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Md Aminul Islam

University of California San Diego

Sara Adibi

San Diego State University

James Friend

`jamesfriend@wustl.edu`

Washington University in St. Louis

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Predicting droplet landing in angle-controlled surface acoustic wave jetting

Md Aminul Islam^{1,2}, Sara Adibi², James Friend^{1,3*}

¹Medically Advanced Devices Laboratory, Department of Mechanical
and Aerospace Engineering, University of California San Diego, 9500
Gilman Dr., La Jolla, 92093, California, USA.

²College of Engineering, Mechanical Engineering, San Diego State
University, 5500 Campanile Drive, San Diego, 92182, California, USA.

^{3*}Medically Advanced Devices Laboratory, Department of Mechanical
Engineering and Materials Science, Washington University in St. Louis,
1 Brookings Drive, St. Louis, 63130, Missouri, USA.

*Corresponding author(s). E-mail(s): jamesfriend@wustl.edu;
Contributing authors: aislam@sdsu.edu; sadibi@sdsu.edu;

Abstract

Nozzle-free droplet generation eliminates the need for a dispensing orifice, but useful printing also requires control over where droplets are deposited. Here we demonstrate predictable droplet deposition using a nozzle-free, angle-controlled surface acoustic wave jetting platform. Opposing focused interdigital transducers steer droplets from a pendant parent drop toward a collection substrate, with the ejection angle set by the time-integrated acoustic acceleration imbalance. The overall acceleration ratio identifies the operating window for single-droplet ejection and separates it from no-ejection, satellite-droplet, and multiple-droplet regimes. We then connect ejection angle to landing position through a geometric deposition model referenced to a balanced shot in each experiment. At a 5.2 mm parent-drop-to-substrate spacing, 80 steered shots across twenty experiments show strongly anisotropic relative placement scatter: 0.59 mm in the steering direction and 0.06 mm transverse to it. In tests conducted independently over several days, a model calibrated on six earlier collection dates predicted landing positions on two later dates with a root-mean-square error of 0.71 mm; bootstrap resampling placed the 95% confidence range for this error between 0.41 and 1.01 mm. The results establish a practical framework for predicting relative

droplet landing in angle-controlled surface acoustic wave jetting and identify the limits imposed by steering angle, separation distance, and actuation regime from an orifice-free, clog-free droplet ejection method.

Keywords: Acoustofluidics, Surface acoustic waves, Acoustic droplet ejection, Nozzle-free printing, Droplet deposition, Droplet positioning

1 Introduction

Precise microdroplet deposition is important for bioprinting, printed electronics, diagnostic assays, and microscale materials assembly (Truby 2016; Hulme 2024; advanced 2025). Conventional drop-on-demand inkjet printing has enabled scalable patterned deposition, yet the use of a nozzle can restrict the range of printable materials. Clogging, shear exposure, thermal stress, and sensitivity to particle loading are especially limiting when working with cells, soft biomaterials, polymer suspensions, and functional inks (de Gans et al. 2004; You et al. 2024; Zhao et al. 2022; Heinrich et al. 2019; Alvarez et al. 2008). These limitations motivate methods that can generate droplets without passing material through a small orifice prone to clogging.

Several noncontact approaches have been developed to address this challenge. Laser-induced forward transfer can deposit a wide range of materials with high spatial resolution, but often requires specialised optical components and absorbing donor layers, and jet breakup may be difficult to control for complex or viscoelastic liquids (Türköz et al. 2018; Theodorakos et al. 2019; Serra and Piqué 2019; Piqué and Chrissey 2002). Other acoustic and cavitation-based jetting methods provide useful alternatives, although they may require complex alignment or careful control of transient regimes (Roudini et al. 2023). Acoustophoretic printing achieves material-independent drop-on-demand placement across a wide viscosity range using a Fabry–Pérot resonator (Foresti et al. 2018), and nozzle-free acoustic droplet printing has been applied

to high-concentration bioinks and tumor microenvironments (Chen et al. 2021); recent reviews survey the broader role of acoustics in additive manufacturing (Chen et al. 2025). Within surface acoustic wave (SAW) jetting specifically, thin-film transducers have been used to vary the jetting angle over a wide range ($\sim 16\text{--}55^\circ$) for printing applications (Li et al. 2020). Surface acoustic wave jetting offers a compact route to nozzle-free actuation because energy from a piezoelectric substrate can be coupled directly into a small parent drop to drive jet formation and droplet pinch-off (Friend and Yeo 2011).

SAW-based microfluidic jetting is attractive because the device is compact, the actuation is rapid, and the liquid does not need to pass through a nozzle. Prior work has shown that SAW devices can eject droplets, dispense biological samples, and support continuous or repeated droplet generation (Tan et al. 2009; Bhattacharjee et al. 2011; Castro et al. 2018; Connacher et al. 2018; Friend 2023; Mei et al. 2020; Friend and Yeo 2011; Yeo and Friend 2014; Rufo et al. 2022). Thin-film and alternative-substrate SAW devices have likewise been characterised for discrete droplet manipulation including pumping and jetting (Zhou et al. 2015), and the underlying jetting deformation and pinch-off mechanisms have been examined in both open and confined geometries (Lei and Hu 2020; Lei et al. 2020). Focused interdigital transducers can localize acoustic energy at a parent drop, and opposing transducers allow the direction of the acoustic streaming impulse to be adjusted, providing a natural route to steering droplets without moving either the source drop or the printhead; numerical and experimental studies of interdigital transducer configuration have shown that transducer placement strongly influences the resulting streaming and jetting behaviour (Biroun et al. 2021).

The physics of controlled-angle SAW jetting was established by Connacher *et al.* (Connacher et al. 2020). That work showed that droplet ejection is not limited to the Rayleigh angle when surface tension and gravity are included with acoustic streaming, introduced a force-balance model for the ejection angle and an acceleration ratio

139 Υ for identifying ejection regimes, and demonstrated how spatiotemporal actuation
 140 asymmetry can steer a droplet; subsequent reviews survey the broader SAW jetting
 141 landscape (Ning et al. 2023; Connacher et al. 2018). The remaining printing questions
 142 are different: once a droplet is steered, where does it land; how large is the placement
 143 error; and under what conditions can sequential droplets form a reliable line?
 144
 145 This work addresses these questions. We use a downward-facing SAW jetting
 146 configuration in which droplets are ejected from a pendant parent drop toward a col-
 147 lection substrate. For pendant-drop SAW jetting, we translate the controlled-angle
 148 ejection model into a quantitative deposition characterization: we connect ejection
 149 angle to landing position relative to a per-experiment balanced reference, quantify
 150 the lateral and transverse placement repeatability and its anisotropy, evaluate the
 151 geometric amplification of error with angle and separation distance, test whether the
 152 ratio-to-landing mapping transfers across experiments conducted on different days,
 153 and use centerline and width metrics to characterize the one-dimensional line geom-
 154 etry that our method produces. We emphasize that all placement metrics here are
 155 referenced to an internal per-experiment origin rather than an externally defined sub-
 156 strate coordinate; the work therefore demonstrates relative landing repeatability and
 157 calibrated relative prediction, not absolute target placement. Placement precision at
 158 the sub-millimeter scale reported here is modest relative to the tens-of-micron place-
 159 ment achieved by established inkjet, acoustophoretic, and machine-learning-guided
 160 drop-on-demand printing (Foresti et al. 2018; Derby 2010; Khalil et al. 2025); the
 161 contribution is the characterization framework and the demonstration that this clog-
 162 resistant method via SAW pendant-drop landing is repeatable and predictable in a
 163 relative sense, providing a foundation for future absolute-placement work.
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2 Results and discussion

