TAIWAN TECH National Taiwan University of Science and Technology
色彩與照明科技研究所
Graduate Institute of Color and Illumination Technology

# Methods for Optimizing Color Uniformity of 3D Printing Surfaces


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Presented at IS&T Electronic Imaging 2016 Previously

# Overview

- Motivation
- **A method for color 3D halftoning**
- **A multi-directional color target** for estimating color variations across different surface directions
- **A color compensation method** to improve the consistency of color across different faces of a 3D print
- Conclusions

# Motivation

- 3D printing becomes widespread in recent years.
- Only few commercial products are capable of generating full-color 3D prints with acceptable quality.

3D Systems - ProJet 460 Plus

Powder-Binder Printing


Stratasys - Objet500 Connex3

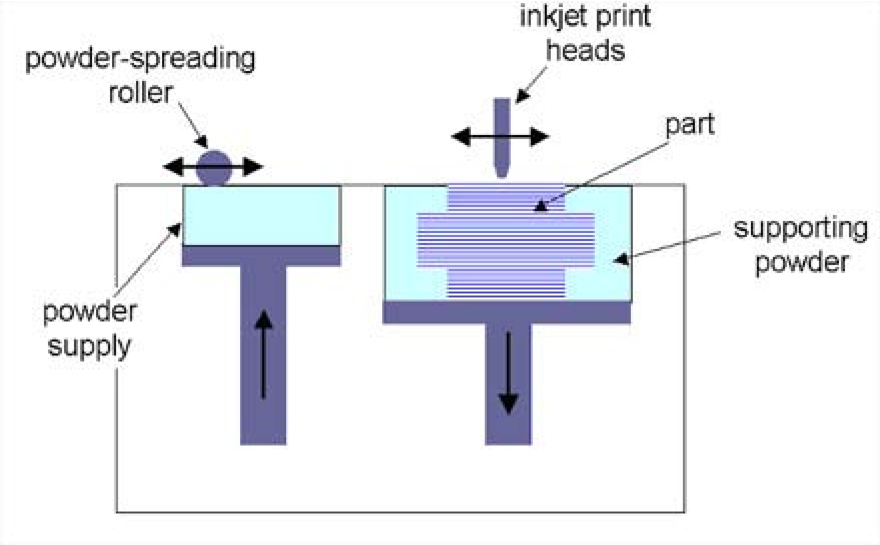
Photopolymer Inkjet

# 3D printing – main categories

- **Lamination**
  - **Laminated object manufacturing (LOM) – low quality, color enable**
- **Extrusion deposition**
  - **Fused deposition modeling (FDM) – cheaper, low quality, multi-materials**
- **Granular Material Binding**
  - **Selective laser sintering (SLS) – high quality, thermoplastics, metal powders, ceramic powders**
  - **Plaster-based 3D printing (PP) – color enable**
- **Photopolymerization (UV curing)**
  - **Stereolithography (SLA) – high quality**
  - **Digital Light Processing (DLP) – faster**
  - **Photopolymer Inkjet (PloyJet) – high quality, multi-materials**

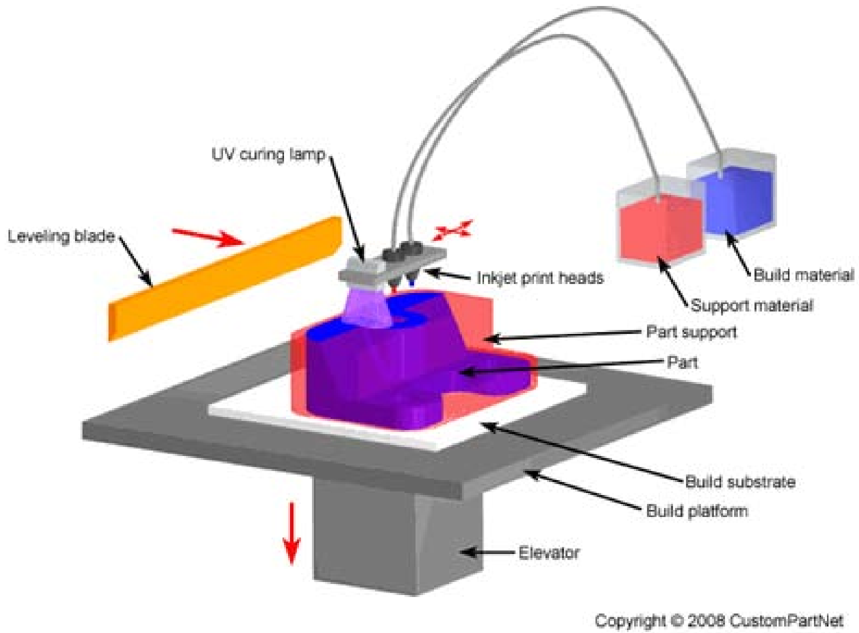
# Plaster-based 3D printing (PP)

- The processing itself is based on ink-jet printing, with the powder being deposited in consecutive layers which are selectively joined by ink-jetting the binder. Three (CMY) or four (CMYK) colored binder together with the clear binder are mixed to print powder material in a full color spectrum layer by layer. After 3D printing, post-processing, including de-powder and infiltration needs to be conducted.



# PolyJet

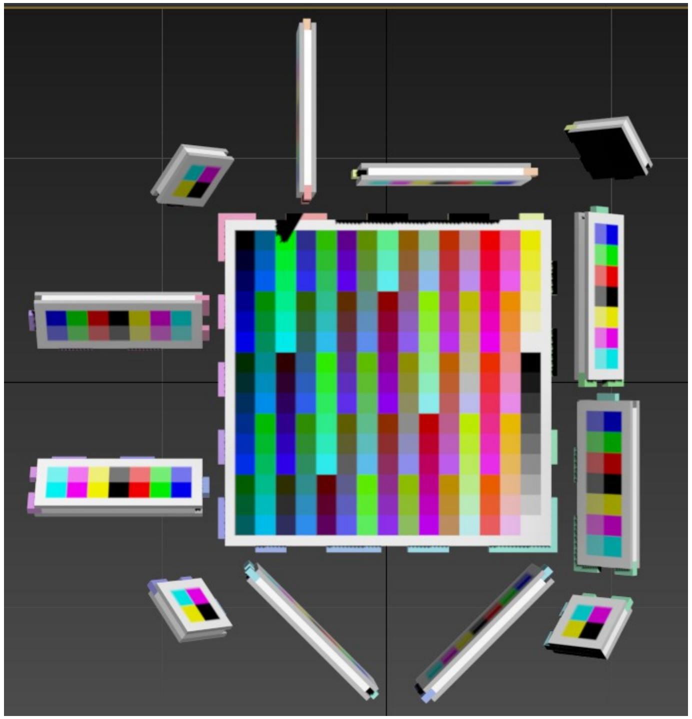
- It combines liquid photopolymer droplets of two or three base materials to produce multi-colour or multi-material parts in a single run. Each photopolymer layer is cured with UV light after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing. Gel-like support material is needed during the printing to support complicated geometries.

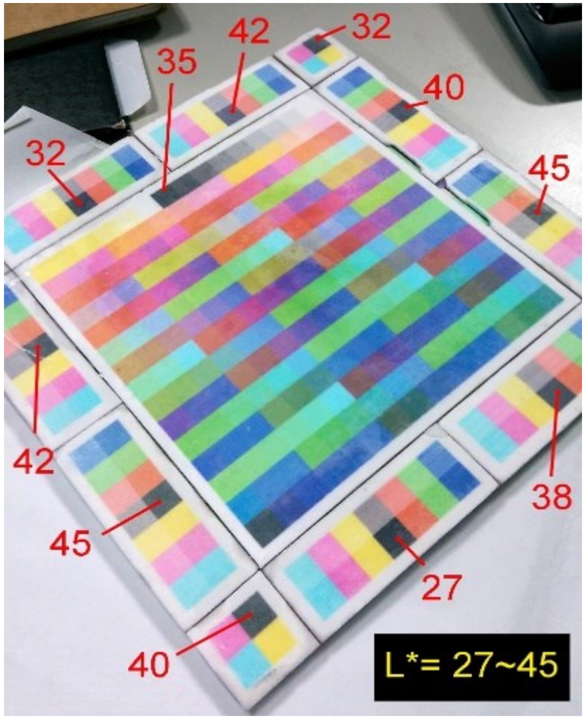



Stratasys - Objet500 Connex3

Photopolymer Inkjet

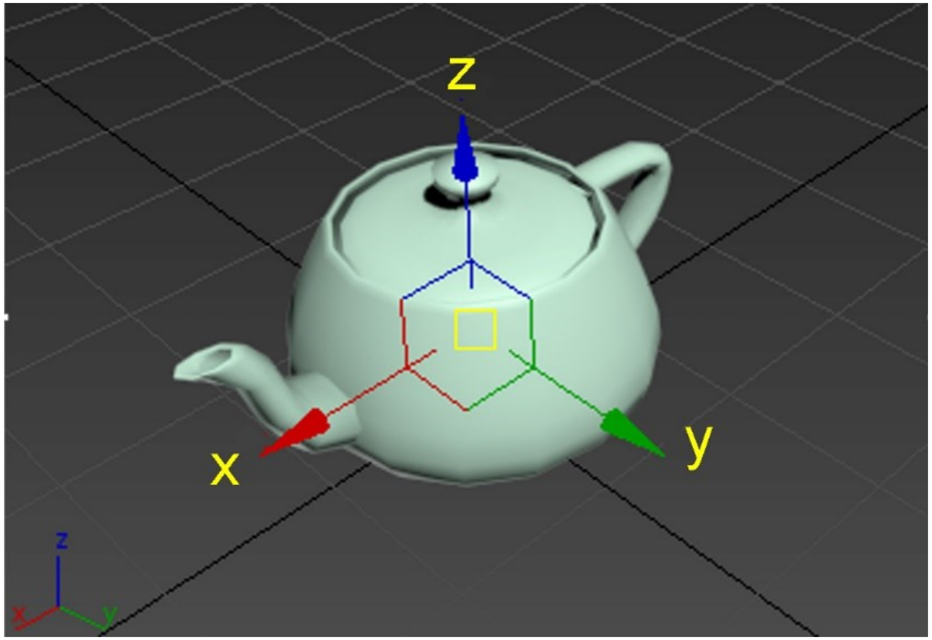
# Colors are inconsistent across different faces






