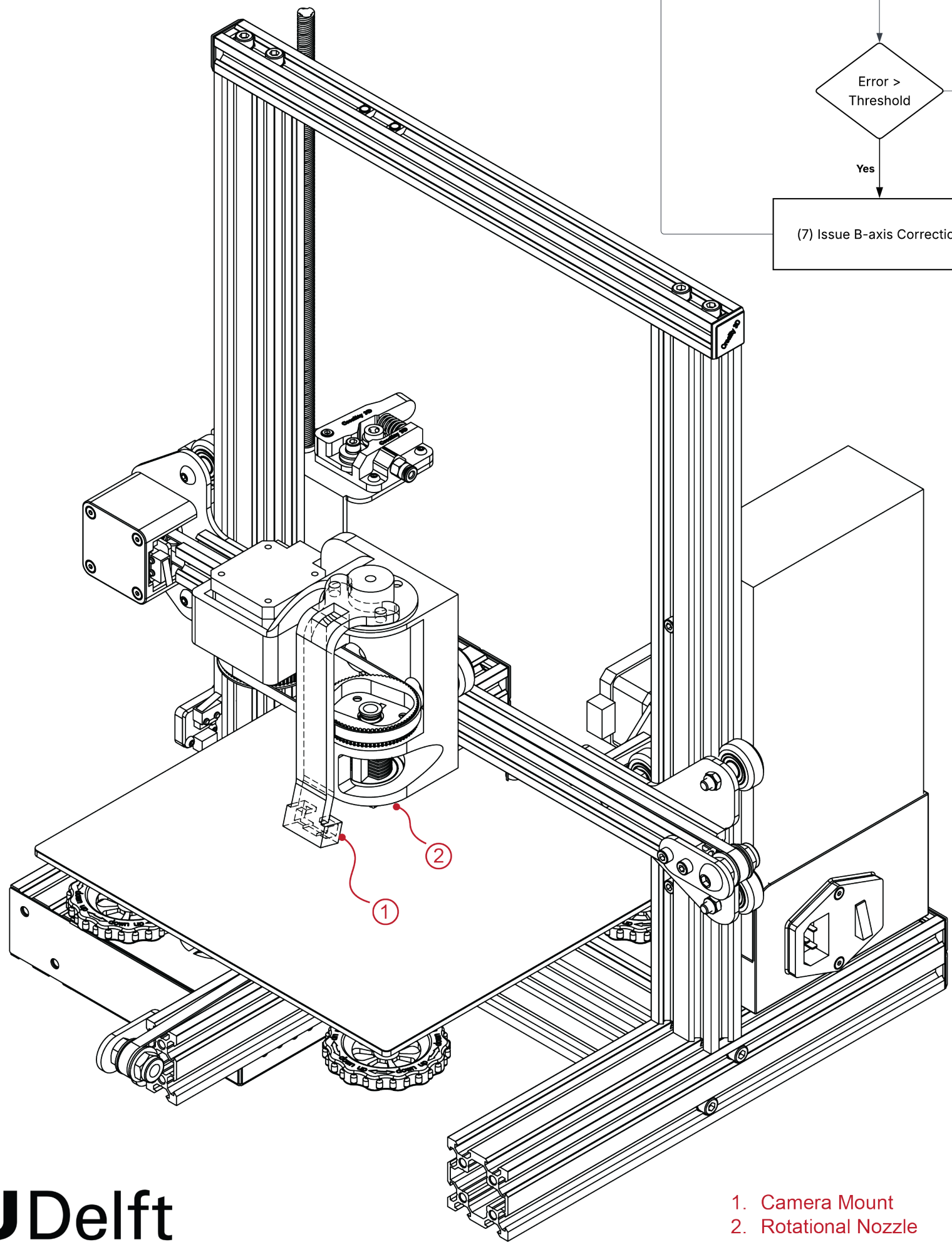
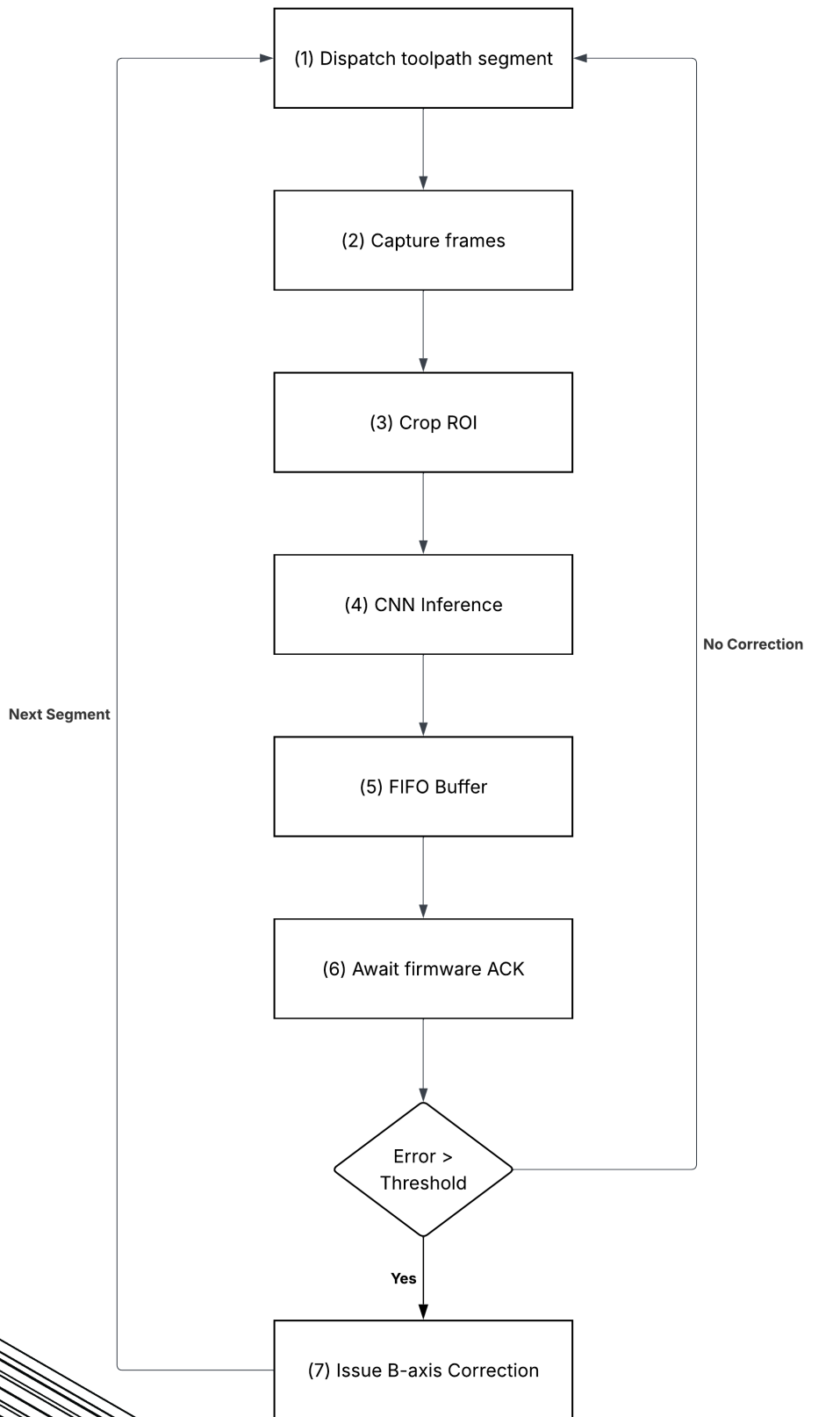
A nozzle-mounted camera crop (224×224×3) is passed through a ResNet-18 backbone that regresses B-axis orientation. In-distribution it was highly accurate: 1.73° mean absolute error, 3.61° P90, and 100% direction accuracy. Grad-CAM analysis revealed it reads nozzle-body reflectance and surrounding geometry rather than the colour boundary it was designed around.

