



## Oriented 3-D Ink Jet Printing

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### ABSTRACT

Ink jet printing onto flat paper is a widely established process. In this paper, we make extensions to printing on target surfaces such as plastics, metals and glass, using a 5-axis orientable head. Original artwork is created using CAD, or digitized using a laser scanner, and is sampled to create the ink jet point cloud. The target surface location is registered using a standard Coordinate Measuring Machine (CMM) 5-axis touch trigger probe. The probe is then replaced with the ink jet head and the printing process is carried out. Demonstration of the system is illustrated using rapid prototyped plastic shapes, flat metal, and glass samples.

**Keywords:** ink jet printing, 5-axis, rapid prototyping.

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### 1. INTRODUCTION

With ever decreasing product development cycle intervals, the need to use prototyping methods to ensure high volume manufacturing success is essential. With rapid prototyping, designers can produce prototypes which convey their vision of scale, shape, and functionality in less time and at a lower cost. The use of CAD software to create and visualize virtual 3-D models is well established, as is rapid prototyping of the geometry of these models. According to Ming et al. [1] adding color to a design would significantly increase the range of potential applications. Although color is available for some materials, it remains unavailable for functional thin walled plastic parts intended for injection molding. In this paper, a practical system for delivering ink onto prototype part surfaces is described. The approach uses a point cloud format to describe both the prototype shape and color. An ink jet printing head, attached to a 5-axis orientable Coordinate Measuring Machine (CMM) probe head, is used to deposit either black or colored ink. Surface pretreating enables ink adherence, erasure, and reuse of the same target surface. The system is demonstrated using plastic, sheet metal, and glass materials, with both flat and curved surfaces.

The remainder of the paper is organized as follows. Section 2 reviews related work on point clouds, rapid prototyping, and 3-D color printing and decorating. Section 3 describes the system architecture, the work flow, and the CMM ink jet implementation. Section 4 describes the CAD implementation of the system, decal colored image-to-point cloud conversion, grid generation, and the path planning needed to implement the system. Section 5 presents experimental results. A summary and conclusion follows in Section 6.

### 2. REVIEW OF PRIOR WORK

Computer Aided Design part representations have evolved from single color primitive wireframe implementations to B-spline surface models with photorealistic textures and rendering. Artifact

scanning has similarly progressed to the point where color laser scanning can simultaneously produce both high resolution geometry and color [2]. Advances in computing and graphics now make point based CAD/CAM systems practical [3]. Implementation of texture resolution color on prototypes, however, is very limited. The closest commercial realization is the Z Corporation 3-D printer [4]. This technology reads VRML or equivalent CAD files, and builds the prototype part by sequentially depositing powder and colored liquid binder. Completed models can be used for casting, etc. but do not provide the functionality associated with other methods such as stereolithography [5] or fused deposition modeling [6] for prototyping thin walled plastic parts. Adding color to these parts is typically accomplished using a high volume pad printing process, or multiple step injection molding. Neither of these processes is cost effective for prototyping, and these limitations inspired the work reported herein. Additional applications for the research include depositing grids for sheet metal strain analysis [7], and tissue engineering [8].



Fig. 1: CMM based 5-axis ink jet printing system architecture: (left) machine and sample part; (middle) touch trigger probe registration; (right) ink jet system mount.

