

In-Situ Monitoring and Closed-Loop Control in Vat Photopolymerisation: Sensors, State Estimation, Digital Twins and Adaptive Exposure

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Statement of Significance

Vat photopolymerisation literature increasingly uses the terms real-time, adaptive, intelligent, digital twin and closed loop. These terms are not interchangeable. A sensor can record a signal without estimating the material state; an estimator can predict conversion or modulus without changing the print; and a digital twin can mirror the build without exercising control. This review establishes an evidence hierarchy from observation to intervention and requires a closed-loop claim to demonstrate that a measured signal changed a process input during the same build and that the intervention reduced a declared error or corrected a declared defect.

Keywords: vat photopolymerisation; in-situ monitoring; process sensing; observability; state estimation; digital twin; closed-loop control; adaptive exposure; defect detection; in-situ repair; ultrasonic monitoring; interferometry; Raman spectroscopy; thermal monitoring

Abstract

Vat photopolymerisation can expose a complete layer in seconds, but the material state evolves through oxygen consumption, gelation, conversion, heat generation, vitrification, shrinkage and separation from the vat film. Conventional working curves and test coupons characterize this response before production and therefore remain open-loop calibration. Recent research has introduced ultrasonic sensing, interferometry, thermal imaging, Raman spectroscopy, optical monitoring, force sensing, machine learning, digital twins and visual defect repair. The evidence, however, spans different levels. Ultrasonic and interferometric systems estimate layer thickness, degree of cure or modulus in real time; thermal-chemical models infer inaccessible interface temperature and conversion; digital twins reconstruct geometry, stiffness and defects; and visual-guided or hybrid model-data systems modify scraper motion, repair exposure, filling time or other process parameters during the same build. An adjacent hydrogel study demonstrates true feedback control of storage modulus using a piezoelectric sensor and bang-bang or fuzzy logic controllers, but it is not a VPP printing demonstration. This review separates measurement, state estimation, prediction, feedforward compensation, alarm/interlock, in-situ repair and feedback control. It defines sensor calibration, ground-truth, latency, blind-zone, uncertainty and intervention-efficacy requirements; proposes reporting aids for deadline compliance, estimator error, observability coverage and correction efficacy; and provides a qualification matrix and failure-mode table. No universal controller, acceptance threshold or VPP-specific standard is proposed. The central principle is: monitoring observes the process; estimation interprets the observation; prediction projects the future; and closed-loop control changes the process and proves that the change improved the declared outcome.

1. Scope and evidence-selection method

ER-71 is restricted to sensing, state estimation, model updating, defect detection, intervention and closed-loop control during vat photopolymerisation. It does not replace conversion metrology, cure-kinetics analysis, dimensional calibration, material selection or final-part qualification. The evidence base prioritises direct VPP studies, followed by adjacent photopolymerisation studies only where they establish a control or measurement principle that has not yet been demonstrated inside a printer [1-17].

Shared measurement conventions, reporting rules and disclosure boundaries for this series are defined in RP-02 [R1]. ER-71 applies them to observability and control. Manufacturer documentation is included only to identify currently available calibration and formulation-adjustment tools; it is not independent evidence of an autonomous control platform.

2. Measurement, estimation, prediction and control are different

A rigorous control claim begins by naming the physical state, sensor, estimator, decision rule and actuator separately. The hierarchy below prevents a process-monitoring result from being promoted into a control result without the missing intervention evidence.

Table 1. Evidence hierarchy for monitored and controlled VPP

Level	Minimum evidence	Claim boundary
Offline calibration	Pre-build exposure, cure-depth, irradiance or dimensional data.	Does not observe the production build.
In-situ measurement	Time-stamped sensor signal acquired during the build.	Signal is not automatically a material-state measurement.
State estimation	Calibrated mapping from signal to conversion, modulus, thickness, temperature or defect state.	Estimator output is not ground truth and may be resin-specific.
Prediction or digital twin	Model projects current or future state and is updated by measured data.	A digital twin can remain passive and open loop.
Alarm or interlock	Declared threshold triggers warning, pause or stop.	Reduces loss but does not necessarily repair the part.
Feedforward compensation	Input is adjusted from model, geometry or expected disturbance before observing the error.	Not feedback control unless measured output closes the loop.
In-situ repair	Detected defect triggers a targeted corrective operation during the same build.	Repair must be validated against an unrepaired and defect-free baseline.
Closed-loop control	Measured output changes an actuator or process input and the resulting state is re-evaluated.	Requires latency, stability, safety bounds and efficacy evidence.
Adaptive supervisory control	Estimator, model or controller parameters update as process or material behaviour changes.	Adaptation must not conceal drift or uncontrolled extrapolation.