2.1 Deposition framework and operating regimes

Figure 1 links the ejection model to the deposition problem. Panel (a) shows the geometric framework: a droplet ejected at angle θ from a pendant parent drop crosses separation distance L to reach the collection substrate. In-plane angular perturbation $\Delta\theta$ and transverse perturbation $\Delta\phi$ move the actual landing position away from the ideal location, giving errors $\Delta x = \bar{x} - x$ and $\Delta y = \bar{y} - y$. Panels (b)–(e) show the ejection regime maps as functions of the four principal actuation parameters.

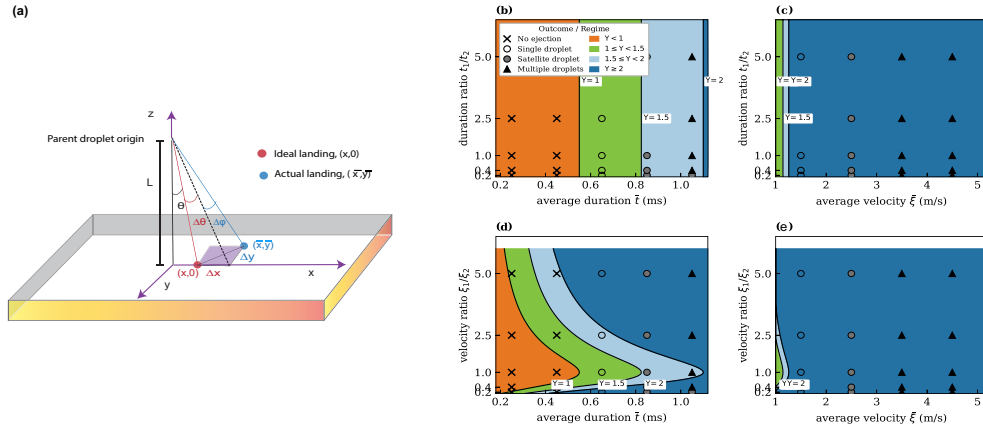


Fig. 1 Framework for predicting droplet landing and selecting actuation regimes. (a) Geometric definition of deposition error: a droplet ejected at angle θ has an ideal landing location $(x, 0)$ after crossing separation distance L ; in-plane angular perturbation $\Delta\theta$ and transverse perturbation $\Delta\phi$ move the measured landing position to $(\bar{x}, \bar{y})$, giving errors Δx and Δy . (b) Regime map: duration ratio t_1/t_2 versus average duration $\bar{t}$. (c) Duration ratio versus average vibrational velocity $\bar{\xi}$. (d) Velocity ratio ξ_1/ξ_2 versus average duration (corrected Υ contours; boundaries curve because $A_s \propto \xi^3$ makes total streaming input depend on the velocity ratio). (e) Velocity ratio versus average vibrational velocity. Colored regions denote no-ejection (orange, $\Upsilon < 1$), single-droplet (green, $1 \leq \Upsilon < 1.5$), satellite (light blue, $1.5 \leq \Upsilon < 2$), and multiple-droplet (blue, $\Upsilon \geq 2$) regimes. The single-droplet region defines the useful operating window for predictable deposition

The regime maps show that steering and droplet formation are governed by different combinations of actuation parameters. The ratio quantities, t_1/t_2 and $v_{a,1}/v_{a,2}$,

determine the signed acoustic imbalance and therefore the ejection direction. The average quantities, $\bar{t}$ and $\bar{\xi}$, determine the total acoustic input and therefore whether a droplet is ejected cleanly. Conditions just above $\Upsilon = 1$ are most useful for deposition because they provide sufficient acoustic input for ejection without introducing satellites or multiple droplets. The boundaries $\Upsilon = 1, 1.5$, and 2 are empirical thresholds calibrated to the transition labels observed in the present dataset; the Connacher *et al.* model predicts the overall scaling of Υ with input parameters, while the specific threshold values are adjusted here to match the experimental classifications. Operationally: a ‘single droplet’ denotes one droplet detached cleanly per burst; a ‘satellite droplet’ denotes one primary droplet accompanied by one or more secondary droplets smaller than half the primary diameter; ‘multiple droplets’ denotes two or more droplets of comparable size per burst.

Because $A_s \propto v_a^3$, the total streaming from two transducers at ratio r is $A_{s,1} + A_{s,2} \propto 8\bar{\xi}^3(r^3 + 1)/(r + 1)^3$. The dimensionless acceleration ratio therefore takes the form

$$\Upsilon = K \bar{t} \bar{\xi}^3 \frac{8(r^3 + 1)}{(r + 1)^3}, \quad (1)$$

where K absorbs the fluid and drop-volume constants. The Υ contours in the $(\bar{\xi}, r)$ plane are curved lines that shift leftward as r departs from unity because asymmetric actuation concentrates streaming into one transducer and raises the total acoustic input at the same mean velocity. At $r = 0.2$ the $\Upsilon = 1$ ejection threshold shifts to approximately 25% below its symmetric value, while the effect is modest ($\sim 10\%$) near $r = 0.5$. The duration-ratio maps in panels (b) and (c) have straight vertical boundaries because the duration ratio does not enter the cubic velocity term; the correction applies only to panels (d) and (e).

2.2 Ejection angle versus velocity ratio

Figure 2 shows the ejection angle versus vibrational velocity ratio for $n = 20$ shots per ratio (one shot per experiment across 20 experiments on up to 8 collection dates). The balanced condition $r = 1$ produces ejection near vertical ($\theta \approx 0^\circ$). As r departs from unity, the acoustic imbalance grows and $|\theta|$ increases. The scatter at each ratio reflects combined shot-to-shot variability and day-to-day drift; $\sigma_\theta \approx 4.9^\circ$ estimated from this dataset is therefore an upper bound on instantaneous angular jitter.

