Construction Robotics (2023) 7:291–306
https://doi.org/10.1007/s41693-023-00107-5

ORIGINAL PAPER

Non-planar granular 3D printing

Barrak Darweesh[1] · Maria Paz Gutierrez[1] · Simon Schleicher[1]

Received: 3 March 2023 / Accepted: 16 June 2023 / Published online: 13 July 2023

Abstract

Most approaches to 3D printing at various scales are layer based, meaning they start with a 3D CAD model that is sliced into planar print paths to be translated to machine code. However, this approach entails a number of drawbacks, such as slow printing speeds, limited build volumes, allowable geometric properties, and material diversity. To overcome these limitations, the authors have developed a novel additive manufacturing process called Non-Planar Granular Printing (NGP). Compared to its layer-based counterpart, NGP enables non-planar 3D printing by selectively binding reusable granular particles to create free-form structures. In doing so, NGP leverages traditional powder-based additive manufacturing processes. However, instead of enclosing the extruded compounds within a three-axis layer-based system, NPG combines multi-axis robotic deposition capabilities with customizable build volume parameters, which drastically improves print speed, scalability and material versatility. The result is a process whose main advantage is to enable the rapid production of support-free and complex geometric forms using a wide range of materials in granular form. This paper introduces and analyzes a series of benchmark experiments conducted to demonstrate the practical workflow, general output capabilities, and volume-material limitations of the system. The research also lays a foundation of non-planar 3D extrusion that enables material transitions for functional gradience capabilities.

Keywords Additive manufacturing · Robotic fabrication · Non-planar 3D printing · Digital fabrication

1 Introduction

With the rise of additive manufacturing technologies, designers today can not only design objects of high geometric complexity in CAD, but also prototype them fairly quickly and inexpensively (Gibson 2021). Most of these additive manufacturing processes rely on a layer-based manufacturing process in which objects are broken down into two-dimensional cross-sections that can be translated into machine paths for material deposition (Chakraborty et al. 2008). In this process, the material is only applied in flat layers over the X–Y planes, with the layer height remaining constant. Once a layer is completed, the material extruder moves up (Z-axis) and the process is repeated to print the next layer. Therefore, the Z-axis only moves when the X- and Y-axes are stopped. Due to the nature of the process, higher resolution objects are made up of thinner layers that often require longer print times. This constraint is particularly noticeable with larger 3D printed objects, where the process can take several hours, if not days. The scalability of the process also comes up against other limits, such as print volume and material variety. The size of the 3D printed object is typically also limited by the dimensions of the 3D printing platform. Usually following the logic, the bigger the machine, the bigger the possible print. In addition, 3D printing materials are often proprietary to the machine manufacturer or limited to a small library of available materials that may be suitable for rapid prototyping but not for industrial-scale manufacturing of final products.

To overcome the current limitations of 3D printing, the authors of this study have developed a new technique called Non-Planar Granular 3D printing (NGP), which is faster, more versatile, customizable, and scalable. NGP is a non-planar 3D printing technique that produces three-dimensional objects by selectively depositing liquid binder into a volume of granular particles. The method enables the rapid production of geometrically complex parts from a wide range of granular materials. However, as this is a new and

✉ Barrak Darweesh
barrakd@berkeley.edu

[1] Department of Architecture, University of California, College of Environmental Design, 232 Wurster Hall, #1800, Berkeley, CA 94720-1800, USA

unexplored method for 3D printing, the authors intend to use the following study and a series of practical experiments to investigate how viable and versatile the NGP process actually is, what its limitations are, and which potential application paths are particularly suitable for this technology.

2 Relevant work

Different 3D printing technologies have their own set of advantages and disadvantages which are important factors to consider depending on the application and requirements. As shown in Table 1, different technologies offer varying production speeds, material palettes, and size limitations. These factors directly influence the suitability of the technology to specific applications. For example, Fused Deposition Modeling (FDM) is commonly used for prototyping and experimental applications, where the manufacturing speed and low cost are of primary importance. On the other hand, Stereolithography (SLA) or Selective Laser Sintering (SLS) may be ideal for producing highly complex geometric features that require smooth surface textures.

Table 1 serves as a loose comparison between various 3D printing technologies listing some of the key specifications that must be considered in the comparison process. The aim of this table is to position NGP within the spectrum of available technologies and to highlight its advantages and disadvantages compared to primary 3D printing processes.

Table 1 highlights some of the common features that have proven to be advantageous in various 3D printing technologies and are adapted in the NGP process. One of the key drawbacks in many 3D printing technologies is their limited build platform dimensions, which is often restricted to the size of the machine. Therefore, the size of the 3D printed object is constrained by the dimensions of the build volume. Technologies such as NGP and Rapid Liquid Printing (RLP) overcome this limitation by separating the build volume from the extrusion platform (Formlabs 2023). By doing so, the build volume can be tailored depending on the desired object scale offering a higher degree of platform flexibility.

NGP also takes advantage of granular support integrations into the 3D printing process. Using 3D printed support structures can be time consuming, wasteful, and sometimes limit the complexity of the 3D printed object. Technologies that use granular support structures benefit from reducing printing time and opening up geometric possibilities that often require 3D-printed supports and sometimes labor-intensive post-processing.

2.1 Granular materials

Granular materials in 3D printing are not entirely uncommon and are used in processes such as binder-jet 3D printing or selective laser sintering (SLS) (Table 1) (Kruth et al. 2003; Mostafaei et al. 2021; Néel et al. 2018). In both processes, a fine layer of powder (~25–150 µm or smaller) is either sprayed, glued, or sintered with a laser beam to create a thin two-dimensional layer of a 3D object (Miyanaji et al. 2020). Incrementally, more powder layers are applied, and the binding/sintering process is repeated until all the layers that make up the three-dimensional object are completed. Binder jet 3D printing, among other additive manufacturing technologies, has the advantage of producing complex isotropic components using a wide variety of materials. This is made possible by the load-bearing capacity of the loose, unadhered powder particles, which temporarily fill all the cavities and unsupported geometric elements until the printing process is completed. The Oakland-based practice Emerging Objects, for example, have demonstrated architectural possibilities through binder-jet 3D-printed cladding and artifacts made of various recycled materials, including Portland cement, salt, sugar, tea, and rubber (Fratello 2021; Rael and San Fratello 2013; Rubber Pouff 2016). However, the process still faces the challenge of layer-based manufacturing, and object size restrictions which are common to most 3D printing methods leading to long printing time (Table 1). This is evident throughout Emerging Objects' work, where large components are often broken down into smaller parts that can fit within the 3D printing machine's allowable volume and be printed simultaneously on multiple machines to save time.

2.2 Non-planar 3D printing

In contrast to layer-by-layer manufacturing and the sequential breakdown of objects into 2D layers, efforts have been made towards free-form 3D printing without auxiliary structures. In such non-planar 3D printing processes, the platform is instructed to move simultaneously in the X, Y and Z axes to freely deposit materials without relying on the previous layer. By eliminating support structures, free-form 3D printing can increase printing speed while reducing the amount of materials used. A good example of the potential of this approach are the experiments conducted by Gramazio Kohler's research team at ETH Zurich. The architectural installation called "Iridescence Print" exhibited at the Palais de Tokyo in Paris, for instance, featured a continuous mesh structure freely constructed in a 3D space (Ziaee and Crane 2019; Helm et al. 2015). The mesh structure had a volume of over eight cubic meters and was printed in 12 segments that were assembled on site. Other recent demonstrations of

Table 1 A comparative summary of some of the characteristics of 3D printing technologies, highlighting common specifications that are present in the Non-Planar Granular Printing method