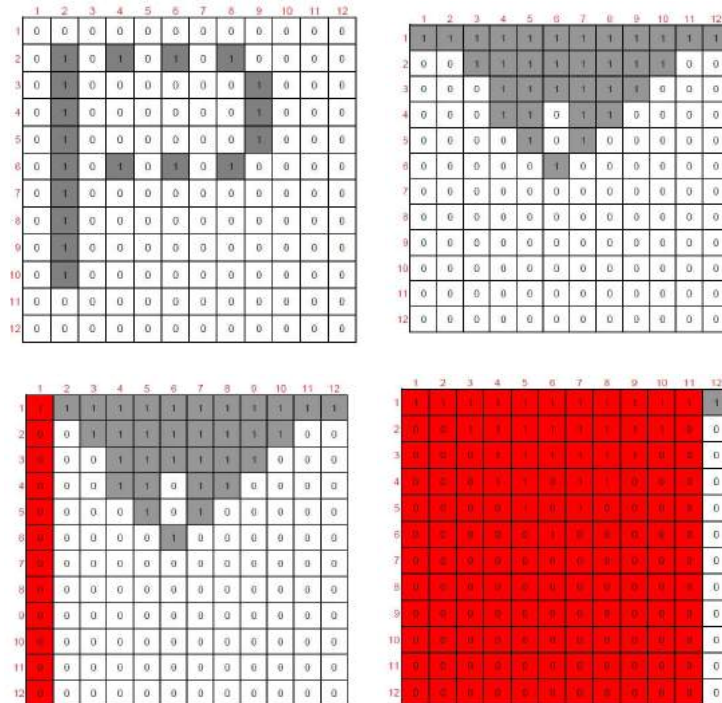


Fig. 2: Font reprogramming and printing: (top left) default storage format for letter “P”; (top right) reprogrammed letter “P”; (bottom left) printing the first column of the new letter “P”; (bottom right) printing column by column until the end the letter.

### 3. CMM 5-AXIS INK JET IMPLEMENTATION

The 5-axis ink jet system (Fig. 1(a)) was implemented on an open architecture Coordinate Measuring Machine (CMM) [9] equipped with a Renishaw PH10 rotating probe head. During registration of the target part surface, a TP6A touch trigger probe is used (Fig. 1(b)). For ink jet printing, this is replaced with an adapter and ink jet print head and microcontroller (Fig.1(c)). The mount uses a PAA1 autojoint adapter to allow for repeatable interchange with the probe, plus a rapid prototyped plastic adapter that mates with the ink jet head carrier. The part is secured using a Rayco fixturing system [10]. The ink jet system consists of a 96 dpi HP 51604 ink jet head and SX28AC/SS based microcontroller board kit [11]. A TTL logic level signal is sent from the CMM motion controller to the ink jet microcomputer to print the next dot row each time a distance of 1/96 of an inch has been travelled. Using a custom program written in MATLAB® [12], the CMM is controlled using the workstation, with Ethernet connections to the CMM motion controller, and a serial connection to the ink jet microcontroller. Each dot pattern is printed by executing the following steps:

1. The CAD created ink jet dot pattern for the current ink jet path is downloaded into the microcontroller font memory, thus altering the existing fonts (Fig. 2). Characters are represented as a 12 by 12 dot matrix, and a total of 64 characters can be stored at once. At 96 dots per inch, this represents 8 inches of travel.
2. The PH10 probe head is rotated to the appropriate angles, and the CMM carriage is translated to the beginning position.
3. A custom CMM motion command is executed to begin linear motion for the length of the current ink jet path. Each time a distance of 1/96 of an inch has been travelled, the CMM pulses the microcontroller to print the next dot row. This synchronization provides independence from CMM acceleration and deceleration, or need to adhere to a constant printing speed. For development work, a reduced printing speed of 60 mm/min was used.

### 4. IMPLEMENTATION

The workflow of the system describing the image processing and printing stages is shown in (Fig. 3). The operation starts with decaling an image onto a CAD part created on the workstation using Autodesk Inventor® [13]. The resolution of any image used for decal in CAD systems follows the DPI settings of the operating system; the later was chosen to be 96 DPI to match the cartridge printing capabilities. The remainder of this section is divided into two parts: image conversion to point clouds for visualization purposes, and printing images on various geometric surfaces.

