Chemical Skin - Computer Numeric Controlled Craftsmanship (CNCC)

Abstract

Most 3D printing technologies excel in delivering geometric complexity, functionality and part precision. Yet, most are not designed to adequately articulate the surface of 3D printed elements with complex patterns, motifs, or colouration. The problem of synthesis between form and surface reaches back to the first forming of clay vessels and the added surface articulation as glazing after the firing of the clay form. In the long history of Chinese ceramics, craftsmen were able to balance an intricate knowledge of material reactions, form, and glazing during the firing process with curiosity and the will to innovate.

This paper presents the results of our investigation into transferring this ancient craft – it combines scientific, historical, cultural and technical considerations to analyze and reflect on the digital making process of a glaze for 3D printed objects. Through an experimental, yet inclusive interdisciplinary research method using a combination of material experiment as well as catalogue and design application, we created an index of suitable chemical reagents and developed robotic and software tools for their application on 3D printed surfaces. The resulting digital craftsmanship is able to extend the repertoire of today's digital working artists and designers.

Keywords

3D printing, CNC, CAD, Cyanotype, Digital Craftsmanship, Laser

Introduction

The impact and urgency of our research into the surface articulation of 3D printed objects is economically supported by the success of 3D printing as a game-changing invention with the value of the Additive Manufacturing Industry in 2015 estimated to be $5.165 billion [1]. Yet, the validity of the research is not primarily based on its economic potential. Its impact through the making of new objects will affect the transfer of images and cultural legacies from one medium and technique to another. This is not only an experimental, technological innovation, but also a form of culturally-led intervention of science into applied arts.

Our research into the transfer of craftsmanship methods to the chemical augmentation of 3D printed surfaces, using digitally controlled activation, results in the development of digital tools and chemical processes that enable new material based expressions for artists and designers. This paper will describe the robotic set-up, chemical recipes and procedures that enabled the precise activation of 3D printed surfaces coated with cyanotype – a photosensitive chemical that changes colour when exposed to UV radiation. We provide a cultural framework to compare this new method to the traditional craft of ceramics.

Design Processes: In ceramics, an object is handmade and all processes are applied analogue to the object - truly emphasizing the relationship between the craftsman's hand and the object [2]. In our project, we aim to extended the digital ontology of 3D printing to the articulation of its surface properties. This post-process operation extends the existing workflow of 3D printing. Our research enables artists and designers to transfer key characteristics of ceramic craftsmanship such as stroke width and type, gradient intensity of lines from analogue to digital – embodying 3D printed objects with artistic merit, variety and expressions.

Material Combinations: Material experiments have been at the core of the development of ceramic glazes. Different firing processes and glazing chemicals allowed new colours to emerge and resulted in a plethora of artistic expressions [3]. Seeing the tremendous impact material libraries have on art and design, [4] we have experimented with common 3D printed substrates (PLA, ABS, Nylon, TPU...) to confirm their compatibility with our processes.

Tools for Making: Compared to the ability to produce geometrically complex forms in 3D Printing, the inability to create surface articulation on the printed objects means simple details on toy figures still demands to be painted by hand. Automatic methods to print on complex surfaces with high definition is becoming increasing relevant and urgent. Recent development such as the precise hydrographic printing and thermoforming are producing a measureable impact in research and the industry [5]. This paper describes a novel method to overcome the reachability problem when printing on complex surfaces. By uniformly coating the object with photosensitive chemicals and selectively exposing the area with laser beams, no direct contact is necessary. Any surface that is visible can be subjected to lazing.

We have developed a comprehensive approach that encompasses artistic, technical and historical resources in order to deliver a culturally engaged research output. This approach can be explained over three key areas.

First, we highlight the cultural significance of ceramic painting as a role model to our research. The intricate interplay between technological advancement and artistic expression in this craft allows for research as an interdisciplinary undertaking that combines art, technology and science.

Second, we explain the technical foundation that leads to the use of cyanotype. This includes the analysis of the technical requirements and challenges to coat plastic surfaces with photosensitive chemicals. It also includes discussions on photo-reactive chemicals in alternative photography and technical research on their activation via computer controlled manipulation of laser beam.

