Large-Scale Rapid Liquid Printing

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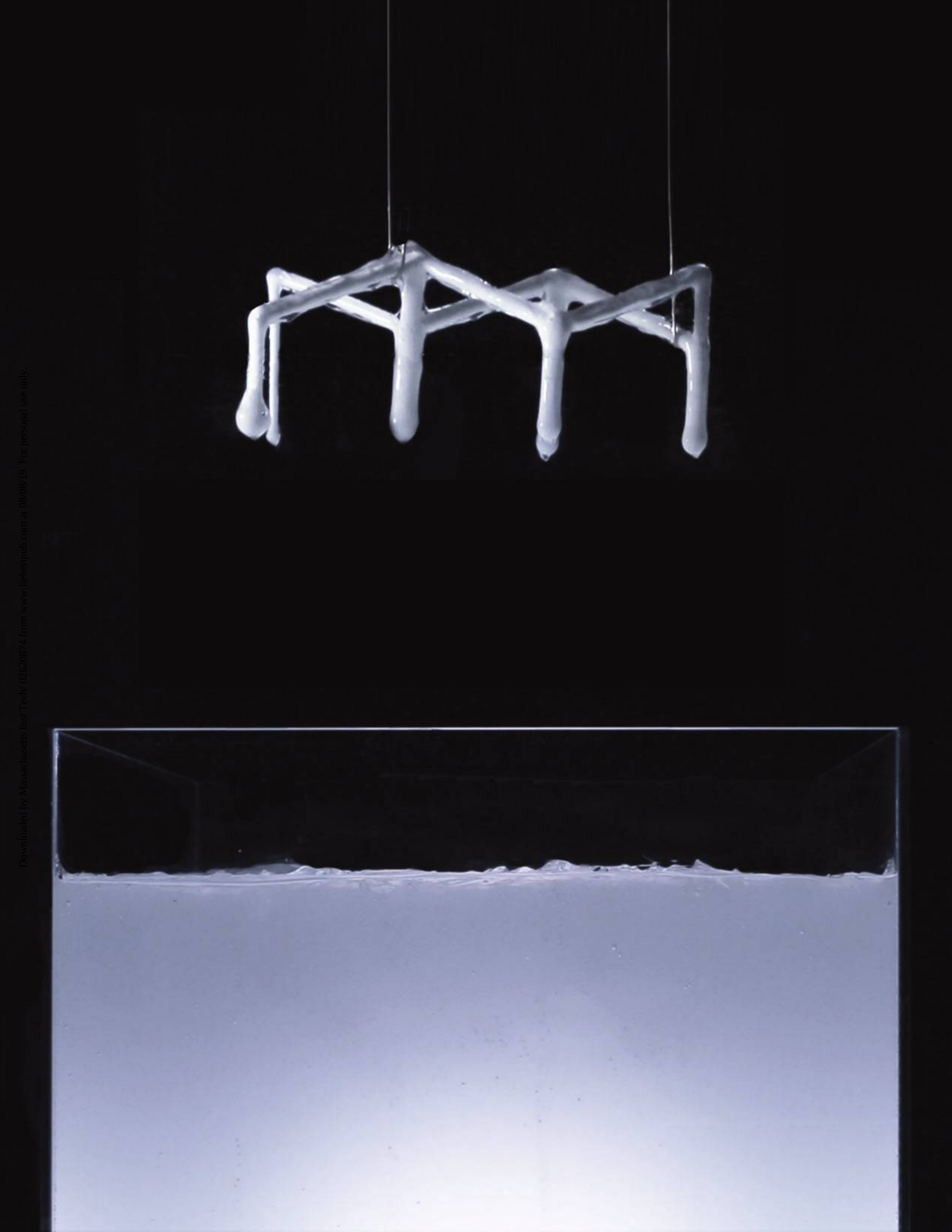

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ORIGINAL ARTICLE

Large-Scale Rapid Liquid Printing

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Abstract

Despite many advances, most three-dimensional (3D) printers today remain in the realm of rapid prototyping, rarely being used for manufacturing. Currently, the greatest challenges to advancing 3D printing technology are small build volumes, long print times, and limited material properties. In this article, we present rapid liquid printing (RLP) as a solution to these challenges. RLP is an experimental process that uses a tank of granular gel as a reusable support medium to greatly increase the speed, size, and material properties in 3D printing. The RLP machine can freely print in any direction, rather than layer by layer, depositing liquid material into the granular gel to form 3D structures. The RLP deposition system can use any one- or two-part material that is photo or chemically cured, expanding the range of possible materials to include high-quality industrial-grade rubbers, foams, and plastics, among many others. It is platform independent and can be implemented on any computer numerically controlled machine, robotic arm, or similar fabrication machine. In our research, we demonstrate the possible range of scales, printing both small- and large-scale objects ranging from inches to many feet. In addition to scale, RLP is fast, capable of printing a complex object in seconds to minutes rather than hours or days. In this article, we outline the three major components in the system: the control platform, deposition system, and granular gel. In addition, we explain our materials research and outline the primary steps of operation. Lastly, we present our results by comparing prints from an RLP machine with a stereolithography printer. With a combination of speed, scale, and a wide range of materials, RLP is an ideal platform for researchers, designers, and manufacturers to quickly print large-scale products with high-quality, industrial-grade materials.

Keywords: 3D printing, large-scale printing, robotic fabrication, rapid liquid printing, additive manufacturing

Introduction

Since its inception 30 years ago, three-dimensional (3D) printing has been revolutionary for rapid prototyping in design and engineering but has had limited applications in mainstream manufacturing. This is, in part, due to clear limitations in the size of build volumes, lengthy print time, low-quality materials, cost, or availability. In standard 3D printing processes, the build volume is limited by the size of the machine, mandating that the printer be significantly larger than the desired object. Typical sizes generally max out at between 300 and 500 mm in the longest dimension. Although there are large-format printers, they remain limited due to their extreme cost, large and complex equipment required, and slow print speeds.

Standard 3D printing processes, such as fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS), take an STL file as input, slice the model into sections, and finally proceed to print, layer by layer.[1] This leads to an extremely slow production process where a small print often takes hours, if not days to produce. In addition, printable materials can be limited depending on the printing process, often proprietary to the manufacturer of the machine, and can have reduced structural properties due to the vertical layering of material, constraining the application and quality of the prints.