Technology	Fused deposition modeling (FDM)	Stereolithography (SLA)	Selective laser sintering (SLS)	Binder jetting	Non-planar granular 3D printing (NGP)	Rapid liquid printing (RLP)
Specifications						
Printing Speed	Slow–Moderate (Ouhsti et al. 2018; Khosravani et al. 2022)	Slow–Moderate (Finnes 2015)	Moderate (Chen 2019)	Moderate (Myers et al. 2021)	Fast	Fast (Hajash et al. 2017)
Materials	Thermoplastics, bio-thermoplastics, Polymeric composites, biopolymeric composites, metals (titanium, copper, aluminum) (Jiang et al. 2018; Ramazani and Kami 2022; Mogas-Soldevila et al. 2014; Depuydt et al. 2019; Duigou et al. 2016; Pop et al. 2019; Chacón et al. 2017)	Thermosets (photopolymers), bio-thermoplastics (gelatins, hyaluronic acids), thermoplastics (polyethylene glycols) (Della Bona et al. 2021; Mukhtarkhanov et al. 2020; Maines et al. 2021)	Thermoplastics (nylon; synthetic polyamides), thermosets, metals, ceramics (Kruth et al. 2005; Lupone et al. 2021; Roy et al. 2019; Ajdary et al. 2021)	Ceramics, metals, composites, thermoplastic biopolymers (Mostafaei et al. 2021; Shakor et al. 2022; Dini et al. 2020)	Binding material: thermoplastics, thermosets, biopolymers (hydrogels)[a] Granular material: ceramics (sand, glass), wood (sawdust), biopolymers (lignocellulose)[a], metals, thermoplastics	Elastomers (urethane rubber, silicone), thermoplastics, metals (Hajash et al. 2017)
Material state	Solid (pre-extrusion), viscous (during extrusion) (Jiang et al. 2018)	Viscous (Huang et al. 2020)	Solid (granular)	Solid (granular), viscous (binder)	Solid (granular), viscous (binder)	Viscous (Hajash et al. 2017)
Support type	3D printed supports (same as 3D printed material) (Jiang et al. 2018)	3D printed supports (same as 3D printed material) (Jiang et al. 2018)	Non-printed granular support (Formlabs 2023; Jiang et al. 2018)	Non-printed granular support (Ziaee and Crane 2019; Jiang et al. 2018)	Non-printed granular support	Non-printed granular support (biopolymers, hydrogels) (Hajash et al. 2017)
Build volume	Limited by printer dimensions (Lemu 2012)	Limited by printer dimensions (Lemu 2012)	Limited by printer dimensions (Lemu 2012)	Limited by printer dimensions (Lemu 2012)	Independently customizable, modular	Independently customizable (Hajash et al. 2017)
Cost per volume	Low (Formlabs 2023)	High	Moderate (Formlabs 2023)	Moderate–High	Low	Low (Hajash et al. 2017)

[a]These materials have not yet been tested, but they have the potential to be used in future experimentation using NGP

non-planar 3D printing are being conducted by U.S.-based Branch Technology using a novel method called cellular Fabrication (CFAB). In this process, elongated extrusions are fused at the corner nodes to form three-dimensional lattice structures, creating large-scale architectural components (Lemu 2012; Shelton 2017). Both projects described above use thermoplastic filament or pellets as 3D printing material. This process depends primarily on thermal adhesion, which allows only certain extrusion lengths and limited geometric shapes.

Another notable approach to non-planar 3D printing that is fast, versatile, and scalable has been demonstrated by MIT's Self-Assembly Lab named Rapid Liquid Printing (RLP) (Hajash et al. 2017; Formlabs 2023; Howarth 2017). Hajash et al. explain that this process uses a pneumatic extruder supported by a robotic arm to inject liquid composite materials into a tank filled with a granular gel. Here, the granular gel acts as a reusable support medium that temporarily carries the extruded liquid until it cures. The versatility of the platform makes it possible to extrude various liquid materials in single or multiple parts. Hajash et al. explored various material options, including urethane rubber and plastics, and discussed the possibility of extruding materials such as foams, plastics, and even concrete. This research team also considered the potential for scalability by increasing the size of the container holding the granular gel and increasing the reach of the robotic arm for large-scale printing. One of the most notable advantages of the RLP system is the ability to print objects quickly and freely without being limited to printing in incremental, flat layers. With the ability to extrude materials in all three dimensions within the granular gel, the system enables the production of complex geometric features that would normally require support structures. However, one of the limitations of RLP is the extrusion thickness, which is limited by the load-bearing capacity of the gel. When 3D printing materials that are dense or heavy, problems can occur, such as inaccuracies due to the displacement of the printed object.

2.3 Non-planar granular 3D printing

The authors' newly developed Non-Planar Granular 3D printing (NGP) technique shares some of the advantages of the aforementioned manufacturing methods and aims to overcome some of their limitations and challenges. Similar to Rapid Liquid Printing (RLP) and other powder-based processes, NGP uses the load-bearing capacity of the surrounding medium as a temporary support to enable free-form 3D printing without being limited on geometric features or relying on material adhesion during printing. The NGP technology is based on an industrial robotic arm that drives a long and slender nozzle through a volume of coarse

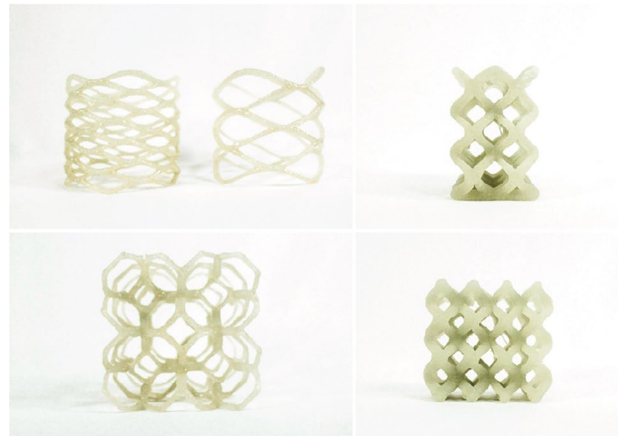

Fig. 1 These prototypes are fabricated using non-planar granular 3D printing (NGP), a process that requires no additional support structures to print overhangs and bridging elements

granular material (~200–600 µm or bigger) and selectively inject a liquid resin to bond particles together and to create a three-dimensional object (Fig. 1). Until the binding agent cures, the dry particles surrounding the 3D printed object provide temporary support. This allows designers to create free-form objects without having to integrate auxiliary scaffolding, as is the case with most other 3D printing technologies. After curing, the 3D printed object can be pulled out of the volume. Like its technological counterparts, the loose granular material in NGP that is left in the container can also be recycled and reused without causing any waste. However, a key advantage of NGP over other processes is that the granules can vary in size, shape, and physical properties, which significantly expands the range of acceptable materials and lowers production costs using recycled waste from other industrial processes that has already been processed through shredding and pelletizing. Another important advantage of NGP technology is that it offers the ability to fine-tune the material throughout the 3D printing process. Thanks to the interchangeability of the used granular materials, and the precise control of the liquid flow and the tunability of platform parameters such as speed and nozzle diameter, the printed objects can vary in resolution, extrusion thickness and material properties.

3 Methodology

To investigate the feasibility and versatility of the newly developed Non-Planar Granular 3D printing (NGP) method, the authors conducted a series of benchmark tests and practical experiments to clarify how this study was conducted. However, it is necessary to first describe the

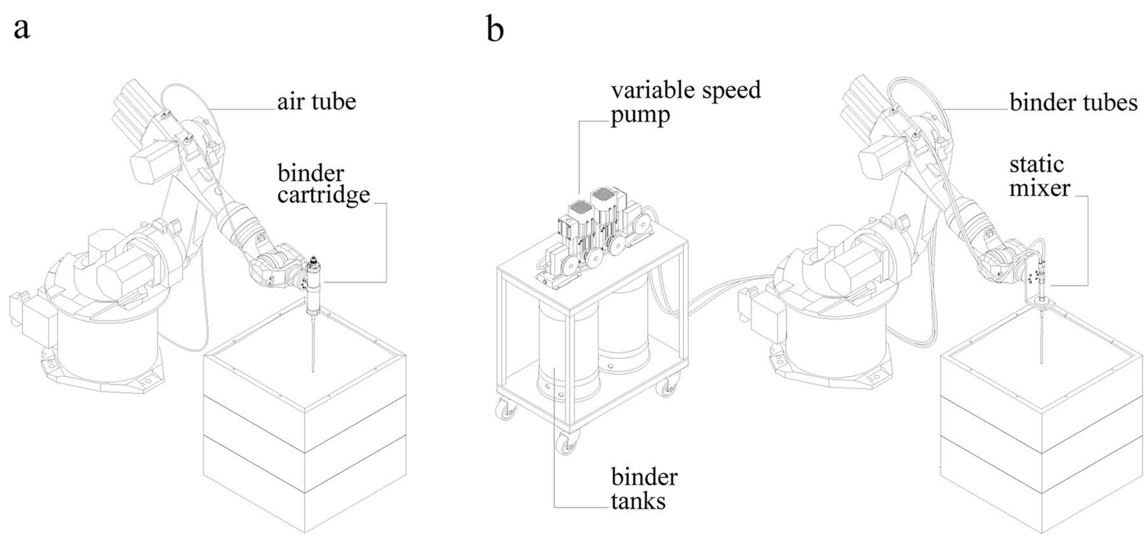

Fig. 2 Two technical solutions have been developed for NGP printing. **a** One consists of a pneumatically operated cartridge system containing 20 oz. of liquid binder. The other (**b**) allows extrusion of larger quantities and consists of two separate tanks and variable speed pumps feeding a mixing nozzle at the end effector

general objectives for these tests, the technical setup, and the materials used before going into further detail.

3.1 Objectives

The overarching research question for the following experiments is to better understand how the NGP method enables the fabrication of digitally designed shapes into physical objects and to what extent this manufacturing process depends on the design workflow, the technical specifications of the 3D printing platform, and the materials used. Since the authors expect that all three aspects will have a significant impact on the design freedom, precision, and accuracy of the manufactured parts, it is important to study these factors in more detail and introduce performance metrics for their evaluation.