Finally, we present a series of experiments conducted to validate our research approach. These experiments act as proof of concept of our printing method applied to a range of plastic materials with planar and 3D surfaces . A palette of artistic expression is presented such as line width, colour intensity, hatching patterns and gradients of colour patches. The experiments are contextualized within the cultural dimension of the research – the interdisciplinary transfer of traditional into digital craftsmanship techniques. This contextualization frames the project not only as an engineering problem or design research, instead it constitutes an innovative approach to articulating a synergy between craft and technology

Craft as a role model for innovation - Historic Dimension

The earliest surface expressions reach back to the New Stone Age. Artefacts from the excavations in Banpo, Miaodigo and Majiayao show a great variety of ceramic paintings depicting decorative motifs, human faces, fish and abstract intricate patterns. These motifs were applied to the surface either before the firing process or, in the case of burial artefacts, after the firing process. It was not until the Tang dynasty that craftsmen in Changsha, Hunan (China) developed new methods and kiln firing techniques that led to the establishment of chemical underglaze using pigments derived from oxides. This allowed for new forms of expression and for the re-articulation of elaborate landscape motifs and more complex patterns to emerge. At the same time as opening up a plethora of artistic expressions, the development of the underglaze and the associated glost firing (firing the ceramic twice and at higher temperature first) limited the spectrum of colours that could withstand the higher temperatures of the first firing process. During the Song dynasty, experimentation and curiosity at the Cizhou kilns (now called Handan in Hebei province) led to the development of a much wider range of colours. White glaze with black underglaze, and the development of red and green glaze, allowed for further artistic freedom. Finally, with the development of the classical white and blue glaze through the use of cobalt oxide, artistic expression was able to articulate up to five shades of colour and hence achieve depth in the depiction of landscapes and natural motifs [6].

Today, the centre of ceramic artistry in China is located in Jingdezhen, Jiangxi province. The city is known to nurture new artistic creativity and engender the development of new ceramic and glazing techniques. It is a reminder that this craft is still highly contemporary and that its culture is alive. The results generated by this community range from new material approaches, new glazes, new firing techniques and new artistic concepts. This exemplary experimentation is a model and subject for our research into surface articulations for 3D printed substrates and the changes it will bring for the creative industry.

Ceramic painting process

The concept behind many of the ceramic painting methods is the interplay between various types of glaze, various temperatures of firing and the correct sequence in between the firing stages and the respect of the behaviour of the glazes with regards to the geometry they are applied onto. Most types of glaze are based on mineral oxides as these are able to withstand higher temperatures in the firing, yet each glaze has its specific behaviour in terms of melting fluidity, temperature expansion and colouration changes to name a few. Broadly speaking, a glaze can be characterised as a chemical component that when applied to pottery, fuses with the substrate when placed in a kiln at high temperature.

In general, glazes can be categorized in two types of glaze with specific application. This simplification allows transferring the logic of glazes from the traditional craft to the application into today's additive manufacturing.

First, in order to create higher levels of articulation and colour differentiation, glazes need to be applied in layers. The first layers of glaze will be able to dry without necessary firing them. However, the layer thickness of these needs to be controlled, as well as the melt fluidity of each ingredient of the glazes. For example, if one uses two layers and both glazes have high melt fluidity, each layer will need to be thinner than normal as otherwise the surface will need to be roughed with contours to be able to tolerate more running. Alternatively a fluid first layer and a non-fluid second will result in the risk of the second layer's weight will create a downward pull and destroy the first layer.

There are numerous constellations of this and with increasing complex and multi-coloured glazes, this chemical behaviour extends. Yet, they all together are called 'underglaze'. One important observation at this point is the deviation from traditional pottery, which often uses dipping techniques to apply glaze and the currently more widespread use of commercially-prepared brush on glaze. As with low fire, these high temperature prepared glazes have added gum to make them paintable. Although this process is slow (compared to dipping) and it is more difficult to get even coverage, the opportunity to layer glazes of different colours and characters to produce reactive visual effects has become highly appealing to many potters. This process is also a point of translation in our digital craftsmanship, the concept of layered applied chemicals with different properties in the laser activated chemical coating.

The second process, after drying the various applied underglazes or in some cases as well firing the underglazes so called biscuit firing, is the glaze. This is used to allow shine and reflection to coat the surface and hardens the entire surface.

The last process is called over glaze. It involves relatively low temperature glaze chemistry. Usually, an "overglaze" is only used in small areas over the glazes and fired surface. The object will need to be fired again after this application.

