

Robotic Dispensing and Formulation of Photocurable Materials: Accuracy, Cross-Contamination, Mixing and Traceability

Metrological control of automated formulation preparation

Juan Seguro

3Dresyns by Resyner Technologies S.L.

© 2026 Juan Seguro. All Rights Reserved.

Correspondence: info@3Dresyns.com · www.3Dresyns.com

ER-408 · Engineering Review · Version 0.1 · 7 October 2026

Abstract

Robotic formulation is often treated as a neutral executor, yet liquid-handling studies show that dispensing speed, syringe or tip geometry, vial configuration and physical setup can create systematic bias. Photocurable formulations add viscosity, density, evaporation, pigment or particle loading, surface wetting, sedimentation and light sensitivity. This review defines a metrological architecture for robotic formulation preparation based on gravimetric verification, material-specific dispensing validation, carryover control, mixing qualification and chain-of-custody records. It distinguishes command volume from delivered mass, preparation repeatability from composition accuracy, and clean-looking automation from validated cross-contamination control. The proposed workflow is suitable for autonomous experimentation only after the executor itself has been qualified.

Keywords: robotic dispensing · photopolymer formulation · gravimetric verification · liquid handling · cross-contamination · mixing · traceability · automation

1. The executor is part of the measurement system

Automated liquid handling improves throughput and reproducibility only when the delivered quantity is known. Recent metrological evaluation of liquid-handling robotics found that setup and dispensing parameters materially affected systematic bias and uncertainty [1]. Autonomous formulation platforms likewise demonstrate the feasibility of automated preparation and integrated measurement for soft materials [2]. For photopolymer work, the formulation robot is therefore not merely a convenience. It is part of the evidence chain that establishes composition.

2. Commanded volume versus delivered amount

Volumetric commands can be biased by viscosity, wetting, compressibility, aspiration speed, tip geometry, bubbles and residual film. Density also changes across formulations. Gravimetric verification is often preferable where the objective is mass fraction, provided the balance and evaporation behaviour are controlled. If volumetric dispensing is used, material-specific calibration should cover the viscosity and surface-tension range of interest rather than relying on water-based factory specifications.

3. Viscosity and flow history

Photocurable resins can be Newtonian, shear-thinning or otherwise rate-dependent, especially when filled (see ER-036 and ER-341). Aspiration and dispense rates can therefore change delivered volume, bubble entrainment and residual material in the line. The executor qualification should include representative low-, medium- and high-viscosity fluids and should define allowable speed, dwell and tip-contact rules for each class.

Table 1. Robotic formulation error sources

Source	Potential consequence	Control
Aspiration/dispense bias	wrong component fraction	gravimetric verification
Viscosity/wetting	residual fluid; bubbles	material-class calibration
Carryover	trace additive contamination	blank/tracer challenge
Mixing	composition gradients	homogeneity test
Evaporation	time-dependent concentration	closed vessels; timing control

4. Cross-contamination and carryover

Carryover can occur through reusable syringes, needles, manifolds, splash, aerosol or contact surfaces. In formulation screening, trace contamination can bias photoinitiator, inhibitor, dye or catalyst studies at low concentration. Carryover should be challenged using a high-sensitivity tracer or analytical marker with blank runs between extremes. Cleaning success should be a measured criterion, not a visual judgement.

5. Mixing qualification

Dispensing the correct components does not guarantee a homogeneous formulation. Mixing efficiency depends on viscosity ratio, density contrast, particle loading, vessel geometry, mixing energy, order of addition and time (see ER-341 and ER-358). Entrained air may change optical and rheological measurements. A mixing protocol should be qualified using a measurable homogeneity endpoint such as concentration, optical response, rheology or solids distribution at defined sampling positions.

6. Evaporation, light and environmental controls

Volatile components can change mass during a long robotic sequence; ambient or stray light can alter photosensitive mixtures; temperature changes viscosity and reaction rate. These effects can become correlated with run order. Environmental records should therefore include temperature, light-protection status and time between dispensing, mixing and measurement. Containers should be compatible with the chemistry and designed to minimise uncontrolled headspace loss where relevant.

Source	Potential consequence	Control
Identity error	wrong lot/sample	digital chain of custody

Table 2. Minimum executor qualification

Test	Measured output	Trigger for requalification
Mass delivery	bias and repeatability	hardware/tip/software change
Carryover	blank contamination	cleaning protocol change
Mixing homogeneity	spatial variance	vessel/mixer/formulation-class change
Reference formulation	final response control chart	drift or maintenance

7. Traceability and identity

Every dispensed component should be linked to material identity, lot, container, expiry or internal control state and dispensing channel. Barcode or equivalent digital identity can reduce manual transcription error but does not replace incoming-material control. The batch record should reconstruct the commanded amount, measured delivered amount where available, deviations, mixing sequence, operator interventions and final sample identifier.