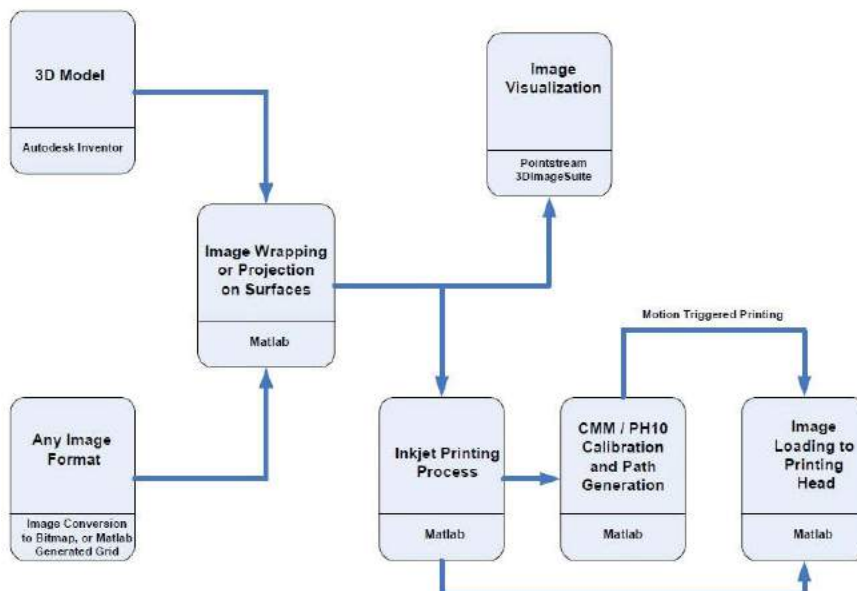


Fig. 3: System workflow.

#### 4.1 CAD Image Processing

The Inventor decal feature applies images using one of two methods: projection and wrapping. Projecting an image is applicable to all faces regardless of their complexity, but this versatility comes at a price of deforming the image. Wrapping keeps the resolution and physical dimensions of the original image intact, but is limited to developable surfaces. For visualization purposes point clouds are generated using the parametric geometry of the solid to calculate the coordinates and normals of the points, combined with the image Red-Green-Blue (RGB) data of the image. The sample cases used are: half cylinders, half elliptical surfaces, and B-spline extrusions, where the wrapping approach can be further developed and explored for decaling images.

For half cylinders, the width of the image is wrapped on the circular face; hence the first and second coordinates are generated using parametric formulae where the angular increment that represents 1/96 inches in arc length along the radially-known circular path is used as the variable. The image length is used to generate the third coordinate by incrementing the starting coordinate by 1/96 inches increments along the whole length. The coordinate values are then used to generate the normal values. RGB data is combined to the generated values according to the width and length indices. This point generation method mimics the CAD system wrapping approach in terms of assigning the wrapping starting point.

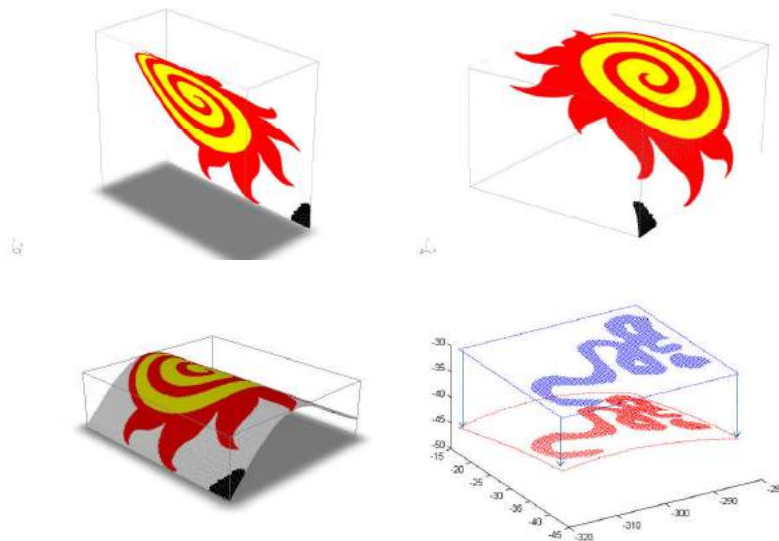


Fig. 4: Image point clouds wrapped on (top left) cylindrical surface (top right) elliptical surface (bottom left) B-spline extruded surface (bottom right) 2D spline surface.

