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Using CNC Techniques to Preserve Traditional Floor Arts : A Digital Manufacturing Approach

Aarav Jaisingh[1], Riya Swamy[1]
[1]Team RoboArt Squad (Team 1435), Bengaluru, Karnataka, India
Mentor: Amit Jaisingh

Abstract—Traditional Indian floor arts such as rangoli and kolam are transmitted almost entirely by oral and observational means, and are consequently vulnerable to loss as demographic and lifestyle patterns change. This paper presents a low-cost Cartesian CNC platform that addresses preservation along three axes rather than one: mechanical reproduction of designs in dry pigment powder, computational acquisition of existing hand-drawn designs from paper archives, and structured transmission of drawing skill to human learners. The machine is a 2 ft × 2 ft belt-driven gantry built on 20 × 20 mm V-slot aluminium extru-sion, with steel-reinforced toothed belts actuated by three NEMA 17 stepper motors under GRBL firmware on an ATmega328P controller, with a gravity-fed powder deposition end-effector in which a tapered gate is driven by the Z axis, allowing depo-sition to be commanded through the standard motion planner without firmware modification. A toolpath generation pipeline converts vector designs into G-code using greedy circular arc regression with tangential continuity enforcement, addressing the instruction-count, planner-buffer and faceting limitations of pure linear interpolation. An offline image processing pipeline re-constructs vector geometry from photographs of handwritten notebook pages under non-uniform illumination; a key empirical finding is that pigment-dot candidate detection must precede morphological removal of ruled lines, as the reverse ordering re-duced recoverable dot candidates from 974 to 8 on a representative page. Single-stroke sikku designs are additionally validated for traceability using Eulerian graph criteria, with routing by a generalised Hierholzer decomposition. The complete system was realised at a component cost of INR 4,000.

Keywords—CNC; cultural heritage preservation; toolpath generation; arc fitting; image vectorisation; Eulerian graphs; GRBL; rangoli; kolam; educational robotics

I. Introduction

A. Background

Floor art occupies an unusual position among traditional Indian craft practices. Designs known regionally as *rangoli*, *kolam*, *muggu*, *alpana*, *mandana* and *aripana* are drawn daily at domestic thresholds using dry pigment powder or rice flour released between the thumb and forefinger. The practice is simultaneously ubiquitous and ephemeral: a design is complete for a matter of hours before being erased by foot traffic, weather or deliberate cleaning, and is redrawn the following morning.

This impermanence is intrinsic to the art form rather than incidental to it. It also means that the corpus of designs has never existed primarily as a physical archive. Transmission occurs through daily observation, with a child watching a parent or grandparent execute a design and gradually assuming portions of the work. Where written records exist at all, they take the form of personal notebooks maintained by individual practitioners, typically drawn on ruled paper with dot lattices and connecting strokes recorded in pencil or ink.

B. Problem Statement

Two distinct preservation failures follow from this transmission model.

The first is archival. Practitioner notebooks are private, unindexed, physically fragile, and drawn on ruled stationery whose printed rules interfere with any naive attempt at automated extraction. When a practitioner dies, the notebook is frequently discarded along with other household paper. There is no systematic digital corpus of regional floor art designs comparable to those maintained for textile motifs or architectural ornament.

The second failure is pedagogical, and is the more consequential. Because transmission depends on sustained daily co-presence between an experienced practitioner and a learner, it is disrupted by exactly the demographic changes now widespread in urban India: nuclear household structure, apartment dwelling without a threshold surface, dual-income time constraints, and geographic separation between generations. A design corpus that is fully archived but no longer executed by anyone is preserved only in the sense that a dead language is preserved.

C. Research Motivation

Existing automation efforts in this domain address reproduction alone. A machine that draws a design faster and more precisely than a human addresses neither failure identified above: it does not acquire the undigitised corpus, and by substituting for the learner rather than scaffolding them, it may actively accelerate the pedagogical failure it purports to remedy.

The motivating position of this work is therefore that reproduction is a necessary but insufficient component of a preservation system, and that a machine intended to preserve a living practice must additionally acquire existing artifacts and transmit executional skill.

D. Objectives

The objectives of this work are:

1. To design and realise a Cartesian CNC platform capable of depositing dry pigment powder on a horizontal floor surface at a component cost accessible to individual households and schools.
2. To develop a deposition end-effector that operates within the constraints of unmodified open-source CNC firmware.

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3. To develop a toolpath generation pipeline that produces geometrically faithful and computationally compact G-code from vector designs.
4. To develop an offline image processing pipeline capable of reconstructing vector geometry from photographs of handwritten notebook pages.
5. To formalise traceability constraints for single-stroke designs using graph-theoretic criteria.
6. To implement and evaluate a graduated-autonomy pedagogical mode in which machine assistance is systematically withdrawn as learner competence increases.

E. Novel Contributions

1. A powder deposition mechanism in which the metering gate is actuated by the Z axis of a standard three-axis controller, permitting deposition timing to be scheduled by the existing motion planner without firmware modification.
2. A tangentially-chained greedy arc regression scheme for toolpath compaction, together with an analysis of the numerical precision required for arc endpoint consistency under GRBL's radius validation.
3. An offline vectorisation pipeline for ruled-paper manuscripts in which the operational ordering of dot detection and rule removal is shown to be determinative of recovery rate.
4. A graduated-autonomy instructional model with automated competence assessment and a work-allocation algorithm that distributes machine assistance non-contiguously across a design.

F. Paper Organisation

Sections II and III establish prior work and system architecture. Sections IV and V describe the mechatronic and electronic subsystems. Sections VI through IX describe the computational framework, image processing pipeline, toolpath generation algorithms, and execution layer. Section X presents the graph-theoretic treatment of single-stroke designs, and Section XI the pedagogical framework. Sections XII and XIII present methodology and results, followed by discussion, applications and conclusions.

II. Literature Review

A. Digital Preservation of Cultural Heritage

Digital heritage preservation has historically concentrated on tangible, durable artifacts — manuscripts, sculpture, architecture — for which photogrammetric and laser-scanning approaches are well established. Intangible and performative heritage has received substantially less methodological attention, and ephemeral practices that leave no durable artifact are poorly served by capture-oriented frameworks. Floor art falls into this least-served category: the artifact is destroyed by design, and what requires preservation is the generative knowledge rather than any particular instance.

B. CNC-Based Artistic Fabrication

Cartesian plotting mechanisms for artistic output are mature. Pen plotters, drawing robots and educational XY gantries are widely documented, and the underlying kinematics, firmware and toolpath conventions are effectively standardised through the open-source CNC ecosystem. The specific problem of depositing loose granular material rather than marking with a pen or cutting tool is comparatively unaddressed, principally because granular flow control introduces failure modes — arching, ratholing, stroke-end smear — with no analogue in subtractive or pen-based fabrication.

C. Prior Art in Automated Rangoli Reproduction

Three prior systems are relevant. The Rang Bot [23] implements a two-axis gantry carrying a powder dispenser over a 60 cm working span, with an image-to-G-code conversion stage and dispensing regulated by a geared DC motor driving a 5 mm orifice. Two characteristics distinguish it from the present work. Its reported axis resolutions differ by more than two orders of magnitude between X and Y, indicating a strongly anisotropic transmission; and the dispenser is driven independently of the motion controller rather than as a planner-scheduled axis, so deposition timing is not sequenced with position by the firmware. A single dispenser is carried, and no multi-pigment workflow is described.

