Development and characterization of a semiautomatic machine for the Drop on Demand Three Dimensional Printing

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Summary

A Three Dimensional Printing (3DP) machine system integrating a Drop on Demand (DoD) printhead is presented. It is based on the rapid prototyping technology developed since the last decade at MIT. To build a three-dimensional part, powder beds are manually spread and powder grains are selectively bound by liquid drops from an inkjet style printhead. Successive layers are added until the part is completed.
The machine target use is making small-scale tests with the real working parameters for the development of new material systems and it is specifically designed to print and examine single scanlines.
Hardware design includes two axes working space and a PC-based control system. Special software to control the printhead and the main axes in different configurations, to print rings and lines, with continuously changing parameters has been developed, which generates a detailed report for the process monitoring.
Methods for the printhead characterization are also described, including a new fast technique to estimate the drop speed. The machine has been successfully exploited using different binders (water solutions of colloidal silica in ethylene glycol and poly acrilic acid) and powders (ceramics and metals). An overview of the available inkjet printing technologies is also given in the paper.

Key words: Rapid prototyping machine, Printing technology, Layered manufacturing, Powder processing.

1 INTRODUCTION

Three Dimensional Printing is a solid free form fabrication or layered manufacturing technology, known more as rapid prototyping. It has been developed since the last decade at the Laboratory for Manufacturing and Productivity at MIT [1] [2] [3]. New applications continue to surface and new systems/processes are being introduced on a regular basis and require the parameters optimization with different material systems.

A new machine to make small-scale tests, which are not possible or convenient to do "on the line" with the machines used for production, will be described.

Rapid prototyping

The term rapid prototyping [4] [5] [6] refers to a number of processes used to manufacture appearance models and functional prototypes that share a number of characteristics. These processes include: Three Dimensional Printing (3DP), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM) and Laminated Object Manufacturing (LOM). The chief characteristic is that all rapid prototyping processes are additive. Three-dimensional objects are usually built up in a sequence of cross sections. This gives the process the greatest amount of access to the geometric features of the object during the build, and reduces the three dimensional fabrication to a sequence of two-dimensional laminations. This characteristic excludes most machining processes. Lamination depends on an adhesive: either a filler material is bonded with an "adhesive" (3DP, SLS) or the part is formed entirely from the "adhesive" (FDM, LOM), which is caused to undergo a phase change for at least a brief period during the forming process. A third general characteristic of rapid prototyping processes is that the interface to a CAD system is relatively direct [3], in contrast to machining, which involves a large amount of calculations for material removal strategies, tool paths, and tool width compensation.

1.1 3DP machines

Current technology

In Three Dimensional Printing, data from a CAD model [3] is used to calculate a sequence of cross sections. Parts are formed from a combination of granulated powder and a liquid binder. In the typical machine configuration, the powder is contained in a rectangular build box with a movable bottom or piston. The binder is dispensed by an inkjet printhead that travels over the powder bed. The printhead is based on the Continuous Jet technology with the piezo principle. In a machine cycle a layer of powder, usually about 200 μm in thickness, is spread by a leveling mechanism onto the upper surface of the body of powder in the build box: the powder bed. Binder is printed to bond the powder into a cross-section of the part being built with a raster motion. The piston is indexed downward by one layer thickness to make room for a new layer. This layer-by-layer process repeats until the part is completed. The unbound powder temporarily supports the unconnected portions of the component as the structure is built. After heat treatment, the unbound powder is removed, leaving the completed part. The only restriction on the forms that can be produced is the necessity for loose powder to be shaken out of hollow spaces. The process can potentially be applied to any form of powdered material and any fluid binder. The filler materials are, just to cite a few: aluminum oxide, fused silica, stainless steel, tungsten and silicon carbide. Two binders are primarily used for these materials: colloidal silica and Acrysol® latex emulsion or Poly Acrilic Acid (PAA) [12] for metals.

Previous work

The primary effort in the early years of the 3DP technology has been in the development of printing hardware for producing ceramic shell-molds for metal casting. The prospect of building ceramic shells directly from CAD models is very attractive. Cores, cavities, surface textures, filters, and structures that control heat transfer can be designed into a part and formed in a single operation [7] [8]. This process utilizes colloidal silica to bond aluminum oxide powder. The optimal binder selection was extensively dealt with by [9]. This combination of materials was selected to closely approximate the material produced by the slurry dipping process that is conventionally used in industry.