For elliptical surfaces the arc length approach is also used to find the coordinate and normal values, and then combine them with the corresponding RGB values to generate the point cloud. The wrapping starting point was chosen as the CAD projection point along the elliptical path closest to the first quadrant. Adaptive numerical integration was used to calculate the parameters of the fixed length elliptical arc, where the starting point angle with respect to the center of the ellipse is considered as the lower limit. The values of these angular increments are stored and were later used for the printer path generation.

For 2D B-spline extrusions the starting and the physical dimensions of the image are user defined. A Visual Basic for Applications (VBA) macro, using the CAD system Application Programming Interface (API) functions, calculates 2D B-spline arc length from the input point to check the wrapping applicability. If wrapping conditions are met, the VBA macro generates the coordinate and normal values of the 2D B-spline at 1/96 inches of arc length. These values are then combined with RGB data, and extrapolated for the extrusion as in the cylinder and elliptical surface cases.

All the generated point cloud values are stored in ASCII files that can be viewed (Fig. 4) using Pointstream 3DImageSuite® [2]. Due to the monochrome nature of the print head, RGB data cannot be

printed, and thus conversion of images to binary is performed. The MATLAB graythresh function that employs the Otsu [14] algorithm is used to perform this task, and the image is stored as a binary matrix.

#### 4.2 Laser Digitizing Image Processing

A CMM mounted Hymarc 45c laser digitizer is used to scan the object surface geometry and to record the decoration information on a clay model (Fig. 6). This system is capable of accurately generating point cloud data (PCD) with information about surface coordinate values and their corresponding intensity [15]. Laser digitizing is used to convert 3D Art work (a handmade clay model decorated by ink) to a digital geometry model, and at the same time to record the decoration information that can be printed at later stage on the rapid prototyped part (Fig 6). However, the original data needs to be processed and thinned down from a nominal scanning resolution of 254 DPI to a 96 DPI resolution for compatibility with the printing apparatus.

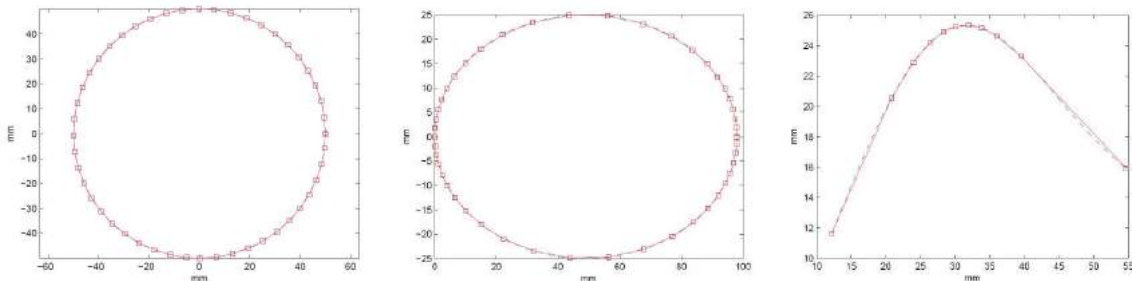


Fig. 5: Line segmentation at  $7.5^\circ$  within the acceptable printing tolerance (left) Circle (middle) Ellipse (right) B-spline.