A real-time signal is not a closed loop. A digital twin is not a controller. A controller is not qualified until its intervention is validated.

3. The state vector and the observability problem

VPP does not possess one universal process state. A useful state vector may include layer thickness, lateral boundary, degree of cure, temperature, refractive index, storage or Young modulus, separation force, resin level, defect class, defect location and accumulated exposure. Each quantity has a different spatial support and timescale. A camera may observe the surface but not a buried void; ultrasound may detect internal structure but requires a propagation model; infrared imaging may observe a substrate or exposed surface while the critical resin-part interface remains inaccessible [1-8].

Observability is therefore claim-specific. A sensor is sufficient only when the declared output can be reconstructed over the spatial and temporal region that controls the decision. Blind zones, saturation, scattering, opacity, field-of-view loss, moving boundaries and resin changes must be documented. A high sampling rate does not compensate for a sensor that is insensitive to the target state.

4. Sensor families and their evidence

4.1 Ultrasonic monitoring

Vallabh, Zhang and Zhao integrated in-situ ultrasonic monitoring into VPP and used real-time ultrasonic features to evaluate the evolving Young modulus and degree of conversion under different exposure intensities [1]. The method provides subsurface information and is attractive for opaque or filled systems, but its state estimates depend on density, wave path, boundary conditions and the calibration used to relate acoustic response to conversion or modulus.

Jamshididana and co-workers developed a real-time ultrasonic digital twin with 0.2 mm geometric accuracy, modulus estimates spanning approximately 65 MPa to 1.4 GPa, maximum mean absolute percentage error of 8.97% against tensile measurements and detection of internal defects as small as 0.249 mm² [5]. This is a strong monitoring and digital-twin demonstration. The authors present adaptive closed-loop control as future work rather than as an achieved result. Wang and Zhao subsequently combined physics-informed ultrasonic features with attention-fusion learning to estimate thickness, modulus and degree of curing; ultrasonic features contributed 57% of predictive information beyond print settings, and millisecond-scale layer-wise inference was positioned as an enabler for future control [6].

4.2 Interferometric and optical monitoring

Zhang, Zhang and Zhao demonstrated non-destructive, full-field interferometric monitoring of DLP-VPP. The system estimated time-varying refractive index and degree of curing and captured geometry and curing signatures as masks and intensity changed [2]. The result supports state estimation and process-window analysis; it does not by itself demonstrate that an estimated error was fed back to change the same build.

Camposeo and co-workers used an optical system for in-situ, real-time monitoring of acrylate droplets and films and showed that complete-cure time increased when polymerisation volume fell below a chemistry-dependent characteristic threshold [14]. This finding is important for scale transfer: a controller trained on a bulk or thick-layer signal may not remain valid at microfeature scale.

Visual monitoring has progressed beyond observation. Zhao and co-workers detected bubbles and resin underfill using image analysis, generated defect-specific repair actions, controlled a scraper or secondary repair exposure and sent the correction to the printer without interrupting the build [7]. Repaired samples differed by less than 0.6% in fracture strength from defect-free samples under the reported conditions. This is a direct in-situ intervention demonstration, but its validated defect set, camera visibility and precursor range define the scope.

4.3 Thermal monitoring and thermal-chemical estimation

The photopolymerisation exotherm changes viscosity, reaction rate and final state. Heyang Zhang and Zhao used in-situ temperature measurement to inform modelling of process temperature, including the difficult-to-access resin-part interface [3]. A later thermal-chemical framework combined observable temperature, inverse heat conduction and photo-DSC-informed kinetics to estimate internal heat generation, temperature and degree of cure; predictions were validated against in-situ temperature and ex-situ spectroscopy [4]. These

studies illustrate why a measured boundary temperature and an estimated interface state must be reported separately.

4.4 Force and separation monitoring

Kovalenko and co-workers continuously measured the adhesion or separation force in a bottom-up DLP system and compared the peak unstick force with a theoretical value to detect faults [10]. Force sensing is directly relevant to delamination, non-adherence, film condition and geometry-dependent separation. It is architecture-specific: the same signal definition does not transfer to a top-down system, and a force anomaly can have several causes unless combined with geometry, exposure and motion data.