In each of the glazing steps, the glaze can be applied via dipping or brushing. For us, the transfer of the logic in this craft lies in the layering of chemical coating and the multi stage processes of photographic exposure and fixing. The main technical challenge were in creating the chemical coating with a chemically compatible binder and the preparation of the surface where it would be applied. Within this challenge, consistency and repeatability is particularly important. Secondly, we need to create the optical setup for delivering a highly parallel laser beam for the photochemical activation of the coated surface of the 3D print. And, lastly, similar to the glaze, what would protect the layer and stop the curing process?

The problem with printing on geometrical complex surfaces

In the context of 3D printing, aesthetically appealing consumer products did not emerge until the invention of powder-bed inkjet printing which offered gradient multi-colour printing (Z Corporation, 3D Systems). Additionally, hot vapour smoothing process provided glossy finished 3D-printed parts [7]. Both methods however are only applicable to a very small range of objects due to the extreme chemical specificity of the hot vapour methods, being limited to ABS and PLA plastics and the structural weakness of the powder-bed process.

Alternatively, printing on non-planar surfaces is a long-standing challenge in product design and manufacturing. Existing techniques such as inkjet printing allow surface fluctuation only within a few centimetres [8]. Letterpress offset printing [9] and screen printing [10] can conform to developable surfaces due to the cylindrical shape of the offset transfer drum and the flexibility of the silkscreen, but are not applicable to non-developable surfaces where the silkscreen needs to be distorted when being wrapped. Recent research in hydrographic printing technologies [11], [12] and colouring 3D printed surfaces by thermoforming [13] provides a new way to predict transfer film distortion, and combined with robotics means of precisely administering the process, results in good registration.

Certainly, this strong rival method to our research provides a larger colour palette as it uses planar printing methods derived from well explored printing onto film. Another approach is using marking technology with lasers. A marking mechanism relies on vaporizing, staining, oxidizing or annealing the substrate only provides gradient control of the stain colour [14]. Laser removal of top coats provides only two coloured results [15].

Our approach

Our clearly defined goal is to harness the precision, repeatability, customizability of computer controlled machines. The hydrographic printing methods mentioned earlier [16] and [17] demonstrate a similar motivation in articulating the often monochromatic 3D printed objects via digital control. Yet, in difference to their research into the application of additional surfaces onto the 3D printed substrate, we apply and activate chemical coloration directly on the surface thus, in the analogy to the glaze firing, are firing the chemical directly onto the surface. The advantages of our research trajectory are a lower machining cost, lower maintenance, less invasive material tensions and no longer applying mechanical forces during the process of application of a surface to the 3D printed form.

The disadvantage is the lack of high fidelity colouration that hydrographic and thermoforming both incorporate through transfer of existing printing technologies. Additionally, our research provides a new application for the recently maturing 3D position and registration techniques (such as photogrammetry and laser scanning) that can precisely relate a physical object to its digital model.

Both physical models that originate from a digital file via 3D printing and models that are hand crafted can benefit from this workflow. This enables a downstream digital design process for surface patterns and articulations that can be digitally simulated, visualized and precisely fabricated. Thus, there were two main technical challenges. First, the chemical component of finding the right chemical mixture that can be activated using UV light and fixed after the process, and second, to develop the appropriate software and hardware tools to register the object and precisely activate the chemicals on complex surfaces.

The chemistry – Alternative Photographic Process

Our research focuses on photosensitive chemical processes that can be activated using UV laser light. While both infrared and ultraviolet lights are possible, UV lasers are widely available in the market and UV sensitive chemicals are in more economic viability and available abundance. Before the widespread use of silver nitrate gelatine photography, many chemists and photographers conducted research into alternative reagents suitable for photographic film and photographic paper - ‘alternative photographic process’[18]. We selected from these well-studied photochemical reactions and focused on those that can provide a change in colour of the reagents upon activation and is stable after fixation. One of these historical processes is the cyanotype [19], otherwise known as the blueprint. The cyanotype is capable of reproducing very fine lines with high fidelity as witnessed in the famous photographic botanical book - Photographs of British Algae: Cyanotype Impressions [20].

In our experiments, we successfully tested the technical aspects of applying UV light reactive cyanotype mixtures onto the surface of the most common and widely available 3D printed surfaces. A key challenge, emerging through this initial testing, was to overcome the difficulty in coating uneven 3D printed surfaces. Historically, photographic chemicals are coated onto either fibrous paper or material with high surface energy (easy for solutions to wet and adhere) such as glass [21].