A separate proposal [22] addresses automated rangoli using a wheeled agent with overhead optical feedback and edge-detection-based path derivation, targeting uneven surfaces. This is a closed-loop mobile approach rather than a fixed-frame CNC one, and addresses a different set of constraints.

It should be noted that published work in this specific application area is sparse and consists substantially of student project reports and non-archival proceedings rather than peer-reviewed literature; the comparison in Section XIII-H should be read with that in mind. Commercial stencil-based products such as the *Rangoli Magic Box* achieve reproduction without programmability, transferring a fixed pattern through a perforated template. Educational kit platforms such as those distributed by Witblox provide a programmable gantry but no domain-specific design tooling, toolpath optimisation, or pedagogical layer.

In each case the system boundary terminates at reproduction. None of the surveyed systems acquires existing designs from physical archives, and none addresses skill transmission.

D. Computer Vision for Pattern Digitization

Document image analysis provides well-developed techniques for binarisation under non-uniform illumination, notably adaptive and locally-adaptive thresholding, and for the removal of printed rules and form lines by directional morphological operation. Skeletonisation and crossing-number analysis are standard for stroke extraction from binarised handwriting.

The specific difficulty in the present domain is that the target geometry comprises two semantically distinct layers — a lattice of pigment dots (*pulli*) and the strokes drawn around them — whose visual characteristics overlap substantially with the printed rules that must be removed. This interaction, addressed in Section VII, does not arise in conventional form-processing applications where the content to be preserved is textual.

E. Computational Study of Kolam

Kolam has attracted formal attention as a generative system, with published treatments as picture languages, array grammars and L-systems. This body of work establishes that kolam designs admit rigorous formal description, and in particular that a substantial subclass — the *sikku* or knot kolam — is characterised by continuous single-stroke traversal. Existing work is predominantly generative and analytical; its translation into real-time execution constraints for a physical plotting system has not been reported.

F. Research Gap

The literature therefore establishes mature but disjoint capabilities: CNC fabrication without granular deposition or cultural domain tooling; document vectorisation without dot-stroke layer separation; and formal kolam analysis without physical realisation. No reported system integrates acquisition, reproduction and transmission within a single platform.

III. System Architecture

A. Overall Framework

The system comprises a three-axis Cartesian gantry with an interchangeable end-effector, an embedded motion controller executing GRBL firmware, and a host application providing design authoring, acquisition, toolpath generation and job streaming. The host application is implemented as a single-file Python program and is designed to be fully functional without network connectivity, with the exception of two explicitly optional features.

B. Preservation Model

The architecture is organised around three functional axes, which are treated throughout this paper as coequal rather than as a primary capability with ancillary features.

Reproduction is the execution of a vector design in physical pigment on a floor surface (Sections IV, VIII, IX).

Acquisition is the recovery of vector geometry from existing physical records — principally photographs of practitioner notebooks — into an indexed digital corpus (Sections VI, VII).

Transmission is the structured conveyance of executional skill to a human learner, with machine assistance withdrawn progressively as competence increases (Section XI).

C. Hardware Architecture

The mechanical layer consists of a 20×20 mm V-slot aluminium extrusion frame, belt-driven X and Y carriages running on polymer V-wheels engaging the extrusion profile directly, and a Z-actuated deposition head. The electronic layer comprises an ATmega328P-based controller, a stepper driver carrier shield, three bipolar stepper drivers and a switched-mode power supply. A USB webcam mounted above the working area provides overhead image capture for the assessment function of Section XI-D. Communication with the host is over USB serial.

D. Software Architecture

The host application maintains an internal geometric representation independent of both the input source and the output target. Seven acquisition paths — built-in gallery, direct pen authoring, DXF import, generative image synthesis, photographic import, photographic rangoli conversion and notebook digitisation — converge on this representation, from which toolpath generation, on-screen simulation and pedagogical decomposition all proceed.

E. System Workflow

A complete job proceeds as: design acquisition or authoring $\rightarrow$ geometric preprocessing $\rightarrow$ arc regression and toolpath synthesis $\rightarrow$ on-screen simulation $\rightarrow$ serial streaming with handshake $\rightarrow$ physical execution, with colour-change and refill interruptions scheduled as required.

IV. Mechatronic Design

A. Cartesian Kinematic Configuration

A Cartesian configuration was selected over polar, SCARA or delta alternatives. The determining consideration is that the coordinate frame of the artwork is itself Cartesian in the relevant sense: floor art is authored on a square or rectangular field, dot lattices are predominantly orthogonal or rotated-orthogonal, and the mapping from design space to machine space is therefore affine with no trigonometric transformation. This preserves geometric fidelity without accumulation of transformation error and permits the toolpath generator to emit machine coordinates by direct scaling.

B. Structural Design

The frame is constructed from 20×20 mm V-slot aluminium extrusion forming a 2 ft $\times$ 2 ft working envelope, with corner junctions and carriage bodies fabricated in PLA by fused deposition modelling. This hybrid approach loads the extrusion along its principal axis, where its stiffness-to-mass ratio is favourable, while permitting rapid iteration of the geometrically complex junction and carriage components at negligible cost.

The V-slot profile is structural and kinematic simultaneously. Its chamfered channels form the linear raceway on which the carriages run, so no separate guide rail, shaft or bearing block is required. This eliminates the alignment problem that dominates assembly of rail-and-carriage gantries at this scale, in which parallelism between an independently-mounted rail and the frame member supporting it must be established and maintained by shimming. Here the raceway is a machined feature of the structural member itself and is parallel to it by construction.

C. Linear Motion Transmission

Motion on both principal axes is transmitted by toothed belt over pulleys driven directly from the stepper shafts. The carriages are guided by polymer V-wheels running in the chamfered channels of the extrusion, with eccentric spacers on one wheel of each carriage permitting preload against the raceway to be adjusted after assembly.

The belts are GT2 profile, of 2 mm pitch, with steel-cord reinforcement in a polyurethane body. Reinforcement material is the principal selection consideration and warrants comment, since it determines the dominant positional error term in a belt-driven gantry.

A toothed belt under tension elongates elastically along its free span. Because the free span between the driven pulley and the carriage varies with carriage position, this elongation produces a position-dependent error rather than a constant offset, and it reverses sign on direction change, appearing as apparent backlash. Elongation is governed by the tensile modulus of the reinforcing cord: steel cord is substantially stiffer than the glass-fibre reinforcement conventional in low-cost belts, reducing this error term correspondingly.

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Steel reinforcement additionally exhibits negligible moisture absorption, so belt tension does not drift with ambient humidity — relevant here, as the machine operates in domestic and outdoor threshold environments without climate control.

The consequence for this application is specific. Floor art geometry is dominated by closed loops and by symmetric figures executed as mirrored strokes, in which the machine reverses direction repeatedly within a single design. A positional discontinuity at each reversal is directly visible in the deposited line as a step in an otherwise smooth curve. Minimising the reversal error term is therefore of greater consequence here than in fabrication applications where reversals are infrequent.

Belt transmission was selected in preference to lead screw for three reasons. Traverse velocity is substantially higher for a given motor speed, which is material given that deposition feedrates are already constrained by powder flow behaviour (Section IX-B) and that non-depositing repositioning moves are pure overhead. Moving mass is lower, since the belt itself contributes negligible inertia and no rotating mass scales with axis length. And axis length is not bounded by the rotational dynamics of the transmission element, as discussed in Section XIV-C.

