

Metrology of Vat Photopolymerisation: Resolution, Trueness, Precision and Geometric Fidelity Across Scales

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Statement of Significance

Vat photopolymerisation is often described by nominal pixel pitch, layer height or a single “accuracy” value, yet those quantities do not describe the same measurand. This review reframes VPP geometric performance as a traceability problem: digital intent must be followed through light delivery, photochemical conversion, mechanical/post-processing evolution and the measurement method itself. The resulting framework separates feature resolution from metrological accuracy, resolves accuracy into trueness and precision, and treats geometric fidelity as scale-, polarity-, orientation- and method-dependent. The proposed minimum-reporting framework is intended to make VPP dimensional studies more comparable without prescribing a proprietary calibration artefact or printer-specific protocol.

Keywords: vat photopolymerisation; metrology; resolution; trueness; precision; dimensional accuracy; geometric fidelity; working curve; measurement uncertainty; calibration; DLP; SLA; LCD.

Abstract

Geometric performance in vat photopolymerisation (VPP) is frequently compressed into terms such as resolution, accuracy and precision even though these descriptors answer different measurement questions. This ambiguity limits comparison across printers, resins, feature scales and studies. This review develops a metrological framework for VPP based on current measurement terminology and additive-manufacturing standards. Resolution is treated as a feature-reproduction capability rather than a synonym for accuracy; accuracy is decomposed into trueness and precision; and realised geometric fidelity is treated as the end result of a multistage chain connecting the digital target, projected optical field, local cure response, layerwise mechanics, post-processing and the measurement system. Recent interlaboratory work on VPP working curves demonstrates that even foundational cure parameters can be poorly reproducible without controlled procedures, while newer studies show that feature size, polarity, orientation, pixel aliasing, stitching, overcuring, warpage and measurement modality can each change the apparent dimensional outcome. The review therefore argues against universal single-number claims of VPP resolution or accuracy. A minimum-reporting framework is proposed covering printer/light-engine state, resin state, exposure variables, feature geometry and polarity, post-processing, measurement method, uncertainty, replicate structure and statistical definitions. The framework is intended to support cross-study comparability, process qualification and defensible engineering claims while remaining independent of any particular commercial calibration system.

1. Introduction

Vat photopolymerisation converts patterned optical exposure into solid geometry through a coupled optical, photochemical and mechanical process. In projection-based systems, a digital image is mapped through a light engine into a resin volume; in scanning stereolithography, a focused beam defines the exposed trajectory. In both cases the manufactured boundary is not a direct copy of the CAD boundary. It is the result of spatially distributed energy delivery, threshold and conversion kinetics, optical absorption and scattering, resin transport, layer separation, polymerisation shrinkage, support and orientation effects, washing, post-curing and the method used to measure the final part [5,6,22].

This process chain explains why nominal hardware descriptors are not sufficient metrological descriptors. Pixel pitch specifies addressability of a projection system, but a pixel is not a guaranteed printed feature. Layer thickness specifies a programmed build increment, but it is not a direct measure of Z trueness or minimum printable Z feature. A visually resolved line can be reproducible but systematically oversized; conversely, a mean dimension may be close to nominal while individual builds are poorly repeatable. Treating these outcomes under a single label obscures the physical source of error and weakens cross-study comparison.

The terminology also requires correction. Under ISO 5725-1:2023, accuracy is associated with both trueness and precision rather than being an independent third property [1]. Trueness concerns closeness of the expectation of measurement results to a reference value, whereas precision concerns agreement among replicate results under specified conditions. Resolution is a separate capability concept. In VPP, the scientifically useful question is therefore not whether resolution, precision and dimensional accuracy are three independent numbers, but how resolution, trueness and precision interact with feature geometry, process state and the measurement chain to produce realised geometric fidelity.

The need for a more explicit framework is reinforced by recent standardisation and reproducibility work. ISO/ASTM 52902:2023 defines benchmarking artefacts for quantitative assessment and calibration of AM-system geometric capability and explicitly includes measurement uncertainty without prescribing a single measurement technology [2]. ISO/ASTM 52927:2024 now provides the general framework for principal part characteristics and corresponding test methods, replacing the withdrawn ISO 17296-3:2014 [3]. Meanwhile, a 24-laboratory interlaboratory study of the VPP working curve found large dispersion in the derived penetration-depth and critical-exposure parameters when procedures and hardware were not harmonised [10]. A follow-up study showed that controlled narrow-band illumination substantially improves interoperability and provides a foundation for a documentary standard [11].