Several printing machines have been built and are operating at the 3DP Lab at MIT. The so-called “alpha machine” is the first prototype and it is still in use for production and research purposes. Production machines are currently available from industrial manufacturers under license. A new machine has been recently developed, which is based on the slurry technology [10]. In order to make experiments [11] [12] and direct observations based on high-speed imaging [13] [14], several setups have been developed and are available as complete machines and individual modules at the 3DP Lab.

2 THE DEVELOPED SYSTEM

System overview

The main system elements are displayed in Figure 1. To build a three-dimensional part, a powder bed is manually spread as explained later, and the powder grains are selectively bound by the liquid drops coming out of the inkjet printhead, which is controlled by a PC. The printhead cartridge and the powder bed support can be easily removed and accurately repositioned to quickly change the binder or the powder type and to observe the printed part on the powder bed support out of the machine.

For the positional repeatability of the cartridge, a commercial printer carriage with wiring has been used. Regarding the powder bed supporting plate, a sphere-based centering system has been used.

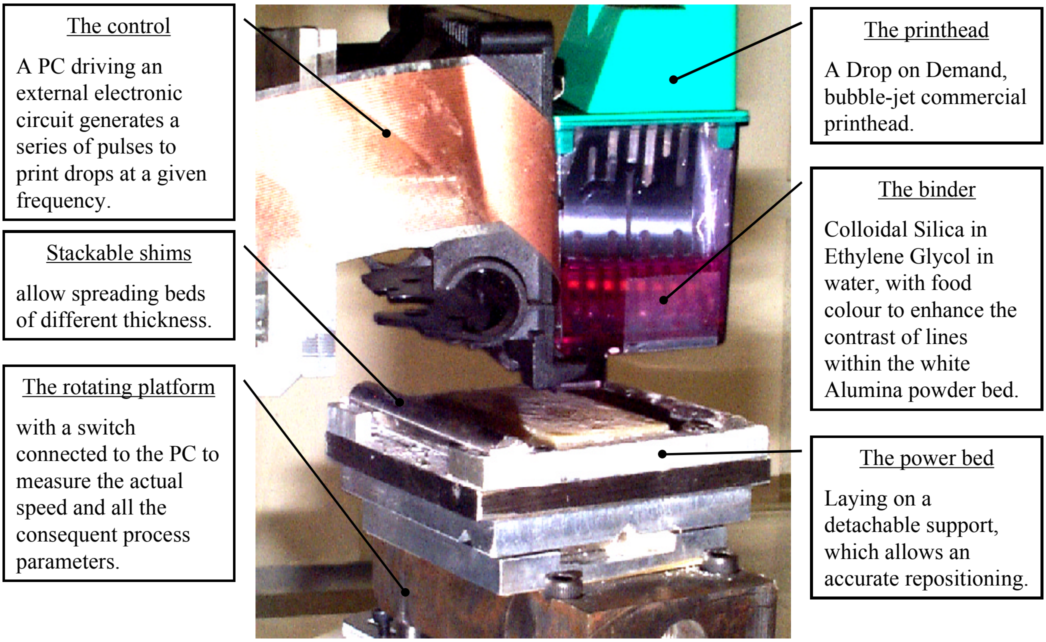
The powder bed support and the printhead own respectively the fast axis, which prints a single pass, and the slow axis, which produces an intermittent movement between passes.

The regularity of the machine speed and of the printhead operations in the working range has been verified by printing drops on paper and by measuring the drop spacing at the microscope.

2.1 The axes configuration

The machine is available in two configurations, which make use respectively of a turntable and a linear guide to move the powder bed support. The motor-controlled axes and conventions are shown in Figure 2. The two configurations are referred to as the “3D Ring” and the “3D Line” machine. The slow axis position is controlled in open loop with a DC motor driving a micrometer guide. The positional repeatability is in the order of 0.01 mm, which is probably only sufficient when building small objects, because the error is cumulated in successive adjacent passes.

The printhead is mounted on a stage with micrometer drives in the three spatial directions. They are used in the setup phase to align the printhead with the powder bed support. The vertical axis is important to set the printhead-powder bed distance, which is critical with



The control

A PC driving an external electronic circuit generates a series of pulses to print drops at a given frequency.

Stackable shims

allow spreading beds of different thickness.

The rotating platform

with a switch connected to the PC to measure the actual speed and all the consequent process parameters.

The printhead

A Drop on Demand, bubble-jet commercial printhead.

The binder

Colloidal Silica in Ethylene Glycol in water, with food colour to enhance the contrast of lines within the white Alumina powder bed.

The power bed

Laying on a detachable support, which allows an accurate repositioning.

Figure 1: A detail of the printing area of the developed machine in the 3D Ring configuration and description of the main elements.