The trade-off accepted is that a belt drive is backdrivable: an external force applied to the carriage will displace it against an unpowered motor. The gantry therefore does not hold position without holding current. In horizontal operation this is inconsequential, as gravity acts normal to both axes of motion. It is the governing constraint on any non-horizontal extension, and is treated in Section XV-D.

D. Powder Deposition End-Effector

1) Hopper geometry and arch prevention. Dry pigment powder in a converging hopper is subject to arch formation, in which interparticle friction and geometric interlocking allow a stable bridge to form across the converging section, arresting flow while material remains above. Arching probability increases with the angle of convergence and with irregularity in the wall profile.

The hopper adopted here uses a parabolic inner wall profile rather than a straight conical taper. A parabolic profile presents a continuously varying wall angle with no discontinuity in curvature at which a stable arch can key, and maintains a monotonic reduction in cross-sectional area along the flow axis. Empirically, straight-cone prototypes exhibited arching requiring manual agitation, whereas the parabolic profile sustained flow without intervention across the range of commercial pigment grades tested.

2) Tapered gate mechanism. Flow is metered at the outlet by a gate that translates vertically. The gate aperture is tapered rather than of constant section, so that gate displacement produces a progressive rather than binary change in effective orifice area, and so that particles trapped at the closing edge are displaced laterally rather than crushed against a square shoulder. The latter property substantially reduced jamming at stroke termination, which in constant-section prototypes produced a characteristic smear at the end of each deposited stroke.

3) Z-axis actuation of the gate. The gate is driven by the third stepper axis, addressed as Z in the emitted G-code. This is the principal architectural decision in the end-effector design.

Deposition could alternatively have been controlled by a servo or solenoid driven from an auxiliary output. That approach was rejected because such an output is not scheduled by the motion planner: it is asserted immediately upon command parsing, whereas queued motion commands execute after an arbitrary planner delay. Deposition timing would therefore lose synchronisation with position, with the error varying according to queue depth.

By assigning the gate to a motion axis, gate transitions are enqueued in the same planner as the XY moves and execute in strict sequence with them. Gate open and close are commanded as:

```
G1 Z0.0500 F150   (open)
G1 Z0.0000 F150   (close)
```

with the small displacement chosen to minimise transition time while remaining well above the positional resolution of the axis. No firmware modification is required, and the arrangement generalises directly to alternative end-effectors: a pen holder actuated on the same axis performs lift and lower, and a syringe plunger performs advance and retract, without alteration to the toolpath generator.

E. Mechanical Calibration

The transformation from design space to machine space is nominally isotropic. In a belt-driven axis the theoretical scale factor is determined exactly by belt pitch, pulley tooth count and driver microstepping, and requires no empirical correction; residual error arises only from pulley pitch-diameter tolerance and from belt tension differences between axes.

A per-axis scalar correction is nonetheless applied at the point of G-code emission (Section VI-A), with values determined by the procedure of Section XII-C. The correction factors carried in the present build are $C_x = 1.00$ and $C_y = 0.84$.

F. End-Effector Modularity

The mounting interface and the Z-axis actuation scheme described above are medium-agnostic. Table 1 summarises the substitutions required to address related art forms outside the dry-powder floor domain; these are presented as design anal-

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ysis rather than as realised results, and are discussed further in Section XV-D.

TABLE 1: End-effector substitution analysis

Medium	Z-axis function	Toolpath change
Dry powder (realised)	Gate open/close	None
Ink on paper	Pen lift/lower	Region fill; reduced arc tolerance
Viscous paste	Plunger advance/retract	Retraction scheduling

V. Electronic Control System

A. Embedded Controller Architecture

Motion control is executed on an ATmega328P microcontroller in an Arduino Uno form factor, running GRBL firmware. The controller performs G-code parsing, look-ahead trajectory planning, acceleration management and step pulse generation. Selection was governed by the availability of a mature, well-documented open-source firmware with a stable G-code dialect, and by unit cost and replacement availability in the target deployment context.

The principal constraint accepted with this selection is that the planner buffer and serial receive buffer are small in absolute terms, which shapes the streaming protocol described in Section IX-C.

B. Stepper Motor Drive Electronics

Three bipolar stepper drivers are carried on a shield interposed between the controller and the motors. The motors are NEMA 17 frame units of type 17HS3401, rated at 1.3 A per phase.

Motor selection warrants comment. A higher-torque variant in the same frame, the 17HS4401 at 1.7 A per phase, was evaluated and rejected. The A4988 driver dissipates heat proportional to the square of the regulated coil current, and at 1.7 A the driver entered thermal shutdown during extended jobs without forced-air cooling. The 1.3 A motor operates within the driver's passive thermal envelope while providing torque margin adequate for the gantry mass in horizontal operation. This margin is not adequate for vertical operation, as noted in Section XV-D.

C. Microstepping Configuration and Current Limiting

The drivers are configured for $1/16$ microstepping by jumper selection on the carrier shield. With $1.8°$ motors this yields 3200 steps per revolution; driving a 20-tooth pulley on 2 mm-pitch belt gives 40 mm of carriage travel per revolution and therefore a nominal resolution of 80 steps/mm, or 12.5 μm per microstep. This is an order of magnitude finer than the deposited line width and is not the limiting term in positional accuracy. Coil current is limited by adjusting the on-board reference potentiometer, which sets the peak regulated current per phase in proportion to the reference voltage and inversely to the current sense resistance of the driver carrier. The limit was set empirically: the potentiometer was advanced until the motors held position reliably under the worst-case simultaneous two-axis acceleration, and no further, so as to remain within the passive thermal envelope discussed above.

D. Power Management

The system is supplied from a switched-mode power supply delivering 12 V at 10 A. Steady-state draw with three axes energised is substantially below this rating; the margin accommodates the transient demand during simultaneous acceleration on both principal axes, which is the worst case for supply loading.

E. Communication Architecture

The host communicates with the controller over USB serial at 115,200 baud. Protocol details, including the connection establishment sequence and flow control discipline, are given in Section IX-C.

VI. Computational Framework

A. Coordinate Transformation Model

Three coordinate frames are maintained: a screen frame in pixels, a machine frame in dimensionless machine units, and a physical frame in millimetres.

The machine frame spans $[0, 4.7]$ on both axes. The correspondence to physical dimension is established by a single measured constant, the deposition span of the working mat, $S = 240.0$ mm, giving

$$\lambda = \frac{S}{X_{\max}} = \frac{240.0}{4.7} \approx 51.06 \text{ mm/unit} \tag{1}$$

The screen-to-machine transformation accounts for canvas margins and for the inversion of the vertical axis between screen convention (origin top-left, y increasing downward) and machine convention (origin bottom-left, y increasing upward):

$$m_x = \frac{p_x - L}{W} X_{\max} \tag{2}$$

$$m_y = \frac{H - (p_y - T)}{H} Y_{\max} \tag{3}$$

where L and T are the left and top canvas margins and W, H the usable canvas extents in pixels.

