

Novel Piezo Inkjet Technology and Printhead Capable of Jetting Extreme Viscosity Fluids for Additive Manufacturing

Ben Hartkopp, Marcel Strobel; Quantica GmbH; Berlin, Germany; Ramon Borrell; borrell.uk Technology Management; Cambridge, UK

Abstract

This paper unveils for the first time a new technology using a novel operation mode for piezo inkjet printheads invented to close the limitations of current commercial printheads in meeting the requirements for advanced additive manufacturing. Subsequently, a printhead using the new technology has been developed along with the necessary sub-systems for integration in a printer. The new inkjet technology brings a combination of advantages, the most relevant being the capability to jet extremely high viscosity fluids, combined with very high productivity per nozzle, very wide drop size control, and the capability to jet fluids with high particle load and large particle sizes. A family of 3D printers for different applications such as realistic permanent dental fixtures is being developed using the new printhead. Multiple applications in additive manufacturing and microfluidics will benefit from the unique qualities of the new technology.

Form ever follows function

Manufacturing requires the use of materials with properties which allow meeting the requirements of the parts and systems in production. However, the narrow range of physical properties existing inkjet printheads demand on fluids to be jettable often excludes the use of the ideal materials. The consequence is either the deployment of less flexible methods of manufacturing or the use of alternative, less desirable materials leading to suboptimal part performance.

The desire to break that limitation, and to build a 3D printer for additive manufacturing of parts meeting demanding functional requirements, led the principal author and his partner to a complete re-thinking from the ground up of the principle of inkjet operation, and subsequently to the technology needed to implement it, to the architecture of the printhead, and to its detailed design decisions. They later founded Quantica GmbH in order to complete the work with additional funding and commercially exploit the results.



Figure 1. Version 1.5 printhead: the UHV Print Engine 15.1

UHV Print Engine 15.1 target specifications

Nozzle count	84
Rows of nozzles	1
Native nozzle pitch	1.1mm
Dimensions (LxDxH)	130mm x 18mm x 25mm
Nozzle exit diameter	60um
Drop volume	25pl – 600pl
Fluid viscosity range	1mPa s – 250mPa s
Operation temperature setting range	15C – 110C
Jetting Frequency	7.7kHz
Minimum Life	All spec met after 3 10 ¹⁰ drops per nozzle
Guaranty	1 year with certified fluids
Fluid flow type	Full back of nozzle recirculation
10. Fluid surface tension	20N/m – 75N/m
11. Nozzle plate	Ni alloy

Requirements

The most important requirement gap is the capability to jet the highly viscous fluids needed for some applications. It is common for many functional materials to contain high concentrations of high molecular weight polymers or high load of solids. Both of those factors have a severe impact on viscosity to the point of making the fluids impossible to jet by conventional inkjet printheads.

Other key requirements relevant to additive manufacturing are: productivity, stability, flexibility, durability, and, crucially, ability to built practical multi-material jetting systems.

Actually the new printheads can straight jet the same high property materials used in 3D printing technologies such as stereolithography and digital light processing (SLA, DLP). A crucial difference is SLA and DLP are intrinsically single material technologies, while inkjet allows use of multiple materials, thus elevating the characteristics of the printed objects to photorealistic or exhibiting complex functional behavior. Those are achieved by using fluids of different colors or by combining materials with very specific physical properties.

The other aforementioned requirements translate to combinations of printhead specifications on nozzle count, jetting frequency, drop size, temperature and back pressure control, voltage control, compactness, cost and material set. Each of those, and in combination, resulted in specific inventions, architecture, and design solutions.