We propose rapid liquid printing (RLP), an experimental printing process that addresses major challenges in standard 3D printing. In contrast, RLP is fast, scalable, and uses industrial-grade materials. The RLP machine deposits

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[1]Self-Assembly Lab, Massachusetts Institute of Technology, Cambridge, Massachusetts.
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Opposite page: Removing a Rapid Liquid Printed part from the gel suspension. *Photo credit:* Self-Assembly Lab, MIT + Christophe Guberan + Steelcase.

a curable, liquid material into a medium of granular gel (see Fig. 1). The gel acts as a reusable support material, allowing users to print any shape without extra scaffolding, avoiding any material waste, eliminating the STL/slicing process, and speeding up print time. Once the material cures, the printed part can be removed from the gel, rinsed off, and the remaining tank of gel can be reused. Using a six-axis industrial robotic arm, as well as two different three-axis computer numerically controlled (CNC) machines as the control system, we have demonstrated that this process can be easily scaled to different types and sizes of machines.

Relevant Work

Outside of standard commercialized printing processes, such as FDM, SLA, and SLS, researchers have expanded into spatial or omnidirectional printing. In large-scale spatial printing, many researchers in architecture and design used thermoplastics, such as acrylonitrile butadiene styrene (ABS)[2–4] or polylactic acid (PLA)[5], in a process similar to FDM but printed in the air, without supports. To overcome the challenge of using a thin filament without support material, some researchers focused on using a 3D lattice structure as their building block[2,3] whereas one group added more strength by developing carbon fiber-reinforced ABS plastic.[2] The lattice approach is ideal for building walls and structures and has been explored by both research groups.[2,3] Unfortunately, it is currently limited to certain lattice geometries and does not allow for long, continuous, freeform extrusions.

Another research group developed structural strands composed of four separate filaments that were inspired by spider's silk.[4] This was appealing for creating long sinuous curves but would lose strength once it grew too long. In addition, it appeared to be able to only print one strand at a time, which was then removed and assembled by hand. Other researchers looked toward different materials, not typically associated with 3D printing, such as a fast-setting two-part thermoset polymer[6] or even metal using welding techniques.[7] These techniques printed much stronger and longer paths in open air that were capable of standing on their own.

Although these advances are impressive, all process are constrained to their respective materials, with little opportunity for flexible materials or multi-material printing. To be structural, these materials need to cure as the machine moves, leading to very slow printing speeds and cold-joints. Typically discussed in concrete pouring, a cold-joint is between a material that has already begun to set and a new material.[8] In 3D printing, these cold-joints are typically very weak and may require complex connections to make them more structural. The challenges from cold-joints and the angle or cooling requirements of the material often limit the types of structures that the machines can print. These factors remain substantial limitations in existing forms of spatial printing.

Over the past decade, researchers in materials science and biomedical engineering have also demonstrated high precision, small-scale printing within a gel substrate with soft materials such as silicones,[9,10] living cells,[10] hydrogels,[10,11] alginate,[11] soft protiens,[12] and colloids.[10] In earlier research on gel printing with microvascular networks, one team developed a permanent gel reservoir that required a fluid filler to infill the void left by the traversing nozzle.[13] More recently, researchers identified and developed yield stress gels that fluidize under high shear stress and rigidify under low stress to act as support structures. Some of these gels include a granular organic microgel system,[9] Carbopol microgel,[10,11] and a gelatin slurry.[12] These researchers developed processes for making highly detailed objects in gels with extremely fine features, but the approaches were limited to small-scale objects with a focus on biomedical applications, not relevant for large-scale design. Alternatively, design researchers also fabricated larger scale structures, printing with ultraviolet (UV) curable resin, and thermoset polymers in suspension mediums such as off-the-shelf hair gel and soaps.[14,15] However, these processes begin to address the challenge of scale, whereas the final objects lack precision, control, and high-quality material properties, limiting their application and functionality.

In RLP, we bring together large-scale fabrication techniques, the granular gel support bath, and high-quality rigid and flexible materials to create a highly controlled process that prints refined and repeatable objects. In contrast to existing spatial printing process, the granular gel supports uncured liquid material, allowing faster print speeds, free-form structures, and stronger bonds by avoiding cold-joints. The scale and size of features are controlled through nozzle design and by adjusting speed or acceleration of the robot or the pressure of extrusion. Designs can easily contain multiple scales of features by adjusting these parameters during the

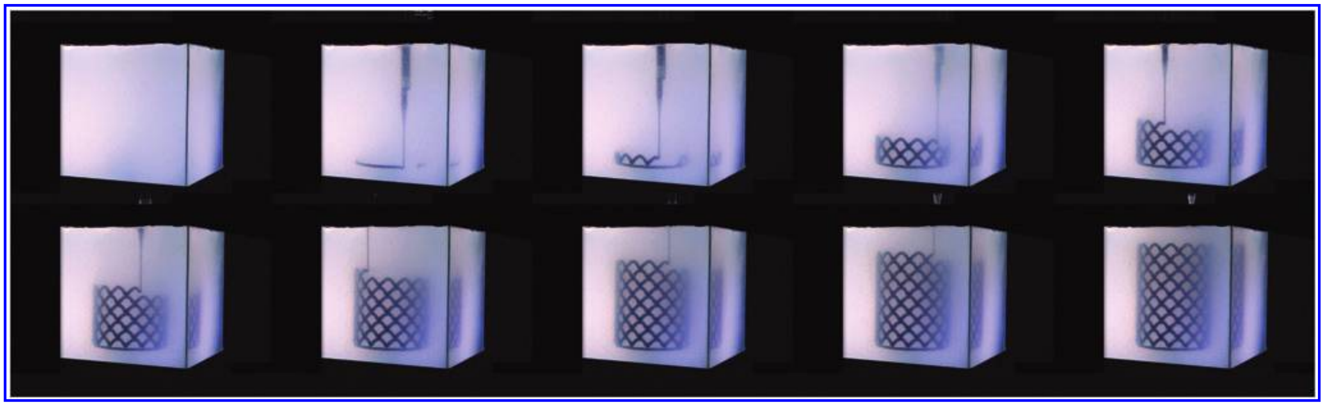

FIG. 1. An RLP machine prints a 6″×6″×8″ cylinder using urethane rubber with a maximum speed of 50 mm/s in 4 min and 49 s.

printing process. These parameters can either be hard-coded or controlled on-the-fly by the designer. In our research, we have explored dozens of different materials ranging from silicones, urethane rubbers, foams, and plastics to epoxy, UV curable resin, concrete, metal-filled epoxy, and more.