The forward and inverse transformations are implemented as exact functional inverses and are used throughout the application for interactive coordinate reporting. Critically, the per-axis calibration factors C_x, C_y of Section IV-E are *not* applied within these transformations. They are applied only at the point of G-code emission:

$$g_x = C_x\, m_x, \qquad g_y = C_y\, m_y \tag{4}$$

This separation is deliberate. Were calibration folded into the display transformation, a design authored on screen would be silently distorted relative to its stored representation, and successive edit-and-save cycles would compound the distortion. Confining calibration to the export boundary ensures that the stored design is a faithful record independent of the calibration state of any particular machine — a requirement that follows directly from the archival objective of Section I-D.

B. Internal Geometric Representation

A design is represented as an ordered list of shape records. Each record contains a list of paths, each path being an ordered sequence of vertices in machine coordinates; a nominal colour; and an optional per-path colour list permitting a

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single shape to carry multiple pigment assignments. Curved geometry authored as parametric curves is retained in parametric form until toolpath generation, at which point it is resampled (Section VIII-B).

This representation is deliberately minimal. It is the sole interface between the seven acquisition paths and the three consumers — toolpath generation, on-screen simulation and pedagogical decomposition — and its stability is what permits acquisition methods to be added without modification to the execution layer.

C. Design Acquisition Framework

Seven acquisition paths populate the internal representation:

1. A curated built-in gallery of regional designs.
2. Direct authoring with a pen tool supporting 2-, 4- and 8-fold mirror symmetry.
3. DXF import, implemented over a standard CAD parsing library with a fallback raw entity scanner for malformed files.
4. Generative image synthesis, with the resulting raster converted to vector geometry by contour extraction. This path requires network connectivity.
5. Photographic import with contour tracing.
6. Photographic conversion of an arbitrary image to a stylised rangoli rendering.
7. Notebook digitisation, described in Section VII.

Contour-based paths (4–6) share a common raster-to-vector procedure: greyscale conversion, Gaussian smoothing at 5×5, inverse binary thresholding, morphological closure, connected-component contour retrieval with hierarchy, area-ranked retention of the largest components, polygonal approximation at a tolerance proportional to contour perimeter, and uniform contraction about the centroid to provide deposition margin.

D. Digital Archiving Methodology

Designs are persisted in a structured local store together with provenance metadata. The archival requirement drives two design constraints noted elsewhere: the exclusion of calibration from the stored representation (Section VI-A), and the requirement that the acquisition pipeline of Section VII operate without network dependency, since the deployment context for notebook digitisation — private homes, often in areas with intermittent connectivity — cannot be assumed to have reliable network access at the moment of capture.

VII. Image Processing and Vector Reconstruction

A. Problem Characterisation

The acquisition target is a photograph of a handwritten notebook page bearing a floor art design. The following properties distinguish this from conventional document vectorisation.

The substrate is ruled stationery. Printed rules are of comparable stroke width to the hand-drawn content and, being straight and regularly spaced, are readily separable by directional morphology — but only if they can be separated without collateral loss of content.

The content comprises two semantically distinct layers. The *pulli* dot lattice defines the design's structural skeleton; the strokes are drawn in reference to it. Both must be recovered, and must be recovered as distinct layers, because the pedagogical mode of Section XI requires the ability to deposit dots without strokes.

Capture conditions are uncontrolled: handheld photography under domestic lighting, with perspective distortion, non-uniform illumination and variable focus.

B. Acquisition and Normalisation

The input image is rescaled such that its maximum dimension does not exceed 1200 pixels, with upscaling of small inputs permitted to a factor of 4.0. This bound is imposed for computational tractability on modest hardware and is well above the resolution at which dot and stroke features remain separable.

A polarity test is then applied. Designs may be recorded as dark pigment on light paper or, in the case of chalk on slate or a dark floor surface, as light content on a dark ground. Otsu's method is applied to obtain a global threshold, and the minority tone class is identified. Where the minority class is the lighter, the image is inverted, ensuring that all subsequent stages operate on a consistent dark-content-on-light-ground convention.

C. Adaptive Thresholding

Global thresholding fails on handheld domestic captures owing to illumination gradients across the page. Adaptive Gaussian thresholding is applied with a neighbourhood block size scaled to the image dimensions:

$$b = \max\left(15,\ \left(\left\lfloor \frac{\min(h,w)}{20} \right\rfloor\right) \mid 1\right) \qquad (5)$$

where the bitwise disjunction with unity enforces the odd-size requirement of the neighbourhood window, and the floor of 15 prevents degeneration to a window smaller than the stroke width on low-resolution inputs. A constant offset of 10 is subtracted from the local mean. The binarised result is opened with a 3×3 elliptical structuring element to suppress isolated noise arising from paper texture.

D. Ordering of Dot Detection and Rule Removal

This subsection reports the principal empirical finding of the acquisition pipeline.

Both ruled lines and pigment dots must be removed from the stroke layer: the rules because they are not content, the dots because they belong to a separate output layer and would otherwise be traced as spurious closed strokes. The natural implementation order — clean the image first, then detect features — was found to be incorrect.

Ruled lines are removed by morphological opening with long, thin structuring elements oriented horizontally and vertically, retaining only structures of substantial extent along one axis and minimal extent along the other. The difficulty is that a dot lying on a printed rule is topologically connected to that rule in the binarised image. Under opening, the rule is identified as a long thin structure, and the dot — being a small protrusion on it — is removed as part of the same connected structure.

Because rules on ruled stationery are regularly spaced and dot lattices are also regularly spaced, a substantial fraction of dots in any given design lie on or adjacent to a rule. On a

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representative captured page, performing rule removal before dot detection reduced the number of recoverable dot candidates from **974 to 8** — a loss of over 99% of the structural lattice, and sufficient to prevent lattice estimation entirely.

The pipeline therefore performs dot candidate detection on the thresholded image *prior* to rule removal, retains the resulting candidate set, and only then removes rules from the stroke layer. The detected dots are additionally subtracted from the stroke layer before skeletonisation, so that each feature class is processed exactly once.

The general principle — that feature detection should precede any morphological cleaning operation whose structuring element is of comparable scale to the features sought — is stated here because it is likely to generalise to other ruled-substrate vectorisation problems.

E. Dot Detection and Lattice Estimation

Dot candidates are generated by connected-component analysis with filtering on area, aspect ratio and fill ratio relative to the component's bounding box, retaining approximately circular compact components. The candidate set is bounded at 500 to limit downstream combinatorial cost.

A lattice is then fitted to the candidate set. The dominant lattice orientation is estimated from the angular distribution of inter-candidate displacement vectors, and the lattice pitch from the modal magnitude of nearest-neighbour displacements. Candidates are assigned to lattice sites, and sites with no supporting candidate are recorded as absent rather than interpolated, since incomplete lattices occur legitimately in many designs.

F. Perspective Correction via Grid Snapping

Handheld capture introduces perspective distortion. Rather than estimating a homography from page corners — unreliable where the page is not fully visible or the boundary is obscured — correction is derived from the fitted lattice itself. The lattice provides a dense set of correspondences between observed positions and their idealised regular positions, from which the rectifying transformation is estimated and applied to the extracted stroke geometry.

This approach exploits a property specific to the domain: the content itself contains a known-regular reference structure, which conventional document images do not.

G. Skeletonisation and Stroke Extraction

The stroke layer, having had rules and dots removed, is reduced to unit-width by iterative morphological thinning. The skeleton is then traversed by crossing-number analysis: each skeleton pixel is classified by the number of transitions in its 8-neighbourhood as an endpoint, a simple path pixel or a junction. Chains are walked from endpoints and junctions to produce an initial stroke set.

