

Exposure-Pattern Compensation in Vat Photopolymerisation: Optical Blur, Cure Spread, Geometry Bias and Model Transfer

A calibrated inverse-control framework for geometric fidelity

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Abstract

Exposure-pattern compensation modifies the image sent to a vat-photopolymerisation system so that the manufactured geometry approaches a target despite optical blur, pixel cross-talk, thresholded polymerisation, cure spread, accumulated dose and deformation. The task is an inverse problem, not a universal XY offset. A pattern that corrects one feature size, resin or projector location can fail on another because the forward response depends on irradiance distribution, spectrum, layer history, resin state, geometry, support and metrology. Positive and negative features can exhibit different bias, and a lower mean dimensional error can coexist with closed channels, missing walls or unacceptable surface shape.

This review defines a qualification framework for feed-forward pattern compensation in masked and projection vat photopolymerisation. It separates projector pixel pitch from measured optical response, optical blur from chemical cure spread and shrinkage, calibration from prospective validation, and geometry correction from deliberate property grading. Direct studies of pixel blending, mask planning, grayscale regulation, pixel-resolved solidification and model-based optimisation support the workflow. Filled-resin light-transport studies demonstrate why scattering must enter the forward model, but their optical parameters are not transferable. A defensible compensation therefore requires radiometry, point- or line-response measurement, feature-class-specific metrology, constrained inverse optimisation, uncertainty reporting and holdouts across location, geometry and process state. No universal point-spread kernel, edge offset, shrinkage factor, compensation image or accuracy improvement follows from the literature.

Keywords: vat photopolymerisation; exposure compensation; inverse problem; point-spread function; cure spread; geometry bias; mask planning; model transfer

1. Significance and scope

Projection systems expose many pixels simultaneously, but the cured boundary is not a direct copy of a binary image. Light spreads through optics and resin, neighbouring pixels interact, chemistry continues beyond an irradiance contour, and the part can deform during separation, washing or post-cure. Compensation is the controlled modification of the exposure pattern to counter a repeatable portion of that response.

ER-241 addresses feed-forward correction of unintended geometric error. It does not define the material working curve, redesign projector hardware or create intentional property gradients.

1.1 Corpus boundary

ER-002 retains cross-platform process equivalence. ER-010 retains dimensional metrology. ER-027 retains conversion metrology and spatial cure heterogeneity. ER-035 retains critical exposure and penetration-depth interpretation. ER-044 and ER-076 retain absorber, scattering and cure-profile physics. ER-071 retains in-situ sensing and closed-loop control. ER-075 retains tomographic material operating windows. ER-171 retains design values and allowables. ER-174 retains optical-state measurement and drift. ER-203 retains radiometric traceability. ER-205 retains cure-state mapping. ER-242 retains intentional spatial dose modulation. ER-243 retains pixel geometry, anti-aliasing and projection optics. ER-249 retains stitching and seam qualification. ER-241 owns feed-forward exposure-pattern compensation for unintended geometric error within a declared optical, resin, process and metrology state.

2. Formulate a forward process before inversion

A simplified forward relation is

$$\tilde{G} = M\{C[O(P), \theta_r, H], \theta_m\}$$

where P is the commanded pattern, O the optical delivery operator, C the cure and deformation response, H the exposure history, M the metrology operator, and θ_r and θ_m the resin and measurement states. Compensation seeks a feasible P^* that makes measured geometry $\tilde{G}$ approach target G_t .

The inverse is generally non-unique. Regularisation, pattern connectivity, dose limits and minimum feature rules are physical constraints, not optional numerical conveniences.

3. Pixel pitch is not optical resolution

Native pixel pitch describes sampling at a declared plane. It does not specify focus, modulation transfer, flare, field curvature, distortion or resin scattering. Zheng and co-workers showed that projection-system variables and cure depth must be characterised together [7]. Kang and co-workers developed a pixel-based solidification model rather than treating a pixel as an isolated voxel [6].

Measure the spatial irradiance response at representative field positions and focus states. A single centre-field measurement cannot establish corner behaviour.

