

# A Multi-Inlet Extrusion System for Closed-Loop Spatial Profile Control in Large-Format Additive Manufacturing

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**Abstract**—Rectangular nozzles are attractive for large-format additive manufacturing (LFAM) due to their improved deposition efficiency. However, single-inlet feeding of high-aspect-ratio nozzles inherently induces lateral pressure gradients, causing center-heavy flow and eliminating localized control during dynamic trajectories. We introduce a distributed multi-inlet extrusion testbed featuring three independently actuated inlets. Functioning as a programmable fluid manifold, this architecture actively manages the internal flow field. In-line laser profilometry is integrated as a continuous state estimator to quantify cross-sectional bead geometry. Experiments confirm this distributed architecture regularizes flow, achieving nominal steady-state extrusion with 33% less input flow and a 78% reduction in required plunger velocity per actuator compared to a single-inlet baseline. Furthermore, differential actuation enables high-resolution lateral steering and improves deposition under simulated outlet constraints with high allocation efficiency. This work establishes the hardware and state-estimation foundation for dynamically reconfigurable nozzle outlets by mapping inputs to spatial outputs.

## I. INTRODUCTION

Rectangular nozzles are attractive in large-format additive manufacturing for improving deposition efficiency and structural performance. However, conventional single-inlet feeds struggle to supply high-aspect-ratio outlets. Feeding from a single central point inherently induces lateral pressure gradients, causing center bulging and edge thinning [1]. This lack of localized control creates severe defects during dynamic trajectories—such as cornering, where outer radii require more material—leading to excess deposition, tearing, and poor starts and stops. While strategies like rotational printheads or path planning attempt to mitigate these macroscopic errors, uniform deposition requires active flow modulation directly at the nozzle. We introduce a distributed multi-inlet extrusion testbed powered by independent linear actuators. Functioning as a programmable fluid manifold, this architecture actively manages the internal flow field. By differentially actuating the inlets, the system laterally steers material to overcome these physical limitations. This spatial control provides a foundation for end-effectors with dynamically reconfigurable nozzles [2], [3], where sliding teeth block sections to create complex, asymmetric, or discontinuous apertures that single inlets cannot supply. This work validates that multi-inlet architectures efficiently route material to open segments, enabling closed-loop deposition.

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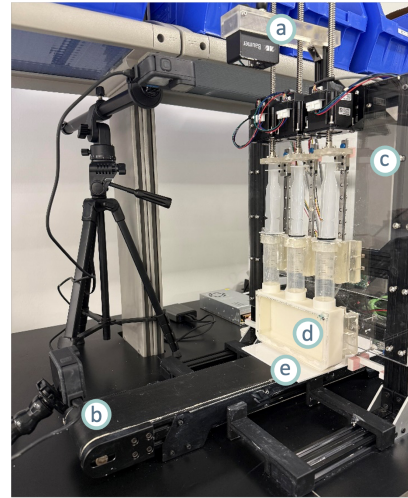


Fig. 1. Testbed comprising (a) laser profilometer sensor, (b) conveyor belt, (c) support structure, (d) multi-inlet extrusion system, and (e) build plate.

## II. SYSTEM ARCHITECTURE

To provide localized deposition control, the proposed architecture is a distributed multi-inlet extrusion system. The architecture consists of a rectangular nozzle fed by three independent syringe inlets. Each inlet is driven by a non-captive linear actuator with magnetic encoder feedback, providing a linear resolution of  $30 \mu m$  per step. Functioning as a programmable fluid manifold, this setup actively manages extrusion and laterally steers material by varying individual inlet velocities. For future autonomous operation, the testbed integrates in-line laser profilometry downstream of the nozzle. This sensor captures the deposited bead's cross-section,  $z(x, t)$ , with lateral and vertical resolutions of  $310 \mu m$  and  $21 \mu m$ , respectively. Operating at a longitudinal spatial resolution of  $1.25 \text{ mm}$ , the profilometer acts as the primary continuous feedback mechanism, quantifying material distribution to enable future closed-loop regulation of the deposition profile.

## III. RESULTS

The multi-inlet architecture is compared against a single-inlet baseline under matched volumetric flow rates. Profilometry data indicates that, compared to the multi-inlet system, single-inlet feeding suffers from severe under-extrusion at lower velocities. The distributed configuration achieves nominal steady-state deposition with 33% less total input flow (Fig. 2). Consequently, the multi-inlet system achieves stable extrusion requiring 78% less plunger velocity per

actuator, significantly lowering the mechanical demand on the extrusion hardware and facilitating scalability for larger robotic AM systems.

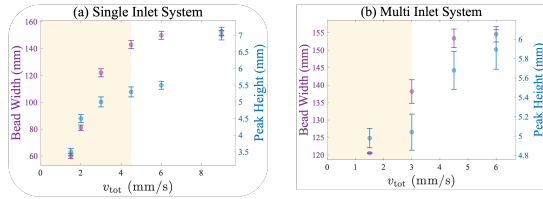


Fig. 2. Bead width and peak height as a function total extrusion velocity. Shaded areas highlight under-extrusion regime. Unshaded areas represent the start of the nominal extrusion regime.