H. Gap Bridging and Stroke Stitching

Hand-drawn strokes captured photographically exhibit breaks arising from pen lift, ink starvation, focal blur and the subtraction of overlapping dots. Endpoints separated by less than a threshold proportional to the estimated lattice pitch are bridged, subject to an angular consistency test on the local stroke tangents at both endpoints, which prevents bridging between strokes that merely pass near one another. Bridged chains are then stitched into maximal continuous strokes. The stroke count is bounded at 140.

Recovered geometry is cropped to the lattice extent and smoothed by two passes of a local averaging filter, which removes the pixel-scale quantisation characteristic of skeleton traversal without materially displacing the stroke centreline.

I. Output

The pipeline returns the stroke path set, the dot positions, the estimated lattice pitch and orientation, the lattice assignment, and flags recording whether rules were detected and whether polarity inversion was applied. Dots and strokes are retained as distinct layers throughout.

VIII. Toolpath Generation Algorithms

A. Geometric Preprocessing

Toolpath generation consumes the internal representation of Section VI-B and emits G-code. Parametric curve segments are first resampled to polylines at a fixed screen-space interval of 1.5 pixels, corresponding to approximately 0.53 mm at the working scale. This interval is chosen to be well below the deposited line width, ensuring that resampling error is not resolvable in the physical output.

B. Circular Arc Regression

Emitting a resampled polyline directly as linear interpolation moves produces a large instruction count, with three consequences: extended transmission time under the line-by-line handshake of Section IX-C, exhaustion of the controller's look-ahead planner buffer with consequent velocity discontinuity at segment boundaries, and visible faceting on large-radius curves.

Circular arc regression addresses all three by representing a curved run as a single instruction rather than many. The fitter operates greedily: from a starting vertex, it extends a candidate arc vertex by vertex, fitting a circle to the accumulated run and testing maximum orthogonal deviation against tolerance. Extension continues while the fit remains within tolerance; on failure, the arc is emitted over the longest satisfactory run and fitting restarts from the terminal vertex.

Governing parameters are given in Table 2. The tolerance is specified in millimetres and converted to machine units at load, so that geometric fidelity is defined with respect to the physical output rather than the internal coordinate system:

$$\epsilon_{\text{machine}} = \epsilon_{\text{mm}} \cdot \frac{X_{\max}}{S} = 0.35 \cdot \frac{4.7}{240.0} \qquad (6)$$

TABLE 2: Arc regression parameters

Parameter	Value
Fit tolerance	0.35 mm
Full-circle tolerance multiplier	$3\times$
Minimum run length	4 vertices
Maximum radius	20.0 units
Maximum sweep	$2\pi - 0.15$ rad
Corner detection threshold	30°
Resampling interval	1.5 px

The maximum radius bound rejects arcs whose curvature is so low that they are better represented as lines, avoiding numerically ill-conditioned centre estimates. The maximum sweep bound prevents a near-complete circle from being emitted as a single arc, where small endpoint errors pro-

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duce large angular ambiguity. The minimum run length prevents the fitter from emitting arcs over vertex runs too short to establish curvature reliably.

C. Tangential Continuity Optimization

Independent per-run fitting produces arcs that meet at shared endpoints but with mismatched tangents, yielding a visible angular discontinuity — a kink — at each junction. On smooth curves such as the lobes characteristic of *sikku* designs, these artifacts are conspicuous.

Tangential continuity is enforced by chaining: the terminal tangent of each emitted arc is propagated as a constraint on the initial tangent of its successor, reducing the fit at each junction from three free parameters to two. Where the polyline exhibits a genuine corner — detected by a local turning angle exceeding $30°$ — the constraint is deliberately released, preserving intentional angularity.

For closed paths, the seam tangent is initialised from the geometry preceding the seam rather than left free, preventing a discontinuity at the closure point, which is otherwise the single most visible defect in a closed design.

D. Path Sequencing Strategy

Paths are ordered to minimise non-depositing traverse and, where multiple pigments are assigned, to minimise the number of colour-change interruptions. Sequencing is performed as a grouping by pigment assignment followed by nearest-neighbour ordering within each group, which is adequate at the path counts encountered and avoids the cost of exact tour optimisation.

E. Numerical Precision Analysis

GRBL validates arc commands by computing the radius from the current position to the specified centre offset and comparing it against the radius from the centre to the specified endpoint. Where these differ by more than an internal tolerance, the command is rejected with `error:33`.

During development, arcs were rejected intermittently despite geometrically valid fits. The cause was inconsistent decimal precision in the emitted G-code: endpoint coordinates and centre offsets were formatted at differing numbers of decimal places, so that rounding introduced an asymmetry between the two computed radii exceeding GRBL's tolerance.

The resolution is to emit all coordinates and offsets at a uniform four decimal places. At the working scale of 51.06 mm per unit, four decimals corresponds to approximately $5\,\mu$m, far below both the mechanical resolution of the axes and the deposited line width, so no fidelity is sacrificed. This is recorded here because the failure presents as an intermittent firmware error with no obvious relationship to its numerical cause.

F. G-Code Synthesis

The emitted job comprises an initialisation preamble establishing absolute positioning and millimetre-equivalent units, a sequence of deposition passes each bracketed by gate-open and gate-close commands, colour-change and refill interruptions where required, and a termination sequence returning the head to origin with the gate closed. A representative extract is given in Appendix E.

IX. Motion Planning and CNC Execution

A. Trajectory Planning and Interpolation

Trajectory planning is delegated to the controller firmware, which performs look-ahead over its planner queue, computing junction velocities from the angular deviation between successive segments and applying trapezoidal acceleration profiles subject to configured maxima. Linear moves are interpolated by Bresenham-equivalent step distribution; arc moves are decomposed internally into linear segments at a firmware-configured chord tolerance.

B. Feedrate Scheduling

Deposition quality is dependent on the ratio of traverse velocity to powder mass flow rate: excessive velocity yields a thin or broken line, insufficient velocity yields over-deposition and loss of edge definition. Because mass flow varies with pigment grade, humidity and hopper fill level, feedrate is exposed as a user selection rather than fixed. Five settings are provided, from $F50$ to $F250$, with $F150$ as default. The gate axis operates at a fixed $F150$ independent of the traverse selection.

C. Real-Time Command Streaming Protocol

Connection establishment requires a delay of approximately two seconds following port opening, during which the controller completes its reset sequence and emits a startup banner; commands transmitted during this interval are lost. The host therefore waits, transmits a paired carriage-return-linefeed sequence to elicit the banner, and flushes the input buffer before beginning transmission.

Streaming proceeds by strict line-by-line handshake: one command is transmitted and no further command is sent until an acknowledgement is received. Character-counting protocols achieve higher throughput by maintaining the receive buffer near capacity, but complicate the abort path, since buffered commands continue to execute after an abort is issued. Given that an aborted job here means pigment already deposited on a floor, deterministic abort behaviour was prioritised over throughput. A silence timeout of 90 s terminates the job where no acknowledgement is received, this bound being set above the longest single-command execution time.

D. Deposition Control and Colour Sequencing

The hopper holds a single pigment at a time. Multi-colour designs are executed by grouping paths by pigment, ordering groups to minimise changes, and suspending the job at each boundary for manual hopper reloading.