4. Separate optical blur from cure spread

An optical point-spread function describes energy delivery under declared conditions. The cured response adds absorption, scattering, inhibition, radical generation, diffusion, threshold crossing and accumulated exposure. Deformation adds a third stage. Fitting one effective kernel can be useful, but it should not be called purely optical unless independently measured.

Deng and co-workers found Gaussian-like single-pixel irradiance and interaction between neighbouring pixels in their system [3]. That observation supports local-response calibration, not a universal Gaussian kernel.

5. Calibrate radiometry before compensation

Record wavelength distribution, irradiance, spatial uniformity, exposure time, grayscale transfer, focus, temperature and optical maintenance state. Linear digital code does not guarantee linear irradiance. Recalibrate after source, optical path, vat window, projector or firmware changes.

Use traceable or at least cross-checked radiometry. A compensation learned from unknown delivered dose can absorb equipment drift and fail when the drift changes.

6. Use feature families, not one calibration object

Include isolated lines, spaces, holes, posts, corners, thin walls, large solid regions and internal negative features over relevant scales. Positive and negative features require separate analysis because cure spread that enlarges a post can close a channel.

Guven and co-workers optimised voxel-level grayscale patterns using a solidification model and validated improvement on microfeatures [4]. Their reported improvement remains bound to that system, part and metric.

7. Measure systematic bias and random dispersion

For feature class c , location x and size d , define signed error

$$e(c,x,d) = d(c,x,d) - dt.$$

Retain sign, distribution and censoring for missing or closed features. Averages cannot include a vanished wall as a normal numerical deviation. Repeat builds, positions and metrology sessions to separate repeatability from bias.

8. Mask planning can redistribute deformation

Liu and co-workers used mask segmentation with digital image correlation to study cure deformation [2]. The work supports temporal and spatial planning as possible control variables. Its scaffold resin, mask shapes and reductions are not transferable constants.

Segmentation can introduce seams, additional exposure boundaries or longer cycle time. These secondary effects require explicit acceptance limits.

9. Pixel blending is constrained optimisation

Zhou, Chen and Waltz formulated mask planning with grayscale pixel blending and optimisation models [1]. A general objective can be expressed as

$$P^* = \arg \min[P \text{ in } \Omega] [wg \text{ Lg}(G,Gt) + \lambda R(P)],$$

where Lg measures geometric loss, R regularises the pattern and Ω enforces exposure and topology constraints. Weights cannot convert a failed critical channel into a pass through improvement elsewhere.

10. Three-dimensional history matters

Each layer can receive intended dose plus penetration from later or neighbouring exposures. Bottom, bulk, roof and interface layers may therefore require different forward models. A two-dimensional edge fit cannot establish three-dimensional cure.

Record layer thickness, sequence, separation time and any continuous motion. Validate internal voids separately from exposed surface features.

11. Shrinkage and post-process deformation are not optics

Measure geometry at defined stages: green, washed, dried and post-cured. A correction aimed at final geometry may intentionally pre-distort the green part, but the contribution of each stage should remain visible.

If the same optical pattern yields different final bias after wash or cure changes, the model has incorporated downstream state. It must be requalified when that state changes.

12. Filled resins require transport-aware caution

Feller and co-workers modelled ceramic-filled VPP resins with Monte Carlo ray tracing [8]. Such work demonstrates that particle size, loading, absorption, scattering and refractive-index contrast can broaden or redirect energy. Those transport parameters cannot be assigned to neat or differently filled systems.

The recent alumina-resin compensation study by Guo and co-workers combines formulation and area-based correction [5]. Its model and results are specific to that composite and apparatus.

13. Prevent infeasible inverse solutions

An unconstrained optimiser may create isolated subpixels, rapid grayscale oscillations, disconnected supports or doses below reliable gelation. Enforce printer quantisation, minimum connected area, allowable gradients, exposure bounds and robust topology.

Inspect the commanded image as a manufacturing object. Numerical loss reduction alone is insufficient.

14. Keep geometry objectives non-compensatory

Evaluate dimensional bias, form, edge placement, topology, void openness, surface roughness and feature survival separately. Report worst critical-feature error alongside distributional metrics.