The PCD processing to create the printable image requires generating a consistent output image resolution, and this is achieved by averaging the intensity and z coordinate values of all the points between every two pixels distanced at 1/96 inches from each other to create one data point, both along horizontal and vertical directions in the control box that contains the art work (Fig. 4(d)). The averaging boundary is set to include all the points located within the 1/96 inches xy domain. PCD averaging and thinning is followed by point intensity value extraction and mapping to a 2D array that represents a 96 DPI grayscale intensity image of the scanned artwork decoration. This image is then converted into binary, again using the graythresh MATLAB function.

When the extracted 2D image is projected back onto the object surface (Fig. 4(d)), this projection will have a printable format at the expense of the authenticity of the original artwork. In this specific model the projection vs. wrapping error was minimal due to the simple geometry of the clay model. For more complex surfaces the averaging of the intensity and the third dimension would be done along the arc path of each two surface patch.

#### 4.3 Path Planning

The CMM was programmed to issue a TTL signal every 1/96 inches of 3-D travel, therefore it was essential that the local coordinate system (LCS) of the sample print be aligned with the machine coordinate system (MCS) to ensure that printing resolution is not distorted by the multi-directional travel of the ink jet head. When the image is not aligned with MCS, the image is rotated about its center and saved as a new image.

For flat surface printing, where the angular alignment difference between the LCS and the image are multiples of  $7.5^\circ$ , software rotation is not applied because the probe head can instead be reoriented. With the image LCS coordinates determined, and the part clamped on the CMM table, the touch probe determines the coordinates of the center of the LCS, and the measurements are converted into a transformation matrix that converts LCS path to MCS. The 5-axis machine operates as a planar inkjet printer where the part can be mounted in any plane parallel to its z-axis, and the printing head moves to the designated printing location, prints a image strip with a width of 1/16 inches in the y direction,



and then moves back to the originating point, plus 1/16 inches along the x direction. This process is repeated until the entire artwork is printed.

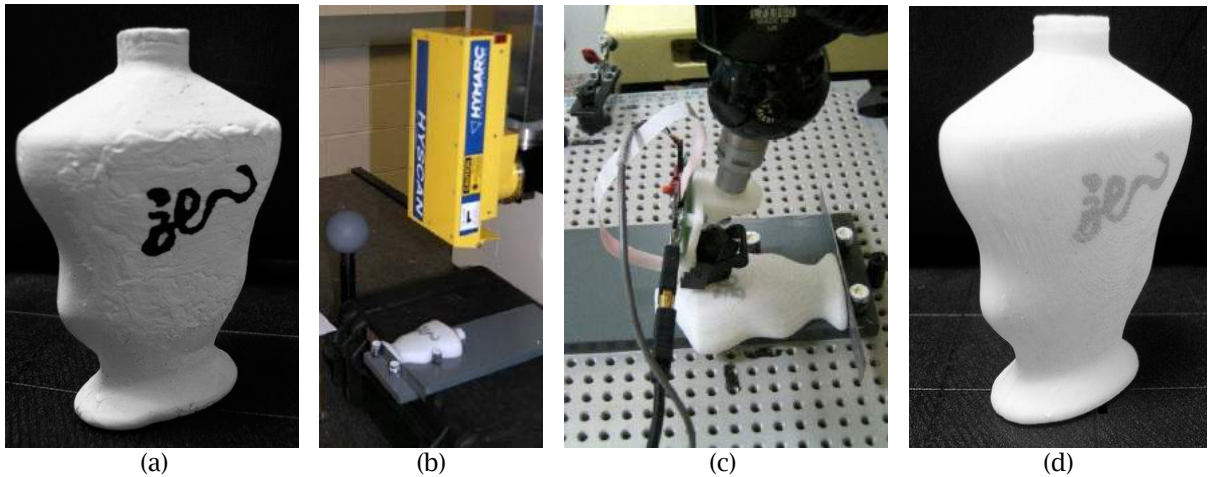


Fig. 6: Artwork reproduction process: (a) clay model art work; (b) clay model scanning; (c) image 3D oriented printing; (d) final reproduction of the artwork.