8. Reference formulations and control charts

Periodic reference formulations can reveal drift in dispense accuracy, mixing or analytical response. Control limits should be based on qualified repeatability rather than arbitrary percentages. When maintenance, tip type, firmware, balance or environmental enclosure changes, equivalence should be demonstrated before historical and new data are pooled.

9. Integration into closed-loop experimentation

An autonomous selector should receive executor-status information. If a dispense is outside tolerance or the balance detects an anomaly, the experiment should be quarantined rather than supplied to the learning model as a normal observation. This prevents the model from learning relationships caused by preparation error and preserves failed execution as a distinct failure class. Self-driving-laboratory architectures provide the broader closed-loop context for integrating robotic formulation with adaptive experiment selection [3].

10. Qualification decision boundary

Robotic formulation can support high-quality photopolymer experimentation when delivered composition, contamination, mixing and identity are demonstrably controlled. The automation layer must be qualified with the same seriousness as the analytical instrument. Only after executor capability is established should higher-level autonomous optimisation be trusted to interpret formulation-response relationships.

11. Gravimetric mass balance and closure

For each formulation, the sum of verified component masses can be compared with final vessel mass to identify transfer loss, evaporation or unrecorded residue. Mass-balance closure is especially useful when many small additions are made because individually acceptable errors can accumulate into a meaningful composition shift. Closure limits should reflect balance uncertainty, expected vessel handling loss and volatile content. A failed closure should quarantine the sample or trigger investigation; it should not be corrected by silently renormalizing the nominal recipe.

12. Particles, pigments and suspensions

Filled photocurable systems introduce additional automation challenges. Settling can change the concentration aspirated from a source vessel; agglomerates can block tips; high shear can alter dispersion state (see ER-036, ER-358 and ER-359); and particles can remain in tubing after cleaning. Source vessels therefore require controlled agitation and defined sampling depth or geometry. Dispersion state should be measured separately from composition. Delivering the correct mass fractions does not prove that a conductive, ceramic, magnetic or optical filler is distributed in the same state across samples.

13. Scale-up and dead-volume effects

Robotic screening often uses small vessels and microlitre-to-millilitre transfers, whereas later manufacturing uses larger batches. Surface-to-volume ratio, mixing power density, heat removal and dead volume change with scale (see ER-341 and ER-351). A recipe proven by small-volume automation therefore requires scale-up qualification. Carryover can also become more important in manifolds or reusable lines with larger wetted volume. Scale-up should include residence-time and cleaning validation rather than assuming geometric similarity.

14. Evidence gaps and research priorities

There is a need for photopolymer-specific robotic-handling studies spanning low-viscosity resins through highly filled suspensions and reporting delivered mass, bubbles, carryover, mixing homogeneity and downstream cure response. Generic liquid-handling validation does not establish performance for these regimes. Interlaboratory reference formulations could provide a practical benchmark for autonomous formulation executors. The target would be agreement in verified composition and measured reference properties, with deviations attributable to declared measurement uncertainty rather than hidden executor bias.

References

1. Hambidge T, Corless S, Cowen S, Short M, Hopley C, Sears P. Pitfalls and Inherent Biases in Liquid Handling Robotics: Investigations in Automation for SI Traceable Measurements. *Analytical Chemistry*. 2026;98(22):16107-16116. doi:10.1021/acs.analchem.6c00078.
2. Beaucage PA, Martin TB. The Autonomous Formulation Laboratory: An Open Liquid Handling Platform for Formulation Discovery Using X-ray and Neutron Scattering. *Chemistry of Materials*. 2023;35(3):846-852. doi:10.1021/acs.chemmater.2c03118.
3. Tom G, Schmid SP, Baird SG, Cao Y, Darvish K, Hao H, Lo S, Pablo-García S, Rajaonson EM, Skreta M, Yoshikawa N, Corapi S, Akkoc GD, Strieth-Kalthoff F, Seifrid M, Aspuru-Guzik A. Self-Driving Laboratories for Chemistry and Materials Science. *Chemical Reviews*. 2024;124(16):9633-9732. doi:10.1021/acs.chemrev.4c00055.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-408 contains no comparative recommendation between commercial products.

Data availability

ER-408 is a literature-based engineering review; no new experimental dataset was generated.