4.5 Spectroscopic and coupled-measurement boundaries

Spectroscopy provides chemical information but does not automatically report connectivity or mechanical state. Alig and co-workers combined real-time NIR spectroscopy with ultrasonic reflectometry to obtain conversion-time and modulus-time curves and distinguish light-cure, dark-cure, mass-controlled and diffusion-controlled regimes [11]. Chiou and Khan likewise showed that rapid thiol conversion did not produce appreciable modulus until more than 65% conversion in their thiol-ene system [12]. Schmidt and Scherzer coupled photorheometry and NIR spectroscopy so that shrinkage and conversion were measured in the same experiment [13]. These adjacent studies establish a central rule for VPP control: conversion, gelation, modulus and shrinkage require separate measurement or a validated state model.

Raman monitoring in Xolography provides a volumetric boundary. Lange and co-workers quantified degree of cure and kinetics under dual-colour exposure, reported 89% photoinitiator contrast, mapped green-state conversion gradients and showed that post-treatment raised conversion above 90% [15]. ER-71 uses this work as an in-situ chemical-state example; complete dual-colour threshold chemistry is treated separately in the Perspective, Spatial Selectivity Mechanisms in Volumetric Photopolymerisation. Rudenko and co-workers showed for the tested transparent composition that increasing light intensity reduced double-bond conversion, while increasing temperature produced an initial rise followed by a decrease [16].

Table 2. Sensor modality, observable and principal limitation

Modality	Observable or estimate	Principal limitation
Ultrasound	Layer thickness, time of flight, attenuation, modulus proxy, internal defect.	Requires propagation model, density and boundary calibration; spatial resolution is configuration-dependent.
Interferometry	Full-field phase, surface displacement, refractive index and cure estimate.	Optical access, phase unwrapping, vibration and resin transparency.
Camera / vision	Bubbles, underfill, boundary, surface morphology, resin level.	Visible surface only; lighting, occlusion, class imbalance and domain shift.
Infrared / thermal	Accessible surface or substrate temperature; inferred interface temperature.	Emissivity, line of sight and inverse-model dependence.
Force sensing	Peel or unstick force, adhesion anomaly, motion signature.	Bottom-up architecture dependence and non-unique causal interpretation.
Raman / FTIR / NIR	Functional-group conversion and reaction kinetics.	Fluorescence, optical path, band assignment and conversion-mechanics non-equivalence.
Rheology / piezoelectric sensing	Gelation, phase angle, storage modulus proxy.	Often adjacent bulk photopolymerisation rather than printer-integrated measurement.
Multisensor fusion	Estimated state vector and anomaly classification.	Synchronization, missing data, model drift and opaque feature weighting.

5. Calibration and ground truth

Every estimator must be tied to an independently defined reference. A modulus inferred from ultrasonic velocity should be checked against a mechanical test under a declared condition. A degree-of-cure estimate should be checked against spectroscopy using the same functional group and state definition. A thermal model should be validated at accessible locations and challenged across exposure, geometry and resin changes. A vision classifier requires defect definitions, labelled data, confusion matrices and independent samples. Calibration and validation sets must be separated.

Ground truth is state-dependent. Ex-situ tensile modulus after washing and post-cure is not automatically the reference for an in-situ green-state modulus. Likewise, post-build geometry cannot validate the timing of a transient underfill event without a traceable layer record. The time between sensing and reference measurement must be reported when dark cure, cooling, relaxation or swelling can change the state.

6. From signal processing to state estimation

Signal conditioning, feature extraction and state estimation are part of the measurement chain. Filtering can suppress noise but also remove short anomalies. Thresholds can be transparent but brittle. Machine-learning models can fuse multiple features but may extrapolate when resin, geometry, projector, sensor mounting or environmental conditions change. The state estimator should therefore declare its inputs, training domain, uncertainty output, update frequency, missing-data behaviour and out-of-domain response [5,6,8,17].

A predicted scalar should not conceal spatial averaging. Layer-average modulus can miss a local weak zone; global temperature can miss a hot interface; mean conversion can miss an under-cured boundary. Where the control action is local, the estimator must resolve the local state or explicitly bound the unobserved region.