Materials and Methods

Setup

The RLP system consists of three major components: the control platform, the deposition system, and the tank of granular gel (see Fig. 2A). Each component can be sized up or down depending on the scale of the final object and feature size desired. This open and flexible system enables users to quickly alternate between materials at various scales.

Control platform. One important characteristic of RLP is that it is platform independent and can be easily setup with any CNC machine that moves in at least three dimensions. A three-axis gantry-style CNC machine is the minimum requirement for the RLP control platform. In this setup, the deposition system is attached to the z-axis drive system. This gantry-style system allows for smooth printing in three dimensions but does not allow for rotation of the nozzle. Therefore, the nozzle would be constrained to a vertical nonrotational position. For a more flexible gantry-style system, a five-axis CNC machine can be used.

Alternatively, a six-axis industrial robotic arm can be used for full control over the nozzle orientation as it moves through the granular gel. This can allow for printing sideways or rotating the nozzle as it moves—either maintaining perpendicular or parallel orientation to the toolpath or creating custom orientation controls. One possible downside to the six-axis robotic arm is the potential decrease in precision or load capacity as the robot stretches to the edges of its build volume. Although advancements have minimized errors to be on average ±0.5 mm for mid-sized robots, this may be mitigated with more precise and stronger six-axis robotic arms, especially for large pieces with heavy loads.[16] In contrast, however, the gantry-style machines with a static base could maintain a consistent level of precision in all areas of its build volume.

To demonstrate the flexibility of RLP, we set up three different platforms that collectively offer a variety of options in scale. First, for small to medium pieces, we use a custom three-axis printing machine, developed with ShopBot, which has a build volume of 24″×48″×12″. Second, for much larger pieces, we use a similar three-axis router with a build volume of 60″×120″×12″. Lastly, for medium-sized objects, such as a chair or table, we use a six-axis robotic arm. As discussed earlier, this setup offers the most flexibility in controlling the angle and direction of the nozzle and allows much taller objects to be printed.

Deposition system. The robotic platform controls the overall movement and placement of the nozzle, whereas the deposition system controls the rate of flow, size, and shape of the printed liquid material (see Fig. 3A). In the RLP system, we use a variety of pneumatic, one- or two-part, dispensing systems that range in total volume from 55 to 1500 mL. The smallest 55 mL one-part cartridges are ideal for material tests and small prints with fine features, whereas the largest 1500 mL two-part 1:1 cartridges are preferred for printing large pieces, such as a table or chair. Primarily, we use a mid-sized system, which takes ∼400 mL cartridges in 1:1, 1:2, and 1:4 ratios.

With any two-part deposition systems, static mixing nozzles are attached to the end of the cartridges to fully mix the two liquids before depositing. Although the length, size, and mixing elements of these vary, preference is given to mixing nozzles with square sections to improve stability when securing them to the dispensing system. At the end of each mixing nozzle, we attach custom nozzles in aluminum, steel, and copper, as well as 3D printed and off-the-shelf shaped plastic nozzles. Typically, the metal nozzles have circular sections with an inner diameter that ranges from 0.006″ to 0.118″. To create calligraphy-like paths and more structural extrusions, we developed custom nozzles with oval, square, rectangular, V-shaped, and L-shaped sections with the end cut perpendicularly or angled at 45 degrees (see Fig. 3B).

For large prints that require multiple cartridges of material, it was necessary to develop a zeroing strategy to perfectly align the new nozzle to its original position. This ensures that the new print will reconnect properly with previously printed

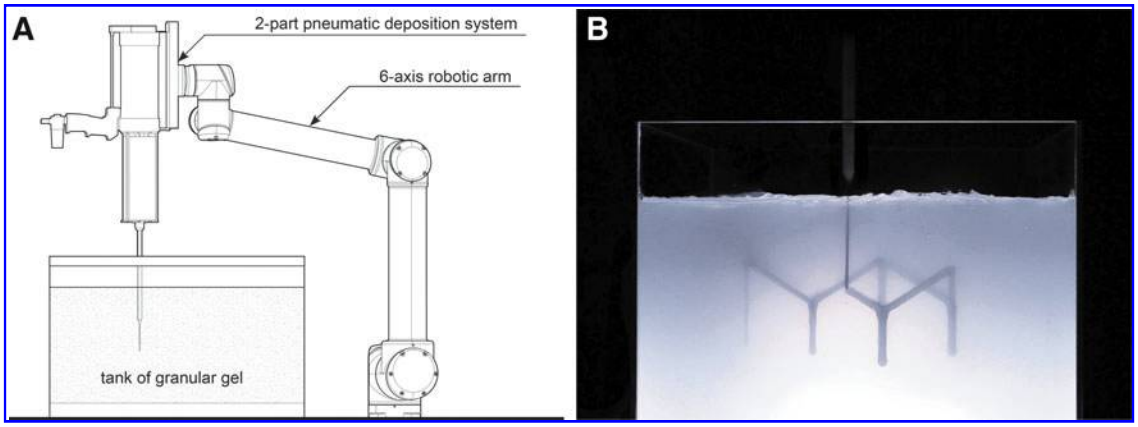

FIG. 2. **(A)** This diagram represents one version of the RLP system that uses a six-axis robotic arm. The setup uses a large two-part pneumatic gun for the deposition system with a static mixing nozzle and a thin metal nozzle. **(B)** Using a similar setup as in **(A)**, the RLP system prints a 10″×4″×5″ structure in 29 s with a maximum speed of 50 mm/s. RLP, rapid liquid printing.