A reduction in mean absolute error does not justify a newly blocked channel. Acceptance should use feature-specific limits fixed before validation.

15. Validate on prospective holdouts

Separate calibration, model selection and validation objects. Hold out geometries, feature sizes and build locations. Where transfer is claimed, hold out machines, resin batches or layer settings as well.

Do not tune the model after seeing holdout results without declaring a new development round and reserving another untouched validation set.

16. Transfer is a claim requiring evidence

Define the transfer vector

$$T = \{\text{machine, wavelength, field, resin, batch, layer, orientation, geometry, postprocess}\}.$$

A compensation is qualified only over tested combinations or a justified interpolation domain. Matching pixel pitch or nominal resin name is not sufficient.

17. Monitor drift without converting ER-241 into closed loop

Before each production campaign, verify radiometric and geometric sentinels against control limits. ER-174 governs optical-state drift measurement, and ER-071 governs adaptive closed-loop response. ER-241 uses those measurements to determine whether a feed-forward map remains valid.

18. Non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Optics	Field-resolved irradiance response	Pixel pitch as resolution
Cure	Resin- and history-specific response	Optical blur as total spread
Geometry	Positive, negative and internal features	One universal offset
Pattern	Feasible quantised solution	Numerically optimal but unprintable mask
Metrology	Stage, uncertainty and missing features	Mean error hiding topology loss
Transfer	Prospective holdout	Copying a fitted map to a new state

19. Minimum reporting set

Report printer and optics; wavelength; field position; resin and batch; layer thickness; exposure sequence; radiometry; point- or line-response method; calibration artefacts; metrology stage and uncertainty; forward model; loss function; constraints; optimisation settings; positive and negative feature results; missing features; calibration, test and holdout split; drift checks; and exact acceptance criteria.

Archive target geometry, original and compensated patterns, machine-readable settings, raw metrology and model version. A screenshot is not an auditable compensation record.

19.1 Propagate uncertainty through the inverse map

Radiometry, registration, focus, resin state and metrology all contribute uncertainty. Refit or resample the forward model across credible input ranges and report the resulting distribution of compensated outcomes. A single best-fit pattern can appear precise while being highly sensitive to a small focus shift or threshold change.

Uncertainty should be expressed at the decision endpoint. For a channel, that may be the probability of remaining open above a minimum width; for a wall, the probability of surviving washing and post-cure within thickness limits. Confidence in fitted parameters is not the same as confidence in manufactured geometry.

19.2 Use sentinel artefacts during production

Place compact positive and negative features at representative field locations and measure them at a declared frequency. Sentinel drift can trigger recalibration without implying that every historical part is invalid. Define warning and action limits from capability data rather than from one successful build.

If a sentinel fails, preserve the exposure file, equipment state and environmental record. Reprinting with an adjusted offset before determining the cause can conceal whether the change arose from optics, resin, temperature, vat condition or downstream processing.

Production records should also retain uncompensated reference artefacts at planned intervals. They help distinguish loss of model validity from a change in the underlying process. A compensated part alone cannot reveal whether the correction remains physically meaningful or merely cancels two drifting errors temporarily.

20. Knowledge boundary

The direct evidence supports pixel blending, mask planning, grayscale regulation and model-based compensation [1-7]. Filled-resin light transport [5,8] explains why transfer can fail. No study supplies a universal point-spread kernel, pixel compensation, edge offset, cure-spread distance, shrinkage factor or accuracy improvement.

21. Limitations

References [1] through [8] were examined at publisher-abstract depth. The evidence supports the bounded mechanisms and qualification architecture stated here, but does not establish transferable numerical compensation parameters.

22. Conclusions

Exposure-pattern compensation is a calibrated inverse-control problem. Optical delivery, cure history, deformation and metrology must remain distinguishable, even when an effective model combines them. Positive and negative features, topology and surface endpoints require separate gates. The compensation map is valid only within a prospectively tested transfer domain. Geometry correction does not by itself establish a property gradient and must remain separate from ER-242.

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