For 3-D surfaces, the points where the tangent angle along the arc path changes by  $7.5^\circ$  are recorded, thus creating a line segment path (Fig. 5) that remains very close to the arc path. These line segments are divisible by 1/96 inches to ensure that no pixel loss occurs. For all of the printing experiments conducted in this work the arc-to-chord deviation remained with the supplier recommended printing gap of  $1 \pm .5$ mm. The line segment width values are then used to section the image accordingly. The image sections shown in (Fig. 7) are then printed as full images on the newly established planar surface.

For undevelopable spline surfaces, the wrapped image can be sliced into smaller surfaces that have a slope difference between its furthest points in one direction, less than or equal to  $7.5^\circ$ , and a directional error in the other direction, less than or equal to 1mm (Fig. 6(d)).

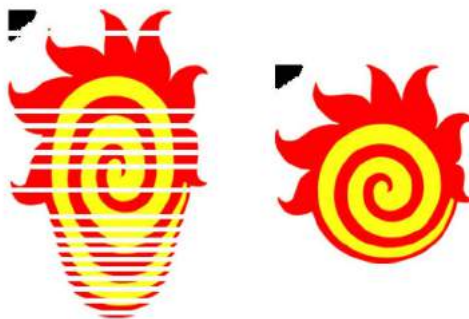


Fig. 7: B-spline image sectioning.

## 5. EXPERIMENTAL RESULTS

The ink jet printing system was first tested on plain white paper. This permitted calibration verification with the touch trigger probe. For printing on material, the surface was first coated with water soluble inkAID™ [16] precoat. This provides a high quality mark that can easily be washed away after use.

To test the ink jet path planning algorithms, the McMaster Engineering fireball logo was used. Different geometrical samples printed on InkAID coated surfaces created using a Dimension BST rapid prototyping machine [6]. The logo was also printed onto planar, cylindrical, elliptical, and B-spline surfaces (Fig. 8).

