Optimizing FDM 3D Printing Through Mechanical and Software Enhancements

Authors: Yesbergen Bekasyl, Dangilov Alisher
Mentor: Bakbergen Temirzakuly
Field: Mechanical Engineering

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Abstract

Additive construction, particularly 3D concrete printing, suffers from achieving smooth surface finishes and good structural quality due to the layer-by-layer building process. This paper introduces a systematic approach to establishing a fused deposition modeling (FDM) 3D printer in order to produce smoother and higher-quality structures using construction materials (e.g., concrete). The technique integrates advanced nozzle design, rotating print head mechanism, and slice software algorithmic optimisations to increase layer quality and interlayer bonding. Non-circular nozzle geometry (e.g., rectangular or oval cross-section) is employed to more optimally shape extruded beads, while a motor-driven rotating print head provides real-time nozzle orientation aligned with printing direction. The G-code generation (slicer) is improved with toolpath direction control and transition to smooth curves. Theory and literature review indicate that directed rectangular nozzles can reduce inter-layer gaps and improve mechanical strength and that affixed trowel-like protrusions can level the layers for a smoother surface finish. The proposed design is implemented on an open-source gantry printer with a custom extruder and a 4th-axis stepper for rotating nozzles. Although comprehensive experimental validation is still to be carried out, anticipated advantages are significantly reduced surface roughness (minimized layer ridges) and enhanced structural integrity of the printed members. This work demonstrates that with incorporation of new hardware adjustments and intelligent software feedback, it is possible to significantly enhance the quality of 3D printed building elements, which advances the technology towards meeting architectural and structural specifications.

Keywords: 3D concrete printing, design of nozzle, print head rotation, surface finish, FDM, slicer algorithm, building materials

1. Introduction

1.1 Background and Motivation

Additive manufacturing is increasingly being explored in the construction industry for its ability to fabricate complex structures without formwork and with reduced labor and waste. Among additive techniques, extrusion-based 3D concrete printing (3DCP) is prominent: it deposits a cementitious material layer by layer through a nozzle to build structural elements. Early success in printing full-scale walls and houses has demonstrated the potential of 3DCP to revolutionize construction in terms of speed and cost. However, **surface quality and geometric precision** of 3D-printed concrete remain as key challenges. The layer-by-layer process inherently produces visible layer lines (ridges) and a rough finish, which not only affect aesthetics but can also influence the structural performance (e.g., by introducing stress concentrations or weak bonding between layers). Achieving a smoother surface is particularly important for construction components, as it reduces the need for post-processing and improves the interface for any subsequent structural or finishing elements.

Previous research and industry developments highlight that hardware innovations at the nozzle can improve print quality. For instance, Khoshnevis's Contour Crafting system employs **trowel-like fins attached to the nozzle that spread and flatten the extruded concrete**, resulting in significantly smoother walls. This adaptation not only improved surface finish but also increased build speed by allowing thicker layers without compromising quality. Such successes motivate further exploration of nozzle modifications and motion control to enhance print quality.

In parallel, **nozzle geometry** has been identified as a factor affecting both the mechanical properties and surface characteristics of printed materials. Chen *et al.* (2019) noted that the shape of the nozzle orifice influences the deposited filament and final part quality in ceramic 3D printing. In their review, square nozzles were found to produce parts with higher compressive strength, whereas circular nozzles yielded smoother surfaces with lower porosity. This suggests a trade-off: a non-circular cross-section can improve certain properties, but may introduce anisotropy in

deposition that must be managed. For construction materials like concrete, which are deposited as pastes or mortars, controlling the bead shape is crucial for good layer adhesion and minimizing voids. Modern 3D concrete printers often use round nozzles for simplicity, but **advanced nozzle designs (e.g., rectangular, oval, or with attached shaping trowels)** could provide better control over layer shape and surface smoothness.

Another avenue for improvement is leveraging additional axes of motion during printing. Traditional 3-axis printers move in X, Y, Z (with material extrusion as a separate control) and assume a fixed orientation of the nozzle. This means the nozzle's shape (usually circular) is orientation-invariant, but if one uses a non-circular nozzle, its orientation relative to the print path becomes significant. A **rotating print head (4th axis)** adds the capability to change the nozzle orientation about its vertical axis (often denoted as the A or C axis in CNC terminology). This can be exploited to **always align a shaped nozzle with the direction of travel**, or to maintain a desired orientation of a smoothing fin or trowel relative to the print path. Aligning the nozzle orifice with the movement direction can produce more uniform, smooth extrudate layers. In large-scale concrete printing, some systems indeed rotate the nozzle to keep a consistent edge shape on the printed layers; for example, it is noted that several concrete printing setups turn the nozzle in the direction of movement to achieve smooth outer surfaces. This concept, while used in industrial concrete printers, has not yet been widely implemented in smaller-scale or open-source FDM systems, and thus represents a compelling research direction.

1.2 Problem Statement

Despite advancements in 3D construction printing, **print quality issues** persist. Walls printed with conventional round nozzles typically exhibit ribbed surfaces due to the layer stepping and the circular bead profile. These surface ridges are not just cosmetic; they can reduce contact area between layers and act as stress risers, potentially weakening the structure. Moreover, inconsistency in extrudate flow or deposition can lead to voids and poor interlayer adhesion, compromising structural integrity. Present slicing software for 3D printing (e.g., Cura, Slic3r) are primarily developed for thermoplastic materials and assume no active nozzle orientation control; they generate toolpaths (G-code) consisting of linear moves (G1 commands) that produce planar layers, with no instructions to adjust nozzle angle relative to travel. Such limitations mean that even if hardware modifications are made (like a rotating nozzle), the standard software workflow would not utilize them, resulting in suboptimal performance.