3.2 Design workflow

The following experiments were designed using the CAD software Rhinoceros and the built-in parametric modeling tool Grasshopper (McNeel 2010). The generated shapes were then converted into non-planar print paths via KUKAlprc, a plugin that enables the simulation of robot movement and the export of G-code files (Braumann 2015).

3.3 Technical setup

The technical setup of the NGP platform consists of a conventional industrial robot arm (KUKA KR16-2) as well as a custom-made resin dispensing system and a build tank containing the granulate material, see Figs. 2 and 3. Although the NGP printing process does not depend on a complicated robot and could have been done with a simpler gantry system or a Scara robot, this 6-axis machine was chosen because it allows free movement of the end effector and is limited only by the robot's kinematics and reach. The attached dispensing system is determined by the design of the nozzle and the resin supply pump. Finally, the build tank is designed as a modular container that can hold a variety of materials and is adjustable in size to accommodate prints at different scales. In this setup, the resin dispensing system and the build tank are specifically designed for the NGP printing process and require further elaboration. The NGP process uses a two-part liquid binder that is stored in a tank or cartridge, mixed, and then selectively distributed through the robotic platform along the planned toolpath. During this process, the liquid flows through a long, thin stainless steel nozzle that injects the binder deep into the volume of the granular material.

Two different types of dispensing systems were developed and tested as part of this study. The first is a simpler cartridge system, as shown in Fig. 2a. Here, the binder is filled into a cartridge and pressed down to the stainless steel nozzle by a pneumatically operated piston. The thickness of the extrusion depends on the level of pressure driving the piston and the speed of movement of the robot platform. A digital compressed air regulator determines the pressure required to extrude the liquid binder. By varying the air pressure selectively over the entire tool path, adjustable extrusion thicknesses can be achieved. This dispensing system is mainly suitable for small applications limited by the size of the cartridge and the amount of liquid binder it can hold.

Figure 2b shows the second, more complex dispensing system used in this study. This system has been developed

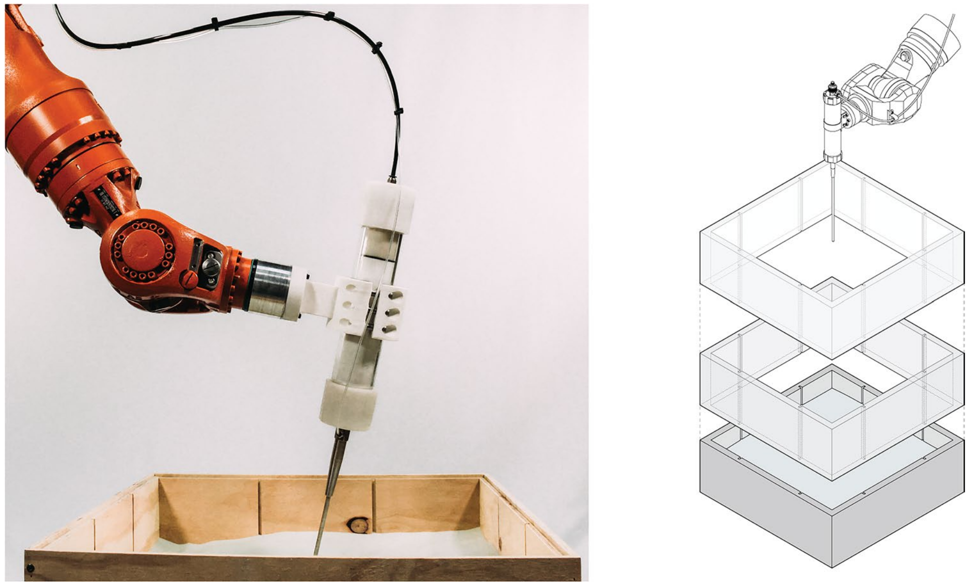

Fig. 3 A custom-made modular container system for holding the granular material was developed for the NGP process. To print, the robot moves the end effector into the volume and injects a liquid binder into the granules along a predefined tool path. After curing, the particles bond together resulting in a 3D-printed part. The remaining loose granulate can be reused for future prints

to increase the capacity of the liquid binder, beyond the small volumes of the cartridges, which is advantageous for printing larger objects. Here, the two-part liquid binder is stored separately from the end effector in special pressure tanks. The pressure tanks use air to feed the two-part resin to a high-capacity, variable-speed gear pump that delivers the liquid material through vinyl tubing to a static mixer that is part of the stainless steel nozzle at the end effector of the robot. A special feature of this NGP system is that the flow rate of the gear pump is variable and can be easily adjusted to achieve either different mixing ratios and viscosities or to process different types of binders, from conventional polyester and epoxy resins to more or less sustainable liquid binders and biomaterials. This offers a great opportunity to optimize the printing process also at the binder level.

Another fundamental part of the technical setup for Non-Planar Granular 3D Printing (NGP) is the stainless steel dispensing nozzle. For the experiments, the authors used a nozzle with a length of 20 cm and an outer diameter of 7 mm. The length of the nozzle is an important factor, as it determines how deep the dispensing nozzle of the printer can penetrate into the volume of the granular particles. To further control the thickness of the extrusion, the nozzle is threaded so that tips of various sizes and inner diameters can be screwed onto it. During the printing process, the nozzle is pulled through the volume of granular particles, following the predetermined toolpath. Depending on the material used, the granulate can cause a deflection of the nozzle, especially with coarser particles or in deeper areas of the volume, where the material cannot evade the nozzle as easily. Nozzle bending and deflection can cause an undesirable mismatch between the toolpath of the designed object and the resulting printed geometry, as shown in Fig. 4a. To overcome this obstacle and reduce the risk of toolpath inaccuracy, the authors developed a novel air-sleeve nozzle design, shown in Fig. 4b. Here, the nozzle consists of two stainless steel cylinders inserted into each other. The inner tube carries the binder fluid to the nozzle tip and the outer tube encapsulates the inner tube and nozzle tip. The outer tube is equipped with an air inlet and perforated in the lower parts of the nozzle. Air can flow between the two tubes and out through the perforations, moving up along the nozzle as it escapes through the perforations and through the surrounding granular material. The rising air creates an air sleeve around the stainless steel nozzle, which clears the path for the moving nozzle by loosening the surrounding granules and reducing the contact area between the nozzle and the particles in the volume.

The last element of the NGP setup is a custom-made build tank that contains the granular material. The stackable container system is designed to be modular from the ground up and thereby addressing a common limitation of many 3D printing processes where the size of the printed object is constrained by the build volume of the printer. While the modular container system is still limited by the reach of the robotic arm, it allows carrying smaller or larger quantities of granules, as well as positioning quantities of material at different height levels. This makes it possible to create a bounding box around the object to be printed and minimize the amount of material required. To demonstrate the capabilities of this stackable system, various prints were made that exceed the volume of a single container. Since the height of each stackable container is determined by the length of the output nozzle, in this case 20 cm, the larger 3D-printed objects are enclosed in several containers of the same height. This allows the binding liquid to be injected within a 20 cm section. In all these cases where the 3D-printed object exceeded the volume of a single container,

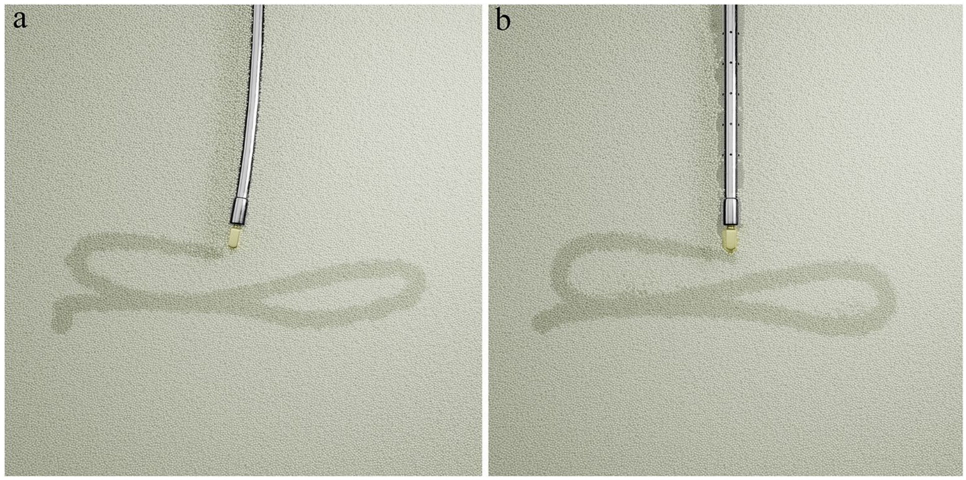

Fig. 4 As the nozzle moves through the build volume, distortion of the toolpath can occur due to particle friction (**a**). To solve this issue, the authors have developed a distributive air-sleeve nozzle (**b**) that experiences less friction during the printing process and provides higher accuracy

additional containers were stacked and filled with granules without having to interrupt the printing process. Since the containers can be filled with any type of granulate and the size and shape of the containers can be varied depending on the robotic platform or material used, this modular container system also allows the tailoring of the printing process at the material level.