DoD. The slow axis position is only important in the ring configuration, because it must intersect the turntable axis or at least it must be tangential to a ring, to have an accurate positional feedback. It should be noticed that in this latter case the relative accuracy of the slow axis is increased for a geometrical amplification of the scan spacing. The table spin for the ring machine and the translation speed for the line machine are manually selected, but they are acquired and saved in a report by the PC through a microswitch.

The 3D Ring machine

In this configuration, the powder bed is placed on a turntable. The powder bed rotates under the printhead and rings of varying radii may be created by changing the distance between the turntable axis and the jet orifice. There were several design issues to be addressed before parts could be generated. Repeatability was the first to be addressed. A certain degree of repeatability is necessary to ensure that lines and layers would stitch together properly. A motor designed to operate at the low speed that where needed for the turntable (approximately 0.5 Hz) was used.
Higher speeds can be achieved printing arcs instead of complete rings, by mounting arms of different length on the turntable.

The 3D Line machine

Another need that emerged during the project, was the possibility to achieve very low printing speed (in the order of 0.1 mm/s) to assess the effect of quasi-static conditions in

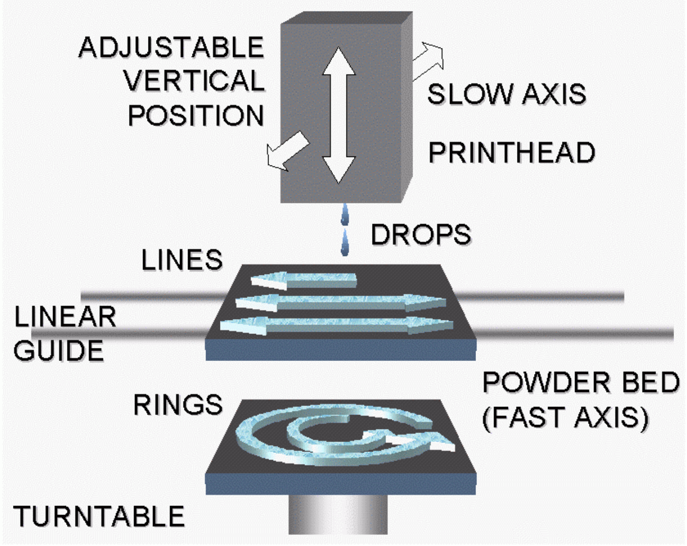


Figure 2: Schematic of the developed machine with the main axes in the two configurations: the 3D Line machine (upper) and the 3D Ring machine (lower).

the part formation under the action of the liquid binder on the powder. The turntable was not able to operate at constant speed in that range. The first possibility was using the slow axis as the main axis, but this option only allows making tests with single scanlines, so a new linear guide with driver has been purchased, sensorized and setup. The control software only needed few modifications.

Discussion

A critical analysis of the two different configurations tested is summarized in Table 1. The main advantage of making a ring machine is that a rotary table is usually less expensive and easier to assemble. Another aspect is that the speed changes proportionally to the radius, yielding parameters variability during tests. The same happens with the slow axis regarding the line spacing, unless the slow axis intersects the rotary table axis. Otherwise, software correction is necessary. The rotary table is suitable to build parts with an axial symmetry for the preferential texture direction obtained, which may be detrimental in other cases. On the opposite, printing lines instead of rings has the following advantages:

- with raster printing, it is easier to define the “filling path”;
- beds are exploited better, as the entire surface can be filled with lines;
- lines are easier to remove and observe in the bed, and they all have also the same length;
- line spacing is constant and requires a less accurate positioning of the two axes at the machine setup.

Feature	*Ring* ○	*Line* ➔	*Preferred*
Machine setup	easier assembly	higher cost	○
Alignment of the two axes	accurate positioning required	not required	➔
Line spacing	accuracy can be increased with axis displacement	easier control, no software correction required	
Fast axis speed	speed range extended	better control	
Powder bed and specimen	worst powder exploitation	easier line extraction and observation	➔

Table 1: Comparison between the ring and the line machine configurations.

2.2 The powderbed generation

Since it was desired to quickly and concurrently test several different powder types, a small manual spreading station was developed. To generate multiple layers to form a part, it was not feasible to build a traditional piston where the powder bed was lowered as the part was built up. Instead a system has been designed to allow the level of spreading to move up as to create multiple layers. Several pairs of high precision gauge pins are used to set the spreading level; each set is 0.025 mm larger in diameter than the last; successive layers can be spread by using the larger gauge pins couple. They are placed along the two sides of the powder bed support (Figure 1). After the powder is poured onto the support, a cylindrical stainless steel bar is counter-rotated across the top of the gauge pins to create a smooth layer of powder. Counter rotation is necessary in order to continuously offer a clean bar surface, because small powders tend to stick and risk to spoil the powder bed surface. Blades can also be used, but they generally deliver worst quality beds for the same reason. To increase the powder density, as required by several applications, the powder bed support can be removed from the machine and manually tapped or placed on a vibrating device. After the layer spreading operations, a centering system allows the correct repositioning of the support on the machine.