Powder-Binder Printing

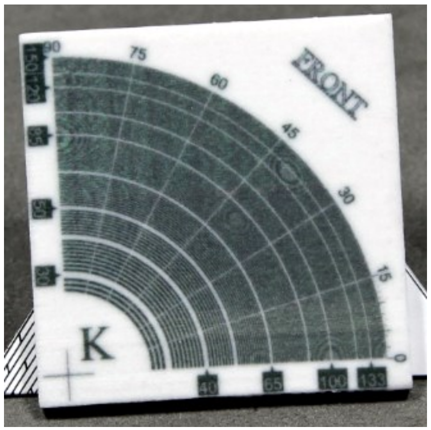
Additive binding

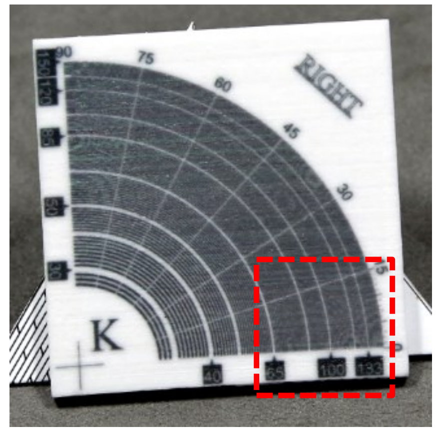


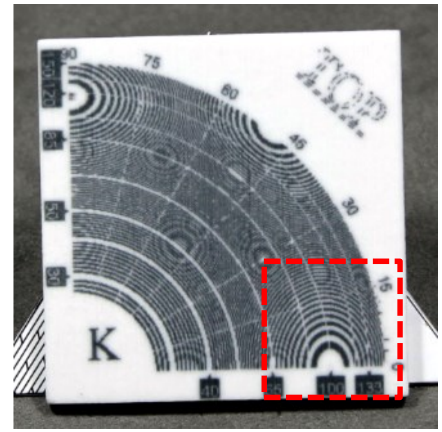
# Moire patterns are inconsistent across different faces

X view | Y view | Z view

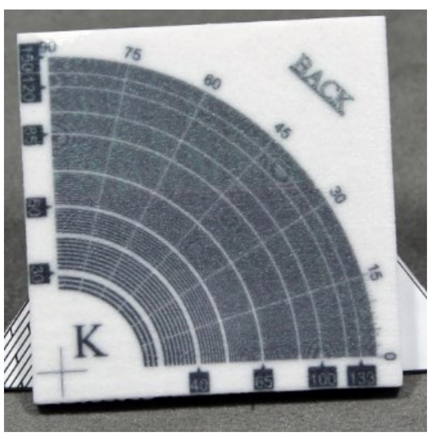
Front

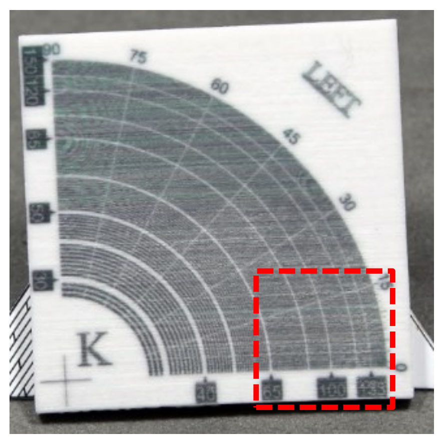


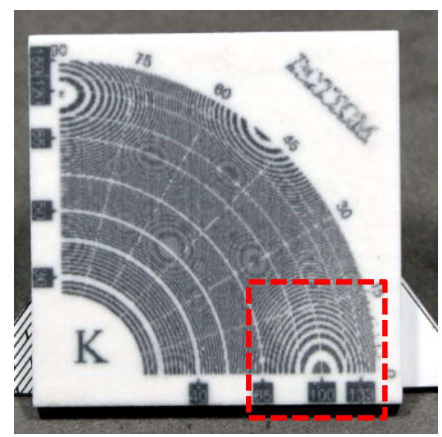




Back



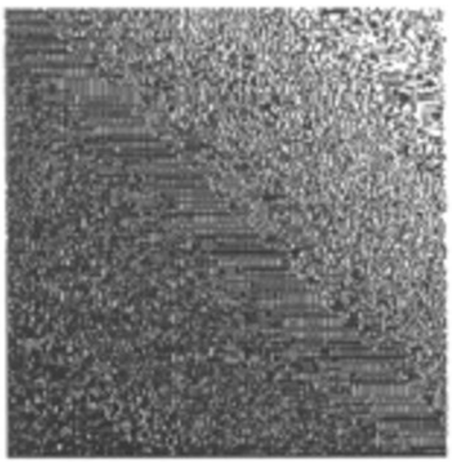



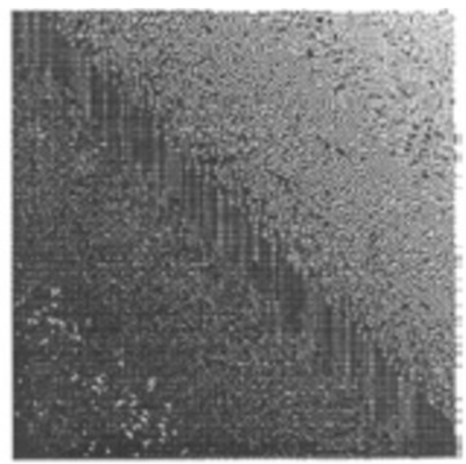
# 2D Error diffusion

- Unwanted stripes in X and Y viewing directions

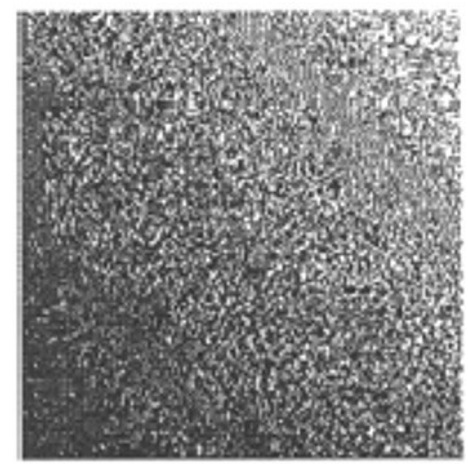
X view



Y view



Z view



# Aims

- To optimize color 3D halftoning for a UV-curing photopolymer inkjet printing system.
- To develop a test target for ICC-based color management and for estimating multi-directional color differences.
- To reduce the omnidirectional color differences based on the above measurement.

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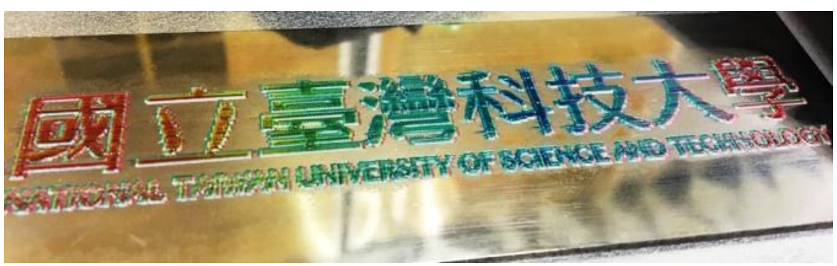
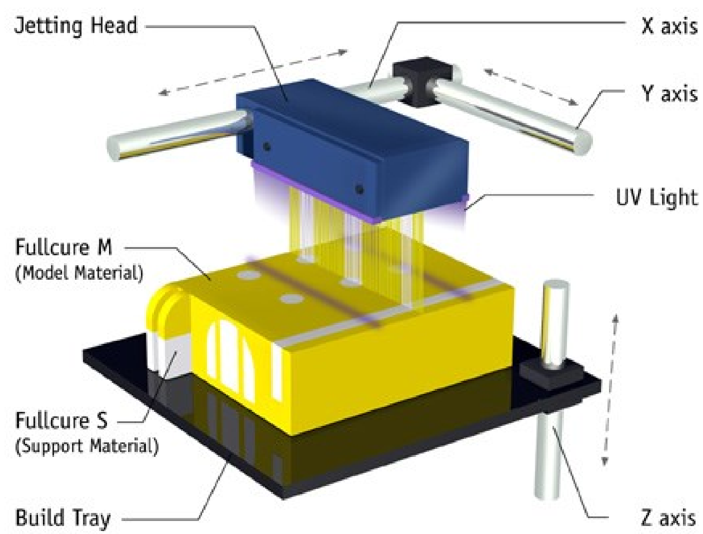
# Optimization of Color 3D Halftoning

# Photopolymer inkjet printing

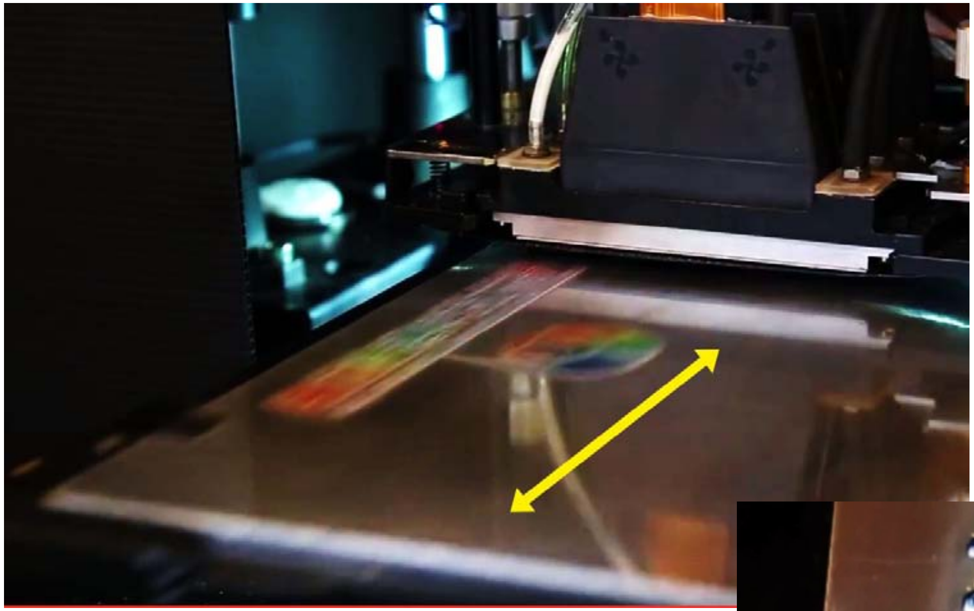
- No white subtract. Opaque white ink is needed.
- To maximize its color gamut, CMYKW is recommended.
- To keep local volume unchanged, each sub-voxel must fill-in only one color ink-droplet. Translucent color inks are needed.
- To speed the process, the printing resolution must be low.