3.4 Materials

One of the main advantages of the NGP process is the wide range of granular materials available. These can have a variety of sizes and properties, from fine powders in the nanometer range to a conglomerate of coarser particles in the centimeter scale (Eltawahni and Yu 2019). Apart from the particle size, the granules can vary in weight, optical properties such as opacity, or geometric characteristics such as sphericity and surface roughness. The flexibility of the printing process proposed here in accepting a wide range of granules even opens the door to one of the richest sources namely waste materials, in other words the materials that are already recycled into particles by shredding, crushing, granulating, and pelletizing.

When selecting suitable materials for NGP, it is particularly important to pay attention to certain material properties, as these can greatly influence the success rate of the process. Aspects such as the shape, size and surface roughness of the particles not only directly affect the accuracy of the 3D print, but also the resistance experienced by the nozzle as it moves through the volume. In general, particles with smooth and spherical shapes have a higher success rate because they have a higher flowability rate and can roll towards one another. In comparison, coarse particles with irregular geometry have higher packing density, and the resulting higher particle friction causes strong resistance to the movement of the 3D printing nozzle. In the experiments conducted, various granular materials were tested and classified. While most granules were successful, some performed better than others. The initial tests showed that coarse particles (~ 850 µm) allowed the binder fluid to seep into the gaps between the particles, resulting in inaccurate toolpath results. On the other hand, materials with small particles (~ 50 µm) showed low binder absorption, granular clustering, and highly saturated areas. Granules between 200 and 600 µm performed best in the tests, showing good binder absorption and strong particle binding. In addition to the size of the particles, the tests performed also showed that the geometry and mass of the particles play an important role in the printing precision. Particles with smoother surface roughness and higher sphericity cause less friction with the dispensing nozzle, allowing the robot to drive the end effector more smoothly through the granular material, which results in higher toolpath accuracy. Further tests have shown that particles with high mass and coarse surface structure, such as steel beads and aluminum oxide particles, create higher friction with the dispensing nozzle, causing it to be deflected in deeper areas of the particle volume, resulting in inaccuracy of the toolpath.

In addition to the granular material, the other defining element in the NGP process is the liquid compound used to bond the particles together along a specific toolpath. Choosing a suitable binder plays an important role in the success of the printing process and its adaptability to a wide range of granules, as well as the resulting accuracy, durability and resolution of the 3D print.

Fortunately, binders are commonly used in other powder-based and granular casting and 3D printing processes, so a wide range of binders can be adapted to the NGP process. Sivarupan et al. lists a selection of liquid binders traditionally used in casting processes, such as Silica (SiO_2), Zirconia (ZrO_2), and Olivine, as well as commercially available liquid binders used in binder-jet 3D printing applications, such as. e.g., Furan (based on chemically cured furfuryl alcohol), HHP binders (acid-cured phenolic resin) and other inorganic binders (water-based, alkali-silicate binders) (Sivarupan, et al. 2021; Sand Materials and Binders 2023). Over the course of this study, the authors investigated the use of industrial adhesives, including thermosetting polymers, which have proven to be particularly successful, and gained initial experience with somewhat less effective bio resins.

4 Experiments

In this section, the authors present a series of experiments to help identify the specific opportunities and challenges associated with the Non-Planar Granular 3D printing (NGP) process. These tests are designed to answer questions related to acceptable geometries, possible materials, scalability of the process, potential applications, and the effects of toolpath planning on the physical properties of the printed object. Each of the experiments presented in this section has a similar general workflow that can be divided into the following phases: Preparation, printing, post-processing. The three experiments themselves are then discussed in terms of objectives, design workflow, technical setup, materials, NGP printing, and results.

4.1 Preparation, NGP printing, and post-printing

The experiments presented in this paper are performed using a KUKA industrial robot. The toolpaths that make up the 3D-printed objects are programmed using KUKA Robotic Language (KRL). Before printing can begin, both the granules and the binding material must be prepared to ensure a smooth process without interruptions. As for the granular material, the process is flexible and can be used with a variety of materials as long as they are carefully sifted to ensure they are free of large chunks or other unwanted pieces that could obstruct the toolpath or cause collisions with the dispensing nozzle. The granular material can then be filled into the modular build tank. The preparation of the liquid binder, on the other hand, depends on the product used. For instance, 2-part resins can either be premixed and filled into a cartridge dispenser or filled into two separate tanks and mixed together with the team's custom-made pump system for large-volume binder delivery.

Once the materials are ready, the NGP printing can be initiated by running the robot program. The parameters that control the toolpath as well as the movement speeds and extrusion rates during this process are embedded in the robot program. This program can also include commands that manage air pressure for binder extrusion, as well as ways to control a solenoid valve that turns the pressure on and off where the toolpaths need to begin or end. Once printing is complete, this phase is followed by a post-printing procedure that ensures the safe removal of the 3D-printed objects and proper maintenance of the equipment for future use. Before the printed parts can be removed from the build tank, users must wait until the liquid binder has cured. Depending on the binder, the duration of curing may vary. After curing, the loose granules can be removed by opening the drain plugs at the bottom of the modular build tanks. The loose material can be emptied into containers for reuse and for the production of future 3D-printed parts. Once the build volume is empty, the printed objects can be collected. Unlike other 3D printing processes, NGP does not require the removal of supports or post-printing processes such as UV curing, heating or other finishing techniques.

4.2 Experiment 1–toolpath limitations

The objective of the first experiment is to determine the limits and best practices in toolpath design. Since the NGP process does not require objects to be printed in successive planar layers, it is important to understand the capabilities and limitations of the process, as well as the effects the toolpath design has on the physical quality of the printed parts. In conventional 3D printing workflows, objects are often printed from the bottom up, avoiding any form of toolpath collisions. In contrast, NGP enables free-form 3D printing capabilities that can lead to intersections and therefore require further planning to avoid self-collision of the toolpath.

Three tests are performed in which the speed of the robot and the flow rate are kept constant while different toolpaths are printed. The technical setup of this experiment is designed in such a way that the three tests can be carried out by printing into three volumes with the same granular material. Each volume is contained in a modular build tank measuring 30 cm × 30 cm × 30 cm, made of 2 cm thick plywood sheets. All three containers are filled with fine glass beads (~ 400 μm). The height of the containers is determined by the length of the stainless steel nozzle used, which is 25 cm long and can thus reach most parts of the build tank. In addition, the nozzle features a tip with a 3 mm inner diameter. The binder for this experiment comes from a 12 oz. cartridge mounted onto the robot's end effector.

Glass beads were chosen as the material for this experiment because preliminary tests have shown that their smooth, spherical shape and small particle size (200–500 μm) lead to high binder absorption, which in turn ensures high print resolution. For the liquid binder in this test, a 2-part epoxy resin with a mixing ratio of 1:1 was used. The binder has a working time of 1 h and a curing time of 6 h.

