

Pixel Geometry, Anti-Aliasing and Projection Optics in Masked Vat Photopolymerisation: Edge Placement and Feature Fidelity

A sampled-imaging framework for qualifying projected boundaries

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Abstract

The nominal pixel pitch of a masked vat-photopolymerisation system is not its printable resolution. A commanded mask is sampled on a finite grid, transformed by pixel aperture and fill factor, projector or LCD optics, focus, magnification, distortion, angular distribution, field nonuniformity, resin transport and cure threshold. Raster orientation and neighbouring pixels alter the delivered edge. Anti-aliasing may improve mean edge placement while broadening transitions, changing local dose or erasing small negative features. A visually smoother contour is therefore not sufficient evidence of dimensional fidelity.

This review defines a metrology-led framework for qualifying pixel geometry, rasterisation, anti-aliasing and projection optics. It separates the design boundary, sampled command, irradiance field, cure-state boundary and measured final edge; treats positive and negative features independently; and distinguishes sampling pitch, optical resolution, process resolution and minimum reliable feature. Point-spread and modulation-transfer measurements are combined with printed line-space, slanted-edge, corner and isolated-feature artefacts. Validation spans orientation, field position, exposure, feature neighbourhood and independent builds. No universal anti-aliasing level, pixel-to-feature ratio, optical kernel or minimum feature size is supported. The defensible result is a bounded edge-placement capability for a declared mask, optical state, resin and process.

Keywords: masked vat photopolymerisation; pixel geometry; anti-aliasing; projection optics; edge placement; feature fidelity; point-spread function; spatial sampling

1. Significance and scope

Masked projection enables parallel exposure but also makes the command grid part of the manufacturing system. Edges aligned with the pixel axes, diagonal edges, curves, isolated pixels and narrow gaps are sampled differently. Optical blur can reduce stair stepping while simultaneously moving the chemical cure boundary. Qualification must therefore resolve the separate contributions of rasterisation, optics and resin response.

ER-243 owns pixel geometry, sampled-mask representation, anti-aliasing and projection-optics effects on edge placement and feature fidelity.

1.1 Corpus boundary

ER-001 retains general optical reporting; ER-002 retains cross-platform process equivalence; ER-010 retains dimensional metrology; ER-027 and ER-205 retain conversion and cure-state mapping; ER-035 retains critical exposure and penetration depth; ER-044 and ER-076 retain material attenuation and scattering; ER-071 retains closed-loop exposure control; ER-159 retains general optical materials; ER-174 and ER-203 retain equipment optical-state and radiometric traceability; ER-241 retains inverse exposure-pattern compensation; ER-242 retains intentional grayscale dose and property gradients; and ER-249 retains multi-field stitching. ER-243 uses these as inputs but owns the sampled single-field boundary transfer.

2. Define five distinct boundaries

Preserve the following records:

1. analytic CAD or vector boundary;
2. sliced continuous-plane boundary;
3. binary or grayscale pixel command;
4. delivered optical and cure-state transition;
5. final measured part boundary.

An edge error must name the compared pair. Comparing CAD directly with a washed and post-cured part combines slicing, rasterisation, optics, cure spread, shrinkage, wash and measurement into one residual.

3. Pixel pitch is a sampling interval, not resolution

Let the projected pixel pitches be p_x and p_y . The corresponding sampling limits are often described by Nyquist frequencies:

$$f_{Nx} = 1 / (2 p_x) ; f_{Ny} = 1 / (2 p_y)$$

where f_{Nx} and f_{Ny} are the Nyquist frequencies of the command grid along the two axes, half the corresponding sampling frequencies $1/p_x$ and $1/p_y$. These limits describe the command grid, not the optical or cured-material response. Fill factor, cross-talk, defocus and cure spread can suppress or merge patterns well below the nominal sampling limit.

The title and bibliographic identity of the early study by Bertsch, Jézéquel and André establish that spatial resolution was examined in dynamic-mask microstereolithography [1]. More recent projection microprinting shows pronounced loss and aliasing of fine features as effective pixel size increases [4]. Neither result supports equating a device pixel with a reliable cured voxel.