3 THE PRINTING TECHNOLOGY

The main principle of the inkjet printing technologies with all possible variations can be found in [15]. Today, commercial inkjet printers rely mainly on the Drop on Demand technology, which produces single droplets when needed. Inkjet printheads either work by the thermal (or bubble jet) or piezo principle.

The drop formation is determined by the fast oscillation of the liquid surface at the nozzle meniscus produced by one of the above two phenomena. The shaping of drops can only be described accurately if pressure and mass forces as well as viscosity and surface forces are considered. Other problems to be dealt with in the nozzle design phase include refilling the channel and reverberations. The inkjet principle is rather simple, but this

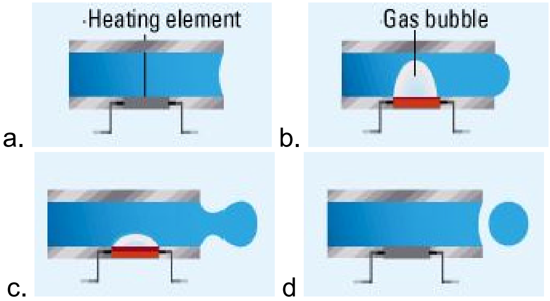


Figure 3: Thermal (or bubble jet) printhead.

happens at very high frequency, so the design details make the difference, and these are highly proprietary [16].

Thermal printhead

In the thermal inkjet printhead, the actuator is a tiny heating plate on each capillary tube (Figure 3.a). It creates a steam bubble in the liquid heating it rapidly to its boiling point (Figure 3.b). This bubble forces a liquid droplet out of the end of the nozzle (Figure 3.c) in a direction either parallel (Canon) or perpendicular (HP) to the heating element. When the heat is turned off, the ink cools, and the tube is ready to be activated again (Figure 3.d). The resistor element takes a fairly severe beating each time a bubble collapses in the fluid chamber. Over time this cause pitting on the resistor and eventually lead to failure. It is also possible that the fluid being jet will leave a residue in the chamber as a result of the boiling. This limits the binder types and may also degrade performance over time.

Piezo printhead

A piezoelectric printhead (Epson, Siemens) uses a special type of crystal that responds to electrical current (Figure 4.a). When a charge is applied, such a crystal deforms slightly. In a printhead, the crystal movement forces a tiny liquid droplet through a capillary tube (Figure 4.b). When the current is removed, the crystal snaps back to its original position (Figure 4.c).

Figure 4: Piezoelectric printhead.

FEATURE	***CJ***	***DoD***	***COMMENT***
DROP SPEED	8 – 15 m/s		depending on the nozzle design
DROP SIZE	30 – 100 µm		smaller drops yield a higher process resolution
FREQUENCY RANGE	30 – 180 kHz	< 3 kHz	higher frequency means higher productivity
CONTROLLABLE FREQUENCY	at the design phase	yes	allows changing the printhead speed in vector printing
STREAM DEFLECTION	yes, 2 mm space can be covered	not possible	obtained by charging droplets electrostatically
PRINTH.-POWDER BED DISTANCE	up to 20 – 30 mm	up to 10 mm	the powder ejected may end up on the orifice
BINDER COMPATIBILITY	steady flow	stepwise pumping	colloids have lower tendency to dry in CJ (cleaner nozzles)
DROP FORMATION PRINCIPLE	piezo	piezo, thermal	DoD is widespread in commercial systems

Table 2: Typical Continuous Jet (CJ) and Drop on Demand (DoD) values and features in Three Dimensional Printing (3DP). With the same printhead, the actual Drop Size, Speed and Frequency depend on the binder used.

In Continuous Jet, liquid jets are generated by forcing the liquid at high pressure through a nozzle with a circular opening. After exiting from the nozzle, the jet usually travels through the air in the form of a continuous flow cylinder, which is laminar or turbulent depending on the speed and on the nozzle length/diameter ratio. The jet disintegrates spontaneously into a train of droplets whose regular size depends on the vibrational waves within the fluid, produced by the piezo movement. Continuous Jet printheads are designed to emit a steady stream of tiny drops. The drops are charged with static electricity and are then "steered" either onto the printing medium (power bed or paper) or into a recycling reservoir (catcher) by charged fields.