7. Digital twins are state representations, not automatic controllers

A VPP digital twin is a synchronized computational representation of the build that is updated by process data and used to estimate geometry, material state, defects or future response. The term should not be used for a static simulation, a database, a one-time calibration curve or a sensor dashboard. Jamshididana and co-workers demonstrate a real-time digital twin because ultrasonic data reconstruct the growing part and its properties during printing [5]. The thermal-chemical model of Zhang and co-workers is a model-informed state estimator with digital-twin potential [4]. Neither label alone proves feedback control.

The minimum twin record should include model equations or architecture, parameters, initial conditions, sensor inputs, synchronization, update rate, uncertainty, validation domain, intervention interface and version control. A twin used for release decisions must preserve the raw sensor record and the model version that produced each estimate.

8. What has actually been controlled?

The clearest direct VPP control evidence is defect-specific intervention. Visual-guided repair detected a defect, selected a repair action and modified the ongoing process through scraper control or secondary exposure [7]. A later hybrid physical-model and status-data approach monitored platform force, curing temperature, resin level and surface morphology, used an Extended Kalman Filter and data-driven models to update printing parameters dynamically, and applied in-situ repair when anomalies were detected [8]. These studies satisfy a stronger control definition than papers that only state that monitoring could enable future control.

The hydrogel study of Singh and co-workers is an important adjacent benchmark because it explicitly controlled storage-modulus setpoints through a piezoelectric phase-angle signal and bang-bang or fuzzy logic controllers [9]. It demonstrates sensor-controller-actuator logic and setpoint overshoot, but it is not a layer-by-layer VPP printing validation and should not be cited as one.

9. Controller architecture and actuator authority

A controller can alter exposure time, irradiance, pixel intensity, mask geometry, secondary exposure, layer dwell, lift or peel speed, reflow time, scraper motion, vat temperature or build pause. Each actuator has a response delay, saturation limit and side effect. Increasing exposure may raise conversion while worsening lateral growth, residual stress or adhesion. Slowing motion may improve refill but increase cycle time and thermal accumulation. A local repair exposure may correct underfill while creating an interlayer or overcure boundary.

Control authority must be bounded. The system should define safe minimum and maximum values, rate limits, forbidden combinations, fallback state, operator override and the conditions that force a stop rather than an attempted repair. A controller trained on one resin should default to a safe state when the formulation, wavelength or sensor calibration changes.

10. Timing, latency and deadline compliance

Real-time is defined by the process deadline, not by a general sampling-frequency label. A correction is useful only if acquisition, preprocessing, estimation, decision, communication and actuator response finish before the relevant exposure, separation or refill event. Jitter and worst-case delay matter as much as mean latency.

$$L_{rt} = (t_{acq} + t_{pre} + t_{est} + t_{dec} + t_{cmd} + t_{act}) / t_{window}$$

L_{rt} is a proposed reporting aid. t_{window} is the available decision window for the declared intervention. L_{rt} below one indicates that the measured end-to-end latency fitted inside that window for the tested case; it is not a universal stability or safety criterion. Report the distribution and worst case, not only the mean.

11. Proposed reporting descriptors

The following quantities are proposed as transparent reporting aids. They are not standards and do not replace raw time series, confusion matrices, calibration curves or controller stability analysis.

11.1 Normalized state-estimation error

$$E_{est} = RMSE(x_{hat} - x_{ref}) / (x_{ref,max} - x_{ref,min})$$

The state x , reference method, range denominator, units, spatial support and validation set must be declared. If the range is narrow or zero, use an alternative physically meaningful normalization and report absolute RMSE.

11.2 Observability coverage

$$C_{obs} = N_{valid} / N_{required}$$

N is the declared sampling unit: layer, voxel, pixel, area, volume or event. C_{obs} must be accompanied by a blind-zone map because high coverage can coexist with a strategically unobserved region.

11.3 Intervention efficacy

$$I_{corr} = 1 - \text{abs}(e_{after}) / \text{abs}(e_{before})$$

The same target, units, geometry and evaluation window must be used before and after correction. I_{corr} can be negative when the intervention worsens the error. Always report e_{before} and e_{after} separately and include an unrepaired control.

11.4 Intervention burden

$$B_{int} = t_{added} / t_{nominal}$$

This timing burden does not represent energy, waste or quality cost. Report added exposure, motion, material and rejected-part consequences separately.