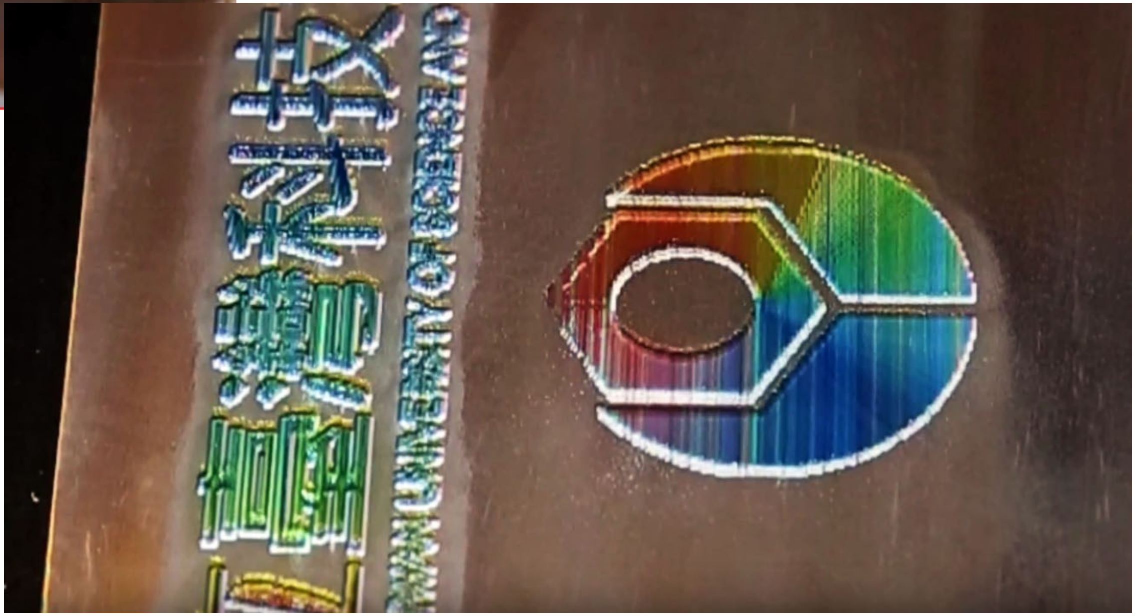




The Objet PolyJet Process

# Develop a photopolymer 3D inkjet printer at NTUST



科技部
Ministry of Science and Technology



Cross-department cooperation:

- Color and 3D scan technologies
- Photopolymer materials
- Inkjet head
- Printing system

# NTUST Prototype + Color RD Group

# Dispersed threshold matrix

| | | | |
|---|---|---|---|
| 1 | 9 | 4 | 11 |
| 13 | 5 | 15 | 7 |
| 4 | 12 | 2 | 10 |
| 16 | 8 | 14 | 6 |

4x4 Bayer

Layer 1

| | | | |
|---|---|---|---|
| 1 | 33 | 9 | 41 |
| 49 | 17 | 57 | 25 |
| 13 | 45 | 5 | 37 |
| 61 | 29 | 53 | 21 |

Layer 2

| | | | |
|---|---|---|---|
| 2 | 34 | 10 | 42 |
| 50 | 18 | 58 | 26 |
| 14 | 46 | 6 | 38 |
| 62 | 30 | 54 | 22 |

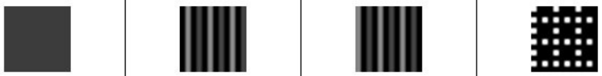
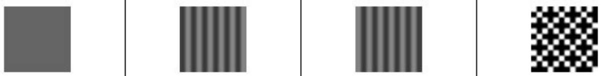
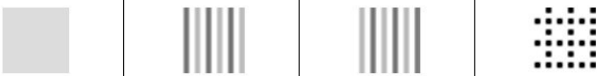
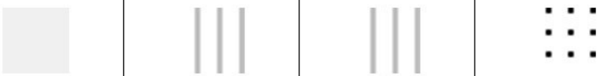
Layer 3

| | | | |
|---|---|---|---|
| 3 | 35 | 11 | 43 |
| 51 | 19 | 59 | 27 |
| 15 | 47 | 7 | 39 |
| 63 | 31 | 55 | 23 |

Layer 4

| | | | |
|---|---|---|---|
| 4 | 36 | 12 | 44 |
| 52 | 20 | 60 | 28 |
| 16 | 48 | 8 | 40 |
| 64 | 32 | 56 | 24 |

6-bit, gray = 13

| 8-bit gray | Input | X view | Y view | Z view |
|---|---|---|---|---|
| 20 |  | | | |
| 60 |  | | | |
| 100 |  | | | |
| 140 |  | | | |
| 180 |  | | | |
| 220 |  | | | |
| 240 |  | | | |

Different patterns across different orientations
High local contrast

# The Initial Matrix

- Well-dispersed in 3D
- Gray can be produced by layering black and white to reduce local contrast

Layer 1

| | | | |
|---|---|---|---|
| 1 | 49 | 7 | 55 |
| 33 | 17 | 39 | 23 |
| 5 | 53 | 3 | 51 |
| 37 | 21 | 35 | 19 |

Layer 2

| | | | |
|---|---|---|---|
| 41 | 25 | 47 | 31 |
| 9 | 57 | 15 | 63 |
| 45 | 29 | 43 | 27 |
| 13 | 61 | 11 | 59 |

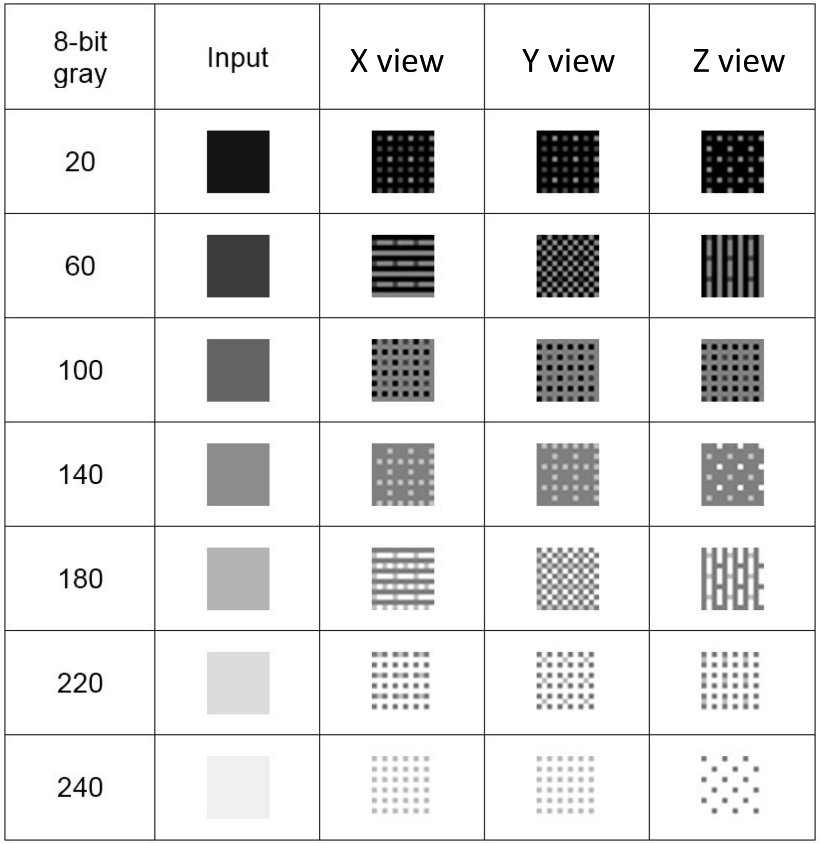
Layer 3

| | | | |
|---|---|---|---|
| 4 | 52 | 6 | 54 |
| 36 | 20 | 38 | 22 |
| 8 | 56 | 2 | 50 |
| 40 | 24 | 34 | 18 |