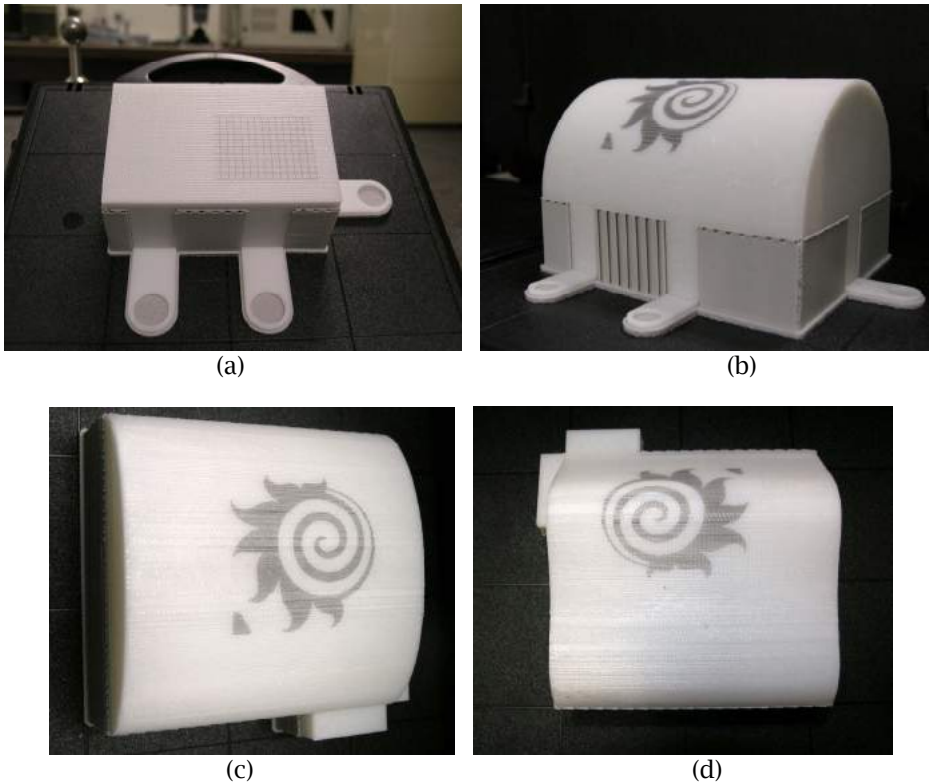


Fig. 8: Ink jet path planning test on precoated rapid prototyped surface results: (a) inclined planes; (b) cylindrical; (c) elliptical surface (d) B-spline extrusion.

Information that can help study the strain and deformation of glass and stamped sheet metals can be acquired by locating and visualizing the individual point using laser scanners or computer vision [17]. For this task, generating a grid with dimensions as low as 1/48 inches would provide the required tool. Such are simple binary MATLAB generated matrices of 0s and 1s, and their physical dimensions are user defined. These matrices can be printed immediately or stored as a bitmap file as an image, where the DPI setting of the system allows MATLAB to keep the image resolution at 96 dpi. Sample grids are shown in Fig. 9.

Implementation and experimental work to date has been limited to developable surfaces onto which the image can be wrapped. For modest curvatures, these are not difficult. For high curvature surfaces, however, ink jet print head access may not be possible, particularly in concave regions. As well, there will be some distortion over the 12 dot width of the head. For non-developable surfaces, a flat texture image cannot be wrapped onto the surface but must instead be projected. This creates additional distortion. In practice, prototyping uses for the system are not highly curved, and competing screen or pad printing processes have similar limitations.

## 6. SUMMARY

This paper has introduced an oriented 3-D ink jet printing system that can be used to transfer textures and other images from CAD systems onto prototype surfaces, metal and glass sheets, and a method of converting decal images into colored point clouds. This printing approach can serve manufacturing at

two different levels: design and material properties. Erasable monochrome printing was achieved with a resolution of 96 dpi on surfaces including flat planes, inclined planes, cylinders, elliptical surfaces, and 2D B-spline extrusions. For material strain and deformation evaluation, printing grids were created on aluminum and glass. Using the surface coating proved to be integral to increasing ink adhesion to the surface.

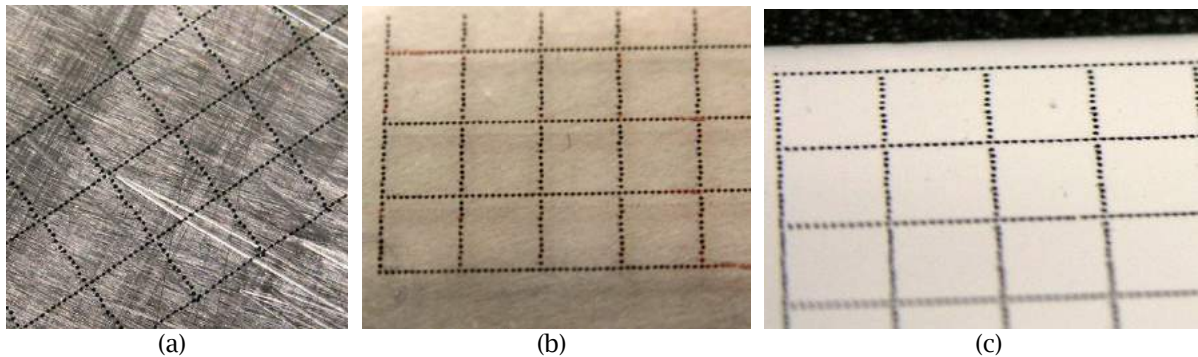


Fig. 9: (a) InkAID Clear Glass Type II coated aluminum grid; (b) InkAID White Matte coated glass grid; (c) InkAID Clear Glass Type II coated glass grid.

## 7. ACKNOWLEDGEMENTS

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