A dedicated refill position is defined at machine coordinate $(5.00, 0.00)$ — outside the 4.7-unit working envelope — so that the head is clear of the artwork during reloading and any spillage or residual discharge falls outside the deposition area. A dwell of 5 s follows resumption before deposition recommences, allowing flow to stabilise.

E. Fault Handling and Recovery

Three interruption paths are provided. Pause transmits the real-time feed hold character (`!`), which decelerates the machine to rest with the planner state intact. Resume transmits the cycle start character (~). Cancellation transmits a feed hold followed by soft reset (`0x18`), clearing the planner queue and returning the controller to an idle state; the gate is commanded closed before reset to prevent continued

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discharge.

X. Mathematical Modelling

A. Graph-Theoretic Representation

A significant subclass of kolam — the *sikku* or knot kolam — is defined by the property of being drawn as a single continuous stroke that returns to its origin, weaving around the *pulli* lattice without lifting the hand. A design that cannot be so drawn is not a well-formed sikku kolam.

This property is directly testable. The design is converted to a multigraph in which stroke intersections and endpoints become vertices and stroke segments become edges. Vertex identification requires tolerance, since hand-authored and photographically-acquired geometry does not produce exactly coincident endpoints; endpoints within 2% of the design's bounding span are welded to a common vertex. Dot association uses a separate threshold of 0.9 of the lattice pitch.

B. Eulerian Traversability Analysis

The single-stroke property is precisely the existence of an Eulerian circuit. By Euler's theorem, a connected multigraph admits an Eulerian circuit if and only if every vertex has even degree, and an Eulerian path if and only if exactly two vertices have odd degree.

Let O denote the number of odd-degree vertices in a connected component. Then:

$$\text{trails}(G_i) = \begin{cases} 1 & O = 0 \quad \text{(closed circuit)} \\ 1 & O = 2 \quad \text{(open path)} \\ \lceil O/2 \rceil & O > 2 \end{cases} \tag{7}$$

and for a design comprising components $G_1 \ldots G_k$, the minimum number of pen-down strokes is $\sum_i \text{trails}(G_i)$.

C. Minimal Trail Decomposition and Routing

Routing employs a generalised Hierholzer construction. Traversal begins at an odd-degree vertex where one exists, and at an arbitrary vertex otherwise. The algorithm walks unused edges until no unused edge remains at the current vertex, then splices closed sub-loops discovered from vertices along the completed walk. Where the walk terminates at a vertex other than its origin, the sub-walk is emitted as a separate trail rather than discarded.

This yields both the minimum stroke count and an explicit ordering, which is used directly for toolpath sequencing and additionally rendered on screen as an animated traversal for instructional purposes.

D. Topological Validation

The analysis provides validation feedback at authoring time. A design intended as a sikku kolam but yielding more than one trail is reported to the author together with the locations of the odd-degree vertices responsible, which correspond precisely to the points at which the intended single stroke is broken. This converts a stylistic property that would otherwise be verified by eye into a checkable constraint.

E. Complexity Analysis

Multigraph construction is $O(n^2)$ in the number of candidate vertices under naive pairwise welding, reducible by spatial indexing. Hierholzer's algorithm is $O(|E|)$ in the number of edges. At the design complexities encountered — typically fewer than several hundred edges — total analysis time is negligible relative to toolpath generation.

XI. Pedagogical Framework for Skill Transmission

A. Rationale

The position advanced in Section I-C — that reproduction alone does not constitute preservation of a living practice — is operationalised here. A machine that executes designs on demand substitutes for the practitioner. The instructional mode inverts this: the machine's role is to be progressively eliminated.

B. Graduated Autonomy Model

Five levels are defined, differing in the proportion of a design executed by the machine. Table 3 gives the allocation.

Table 3: Machine assistance by instructional level

Level	Designation	Machine share
1	Guided	0.70
2	Assisted	0.55
3	Shared	0.40
4	Supported	0.20
5	Pulli Mode	0.00

At Level 5 the machine deposits only the *pulli* lattice — the structural scaffold — and the learner executes all strokes. This is the terminal state of the progression, and corresponds to the condition of an independent practitioner, for whom the dot lattice is a conventional preparatory step rather than assistance.

C. Work Allocation Algorithm

Given a design decomposed into n parts and a target machine share s, allocation follows three rules.

The machine always executes part 0. The learner's first observation in any session is therefore a complete, correctly-executed exemplar.

The minority side is distributed rather than assigned contiguously. Where the machine share is below one half, machine-executed parts are spread across the design rather than concentrated; where it is above one half, learner parts are spread. Contiguous allocation would produce a design half-executed in one region and half in another, from which the learner receives no local reference for the portion they are executing. Distributed allocation ensures that adjacent completed geometry is available as a reference at every point.

The learner always retains at least one part, at every level including Level 1.

D. Automated Skill Assessment

Image capture for assessment is performed by a USB webcam mounted on the frame above the working area and addressed directly by the host application, rather than by handheld photography.

This is a deliberate departure from the acquisition pipeline of Section VII, which is explicitly designed to tolerate handheld capture under uncontrolled conditions. The requirements differ. Acquisition operates on artifacts that already exist in arbitrary settings, so robustness to poor capture is unavoidable. Assessment operates on a design executed on

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the machine's own bed moments earlier, so the capture geometry is known in advance and can be fixed.

Fixing it yields three properties that handheld capture cannot provide. The camera pose relative to the deposition bed is constant, so the homography between image coordinates and machine coordinates is established once at installation and reused, removing the per-capture perspective estimation of Section VII-F and its associated failure modes. The correspondence between the captured image and the reference geometry is therefore metric, permitting deviation to be evaluated in millimetres at specific lattice positions rather than assessed only as an overall visual impression. And capture is unattended: a learner mid-session need not locate a phone, frame the shot and upload it, which is a material consideration where the intended learners are children.

The mounting position is constrained by the deposition head, which must not occlude the field of view. The head is therefore commanded to the refill position at $(5.00, 0.00)$ — already outside the working envelope for the reason given in Section IX-D — before capture is triggered.

The camera is mounted approximately 800 mm above the deposition surface and connected to the host by a USB Type-A extension lead, the frame-mounted position being beyond the reach of the camera's captive cable. At that standoff the 240 mm deposition span subtends a comfortable fraction of the field of view of a typical webcam lens, so the design is captured without the barrel distortion that a shorter standoff and wider effective angle would introduce.

Assessment is performed by a vision-language model against the reference geometry, returning a score on a ten-point scale with structured feedback on line continuity, symmetry and lattice adherence. This path requires network connectivity.

Where the model is unavailable, a deterministic fallback verdict is issued so that the session may complete. Fallback verdicts are recorded with an explicit provenance marker and are *excluded* from level progression calculations. This exclusion is important: a fallback verdict carries no evidence about learner competence, and permitting it to influence progression would allow level changes driven by network conditions rather than performance.

E. Progression Criteria

Progression is evaluated over a sliding window of the two most recent assessed attempts. Promotion requires both attempts in the window to score at least 8.0; demotion follows where both fall below 5.0. Requiring consistency across two attempts rather than acting on a single result prevents oscillation driven by individual anomalous sessions.

F. Symmetry-Based Instruction

Symmetry is treated as an explicit instructional dimension, with the order of symmetry increasing across levels from 2-fold through 4-fold to 8-fold. At each order, the learner executes only the fundamental domain — the half, quadrant or octant from which the complete design is generated by reflection — with the machine generating the remainder. This makes the generative structure of the design explicit rather than leaving it to be inferred, and reuses the same transformation engine that implements the mirror pen tool of Section VI-C.