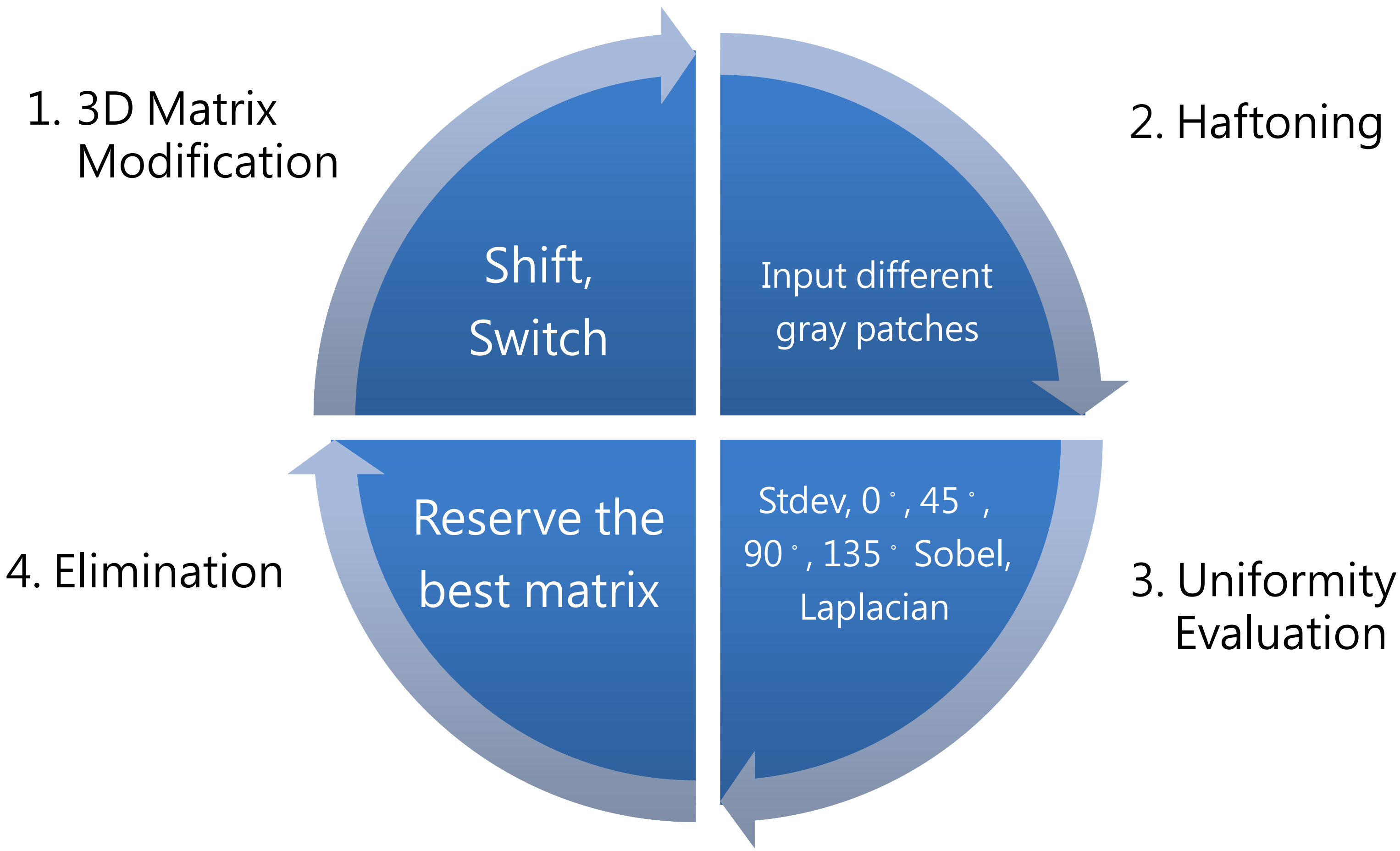
Layer 4

| | | | |
|---|---|---|---|
| 44 | 28 | 46 | 30 |
| 12 | 60 | 14 | 62 |
| 48 | 32 | 42 | 26 |
| 16 | 64 | 10 | 58 |

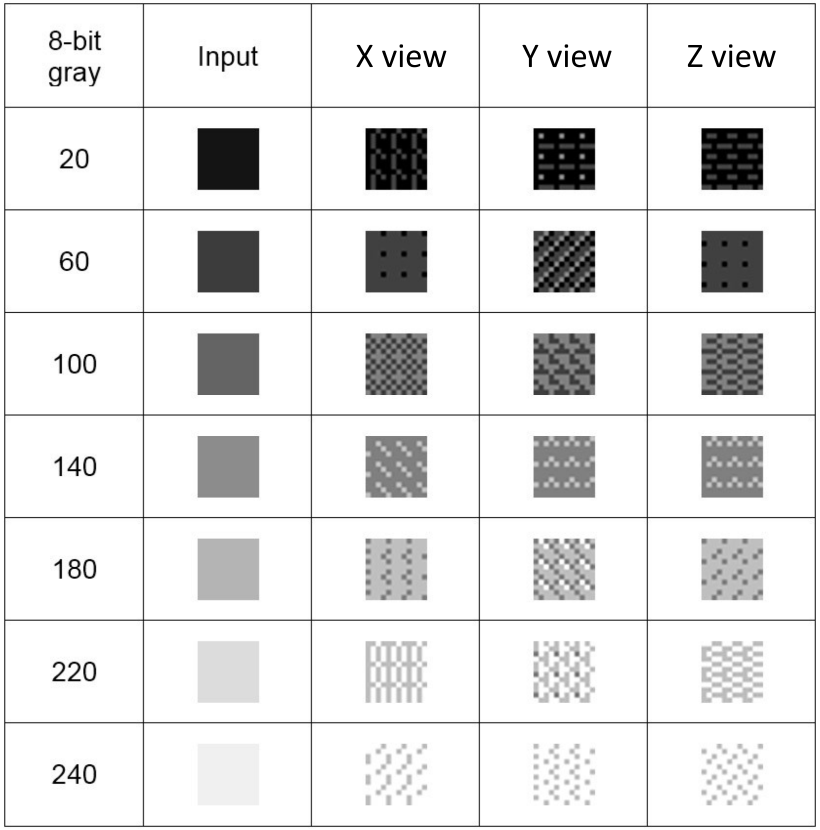
Not bad



# 4x4x4 3D Matrix Optimization



# The Optimal Matrix




Layer 1

| | | | |
|---|---|---|---|
| 17 | 46 | 55 | 1 |
| 57 | 7 | 38 | 31 |
| 9 | 52 | 2 | 54 |
| 36 | 28 | 19 | 44 |

Layer 2

| | | | |
|---|---|---|---|
| 53 | 20 | 47 | 22 |
| 29 | 60 | 62 | 12 |
| 45 | 14 | 26 | 33 |
| 8 | 39 | 11 | 63 |

Layer 3

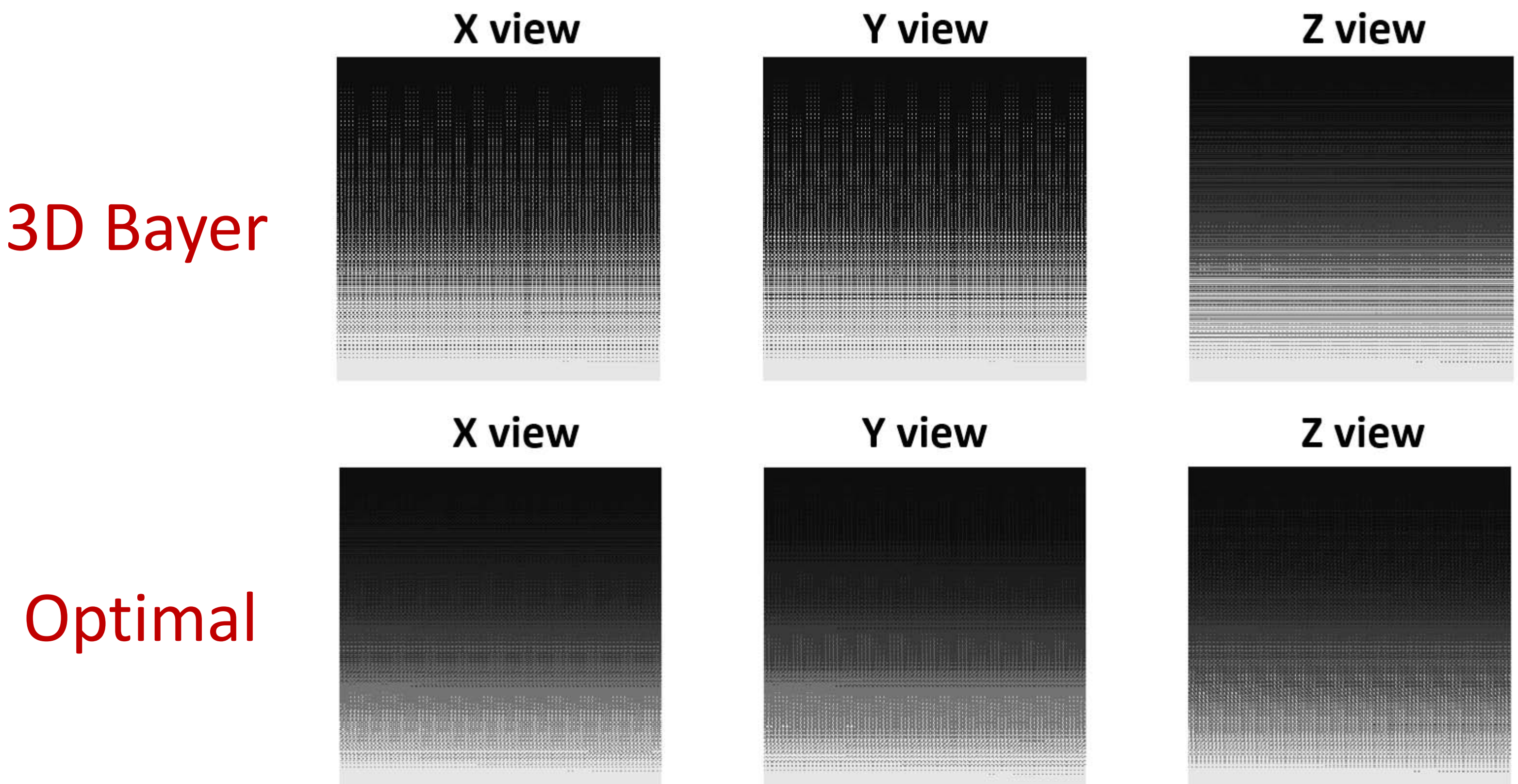
| | | | |
|---|---|---|---|
| 13 | 56 | 6 | 50 |
| 40 | 32 | 23 | 48 |
| 21 | 42 | 51 | 5 |
| 61 | 3 | 34 | 27 |

Layer 4

| | | | |
|---|---|---|---|
| 41 | 10 | 30 | 37 |
| 4 | 35 | 15 | 59 |
| 49 | 24 | 43 | 18 |
| 25 | 64 | 58 | 16 |

The patterns are similar across different orientations and the local contrast are smaller.

# Grayscale Comparison



# RGB to CMYKW conversion

$$\{R,G,B,C,M,Y,K,W\}\in[0 \quad 1]$$

### 1. Gray Component Replacement

$$\begin{bmatrix} C' \\ M' \\ Y' \end{bmatrix} = \begin{bmatrix} 1-R \\ 1-G \\ 1-B \end{bmatrix}$$

$$K = \min(C', M', Y')$$

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} C'-K \\ Y'-K \\ M'-K \end{bmatrix}$$