The objective of this review is to organise these developments into a VPP-specific metrological architecture. The scope is geometric performance of layerwise SLA, DLP and LCD/masked VPP systems, with occasional examples from closely related light-based platforms when they clarify a measurement principle. The review does not endorse a particular commercial calibration artefact, compensation algorithm or resin formulation. Instead, it proposes a traceability chain and a minimum-reporting framework that can be applied to academic studies, supplier characterisation and industrial process qualification.

2. Metrology vocabulary for VPP

2.1 Resolution and addressability

Resolution should be reserved for a capability to distinguish or reproduce spatial features under defined conditions. In a projection system, nominal pixel pitch is a digital and optical sampling descriptor. The printed feature boundary additionally depends on the point-spread behaviour of the optical system, defocus, diffraction, light leakage, resin attenuation, exposure threshold, conversion kinetics and the geometry of adjacent illuminated pixels [6,8,13]. Consequently, a quoted pixel size is not itself a demonstrated minimum positive feature, minimum negative feature or dimensional tolerance.

The distinction becomes stronger near the hardware limit. Pixelated aliasing can dominate oblique or narrow features in LCD-based systems, while subpixel control can be achieved by deliberately redistributing optical dose rather than by changing the physical pixel pitch [20]. In other words, digital addressability establishes one boundary condition; realised feature resolution is an emergent process result.

2.2 Trueness, precision and accuracy

ISO 5725-1:2023 provides a useful discipline for AM terminology [1]. Trueness concerns systematic displacement from a reference value; precision concerns scatter among replicate measurements under specified repeatability or reproducibility conditions; accuracy incorporates both. This distinction prevents a common VPP ambiguity: reporting a small mean dimensional error without showing replicate scatter, or reporting low scatter around a systematically biased mean and calling the process accurate.

The conditions attached to precision must also be stated. Within-build repeatability, build-to-build repeatability on one machine, day-to-day repeatability, operator-to-operator variation and cross-machine reproducibility are not interchangeable. The corresponding variance components can arise from irradiance drift, resin age and reuse, temperature, vat/window state, build-platform alignment, optical-field nonuniformity and measurement-system variation. A precision number without its reproducibility condition is therefore incomplete.

2.3 Geometric fidelity as a system-level outcome

Geometric fidelity is used here as an umbrella engineering descriptor for how faithfully the manufactured and post-processed part reproduces the intended geometry across relevant scales. It is not proposed as a replacement for standard metrological terms. Rather, it reminds the reader that a part contains multiple measurands—external dimensions, internal channels, holes, thin walls, angles, surface form, local curvature and feature position—and that each may exhibit different trueness and precision. Studies of micro-geometries already show geometry-dependent error, while negative embedded features introduce clogging and collapse modes that are absent from positive protrusions [16–18].

Term	Primary question	What should be reported	Common misuse to avoid
Digital addressability	What optical sampling increment is commanded?	Pixel pitch, projected pixel size, scan spot/step, layer increment.	Calling pixel pitch “print resolution”.
Feature resolution	What smallest defined positive or negative feature is reproduced under stated criteria?	Feature geometry, polarity, orientation, success criterion, replicate count, measurement method.	One universal minimum feature size for all geometries.
Trueness	How far is the expectation of measured geometry from the reference/nominal?	Signed or absolute deviation, reference definition, axis/location, uncertainty.	Calling low scatter around a biased result “accurate”.
Precision	How closely do replicate results agree under stated conditions?	Repeatability/reproducibility condition, SD or other dispersion metric, n.	Reporting a single build as “high precision”.
Accuracy	How good is the result considering trueness and precision?	Both systematic deviation and replicate variation.	Treating accuracy as a third independent property alongside precision.
Geometric fidelity	How faithfully is a complex geometry realised across relevant scales?	A set of feature-specific trueness/precision metrics, form deviations and failure criteria.	Reducing a complex part to one vendor “accuracy” number.

Table 1. Recommended use of geometric-performance terms in VPP.