However, 3D printed objects have very different surface textures depending on the processes used for printing. For example, a highly absorbent surface from gypsum powder prints reacts differently to a low surface energy plastic surface from SLA prints [22]. These surface properties initially prevent the photochemical coating to adhere or disturb the fixing process and a binding layer needed to be introduced between the substrate and the coating [23].

The tool - Selective Laser Activation

The main challenge in precisely activating a layer of photosensitive chemical – coated on non-planar, complex surface – is the difference in distance to the light source and thus the constantly shifting focus. This problem was solved by using a highly collimated laser beam for projection, which does not require focusing [24].

In our initial experiments, we have used a low energy 5-watt UV laser with 405 nm to activate the cyanotype. Extending the project, we propose the use of scanning laser projection. Scanning laser projection technology has been available for many years for entertainment purposes but finds limited use in high fidelity video projection due to its monochromic colour, difficulty in combining RGB lasers for wider gamut, and low refresh rates. However, it is ideal for our application because our chemical activation does not require high refresh rates nor colour projection. A pair of mirror galvanometers is commonly used to change the projection angle of the laser beam. With the recent advances in digital to analogue converters (DAC), such mirrors can be controlled with 12 bits of resolution - equivalent to a 16 megapixels / 4K screen [25].

A secondary task is to employ a laser beam of good characteristic that can create high resolution and sharp images within our budget. A low-cost diode-pump laser was modified and filtered to provide a clean wave front for such a purpose [26]. Lastly, regarding the hardware component, we are planning to deploy the laser with various degrees of freedom (DOF) - from 1DOF turntables to 6DOF. This will allow positioning a 3D printed object in such way, that all of its surfaces can be exposed by the laser projection. In our experiment we successfully used a turntable with a z-axis controlled laser attachment and achieved 3DOF. Variable colour intensity can also be created by controlling the amount light exposure, by modulating laser intensity or exposure time. Since the laser beam inherently creates a vector graphic projection such as lines and curves, solid colour infills and gradients infills need to be vectorized and approximated by algorithms.

Underglaze_New Photosensitive coating

The cyanotype process is a historically significant photographic process before the advent of silver nitrate printing process. It was also used extensively as a photocopying method by architects and engineers and earned its commonly known name as ‘blueprints’. The photographic reaction took place when ferrous cation and ferricyanide anion in the sensitizer is exposed to light. The soluble salt is reacted to give ferric ferrocyanide which is insoluble and possess an intense blue colour, commonly known as Prussian blue.

There are multiple methods to prepare the cyanotype sensitizer. Traditionally, it is done by mixing aqueous solution of ammonium iron (III) citrate and potassium ferricyanide [27]. Despite its popularity and long history, this preparation method suffers from unpredictability and inconsistency. One of the reasons is the difficulty to obtain a pure source of ammonium iron (III) citrate. In 2004, Mike Ware published an improved preparation method in his PhD thesis [28]. His sensitizer has a faster reaction, stronger blue color, wider dynamic range and most importantly high consistency. His method uses ammonium iron (III) oxalate instead of ammonium iron (III) citrate, and involves a super saturation purification step. Although it requires more laboratory equipment and preparation time, we have considered the higher predictability and consistency to be significantly advantageous. We have therefore followed Ware’s preparation method in this project.

In light of the intention to spray the cyanotype coating onto complex surfaces, we have not added the toxic ammonium dichromate that improves contrast

Binder

No binder was used in the traditional cyanotype process on paper substrate. The liquid sensitizer is first rolled onto the paper and air dried, before photographic exposure. The cellulose fibre absorbs and retains the dehydrated cyanotype salt. After exposure, the unreacted cyanotype can be washed from the paper while the insoluble Prussian blue is trapped in the paper fibre. The goal of our project is to apply the cyanotype process onto 3D printed surfaces, which are predominantly made of plastic material with no absorbance. A binder is necessary for the Prussian blue to stick to the surface after exposure and washing.

We have identified gelatine among other photographic binders suitable for creating an emulsion with the cyanotype sensitizer. Gelatine is a translucent and colourless material derived from collagen obtained from animal parts. When dissolved in a small amount of hot water, its viscosity changes increase dramatically as temperature decrease, eventually forming a gel at lower temperatures. When dried, the gelatine provides a chemically stable layer that can hold the soluble cyanotype and the insoluble Prussian Blue crystals. During the washing process, the gelatine layer swells and allows the unreacted soluble cyanotype to dissolve out, yet retaining the Prussian Blue, thereby achieving a photographic fix.