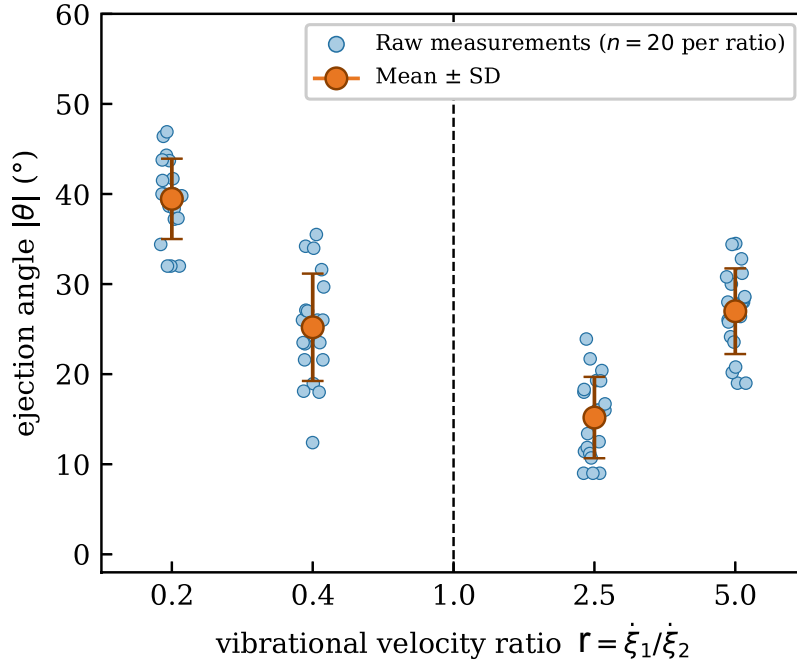


Fig. 2 Ejection angle $|\theta|$ as a function of vibrational velocity ratio $r = \dot{\xi}_1/\dot{\xi}_2$. Each point is one shot from a distinct experiment ($n = 20$ shots per ratio, one per experiment across 20 experiments on up to 8 collection dates; scatter therefore reflects combined shot-to-shot and day-to-day variability, not purely instantaneous repeatability). Individual measurements (light points) and mean $\pm$ standard deviation (SD; filled markers) are shown. The dashed vertical line marks $r = 1$ ($\theta = 0^\circ$). Increasing imbalance increases $|\theta|$, consistent with the signed time-integrated acceleration imbalance $t_1 A_{s,1} - t_2 A_{s,2}$

At balanced actuation the two acoustic impulses are equal and the ejection angle approaches zero. For ratios below or above one the acoustic balance is broken and the

droplet is steered away from vertical. The response is strong because $A_{s,i}$ scales with the cube of acoustic particle velocity. The effect of parent drop volume on ejection angle is discussed in Fig. S2 of the Supplementary Information as an exploratory result; briefly, larger parent drops produce smaller ejection angles under otherwise identical actuation, and source-volume drift is therefore a candidate contributor to the day-to-day variation visible in Fig. 2.

From Eq. (1), the factor $8(r^3 + 1)/(r + 1)^3$ is symmetric under $r \rightarrow 1/r$, so the ejection model predicts equal $|\theta|$ for reciprocal ratio pairs at the same mean velocity. The data show a consistent asymmetry: $|\bar{\theta}| = 39.5^\circ$ at $r = 0.2$ versus 27.0° at $r = 5.0$, and 25.2° at $r = 0.4$ versus 15.2° at $r = 2.5$ (Table S3). This systematic offset is consistent with a fixed inter-FIDT power or impedance imbalance, which is a device-level bias rather than shot-to-shot noise, that shifts the acoustic null away from the geometric center of the parent drop. Such a bias produces a constant additive offset in the signed imbalance $t_1 A_{s,1} - t_2 A_{s,2}$ and would be removed by an in-situ recalibration of the velocity ratio scale. It does not affect the deposition repeatability statistics, which are referenced to each condition's own mean landing position.

2.3 Landing variability and angular-noise scaling

Figure 3 characterizes shot-to-shot landing placement variability at $L = 5.2$ mm across twenty experiments (one shot per ratio per experiment). Within each experiment the $r = 1$ landing defines the coordinate origin $(x, y) = (0, 0)$; the signed errors e_x and e_y are therefore deviations from each commanded condition's in-sample mean, and the overall mean error is zero by construction. This analysis quantifies angular-noise scaling and placement variability rather than independent target prediction, which is addressed separately in Sect. 2.4. Panel (a) shows the signed errors versus ejection angle with the angular noise envelopes $\pm L\sigma_\theta \sec^2 \theta$ and $\pm L\sigma_\phi$. Panel (b) reports the

root mean square error within absolute angle bins. Panel (c) shows the error, and panel (d) compares the measured landing against the geometric prediction $L \tan \theta$.