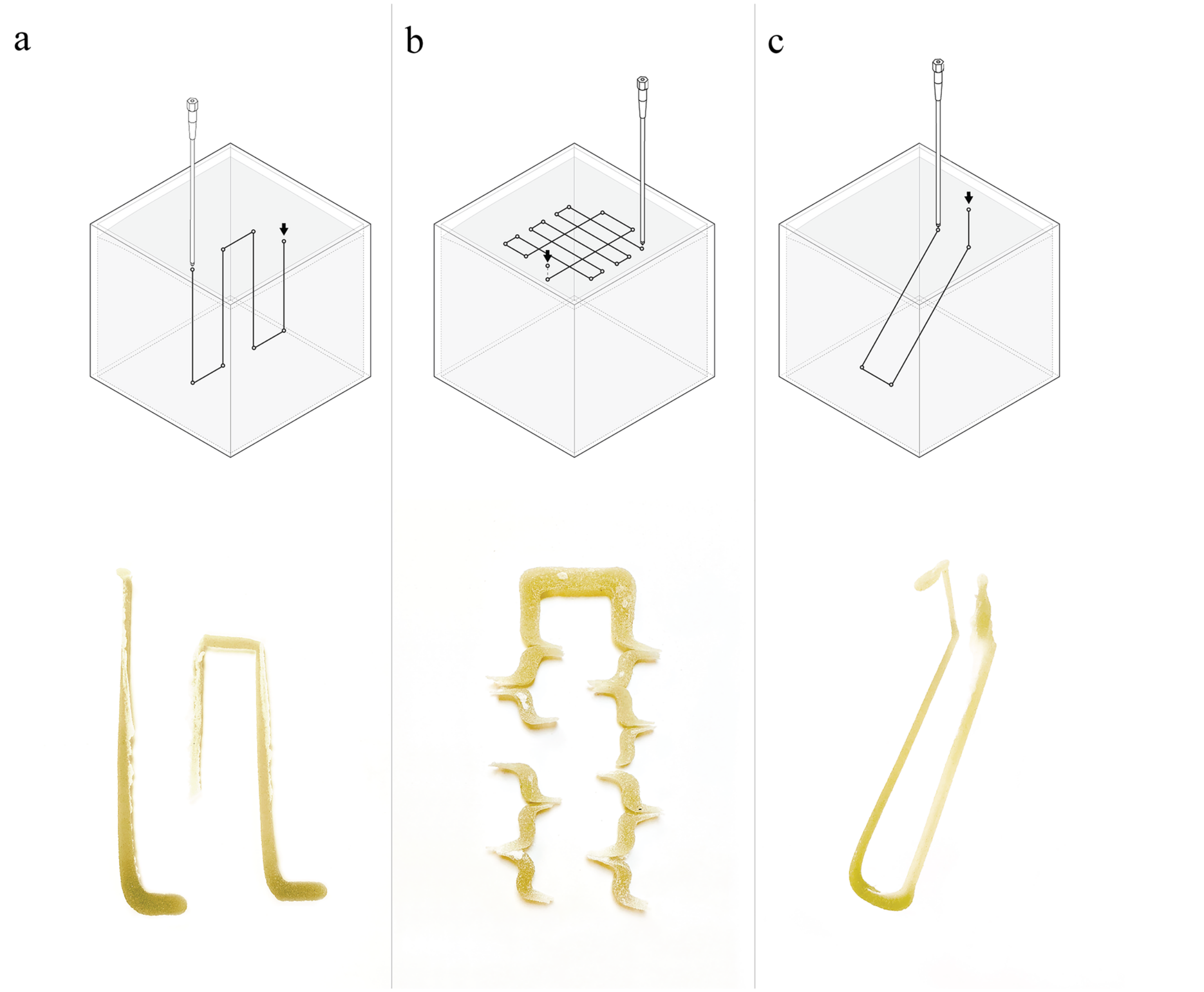

Fig. 5 The first experiment explores the limits of toolpath design by testing vertical toolpath movements (**a**), lateral toolpath collisions (**b**), and diagonal toolpath movements (**c**)

Three test prints were performed. In the first, the robot was programmed to drive the dispensing nozzle in a square wave through the granular volume, as illustrated in Fig. 5a. Here the nozzle moves in straight lines down to the bottom of the container, then to the side and up again. This toolpath is repeated twice. The aim of this particular test is to determine whether the second pass and subsequent collision of the nozzle with the wet binder from the first pass would have a negative impact on the printed object. The second test, shown in Fig. 5b, is intended to determine the effects of lateral collisions between the nozzle and the wet binder of the previous passes. For this purpose, the nozzle is moved 3 cm below the surface of the volume, drawing an open rectangle. The robot is then programmed to drive the dispenser in a criss-crossing motion through the wet binder of the previous pass. Finally, Fig. 5c shows the third test, comparing the print quality of the vertical toolpaths of the previous test with a toolpath moving diagonally through the granular material. Here, the nozzle follows a 45° angle as it travels through the volume.

From the first tests in Fig. 5a, it can be concluded that vertical movements of the dispenser through the volume can lead to uneven and interrupted extrusions. Most likely, this is because the nozzle collides with the wet binder from the first pass aligned in exactly the same direction it uses for the second pass. A closer look at the 3D-printed object also shows that straight downward motions have discontinuities in the print, while straight upward motions result in continuous but uneven extrusions with varying thickness along the path. Additionally noteworthy is that the horizontal portions of the print, where the nozzle was not aligned with the tool path but oriented perpendicular to it, showed no irregularities and the extrusion was smooth and uninterrupted. A look at the second test print in Fig. 5b shows that crossing tool paths in the horizontal direction can also have a negative effect on extrusion quality. Here, the self-intersecting path

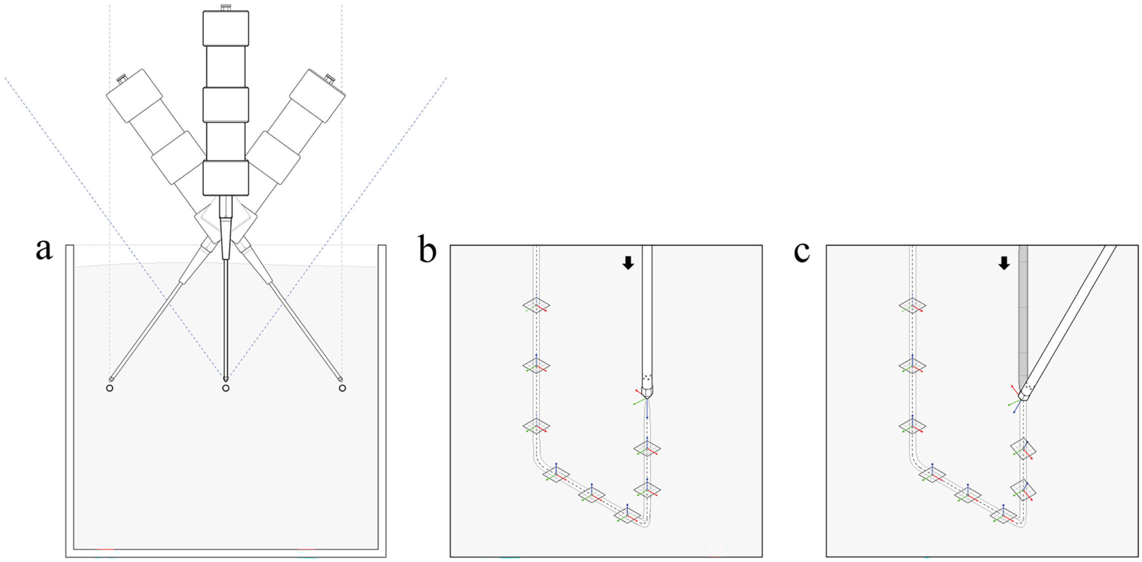

Fig. 6 Utilizing the degrees of freedom offered by industrial robotic arms, the dispensing nozzle can be tilted to avoid toolpath collisions (**a**). This challenge is particularly present in straight downward movements when the toolpath plane normals are aligned with the tooltip normal vector (**b**). To resolve this problem, the toolpath planes can be reoriented to avoid collisions with the dispensing nozzle (**c**)

caused the extrusion to shift, resulting in inaccuracies, uneven thicknesses, and splitting of the extrusion. Finally, the third test print, shown in Fig. 5c, reveals that diagonal paths produce the most accurate and consistent extrusions. Both downward and upward motions had similarly good extrusion thicknesses across the entire toolpath.

From the observations of the three performed tests, it can be concluded that toolpaths with horizontal and diagonal movements and nozzle orientations that are not congruent with the toolpath provide the most accurate and consistent print results. One of the biggest challenges are downward traveling toolpaths. Figure 6b shows that when the Z-axes of both the toolpath planes and the tooltip are aligned, the extruded binder collides with the nozzle which causes the print to fail, as shown in Fig. 5a. To overcome this limitation, Fig. 6a shows that the nozzle can be tilted away from the vertical segments of the toolpath, taking advantage of the additional degrees of freedom offered by the industrial robotic arm. By tilting the nozzle away, it is ensured that self-collisions are avoided throughout the toolpath. To provide the most accurate and consistent print results, nozzle reorientation can be used throughout the printing process in areas where nozzle collision avoidance is required. Figure 6c**,** for example, illustrates how toolpath planes are only reoriented in downward traveling motions where self-collisions may occur. To identify areas of potential collision, toolpaths should go through a collision checking process that highlights toolpath planes where the normals are aligned with the world Z coordinate.

Although the nozzle reorientation strategy resolves many of the toolpath obstructions, it is limited by the toolpath depth and the size of the build volume. As shown in Fig. 6a, different areas within the build volume can be reached by tilting the dispensing nozzle. However, excessive tilting of the dispenser may cause collisions between the dispenser and the build volume frame or the granular material bed.

A different approach to resolving nozzle and toolpath alignment is to reorient the 3D printed object instead of the dispensing nozzle. As shown in Fig. 7a, straight down toolpath motions are avoided by tilting the object at a 45 degree angle. By doing so, the vertical lines in the toolpath are tilted so that the nozzle can be vertically aligned with the Z-vector of the world coordinate system without colliding with the toolpath.

Another notable challenge in toolpath planning for NGP are the intersections where toolpaths cross. As shown in Fig. 5b, horizontal crossing through the printed extrusion may cause the wet binder to smear or split. Therefore, the order of printing and the distance between toolpath segments must be carefully planned. In Fig. 7b, segments of the toolpath are offset by a distance equal to the thickness of the extrusion. This allows the different segments to adhere to one another once the binder is absorbed by the particles in the build volume. Therefore, by offsetting the toolpath segments, the moving nozzle no longer collides with the wet extrusions avoiding smearing, splitting, and delamination.