3.1 Drop on Demand (DoD) versus Continuous Jet (CJ)

A comparison between the main features of the two technologies is given in Table 2 and Table 3.
DoD can overcome several inherent limitations of CJ printing, which has been traditionally used since the beginning of the 3DP technology [9]. The drop speed, which affects the binder penetration into the powder bed, is about the same. In DoD, the drop frequency, which directly affects productivity, is about two orders of magnitude lower. Thermal nozzles are comparatively inexpensive to produce and because of their simplicity they can be mounted close to each other to form a multinozzle array, whereby the speed (the flow rates and the productivity) becomes comparable to that of CJ systems. With DoD, a better control over the drop size is possible by changing the voltage. Smaller nozzles also determine a smaller drop size and a better nominal process resolution. Some advantages

Feature	***Thermal***	***Piezo***
life	shorter	longer
manufacturing difficulty and cost	lower	higher
multinozzle arrays	possible, smaller space required	possible

Table 3: Comparison between the piezo and the thermal principle in inkjet printing.

of DoD are related to vector printing, because the execution of curved trajectories and the associated speed changes require controlling the drop frequency in a wide range, which is only possible with DoD. Vector printing gives higher flexibility and better surface finish with a suitable path design than raster printing. In CJ it is possible to give to the stream a deflection, so that every nozzle is able to cover a space of 2 mm of the powder bed. This defection procedure is allowed by the combination of two different electric fields located in the printhead. A proportional deflection is used to improve the surface finish. More on the comparison between raster and vector printing can also be found in [17].

4 THE PRINTHEAD CHARACTERIZATION

In addition to the CJ printhead developed for the alpha machine, a new DoD printhead is under development at MIT [17]. It is based on the piezo technology and it can operate between single drop and 3 kHz. Commercial bubble jet printheads can operate in a similar range. Before the new printhead is delivered, a commercial printhead is mounted on the machine. Previous work [12] was already carried out at the 3DP Lab using a thermal DoD printhead, from HP, model 51626A [18].

52 nozzles are available on two parallel columns, but only one control circuit has been developed at this stage and only one nozzle at a time is used. Specific tests have shown that up to three nozzles can be simultaneously driven (with the same parameters) using the available electronic circuit. The selection of two nozzles on the same row or on the same column allows different printing configurations, like (i) printing twice the same line or (ii) printing two parallel lines. Reprinting a line has potential quality benefits still under investigation. By changing the angular position of the printhead about the vertical axis, different distances between the two parallel lines can be set.

Several binders with similar physical properties (viscosity) [15] can be printed and have been tested (more data are available in Table 2):

- CSEG: colloidal silica in ethylene glycol has been printed diluted in a 20% and 50% (vol.) water solution;
- PAA: poly acrylic acid has been diluted 10% (vol.) in water.
- INK: it has a similar density as CSEG and a lower viscosity; it may contain between 20 and 40% of ethylene glycol in water solution [18];

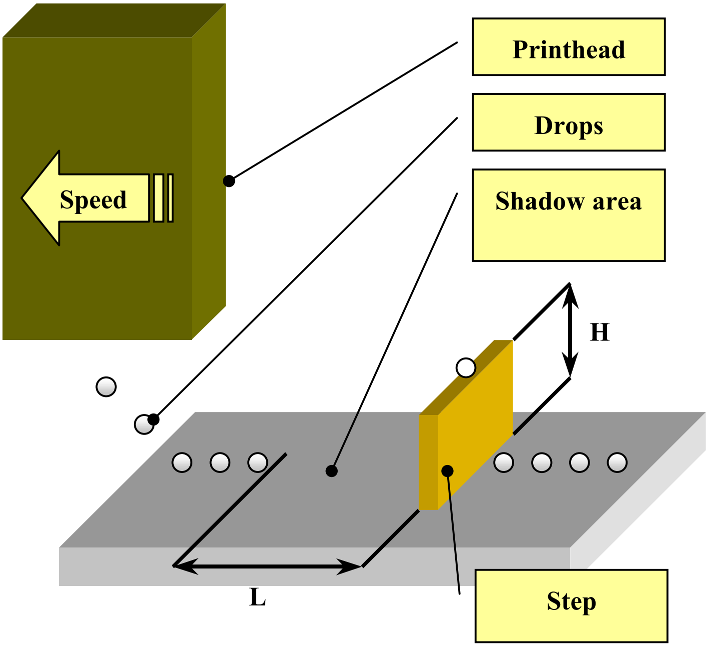


Figure 5: Scheme of the drop speed measuring station, based on the step method.