### 2. White Extraction

$$W = \min(R, G, B)$$

### 3. Scaling

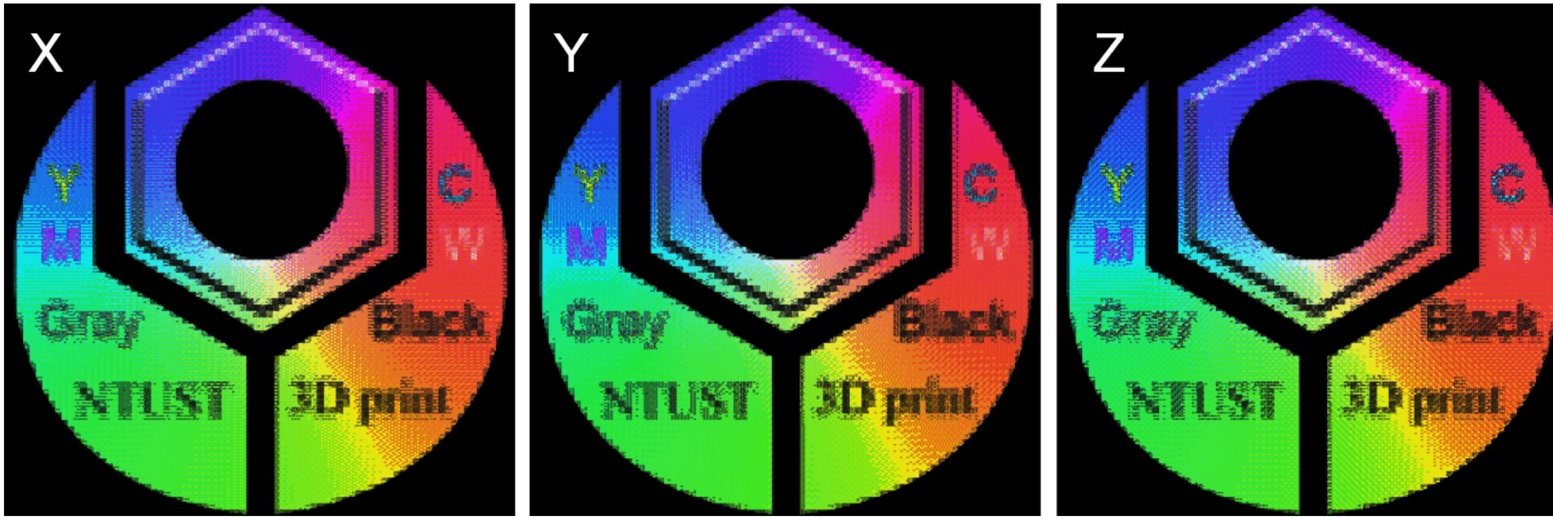
$$\begin{bmatrix} C_{\%} \\ M_{\%} \\ Y_{\%} \\ K_{\%} \\ W_{\%} \end{bmatrix} = \frac{1}{C+M+Y+K+W} \begin{bmatrix} C \\ M \\ Y \\ K \\ W \end{bmatrix}$$

### 4. Quantization

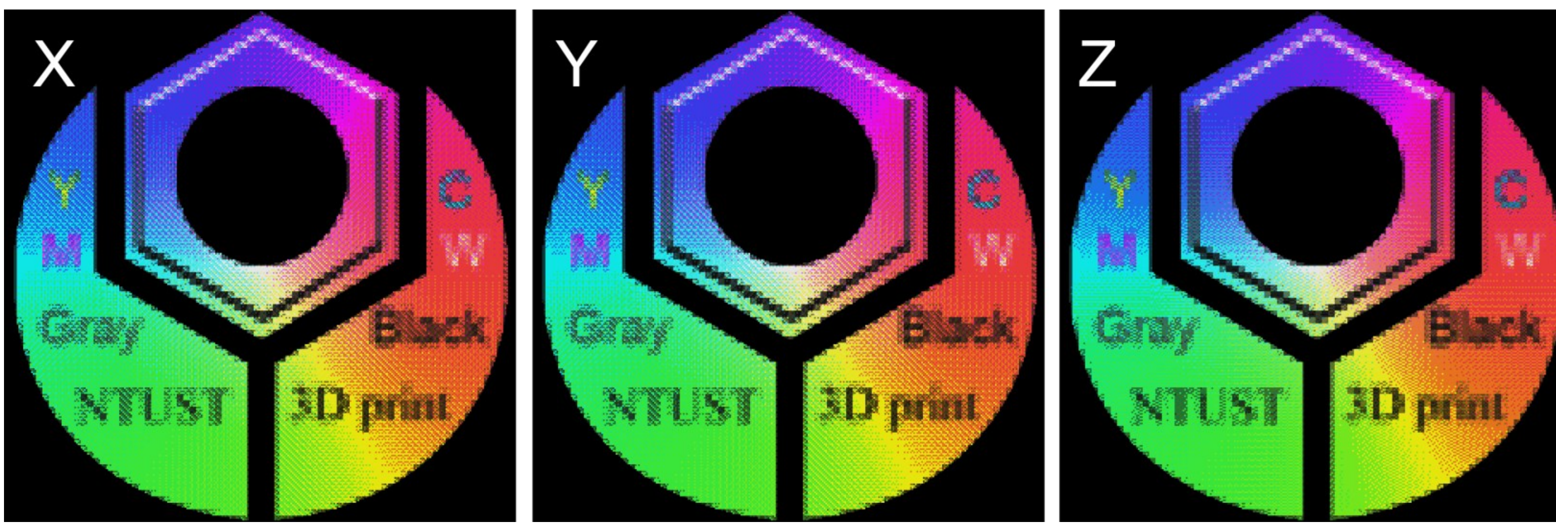
$$\begin{bmatrix} C_n \\ M_n \\ Y_n \\ K_n \\ W_n \end{bmatrix} = round\left\{ 64 \begin{bmatrix} C_{\%} \\ M_{\%} \\ Y_{\%} \\ K_{\%} \\ W_{\%} \end{bmatrix} \right\}$$