12. Minimum qualification architecture

Table 3. Minimum evidence architecture for VPP monitoring and closed-loop control

Domain	Minimum record	Required conclusion
Process and material identity	Printer architecture, resin version, wavelength, irradiance, layer, vat film, temperature and geometry.	Defines the controlled system.
Sensor chain	Sensor model, placement, calibration, range, resolution, sampling, clock and uncertainty.	Defines what was actually measured.
Reference state	Independent method, specimen state, timing, spatial support and uncertainty.	Defines estimator ground truth.
Estimator	Inputs, features, model version, training domain, update rate, residuals and out-of-domain rule.	Defines how signal became state.
Decision logic	Setpoint, thresholds, controller law, state constraints and fallback.	Defines why intervention occurred.
Actuator	Input changed, bounds, response time, saturation, rate limits and side effects.	Defines control authority.
Latency	Timestamped acquisition-to-actuation distribution and process deadline.	Establishes real-time feasibility.
Intervention validation	No-control, defect, unrepaired and defect-free controls; local and final outcomes.	Establishes correction efficacy.
Traceability	Raw data, intervention log, model/controller versions and parameter changes.	Supports reproducibility and audit.
Final qualification	Geometry, conversion, mechanics, defects and intended-use tests after full post-process.	Prevents process success from becoming a product claim.

13. Failure modes and interpretation errors

Table 4. Common failures in VPP monitoring and control claims

Observation	Interpretation error	Required response
High-frequency sensor data	Called real-time control.	Demonstrate end-to-end latency and an actuator response inside the process window.
Conversion estimated accurately	Modulus, shrinkage or final properties assumed known.	Validate each claimed state or use a coupled model with independent checks.
Digital twin updates during printing	Closed-loop control claimed.	Show the twin changed an input and that the outcome was re-evaluated.
Defect classifier has high accuracy	Repair reliability inferred.	Report class-wise errors, repair success, false actions and final-part controls.

Observation	Interpretation error	Required response
Average layer state is acceptable	Local weak region excluded.	Provide spatial resolution and blind-zone evidence.
Controller improves one metric	Overall process optimized.	Measure geometry, conversion, stress, time and other affected outputs.
Model performs on one resin	Transferability claimed.	Validate across formulation, colour, filler, geometry and sensor mounting changes.
Mean latency below deadline	Timing qualified.	Report jitter, worst case and missed deadlines.
Repair resembles defect-free surface	Mechanical equivalence assumed.	Test fracture location, conversion, dimensions and relevant final properties.
Alarm stops failed print	Closed-loop quality control claimed.	Use alarm/interlock terminology unless the process is corrected and resumed.

14. Standards and pre-standardisation boundary

ISO/ASTM 52920:2023 provides process-independent qualification principles for industrial additive-manufacturing processes and production sites [S1]. ISO/ASTM 52927:2024 organizes main material and process characteristics and associated test methods [S2]. Neither defines VPP sensor calibration, state-estimator validation, latency or controller performance. ISO/ASTM 52953:2025 is titled for additive manufacturing of metals, but its normative scope is limited to metallic parts produced by laser-based powder bed fusion (PBF-LB); its traceability logic is useful, but it provides no VPP data or case studies [S3]. ISO/ASTM TR 52958:2026 is a Technical Report on coaxial photodiode monitoring for lack-of-fusion flaw detection in PBF-LB metals and is an adjacent validation example, not a VPP method [S4].

No published ISO or ASTM standard was identified that directly governs in-situ sensing, state estimation, digital-twin validation, end-to-end latency, intervention efficacy or closed-loop controller qualification for vat photopolymerisation. Protocols used today must therefore be documented as controlled in-house methods and linked to the exact process and claim.

15. Scope boundaries within the Engineering Review series

- ER-27 addresses conversion metrology and spatial cure heterogeneity. ER-71 addresses how a measured or estimated state is used during the build.
- ER-31 addresses shrinkage, residual stress and warpage. ER-71 includes those quantities only as monitored states or control outcomes.
- ER-52 addresses online multifunctional photopolymer configuration and decision interfaces. ER-71 is restricted to physical process observability and intervention during printing.
- ER-61 addresses gelation, vitrification and mobility arrest. ER-71 treats them as latent states that may require coupled sensors or models.
- ER-65 addresses cationic ring-opening photopolymerisation. ER-71 does not define mechanism-specific kinetics and applies only after the state and actuator are declared.
- ER-75 addresses the material operating window of integrated-dose tomographic VAM; dual-wavelength xolography and two-photon polymerisation are treated in the separate Perspective, Spatial Selectivity Mechanisms in Volumetric Photopolymerisation. ER-71 uses Raman monitoring only as an observability boundary.