- and, of course, pure water.

4.1 The drop traveling speed

The available measuring station

A droplet velocity measuring station is available at the 3DP Lab [14]. It allows measuring both the drop speed and size. The principle to determine the jet velocity is the following. The printhead is mounted to a vertical micrometer stage and the droplet stream is lit from behind with a strobe light connected to a variable time delay. The stream is observed on a TV screen with a CCD camera. First the delay is set to zero and the micrometer is used to measure a known distance on the TV screen. As the time delay is increased or reduced, the droplet moves down or up in the screen. The time delay to have the droplet moved between the top and the bottom position and the distance measured between the two positions allows calculating the drop speed. By calibrating the CCD camera, e.g. by observing a ruler at the same distance from the lens, droplets can also be measured.

The developed method

Special device, whose principle is displayed in Figure 5, has been developed to measure the speed drops are printed. Sufficient relative speed between the printhead and the printing medium (a disk of paper or a transparent film) has been obtained using a high

	High Voltage 17 Volt	Low Voltage 14 Volt
High Frequency CSEG 1 kHz	**15.5**	**11.8**
Low Frequency CSEG 230 Hz	**15.3**	**11.4**
High Frequency INK 1 kHz *16 Volt	**12.5***	**-**

Table 4: The effects on the traveling speed of drops caused by different parameters. High and low drop frequencies are considered. By voltage the amplitude of the square wave driving the printhead is meant. Two different liquids are compared: the CSEG binder used with ceramic powders (a 50% vol. water solution of Colloidal Silica in Ethylene Glycol) and the standard cartridge ink.

spindle speed motor (up to 6000 rpm). The actual speed is measured using a strobe light. Considering the low available spindle power, it was necessary to use a light rotating disk and to fair the step to reduce the drag coefficient. The printing test is stopped when a continuous printed circle is observed, using ink. When testing the other binders, which are transparent, a fixed number of drops, determined by previously printing ink, is selected. The distance L in Figure 5 is measured at the optical microscope. Some results of tests are reported in Table 4. Considering the accuracy of this method (about 10%), it is more useful for comparative tests. A weak dependence of the drop speed on the nozzle frequency is observed.

4.2 The drop frequency and size

The drop frequency is controlled from the main program. A correlation between the drop frequency and the nozzle resistance, due to heating, was also found. This observation has a practical interest: it yields a fast and economical verification using a tester instead of an oscilloscope. From the frequency and the flow rate (0.18 picoliters per second @ 1 kHz), determined by weighing, the drop size was also estimated. Drops of CSEG are larger than ink drops. The drop size also depends on the binder type and on the voltage applied to the nozzle. Simple cinematic relations allow an indirect measurement of the drop speed from the flow rate [9]. The results of tests are summarized in Table 5.

5 THE MACHINE CONTROL

A special program, whose interface is shown in Figure 6, to control the printhead and the main axes in different configurations, has been developed. It makes use of a standard

PARAMETER	RANGE
PRINTHEAD SPEED	0.1 – 8 MM/S
DROP FREQUENCY	0.01 – 1.4 KHZ
DROP SPACING	6 – 30 μM
DROP DIAMETER	50 – 60 μM
DROP SPEED (±10%)	10 – 15 M/S
PRINTHEAD-POWDER BED DISTANCE	1 – 6 MM

Table 5: The process parameter range.

bidirectional (parallel) PC port to send commands to the driving electronic circuits and to read the signals from microswitches.