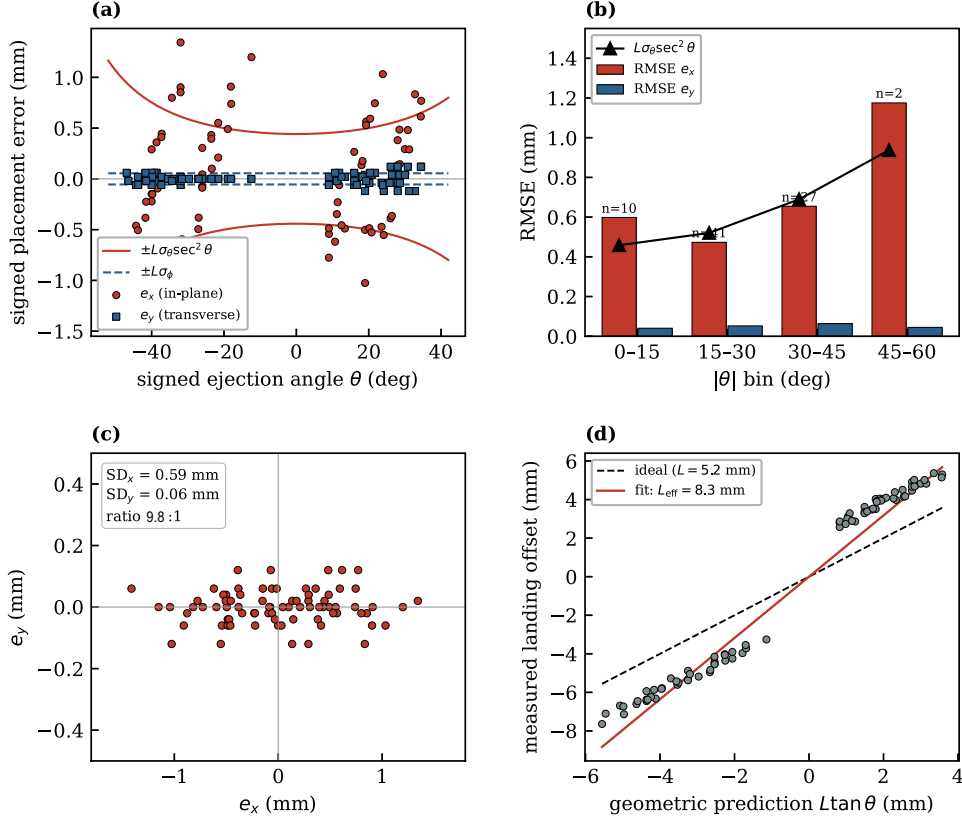


Fig. 3 Repeated-shot/run-to-run relative landing variability and angular-noise scaling for angle-controlled SAW jetting at $L = 5.2$ mm ($n = 80$ steered shots, one shot per ratio per experiment, PDMS-coated substrate). Errors are deviations from in-sample condition means; mean error is zero by construction. (a) Signed in-plane scatter e_x and transverse scatter e_y versus ejection angle θ . Solid curves show the angular-noise envelope $\pm L\sigma_\theta \sec^2 \theta$; dashed lines show the constant transverse envelope $\pm L\sigma_\phi$. (b) RMS scatter within absolute angle bins; the angular jitter model with $\sigma_\theta \approx 4.9^\circ$ tracks the binned in-plane RMS. (c) Anisotropy: the in-plane scatter exceeds the transverse by roughly an order of magnitude. (d) Measured landing offset versus the geometric prediction $L \tan \theta$. The slope corresponds to an empirical lever arm $L_{\text{eff}} \approx 8.3$ mm, about 1.6 times the physical separation

Table 1 quantifies the anisotropy. The in-plane error has a standard deviation of 0.59 mm and grows with steering angle, whereas the transverse error has a standard deviation of 0.06 mm — a $\sim 10:1$ ratio (precisely 9.8:1). The angular jitter model

Table 1 Signed variability statistics about in-sample condition means for the $n = 80$ steered shots at $L = 5.2$ mm (PDMS substrate, one shot per ratio per experiment). Errors are deviations from the per-condition mean, so the overall mean and bias are zero by construction; these values characterize angular-noise scaling and anisotropy, not independent prediction accuracy. The final column is the 95% CI half-width of the condition mean

Component	n	Mean (mm)	SD (mm)	MAE (mm)	RMSE (mm)	Bias (mm)	95% CI half-width (mm)
e_x	80	0.00	0.59	0.48	0.58	0.00	0.13
e_y	80	0.00	0.06	0.04	0.06	0.00	0.01

MAE, mean absolute error; RMSE, root mean square error; CI, confidence interval. The 95% CI is reported as its half-width.

$L\sigma_\theta \sec^2 \theta$, with $\sigma_\theta \approx 4.9^\circ$ calibrated from the same dataset, tracks the measured in-plane RMSE across the populated angle bins. Because σ_θ is estimated in-sample, this comparison is a self-consistency check confirming that the in-plane scatter scales as $\sec^2 \theta$, not an out-of-sample prediction. The $45\text{--}60^\circ$ bin ($n = 2$) is excluded from this quantitative comparison. The transverse error remains bounded because it depends only on the smaller out-of-plane perturbation $\Delta\phi$. These results support the following variability statement: run-to-run relative placement variability is strongly anisotropic. The in-plane component, consistent with angular jitter amplified by $\sec^2 \theta$, grows from ~ 0.5 mm near $\theta = 0^\circ$ and approaches 1 mm in the sparsely sampled $45\text{--}60^\circ$ bin ($n = 2$). The transverse component remains below 0.1 mm across all conditions. Independent predictive accuracy is evaluated next in Sect. 2.4.

High-speed imaging provides measurements of the exit velocity U and neck diameter d_{neck} ($n = 1$ representative frame per condition). The measured values span $U = 0.25$ m/s at $r = 0.2$ ($\theta \approx 45^\circ$) to $U = 1.20$ m/s at $r = 1.0$ ($\theta = 0^\circ$), and d_{neck} increases from approximately $50 \mu\text{m}$ to $160 \mu\text{m}$ over the same range. Applying the Rayleigh breakup scaling (Eggers and Villermaux 2008) $d_{\text{drop}} \approx 1.9 d_{\text{neck}}$ gives ejected droplet diameters from approximately $95 \mu\text{m}$ at $r = 0.2$ to $300 \mu\text{m}$ at $r = 1.0$. The in-plane variability standard deviation of $\sigma_x = 0.59$ mm corresponds to $6.2 d_{\text{drop}}$ at the most strongly steered condition ($r = 0.2$, $d_{\text{drop}} \approx 95 \mu\text{m}$) and $2.0 d_{\text{drop}}$ at $r = 5.0$

($d_{\text{drop}} \approx 300 \mu\text{m}$), showing that placement scatter relative to droplet size decreases as the velocity ratio approaches unity, because less-steered droplets are larger and experience lower $\sec^2 \theta$ amplification.

At the measured $L = 5.2 \text{ mm}$, the best-fit slope of measured landing against $L \tan \theta$ corresponds to an empirical lever arm $L_{\text{eff}} \approx 8.3 \text{ mm}$ (Fig. 3d), i.e. $L_{\text{eff}}/L \approx 1.6$, a $\sim 60\%$ larger effective lever arm than the physical separation. (The slope is reported with a near-zero intercept; an alternative fit allowing a non-zero intercept reduces the apparent slope. Moreover, the per-condition ratio $\hat{x}(r)/[L \tan \bar{\theta}]$ varies from ~ 1.4 to ~ 2.3 across the four ratios, so L_{eff} is a single-parameter summary of a structured residual rather than a true physical length, and the noise envelope in panel (a) is computed at the physical $L = 5.2 \text{ mm}$.) A ballistic estimate shows that at $r = 0.2$ ($\theta \approx 45^\circ$, $U = 0.25 \text{ m/s}$) the straight projection gives $x = 5.2 \text{ mm}$ while the ballistic result ($t_f = (-U \cos \theta + \sqrt{U^2 \cos^2 \theta + 2gL})/g$, $x_{\text{bal}} = U \sin \theta t_f$) gives $x_{\text{bal}} \approx 3.4 \text{ mm}$ —an inward shift, not an outward one. Ballistic curvature therefore cannot explain the overshoot; it acts in the opposite direction. The discrepancy is attributed to a combination of: trajectory-angle measurement rather than immediately before impact, systematic offset in the per-experiment $r = 1$ coordinate origin, and post-impact centroid displacement (Yarin 2006; Josserand and Thoroddsen 2016) on the PDMS-coated substrate. Without fixed-reference absolute position measurements, these three contributions cannot be separated from the available data; L_{eff} is therefore reported as a descriptive empirical observation. Future work measuring the $r = 1$ landing against a fixed geometric target will separate origin-placement bias from spreading and trajectory effects. Reducing L toward the millimeter scale, as in a compact or handheld printhead (Huang et al. 2021), is expected to reduce all three contributions and is identified as a primary route to improved placement accuracy.