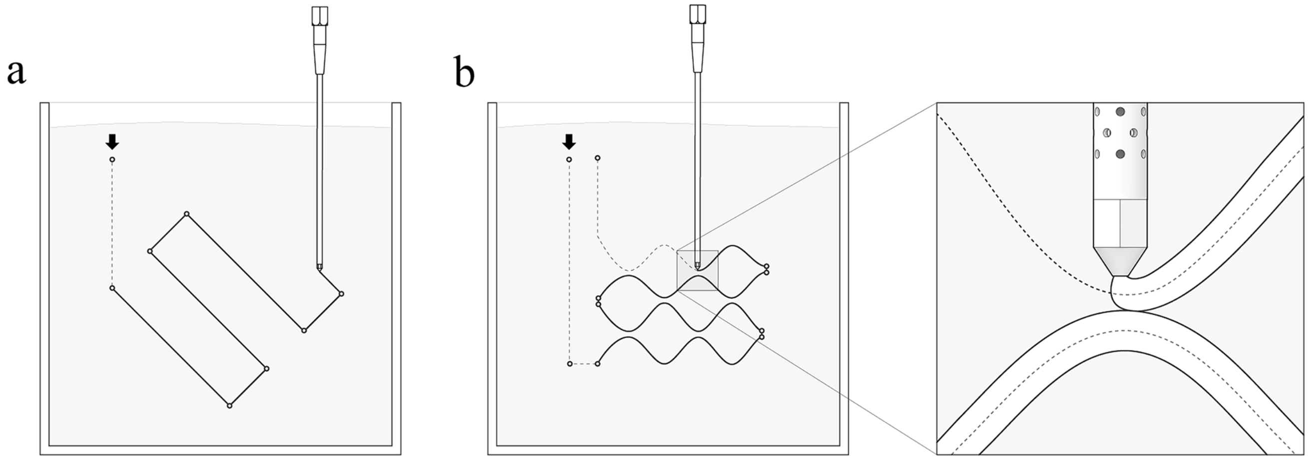

Fig. 7 Strategies for avoiding self-intersecting and colliding toolpath segments include object reorientation within the build volume (**a**), and offsetting toolpaths by a distance that is equal to the width of the extrusion (**b**)

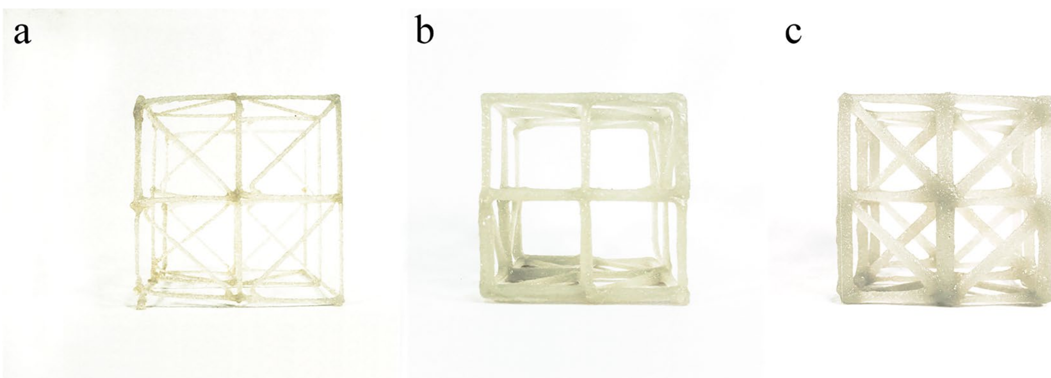

Fig. 8 The second experiment investigates the relationships between robot speed and extrusion thickness by printing the same lattice cube at different speed settings. **a** Printed at 0.4 m/s gives a 3 mm thick extrusion, **b** printed at 0.1 m/s gives an 8 mm thick extrusion, **c** printed at 0.025 m/s gives a 12 mm thick extrusion

4.3 Experiment 2–thickness variation

Building on the findings of the previous experiment, the second experiment investigates the relationship between nozzle speed and extrusion quality and the extent to which these parameters affect the properties of the 3D-printed object. Again, three tests were performed with the same setup and glass beads as the granular material. However, this time the same object was printed, i.e., keeping the geometry constant while changing the movement of the robot arm during the printing process. The nozzle used for these tests is 25 cm long and has an inner diameter of 3 mm.

In all three tests, the robotic arm is programmed to print a cubic lattice structure measuring 15 cm × 15 cm × 15 cm. The lattice geometry consists of four cells with diagonal cross members in four of its faces. To avoid irregularities in the print caused by the vertical movement of the nozzle, as studied in the first experiment, the shape of the lattice cube is rotated so that it sits diagonally in the build tank. In addition, the lattice cube is designed to be printed in a single continuous toolpath that starts from the lower levels of the build tank and moves upward to avoid self-collisions. Each cube was printed in the same sized build tank, but the speed of the nozzle as it moved through the granules was reduced from print to print. For the first test, shown in Fig. 8a, the robot speed was set to 0.4 m/s. For the second test print, shown in Fig. 8b, the robot speed was lowered to 0.1 m/s and for the last test, as seen in Fig. 8c, the robot speed was further reduced to 0.025 m/s.

After curing, the prints were carefully removed from the build tanks and compared with each other. It became immediately clear that the speed at which the robot follows the toolpath plays a crucial role in the thickness of the extrusion. The members of the first printed lattice cube, in which the robot moved the fastest, were the thinnest and weakest, with a diameter of only 3 mm. In the second test,

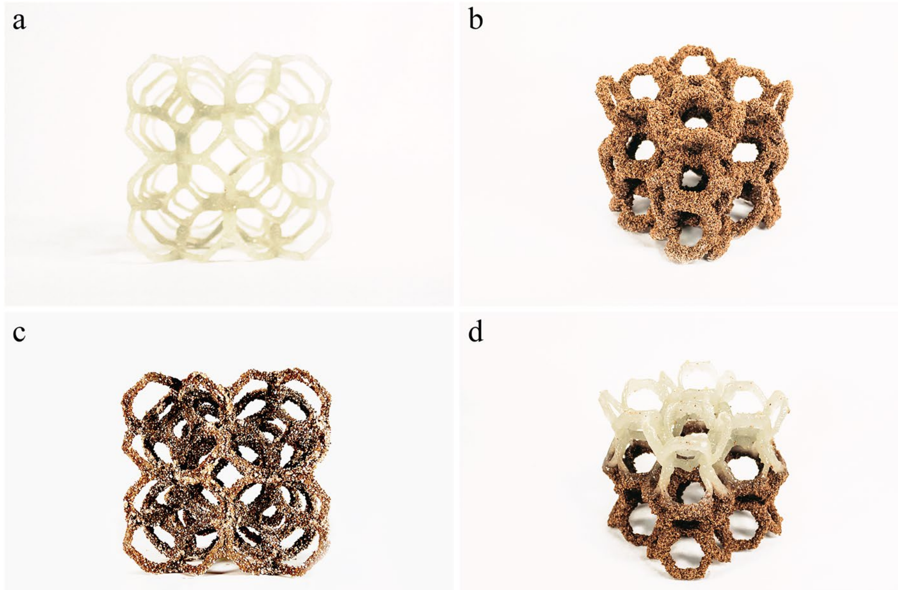

Fig. 9 The third experiment investigates the flexibility of the NGP process when printing the same geometry from different materials. These prints were made from **a** glass beads, **b** walnut chips, **c** sand, **d** and a combination of glass beads and walnut chips

the slower speed of the robot resulted in stronger member sizes of 8 mm in diameter. And in the third test with the slowest robot movement, the diameter of the members was 12 mm, which resulted in a very sturdy print. This increase in extrusion thickness in response to robot speed is significant and must be taken into account at an early stage when using this printing technology. However, it also demonstrates the unique potential of the NGP process to create objects with very different physical properties and stiffness gradients by simply changing the speed settings in the toolpath programming.

4.4 Experiment 3–material variation

In the third experiment, the authors explore one of the key promises of the NGP process proposed here, namely its flexibility to print with a wide variety of materials, thus exploiting a seemingly endless source of materials from industrial processes that are already available in granular form. To test this hypothesis, several test objects were printed, keeping the geometry and machine settings constant, while the build tank was filled with different materials with particles of varying shape, size, mass, and density. Four build tanks were used in this experiment, measuring 30 cm × 30 cm × 30 cm, and filled with different materials. Three of them were filled with a homogeneous material, either glass beads, sand or walnut shells. One container was filled with a mixture of materials in which walnut shells were layered with glass beads.