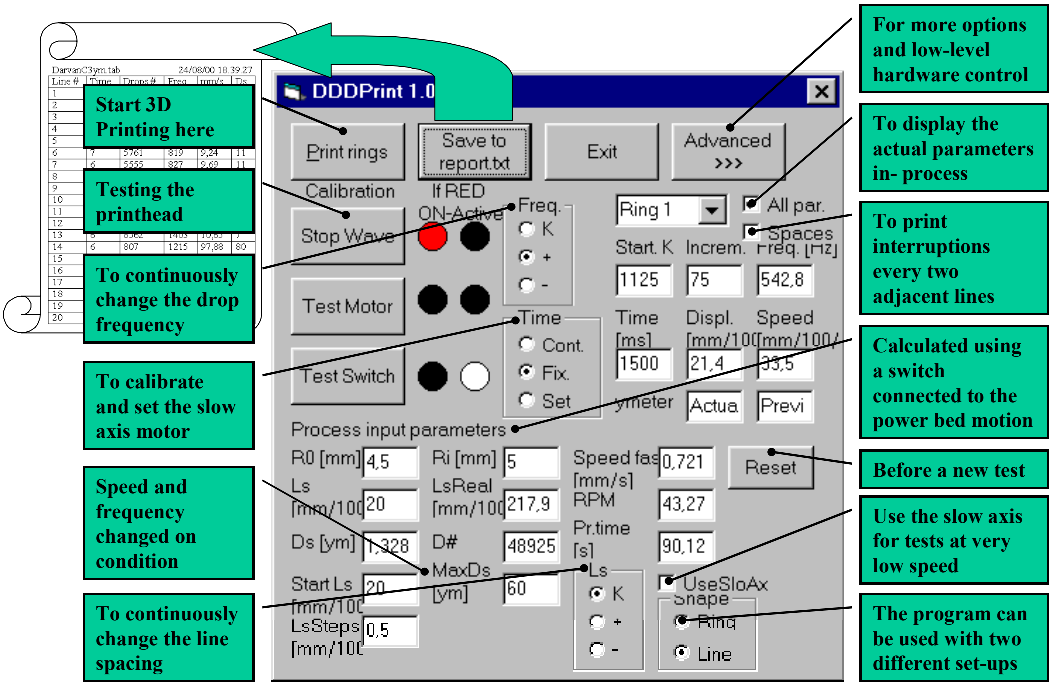
5.1 The electronic circuitry

The waveform to drive the individual jets on the HP printhead is a square wave of amplitude 15 – 20 V and duration of 3 to 6 μs. A possible circuit is described in [12]. Another circuit has been developed to drive the DC motor of the slow axis to determine the scan spacing. The position control is performed in open loop at selectable constant speed by switching it on for a fixed time. A calibration routine has been implemented to automatically determine the *on* time, based on the selected speed of the slow axis motor, and to estimate its positional accuracy. The fast axis (or traverse) speed is also manually selected from the rotary table or the linear guide console. When moving, the powder bed support activates a microswitch. The actual speed is determined by the control program by calculating the time for a complete revolution or for a single pass. The microswitch also alternatively turns printing on and off. When printing is off, the slow axis is activated. During printing, the PC acts as a waveform generator at the selected frequency. To overcome the real-time problems of the multitasking operating system, special routines check the actual frequency using the system clock.

5.2 The control software

The program has a single interface containing all the controllable parameters (Figure 6). The main benefit of the developed software is to automatically change, during a single printing test, the main process parameters within a user-predefined range, which is not possible with the standard waveform generator. This feature is very important for the following reasons:

1. it reduces the number of tests and consequently the time necessary for a group of experiments;
2. it allows making comparative tests in the same conditions by having many samples on the same power bed. It should be emphasized that each powder bed is unique, so it is



Line #	Time	Drops #	Freq	mm/s	Ds
6	7	5761	819	9,24	11
7	6	5555	827	9,69	11
14	6	807	1215	97,88	80

Ring 1
Freq. ● +
Time ● Fix.
Start. K 1125
Increm. 75
Freq. [Hz] 542,8
Time [ms] 1500
Displ. [mm/100] 21,4
Speed [mm/100/ 33,5
☑ All par.
☑ Spaces
R0 [mm] 4,5
Ri [mm] 5
Speed fas [mm/s] 0,721
Ls [mm/100] 20
LsReal [mm/100] 217,9
RPM 43,27
Ds [ym] 1,328
D# 48925
Pr.time [s] 90,12
Start Ls [mm/100] 20
MaxDs [ym] 60
LsSteps [mm/100] 0,5
Ls ● K
☑ UseSloAx
Shape ○ Ring ● Line

Start 3D Printing here

Testing the printhead

To continuously change the drop frequency

To calibrate and set the slow axis motor

Speed and frequency changed on condition

To continuously change the line spacing

For more options and low-level hardware control

To display the actual parameters in- process

To print interruptions every two adjacent lines

Calculated using a switch connected to the power bed motion

Before a new test

Use the slow axis for tests at very low speed

The program can be used with two different set-ups

Figure 6: The main interface of the control software.

very useful to change the see the effect of the “other” process parameters on the same powder bed;

3. direct observations are easier when all samples are in a single place; they can be compared to each other, they are easier to store, and less powder is wasted with an intense exploitation of the available space.

In addition, all the actual values are saved in a detailed report. Regarding the printhead position control, the software is able to take into account the initial printhead position to estimate the scan spacing and the other process parameters; e.g., in the ring configuration, the software calculates the actual ring radius, when moving to adjacent passes, and consequently all the printing parameters.