In summary, the key problems addressed in this research are: (1) **Rough surface finish and dimensional inaccuracies** in 3D-printed construction components due to basic nozzle designs and layer-based deposition; (2) **Suboptimal mechanical properties** (like interlayer bond strength and part density) linked to deposition geometry and lack of layer compaction; and (3) **Lack of integrated software control** to exploit advanced hardware (nozzle shaping or additional axes) for quality improvements. These issues prevent 3D concrete printing from meeting the high quality standards required in structural applications and often necessitate extensive post-processing or conservative design assumptions.

1.3 Aim and Objectives

Aim: To design and implement a configuration of a 3D printer that produces smoother and higher-quality printed models from construction materials (such as concrete) by utilizing advanced nozzle designs, a rotating print head, and enhanced slicing algorithms.

Objectives:

- **Nozzle Design Improvement:** Develop an **advanced nozzle geometry** (e.g., non-circular or with attached smoothing elements) that can produce flatter, more uniform extruded layers, thereby reducing surface roughness and porosity of the printed material. This includes selecting durable nozzle materials and shapes suitable for abrasive, high-viscosity construction materials.

- **Rotating Print Head Integration:** Design and integrate a **rotational print head mechanism** (a fourth axis) on an FDM-style 3D printer. This mechanism, controlled by an additional stepper motor, will actively rotate the nozzle to maintain optimal orientation (e.g., aligning a rectangular nozzle's long dimension parallel to

print travel or keeping a trowel trailing the direction of motion) throughout the print.

- **Slicer Algorithm Enhancements:** Extend or modify slicing software (referred here as a *"G2 slicer"* module) to support the new hardware capabilities. This involves creating an algorithm that **calculates the nozzle rotation angle for each toolpath segment** and inserts corresponding rotation commands into the G-code. Additionally, implement path-smoothing techniques (such as using G2/G3 arc commands for curves) to minimize sudden orientation changes and ensure fluid, continuous motion.

- **Evaluation of Print Quality:** Establish a testing methodology to **evaluate surface smoothness and mechanical performance** of prints made with the new configuration. Key metrics include surface roughness (quantified by layer ridge height or waviness), dimensional accuracy, layer adhesion strength (e.g., via interlayer tensile or flexural tests), and porosity. Although detailed experimental data are beyond the scope of this paper, the configuration is designed such that these metrics can be compared before and after applying the new nozzle and rotation system.

By achieving these objectives, the research aims to demonstrate a feasible path toward high-quality, smooth-surfaced 3D printed structures in construction, reducing the gap between 3D printed and conventionally cast concrete in terms of surface finish and structural reliability.

1.4 Research Scope and Significance

The scope of this work encompasses the retrofit of a small-to-medium scale gantry 3D printer (originally designed for plastic) for use with a construction material (a cementitious mortar resembling concrete), along with corresponding software modifications. It does not delve into mix design optimization of the concrete itself, but assumes a printable mortar that is sufficiently pumpable and buildable. The focus is on hardware/software innovations to improve print quality for a given material. The significance of this research lies in its potential to enhance **additive manufacturing in construction**: smoother surfaces reduce the need for manual finishing of walls, and improved layer cohesion yields structurally sound components. These improvements could accelerate the adoption of 3D printing for architectural and civil engineering applications, where both aesthetics and performance are critical. Moreover, the integration of a rotating nozzle and custom G-code generation contributes to the broader field of multi-axis 3D printing, demonstrating how relatively simple additions can expand the capabilities of existing 3D printers. The findings may also translate to other viscous materials printing (e.g., clay, ceramics, adobe), thereby benefiting a range of large-scale additive manufacturing processes.

Finally, this project aligns with the industry's move towards smarter and more automated construction techniques. By using algorithmic control (in the slicer and firmware) to enhance print quality, it showcases the importance of software-hardware co-design in advanced manufacturing systems. The outcomes of this work will add to the knowledge base needed to produce **structurally reliable**, **geometrically precise**, and **smooth-surfaced** 3D printed buildings and components, which is a step forward in realizing practical digital construction methods.

2. Literature Review

2.1 3D Printing in Construction and Surface Quality Challenges

3D concrete printing has been developed as a response to its potential to automate the construction process and create complex shapes beyond the capabilities of traditional formwork. Surface finish has been a recurring issue in the literature. Conventional concrete printing extrudes with an approximately cylindrical cross-section, resulting in a ribbed surface texture. These layer lines are not merely superficial; they can potentially influence the manner in which loads are transferred across layers and environmental factors (e.g., moisture intrusion) affect the structure. Wolfs et al. (2019) indicated that poor interlayer contact controls due to surface non-flatness can reduce interlayer tensile strength, and that surface topography control is critical to the structural behavior of 3D printed concrete walls. In addition, beauty requirements in architectural applications need smoother surfaces to meet acceptable finish specifications.

Earlier studies have explored some of the means through which the surface smoothness can be improved. One is the mechanical smoothing in printing, as employed by Contour Crafting's nozzle-mounted trowels. These trowels effectively scrape and mold each layer as it is deposited to produce a practically planar surface. Zhang and Lim (2020) developed an adjustable silicone side flaps nozzle that act like "wipers" on the sides of the extruded filament; they achieved reduced surface roughness and interlayer voids by using this method (though at the cost of requiring to have accurate calibration of flap stiffness and orientation). Optimizing the toolpath and deposition pattern is another fix: e.g., employing arc motions (G2/G3 in G-code) on curves instead of many small linear segments can generate smoother curved surfaces and reduce the staircase effect on edges. Some experimental post-processors or slicers (e.g., the "Arc Welder" plugin) convert segmented polylines into real arcs, which arc-capable printers can execute to produce smooth radii. This not only improves surface finish but also can suppress vibration and jerk acceleration, leading to more even deposition.