Glass beads, sand and walnut shells were chosen as materials for this experiment because they are widely available as a waste product from manufacturing processes and find reuse in recycled form in other industries involved in, for example, surface preparation and sandblasting. In the context of this study, however, these materials present an additional interesting challenge because their participles differ in several characteristics. Glass beads, sand, and walnut shells, for example, vary in size from ~ 400 µm, to ~ 850 µm, to ~ 1000 µm. In addition, they differ drastically in surface texture, with glass beads being much smoother than sand and walnut shells being much rougher. Finally, they also have differences in their weight, visual appearance, and ability to absorb liquid.

For all four test prints, the identical toolpath was used to create a hexagonal lattice structure of 12 cells. This object measured 15 cm × 15 cm × 15 cm. The toolpath was adjusted to print the object along a continuous spatial polyline, starting at the lower portions of the build tank and moving the nozzle up through the granule volume. The geometry of the lattice structure and its orientation in the tank avoided any vertical lines or alignment between the nozzle and the toolpath, and instead consisted mainly of diagonal movements of the dispensing system.

The subsequent NGP printing process used exactly the same technical settings for all four objects. After curing, the parts were carefully removed from the build tank and compared with each other, as seen in Fig. 9. As expected, the print made from the fine glass beads (Fig. 9a) is the most accurate, while the coarser sand and walnut shells resulted in rougher print quality. This is likely due to the smaller particle size of the glass beads, which absorb the binder better, and their smoother surface, which creates less friction as the nozzle moves through the volume. It is also noteworthy that the print made from walnut shells also is visibly thicker than the other. This is probably the result of the larger particle size of the material. In addition, it could also be related

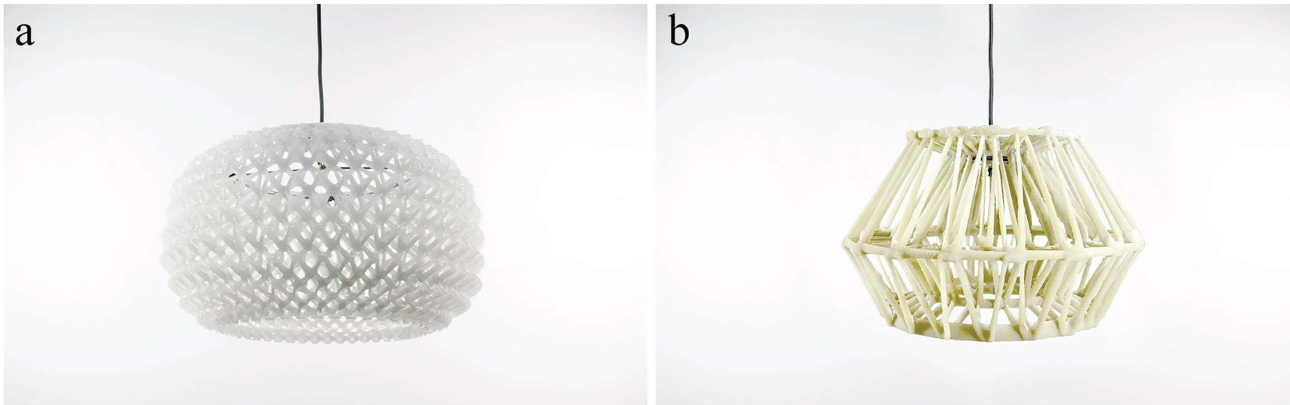

Fig. 10 The final experiment applies the NGP process in the context of a product development, in this case the design of two lattice lampshades. **a** Printed in 6 h and **b** printed in less than 45 min

to the fact that the coarser geometry of the particles creates larger air pockets between them, which are filled with more binder, which in turn can bond with more particles. In comparison, the result of the sand print is between the other two. However, the sand print was remarkable during the printing process itself, as the print was accompanied by a noticeable scratching noise, probably caused by the friction between the stainless steel nozzle and the granular sand particles. Finally, the dual-material print also turned out to be surprisingly successful, showing high accuracy compared to the digital toolpath. Regardless of the different materials, the liquid binder was able to adhere the glass beads and the walnut shells well to each other, resulting in a quite strong hybrid part with different mechanical properties. Even the reuse of the mixed material left in the build tank did not turn out to be much of a problem. Since the particle sizes of the two materials used differed greatly, they could be easily separated from each other using a coarser strainer that only allowed one material to pass through.

4.5 Experiment 4–sample application

To conclude this study, the fourth experiment will now be conducted to determine whether the NGP process can be used for a new product development, in this case a lampshade. This experiment was performed taking into account the findings and best practices from the previous experiments which influenced decisions related to toolpath design, printing speed, and material selection. The main challenge here is that the object to be printed is larger than a single container and taller than the printing nozzle. In the previous tests, the size of the tank and the amount of material it contained depended on the length of the dispensing nozzle. Therefore, the depth of the granular volume in the tank must be approximately less than or equal to the length of the nozzle. This relationship also limited the size of the printed test objects in the previous experiments. To overcome this limitation, the authors developed a bespoke modular build tank that allows multiple containers to be stacked and sequentially filled with granular material during the printing process to increase the effective print volume.

In this experiment, two test objects were printed, as shown in Fig. 10. Both lampshade designs exceeded the print volume of a single container and took advantage of the modularity of the build tank design. The larger size of the test objects also required larger quantities of liquid binder than a single cartridge can provide. This challenge was approached in two different ways. The first lampshade design had an outer diameter of 50 cm and 35 cm height, shown in Fig. 10a, and was divided into four toolpaths, each requiring approximately the amount of binder in a 20 oz. cartridge. This printing process therefore necessitated the replacement of cartridges after the completion of each of the four toolpaths. While this was in principle possible without any problems, it meant that the team had to be ready in time with the pre-mixed liquid resin to quickly exchange the cartridges manually.

The second lampshade had an outer diameter of 50 cm and a height of 40 cm and due to its size was divided into three toolpaths, as shown in Fig. 10b. In comparison, the printing process for the second lampshade was much smoother. This was mainly due to the more complex dispensing system used. Here, the two-part resin was stored in two tanks and fed in a 3:1 ratio via a variable speed pump to a mixing nozzle at the end effector. With this setup it is easily possible to inject larger amounts of resins into the granular material and to fine-tune the mixing ratios and curing times to the specific needs. This setup also made the printing process much faster, as no manual steps were required. While the first lampshade took 4 h to print, the printing time for the second was less than 45 min. The same glass beads were used as granules in both tests. Another reason why the second print was significantly faster is the use of an epoxy resin with a lower viscosity, which was absorbed more quickly by the glass beads and therefore resulted in more significant thickness variations depending on the motion speed of the robot. To account for this material behavior, the three toolpaths of this test object were programmed with variable speeds for different sections of the printed geometry. This ensured that the base and central attachment point of the lampshade were printed with thicker extrusions, making these areas stronger.

As a conclusion of these two tests, it can be stated that the NGP process can be successfully integrated into the fabrication of products and even enables the printing of shapes larger than the nozzle and the original build tank. Although both lampshades are quite similar in their external dimensions, the first test took about five times as long as the second. This was mainly due to the fact that the cartridges had to be refilled manually and the liquid binder had to be mixed in a cumbersome way. The second test was much faster and took only around 45 min to complete. While the size of this print also required stacking more sections of the modular containers and filling them with granules, this step only took about 2 min. The decisive time saving observed in the second test came from the use of the complex dispensing system. The ability to store the 2-part binder in separate containers and mix it by means of precise pumps automated the process and made the printing sequence much cleaner and less prone to human error.

5 Conclusion and future outlook

This study contributes to the field of large-scale 3D printing by introducing a novel additive manufacturing process called Non-Planar Granular 3D Printing (NGP). With this technology, the authors aim to address some of the key challenges in 3D printing and open up new opportunities in terms of printing speed, material diversity, scalability, and more sustainable fabrication. The experiments presented in this paper explored some of the key capabilities and limitations of the new NGP process. This was demonstrated using a series of benchmark tests that had challenging geometric features which would be difficult to produce using conventional 3D printing techniques. All four experiments have shown that the NGP process is a technology that may be in its infancy, but is nevertheless a viable alternative method that could revolutionize 3D printing in the future.

Based on the results of this study, there are several possible avenues for future work that builds on the findings presented. First, further research and experimentation can be conducted to refine the process of developing multi-material objects, which seems to be one of the most unique features of the NGP process. For example, by developing a system to selectively fill the tanks, granules could be placed exactly where a particular material is desired. This could result in opportunities to fabricate structures with mechanical and functional material gradients. In addition, future research could investigate the integration of mechanical components into the NGP process. For example, hardware embedded in the build volume can be enclosed by the 3D printed material and serve as reinforcing elements or mechanical fasteners and connectors.

All these are speculations on how the NGP process presented here could be further improved, either by the authors of this paper themselves or in collaboration with other research teams. For this, the results of this study form a solid basis and should be understood as an invitation to further develop this promising technology.