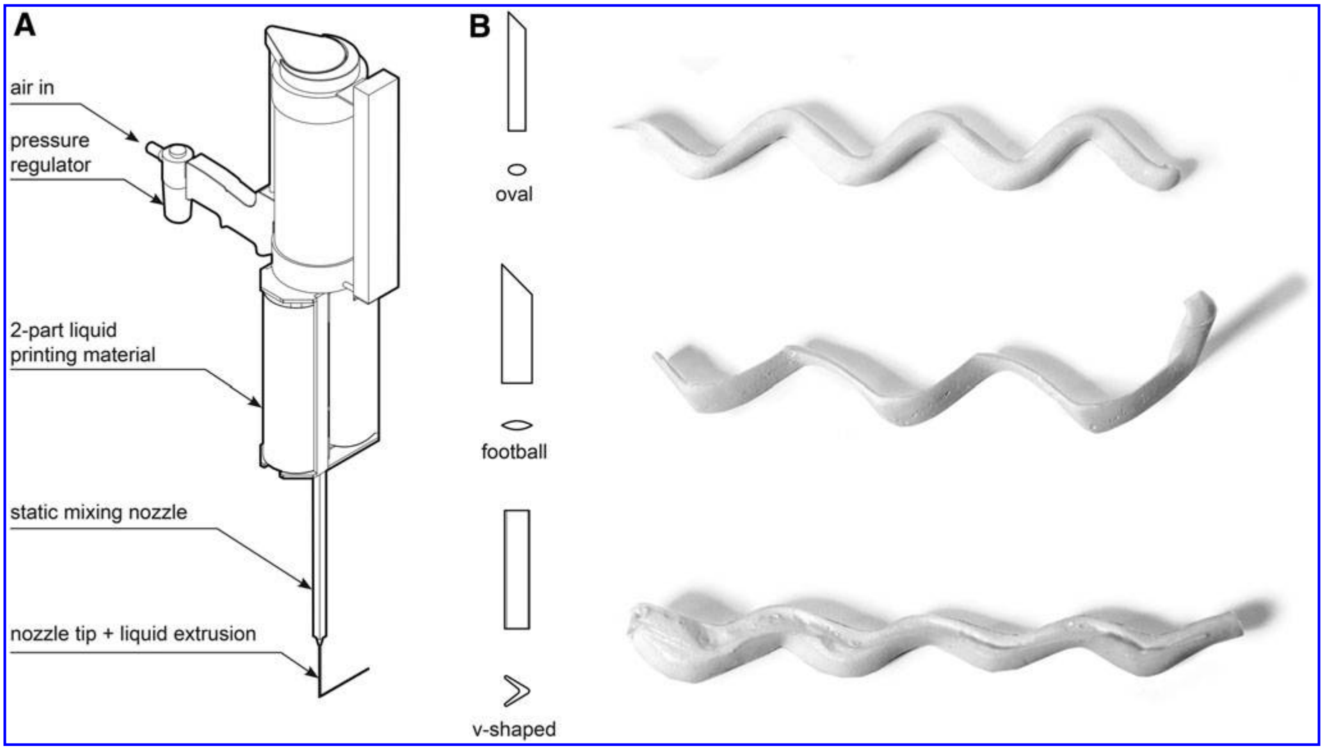

FIG. 3. **(A)** The deposition system is composed of five main components: the pneumatic gun, pressure regulator, cartridges filled with material, a static mixing nozzle, and a custom nozzle tip. The pressure regulator controls the rate of flow and the overall size of printed material. The static mixing nozzle mixes the two materials coming from the printing cartridges, ensuring consistency in extruded material. The nozzle tip is responsible for controlling the shape of the extrusion. **(B)** In addition to standard sections for nozzle tips, we tested many custom sections, some of which include *squares, ovals, circles, footballs, V shapes*, and *L shapes*.

material. Because the deposited material stays liquid for seconds to minutes, new paths are able to intersect and fuse with old paths, making much stronger connections than the cold-joints in typical spatial printing. To properly zero the nozzles, we calculate when it is necessary to replace the cartridges based on the print design, toolpath length, rate of flow, material viscosity, and cartridge size. The control platform is assigned a refill coordinate to travel back to at the end of each section where the cartridge is replaced and the nozzle is zeroed.

Granular gel. The suspension medium is a granular gel, similar in consistency to hair gel or hand sanitizer. It is produced by using carbomer 940, a crosslinked polyacrylic acid polymer in the form of white powder. The carbomer is mixed into water until it is fully dissolved. At this point, a 0.5% (w/v) carbomer-water mixture typically has a pH value around 4.0. Next, a neutralizing agent, such as a sodium hydroxide solution, is added until the mixture reaches a pH value of 7.0. The carbomer-water mixture transforms into a thick gel as it approaches a neutral pH, with an ideal gelling range between 6.0 and 9.0 for a 0.5% (w/v) carbomer mixture.[17] This exact range varies depending on how much carbomer is added, with a smaller range for less carbomer and a wider range for more. To maintain consistency in our experiments, we always mix our gel to a pH of 7.0.

In developing RLP, we tested proportions between 0.25% and 1.0% (w/v) of carbomer to water. The percentage of carbomer in the gel is directly related to the viscosity of the gel and the density of material that it can suspend. A higher percentage of carbomer results in a gel with higher viscosity and shear stress. In our experiments, the gel of 0.5% (w/v) carbomer and above was able to suspend materials with densities much lower and higher than its own, such as foam (0.27 g/cm^3), aluminum (2.7 g/cm^3), and steel (7.75 g/cm^3). In addition, gel with 1.0% (w/v) carbomer was able to suspend a lead sphere (11.34 g/cm^3). In contrast, 0.25% (w/v) carbomer gel was unable to suspend any materials tested. The foam sphere immediately floated to the surface, whereas each of the metals dropped to the bottom.

An additional characteristic of the granular support gel is its ability to freely flow around the nozzle, allowing the RLP machine to cross over already printed paths. As the nozzle moves, it exerts high shear stress onto the gel, which acts as a fluid, flowing around the nozzle. Then at low shear stress, the gel acts as a solid, supporting the printed liquid material (see Fig. 4A). The gel's ability to flow quickly around the nozzle is determined by a number of factors, including: the percentage of carbomer (w/v) in the gel, the nozzle design, and the speed at which the nozzle moves. Lower-viscosity gel and slower nozzle speed permit the gel to flow quickly around the nozzle. This allows for more consistency and control over the extrusion shape.