Principle of operation: jetting

Dijksman [1] wonderfully describes in analytical manner the dominant vibration modes inside a piezo printhead, noting specifically anti phase ink motion (high frequency Helmholtz mode) and low frequency in-phase ink motion mode (Slosh mode). He further describes higher order modes as generated by meniscus ink surface vibration, a mode of operation very seldom used. Interactions between the modes of operation cause multiple transient effects and inconsistencies during printing, while the nature of the modes themselves define limits to the physical properties of the fluids that can be successfully jetted. It was precisely the need to escape those limitations that prompted the development of a different operation principle. The new principle of operation is neither of them; it works by pushing a volume of fluid in the vicinity of the nozzle hard in the direction of the nozzle axis, being the principle volumetric displacement, and with little reliance on the acoustics of the chamber. In that regard, and contrary to the normal operation of acoustic inkjet printheads, the head operates far from Helmholtz resonance. Acoustic effects will indeed be present and interact with the volumetric approach, playing a role in frequency response. This is currently a subject of deeper study as future designs intended for more conventional fluids may operate within overlapping acoustic and volumetric effects. The virtual chamber is actually made of the space between the nozzle plate and a roof piston with the perimeter open to a local manifold area. The openness of the design provides fast refill even with high viscosity fluids.

The apparent brute force approach derives in a number of very interesting properties.

First, given sufficient volumetric displacement is achieved (by means of a large deflection of the “roof” and substantial pressure) ejection will happen even for extremely high viscous materials. The printhead has been successfully characterized with materials showing up to 230mPa s at jetting temperature of 86C (the material itself is 2,400mPa s at room temperature). Beyond that, incidental experimental data shows jetting with viscosities above 350mPa s. While full characterization is pending, current printhead specification is 250mPa s maximum.

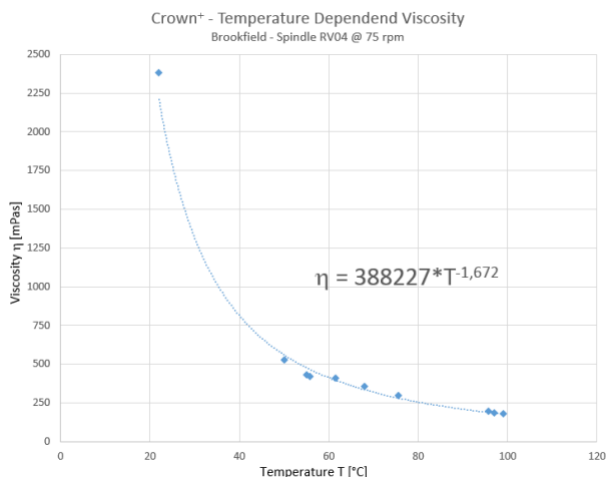


Figure 2. Viscosity characteristics of one target dental material

Second, the large volumetric displacement enables very large drops, that in combination with high frequencies deliver extreme productivity by nozzle. It is expected that future models in the roadmap will be able to pump over 11 liters of fluid per hour.

Third, by adjusting the displacement of the virtual chamber roof, substantial control can be exercised on the drop size. This is done by modulating the voltage applied to the piezo-electric actuator. The designers have verified a nozzle with 40um of aperture can jet drops between 25pl and 600pl. It is worth noting that while there is a practical upper limit on fluid viscosity, it has not been observed a lower limit leading to defective function, with fluids down to 1mPa s successfully jetted. Of course operation must be tuned for the different viscosities. That includes adjusting the height of the chamber when resting, along with the maximum frequency, temperature, back pressure and, of course, waveform.

Fourth, the open nature of the chamber at the periphery of the piston enables easy fluid refill to the virtual chamber even with extremely viscous fluids and very high material lay down. It also allows very effective high flow recirculation at the nozzle, operating successfully even with fluids containing up to 40% 4um inorganic particles by volume. To this purpose internal geometry of other elements in the fluid path have been designed to facilitate flow, avoid settling and facilitate de-agglomeration. For the same reason jetting is highly insensitive to the presence of air bubbles and the self-priming effect associated with high flow recirculation is fully effective. Figure 3 schematically shows the main operational elements: deflection plate 101, piezo-electric layer laminated on the deflection plate 102, piston 401, nozzle plate 800, nozzle 801. The virtual chamber is the space between the piston 401 and the nozzle 801.