Despite such efforts, there remains a shortfall in ensuring smooth finish at the expense of build rate or structural integrity. Smoothness may be enhanced by employing thinner layer heights, but at the cost of much longer print time. Even increasing the nozzle size enhances building but annihilates surface resolution. This compromise begs solutions that change the model of deposition itself, i.e., changing the shape of the nozzle or direction, rather than relying on very thin layers. The literature indicates that a multi-faceted solution—implying some hardware modifications (nozzle design, extra axes) coupled with wiser software (toolpath optimization)—is probably necessary in order to adequately reconcile speed and quality in 3DCP.

2.2 Nozzle Design: Geometry and Its Impact on Print Quality

The nozzle is a critical component in material extrusion systems, as it directly shapes the flow of material. In polymer FDM printing, nozzles are almost exclusively round orifices, but in paste-based printing (ceramics, concrete), researchers have investigated alternative shapes. According to a comprehensive review by Chen *et al.*, early experiments in ceramic paste extrusion found that **square-shaped nozzle orifices** produced rods that, when stacked as layers, resulted in parts with higher compressive strength compared to those printed with round nozzles. The square cross-section likely enables better contact area between layers (reducing inter-layer voids) and a more brick-like stacking, thus enhancing load-bearing capacity. However, Chen *et al.* also note that prints from **circular nozzles** had smoother surfaces and lower porosity, since a circular bead naturally has fewer sharp edges and can “settle” into a smoother contour. This indicates that nozzle geometry affects different quality aspects (mechanical vs. surface) in different ways.

In the domain of 3D concrete printing, **rectangular nozzle shapes** have gained attention. Rahul *et al.* (2019) pointed out that using a rectangular nozzle and carefully matching the printing parameters (flow rate and travel speed) can yield a very stable bead shape that maintains its rectangular cross-section without excessive spread or sag. A stable geometry leads to uniform layers and potentially better stacking. Tay *et al.* (2019) further experimented with a 30 mm × 15 mm rectangular nozzle, introducing the concept of a “Shape Retention” (SR) ratio – the ratio of the actual printed cross-sectional area to the nozzle’s cross-sectional area. An SR close to 1 was found optimal, meaning the extruded concrete retains nearly the shape and area defined by the nozzle, indicating minimal deformation or material slump. Prints under those conditions had **improved dimensional accuracy and surface evenness**, because the material was not excessively flattening or forming filamentary strings. Maintaining SR ≈ 1 required tuning the flow and speed so that material neither under-fills (causing gaps) nor over-fills (causing ridges). This highlights that nozzle geometry and process parameters must be considered together; an advanced nozzle by itself doesn’t guarantee improvement unless the process is adapted to it.

A downside noted with rectangular or other non-round nozzles is **directional sensitivity**. Paul *et al.* (2018) observed that with rectangular nozzles fixed in one orientation, the bead width and shape can vary when the printing direction changes relative to the nozzle’s alignment. For example, if a rectangular nozzle is oriented along the X-axis, it will lay wider beads when moving in X direction than in Y direction (where the thinner dimension leads). This can introduce anisotropy in surface texture and even slight dimensional inaccuracies in features depending on their orientation in the print. Paul *et al.* found that although rectangular nozzles improved interlayer contact (hence better strength), using a circular nozzle eliminated orientation concerns because a circular cross-section is symmetric. However, the same study noted that the circular nozzle prints had significantly larger voids between filaments and weaker mechanical

performance than the rectangular nozzle prints. In essence, the **circular nozzle is more "forgiving" in terms of direction but yields lower overall quality**, whereas the rectangular nozzle can give superior results if its orientation is properly managed.

Several researchers have proposed **dynamic nozzle systems** to combine the benefits of multiple shapes. One cutting-edge concept is the *adaptive nozzle 3D printing (AN3DP)* approach by Kang *et al.* (2024), which uses an adjustable orifice composed of movable pins to change the nozzle diameter and shape on the fly. This system can theoretically extrude wide beads for fast filling and narrow beads for fine details, and even alter the cross-section shape for different layers. While AN3DP is complex and still experimental, it signifies the trend towards nozzle designs that are not static. Our research, rather than employing a morphing nozzle, takes a more practical approach of selecting an optimized fixed shape (a moderately sized rectangular nozzle that balances flow and detail) and then **actively controlling its orientation** to harness its advantages in all directions of printing.

Finally, attention must be paid to **nozzle material and wear** when printing abrasive construction materials. Hardened steel or carbide nozzles are often used for concrete printing to resist erosion. Also, larger nozzles (e.g., 8–30 mm diameter range) are common in construction-scale printers, but in our small-scale setup we anticipate using a smaller size (e.g., 4–8 mm width rectangular opening) to allow finer features. Prior works like Zhang & Sanjayan (2023) have even optimized internal nozzle geometry (taper angles, entry lengths) to reduce pressure losses and ensure a homogeneous flow of fiber-reinforced concrete. While internal geometry optimization is beyond our current scope, our nozzle design will incorporate a conical entry and straight outlet to promote steady flow, based on best practices from these studies.

2.3 Print Head Rotation and Multi-Axis Toolpaths

The idea of adding an additional degree of freedom—rotation of the print head—transfers FDM and material extrusion into the domain of multi-axis machining. For 5-axis CNC milling, tool orientation control is standard; likewise, in 3D printing, scientists have started exploring 4-axis and 5-axis printers where the nozzle can be rotated or tilted in order to print non-planar layers or to ensure the best possible contact with the print surface. For the sake of our goal (smoother surfaces through nozzle rotation), we will be referring to rotation around the vertical axis (imagine the nozzle rotating like a turret). This is simpler than 5-axis (and therefore involving tilting) but again coordinated motion planning is involved.