4. Characterise the pixel aperture and grid geometry

Measure projected pitch, aspect ratio, rotation, skew, fill factor, dead space and local distortion across the field. Determine whether the physical emitter, micromirror or LCD subpixel geometry introduces direction-dependent aperture or leakage. Record the mask scaling and any resampling performed by firmware.

Use a coordinate transform with residual maps rather than a single nominal magnification. A central calibration cannot establish edge placement at field corners.

5. Measure the optical transfer before printing

Characterise point-spread function, line-spread function and modulation transfer at the resin plane or a justified optical surrogate. Measure focus and transfer at multiple field positions and, where relevant, depths. The projected irradiance field can be represented generically as

$$I(x,y) = \sum_{i,j} M_{ij} h(x-i \text{ px}, y-j \text{ py}) + B(x,y)$$

where M_{ij} is the command at pixel indices i,j , h is the position-dependent optical response, and B is background light. This linear form is only an optical starting point; cure chemistry may add nonlinearity and history dependence.

6. Treat rasterisation as a controlled transformation

Archive slicer version, layer geometry, supersampling, contour rule, threshold, image format and final machine-readable mask. Verify that scaling, colour management, compression and bit-depth conversion do not alter pixel values. A preview image is not evidence of the executed mask.

Use known vector primitives to test rasterisation separately from printing. Include translations smaller than one pixel to expose phase sensitivity between the design edge and grid.

7. Define anti-aliasing by its executed algorithm

“Anti-aliasing on” is not reproducible. State whether the method uses area coverage, filtered sampling, temporal dithering, multi-mask exposure, grayscale edge pixels or contour offsets. Record kernel, radius, levels, threshold and exposure sequence.

Zhou and Chen showed that planned mask sequences and pixel blending can improve accuracy in a specific projection process [2]. Xue, Wang and Mei used multiple gradient masks to improve thickness uniformity in their system [3]. These studies establish feasibility, not a universal setting.

8. Separate smoothing from edge accuracy

Assess surface stair stepping, edge transition width, signed contour error and topology separately. An anti-aliased diagonal can appear smoother while its 50% transition or cured threshold moves systematically. Report both mean bias and transition width.

Do not use one aesthetic image as qualification. The acceptance variable must be linked to the drawing or functional requirement.

9. Test orientation and subpixel phase

Use edges at multiple angles, including grid-aligned, diagonal and shallow angles. Translate repeated features through controlled subpixel phases. Report periodic edge error and roughness against phase and orientation.

Pixel-grid anisotropy can be hidden by pooling all orientations. Present polar or orientation-resolved results where the application includes arbitrary contours.

10. Test positive, negative and isolated features

Bars, posts and islands accumulate different neighbourhood exposure from slots, holes and channels. Light tails that enlarge a positive feature may close a negative feature. Test isolated pixels, line-space pairs, corners, junctions and crowded arrays.

Vidler, Crozier and Collins showed that size, spacing and exposure jointly affected whether micron-scale projected features were resolved [4]. The important conclusion is neighbourhood dependence, not transfer of their feature limits.

11. Resolve focus, telecentricity and angular effects

Map best focus, depth of focus, magnification and chief-ray angle across the working plane. Non-telecentric projection can change apparent pitch and wall angle with depth. Window thickness, refractive index and resin depth can shift focus from an air calibration.

Repeat optical checks after any source, lens, mask, window, vat or build-plane intervention. ER-174 owns the equipment-state programme; ER-243 binds that state to feature fidelity.

12. Map field uniformity without confusing it with resolution

Irradiance nonuniformity changes the local cure threshold and feature size but is not itself spatial resolution. Measure uniformity and optical transfer separately. Wang, Xue and Mei demonstrated grayscale correction of nonuniform illumination for one continuous projection system [7]. The correction mask does not replace a point-spread or feature test.

Use field-position replicates and withhold some positions from calibration.