6 EXAMPLE APPLICATIONS AND WORKING RANGE

The described machine has been exploited within several projects [19] [20]. Regarding the quality optimization of scanlines (the basic 3DP element) the determined parameters range has been reported in Table 5. Several ceramic and metal powder mixtures in the range 10 to 30 µm have been printed respectively using the CSEG and PAA binders.

Two examples of specimens are displayed in Figure 7 and Figure 8. The scanlines shown have been extracted cleaning away the submerging loose powder with an air jet. No

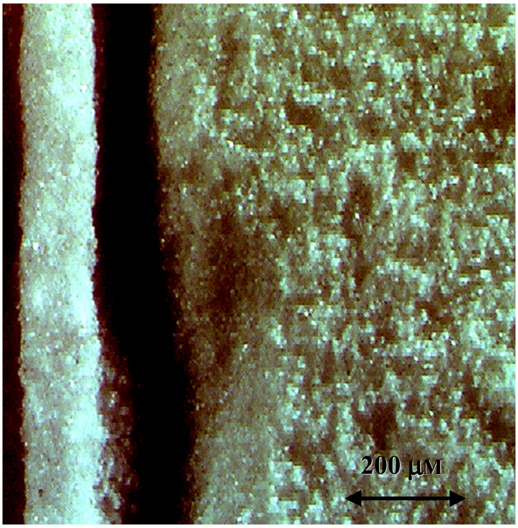


Figure 7: Top view of a powder bed and a line (left) made with alumina powder. Powder composition: 20 μm spherical with 12.5% (wt.) of < 5 μm platelet. Packing density = 40%. Printing parameters: Drop Spacing = 20 μm; Drop Frequency = 1.28 kHz; Printhead Speed = 20 mm/s.

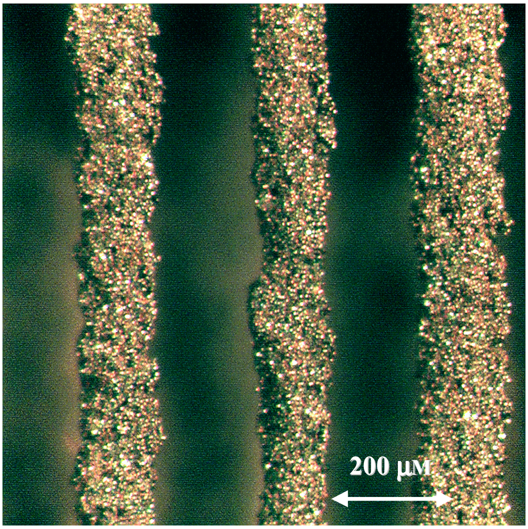


Figure 8: Arcs of rings made with stainless steel powder. Ring radius = 7.5 mm; Powder: material = ss 17-4; average size = 15 μm, packing density = 55%. Printing parameters: Drop Frequency = 640 Hz, Drop Spacing = 30 μm; Printhead Speed: 20 mm/s; Table Spin: 25 rpm.

special effect of the drop frequency has been noticed in the tested range. The drop spacing is upper limited to 30 μm. Lower drop spacings determine larger but more regular lines. The printhead traverse speed can be determined accordingly from the selected drop spacing and frequency with a simple cinematic relation [20].

7 SUMMARY

A simple 3DP machine was constructed. After consideration of several ideas, it was decided that a machine that could print small, ring geometries offered the highest return for the effort. The machine has been designed without paying attention to productivity, focusing on modularity and flexibility and on the operative range and it has evolved in two configurations, the ring and the line machine, whose main features have been discussed.

The printhead cartridge and the powder bed support can be easily removed and accurately repositioned to quickly change the binder or the powder type and make direct observations on the printed part, typically individual scanlines. Hardware design includes two axes working space and a PC-based control system. Though it is not completely automatic, the machine operates with the real working parameters and accuracy. In addition, the control software has a report generation option, to help the researcher and

the technician for the setup and the optimization of new material systems. The main features of the developed program and circuitry have also been described.
The powder bed support and the printhead own respectively the fast and the slow axis. To improve the slow axis accuracy, some feedback on the actual position will be required. Three-dimensional parts, limited to approximately 30×50 mm and about 10 layers, depending on the operator's ability, can be built.
Methods for the printhead characterization have been described, including new fast techniques to estimate the printing speed and the frequency. They are less accurate than current methods, but they require no special device, lower setup time and they can also be used on the machine itself. The machine has been successfully exploited in several research projects using different binders (water solutions of colloidal silica in ethylene glycol and poly acrilic acid) and powders (ceramic and metal).

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