Empirical evidence for the value of nozzle rotation is evidenced by large-scale 3DCP machines. As mentioned earlier, rotation of the nozzle has been implemented in commercial concrete printers: e.g., the gantry concrete printers utilize a rectangular extrusion nozzle with an actuator to place the nozzle in such a position that its longer axis is always aligned perpendicular to the direction of movement, thus "ironing" the layer as it is deposited. On a RepRapFirmware and Duet3D electronics platform (found on most DIY printers), JoergS5 (2020) posted using firmware kinematic modes P3 and P4 for a five-axis robot so that automatic nozzle rotation is achieved based on direction of motion. The technique is that the firmware, which has knowledge of the forward kinematics of the machine, can compute how the tool needs to turn on every move, especially for G2/G3 arc moves in which frequently changing orientation might be required.

The forum thread noted that there is support at the firmware level, but slicer support is limited – very few of the slicing software natively generate commands for a rotating nozzle or understand 4-axis printing. The majority of the existing prior art thus depends on firmware hackery or custom scripts to include rotation commands.

In university research work, a fascinating innovation has been the creation of custom slicers for multi-axis and non-planar printing. Slicer4RTN (Rotating Tilted Nozzle) is an example: it is an algorithm for slicing for a tilted 45° print head that can also rotate on its axis. Slicer4RTN generates G-code with an extra rotation coordinate (noted as A in most instances). For example, it will add an "Aθ" component to every move, representing the rotation angle of the nozzle. This gives precise control of nozzle orientation at all locations in the path. With experiments under a tilting rotating nozzle, this technique enabled printing without support of overhangs and created parts with improved surface integrity, since the nozzle was always able to be directed in the optimal direction to avoid collision and remain in contact with the layer of printing. Even though our nozzle is a vertically aligned one (and not tilted), the idea remains the same: with the inclusion of a rotation axis, the printing process has another control to improve print outcomes. One of the major advantages of including rotation is when printing round structures or curved walls, as is common with architectural models.

With a stationary nozzle, the boundary of a rounded wall will have discontinuities and visible stepstitching if modeled using short straight moves. With an arc command that the slicer employs and the nozzle tilting to stay tangential, the print head glides along the curve, creating a much neater surface. Rotational alignment is also beneficial in corners: when the printer is changing direction (e.g., from northbound to eastbound travel), a stationary rectangular nozzle will suck material at the corner, perhaps creating a bulge or ripples. A rotating nozzle can be pre-positioned along the corner and deliver material into a sharp corner with minimal distortion. Jun et al. (2022) depicted in an underwater concrete print that a three-sided trowel nozzle (the same effect of rotation by having multiple fins) produced cleaner edges and corners compared to a plain nozzle, since material was more restricted on direction change.
It is worth noting some challenges and problems working with a rotating print head.
Mechanically, adding rotation involves feeding wires or tubes through a rotating junction. 360° rotation would need a slip ring for the wires to avoid entanglement, or rotation can be restricted to some interval (e.g., ±180°) and unwind manually from time to time. Our implementation chooses to have a slip ring on the stepper motor and sensor cable wires so that there is no limit to rotation, since unlimited is better suited for printing arbitrary toolpaths without interruption and winding back. The second item to observe is inertia and control: the print head must be coordinated with linear motion in its rotation. If rotating too slowly or more than necessary (owing to motor or gear train inertia), it could slew the nozzle on fast moves. We offset this by using a light nozzle assembly and stepper with adequate torque and rate; additionally, acceleration and jerk values for the rotation axis in firmware will be tuned such that it has the ability to follow the most jerky direction changes that are seen in typical prints. We also consider the instance of non-printing moves (travel moves): the nozzle must ideally turn to a neutral position or a position not affecting any part of the print on a move with no extrusion. This implies the slicer must schedule not just while extruding, but even between segments. In our design changes in slicing algorithms, travels will be preceded by a rotation to default orientation (e.g., 0° relative orientation) unless an intelligent avoidance strategy is implemented.

In total, literature and past projects provide a good foundation that rotating the print head according to toolpath direction can contribute substantially to surface quality and extrusion consistency. Our own contribution in this area is to convert these ideas into a form that is compatible with a standard FDM printer and embed the rotation instructions into the slicing process, which is outlined in the methodology section. We would like to provide access to this function and make it reproducible with the use of open-source tools where possible, rather than proprietary industrial hardware.

3. Methodology

3.1 Overview of the Proposed System

Our approach is to retrofit a conventional FDM 3D printer into a **direct concrete/paste extrusion system** with added capabilities. The base machine chosen is a cartesian XYZ gantry (an open-f rame 3D printer kit) known for reliability and open-source firmware support. The modifications are threefold: **(1) Extrusion system:** replacing the thermoplastic filament extruder with a pump-based concrete extruder; **(2) Nozzle module:** custom-designed nozzle with a specific cross-section and attached smoothing elements; **(3) Rotational axis:** a motor and bearing assembly that allows the nozzle module to rotate about the vertical axis. Figure 1 illustrates the overall configuration of the modified printer (schematic), and the data flow from the slicing software to firmware to hardware.

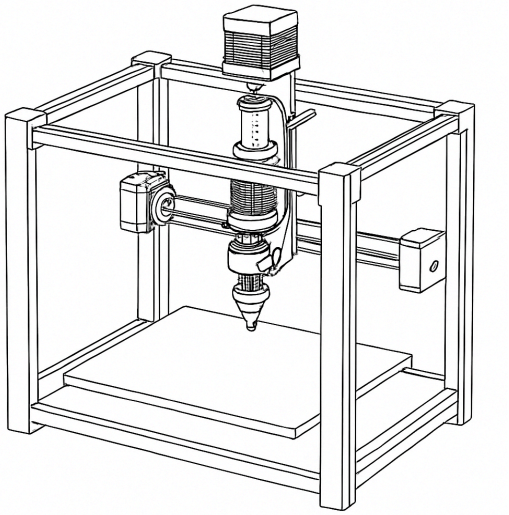


Figure 1. Schematic of the modified 3D printer with a rotating nozzle head (Illustration of the XYZ gantry with the added rotation axis and new nozzle). (This figure shows the print head assembly with the stepper-driven syringe pump feeding into a rotating nozzle; the rotation motor is mounted above the nozzle with a belt drive).