2.4 Held-out predictive deposition test

Figure 4 presents the held-out predictive test. The dataset spans eight different collection dates (20 experiments total; one shot per ratio per experiment, four steered ratios $r \in \{0.2, 0.4, 2.5, 5.0\}$ plus one reference shot at $r = 1$). The per-experiment $r = 1$ shot defines the coordinate origin independently for each test-day experiment, so no training-day absolute position information is used on test days. The commanded-ratio-to-landing mapping—the mean in-plane landing position at each ratio—was estimated from the six earliest collection dates ($n_{\text{train}} = 60$; 15 shots per ratio on dates 1–6, one shot per ratio per experiment across 15 experiments) and applied without recalibration to the two later dates ($n_{\text{test}} = 20$; 5 shots per ratio on dates 7–8, one shot per ratio per experiment across 5 experiments).

The held-out prediction achieved $\text{RMSE} = 0.71$ mm and $\text{MAE} = 0.62$ mm. Given the test-set size ($n_{\text{test}} = 20$ shots across 5 experiments), the bootstrap 95% confidence interval on the RMSE is approximately 0.41–1.01 mm; this uncertainty should be borne in mind when interpreting the precision of the result. The largest residual errors occur at $r = 0.2$, the strongest steering condition, where day-to-day drift is most amplified by the $\sec^2 \theta$ projection. The four-ratio mapping transferred to the later experimental days, demonstrating calibrated relative prediction at this scale. We note two limitations of this test. First, the predictor is a four-value lookup of the training-day mean at each commanded ratio; it does not interpolate to untested ratios and does not use the physics model, so it should be read as evidence that the ratio-to-landing relationship is stable across days rather than as a general predictive model. Second, the baseline against which it is compared (predicting the global mean, which is zero by the per-experiment origin convention) is weak, so the apparent improvement factor mainly reflects that different ratios land in systematically different places. Full per-ratio held-out errors, training details, and the baseline comparison are provided in Sect. S10 of the Supplementary Information.

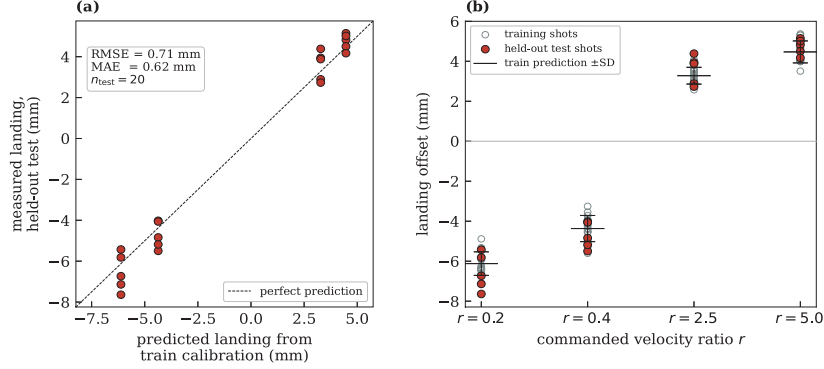


Fig. 4 Held-out predictive deposition test ($n_{\text{train}} = 60$, dates 1–6; $n_{\text{test}} = 20$, dates 7–8; one shot per ratio per experiment). The per-experiment $r = 1$ reference shot defines the coordinate origin independently on training and test days. The training-day condition mean at each ratio is used as the predicted landing for test-day shots. (a) Parity plot: predicted versus measured in-plane landing on the 20 held-out shots (RMSE = 0.71 mm, MAE = 0.62 mm). (b) Per-ratio landing positions for training shots (open circles) and held-out test shots (filled circles) with the training-day mean and standard deviation; the mapping transfers to the later dates, with the largest residual drift at $r = 0.2$, the strongest steering condition

2.5 Illustrative line deposition

After characterizing single-droplet repeatability and calibrated relative prediction, we examined the internal geometry of one-dimensional patterns formed by sequential deposition. This analysis characterizes the *internal geometric fidelity* of each deposited line, that is, its straightness relative to its own mean path and the uniformity of its local width, rather than its placement relative to an externally commanded target, which the present substrate does not reference. Figure 5 shows the extracted line metrics for five printed lines using two independent quantities: the centerline offset $y_c(\ell) = y_{\text{centerline}}(\ell) - \overline{y_{\text{centerline}}}$, which measures local straightness about each line's own mean path, and the local width $w(\ell)$, measured perpendicular to the skeleton centerline (Soltman and Subramanian 2008; Derby 2010; Stringer and Derby 2010; Lohse 2022).

The five lines used the same device and general actuation range as the single-droplet experiments, but each line was printed under a different command condition; the five lines are therefore not statistical replicates. The substrate was coated with

a hydrophilic solution to obtain a contact angle of $\approx 7.6^\circ$ to promote lateral spreading and coalescence. The number of drops deposited per line was as follows: line 1 (12 drops), line 2 (10 drops), line 3 (8 drops), line 4 (11 drops), line 5 (13 drops). Spreading on the hydrophilic surface is the dominant source of width variability and is a confound relative to the steering variability measured in the single-droplet experiments. Segmented masks with centerlines are provided in Fig. S4 of the Supplementary Information.