3. The VPP geometric traceability chain

A useful way to interpret VPP metrology is to treat geometry as a sequence of state transformations rather than as a direct CAD-to-part mapping. The proposed VPP Geometric Traceability Chain has five linked states: (1) digital target geometry; (2) delivered optical field; (3) as-cured layer/voxel geometry; (4) post-processed part geometry; and (5) measured geometry. Each transition introduces identifiable uncertainty or bias. The framework is conceptual; it is intended to structure measurements and reporting rather than to prescribe a new standard.

3.1 Digital target to delivered optical field

The first transition includes image rasterisation, pixel sampling, projector magnification, distortion, focus, grayscale transfer, optical-field uniformity and—where applicable—stitching. Projection micro-stereolithography studies established early that the mask and optical system determine process-scale behaviour rather than merely transmitting CAD geometry [6]. More recent work has shown that mask-image optimisation can compensate diffraction and transmission-driven light spread by redistributing grayscale dose on a voxel basis [13]. Large-area systems add another error channel because mechanically or optically stitched fields can create overlap or gaps; the SPIC method illustrates how motion and pixel compensation can be separated to reduce such stitching error [15].

3.2 Delivered optical field to cured geometry

The second transition is governed by photochemical response. Classical working-curve parameters remain useful because they link cure depth to radiant exposure, but they are not invariant material constants unless the measurement procedure, wavelength, irradiance distribution, dose range and thickness measurement are controlled. Bennett showed that different thickness-measurement methods can agree for rigid cured films yet fail for soft materials [7]. The 2024 NIST-led interlaboratory study then demonstrated that procedural heterogeneity can produce dispersion of up to roughly seven-fold in fitted penetration depth and seventy-fold in critical exposure across laboratories [10]. The 2025 follow-up materially improved reproducibility through a controlled filtered light source [11].

Even a well-controlled working curve may not fully predict microfeature behaviour. Wendland and co-workers reported strong feature-size dependence of critical exposure in high-resolution hydrogel VPP, particularly at low irradiance, high dye loading and with oxygen-permeable windows [12]. This result is important metrologically: a calibration obtained from one exposure geometry can fail when transferred to features with substantially different lateral scale or oxygen-transport environment. Working curves should therefore be treated as test-method outputs with a defined validity envelope, not as universal geometry predictors.

3.3 Cured geometry to post-processed geometry

The as-cured green part continues to evolve during separation, washing, drying, post-curing and thermal conditioning. Polymerisation-induced shrinkage, residual stress and nonuniform conversion can change global and local form after the exposure step has ended. Lee et al. linked VPP warpage to nonuniform cumulative light absorption and layer-to-layer cure differences and demonstrated a correction strategy based on equalising absorbed energy [19]. Whether or not a particular compensation method is adopted, the metrological implication is general: the time and process state at which a dimension is measured must be reported. A green-part dimension and a final post-cured dimension are different measurands.

3.4 Post-processed geometry to measured geometry

The final transition is the measurement system. Contact micrometers, stylus methods, optical microscopy, confocal methods, structured-light scanners and micro-computed tomography do not sample the same surface in the same way. Bennett's cure-thickness study already demonstrated material-dependent method effects [7]. In a 2026 comparison of additively manufactured cube specimens, Suta et al. found systematic differences among micrometer, micro-CT and optical-scanner measurements, with the optical scanner underestimating dimensions in that experiment [21]. The measurement system is therefore part of the VPP performance claim, not a neutral observer outside the process.

State / transition	Representative error channels	Useful observations or measurements	Typical interpretation risk
Digital target → optical field	Rasterisation, pixel aliasing, magnification, focus, irradiance nonuniformity, stitching.	Projected-pixel calibration, field map, focus/MTF proxy, grayscale transfer, stitching test.	Assuming CAD or pixel boundaries equal exposure boundaries.
Optical field → cured geometry	Absorption/scattering, oxygen inhibition, threshold kinetics, working-curve dependence, exposure accumulation.	Working curve under stated conditions, feature-size study, positive/negative coupons.	Treating Dp/Ec as method-independent constants.
Layer/voxel integration	Peel/separation stress, resin renewal, trapped resin, orientation and support effects.	Layer-failure map, negative-feature success, orientation series, force data when available.	Attributing all deviations to "overcure".
Green → post-processed part	Washing deformation, shrinkage, residual stress, post-cure gradients, thermal conditioning.	Before/after dimensions, time-to-measure, post-cure protocol, warpage/form measurement.	Mixing green-state and final-state dimensions.
Part → measured result	Probe force, optical reflectivity, segmentation, scanner smoothing, voxel size, registration.	Method, calibration, uncertainty, sampling density, segmentation/registration procedure.	Treating measurement output as ground truth without method uncertainty.

