Phase Change Rapid Prototyping with Aqueous Inks

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Abstract

We present the first results of a new rapid prototyping technique that has been developed, which can produce structures with high aspect ratios (44:1) and freeform overhangs. The technique uses a piezoelectric printhead to precisely deposit material drop by drop at predetermined positions on a substrate. The temperature of the printhead can be varied so as to adjust the ink's viscosity, in order to improve its printability. The substrate on the other hand is kept below the ink's freezing point. For a normal water-based ink this means that the printhead is kept at room temperature and the substrate is kept at -20°C. When a droplet hits the surface its small thermal volume is almost instantly cooled. As a result of this fast freezing, the droplet does not spread but retains the shape of a half sphere. The next falling droplet lands on top of the first and covers it; heat is removed to the substrate through this contact area. Successive droplets result in the formation of a pillar with a rounded top. Finally, by moving the translational stage during printing simple, freestanding step structures can be fabricated.

Introduction

Inkjet printing has matured into a technology that is exploited for a variety of applications. One particular application is rapid prototyping, in which a two-dimensional layer is printed repeatedly to produce three-dimensional (3D) structures. Rapid prototyping, or layered manufacture as it is sometimes called, has become useful to industry since it allows the swift visualization of concept models. Sachs et al. pioneered the technique by printing a binder onto a bed of powder to produce ceramic components [1]. After the requisite number of layers was printed, the free powder was removed, leaving the 3D object. This approach, however, has limitations since the use of a powder bed limits the range of composition variation. Evans and co-workers [2] developed a direct inkjet deposition method, whereby they used dilute particle suspensions and a modified, commercially available desktop printer to build up ceramic structures ‘voxel by voxel’. Unfortunately, this approach was disadvantaged by the very dilute nature of the ceramic inks, which required an increase in processing time since a large number of layers had to be deposited in order to obtain a specified thickness.

An alternative way to prepare structures uses a ‘phase-change’ ink, which solidifies upon impact with the substrate, such as molten wax [3]. Derby and co-workers used this approach to print ceramic structures using a wax-based ink with solids loadings as high as 40% [4]. The approach, however, has the disadvantages that the carrier has to be removed, the impinging droplets melt the layer upon which they fall and that the final part shrinks anisotropically upon sintering [5]. Related methods to the phase change approach involve printing an ink that undergoes a gel transition via a photo-induced cross-linking step [6] or a 40% loaded polyurethane suspension [7].

Here we present an in-house rapid prototyping system based on inkjet printing. The system uses a modular design, which allows the experimentalist to easily adapt the printer to the system to be used. The rapid prototyping printer was designed using readily affordable components and exploits the phase-change approach by using a platen, which can be chilled to -40°C. Finally, using an aqueous ink we demonstrate the capability of the system to print structures with high aspect ratios and complex geometries.

Results and Discussion

A highly versatile system was built using standard components. The system was built in a modular way, to allow optimisation of individual parts. This modular approach also reduces dependence on specific technologies. All of the modules have been built on PCI-cards, which allow all of the interconnections to be made by plugging them into a slotted bus system. Table 1 shows which parameters are controlled by the system.

Table 1. System parameters for the in-house assembled printer

Property	*Range*	*Type*
Platen movement	5cm × 5cm, 1µm resolution	Actuator
Droplet Volume	10 – 1000pl	Actuator
Environmental Sensors	Temperature, humidity, pressure	Sensor
Platen Temperature	-40°C – 180°C	Actuator
Printhead Temperature	RT – 70°C	Actuator

Although each module was individually

designed, the components work together under the control of an ARM7 micro-controller, which has a real-time accuracy of less than 10 microsecond. As these times are difficult to obtain with a normal PC, the ARM7 is assisted by an ATMega32 microcontroller, which handles the communication protocols with the sensors and actuators; this allows the ARM7 to deliver improved timing accuracy. Figure 1 shows a schematic illustration of the set-up.