In contrast, with high viscosity gel, printed liquid material flows into the cavity left by the nozzle before the gel is able to completely recover. This effectively elongates circular depositions into a teardrop shape. The wider the nozzle, the more gel it displaces and the larger the teardrop shape. With wide

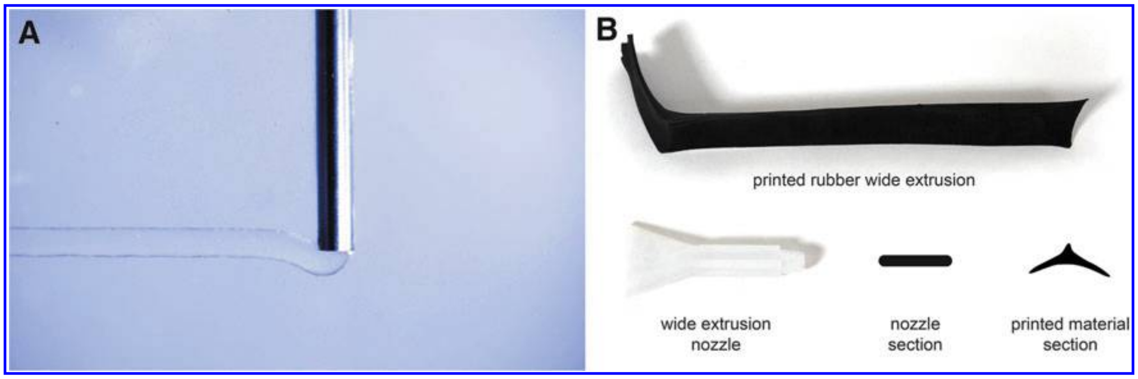

FIG. 4. **(A)** A stainless steel cylindrical nozzle tip moves through the granular gel medium, depositing liquid urethane plastic. The nozzle easily moves through the gel as it self-heals around the nozzle and the printed medium. **(B)** Testing a wide extrusion plastic nozzle, we printed a straight line that lifted upward at the end. The wide nozzle slows the self-healing process of the gel. This in combination with the buoyancy of the gel forms the rubber section into a *triangle shape* with a concave base.

extrusions, the buoyancy of the gel can also cause the underside of the print to have concave curvature (see Fig. 4B). If this is not desired, custom nozzles can be made that are L shaped in section, ensuring the gel can completely flow around the nozzle, allowing it to print large sections with higher accuracy.

The granular gel can be reused many times. When printing with silicones, urethane rubbers, plastics, UV curable resins, and other materials, our experiments have shown that the gel can be maintained for more than 3 months with more than 20 parts printed and removed successfully. However, the gel should be covered to minimize the evaporation of the water. Carbomer is also very affordable at under $20/lb. This can produce more than 90 L of 0.5% (w/v) carbomer-based granular gel.

Materials

Another significant advance in RLP over traditional 3D printing is its ability to use any liquid material that is photo, chemically, or otherwise curable. Because we are printing with a liquid deposition system, we are able to print with high-quality materials such as urethane rubber, urethane foam, urethane plastic, silicones, acrylics, epoxy, concrete, liquid metals, wood slurries, and many other liquid materials. Most 3D printing technology today requires very specialized materials, limiting the available materials and range of applications.

For example, FDM printing uses a spool of filament as the printing medium. This filament then needs to be heated by the printer and extruded at its melting temperature. It then cools and hardens into the 3D structure. This process limits the types of materials available to thermoplastics, with some machines requiring the manufacturer's proprietary material and cartridge. In addition, the layered nature of the FDM printing process dramatically reduces the structural integrity of the printed part compared with injection molding or our RLP process, which can create a homogenous material cross-section. Another challenge with FDM printing is the heating/cooling process of the filament that often causes clogged nozzles, burned plastics, or moisture-causing bubbles in the prints.

Similarly, SLA printing is limited to photopolymers that are cured through light exposure, typically UV light or other wavelengths within the visible light range.[1] In contrast, RLP uses the same materials that are available today in a variety of industrial settings. These materials do not require heat, sintering, or hot extrusion; rather, they are chemically, photo, or otherwise cured. Similarly, RLP does not rely on successive layering. This means that the parts can be printed fast and have a homogenous cross-section, resulting in a similar strength to those produced through traditional industrial processes.

Urethane plastic. For a rigid material, we experimented with a number of urethane plastic casting resins, selecting two plastics with different properties to continue testing. One plastic has a fast working time of 30 s and a cure time of 5 min, whereas the other has a working time of 7 min and a cure time of more than an hour. Each material carries both advantages and disadvantages. Fast cure times allows for printing many pieces quickly, by being able to remove the printed piece in a matter of minutes. The biggest disadvantage is that once the printed material begins curing it becomes more difficult to bond to, similar to cold-joints in spatial printing. Throughout testing, we used materials that cure in seconds all the way to many hours. It is beneficial to have fast cure times to remove parts quickly, but it is also beneficial to have delayed cure times so that the material remains liquid while you are printing the entire structure, ensuring stronger connections.

The biggest challenge that we faced with urethane plastics is their reaction to the water in the gel. The isocyanate group in liquid urethane reacts when exposed to water, bubbling, and releasing CO_2.[18] This reaction, when controlled, is a key step in manufacturing foams, but it is not ideal for our process. With some materials in our tests, the reaction started almost immediately and would transform the printed material into a completely expanded foam-like plastic. Other materials had a slower and weaker reaction and could be printed cleanly if removed from the gel quickly.

Urethane rubber. For an elastomeric material, we use a urethane rubber with no visible reaction to the gel and a shore hardness of 80A (see Fig. 5). Softer and harder rubbers are available in both urethane and silicone rubbers. The biggest challenge with this urethane rubber was developing strong connections at points of intersection. In early tests, it was noted that rather than connecting to itself, an intersecting toolpath would move through the previously printed material without bonding at all. The granular gel formed a thin layer around the

FIG. 5. **(A–C)** Polyurethane rubber printed parts with various shapes and connections. **(A)** Ball-joint cylinder. **(B)** Variable surface. **(C)** 2.5D Lattice.

rubber, preventing connection to existing material. An interesting discovery was that complex ball joints could be printed by re-intersecting with an already printed line from the side and pausing for a second or two in that location. This would deposit a ball within the already printed line that could be removed and reinserted repeatedly once fully cured.