Table 2. VPP geometric traceability chain and representative error channels.

4. Scale, feature polarity and orientation

4.1 Positive and negative features are different measurands

A minimum printable pillar and a minimum open channel should not be placed on one resolution axis. Positive features primarily fail through insufficient cure, optical broadening, mechanical damage or loss during separation. Negative features can fail because excess cure closes the void, uncured resin cannot be renewed or removed, or unsupported roofs collapse. Wang et al. showed that microchannel overcuring depends on coupled resin and structural variables rather than on nominal pixel size alone [16]. Torres-Alvarez and co-workers introduced the lowest printable channel characteristic length to capture orientation-dependent printability of embedded hollow structures [17]. These results support a polarity-specific reporting principle: positive and negative feature capability should be measured separately.

4.2 Feature size changes the process window

Feature-scale effects appear both in polymerisation and measurement. The size-dependent critical exposure reported for hydrogel VPP [12] indicates that lateral scale can modify the apparent cure threshold. At the manufactured-part level, Almanza-Vázquez et al. found geometry-dependent relative errors among circular, triangular, quadrangular, pentagonal and hexagonal micro-geometries, with location in the build area also considered [18]. These findings argue against a scale-free statement such as "accuracy $\pm X \mu\text{m}$ " without specifying the feature family and dimensional range over which that statement was verified.

4.3 Orientation and anisotropic process history

VPP orientation changes layer count, stair-stepping, support interaction, peel loading, drainage and the direction in which pixel sampling intersects a boundary. For embedded channels it can also alter resin removal and roof stability [17]. Orientation is therefore a metrological factor even when the underlying resin and printer settings are unchanged. A defensible qualification study should either fix orientation explicitly or include orientation as a controlled factor rather than pool measurements from differently oriented features.

4.4 Large-scale geometry adds new error modes

At centimetre scales, the dominant error can move away from microfeature broadening toward optical-field distortion, stage repeatability, stitching, global shrinkage and warpage. The SPIC study demonstrates that maintaining local projection precision does not guarantee large-area geometric continuity [15]. Metrology across scales therefore requires nested artefacts or a hierarchy of measurands rather than one test feature assumed to represent the full build volume.

5. Process contributions to geometric error

5.1 Optical dose and spatial energy distribution

Spatial dose is the first process variable that converts digital geometry into a physical boundary. Diffraction, transmission through cured or partially cured material, defocus and stray light can extend the effective exposure outside the intended mask. Wang et al. improved DLP printing accuracy by optimising projected mask grayscale to compensate this spread [13]. Ma et al. similarly used machine-learning-driven boundary prediction to tune local grayscale and improve fidelity [14]. These studies show that geometric error can be systematic and model-correctable, but they also illustrate an important reporting issue: an apparently high-resolution part may be the output of an active compensation algorithm, not the raw capability of the optical hardware.

5.2 Cure kinetics and working-curve uncertainty

Working curves remain valuable because they provide an empirical relationship between radiant exposure and cure depth, and their parameters are widely used to initialise exposure settings [7,9]. Their metrological use is strongest when the illumination spectrum, irradiance, exposure geometry, resin conditioning, sample preparation and thickness measurement are specified. The two NIST-led interlaboratory studies demonstrate both the scale of the reproducibility problem and a practical path toward harmonisation [10,11]. Reporting only fitted E_c and D_p values without the measurement procedure makes transfer between laboratories and printers unreliable.

5.3 Resin transport, separation and negative-space fidelity

Not all dimensional deviation is optical. Bottom-up VPP imposes separation forces after each layer, while resin must refill the interfacial gap before the next exposure. For narrow cavities or embedded channels, fluid retention and drainage interact with curing. The LPCL study explicitly connects negative-feature printability to geometry and orientation [17], and microchannel modelling/experiments show that overcuring of voids depends on both cure and flow-related conditions [16]. Failure diagnosis therefore requires discriminating among optical exposure, resin transport and mechanical separation instead of assigning every enlarged or closed feature to a single mechanism.