Architecture



The platform is a modified Creality Ender 3 with a rotational B-axis nozzle, a Duet 3 Mini 5+ board, and a carriage-mounted camera that keeps the nozzle tip in view. It runs as a closed loop across three layers: hardware (nozzle, camera, stepper), perception (the CNN), and control (the correction algorithm). Each cycle flows nozzle, camera, CNN, correction, Duet board, stepper, feeding the estimated orientation back to the nozzle in real time.

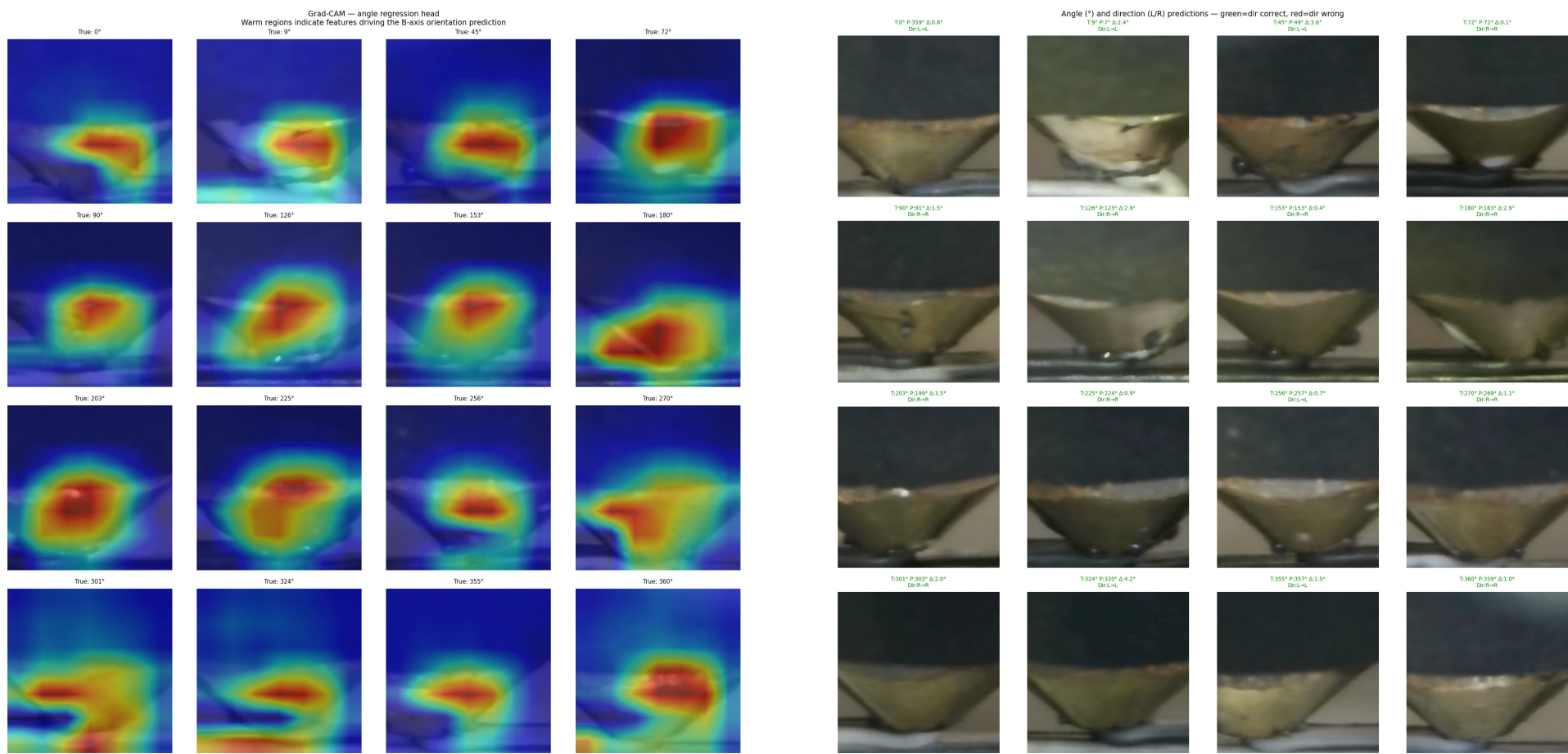