After additional connection tests with urethane rubber, it was confirmed that RLP could produce strong connections, in addition to complex ball and socket joints. Two approaches to connections were subsequently developed: the PAUSE method and the CLONE method. Both methods required entry from above rather than from the side and enough material for the next pass to be able to re-enter and fuse.

Our experiments showed that in the PAUSE method with the pressure at 84 psi, a 0.083″ ID nozzle would need to pause for 0.75 s at the intended point of connection for the first pass. This ensures that enough material is deposited to connect to. In the second pass, the nozzle re-enters the connection point from above, passes through the connection point, and finally backs out. The PAUSE method often produces a piece with a sphere at each point of connection. If this is not desired, then the CLONE method may be preferable.

The CLONE method is so named because it requires reprinting part or all of a line segment. This connection has been successfully tested with vertical, horizontal, and angled lines. For a successful connection, the lines must overlap a significant amount. This length varies dependent on nozzle size, material deposited in first pass, speed, and pressure. The PAUSE method has proved preferable when printing lattices, whereas the CLONE method works better for surfaces.

Other materials. In addition, we have tested plaster, concrete, urethane expanding foam, epoxy, UV curable resin, marine sealants, casting alloys, silicones, and metal-filled epoxy. Among these, silicones have proved to be very successful, printing cleanly and making much stronger bonds than urethane rubber with a simple intersection. Some areas where challenges can occur are the material's density compared with the gel viscosity, the material's reaction to the gel, or the material's curing process. In the future, we intend to continue developing our material library and refining precise connection details.

Operation

The RLP process involves five steps: (1) designing the linework in any 3D modeling software, (2) generating the machine code, (3) preparing the deposition system, (4) running the file, and (5) removing the object. The process outlined next is specifically for the three-axis gantry-style system but is similar to printing with the robotic arm.

CAD model. To begin with, a user only needs to produce lines, polylines, or curves that define the toolpath of the nozzle. The linework can be created as a 3D curve or polyline in any standard 3D modeling software. The two or 3D curve is rebuilt to a degree-one curve to ensure that the machine will follow the control points (CP) directly on the curve. This design process is very different compared with standard commercialized 3D printing methods, which require solid or surface modeling, triangulation/STL generation, and slicing. Our process is easy to model and relates much more to spatial 3D printing and CNC machining with tool path generation where the user designs the precise path that the machine will take. This comes in contrast to the typical process where the user designs a mesh or solid surface and then requires an interpolation step to translate the desired surface to the machine paths. The simplicity of the process also allows for small print files, easy communication between the file and the machine, and simple visualization of the tool path without complex slicing algorithms.

Generating code. Next, a custom python script is run, which prompts the user to select the lines, polylines, or curves. The script then evaluates each CP and generates commands in machine code that direct the machine to travel to each CP. This file is then saved as an SBP file to be run on a ShopBot machine, but it can also be exported to communicate with other machines.

Deposition preparation. Once the file is generated, it is then loaded into the machine and the prepared cartridges are loaded into the pneumatic deposition system. The system is started, and the pressure is adjusted to match the desired line thickness. If using a two-part material, the system should be run until it is evident that the two parts have fully mixed through the static mixing nozzle.

Printing process. Once the file is ready to run and the deposition system has been adjusted, the printing process can begin. To do this, the machine file is opened in the machine's control software. Then, the speed, acceleration, offset, and home positions are set. Finally, the file can be run. The pressure can either be hard-coded to run whenever the program reads an output command or controlled manually.

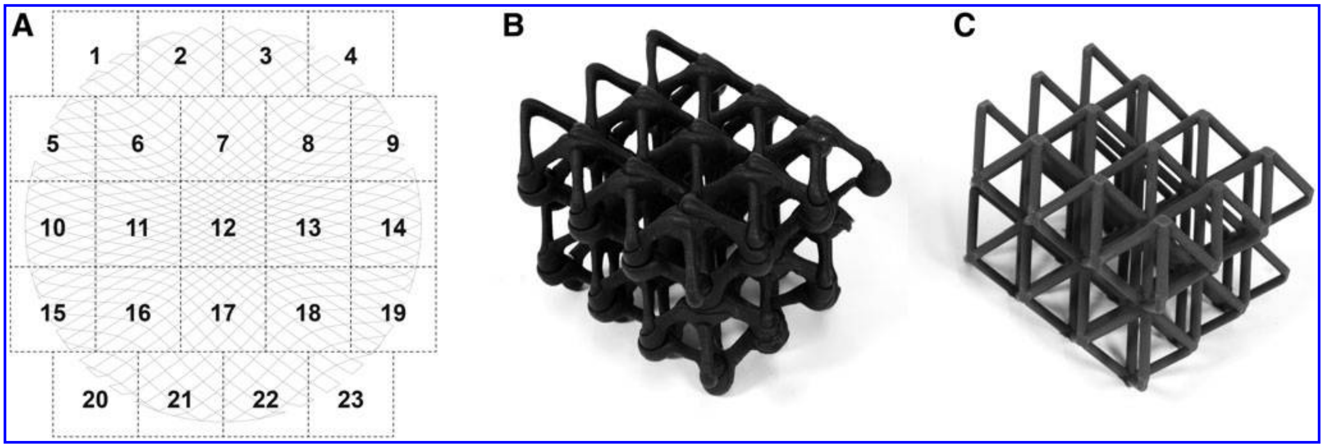

FIG. 6. (**A**) The largest print completed on the RLP system was a 25″ diameter table with a 3″ depth, printed in only 28 min. If this were printed by using a standard SLA printer with a 145 × 145 mm work area, this table would need to be broken into 23 sections and glued together. The *gray lines* represent the toolpath for printing, and the *dotted boxes* show how the table would be broken into sections. (**B**) This 4″ × 3″ × 4″ flexible rubber lattice was printed on the RLP system in only 3 min and 46 s. (**C**) Using an SLA printer, the same lattice would take 8 h and 45 min, or 525 min, more than 139 × longer. SLA, stereolithography.