13. Connect optical edges to cured edges

Measure printed features over an exposure range and compare optical transition, green boundary and final boundary. Use the same segmentation rule and report uncertainty. The Wen study showed geometry- and polarity-dependent errors in projection stereolithography microfeatures [5]. Guven, Karpat and Cakmakci likewise modelled neighbourhood contributions in grayscale optimisation [6].

Do not assign a resin-independent edge to a measured optical threshold. The threshold is an identified process response for a declared state.

14. Use identifiable calibration artefacts

Include slanted edges, line-space pairs, isolated dots, holes, posts, narrow walls, corners, arcs and mixed-density regions. Span multiple sizes rather than only the expected limit. Replicate at centre, edges and corners of the field.

A single “resolution test” confounds failure modes. Slanted edges estimate sampled transfer; line-space pairs test contrast and merging; isolated features test neighbourhood support; holes test negative-feature closure.

15. Control measurement and segmentation

State instrument, magnification, sampling interval, focus method, surface preparation, segmentation threshold, edge operator and registration. Use traceable dimensional standards where available. Compare multiple segmentation thresholds when edge contrast is low.

If the measurement pixel is similar to the claimed edge precision, the claim is unresolved. Report repeatability and uncertainty separately from manufacturing variation.

16. Validate without pixel leakage

Partition validation by geometry class, field position and build, not by randomly splitting pixels from the same image. Withhold orientations, subpixel phases and neighbourhoods. Validate both improvement and no-harm conditions, including topology preservation.

Report failed or saturated cases. A setting that improves broad diagonals but removes small holes has not improved general feature fidelity.

17. Transfer and change control

Revalidate after changes to projector or LCD, lens, source spectrum, focus, vat window, optical path, slicer, firmware, layer thickness, resin, exposure or post-cure. A nominally identical machine requires an independent optical and printed-feature comparison.

Treat anti-aliasing parameters as controlled process data. Version them with hashes of the executed masks and software environment.

18. Non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Sampling	Projected pitch, grid transform and subpixel phase	Calling pixel pitch resolution
Optics	Point/line spread, transfer and focus by position	Inferring optics from one printed coupon
Raster	Exact executed mask and algorithm	Treating a preview as the command
Cure	Positive and negative features across exposure	Assigning one optical threshold to all resins
Validation	Withheld geometry, orientation, phase and field	Reporting calibration images as performance
Change control	State version and requalification triggers	Reusing settings after hardware or software drift

19. Minimum reporting set

Report CAD and slice geometry; projected pitch and grid transform; pixel aperture and fill factor; mask bit depth and values; rasterisation and anti-aliasing algorithm; optical spectrum, irradiance, point/line spread, transfer, focus and distortion; resin identity and state; exposure and layer history; positive and negative artefacts; orientation, subpixel phase and field position; green and final geometry; measurement and segmentation; uncertainty; validation partitions; topology failures; transfer limits; and hashes of masks, configuration, code and results.

20. Knowledge boundary

Primary studies show that pixel blending, multi-step masks, small projected pixels, geometry correction and grayscale optimisation can improve bounded systems [2-7]. They also show dependence on spacing, polarity, field and resin response. Reference [1] establishes only the bibliographic identity and spatial-resolution scope of the early dynamic-mask study. This evidence supports a sampled-imaging qualification framework. It does not establish a universal anti-aliasing level, pixels-per-feature rule, point-spread function, edge threshold or minimum printable feature.

21. Limitations

Reference [1] was examined at bibliographic-record depth; references [2], [3], [6] and [7] at publisher-abstract depth; and references [4] and [5] at full-text depth. The studies span early LCD masks, DMD projection, continuous printing and microprinting with different resins and measurement methods. This review does not disclose product-specific masks, optical correction tables or proprietary printer settings.

22. Conclusions

Feature fidelity in masked vat photopolymerisation is a sampled optical and photochemical transfer problem. Pixel pitch, optical resolution, cured-edge transition and reliable feature size are different quantities. Qualification requires exact executed masks, spatial optical metrology, orientation and phase tests, polarity-resolved printed artefacts, measurement uncertainty and independent validation. Anti-aliasing is acceptable only inside a declared domain that improves the relevant edge metric without topology loss.

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