Control



1. Camera Mount
2. Rotational Nozzle

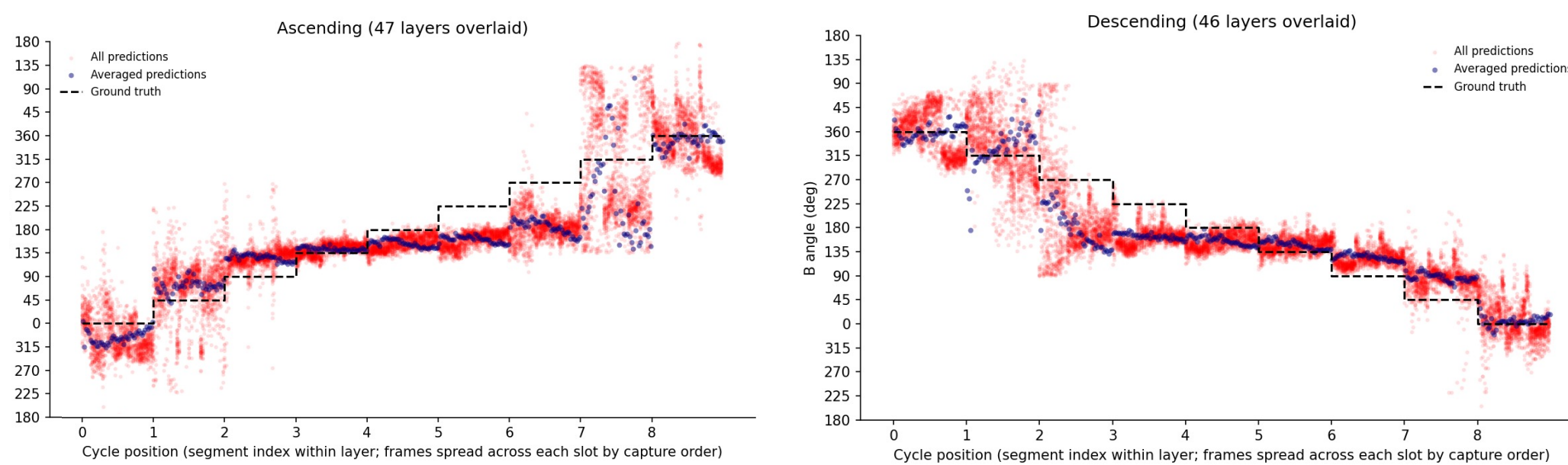
Results

Perception - Experiment1

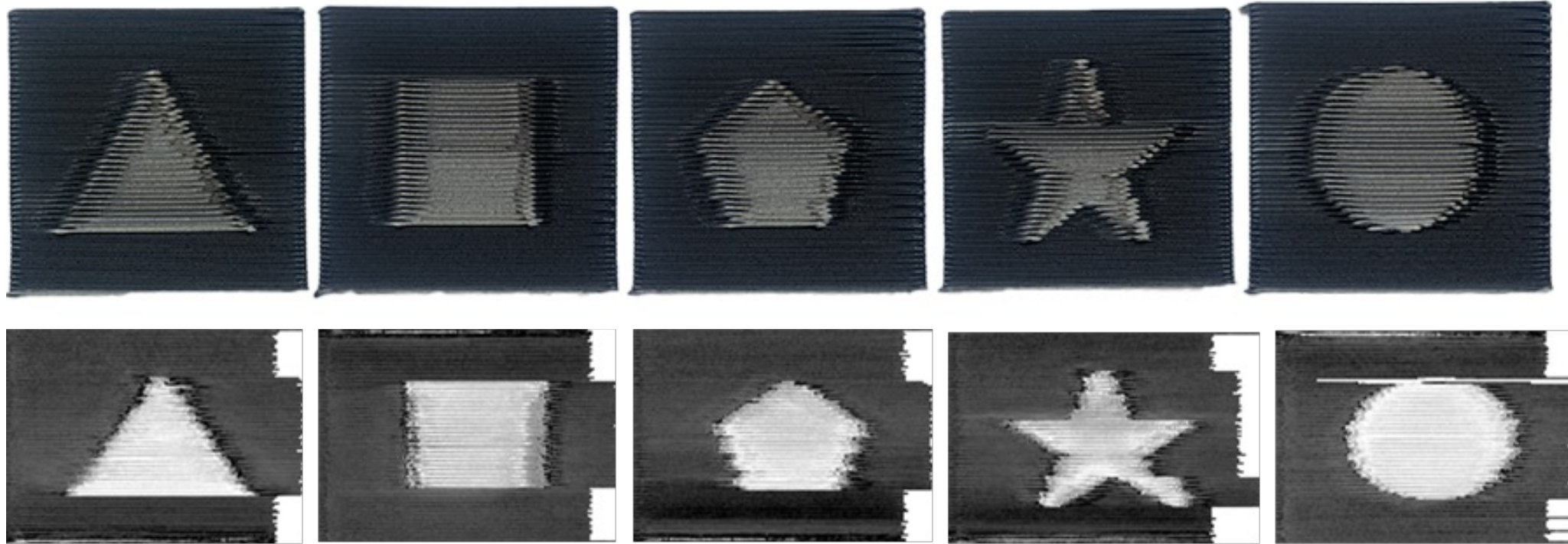


Right: the raw 224×224 camera crops the model actually sees, the nozzle tip at a range of B-axis orientations, the only input it gets. Left: the matching Grad-CAM saliency maps, where colour shows how much each region drives the prediction (red means the model relies on it heavily, blue means barely at all).