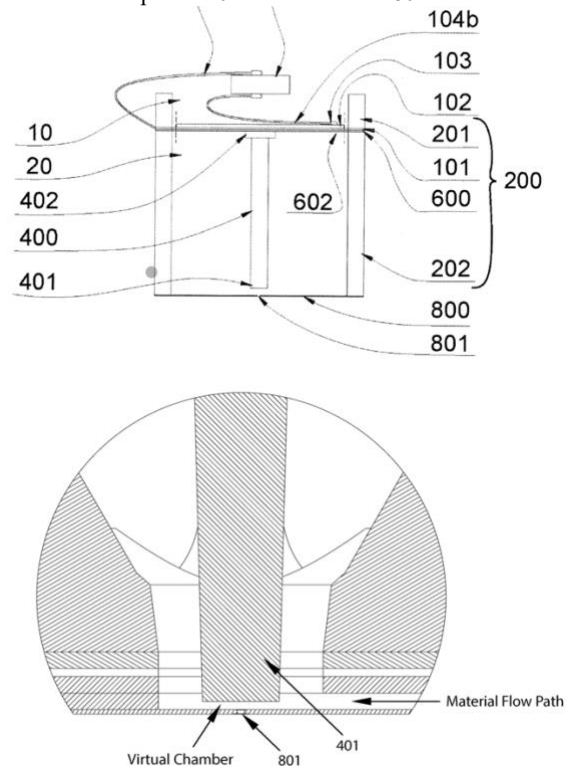


Figure 3. Schematic cross section [2] and virtual chamber detail

Principle of operation: actuation

The very unique value proposition of the Quantica printhead demands some trade-offs and the need for very specific architecture and design solutions elsewhere. The two biggest impacts relate to the area devoted to each individual nozzle.

First, the piston must cover sufficient area in all directions around the nozzle in order to be effective at pushing. That defines a relatively large separation between nozzles in a row. The Version 1 commercial model will have a single row of nozzles spaced 2.2mm. The pitch is halved in Version 1.5 model.

Second, a large displacement is needed for forceful volumetric displacement at higher frequencies. This is achieved by uni-morph bending action of the multilayer actuator primarily taking advantage of d_{31} inverse piezoelectric effect. However, different than usual long chamber roof bending mode piezoelectric printheads, the effect is achieved on the long direction, not the transverse (chamber width) direction. Since the deflection of a supported beam under uniformly distributed tension is roughly proportional to the fourth power of its active length, such arrangement substantially amplifies the displacement, even if at the expense of using a large foot print per nozzle, and provided enough voltage and current are supplied to the piezo element for such forceful actuation. It is important to note that in order to avoid cross talk the actuation plate is physically divided in independent actuation elements by slits between consecutive actuators as shown in figure 4.

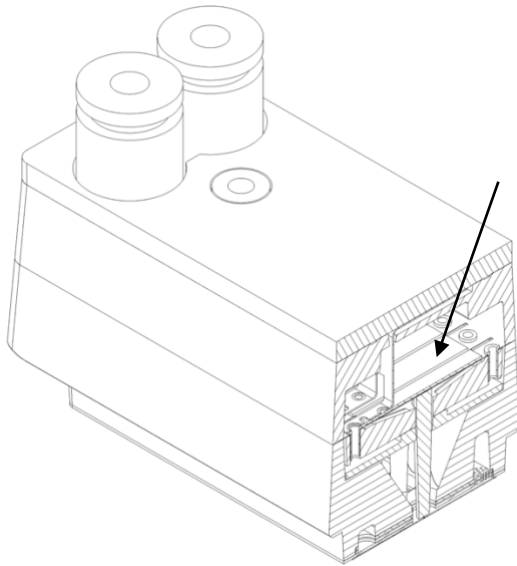


Figure 4. Printhead V1 section. Arrow points to individual actuation element

Other architecture and design considerations

In addition to the novel principles of operation and actuator concept described above, meeting the requirements in practice demanded more architecture and design actions.