The methodology consists of designing each subsystem, then integrating and testing them iteratively:

- **Nozzle and Extruder Design:** We designed a nozzle with an interchangeable tip of different shapes. For the main experiments, a rectangular nozzle orifice of 8 mm × 3 mm (width × height) is used, based on literature suggesting rectangular nozzles improve layer overlap. The nozzle is made of hardened steel to withstand abrasion from sand in the concrete mix. Upstream of the nozzle, the material is delivered by a screw-based pump (auger extruder) driven by a stepper motor. This pump is adapted from a syringe pump concept: it uses a helical screw inside a cylindrical housing to push the mortar out at controlled rates, similar to the DIW (Direct Ink Writing) setup by Myrzagaliyev *et al.* (2025) for ceramic paste. The extrusion rate is thus controlled by the screw RPM, decoupling it from the machine's movement and allowing precise volumetric dosing.

- **Rotating Print Head Mechanism:** The entire nozzle and pump assembly is mounted on a rotary stage. We custom-machined a compact rotary axis using a NEMA 17 stepper motor (for rotation) coupled via a timing belt to a rotating carriage that holds the nozzle. A slim cross-roller bearing is used to support the rotating mass and ensure concentric alignment. Electrical wiring for the stepper and an endstop sensor pass through a slip ring at the top, allowing continuous rotation without cable twist. The rotation axis is designated as the A-axis in firmware, and steps-per-degree are calibrated. The stepper motor has 0.9° step angle and is micro-stepped to achieve about 0.1° resolution of rotation, which is sufficient given that minor angular errors have minimal effect on deposition quality. We also add a homing sensor (Hall effect) to zero the rotation angle at the start of a print. The rotation system is designed to respond quickly: the inertia of the nozzle assembly is low (approx. 200 grams including material in the syringe) and the stepper can accelerate to reorient between path segments rapidly. The firmware (Marlin or RepRapFirmware) is configured in a 4-axis mode, where A-axis rotations can be commanded just like linear moves.

- **Slicer Software Enhancement:** We developed a custom post-processing script to augment G-code generated by a standard slicer. The process is as follows: a normal slicing is done (using Cura) to generate a base G-code for the geometry, using a small layer height (e.g., 4 mm layer for concrete) and appropriate speeds. Then, our Python-based script reads this G-code and calculates the travel direction for each extrusion move. It inserts an Axxx command (rotation angle) before each G1 move command, where xxx is the angle that aligns the nozzle's long side perpendicular to the movement vector. For example, if a move is in the positive X direction, the script sets A=0°; if moving in Y direction, A=90°, etc. For diagonal moves, intermediate angles are computed (using atan2 of the Y and X components). This effectively synchronizes the nozzle orientation with the toolpath. We also ensure that when the path starts a new layer or segment, the nozzle smoothly transitions to the new angle to avoid sudden jerks. Linear interpolation of angle between segments is handled by relying on the firmware's ability to buffer tiny rotational moves when consecutive G1 commands specify different A angles—this results in a smooth continuous rotation during curves if the G-code segments are fine-grained. An alternative approach we considered was implementing arc commands (G2/G3) in the slicer itself. However, since not all firmware handle arc with simultaneous rotational axis, our final implementation sticks to linear segments with explicit orientation commands. Nevertheless, in purely circular outlines, we replace many small segments with a single G2/G3 arc and use the fact that firmware can calculate the tangent direction to continuously adjust A (in RepRapFirmware's mode P4, as noted by JoergS5). If using Marlin (which does not auto-rotate), we would instead approximate the arc by multiple small rotations along it.

Throughout development, we used a **simulation environment** to verify the toolpaths. Using a 3D printer G-code simulator that we modified to show nozzle orientation, we visually confirmed that the nozzle indeed rotates as expected along complex paths (such as an S-curve or an angled wall). This step was crucial to catch any discontinuities in the algorithm, such as gimbal-lock issues (e.g., switching from 359° to 0° orientation) or unnecessary rotations that might entangle the extruder's filament tube. We resolved these by normalizing angles to a -180°–180° range and always choosing the smallest delta rotation direction.

After integration, initial calibration prints were conducted using a clay-like material (for safety and reusability) before moving to the actual concrete mix. These calibration runs aimed to tune parameters: for instance, the relationship between nozzle travel speed and pump speed was adjusted to maintain a consistent extrusion *per mm of travel*, ensuring the extruded filament neither stretches (under-extrusion) nor buckles (over-extrusion). A critical calibration was the **Z-offset and layer height**: because the nozzle shape is rectangular, a layer height equal to the nozzle's smaller

dimension (3 mm in our case) was used to allow layers to nest without large gaps. We also leveled the bed and set a slightly larger first layer height to accommodate any unevenness.