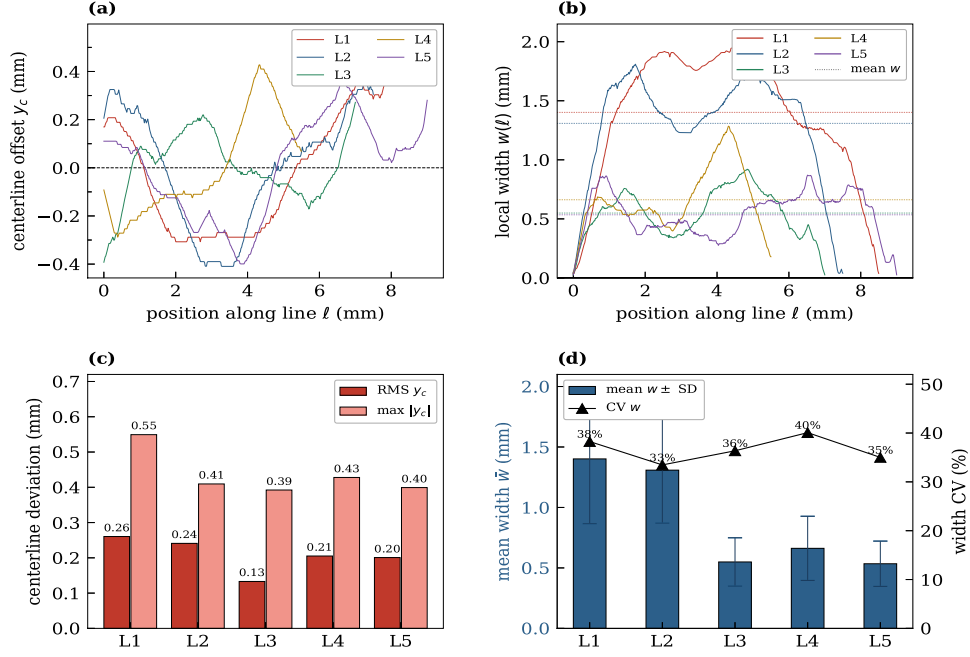


Fig. 5 Quantitative assessment of one-dimensional line deposition fidelity for five printed lines (all quantities in mm). (a) Centerline offset $y_c(\ell)$ along each line; the dashed line marks the ideal $y_c = 0$. This measures local straightness about each line's own mean path, not absolute placement relative to a commanded target. (b) Local width $w(\ell)$ along each line; dotted lines mark each line's mean width. (c) Summary centerline deviation per line: root mean square y_c and maximum $|y_c|$. (d) Summary width statistics per line: mean width with standard deviation (bars) and coefficient of variation (markers). The five lines differ in length and width and represent different operating conditions rather than replicates; the hydrophilic-treated surface introduces wetting and coalescence as confounding variables relative to the single-droplet experiments

Table 2 Line fidelity metrics extracted from the centerline and local width profiles in Fig. 5 (all values in mm). Centerline straightness is quantified by the root mean square offset y_{RMS} , mean absolute offset, and maximum absolute offset about each line’s own mean path. Width uniformity is quantified by the mean local width $\bar{w}$, its standard deviation, and its coefficient of variation. The five lines are different operating conditions, not replicates; the CV range therefore describes individual outcomes, not a statistical characterization of line-fidelity precision

Line	y_{RMS}	Mean $ y_c $	$ y_c _{\text{max}}$	$\bar{w}$	SD w	CV_w (%)
Line 1	0.260	0.232	0.549	1.402	0.536	38.3
Line 2	0.241	0.204	0.410	1.308	0.438	33.5
Line 3	0.133	0.105	0.392	0.549	0.200	36.4
Line 4	0.205	0.178	0.428	0.662	0.265	40.1
Line 5	0.201	0.173	0.399	0.535	0.187	35.0

Among the five lines, line 3 had the smallest centerline root mean square offset (0.13 mm) and line 2 had the lowest width coefficient of variation (33.5%). Because each line was printed under a different command condition with $n = 1$ per condition, and because spreading on the hydrophilic surface is the dominant width confound, these values are reported as a qualitative proof-of-concept demonstration that continuous one-dimensional deposition with quantifiable internal geometry is achievable — not as a statistical characterization of line-fidelity precision. A systematic study would require replicate lines at a single fixed command condition; this is identified as future work. The demonstration nonetheless shows that both centerline and width metrics are needed to describe line geometry: a line can remain near its own mean path while showing local width variability, or hold uniform width while its centerline drifts.

2.6 Estimated recovery-limited repetition rate

Printing rate was estimated from high-speed images. For each input condition, the ejection onset time t_i and the end of visible relaxation t_f were identified frame by frame. The recovery-limited cycle frequency was estimated as

$$f_{\text{est}} = \frac{1}{t_f - t_i}. \quad (2)$$

691 Across $n = 5$ analysed ejection intervals, the mean estimated rate was 7.90 Hz and the
692 highest single-interval value was 8.83 Hz. These values represent inverse relaxation-
693 interval estimates obtained under manual triggering, not demonstrated sustained
694 throughput. Automated waveform timing and closed-loop triggering are expected to
695 improve both rate stability and deposition repeatability.

699

700

701 3 Conclusions

702

703 This work reframes angle-controlled SAW jetting as a deposition control problem. The
704 ejection angle model and regime parameter from Connacher *et al.* provide the basis
705 for steering and for selecting single-droplet conditions. We extend that framework by
706 linking ejection angle to landing position, measuring deposition errors, and quantify-
707 ing line formation. The signed time-integrated acceleration imbalance $t_1 A_{s,1} - t_2 A_{s,2}$
708 controls the direction of ejection, while Υ identifies the ejection regime.

713

714 The landing model explains why deposition error is anisotropic: in-plane error
715 grows as $L\Delta\theta \sec^2 \theta$ and is therefore amplified at high steering angles and large sepa-
716 ration distances, while transverse error depends primarily on the smaller perturbation
717 $L\Delta\phi$. Twenty experiments at $L = 5.2$ mm characterized shot-to-shot repeatability: in-
718 plane scatter SD = 0.59 mm, transverse scatter SD = 0.06 mm (a $\sim 10:1$ ratio), with
719 the in-plane scatter consistent with angular jitter of $\sigma_\theta \approx 4.9^\circ$ amplified by the $\sec^2 \theta$
720 projection factor. A separate held-out date-split test, calibrating the four-ratio land-
721 ing mapping on six earlier collection dates and predicting on two later dates, achieved
722 RMSE = 0.71 mm (bootstrap 95% CI 0.41–1.01 mm; $n_{\text{test}} = 20$ shots across 5 experi-
723 ments), a first demonstration of calibrated relative landing prediction for this platform.
724 All placement metrics are referenced to a per-experiment balanced shot; the work
725 therefore establishes run-to-run relative placement variability and placement predic-
726 tion, while absolute target placement remains for future work. The deposited-centroid
727 span exceeds the straight-line projection at $L = 5.2$ mm; ballistic curvature acts in
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the opposite direction to the observed overshoot, and the discrepancy is attributed to trajectory-angle measurement, per-experiment origin placement, and post-impact centroid displacement on the PDMS substrate. Reducing L toward the millimeter scale, as in a compact or handheld printhead (Huang et al. 2021), is expected to suppress these contributions and is identified as a primary route to improved placement accuracy.

A proof-of-concept line-deposition study showed that the internal geometry of one-dimensional patterns, namely centerline straightness and local width uniformity, can be quantified, with width coefficients of variation of 33–40% across five single-condition demonstrations; a statistically powered line-fidelity study at fixed conditions remains future work. The kinematic projection from a known exit direction to a landing point is independent of fluid properties under the straight-trajectory approximation; the ejection window, angular scatter, droplet breakup, exit speed, and post-impact spreading remain fluid dependent. Specific near-term steps include: (i) reducing L below 2 mm to test the predicted suppression of L_{eff} overshoot; (ii) volume-controlled dispensing to separate parent-drop-volume drift from actuation variability (see Sect. S4 of the Supplementary Information); and (iii) replicate line experiments at a fixed command condition for a rigorous statistical characterization of line fidelity. Future work will also address automated waveform control, real-time feedback, and extended material sets including bio-inks and functional inks (Rufo et al. 2022; Jentsch et al. 2021).