The most relevant is fluid heating to bring it to a controlled jettable viscosity. This is achieved by providing a heating element laminated on the nozzle plate that progressively increases the temperature under close loop control provided by embedded thermal sensors. Temperature gradients combined with fluidic path design features facilitate fluid degassing, which in turn requires some elements for air separation and

management. Those elements include geometry and vacuum control via sensors. Finally, the internal fluid manifold has a tall design to create sufficient distance between the high temperature zone and the piezo electric elements to avoid subjecting them to excessive temperature which might reduce its long term stability and life.

Each nozzle can be driven independently and the voltage applied to each actuator adjusted to fine tune the amount of material deposited by each individual drop. To that extend an external close loop is provided by an optical system that measures and analyses drops in flight and ensures completely reliable operation.

Chemically robust materials have been selected and options are under consideration for designs without adhesives in contact with the fluid to be jetted.

The general design and architecture of the current printhead concept is highly scalable, with the possibility in principle to manufacture printheads of any length or height. Current high nozzle pitch design is manufactured mostly by conventional moulding and micro machining parts, without the need for costly MEMS processes. In practice, designs and manufacturing of optimized printheads for different applications and printers is possible and affordable. Quantica's printhead roadmap depicts several models of V2 multi-row printheads up to 252 and 504 nozzles and higher nozzle density in the near future, with or without multi-material capability. Multi-material capability is a critical requirements in some targeted advanced additive manufacturing applications and it can be provided either via multi-material capable printheads with dedicated rows of nozzles to each material, or by adding printheads for combined material count and productivity. Compactness of the printhead in order to enable practical printers has been a major driver of architecture and design.

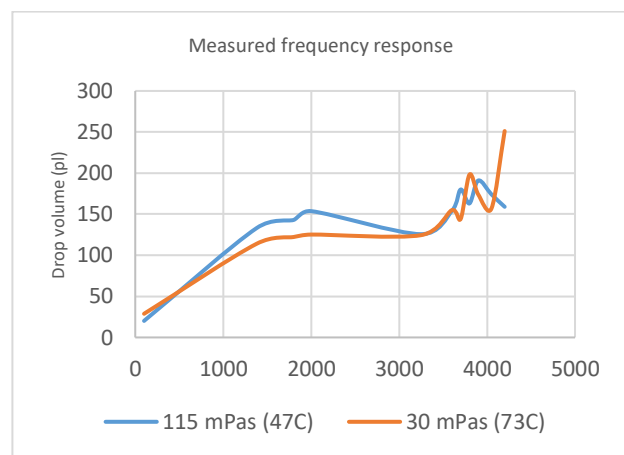


Figure 5. Frequency response measured on drop watcher at two viscosities (voltage adjusted for normalized drop volume)

Full system implementation

Since Quantica's mission is to provide solutions enabling new and demanding additive manufacturing applications alongside with the printheads, all necessary ancillary sub-systems needed for use of the jetting technology have been closely developed for perfect integration, and later combined with transport and motion systems adequate for the target applications.

The developed sub-systems and components include driver electronics, fluid delivery system, closed loop controlled vacuum, temperature and nozzle health, maintenance and multi-axis transports.

The set is completed by a water soluble support material. Given the complexity of developing large number of specialty high performance materials, this task is reserved for users and development partners, either fluid formulators/manufacturers or integrators/OEMs.

The full capabilities of the technology are now fully demonstrable via the first commercial product, the T1 Pro intended for material and application development in R&D environments and for generic low volume production.