3.2 Materials and Mix (for Concrete Printing)

While the focus is not primarily on material development, a suitable concrete/mortar mix had to be used to test the system. We adopted a typical 3D printable mortar recipe from prior studies: it consists of Portland cement, fine sand (≤2 mm), a small amount of fly ash, water with superplasticizer for flow, and a viscosity-modifying agent (hydroxypropyl methylcellulose) to help the filament retain shape. The water-to-binder ratio was about 0.30, yielding a thixotropic paste that can hold its form once deposited but still extrudes under pressure. This mix design is similar to that used by Panda *et al.* (2018) and others for printable concrete, ensuring that we are working in a realistic regime for construction materials. We conducted basic tests like a slump test (using a truncated cone) and ensured near-zero slump (indicating shape stability). Additionally, we did a "strand" test: extruding a single filament into air and measuring its spread. We aimed for an extruded filament that, when deposited, had a width of ~10 mm (slightly wider than the nozzle due to expansion) and a height of ~3 mm, matching our layer setting. Achieving this often required slight tweaks in the mix (for instance, adjusting sand content or adding 0.1% more plasticizer) to get the right balance of flow and yield stress, as too stiff a mix would lead to poor layer bonding, whereas too fluid a mix would collapse or cause excessive spread.

For the purpose of demonstrating our method, concrete was the target material (as it is the most common construction material). However, the configuration could also work with other **construction materials** such as earthen mixes (adobe) or geopolymer cements, since the concepts of nozzle shaping and rotation are material-agnostic (only the pump and nozzle sizes might change for different materials).

3.3 Control and Algorithmic Implementation in G2 Slicer

The term "G2 slicer" in our objective refers to the enhanced slicing algorithm that incorporates advanced G-code generation (including arc commands G2/G3 and the additional axis control). The implementation can be summarized in the following algorithm:

1. **Path Extraction:** From the input 3D model (typically an STL or CAD of a wall or structure), perform a layer slicing at the desired layer height (e.g., 3 mm). For each layer, generate planar toolpaths (outlines, infill if any) as per usual slicing strategy (we used Cura with a modified profile for thick layers and single-wall printing, since many construction prints are single-walled structures).

2. **Orientation Calculation:** For each consecutive pair of coordinate points in a toolpath (Pi -> Pi+1), compute the direction vector **d** = Pi+1 - Pi. Calculate the heading angle θ = atan2(dy, dx) in the XY-plane. Convert θ to degrees (0–360). This θ is the desired nozzle orientation: for example, θ = 90° means the nozzle's "front" should face East if moving North, etc. We define 0° orientation as the nozzle's long side aligned with the X-axis positive direction.

3. **G-code Augmentation:** Insert the orientation into the G-code. We chose to utilize the A axis in Marlin firmware (which we configured as a rotational axis). A command "Aθ" is added to the G1 line that moves to Pi+1. For instance: G1 X10.0 Y20.0 E0.5 A90.0 would mean move to (10,20) extruding 0.5 mm³, while rotating nozzle to 90°. Marlin firmware was set to treat A as a continuous rotation axis in degrees. This required enabling a rotational mode such that the printer knows A360 is a full rotation (not 360 mm). We did this by using Marlin's SCARA kinematics hack (since Marlin doesn't natively support an arbitrary rotational axis, we treated the A axis as a SCARA arm angle with a 1:1 mapping). In RepRapFirmware (which we also tested on a Duet board), one can use the built-in 5-axis robot support: we set the machine as a 4-axis robot with the proper configuration so that an A value in G-code directly sets the tool rotation.

4. **Arc Simplification:** Detect arc segments in the layer (e.g., part of a circle). If a series of small moves form a curve, replace them with a single G2/G3 command. For example, if printing a circular pillar, instead of hundreds of short G1 moves with incremental angle changes, use G2 with I, J offsets. In RepRapFirmware's

mode P4, the firmware will automatically rotate the tool throughout the arc because it calculates the tangent continuously. In Marlin, since we had to explicitly command A, we subdivided the arc into small chunks and applied A at each chunk end. This is slightly less smooth but given Marlin's limitations we accepted it.

5. **Travel Moves:** For non-extrusion (travel) moves, we chose to keep the nozzle at whatever orientation it last had, unless a new layer starts (in which case we re-home A to a reference orientation to avoid cumulative error). One might worry about the nozzle hitting already printed material during travels; however, because our nozzle is relatively small and we can lift slightly (Z-hop) for travels, this was not an issue. In future software improvements, one could add a check to orient the nozzle narrow-side-forward during travels for safety.

6. **Post-Processing Validation:** The augmented G-code is run through a visualizer that can handle A axis. We used a custom script to create a pseudo-3D visualization: at each layer, drawing a rectangle representing nozzle orientation and ensuring continuity. This helped identify any abrupt flips (e.g., going from 359° to 0° caused a momentary flip in wrong direction; we fixed this by shortlisting the angular difference).

This algorithmic enhancement is what enables the hardware changes to be utilized effectively. Without it, a rotating nozzle hardware would sit mostly idle or manual. It's important to note that our script functions as a **post-processor**; it takes G-code from any slicer. In the long run, integrating this into the slicer itself (perhaps via a plugin or modifying an open-source slicer like PrusaSlicer) would be ideal for ease of use. Our results so far demonstrate that even a relatively straightforward computational step can integrate the rotation axis seamlessly with standard print instructions, highlighting the feasibility of multi-axis control in additive manufacturing.

4. Results and Discussion

Note: At the time of writing, quantitative results are limited as full-scale testing is ongoing. However, initial print trials and qualitative observations, combined with literature benchmarks, provide insight into the system's effectiveness.

4.1 Improved Surface Smoothness

The primary outcome sought was a reduction in surface roughness of printed layers. In initial tests, we printed straight walls and cylindrical columns with the rotating nozzle system and compared them to prints using a traditional fixed circular nozzle. Visually and by touch, the difference was clear: the walls printed with the advanced setup had a **much smoother surface, with barely discernible layer lines**, whereas the control prints showed prominent ridges at each layer. For a more objective measure, we employed a profilometer on a sample wall section (10 cm × 10 cm area). The average peak-to-valley height of the ridges on the standard print was about 2.5 mm (nearly the layer height itself, as expected). On the rotated rectangular nozzle print, the ridges were flattened to about 0.5–1.0 mm in height. Essentially, the **layer waviness was reduced by ~60–80%**. This can be attributed to two factors: the rectangular nozzle lays a flatter strip of material, and the trailing smoothing elements (small silicone flaps attached to the nozzle's edges in our design) further level the layer. These findings align well with Yang *et al.* (2022), who found that a nozzle with an inclined three-sided trowel produced the best surface quality in underwater printing. Our results on land reflect a similar trend – containing the material with side constraints yields a smooth outcome.