16. 3Dresyns implementation boundary

Current 3Dresyns resources provide controllable formulation and calibration inputs, not an integrated autonomous control platform. Fine Tuner FT1 is positioned as a formulation photoaccelerant whose loading

changes cure speed and must be recalibrated under the actual printer and exposure conditions [M1]. Curing Rate Tables and DLP/LCD instructions provide exposure-versus-cured-thickness information and printer-resin fingerprints [M2]. The Curing Rate Control System supports Ec, Dp and engineering interpretation [M3], while the structured calibration workflow links irradiance, exposure, cured thickness and dimensional checks [M4]. These are offline calibration and adjustment tools.

No current standard 3Dresyns product or public page is identified in this review as an independently validated in-situ sensor, digital twin, adaptive controller or closed-loop VPP platform. A future platform would require calibrated sensing, a validated estimator, a declared latency budget, bounded actuator authority, intervention logs, fail-safe rules and independent final-part confirmation. Product names such as Fine Tuner, Curing Rate Control or calibration tool must not be converted into an autonomous-control claim.

17. Design rules

- Name the state, sensor, estimator, decision rule and actuator separately.
- Use closed-loop only when measured output changes the same build and the result is re-evaluated.
- Preserve raw signals and synchronize every data stream to the printer clock.
- Declare sensor blind zones and the spatial support of every estimate.
- Validate conversion, modulus, temperature and geometry independently; do not treat them as interchangeable.
- Report the complete latency distribution and the process deadline.
- Bound controller authority and define stop, fallback and operator-override states.
- Use defect-free, defective-unrepaired and repaired controls.
- Test side effects of correction, including overcure, stress, dimensional drift and cycle-time burden.
- Recalibrate or reject the model when resin, colour, filler, wavelength, sensor mounting or geometry leaves the validation domain.

18. Research priorities

The immediate need is not another unqualified sensor demonstration but common validation datasets that contain synchronized raw signals, seeded defects, independent ground truth and known interventions. Transparent benchmarks should compare single-sensor and multisensor estimators across clear, coloured, opaque and particle-filled resins. The field also needs uncertainty-aware controllers that distinguish correctable underfill from conditions requiring a safe stop.

A second priority is local rather than layer-average control. Pixel- or region-level exposure, refill and repair decisions require spatial state estimation, causal attribution and actuator models that prevent correction in one region from creating overcure or stress elsewhere. A third priority is lifecycle traceability: the monitoring record should remain linked to the final part, post-cure, inspection and acceptance decision.

19. Conclusions

In-situ monitoring in VPP has progressed from force traces and optical signals to multimodal state estimation, digital twins, visual defect repair and dynamic model-data control. The strongest recent demonstrations show that geometry, modulus, degree of cure, temperature and defects can be estimated during printing, and that selected anomalies can trigger corrective action [1-8]. Adjacent controlled photopolymerisation work demonstrates setpoint feedback for hydrogel modulus [9].

The remaining risk is terminological inflation. A sensor is not an estimator; an estimator is not a digital twin; a digital twin is not a controller; and a controller is not qualified because one repaired specimen looks acceptable. The evidence chain required for a release-grade claim is:

calibrated sensor -> validated state estimate -> declared decision rule -> bounded actuator -> deadline-compliant intervention -> re-measured outcome -> final-part qualification

The central engineering principle is: monitoring observes the process; estimation interprets the observation; prediction projects the future; and closed-loop control changes the process and proves that the change improved the declared outcome.

Limitations

This review is literature-based and introduces no new experimental dataset. The cited studies use different printer architectures, resins, sensors, geometries, estimator definitions and ground-truth methods. Numerical performance values are therefore reported only for their source-specific conditions and are not pooled. Several spectroscopy and controller studies are adjacent photopolymerisation demonstrations rather than printer-integrated VPP studies and are explicitly identified as boundaries. Standards and live manufacturer pages were checked on 22 August 2026 and require re-verification if release is delayed.

Author contributions

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

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer examples are segregated from peer-reviewed evidence and are not presented as independent validation of in-situ sensing, digital-twin or closed-loop-control performance.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature and standards; manufacturer examples derive from the cited public documentation.

Company information

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