By controlling the gelatine concentration, we are able to obtain a gel that has low viscosity at warm temperature (70 – 80 degrees Celsius) and has high mechanical strength when cooled to room temperature (22 degrees Celsius) [29]. Alcohol was added as a quick drying solvent to reduce the viscosity and allows the coating to be sprayable. Citric acid was added to improve the photographic clarity of cyanotype and avoid ‘fogging’ due to impurities [30]. Tween 20 was added as surfactant to improve wettability.

To prepare the photosensitive coating, we dissolved the gelatine powder in warm water using a hot water bath. Diluted alcohol was slowly added with stirring until viscosity reaches a sprayable state. Tween 20, citric acid and the cyanotype were added subsequently and stirred. The coating was then ready to be sprayed. .

Glaze_Substrate Preparation and Spray Coating

We have performed most of the coating and exposure experiments using flat ABS plastic sheets (60mm x 120mm) as substrates. It was necessary to roughen the plastic surface by sanding to improve coating adhesion. For FDM printed substrates, it turned out to be ideal to first remove the highly visible layering artefact with a vapour polishing step (ethyl acetate and acetone can be used to polish PLA and ABS prints respectively). Sanding pads can be used to roughen the printed surfaces. For SLA resin and SLS nylon based material, depending on printer settings, the surface roughness may be sufficient for coating adhesion and no further sanding is required.

A double action airbrush with 0.3mm nozzle was used to spray the coating. Spraying distance was maintained between 100 and 150 mm. We aimed to apply a single continuous coat of wet paint across the surface of our plastic substrate. Care must be taken not to spray excessively and cause dripping. Incandescent light should be used in the spray painting room and sun light should be blocked. The coated substrate is immediately placed in a dark box for drying. 2 to 4 hours of drying time is needed depending on air humidity. The coating has a lime-yellow color with matte texture after drying.

The Kiln_ Laser Exposure Machine

The cyanotype reaction is sensitive to wavelength between 210nm to 410nm [31]. We used a 500mW 405nm multi-mode UV laser module mounted on a 2 DOF CNC machine (fig.1) to selectively expose the cyanotype-coated objects. The focus lens was adjusted such that the laser beam is as parallel as possible. A pinhole with 0.1mm diameter was placed in front of the laser module to circularize the laser spot by cropping. The laser module and the pinhole are mounted on a screw-driven linear robotic module with 200mm linear travel and 0.00625 mm positioning accuracy. The coated object is placed on a 270mm diameter belt-driven robotic turntable that is capable of continuous revolution, with 0.0075 degree positioning accuracy. The laser beam is positioned parallel to the surface and passes through the center of this turntable. Custom shaped fixture is required for each freeform shaped object. A calibration point is marked on the fixture and the laser beam is moved to that point to zero the machine.

Fig. 1 Custom CNC controlled laser positioning machine for laser exposure experiments © copyright Authors, Photo Authors

This two degrees-of-freedom machine allows us to perform laser exposure experiments on planar and freeform surfaces. Its axis configuration predominately favours tube-like objects to be exposed on all sides. Two NEMA 17 stepper motors are used to actuate the linear and rotary axis. They are driven by industrial stepper motor drivers with micro stepping enabled.

A laser path file is modelled and generated using custom written script in Rhino 5 using Grasshopper plugin. The file is written in G-Code and sent via USB serial port to an Arduino microcontroller running grbl v1.1 CNC controller. The controller can perform synchronized movement of the two axes with programmable speed. It can also modulate the laser output power from 0% to 100%. By controlling the moving speed of the axis or the laser power, we can control the exposure intensity (in J/mm^2) over the area swept by the beam spot. In practice, we always use the laser in 100% power and vary the path-tracing speed, this can minimize the lazing time.

First Laser activated Cyanotype Glazes

In order to develop this photographic printing method for artistic application, a number of experiments were conducted to achieve a control of the exposure intensity. As explained before, the exposure intensity along the laser path can be controlled by changing the path tracing speed. This creates lines of equal width (approximately 0.2mm) with different blue intensity. The width of the lines can be changed by using a pinhole with different diameters.

Due to the vector nature of the laser beam, it produces only line drawings. Patches of colours have to be created by scanning the beam over an area. The colour intensity of the patch is determined by the scanning speed and the scanning spacing.