Live Monitoring - Experiment2

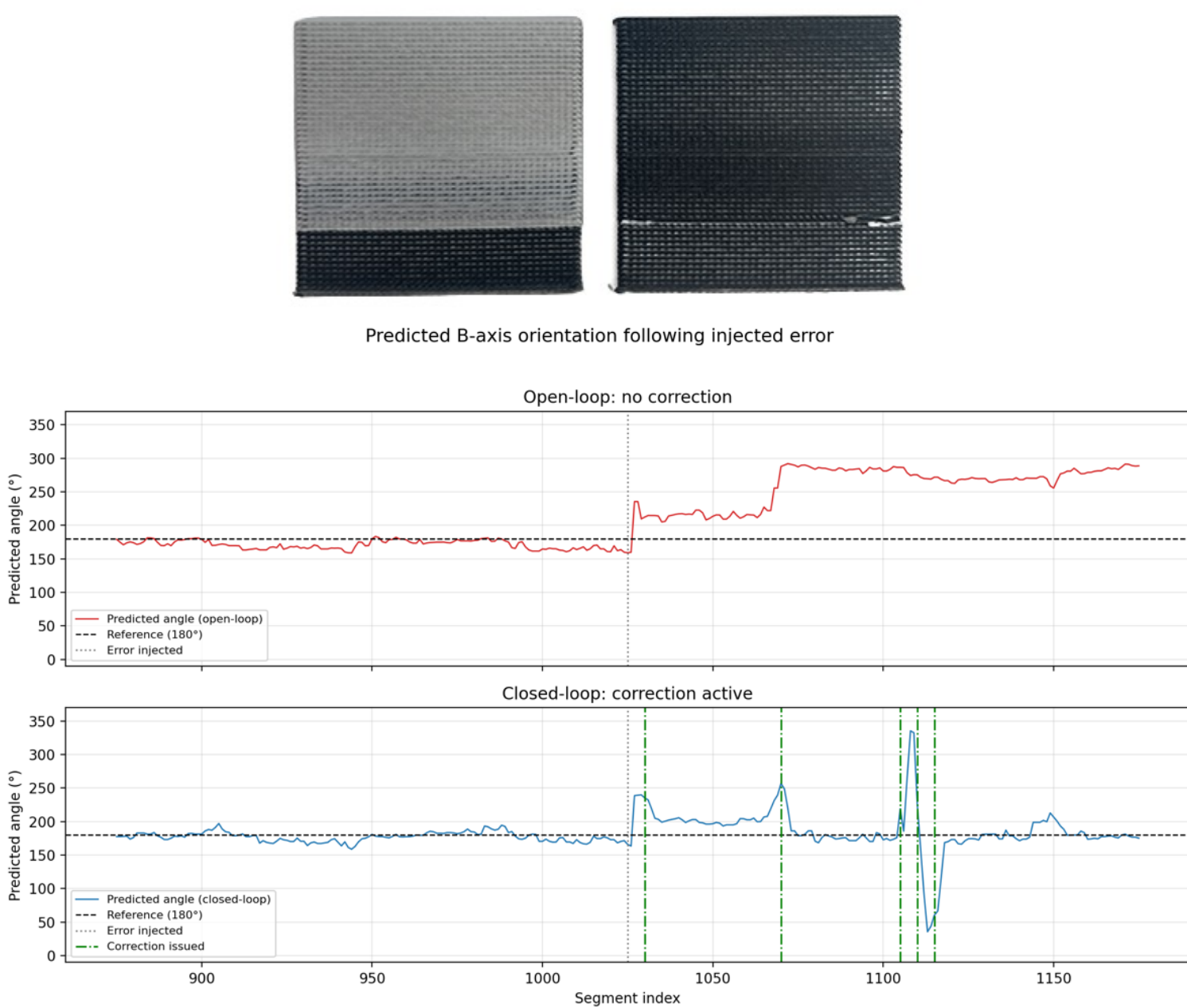


Tracking plots. Predicted B-axis angle across every layer (red) against the commanded stepped reference (dashed) over a full 0°–360° sweep, shown ascending and descending. Blue dots are the per-step averages of those predictions, they follow each step in real time, confirming the model tracks orientation live during a print.



Geometry reconstructions. Five unseen shapes: the actual printed samples (top) beside the model's live digital reconstructions (bottom). The reconstructed colour gradients stay spatially consistent with the printed pattern, showing coherent live sensing beyond the training geometry.

Closed Loop - Experiment3



Physical prints under the same injected error, open-loop (left) vs closed-loop (right), with the predicted B-axis orientation over the print below. Open-loop drifts away from the 180° target and never returns; closed-loop detects the errors and snaps back within a few segments.

Outcomes

The control architecture is largely sound: large, resolvable errors were detected and corrected. But angular precision did not transfer to unseen geometries (MAE 11.09°, P90 19.97°), and errors near the filament's resting state were imperceptible. Held non-equilibrium orientations pushed the filament into untrained states, making the loop act on confidently wrong estimates so closed-loop performance is governed by perception reliability, not the loop itself.