To quantify spatial control, three morphological descriptors are extracted from profilometry data: Lateral Steering Index ( $LSI$ ), Bifurcation Ratio ( $BR$ ), and Dispersion Factor ( $D$ ). Experiments using discrete binary activation patterns (e.g., activating only the left and right inlets,  $p = 101$ ) validate that differential actuation reliably shifts the profile's centroid. Furthermore, graded flow splits confirm that the system provides high-resolution, continuous lateral steering. The  $BR$  and  $D$  metrics show the system's ability to internally redistribute material, distinguishing between center-dominant and edge-loaded profiles at a constant total flow rate (Fig. 3).

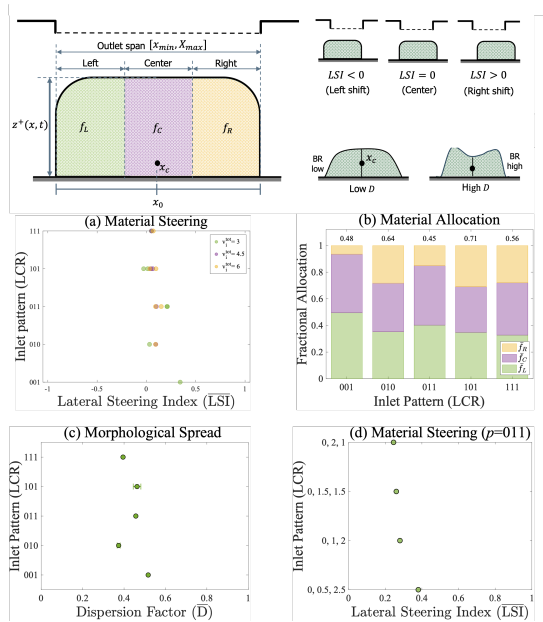


Fig. 3. Analysis of programmable spatial control. (a) Mean  $LSI$  as a function of inlet pattern and total extrusion velocity. (b) Material allocation on the print bead area.  $BR$  annotated per inlet pattern. (c) Mean  $D$  by pattern at extrusion velocity 3 mm/s. (d)  $LSI$  response for graded splits within pattern 011 at extrusion velocity 3 mm/s.

To evaluate adaptability to physical outlet restrictions (simulating discrete aperture states typical of variable-geometry outlets), the nozzle is tested with partial-outlet blockages. Material Allocation Efficiency ( $\eta_{allocation}$ ) measures the fraction of material successfully routed to open

segments. When the central segment is blocked ( $s = 101$ ), the multi-inlet system outperforms the single-inlet baseline in supplying the open edges, maintaining an  $\eta_{allocation} \geq 0.85$ . Across all partial-outlet states, the single-inlet system achieves a Versatility Score of 25%, while the distributed architecture achieves 100% (Fig. 4). This validates the system's capacity to map internal flow, establishing a hardware foundation to support dynamically reconfigurable nozzle outlets.

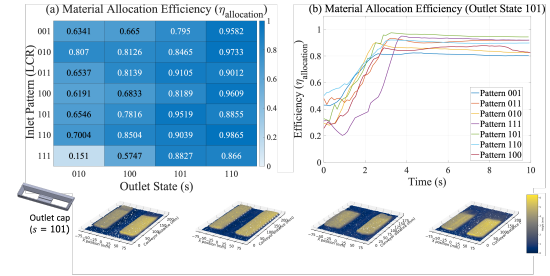


Fig. 4. Allocation Efficiency of the multi-inlet nozzle with simulated outlet states. (a) Time-averaged efficiency across a 15 seconds for every combination of inlet patterns and tested outlet states, (b) Dynamic material allocation efficiency over a 10-second printing window for the 'Left + Right' outlet state (101) comparing all tested inlet patterns.

#### IV. CONCLUSION AND FUTURE WORK

This work presents a distributed multi-inlet extrusion system for large-format additive manufacturing. By replacing a conventional single-inlet feed with three independently controlled linear actuators, the system overcomes the limitations in rectangular nozzles. Experimental validation shows nominal extrusion with 33% less total input flow and a 78% reduction in required velocity per actuator. The architecture enables programmable lateral steering and material allocation efficiency across varying outlet states. Mapping inputs to spatial outputs establishes the foundation for closed-loop profile control. Future efforts will integrate in-line profilometry to enable autonomous, closed-loop spatial profile control, while also exploring potential integration with dynamic, variable-geometry outlet mechanisms (Fig. 5).



Fig. 5. (a) SSE variable-geometry outlet, (b) Integrated architecture: multi-inlet paired with the Selective Sheet Extrusion (SSE) system

#### REFERENCES

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