XII. Experimental Methodology

A. Experimental Setup

Testing was conducted on a level tiled floor, chosen for its flatness and for the visual contrast it provides against light-coloured pigment. Positional measurements were taken with a vernier caliper of 0.02 mm resolution, which is an order of magnitude finer than the expected deviations and therefore does not limit the reported figures.

Four deposition media were used across testing: commercially available coloured rangoli powder, rice flour, dry kolam maavu, and coloured sand. These span a considerable range of particle size, density and cohesion — from the fine, low-cohesion market powders through rice flour, which is finer still and more prone to bridging, to coloured sand, which is coarse and free-flowing. All four were dispensed by the parabolic hopper and tapered gate without mechanical agitation or modification of the end-effector.

This is reported as a robustness observation rather than a controlled study: the media were not characterised for particle size distribution, and flow rate was not measured per medium. It nonetheless indicates that the hopper geometry of Section IV-D is not tuned to a single material, which is relevant given that regional practice varies in the medium used.

B. Performance Metrics

The following metrics are defined for evaluation:

- *Positional accuracy*: deviation between commanded and achieved position, measured at lattice reference points across the working envelope.
- *Repeatability*: dispersion of achieved position over repeated approaches to the same commanded point, evaluated separately for unidirectional and bidirectional approach.
- *Geometric fidelity*: maximum orthogonal deviation of the deposited line from the commanded path.
- *Toolpath reduction*: ratio of emitted instruction count with arc regression enabled to that with linear interpolation only, over a fixed design corpus.
- *Execution time*: wall-clock job duration under both conditions above.
- *Digitisation recovery rate*: proportion of ground-truth dots and strokes correctly recovered from captured notebook pages.

C. Calibration Procedure

Per-axis calibration factors are determined by commanding a traverse of known extent in machine units, measuring the achieved physical displacement, and computing the ratio. The procedure is repeated across the working envelope to confirm that the error is proportional rather than offset in

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character. Measurements were taken with the vernier caliper described in Section XII-A

XIII. Results and Performance Evaluation

A. Positional Accuracy

Deviation between commanded and achieved position was observed to fall in the range 1–3 mm across the working envelope. This is an indicative figure from routine operation rather than the outcome of a controlled measurement campaign, and is reported as such.

Relative to the 240 mm deposition span this represents approximately 0.4–1.3% of full scale. It substantially exceeds the 12.5 μm microstep resolution of Section V-C, confirming that stepping resolution is not the limiting term; the dominant contributions are expected to be belt elongation and reversal error (Section XIV-B). It is, however, of the same order as the deposited line width, so the error is at the threshold of visibility in the physical output rather than well below it.

B. Repeatability

C. Geometric Fidelity

D. Toolpath Compaction

Arc regression is retained on the grounds given in Section VIII-B: a curved run is emitted as one instruction rather than many, which reduces transmission time under the line-by-line handshake, reduces pressure on the controller's look-ahead buffer, and removes visible faceting on large-radius curves. A controlled comparison of instruction count and job duration with regression enabled and disabled was not performed, and no quantitative reduction is claimed here. Such a comparison is identified as immediate further work in Section XV-E.

E. Digitization Accuracy

The pipeline was evaluated on a set of captured notebook pages spanning differing lighting conditions, substrates and design complexities. For each page, ground truth was established by manual inspection of the original photograph, counting the *pulli* dots and the distinct strokes visible to a human reader. Pipeline output was then compared against this ground truth.

A recovered dot was counted as correct where it fell within half a lattice pitch of a ground-truth dot; a recovered stroke was counted as correct where it followed the same route between the same lattice positions as a ground-truth stroke, allowing for the smoothing of Section VII-H. Recovered features with no ground-truth counterpart were counted as false positives.

TABLE 4: Digitisation recovery by page

		Dots		Strokes			
Pg	**Condition**	GT	Rec.	GT	Rec.	**FP**	**Rec.%**
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
Mean							

GT: ground truth by manual inspection. Rec.: correctly recovered. FP: false positives. Condition: describe substrate and lighting, e.g. "ruled, daylight" or "unruled, indoor lamp".

The ordering effect of Section VII-D was quantified separately on a representative page: dot candidates recovered fell from 974 under detection-before-rule-removal to 8 under the reverse ordering, a reduction of over 99%.

F. Computational Performance

The digitisation pipeline completes in approximately 1–5 s per page on the host described below, which is well within the tolerance for an interactive acquisition workflow and does not constitute a practical constraint on archiving throughput.

The host is a macOS laptop

G. Comparative Analysis

Table 5 positions the system against the prior art surveyed in Section II-C.

TABLE 5: Comparison with prior systems

Capability	**Stencil**	**RangBot**	**Kit**	**This**
Powder deposition	✓	✓	—	✓
User design authoring	—	—	✓	✓
Toolpath optimisation	—	—	—	✓
Multi-pigment	—	—	—	✓
Archive acquisition	—	—	—	✓
Skill transmission	—	—	—	✓

XIV. Discussion

A. Engineering Trade-offs

Three selections traded performance for properties judged more material to the application.

Belt transmission was adopted in exchange for traverse velocity, low moving mass and unbounded axis length, at the cost of backdrivability and of a position-dependent elongation term absent in screw drives. The latter is mitigated but not eliminated by steel-cord reinforcement.

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Line-by-line streaming was adopted at a cost in throughput, in exchange for deterministic abort behaviour — justified by the irreversibility of deposition onto a floor.

The lower-current motor variant was adopted at a cost in torque margin, in exchange for operation within the driver's passive thermal envelope, avoiding forced-air cooling and its associated cost, noise and disturbance of deposited powder.

B. Sources of Error

Positional error arises from four sources. Belt elongation under tension varies with the free span between pulley and carriage and therefore with carriage position, reversing sign on direction change; steel-cord reinforcement reduces this term but does not remove it. Pulley pitch-diameter tolerance produces a proportional scale error, addressed by per-axis calibration. Tooth engagement backlash contributes a small reversal error, minimised by belt preload. Step loss under transient load is undetectable in an open-loop configuration.

Deposition error arises from variation in mass flow with hopper fill level, since the discharge rate of a gravity-fed hopper is weakly dependent on head height, with ambient humidity, which alters interparticle cohesion, and with the medium itself, since the four materials of Section XII-A differ in bulk density and therefore in mass discharged per unit time at a given gate opening.

Acquisition error arises principally from lattice estimation failure on designs with sparse or highly irregular dot placement, where insufficient candidates survive filtering to establish pitch and orientation reliably.

C. Scalability

The working envelope is fixed by the frame. Belt transmission scales more favourably in length than a screw drive, since no rotating element spans the axis and the critical-speed limit that bounds long screws does not arise; enlargement requires only longer extrusion and belt. The limiting factors at increased length are instead belt sag under its own weight in long unsupported spans, which requires intermediate support or increased tension, and the reduction in first natural frequency of the extended span, which lowers the acceleration achievable before excitation of frame resonance.

D. Limitations

The system is open-loop; no position feedback is available, and step loss is therefore undetected. Only a single pigment may be loaded at any time, so multi-colour designs require manual intervention. The digitisation pipeline requires reasonably diffuse illumination and fails on strongly specular or heavily creased substrates. The instructional framework has been used by more than ten learners over a period of several week

These sessions were conducted as informal use rather than as a controlled study: there was no control group, no pre- and post-test instrument, and no blinding. The results reported therefore concern system behaviour and learner engagement, and do not support claims regarding learning outcomes.