Therefore, we created a number of sample cards (fig.2) to adjust and calibrate different colour patch intensity with differently spaced diagonal straight hatching. Other types of hatching pattern can create different visual effect similar to the techniques used in intaglio prints.

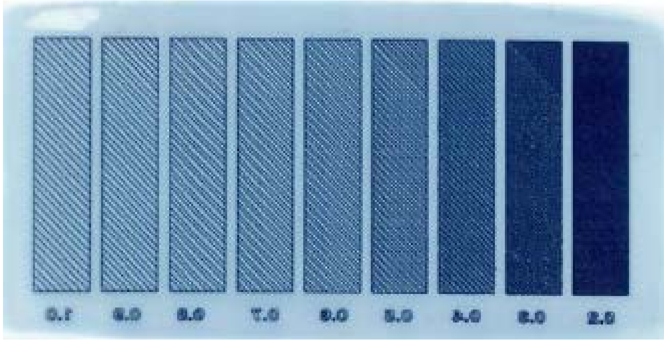

Fig.2 Hatching sample card with different hatch spacing. © copyright Authors, Photo Authors

We extended the hatching test to demonstrate the two effects at the same time (fig. 3). From top to bottom, the L-shaped lines have decreasing spacing. From left to right, the lines are exposed with increasing speed. An artist can pick the desired visual outcome from the matrix and program the laser with the corresponding speed and spacing. It should be noted that the laser speed is not directly proportional to the exposed blue color intensity.

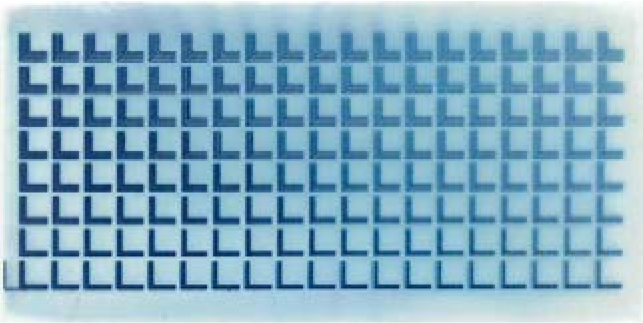

Fig.3 Gradient and line graphic printed on flat ABS plate © copyright Authors, Photo Authors

Lastly in this test series of working with a planar surface exposure, we created the intricate image of a Chinese flower painting as traditionally seen on the classic blue and white ceramic paintings. We used, as discussed gradients described through variation of hatchings as density of lines with exposure differences (fig. 4). The gradient patches are created with equal hatching spacing and varying laser speed. Custom scripts allow the artist to select the starting and ending intensity and the orientation of the hatching. The substrate is ABS sheet (60mm x 120mm x 2mm) roughened with sand paper. Total laser exposure time is approximately 2 hours.

Fig.3 Gradient and line graphic printed on flat ABS plate © copyright Authors, Photo Authors

In the current state of the research we have achieved control over the parameters described before on planar surfaces. Furthermore and in plane with the rotational geometries of traditional pottery, we have achieved to successfully adjust the parameters of our current set-up to print on double curved 3D printed oobjects. To demonstrate this ability, we printed (Fig. 4) a vector image on a circular bracelet (80mm diameter, 18 mm height). The substrate is PLA plastic printed with FDM 3D printer, vapour polished and then roughened. The exposure time is approximately 40 minutes.

Fig.5 Vector graphic printed on FDM printed PLA bracelet © copyright Authors, Photo Authors

Conclusion

Digital Craftsmanship is still an under-defined concept. It involves the ability to control tool and material to artistically creating a synthesis between them. Certainly, the construct of Craftsmanship, independent of the analogue or digital, is a cultural construct embedded within a technological context. Historically, the craftsmen have understood the value of combining technology and art into an interdisciplinary approach and as shown throughout the last millennia, curiosity and the will to innovate has driven artistic expression and technological development. The relationship between tool development and artistic expression is undeniable.

Within this research, we adopted techniques and methods from one of the oldest artistic expression and transferred them to the current state of the art additive manufacturing technologies. We focused on the development of tools for today's digital artists and designers and the global maker community.

In this technological yet as well cultural context, we are speculating that the artistic response to a new expression and tool will, as with all new developed media, from the printing press to stereoscopic projection, open a plethora of translations, use and misuse of the developed media and create output and discussion about the relationship between techne and poiesis.

We are happy to contribute.

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