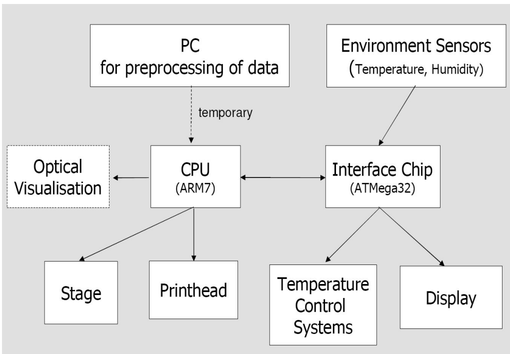

Figure 1. *A Schematic illustration of the experimental set-up.*

The assembly of the printer was performed with consideration given to ease of use, price and flexibility. In order to achieve these targets the modularisation needs to be made in a properly structured way. For example, each heater module needs to have the same interface to the ATMega32 chip. In particular, the ATMega32 can set the temperature module to heat or cool, by reversing the current. This works fine for peltier elements but if a simple thermal resistor is used heating occurs regardless of current direction. Therefore, a diode is used, which ensures that the only difference for the ATMega32 is that the time constants for cooling are larger. It is the same case for the printhead since each type of printhead needs its own driving electronics, which have to have a fire-pulse input which interfaces with the ARM7.

To give a first proof of principle, an aqueous ink was jetted onto a chilled platen. The used ink was standard HP ink, whose melting point was observed to be -8 °C. The temperature of the platen was lowered to -20°C using peltier coolers. The droplet volume was 35 pl, and was calculated to take about 1 ms to freeze, which ensures that it does not spread out but keeps a roughly spherical shape, with dimensions of approximately 18 µm in height and 66 µm in diameter. Figure 2 shows a droplet that had been printed onto a screw head to illustrate scale.

Up to a certain height, the low platen temperature allows successive droplets to be printed on top of each other without loss of feature definition. This process is assisted by the thermal conduction of ice (2.33 W/m K) being much higher than in water (0.6 W/m K) [8], which allows heat to dissipate from the new droplet through the underlying structure. (The data for water and ice is applied to the ink since it is composed of >95% water.)

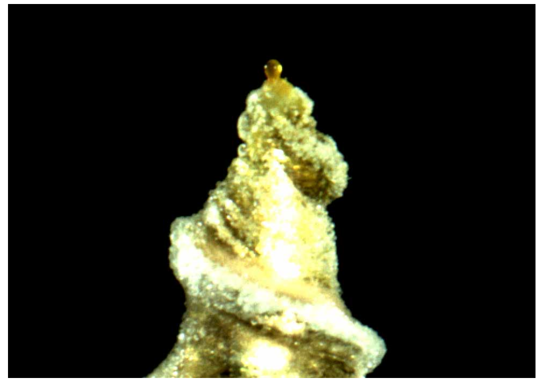

Figure 2. *A single frozen droplet demonstrating that the droplet freezes almost instantaneously upon impact.*

As was mentioned earlier, there is a certain height restriction to the features that can be produced. The long pillar shown in Figure 3 has a bulge at about 2,000 mm. Up until that height, the constituent droplets had been printed using a frequency of 40Hz. After this height, droplets were printed at a lower frequency of 20 Hz, since their heat could not be dissipated fast enough, which meant that successive droplets landed on a partially frozen substrate. This allowed a final column height of nearly 3,000µm to be produced.

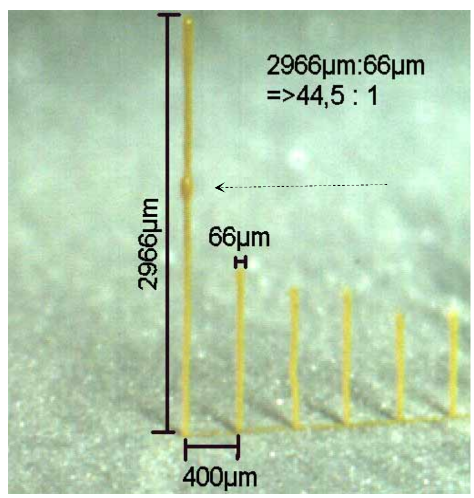

Figure 3. *Ink structure with bubble on top illustrating the height limitation. To the right of this pillar smaller columns without bubbles can be seen. (The dashed arrow indicates the bubble.)*

To predict the shape of structure if the droplets are printed a rate that the last droplet is not completely frozen or that it is residing only partially on the underlying structure is difficult but possible, as shown by the next experiment.

Moving the substrate underneath the printhead can enhance the printing process, if the print rate is known. Figure 4 shows a step structure that was produced using this technique. The step structure was created by printing at a constant frequency of 20Hz. First the platen was kept stationary to allow an initial stack of droplets to build up. The stage was then moved 240µm to the left at a constant velocity of 200µm/sec, which meant that successive droplets didn't land directly on top of their predecessor but instead had a slight offset, which resulted in a slope. This process was repeated but it can be observed that the slopes are not equal from step to step. This is due to the fact that when a droplet lands partly on the already frozen structures it starts to roll down at this side until it freezes, the higher the structure the slower the freezing. A slower freezing results in a less steeper slope.