XV. Applications and Future Work

A. Digital Cultural Heritage Preservation

The acquisition pipeline enables systematic digitisation of practitioner notebooks into an indexed, searchable corpus with regional provenance — material that is currently held privately and lost on disposal.

B. Educational Deployment

The instructional mode addresses the transmission failure directly in contexts where daily co-presence with an experienced practitioner is unavailable, and is suitable for school and community-centre deployment given the component cost reported in Section XVI.

C. Institutional Automation

Temples, cultural institutions and hospitality venues execute floor designs at daily or event frequency, currently by skilled manual labour under time pressure. The system addresses this reproduction requirement without displacing the transmission function, which is served separately.

D. Extension to Additional Art Forms

The end-effector modularity of Section IV-F suggests extension beyond dry-powder floor art. Pigment-on-substrate forms such as Madhubani require a spring-loaded pen carrier, hole-aware contour extraction with even-odd fill determination, and hatching or inward-offset fill generation, none of which exist in the present toolpath generator; the arc tolerance would also require reduction from 0.35 mm, which is imperceptible under a powder line but not under a fine pen.

Wall-executed forms such as Warli require vertical mounting, which the present transmission does not support without modification. Because a belt drive is backdrivable (Section IV-C), the gantry would descend under its own weight whenever the vertical-axis motor is unpowered — including during the idle intervals between jobs and following any fault-induced reset. Three remedies are available: a counterweight or gas spring offsetting the head mass, so that the net static load on the belt approaches zero; a fail-safe electromagnetic brake on the motor shaft; or a change of transmission on the vertical axis alone to a non-backdrivable screw. The first is the least costly and the most consistent with the platform's cost objective.

Continuous holding current is not an adequate remedy, as it provides no protection during power interruption and imposes a sustained thermal load on a driver already operating without forced-air cooling (Section V-B).

Vertical operation additionally requires a stepper-driven syringe extruder for viscous paste and standoff compliance to accommodate surface irregularity. The torque margin of the selected motor is a further limiting consideration, as the vertical axis must accelerate the head mass against gravity rather than normal to it.

These extensions are presented as analysis. No non-powder output has been produced, and the claims of this paper are confined to the dry-powder floor domain.

E. Further Work

A controlled comparison of toolpath compaction — instruction count and job duration with arc regression enabled and disabled, over a fixed design corpus — would quantify a benefit currently argued only on structural grounds. Closed-loop position feedback would permit step-loss detection. Wireless streaming would remove the tethered host requirement. A multi-hopper carousel would eliminate manual pigment changes. Controlled evaluation of the instructional frame-

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work at adequate scale and duration is required before any claim regarding learning outcomes can be advanced.

XVI. Conclusion

This paper has presented a low-cost Cartesian CNC platform for the preservation of traditional Indian floor arts, constructed around the position that preservation of a living practice requires acquisition and transmission in addition to reproduction.

The mechatronic contribution is a powder deposition end-effector whose metering gate is actuated by the Z axis of an unmodified three-axis controller, obtaining planner-scheduled deposition timing without firmware modification, and generalising to alternative media by substitution of the end-effector alone.

The algorithmic contributions are a tangentially-chained greedy arc regression scheme for toolpath compaction, together with the numerical precision discipline required for arc endpoint consistency; and an offline vectorisation pipeline for ruled-substrate manuscripts in which the ordering of dot detection relative to morphological rule removal is shown to be determinative, with recovery falling from 974 to 8 candidates under the incorrect ordering.

Single-stroke designs are additionally validated against Eulerian criteria with routing by generalised Hierholzer decomposition, converting a stylistic property into a checkable constraint.

The system was realised at a component cost of INR 4,000, within reach of individual households and schools in the target deployment context.

The instructional framework, in which machine assistance is systematically withdrawn to a terminal state at which the machine deposits only the structural lattice, is reported as an implemented mechanism. Its efficacy is not established by this work and requires controlled evaluation at scale.

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Appendix A: Machine Parameters

Working envelope	4.7×4.7 units
Mat deposition span	240.0 mm
Scale factor	≈ 51.06 mm/unit
Frame	2 ft $\times$ 2 ft, 20×20 V-slot
Transmission	Steel-cord toothed belt
Guidance	Polymer V-wheels on profile
Calibration C_x, C_y	1.00, 0.84
Gate open / closed (Z)	0.0500 / 0.0000
Gate feedrate	$F150$
Refill position	$(5.00,\ 0.00)$
Refill dwell	5 s
Motors	NEMA 17, 17HS3401, 1.3 A/phase
Drivers	A4988
Supply	12 V, 10 A SMPS
Belt	GT2, 2 mm pitch, steel cord
Pulley tooth count	20T, both axes
Microstepping	$1/16$
Nominal resolution	80 steps/mm (12.5 μm)
Assessment camera	USB webcam, frame-mounted
Camera mounting height	$\approx$ 800 mm above bed
Camera model / resolution	
Motion platform subtotal	INR 3,250
Assessment camera	INR 750
Total component cost	**INR 4,000**

Appendix B: GRBL Configuration

`$100`, `$101` (X, Y steps/mm)	80 (nominal, from Sec. V-C)
`$102` (Z steps/mm)	
`$110`, `$111` (max rate)	
`$120`, `$121` (acceleration)	
`$130`, `$131` (max travel)	

Appendix C: Algorithm Parameters

Arc regression	
Fit tolerance	0.35 mm
Full-circle multiplier	$3\times$
Minimum run	4 vertices
Maximum radius	20.0 units
Maximum sweep	$2\pi - 0.15$ rad
Corner threshold	$30°$
Resample interval	1.5 px
Output precision	4 decimals
Digitisation	
Maximum dimension	1200 px
Maximum upscale	$4.0\times$
Threshold block	$\max(15, (\min(h, w)/20) \mid 1)$
Threshold constant	10
Blur kernel	5×5 Gaussian
Open kernel	3×3 ellipse
Dot candidate cap	500
Stroke cap	140
Smoothing passes	2
Graph analysis	
Weld fraction	0.02 of span
Dot hit fraction	0.9 of pitch
Instruction	
Machine share by level	$0.70/0.55/0.40/0.20/0.00$
Assessment window	2 attempts
Promotion / demotion	≥ 8.0 / < 5.0
Dots per part (Pulli)	6
Maximum dots	48

Appendix D: Serial Protocol

Baud rate	115,200
Wake delay	2 s
Wake sequence	`\r\n\r\n`
Flow control	Line-by-line, await `ok`
Silence timeout	90 s
Feed hold	`!`
Cycle start	`~`
Soft reset	`0x18`

Appendix E: Sample Toolpath

```
G21 G90
G0 X0.0000 Y0.0000
G1 Z0.0500 F150
G1 X1.2400 Y0.8830 F150
G2 X2.1150 Y1.4420 I0.4380 J0.2790
G2 X2.9880 Y0.8830 I0.4370 J-0.5590
G1 X4.2280 Y0.0000
G1 Z0.0000 F150
G0 X5.0000 Y0.0000
G4 P5
...
G1 Z0.0000 F150
G0 X0.0000 Y0.0000
```