5.4 Shrinkage, residual stress and warpage

Polymerisation creates a network while simultaneously changing density and mechanical state. Conversion gradients through layers can create nonuniform strain and residual stress. Warpage is consequently a form error, not merely a dimensional scale factor. Lee et al. demonstrated that cumulative absorbed energy can be used to model and compensate warpage in VPP [19]. The metrological consequence is that global scaling compensation and local form correction should be distinguished: a part can have correct average dimensions while remaining warped, or can be flat but uniformly oversized.

5.5 Post-processing is part of the geometric process

Washing, support removal, drying and post-curing can alter geometry after printing. The effect is material-, geometry- and workflow-dependent, and may be larger for thin walls, soft networks and solvent-sensitive materials. Accordingly, dimensional claims should specify the post-processing state. Where a study seeks to characterise printer capability, green-state and final-state results should be separated. Where the goal is final-part qualification, the complete validated workflow should be included in the measurand definition.

6. Measurement methods and measurement-chain bias

6.1 Contact dimensional measurement

Micrometers and calipers are attractive because they are direct, inexpensive and traceable when properly calibrated. They are appropriate for accessible macroscopic dimensions on sufficiently rigid parts. Their limitations include probe-force deformation, operator positioning, inability to capture local form and restricted access to internal features. Bennett's study is a useful warning: caliper measurement was unsuitable for a soft elastomeric cured specimen even when other methods agreed for harder materials [7].

6.2 Optical microscopy and profilometry

Microscopy and profilometry provide higher spatial sampling for microfeatures and surfaces but introduce edge-detection, focus and reflectivity decisions. For thresholded images, the selected segmentation rule can shift the reported edge. For steep or highly curved surfaces, line-of-sight limitations can produce missing data. The measurement protocol should therefore report magnification, calibration, image-processing threshold and whether the result represents an average width, minimum width, maximum width or a fitted geometric primitive.

6.3 Three-dimensional optical scanning

Structured-light and laser scanners can rapidly capture whole-part form and are valuable for CAD-to-part deviation maps, but their result depends on surface optical properties, spatial filtering, registration and meshing. Suta et al. observed systematic underestimation from an optical scanner in their 2026 comparison, whereas micrometer and micro-CT measurements provided different performance characteristics [21]. This should not be generalised to all scanners; rather, it demonstrates why the measurement device must be validated for the material and feature scale under study.

6.4 Micro-computed tomography

Micro-CT is particularly valuable for internal channels, pores and complex three-dimensional deviations because it avoids destructive sectioning. Its uncertainties include voxel size, X-ray attenuation contrast, reconstruction artefacts and segmentation threshold. It can provide a more complete volumetric representation than contact methods, but it does not remove the need for calibration or uncertainty estimation. For multimaterial or low-contrast systems, segmentation can become the dominant measurement decision.

Method	Strength	Important limitation	Best-fit use
Micrometer / caliper	Direct and traceable for accessible rigid dimensions.	Probe force, operator placement, no internal geometry, limited form information.	Macroscopic widths, thicknesses and external dimensions.
Optical microscopy / profilometry	High local spatial resolution; strong for edges and surface profiles.	Threshold/focus/reflectivity effects; limited field and line of sight.	Microfeatures, line width, surface steps, local cure thickness.
3D optical scanner	Fast whole-part point cloud and CAD deviation mapping.	Material reflectivity, smoothing, registration and meshing biases.	External form and medium-to-large geometry.
Micro-CT	Volumetric access to internal and external geometry.	Voxel size, reconstruction and segmentation uncertainty; cost/time.	Channels, pores, internal voids and 3D form.
Hybrid approach	Cross-validates method-dependent bias and expands scale range.	Requires explicit registration and uncertainty treatment.	Reference studies and method-validation work.

Table 3. Measurement methods for VPP geometric studies.

7. Compensation is not metrology

Compensation methods are increasingly capable of improving realised geometry. Grayscale redistribution can counter optical spread [13], machine-learning boundary prediction can localise dose corrections [14], stitching-specific compensation can preserve large-area continuity [15], feature-oriented vibration can reduce pixel aliasing in LCD systems [20], and exposure redistribution can reduce warpage [19]. These methods are important process-control advances, but they should be separated conceptually from metrology.

Metrology determines what the process produced and with what uncertainty. Compensation uses that information, plus a model or empirical mapping, to change the next process input. A compensation algorithm can make a nominally coarse optical system produce a dimensionally improved feature, but the improvement should be demonstrated using an independent measurement procedure. Otherwise the correction model and the measurement model can share assumptions and create circular validation.