# The color order is matter!

CMYK W

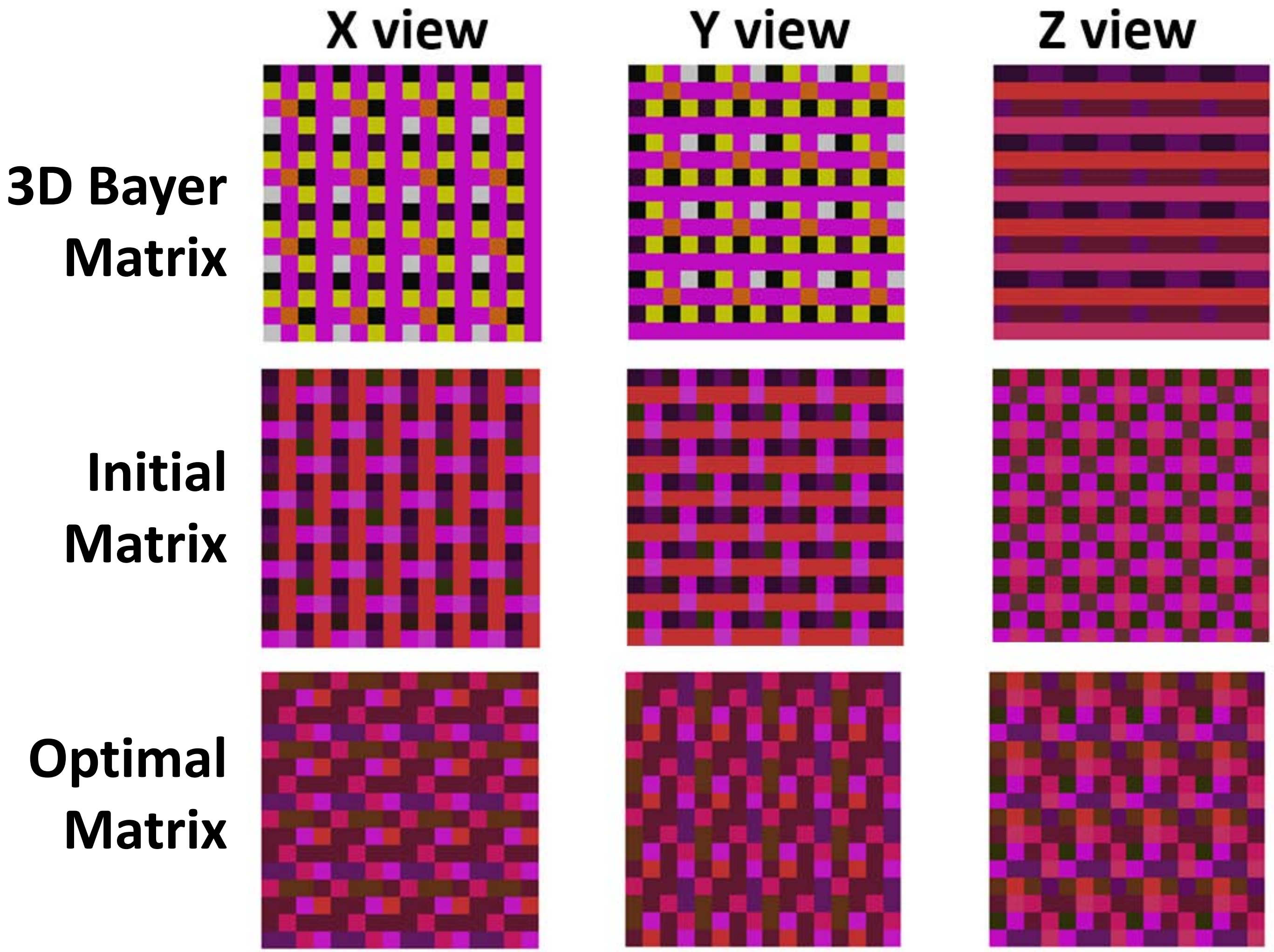



KMCY W



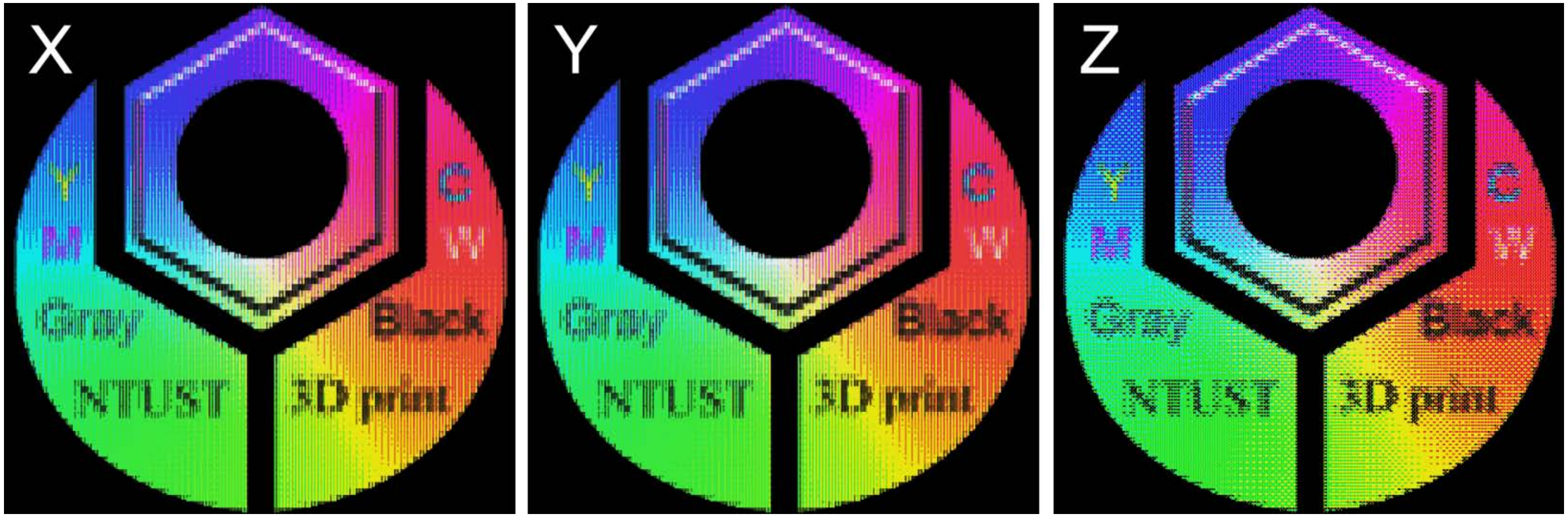
# Comparison

(R, G, B)=(0.8, 0.1, 0.5) as an example

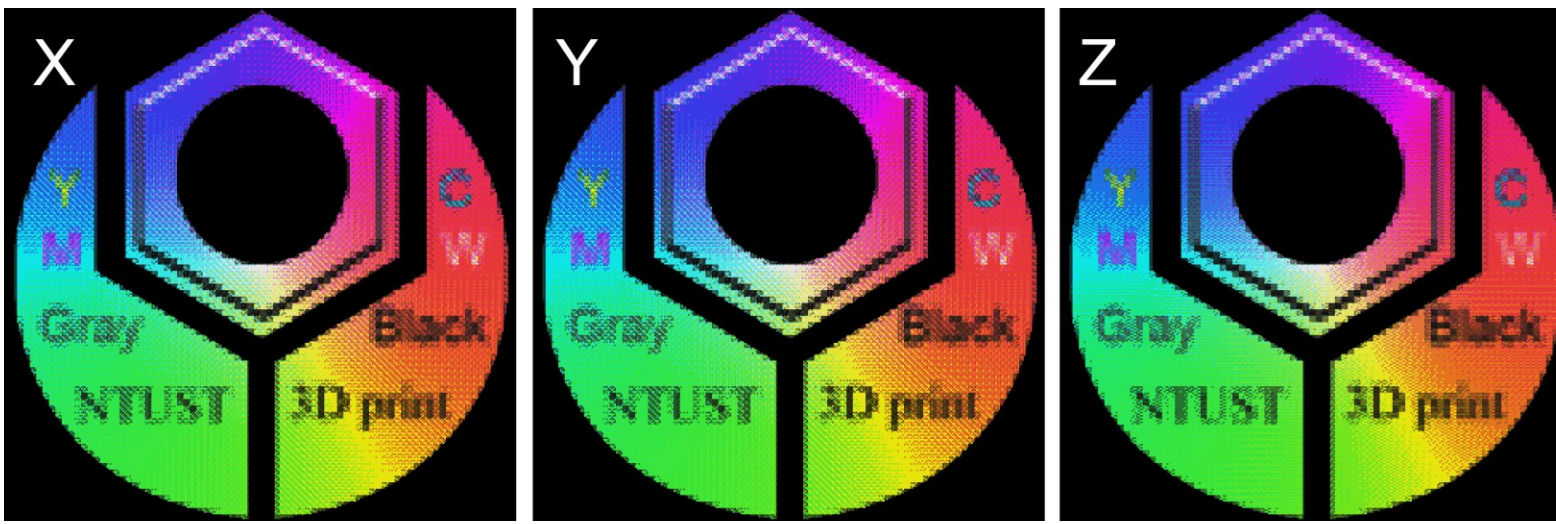


# Comparison

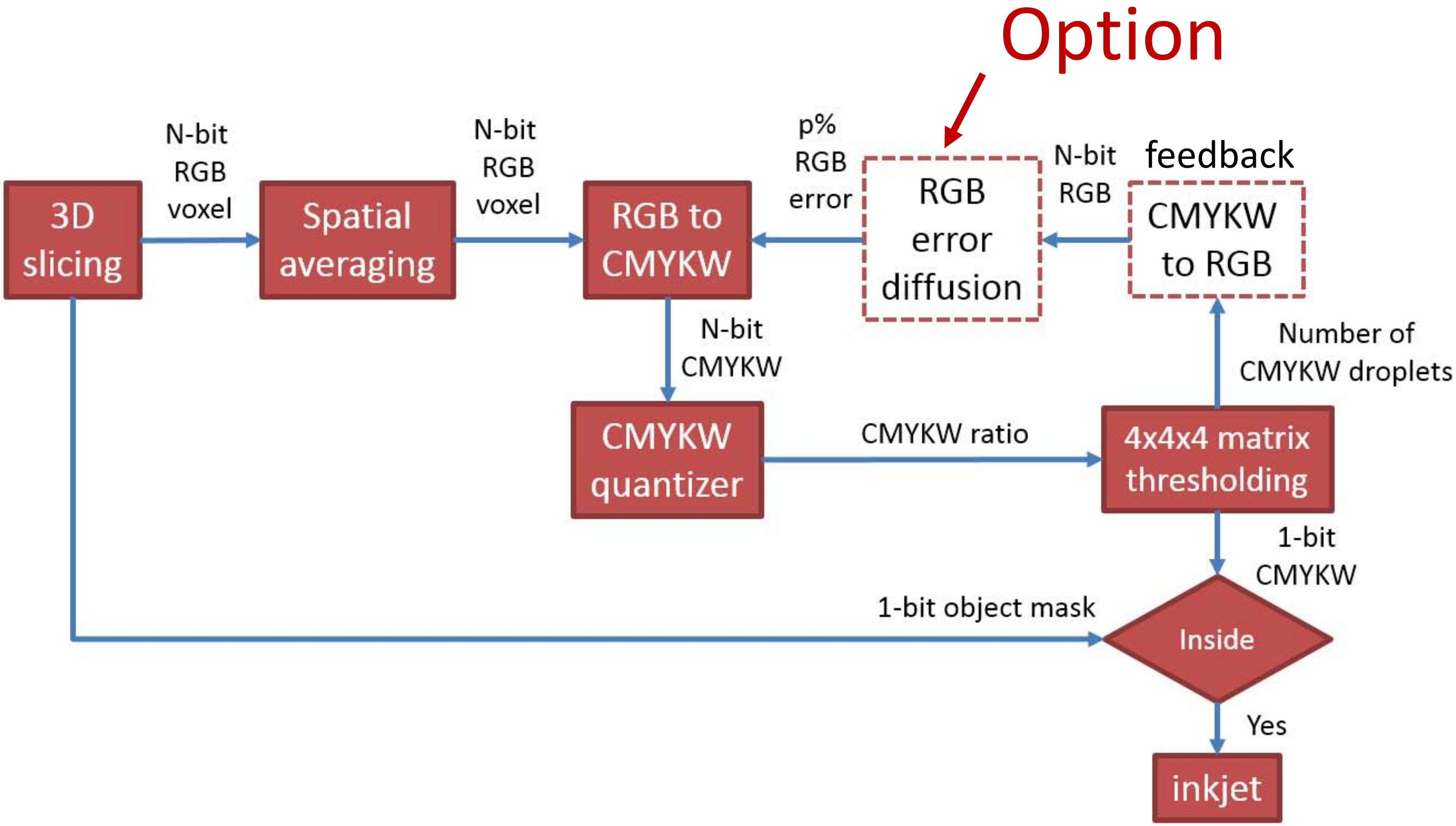
**3D Bayer Matrix**




**Optimal Matrix**

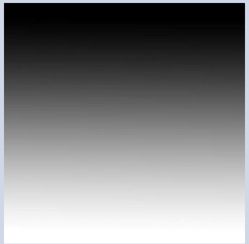


# Workflow

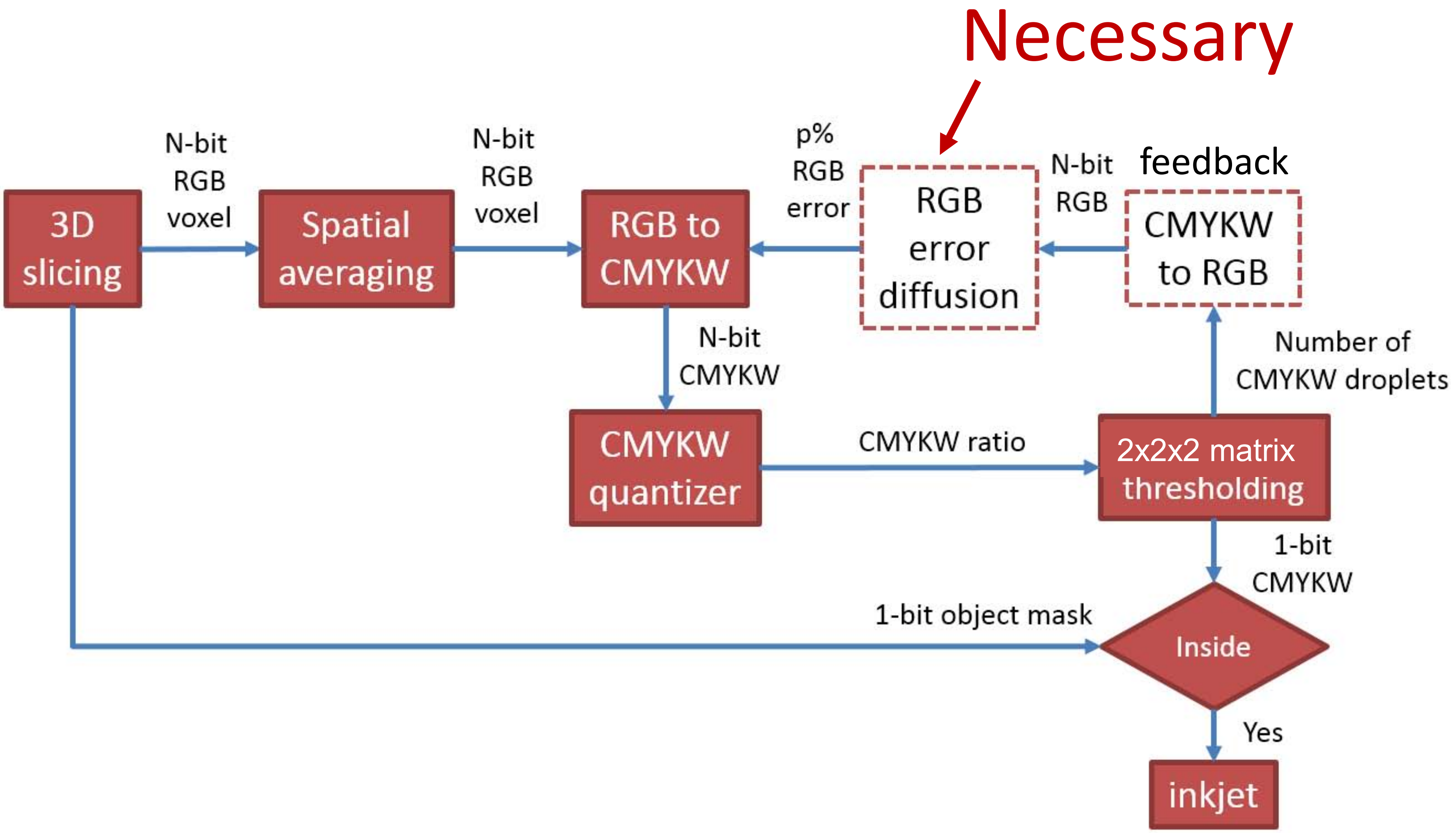

Option
3D slicing
N-bit RGB voxel
Spatial averaging
N-bit RGB voxel
RGB to CMYKW
p% RGB error
RGB error diffusion
N-bit RGB
feedback
CMYKW to RGB
N-bit CMYKW
Number of CMYKW droplets
CMYKW quantizer
CMYKW ratio
4x4x4 matrix thresholding
1-bit CMYKW
1-bit object mask
Inside
Yes
inkjet

# Quantization error with 4x4x4 matrix

Unit: $\Delta E_{RGB}$