Object removal and processing. After printing is complete, the material must fully cure before removal. For chemically cured materials, nothing needs to be done except wait for the designated cure time to be complete. For UV curable resin, UV lights are placed over the tank for 2–30 min, depending on the size of the print. Once the curing process is complete, the objects are removed from the tank and excess gel is removed by simply washing it with water or blowing it off with an air compressor. If necessary, the objects can be postcured by placing them on a low-temperature hot plate with a cover or under UV lights. The simplicity of postprocessing is highly desirable compared with the tedious removal of supports in typical 3D printing processes. Often, traditional postprocessing involves hours if not days of postprocessing in addition to long printing times.[1] This may include dissolving or manually removing support material, necessary postcuring, and alcohol baths.

Results

3D printing today has not yet realized the promise of true customized manufacturing and production because it is often far too small, too slow, and limited to poor-quality materials. We propose RLP as a solution to these challenges. RLP is scalable to both small- and large-scale objects; it is fast and can use any liquid curable material.

Large scale

To demonstrate scale, we looked at the challenge of printing a custom 25″ diameter tabletop with a 3″ depth. Using an SLA printer with a 145 mm by 145 mm work area, this tabletop would need to be split into 23 sections, taking many days or weeks to print on a single machine (see Fig. 6A). In contrast, the RLP system is capable of printing the same tabletop in only 28 min and 30 s, with a maximum speed of 50 mm/s.

For this product, we chose to use urethane plastic in a 30″ diameter tank of granular gel with 0.5% (w/v) carbomer gel. This two-part urethane plastic has a working time of 30 s and a cure time of 5 min, so it was important to work quickly and design accordingly. Early table designs were initially printed in the x-axis direction and then in the y-axis. Although this was acceptable with small-scale, fast prints, it became an issue with larger prints where the initial material cured before completion. To accommodate this, we developed a new design that was printed in a way similar to knitting, where each new layer was connected to the layer immediately preceding it. In this way, the cure time was no longer an issue and the entire tabletop could be removed within minutes of completion. This tabletop was printed with the large 60″ × 120″ three-axis machine. With larger industrial robotic arms or a custom gantry setup, RLP could conceivably print any size structure.

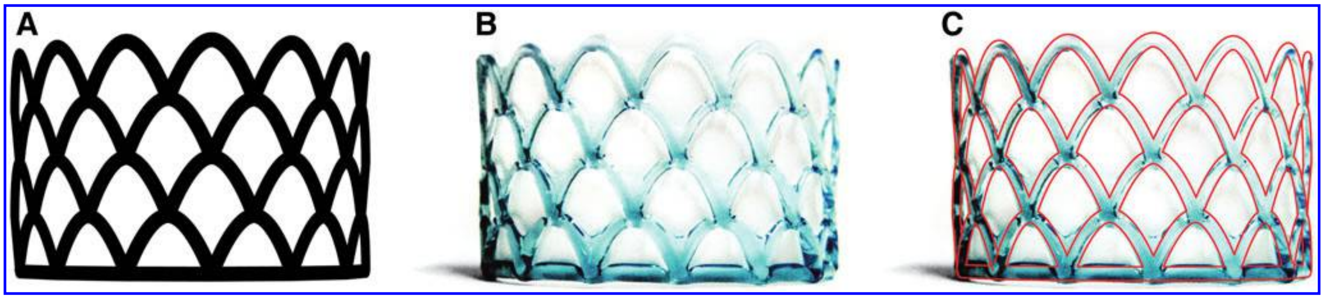

FIG. 7. (**A**) Drawing of predicted cylinder print. (**B**) Photograph of print using ultraviolet curable resin. (**C**) Overlay comparison of predicted print to final print.

Fast

Using the RLP system, the maximum speed is limited by the chosen control platform. With our six-axis robotic arm, the maximum speed is 1 m/s; whereas on our three-axis gantry machine, it is 0.25 m/s. Because RLP uses granular gel instead of printed supports, it minimizes material waste and printing time. To highlight speed, we compare RLP with existing 3D printing processes, in this case an SLA printer, by producing a small flexible lattice (see Fig. 6B–C). The resolution and quality is high with an SLA printer, whereas the build volume is small and the process is slow, often taking hours or days depending on the complexity of the piece. For example, a 4″ × 3″ × 4″ flexible lattice that was printed with an SLA printer was printed in roughly 8 h and 45 min (525 min). In contrast, the RLP process finished printing in only 3 min and 46 s. That is more than 139 × faster than SLA printing the same part.

The feature size and resolution, typically measured in the XY plane and Z-axis layers, respectively, are difficult to compare directly because of the omnidirectional printing process. Nevertheless, the feature size and resolution are first controlled by the nozzle size, then by the speed and pressure parameters. The finest features were achieved with silicone with a 0.042″ ID cylindrical nozzle, with a cross-section of the printed part measuring 0.040″ in height and 0.045″ in width. The silicone bonds extremely well to previously printed paths, negating any need for complex connections. To demonstrate much larger features and faster speeds, we printed a path with a width of 1.83″ and a depth of 0.69″ in one pass by using a custom-wide extrusion nozzle. Some printed structures we have experimented with are lattices, cylinders, surfaces (both through raster printing and through wide extrusion nozzles), textiles/netting, and other complex extrusion structures that can be drawn in 3D space (see Fig. 7).

Industrial-grade materials

Looking at material properties and availability, RLP has a significant advantage over standard 3D printing processes. Most commercially available 3D printers have a variety of rigid materials that vary in strength, color, and rigidity, whereas some offer flexible materials. These materials may be flexible; however, the elongation, tear resistance, or many other properties often do not compare with other industrial-grade rubbers used in traditional manufacturing. In addition, because they are printed in layers, typical printed structures are more easily broken along those strata.