This distinction also affects supplier claims. If a quoted dimensional capability depends on a calibrated material profile, grayscale correction, software compensation or orientation-specific scale factor, those dependencies belong to the performance definition. A user should not be expected to reproduce compensated performance from nominal pixel pitch alone.

8. Reproducibility, standardisation and cross-study comparison

8.1 What standards already provide

Current standards provide much of the vocabulary and test-architecture needed for better VPP reporting. ISO 5725-1:2023 supplies the trueness/precision framework [1]. ISO/ASTM 52902:2023 defines AM benchmarking artefacts and makes measurement uncertainty explicit [2]. ISO/ASTM 52927:2024 establishes general part characteristics and test-method communication for AM and supersedes ISO 17296-3:2014 [3]. ISO/ASTM 52900:2021 remains the general vocabulary foundation for AM process terminology [4]. The remaining need is not a new proprietary terminology, but consistent VPP-specific implementation of these principles.

8.2 The working-curve reproducibility lesson

The working-curve interlaboratory studies provide a useful model for how VPP metrology can mature. The first study exposed large cross-laboratory scatter arising from procedure, light-engine and measurement differences [10]. The second constrained the illumination and procedure more tightly and obtained substantially better interoperability [11]. The lesson extends beyond working curves: a geometric benchmark only becomes comparable when the reference geometry, material state, exposure field, post-processing, measurement method and uncertainty are all controlled or reported.

8.3 Minimum evidence for a dimensional performance claim

A defensible claim should identify the measurand and the conditions. For example, “50 μm pixel size” is a hardware statement; “100 μm positive wall resolved” is a feature-capability statement; “20.00 mm external width with mean signed error of -0.08 mm and SD 0.03 mm across $n=10$ builds” is a trueness/precision statement. Each can be valid, but they cannot substitute for one another. Claims should also distinguish machine capability under a reference resin from material-specific performance and application-specific final-part qualification.

9. Proposed minimum reporting framework for VPP geometric studies

The following framework is proposed as a practical minimum for studies intended to support cross-study comparison, qualification or public dimensional claims. It is deliberately compatible with existing AM standards rather than replacing them. Not every study requires every field, but omission should be justified when a variable is known to affect the investigated measurand.

Reporting block	Minimum information	Why it matters
Printer / light engine	VPP subtype; wavelength/spectrum; projected pixel or scan descriptor; nominal build area; relevant optical calibration; irradiance measurement method and date.	Defines the delivered-field context rather than relying on model name alone.
Resin state	Material identity or generic chemistry class; batch; age; temperature; mixing/degassing; reuse history; pigment/filler state where relevant.	Resin conditioning changes cure and transport behaviour.
Exposure / layer process	Layer thickness; exposure time/dose; bottom-layer exceptions; grayscale/compensation; wait/lift/peel parameters when relevant.	Separates optical dose from nominal machine resolution.
Test geometry	CAD dimensions; positive/negative polarity; orientation; build position; support state; feature-scale range.	Prevents transfer of one feature result to another geometry class.
Post-processing	Wash chemistry/time; drying; support removal; post-cure wavelength/dose/time/temperature; time before measurement.	Defines the geometric state being measured.

Reporting block	Minimum information	Why it matters
Measurement system	Instrument; calibration; spatial resolution/voxel size; probe force if relevant; segmentation/registration; uncertainty or repeatability.	Makes the measurement chain auditable.
Statistics	Replicate definition and n; signed bias/trueness metric; precision metric; outlier rule; confidence intervals where appropriate.	Separates systematic bias from scatter.
Claim boundary	Explicit statement whether result represents hardware, material-process pair, compensated process or final workflow.	Prevents overgeneralisation beyond the validated configuration.

Table 4. Minimum reporting framework proposed for VPP geometric performance studies.

9.1 A hierarchy of claims

The framework suggests a useful hierarchy. Level 1 is hardware description: pixel pitch, layer increment, wavelength and build volume. Level 2 is reference-process capability under a defined resin and calibration state. Level 3 is material–process capability for a specified feature family. Level 4 is final-workflow capability after post-processing. Level 5 is application-specific tolerance capability under the relevant environment and inspection method. Moving upward requires more evidence, not merely more precise wording.