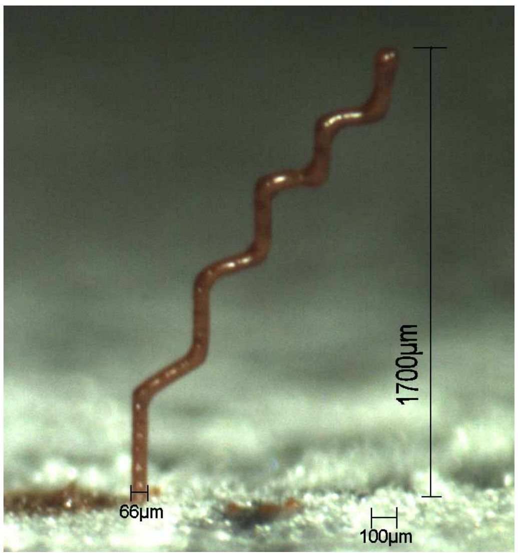

Figure 4. *Simple step structure, illustrating that freeform overhang structures can be made.*

By combining the demonstrated elements of the structures the machine can be used to create a large variety of three-dimensional structures, (Figure 5) without the need of a scaffold. Future work will focus on using inks that are jetted at elevated temperature since they are solid at room temperature.

Conclusions

The first results of a new rapid prototyping technique, which uses a piezoelectric printhead to precisely deposit material drop by drop, are presented using a commercial ink that is ~95% aqueous. Simple structures with aspect ratios as high as 44:1 can be printed and other structures that contain freeform overhangs can also be produced. The temperature of the platen can be controlled and can be kept well below the freezing point of water. For the experiments reported in this paper, the platen was kept at -20°C, while the printhead operated at room temperature.

The small size of a droplet means that when it lands upon the substrate it is rapidly frozen. It, thereby, retains its in-flight morphology. High aspect ratio columns can be built up, or by moving the platen freestanding step structures can be fabricated.

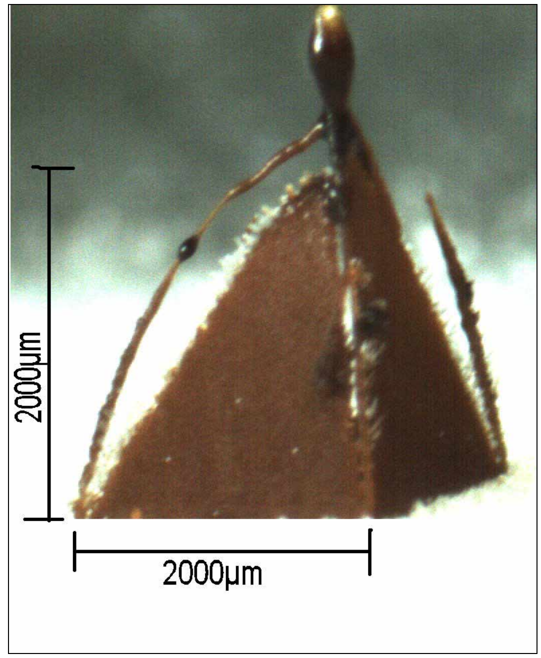

Figure 5. *Pyramid structure with curving side bars demonstrating that freeform scaffoldless overhangs can be produced.*

Experimental

The printer used in this study was composed of a number of off-the-shelf and customised components. The printhead was a SE-128, which was purchased from Spectra (Lebanon, New Hampshire, USA), which typically produced droplets with a volume of 35 pl. The platen was moved in *X* and *Y* using an M-410.CG positioning system from Physik Instrumente (Karlsruhe, Germany), which has a positioning accuracy of ~200nm. The ink was C1809A) purchased from Hewlett-Packard. To cool the substrate a custom-made peltier based system was used. All of the controlling electronics were also custom-made.

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Author Biography

Dario Mager received his Dipl.-Ing. (Master) degree in the field of MEMS at IMTEK in Freiburg, Germany in 2004. His diploma thesis was the development of a simulation and optimization tool for FET-based piezoresistive stress sensors at the Laboratory for Microsystems Materials of Prof. Oliver Paul. In 2005 he started to work on his PhD thesis about rapid prototyping using inkjet technology at the Laboratory for Simulation of Prof. Jan G. Korvink.