Acknowledgements This research was conducted with the generous support of the Kuwait University Scholarship and the Bakar Fellowship Program at UC Berkeley. B. Darweesh and M.P. Gutierrez developed the Non-Planar Granular 3D Printing technology and are a US provisional patent Serial Number 63/383,322 Filing Date: 11/11/2022.

Author contributions BD has undertaken a comprehensive role in designing the studies and experiments in this paper. The role includes hardware and software developments, data analysis, and the writing of this manuscript. MG has supervised the development of the experiments and technologies including material performance as an independent study advisor at UC Berkeley and has contributed to the writing and literature review of this article. SS supervised BD as his primary PhD advisor and assisted in the further development of the experiments and technology, as well as in the writing of this article.

Funding The research has not been directly funded by any entity, but the authors have been generously supported by the Kuwait University Scholarship and the Bakar Fellowship program at UC Berkeley.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Ajdary R et al (2021) Selective laser sintering of lignin-based composites. ACS Sustain Chem Eng 9(7):2727–2735

Branch Technology (2023) Design Miami Pavilions. https://branchtechnology.com/design-miami-pavilions/
Braumann J (2015) Adaptive robot control—new parametric workflows directly from design to KUKA robots. In: Proceedings of the 33th international conference on education and research in Computer Aided Architectural Design in Europe (eCAADe), vol 2
Chacón JM, Caminero MA, García-Plaza E, Núnez PJ (2017) Additive manufacturing of PLA structures using fused deposition modelling: effect of process parameters on mechanical properties and their optimal selection. Mater Des 124:143–157
Chakraborty D, Reddy BA, Choudhury AR (2008) Extruder path generation for curved layer fused deposition modeling. Comput Aided Des 40(2):235–243
Chen A (2019) Detail Comparison of 3D printing methods: SLS vs FDM & SLA vs DLP. CMAC Industries Pty Ltd. https://www.cmac.com.au/blog
Della Bona A, Cantelli V, Britto VT, Collares KF, Stansbury JW (2021) 3D printing restorative materials using a stereolithographic technique: a systematic review. Dent Mater 37(2):336–350
Depuydt D et al (2019) Production and characterization of bamboo and flax fiber reinforced polylactic acid filaments for fused deposition modeling (FDM). Polym Compos 40(5):1951–1963
Dini F, Ghaffari SA, Jafar J, Hamidreza R, Marjan S (2020) A review of binder jet process parameters; powder, binder, printing and sintering condition. Met Powder Rep 75(2):95–100
Du W, Ren X, Ma C, Pei Z (2017) Binder jetting additive manufacturing of ceramics: a literature review. ASME international mechanical engineering congress and exposition. American Society of Mechanical Engineers, p V014T07A006
Eltawahni HA, Yu AB (2019) Powder processing: models and simulations. Reference module in materials science and materials engineering. Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.11651-0
Finnes T (2015) High definition 3d printing–comparing SLA and FDM printing technologies. J Undergrad Res 13(1):3
Formlabs (2023) 3D printing technology comparison: FDM vs. SLA vs. SLS. https://formlabs.com/blog/fdm-vs-sla-vs-sls-how-to-choose-the-right-3d-printing-technology/
Fratello VS (2021) 3D printing architecture. TMS 2021 150th annual meeting and exhibition supplemental proceedings. Springer, pp 37–49
Gibson I et al (2021) Additive manufacturing technologies, 17th edn. Springer, Cham
Gramazio Kohler Research (2023) Iridescence Print. https://gramaziokohler.arch.ethz.ch/web/e/projekte/296.html
Hajash K, Sparrman B, Guberan C, Laucks J, Tibbits S (2017) Large-scale rapid liquid printing. 3D Print Addit Manuf 4(3):123–132
Helm V et al (2015) Iridescence print: robotically printed lightweight mesh structures. 3D Print Addit Manuf 2(3):117–122
Howarth D (2017) MIT Self-Assembly Lab's Rapid Liquid Printing Technology can print furniture in minutes. https://www.dezeen.com/2017/04/28/mit-self-assembly-lab-rapid-liquid-printing-technology-produce-furniture-minutes-design/
Huang J, Qin Q, Wang J (2020) A review of stereolithography: processes and systems. Processes 8(9):1138
Jiang J, Xu X, Stringer J (2018) Support structures for additive manufacturing: a review. J Manuf Mater Process 2(4):64
Karakurt I, Lin L (2020) 3D printing technologies: techniques, materials, and post-processing. Mater Eng Sep Eng 28:134–143. https://doi.org/10.1016/j.coche.2020.04.001
Khosravani MR, Berto F, Ayatollahi MR, Reinicke T (2022) Characterization of 3D-printed PLA parts with different raster orientations and printing speeds. Sci Rep 12(1):1016
Kruth J-P, Wang X, Laoui T, Froyen L (2003) Lasers and materials in selective laser sintering. Assem Autom 23(4):357–371
Kruth J-P, Mercelis P, Van Vaerenbergh J, Froyen L, Rombouts M (2005) Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyp J 11:26
Le Duigou A, Castro M, Bevan R, Martin N (2016) 3D printing of wood fibre biocomposites: From mechanical to actuation functionality. Mater Des 96:106–114
Le Néel TA, Mognol P, Hascoët J-Y (2018) A review on additive manufacturing of sand molds by binder jetting and selective laser sintering. Rapid Prototyp J 24(8):1325–1336. https://doi.org/10.1108/RPJ-10-2016-0161
Lemu HG (2012) Study of capabilities and limitations of 3D printing technology. AIP conference proceedings. American Institute of Physics, pp 857–865
Lupone F, Padovano E, Casamento F, Badini C (2021) Process phenomena and material properties in selective laser sintering of polymers: a review. Materials 15(1):183
Maines EM, Porwal MK, Ellison CJ, Reineke TM (2021) Sustainable advances in SLA/DLP 3D printing materials and processes. Green Chem 23(18):6863–6897
McNeel R (2010) Rhinoceros 3D. Robert McNeel & Associates, Seattle
Milosevic M, Stoof D, Pickering KL (2017) Characterizing the mechanical properties of fused deposition modelling natural fiber recycled polypropylene composites. J Compos Sci 1(1):7
Miyanaji H, Rahman KM, Da M, Williams CB (2020) Effect of fine powder particles on quality of binder jetting parts. Addit Manuf 36:10587. https://doi.org/10.1016/j.addma.2020.101587
Mogas-Soldevila L, Duro-Royo J, Oxman N (2014) Water-based robotic fabrication: large-scale additive manufacturing of functionally graded hydrogel composites via multichamber extrusion. 3D Print Addit Manuf 1(3):141–151
Mostafaei A et al (2021) Binder jet 3D printing—process parameters, materials, properties, modeling, and challenges. Prog Mater Sci 119:100707
Mukhtarkhanov M, Perveen A, Talamona D (2020) Application of stereolithography based 3D printing technology in investment casting. Micromachines 11(10):946
Myers K, Paterson A, Iizuka T, Klein A (2021) The effect of print speed on surface roughness and density uniformity of parts produced using binder jet 3D printing. https://doi.org/10.26153/tsw/17245
Ouhsti M, El Haddadi B, Belhouideg S (2018) Effect of printing parameters on the mechanical properties of parts fabricated with open-source 3D printers in PLA by fused deposition modeling. Mech Mech Eng 22(4):895–907
Pop MA et al (2019) Structural changes during 3D printing of bio-derived and synthetic thermoplastic materials. J Appl Polym Sci 136(17):47382
Rael R, San Fratello V (2013) Saltygloo. Emerging objects. http://emergingobjects.com/project/saltygloo/
Ramazani H, Kami A (2022) Metal FDM, a new extrusion-based additive manufacturing technology for manufacturing of metallic parts: a review. Prog Addit Manuf 7(4):609–626
RLP (2023) Rapid liquid print. https://www.rapidliquidprint.co/
Roy NK, Behera D, Dibua OG, Foong CS, Cullinan MA (2019) A novel microscale selective laser sintering (μ-SLS) process for the fabrication of microelectronic parts. Microsyst Nanoeng 5(1):64
Rubber Pouff (2016). http://emergingobjects.com/project/rubber-pouff/
Sand Materials and Binders (2023) ExOne. https://www.exone.com/en-US/3d-printing-materials-and-binders.
Shakor P, Chu SH, Puzatova A, Dini E (2022) Review of binder jetting 3D printing in the construction industry. Prog Addit Manuf 7(4):643–669
Shelton T (2017) Cellular fabrication. Technol Des 1(2):251–253. https://doi.org/10.1080/24751448.2017.1354636
Sivarupan T et al (2021) A review on the progress and challenges of binder jet 3D printing of sand moulds for advanced casting.

Addit Manuf 40:889. https://doi.org/10.1016/j.addma.2021.101889(2021)
Ziaee M, Crane NB (2019) Binder jetting: a review of process, materials, and methods. Addit Manuf 28:781–801