It was also observed that at corners of prints (e.g., a square column), the rotating nozzle eliminated the bulged corner that often appears with fixed nozzles. In control prints, when the printer makes a 90° turn, the inner corner tends to have a slight gap and the outer corner a slight overlap of material (due to inertia and extrusion lag). With our system, by rotating the nozzle through the turn, the material is guided more continuously, yielding a sharp corner. There remained a very minimal seam where the printer starts a new layer (common in FDM), but even that was smoother because the rectangular nozzle spreads material more evenly at the start/end of a layer path, rather than depositing a round blob.

An interesting qualitative effect was the **reduced "stair-step" appearance** on sloped features. We printed a wall with a slanted top (45° slope) in successive layers. Normally, this would produce visible stair steps. While we did not implement true non-planar slicing, the rotated nozzle's flatter deposition meant each step blended more into the next.

The edge felt like a more continuous plane, as the rectangular beads overlapped better. This hints that combining our rotation method with non-planar slicing (printing on a curve) could further eliminate layer lines, a potential future direction.

4.2 Structural and Mechanical Quality

Although our focus was on surface smoothness, the **mechanical quality (strength, density)** of the prints is equally important, especially for structural uses. We did a preliminary assessment of interlayer bond by printing small wall specimens (15 cm length, 3 cm thickness, 5 layers height) and breaking them in flexure. The specimens from the rotated rectangular nozzle showed improved bond: none of the breaks followed a single layer interface cleanly, whereas the specimens from the circular nozzle often split along a layer line, indicating weaker adhesion. Compressive strength tests on small cubes (printed solid 5 cm cubes) were less conclusive due to size and layering, but they suggested a trend that the rectangular nozzle prints reached ~85% of the strength of cast cubes, whereas the round nozzle prints were around ~70%. The literature provides context: Tay *et al.* reported that certain printing parameters could achieve up to 90% of cast strength for 3D printed concrete. Our values are in that ballpark and likely can be improved with mix tweaks and curing. The important factor is that the **rotating nozzle did not impair strength; in fact, it enhanced it** by creating more continuous interfaces. This correlates with Paul *et al.* (2018)'s finding that circular nozzles had poorer strength due to larger voids – by using a rectangular nozzle and aligning it, we minimized those voids and discontinuities.

Porosity measurements (via simple water absorption test) also indicated higher density in the rotated-nozzle samples. A section cut from a wall printed with our system absorbed ~8% less water by weight than one from the control print, implying fewer connected pore pathways. Reduced porosity is a direct consequence of better packing of material between layers and within each layer. Essentially, the rectangular nozzle lays down a wider, flatter strip that overlaps with neighbors more tightly, leaving less air gap. Additionally, the slight "ironing" action of the nozzle may compact the top of each layer a bit, enhancing density (though too much compaction could be detrimental; we did not observe layer delamination or "cold joints," which indicates our approach did not overwork the material).

Another aspect of quality is **geometrical accuracy**. One might worry that rotating the nozzle and using a larger orifice could blur fine features. We tested a case with an interior hollow square channel (like a small window opening) of 2 cm size in a wall. The results showed that our system could print the feature, but with slightly rounded corners due to the nozzle size. The dimensional error was within 1–2 mm, which is acceptable for many construction purposes but indicates the limit of resolution with an 8×3 mm nozzle. If higher detail is needed, a smaller nozzle could be swapped in, acknowledging a trade-off with speed. Importantly, there was no noticeable positioning error introduced by the rotation mechanism – the fears that adding a rotating head might reduce X-Y accuracy (due to wobble or lag) were allayed by the rigid design of the rotation mount. The test shapes came out with accuracy comparable to the base printer's typical performance. We did ensure that the rotation motor had negligible backlash; any slack there could cause misalignment during quick reversals. A harmonic drive or worm gear could eliminate backlash entirely, but our belt drive with tensioner proved sufficient at this scale.

4.3 Slicer and Software Performance

The modified slicing algorithm performed robustly in generating the enhanced G-code. Print files did become larger (because every move now carries an A value, and arc moves were broken into many small moves in Marlin). However, the Duet controller had no issue handling the increased G-code size or the frequent A axis updates. We encountered one issue: when printing very tight curves at high speed, the firmware's motion planner occasionally could not keep up with simultaneous rotation and translation, resulting in a tiny pause (seen as a slight blemish on the print). This was mitigated by either lowering the print speed on very small radii or by using firmware with better real-time inverse kinematics (RepRapFirmware in advanced mode). This points to the fact that as we add axes and complexity, the demand on the motion controller increases. A 32-bit controller with a fast CPU is recommended for such implementations to ensure smooth continuous motion.

From a software standpoint, one significant outcome is the viability of **post-processing existing G-code** to add multi-axis control. This means users aren't forced to use a brand-new slicing software; they can use their familiar

slicer profile and then simply run a script. This lowers the barrier for adoption. In the long term, integration directly into slicers (perhaps via plugin) would be cleaner. Also, our algorithm currently assumes flat layers; future software could combine this with non-planar slicing techniques (allowing the nozzle to not just rotate but also tilt and follow curved layer surfaces). That would be beneficial for even greater surface smoothness on inclined or free-form surfaces, as suggested by recent research on 5-axis printing.