4 Materials and methods

4.1 SAW device assembly and experimental configuration

SAW devices were fabricated on 127.68° Y-rotated, X-propagating lithium niobate (LiNbO_3) substrates (Roditi Ltd., UK) and were designed to operate near 40 MHz. Focused interdigital transducers were patterned using photolithography and electron-beam metal deposition as described by Mei et al. (2020). Each focused interdigital

transducer (FIDT) consisted of 20 finger pairs arranged in a mirrored arc geometry so that acoustic energy was focused at the device center.

A Luer-lock syringe was mounted vertically above the acoustic focal region using a rigid holder. Deionised water was used as the working liquid for the main experiments. Pendant parent drops were formed at the syringe tip and allowed to stabilise before actuation. The collection substrate was positioned below the pendant parent drop on a manually adjustable vertical z stage. The separation distance, L , was defined as the vertical distance between the droplet origin and the collection substrate. Glass microscope slides were used as collection substrates. For single-droplet deposition experiments, slides were coated with polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning, 10:1 base to curing agent ratio, cured at 60°C for 24 h). For line deposition experiments, substrates were treated with a commercial hydrophilic coating (Aculon, San Diego, CA, USA) to promote spreading and continuous line formation; this treatment produces a static contact angle of approximately 7.6°, near the conventional superhydrophilic threshold ($\theta < 10^\circ$), and promotes rapid lateral spreading upon droplet impact.

4.2 Acoustic actuation, calibration, and imaging

The two FIDTs were driven using a dual-channel function generator (WF1968, NF Corporation, Japan) and broadband RF amplifiers (Model 5U1000, Amplifier Research). Sinusoidal bursts were applied to FIDT1 and FIDT2 with independently assigned burst durations t_1 and t_2 . Actuation asymmetry was introduced either by changing the vibrational velocity ratio, $\dot{\xi}_1/\dot{\xi}_2$, or by changing the burst duration ratio, t_1/t_2 . The average burst duration and average vibrational velocity were defined as

$$\bar{t} = \frac{t_1 + t_2}{2}, \quad \bar{\dot{\xi}} = \frac{\dot{\xi}_1 + \dot{\xi}_2}{2}. \quad (3)$$

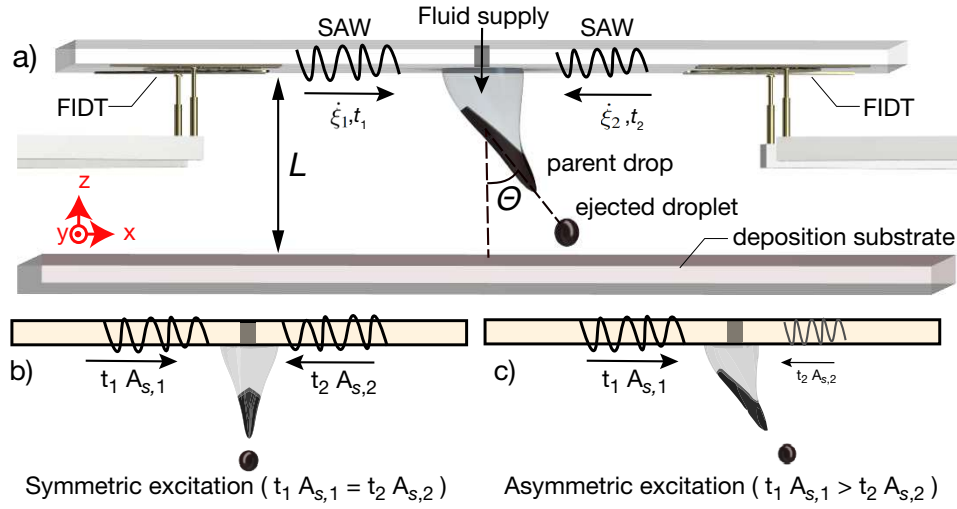


Fig. 6 Experimental configuration for angle-controlled SAW droplet deposition. A pendant parent drop is held below the syringe and above a collection substrate separated by distance L . Opposing focused interdigital transducers generate acoustic streaming toward the parent drop. When the acoustic impulses are balanced, $t_1 A_{s,1} = t_2 A_{s,2}$, the droplet ejects vertically with $\theta = 0^\circ$. When the impulses are unequal, $t_1 A_{s,1} \neq t_2 A_{s,2}$, the droplet ejects at a signed angle θ toward the weaker side

The focal vibrational velocity was measured by laser Doppler vibrometry (LDV; UHF 120, Polytec, Germany); LDV calibration curves for both transducers are provided in Fig. S1 of the Supplementary Information. The measured focal velocity was used to relate the applied input voltage to the acoustic velocity used in the model, following the calibration approach of [Connacher et al. \(2020\)](#). High-speed imaging was performed at 4000 fps using a Fastcam Mini UX100 camera (Photron) with a Nikon 105 mm f/2.8 Micro NIKKOR lens. A diffuse LED source provided back-illumination. Image sequences were analysed in ImageJ and MATLAB to extract ejection angle, droplet trajectory, and line profiles. Unless otherwise stated, repeated measurements are reported as mean values with one standard deviation.

Landing position was determined from top-view images of the dried deposit recorded after each deposited droplet had fully evaporated on the substrate. The centroid of the dried deposit was located in each image after background subtraction using a thresholded binary mask; centroid coordinates were extracted in ImageJ and

converted to physical units using the pixel-to-length calibration described in Sect. S7 of the Supplementary Information. Because the droplet was allowed to dry completely before imaging, the measured centroid reflects the final deposit position rather than a transient spreading state. On the PDMS-coated substrate, evaporation of deionised water produces a thin deposit ring whose centroid was used as the landing position; any systematic offset between this dried-deposit centroid and the true impact centroid is expected to be small and approximately symmetric for the conditions studied, and is subsumed into the empirical lever arm L_{eff} discussed in Sect. 2.3. The balanced $r = 1$ deposit centroid in each experiment served as the coordinate origin, so that all reported placement errors are relative displacements rather than absolute substrate coordinates.

4.3 Ejection angle and regime model

The ejection angle model used here follows the force-balance framework of Connacher et al. (2020). We use it as the basis for controlled droplet steering, then extend the analysis to deposition error. The acoustic streaming acceleration generated by the i^{th} FIDT is

$$A_{s,i} = \frac{\pi v_{a,i}^3 f \beta}{2c_l^2}, \quad (4)$$

where $v_{a,i}$ is the acoustic particle velocity associated with FIDT i , f is the actuation frequency, β is the nonlinear compressibility parameter of the liquid, and c_l is the sound speed in the liquid. Because $A_{s,i}$ scales with $v_{a,i}^3$, small changes in velocity can produce large changes in acoustic input as shown by Orosco and Friend (2022).