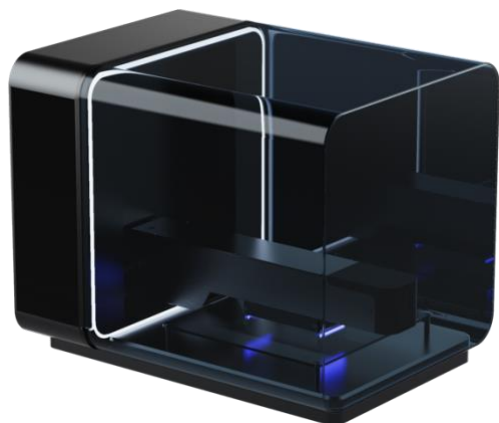


Figure 6. Quantica's Desktop modeling multi-material 3D printer

Applications

Alongside the T1 Pro, a Desktop printer with multi-material capability has been designed for generic modeling, prototyping, and specialty use. The architecture of Desktop is the platform for development of more specific applications in partnership with specialists.

The first such application is dental. Quantica has signed a Joint Development Agreement with a dental company. The program will deliver a full 3D printing system complete with materials, software and user friendly interfaces for productive manufacturing of realistic multi material permanent dental applications.

The above is a neat example of the business model that is seen as most adequate for enabling novel and demanding additive manufacturing applications combining technology, process knowledge, application insight and market reach. Therefore, that is the path Quantica plans pursuing further.

At this moment Quantica is seeking specific partner funded applications by re-using or re-shaping the technology already developed and by joining strengths with companies with market knowledge and access. Applications seen with good fit under the technology and business model include micro-fluidics, bio-

medical, optics, printed electronics, flat panel displays, adhesives and coatings.

Future work

Alongside the development of the dental printer and other specific applications in partnership with application specialists, Quantica is considering expanding into further development of the printhead technology with multiple printhead models and a range of capabilities for other OEMs to integrate into their own printers and applications. That expansion of activities requires additional funding which is now open to strategic investors.

It is worth noting that the principle of operation stays valid with scaled down dimensions of all the elements, leading to printheads with much higher nozzle count when trading off certain features. In some cases acoustic actuation may become the predominant vibration mode. Such future developments may provide extremely competitive printheads for traditional industrial printing applications such as textiles, ceramics, construction materials, or printed electronics to mention just a few. However resources are currently focused on enabling the most demanding additive manufacturing applications that were not possible yet with existing commercial printheads.

References

- [1] J. Frits Dijksmann, Design of Piezo Inkjet Printheads, from Acoustics to Applications (Wiley-VCH, 2019)
- [2] L. Färber, B. Hartkopp; Material Ejection System, Print head, 3D Printer, and Method for Material Ejection; EPO Bulletin 2021/21, 2021

Authors' Biographies

Ben Hartkopp has a background as an independent researcher in the field of physics and has been co-developing the UHV Print Engine since 2016. He currently holds the position of Chief Product Officer at Quantica in Berlin, Germany and is further responsible for IP protection as well as research and development of print heads and liquid photopolymers. He filed the core patent as co-inventor for the Quantica Material Ejection System in 2019.

Marcel Strobel has been responsible for quality and product management in manufacturing and trading companies for more than 25 years. Most recently, he was CEO of a manufacturing company in the USA and a management consultant. He conducted feasibility studies for the use of additive manufacturing for electronics manufacturers and thus recognized the limitations of the available technologies and the need for the print head technology developed by Quantica, leading him to join the company.

Ramon Borrell received a MSc in Industrial Engineering (1987) and a MSc on Automotive Business (1993) from Universitat Politècnica de Catalunya in Barcelona. He held a number of technical and management positions developing large format inkjet printers at HP. In 2007 he was appointed R&D Director of Xaar plc in Cambridge, England where he led the development of the printhead portfolio including the 5601 printhead featuring Thin Film Piezo MEMS for industrial printing. In 2020 he founded borrell.uk Technology Management aimed at helping companies globally with their technical, business and strategic developments. He is member of IS&T, served at its Board between 2006 and 2010, and was General Chair of NIP23.