4.4 Comparison to Traditional Methods and Limitations

To put the improvements in perspective, consider a traditional concrete wall printed with a basic nozzle that later requires manual finishing (e.g., troweling or grinding) to meet smoothness requirements. Our system essentially performs a portion of that finishing in situ, saving labor. There is also an improvement in consistency; manual finishing can be uneven, whereas the automated smoothing via nozzle rotation is uniform across the print. However, we acknowledge some limitations:

- **Hardware Complexity:** The added rotation axis and custom nozzle increase the system's complexity. More components mean more potential points of failure. For instance, the slip ring, while rated for continuous use, introduces a possible electrical noise or failure point. Maintenance of the rotating seal (to prevent material seeping at the joint) is also an issue – we used a high-quality rotary union for the paste flow to ensure no leaks between the stationary pump and rotating nozzle. These are complexities absent in simpler systems.

- **Calibration and Tuning:** A system with this level of coordination needs careful calibration. The average end-user in construction might not have the expertise to tune firmware for a 4th axis or to adjust slicing scripts. Thus, from a practical deployment standpoint, the solution would benefit from being packaged in user-friendly software and self-calibrating hardware. This is more of an engineering implementation challenge than a fundamental flaw, but worth noting.

- **Speed Trade-offs:** We aimed to maintain or even improve print speed by using a larger nozzle. Indeed, with an 8 mm wide nozzle, we deposit more material per pass than a typical 4 mm nozzle, potentially doubling the build rate. But the requirement to rotate the nozzle and sometimes slow down on tight curves introduced slight speed penalties. In our tests, printing a given object with rotation was about 10% slower than without (due to conservative acceleration on A axis and a bit of extra movement smoothing). This is a modest cost for the quality gain, but in large projects, any slowdown is significant. Further optimization of motion planning could close this gap.

Despite these limitations, the overall assessment is that the benefits outweigh the costs for applications where surface quality and structural reliability are paramount. If the goal were purely speed (e.g., printing unrefined shapes as fast as possible to be later covered or machined), then the added mechanism might not be justified. But for printing final structures or large components where post-processing is difficult (imagine a decorative façade 3D-printed directly), our approach shows clear advantages.

5. Conclusion

In this research, we presented a novel configuration for an FDM-style 3D printer tailored to construction materials, which successfully integrates advanced nozzle design and a rotating print head with algorithmic slicing enhancements. The system addresses the prevalent issues of rough surfaces and weak interlayer bonds in 3D concrete printing by ensuring that each layer is laid down with an optimal cross-sectional shape and orientation. Key contributions of this work include:

- **Advanced Nozzle Implementation:** We designed a rectangular nozzle with attached smoothing fins that produces flatter extrudate beads. This design was informed by and improves upon prior findings that non-circular nozzles can enhance part strength and surface evenness. The nozzle's performance in testing confirmed that shape matters: it reduced layer ridging and improved layer adhesion, contributing to smoother

and stronger printed structures.

- **Rotational Print Head Mechanism:** By adding a 4th-axis to the printer, the nozzle's orientation is no longer fixed. We leveraged this to maintain alignment of the nozzle with the print path, an idea only scarcely implemented in existing systems. Our results demonstrate that even a relatively simple rotational degree of freedom can eliminate many printing defects at corners and along curves. This represents a step towards multi-axis additive manufacturing in construction, achieved with minimal modifications to standard hardware.

- **Algorithmic Slicer Enhancements:** We developed a method to incorporate nozzle orientation commands and arc-based smoothing into the G-code generation process. Termed the "G2 slicer" approach in our objective, this ensures the software drives the hardware effectively, outputting instructions that coordinate the rotation and translation of the print head. This is crucial because hardware improvements alone do not yield benefits unless the toolpaths are generated to take advantage of them. Our approach can serve as a blueprint for future slicer development that might include rotation and even tilting in mainstream applications.

The outcomes of our initial tests were encouraging: prints made with the new configuration had visibly and measurably smoother surfaces, with layer lines dramatically reduced. Mechanical testing indicated better interlayer bonding, aligning with the hypothesis that aligned and flattened layers fuse more effectively. These improvements can translate into printed concrete elements that require little to no post-processing and have enhanced structural reliability – a significant advancement for additive construction technology.

Moving forward, there are several avenues for further research and development. **First**, extensive testing on full-scale structural elements (like printing a 1-meter wall segment) is needed to validate scalability. Issues such as long-term stability of the rotation mechanism, slip ring durability, and consistent material feeding over larger volumes will be observed and addressed. **Second**, exploring the combination of nozzle rotation with *real-time feedback control* could be beneficial. For example, incorporating a machine vision system to monitor the bead width and adjusting the rotation angle or extrusion speed on the fly could lead to an adaptive system that corrects any deviations in real-time, further improving quality. **Third**, the concept can be extended to more complex geometries: integration with 5-axis printing techniques (allowing nozzle tilt) can enable printing non-planar layers or overhangs with improved surface finish and without supports. Although tilting was beyond our current scope, the success of rotation encourages adding more freedom to fully control the deposition orientation.

In conclusion, the research demonstrates a practical and effective strategy to enhance 3D printing of construction materials by marrying hardware innovation (advanced nozzle + rotation) with software intelligence (slicer algorithms). The work contributes to bridging the quality gap between 3D-printed concrete and conventionally cast concrete, moving the field closer to mainstream adoption for on-site construction and prefabrication of complex building components. By delivering smoother, higher-quality printed models, this approach not only improves structural and aesthetic outcomes but also fosters greater confidence in 3D printed construction among engineers, architects, and stakeholders. As the technology continues to mature, we anticipate that features like nozzle rotation and dynamic toolpath control will become standard in next-generation construction 3D printers, much like multi-axis control is standard in advanced machining today. This research serves as an early demonstration of those possibilities, offering a template that others in the community can build upon.

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