| 8-bit (256 level for each channel) | | Primary | Mean | Max |
|---|---|---|---|---|
| **Gray** |  | **KW** | 1.72 | 3.44 |
| **Color** |  | **CMYKW** | 0.45 | 16.06 |

# Workflow


Necessary
3D slicing
N-bit RGB voxel
Spatial averaging
N-bit RGB voxel
RGB to CMYKW
p% RGB error
RGB error diffusion
N-bit RGB
feedback
CMYKW to RGB
N-bit CMYKW
Number of CMYKW droplets
CMYKW quantizer
CMYKW ratio
2x2x2 matrix thresholding
1-bit CMYKW
1-bit object mask
Inside
Yes
inkjet

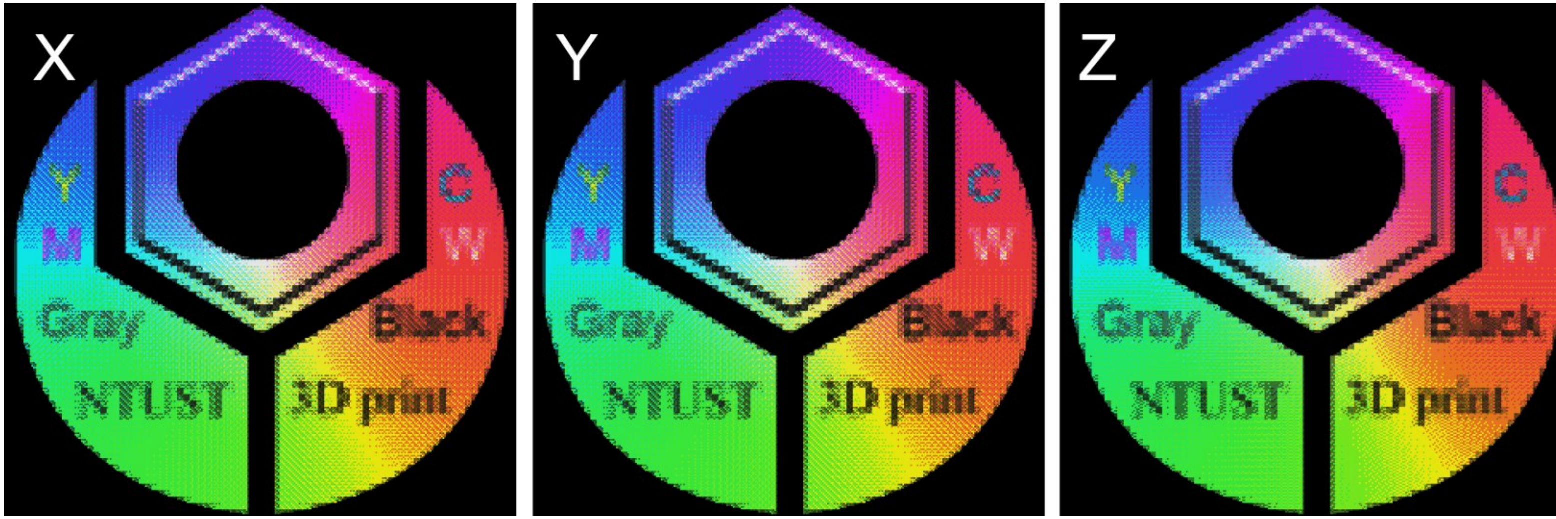
# Quantization error with 2x2x2 matrix

unit: $\Delta E_{RGB}$

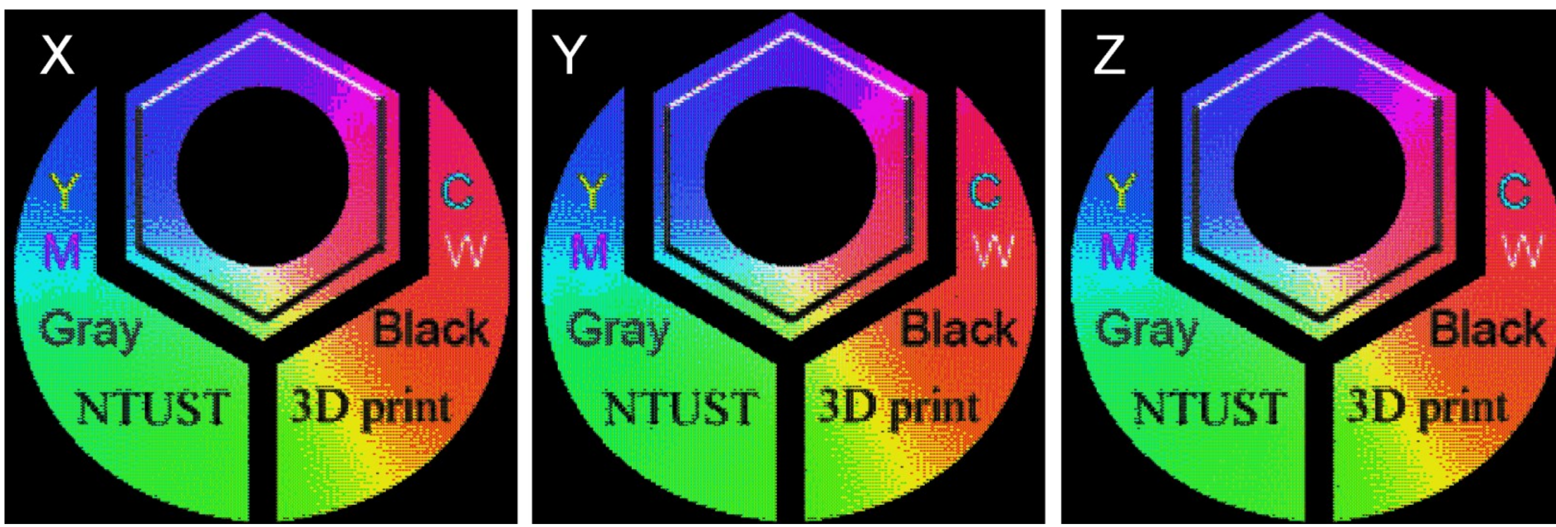
| 8-bit (256 level for each channel) | | Primary | Mean | Max. |
|---|---|---|---|---|
| **Gray** |  | **KW** | 13.75 | 27.50 |
| **Color** |  | **CMYKW** | 3.33 | 87.40 |