9.2 Reporting negative results

Failed features are metrological data. A channel that closes, a wall that detaches or a hole that cannot be cleared should not simply be removed from dimensional analysis. Success probability as a function of feature size can be more informative than the dimension of the surviving specimens alone. The LPCL approach is one example of explicitly integrating printability with dimensional fidelity for negative features [17]. This principle should be generalised to other geometry classes where censoring of failed specimens can make a process appear more accurate than it is.

9.3 Research priorities

Three research gaps are especially important. First, cross-laboratory geometric artefact studies for polymer VPP are needed at multiple scales, analogous to the working-curve ILS but focused on part geometry. Second, uncertainty budgets should separate printer/process variance from measurement-system variance, particularly for microfeatures and soft materials. Third, compensation algorithms should be validated against independent metrology and should report transferability across resin batches, printers, build positions and feature polarities. These questions are prerequisites for converting impressive single-system demonstrations into interoperable engineering capability.

3Dresyns implementation examples

The following commercial examples connect the metrology framework in this review to current 3Dresyns process-control products. They are implementation examples from company product documentation, not independent evidence of dimensional accuracy; each resin-printer combination still requires its own working-curve, feature and dimensional validation.

Fine Tuner FT1. A photoaccelerant product used to increase cure speed in compatible photopolymer systems. From a metrology perspective, changing cure kinetics changes the exposure-to-conversion relationship, so dimensional performance must be re-qualified rather than assumed to improve.

Fine Tuner FT1 Bio. A photoaccelerant for compatible bio-oriented photopolymer systems. Its engineering relevance is kinetic control; it should be treated as a process variable whose effect on cure depth, lateral growth and geometric error must be measured under the selected wavelength and exposure conditions.

Fine Tuner LB1 Bio. A resolution-oriented additive for compatible photopolymer systems. It illustrates optical/cure-confinement tuning, but a product-level resolution function does not by itself establish feature trueness, precision or minimum printable feature size without a defined artefact and measurement method.

Source basis: current 3Dresyns product and Technical Data Sheet documentation, August 2026. These commercial examples are included to connect the review framework to implementation and are not substitutes for independent application-specific validation.

10. Conclusions

- Resolution is not synonymous with pixel pitch, layer height, precision or dimensional accuracy. In VPP it is a feature-reproduction capability that must be defined for a geometry, scale, polarity and success criterion.
- Accuracy should be interpreted through trueness and precision in accordance with ISO 5725 terminology. Reporting only mean deviation or only replicate scatter is insufficient for an accuracy claim.
- VPP geometry is produced through a multistage chain: digital target → optical field → cured geometry → post-processed geometry → measured result. Each transition can introduce systematic bias and uncertainty.
- Working-curve parameters are valuable process descriptors but recent interlaboratory work shows that they are test-method outputs whose reproducibility depends strongly on controlled illumination, procedure and measurement.
- Positive and negative features should be qualified separately. Feature size, orientation, resin transport, overcuring, pixel aliasing, stitching, shrinkage and warpage can dominate different regimes.
- The measurement method is part of the performance statement. Contact measurement, microscopy, optical scanning and micro-CT can yield different apparent dimensions and must be validated for the material and scale.
- Compensation algorithms can improve realised geometry but do not replace independent metrology. Their use should be disclosed as part of the process capability being claimed.
- A minimum reporting framework covering printer/light-engine state, resin state, exposure, test geometry, post-processing, measurement uncertainty, replicates and claim boundary would materially improve cross-study comparability and industrial qualification.

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Limitations

This review is a methodological synthesis rather than a systematic review with a preregistered search protocol. The literature examples were selected because they expose recurrent metrological mechanisms—working-curve reproducibility, feature-scale effects, positive/negative geometry, compensation, warpage and measurement-method bias—rather than to rank commercial systems. The proposed traceability chain and reporting framework have not yet been validated through a dedicated multi-laboratory artefact study and should therefore be regarded as testable engineering proposals.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L., a developer and supplier of photopolymer materials and process-engineering resources. No proprietary formulation composition, unpublished additive dosage, unpublished calibration dataset or commercial product-performance map is used as evidence in this review. The proposed metrological framework is intended to be applicable independently of any particular supplier, printer or calibration artefact.

Data availability

No new experimental dataset was generated for this review. The analysis and framework derive from the standards and published sources cited below.

Company information

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