For two opposing FIDTs, the signed ejection angle including acoustic streaming, time-averaged surface tension, and gravity is

$$\theta = \arctan \left[\frac{(t_1 A_{s,1} - t_2 A_{s,2}) \sin \theta_R}{(t_1 A_{s,1} + t_2 A_{s,2}) \cos \theta_R - t_{\text{df}} (D_{\text{st}} \sin \theta_s / 4 + g)} \right], \quad (5)$$

where θ_R is the Rayleigh angle, θ_s is the local interface angle, g is gravitational acceleration (noting that in the pendant geometry used here gravity acts in the direction of ejection, reversing its sign relative to the sessile-drop derivation of Connacher *et al.*), and $D_{\text{st}} = 2\pi\gamma r_s/(V\rho_l)$ is the surface tension acceleration with γ the surface tension, r_s the local radius of curvature, V the parent drop volume, and ρ_l the liquid density. The local interface angle θ_s is taken from high-speed images of the deforming parent drop at the moment of column formation. The deformation time

$$t_{\text{df}} = \frac{a - \alpha_r^{-1}/4}{\sin(\theta_R) v_a} + \sqrt{\frac{\rho_l r_s^3}{\gamma}} \quad (6)$$

accounts for the column formation time and the capillary breakup time, where a is the parent drop footprint radius and α_r^{-1} is the Rayleigh wave attenuation length (the characteristic distance over which the surface wave amplitude decays as it couples into the liquid).

Steering is controlled by the signed time-integrated acceleration imbalance $t_1 A_{s,1} - t_2 A_{s,2}$. Balanced actuation gives $t_1 A_{s,1} = t_2 A_{s,2}$ and predicts $\theta = 0^\circ$. Unequal actuation produces a finite signed imbalance and therefore a nonzero ejection angle. Direction can accordingly be controlled by changing t_1/t_2 , $v_{a,1}/v_{a,2}$, or both of them.

The ejection regime was classified using the acceleration ratio

$$\Upsilon = \frac{(t_1 A_{s,1} + t_2 A_{s,2}) \cos \theta_R}{t_{\text{df}}(D_{\text{st}}/4 + g)}. \quad (7)$$

This ratio compares the acoustic streaming input with the restoring effects of surface tension and gravity. Following the Connacher interpretation: $\Upsilon < 1$ indicates no ejection, values just above one produce single-droplet ejection, intermediate values produce satellite droplets, and larger values produce multiple droplets. The single-droplet region defines the useful operating window for predictable deposition.

967 4.4 Landing position model and statistical measures

968
 969 Neglecting ballistic propagation of the ejected droplets based on the short times and
 970 small distances involved, and therefore assuming a simple geometric relation instead,
 971 for an ideal trajectory in the xz plane, a droplet ejected at angle θ lands at
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$$974 \quad x = L \tan \theta. \quad (8)$$

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 979 Small angular perturbations $\Delta\theta$ (in the xz plane) and $\Delta\phi$ (transverse in the yz plane)
 980 shift the measured landing position $(\bar{x}, \bar{y})$ away from the ideal position $(x, 0)$:
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$$982 \quad \bar{x} = L \tan(\theta + \Delta\theta), \quad (9)$$

$$983 \quad \bar{y} = L \tan(\Delta\phi). \quad (10)$$

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 989 For small angular errors the linearized forms are
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$$991 \quad \Delta x = L[\tan(\theta + \Delta\theta) - \tan \theta] \approx L\Delta\theta \sec^2 \theta, \quad (11)$$

$$992 \quad \Delta y = L \tan(\Delta\phi) \approx L\Delta\phi. \quad (12)$$

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 998 In-plane error therefore grows with $\sec^2 \theta$, while transverse error remains approxi-
 999 mately proportional to $L\Delta\phi$. In both directions, the separation distance L acts as a
 1000 lever arm. A droplet reaches the substrate after traveling over a path set by the drop-to-
 1001 substrate spacing, so a larger L projects the same angular jitter over a longer distance
 1002 and increases the scatter in the landing position. The two directions differ in their
 1003 dependence on steering angle. The in-plane error includes the $\sec^2 \theta$ amplification in
 1004 Eq. (11), whereas the transverse error in Eq. (12) has no corresponding angular ampli-
 1005 fication and therefore remains nearly angle independent. This separation-distance
 1006 scaling is examined in Fig. S3 of the Supplementary Information.
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Landing repeatability is quantified using signed errors $e_x = x_{\text{meas}} - x_{\text{pred}}$ and $e_y = y_{\text{meas}} - y_{\text{pred}}$, where x_{pred} and y_{pred} are the in-sample condition means for each commanded ratio. Because the reference is the mean, the mean error is zero by construction; the statistics therefore characterize shot-to-shot angular scatter rather than independent target prediction. Standard deviation, mean absolute error, root mean square error, and the 95% confidence-interval half-width are reported.

Within each experiment, the balanced $r = 1$ shot defines the per-experiment coordinate origin: the landing position of the $r = 1$ droplet is treated as the coordinate zero for all other shots in that same experiment, so that inter-experiment variability in absolute device position does not enter the placement errors. The balanced shots are retained and reported as reference measurements but are excluded from Table 1 because they define the run-level origin. Independent prediction accuracy is evaluated in Sect. 2.4. The ratio-to-landing mapping is trained only on earlier collection dates and tested on later dates; each test-day experiment still uses its own balanced single ($r = 1$) shot to define the relative coordinate origin.

Supplementary information. This article has accompanying Supplementary Information containing: device and acquisition parameters (Table S1) and fixed physical constants (Table S2); LDV calibration curves for both transducers (Fig. S1); ejection angle as a function of parent drop volume under fixed asymmetric actuation (Fig. S2, exploratory, $n = 1$ per volume); height-dependent deposition error measurements at $L = 3.8, 5.2$, and 6.6 mm as a geometric scaling check (Fig. S3); segmented line masks with extracted centerlines and local width profiles for the five printed lines (Fig. S4); image analysis procedures (Sect. S7); per-condition and angle-binned deposition statistics (Tables S3 and S4); the held-out predictive test protocol with per-ratio errors (Sect. S10, Table S5); and full line-fidelity statistics (Table S6).

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1067
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1074
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1076

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1078

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1082

1083 **Data availability.** The processed datasets, calibration files, and analysis scripts
1084 that support the findings of this study are openly available in a Zenodo repository
1085 at <https://doi.org/10.5281/zenodo.21071811>. Raw high-speed image sequences are
1086 available from the corresponding author upon reasonable request owing to their size.
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1092
1093 **Code availability.** The Python analysis and plotting scripts supporting all figures
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1095

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1098 planning, data interpretation, and manuscript revision. J.F. conceived and supervised
1099 the project, contributed to model development and interpretation, and revised the
1100 manuscript. All authors reviewed and approved the final manuscript.
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