For example, a comparable flexible SLA material has a shore hardness of 90–100A with a tensile strength of 1015–1595 psi and 35–45% elongation at break.* Our urethane rubber has a 90A shore hardness with a tensile strength of 2000 psi and 550% elongation at break.† Although shore hardness may be comparable in this example, tensile strength is 1.25–1.97 × higher with the urethane rubber and elongation at break is 12–16 × higher. Across the board, elongation at break is significantly higher with true rubbers over rubber-like materials. In addition, RLP can use silicone or urethane rubbers, with shore hardness ranging from 00A to 90A and with elongation at break varying from 1000% to 550%, respectively.‡ The number of material options available for the RLP allows designers, researchers, and manufacturers to experiment with a wide variety of material properties and choose a material suitable for the design.

Conclusion and Next Steps

This work presents an experimental printing process called RLP and our research into the practical parameters of size, speed, and material properties. RLP is a framework for pushing large-scale rapid prototyping to the next level in speed, customization, and material quality. There are many directions for future research, some of which include furniture and other large-scale fabrication, interactive design and fabrication, clothing, and sportswear manufacturing. In the future, we imagine that manufacturers will be able to print custom shoes, sports equipment, car components, or other large products in a matter of minutes with high-quality materials. It will also likely be possible to print large tables, chairs, or even building components with this process.

Looking at the interaction, this technology allows for objects at small or large scales to be printed in a manner that is reminiscent of two-dimensional drawing or sketching in 3D space. When connected with design software, a modeling tool, or virtual reality (VR) headset, this printing technology could allow for a designer to sketch and design in mid-air while simultaneously printing at the same time and same scale. This 1:1 design to production process has not been realized before due to time constraints that are inherent with physical fabrication. Most fabrication processes, even for quick sketch models, take significant amounts of time and, therefore, cannot be as fast as sketching. With this technology, a printed part can be created at the same speed that a robot or a human moves their arm through the air.

The primary contribution of this article is the development and presentation of RLP, a new printing process that directly addresses the challenges of scale, speed, and material quality in standard 3D printing technology. In addition, we presented our research on materials, including their printing requirements, cure times, mechanical properties, their relationship to the granular gel suspension, new discoveries in mechanical connections, and successful large- or small-scale prints. We also outlined the steps to produce a final object from design to completion, including the tool path design, machine interface, and the liquid deposition system. Lastly, we identified possible areas of application in furniture manufacturing, large-scale products, sports equipment, and interactive design process. We see RLP as a promising new production process that brings speed, scale, and material properties to the forefront of design creation.

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[*] Stratasys. Digital Materials Data Sheet–FLX9130-DM (I); FLX9430-DM (II); FLX9230-DM (III); FLX9330-DM (IIII) http://global72.stratasys.com/~/media/Main/Files/Material_Spec_Sheets/MSS_PJ_DigitalMaterials_Datasheet_0617.ashx#_ga=2.51878827.345857124.1501511387-1426957060.1501369920 (last accessed on July 30, 2017).

[†] Smooth-On PMC 790, Reynolds Advanced Materials, Brighton, MA.

[‡] Smooth-On PU rubber and silicone products, Reynolds Advanced Materials, Brighton, MA.

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Author Disclosure Statement

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References

1. Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies. Boston, MA: Springer US, 2010.
2. Busta H. Architect Magazine. This Architect-Designed Wall System Has a 3D-Printed Core. www.architectmagazine.com/technology/this-architect-designed-wall-system-has-a-3d-printed-core_o (last accessed on July 29, 2017).
3. Helm V, Willmann J, Thoma A, *et al.* Iridescence print: robotically printed lightweight mesh structures. 3D Print Addit Manuf 2015;2:117–122.
4. Yu L, Shi J, Liu X, *et al.* Robotic Extrusion (Robotic 6-Axis 3D Printing). https://www.behance.net/gallery/22536831/ROBOTIC-EXTRUSION(6-Axis-KUKAABS-3D-Printing) (last accessed on July 30, 2017).
5. Garcia MJ, Restin G. Design Computation Lab UCL. Voxel Chair V1.0. www.designcomputationlab.org/voxelchair-v10 (last accessed on July 29, 2017).
6. Jokić S, Novikov P. Mataerial. www.mataerial.com/ (last accessed on July 27, 2017).
7. MX3D. MX3D Bridge. http://mx3d.com/projects/bridge/ (last accessed on July 7, 2017).
8. Ohdaira E, Masuzawa N. Presuming the strength of concrete cold joint by ultrasound. Ultrasonics Symposium. October 7–10, 2001. IEEE, Atlanta, GA, 2002, pp. 755–760.
9. O'Bryan CS, Bhattacharjee T, Hart S, *et al.* Self-assembled micro-organogels for 3D printing silicone structures. Sci Adv 2017;3:e1602800.
10. Bhattacharjee T, Zehnder SM, Rowe KG, *et al.* Writing in the granular gel medium. Sci Adv 2015;1:e1500655.
11. Jin Y, Compaan A, Bhattacharjee T, *et al.* Granular gel support-enabled extrusion of three-dimensional alginate and cellular structure. Biofabrication 2016;8:025016.
12. Hinton TJ, Jallerat Q, Palchesko RN, *et al.* Three-dimensional printing of complex biological structures by freeform reversible embedding of suspended hydrogels. Sci Adv 2017;3:e1602800
13. Wu W, DeConinck A, Lewis JA. Omnidirectional printing of 3D microvascular network. Adv Mater 2011;23:H178–H183.
14. Johns RL, Kilian A, Foley N. 2014. Design approaches through augmented materiality and embodied computation. In: Robotic Fabrication in Architecture, Art and Design 2014. Springer International Publishing, Cham, Switzerland, 2014, pp. 319–332.
15. Clark L. How Hair Gel Enables Freeform 3D Printing with an Undo Function. WIRED UK. July 25. www.wired.co.uk/article/undo-3d-printing (last accessed on June 6, 2017).
16. Hixon D. The Evolution of Precision Robotics. The Fabricator. Elgin, IL: FMA Communications, Inc. 2013.
17. Lubrizol. Thickening Properties. Cleveland, OH: Lubrizol Advanced Materials, Inc. 2011.
18. Armistead JP, Wilkes GL, Turner RB. Morphology of water-blown flexible polyurethane foams. J Appl Polym Sci 1988;35:601–629.

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