# Compare the size of threshold matrix

4x4x4

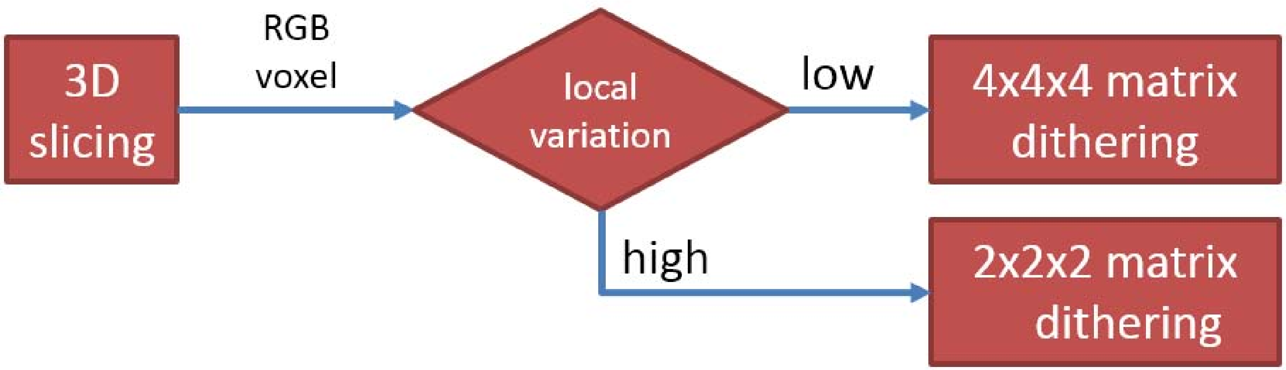


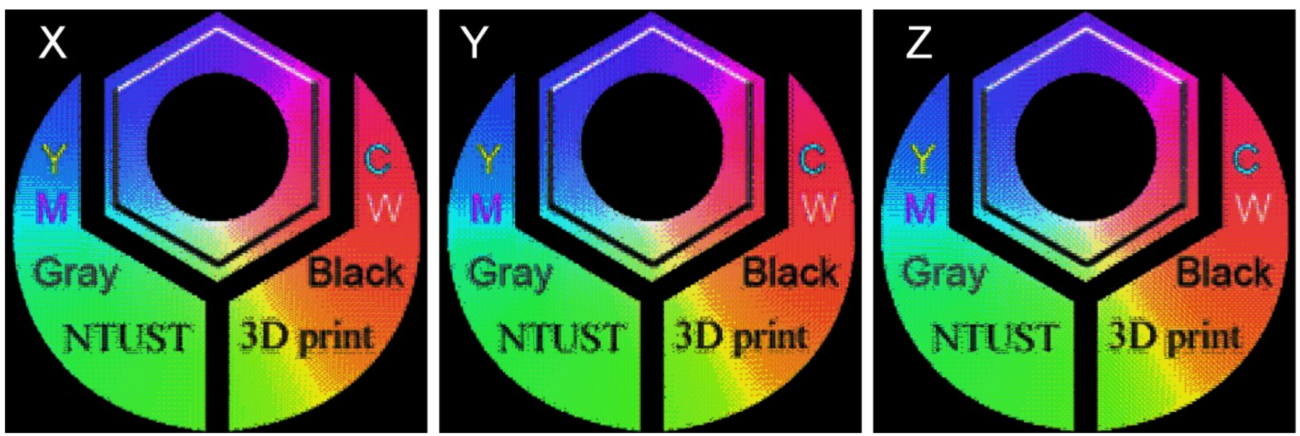

2x2x2




**Lower uniformity, Worm patterns**

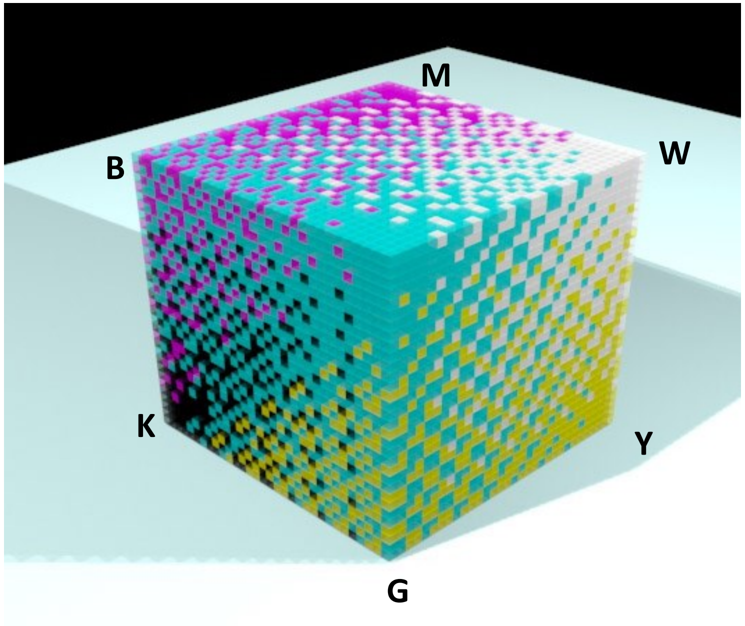
# Hybrid Approach

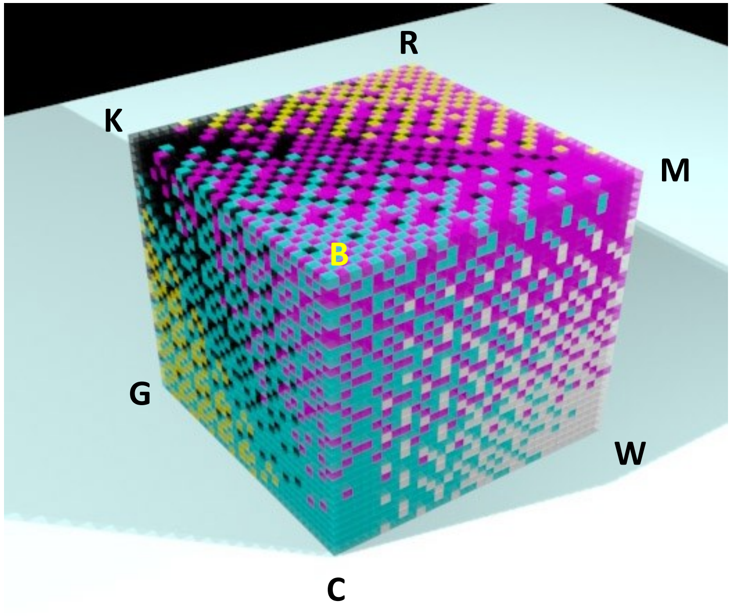



Result in good sharpness and good uniformity

# 3dsMax simulation




8x8x8 input voxels

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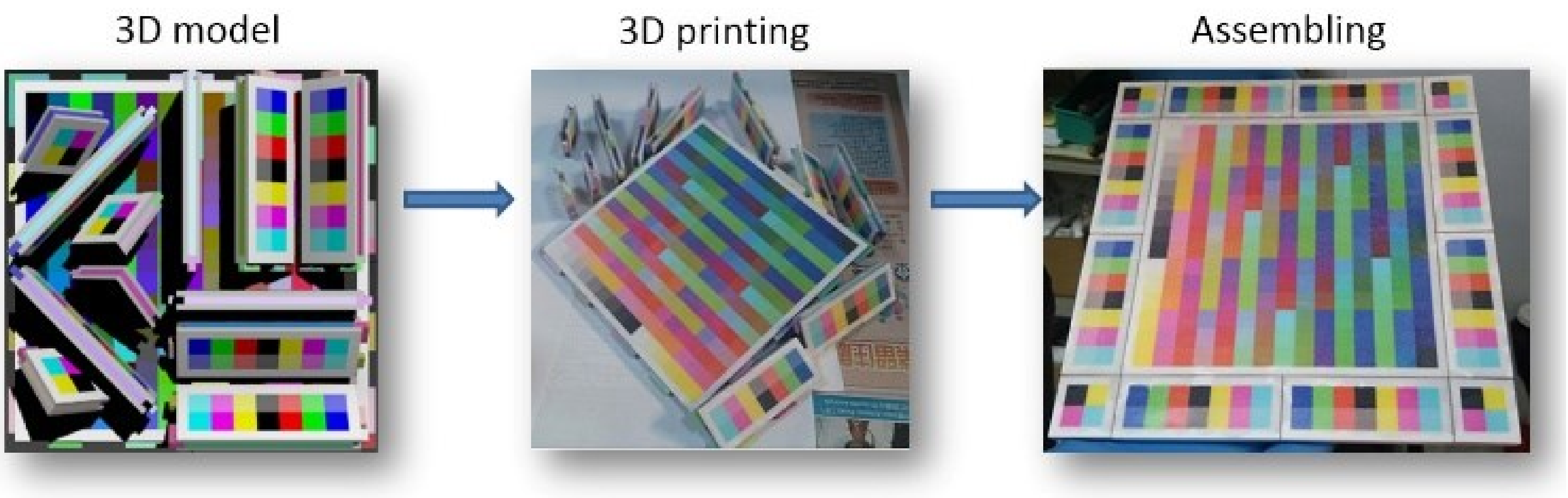
# A test target for estimating multi-directional color differences

# Equipment

3D Systems - ProJet 460 Plus

Powder-Binder Printing

# Patented test target




- 13 pieces, puzzle-like target
- 26 orientations
- Generate ICC profile based on the central puzzle

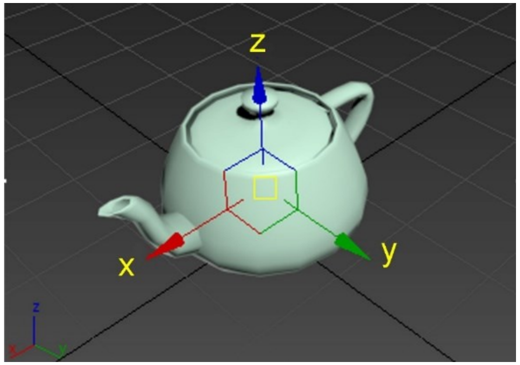
# Compatible to X-rite i1 toolkit

Manual Scan or Auto Scan

- Both sides must be measured.

# Multi-directional color differences

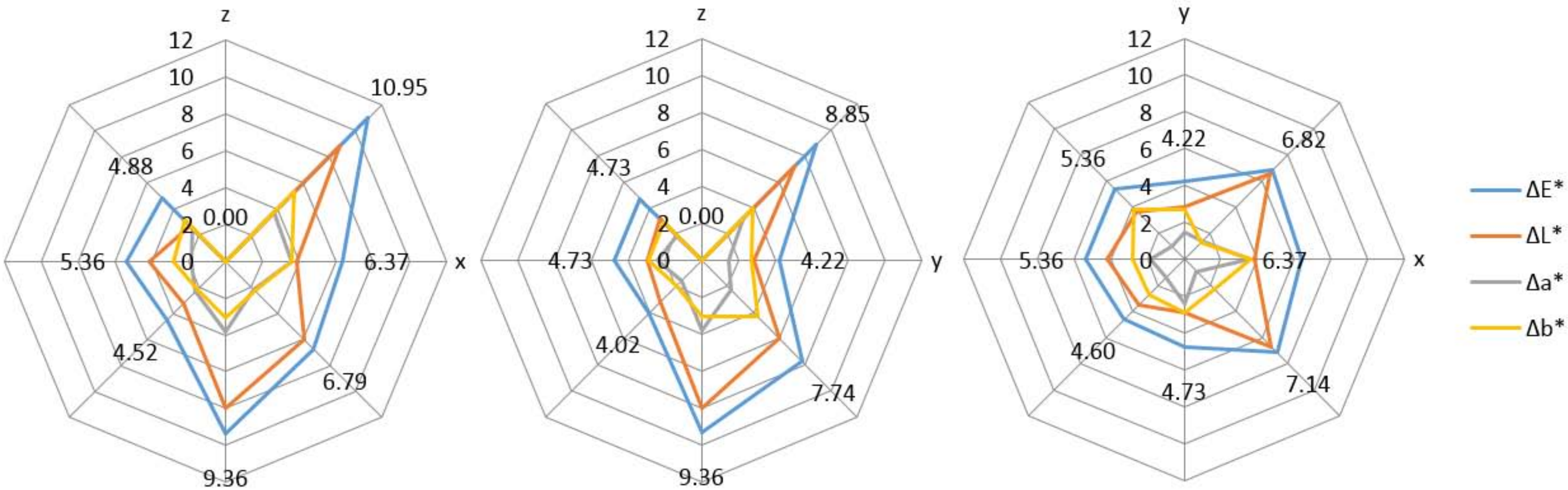
## Compared to the Z direction




X-Z plane

Y-Z plane

X-Y plane




## Mean Errors

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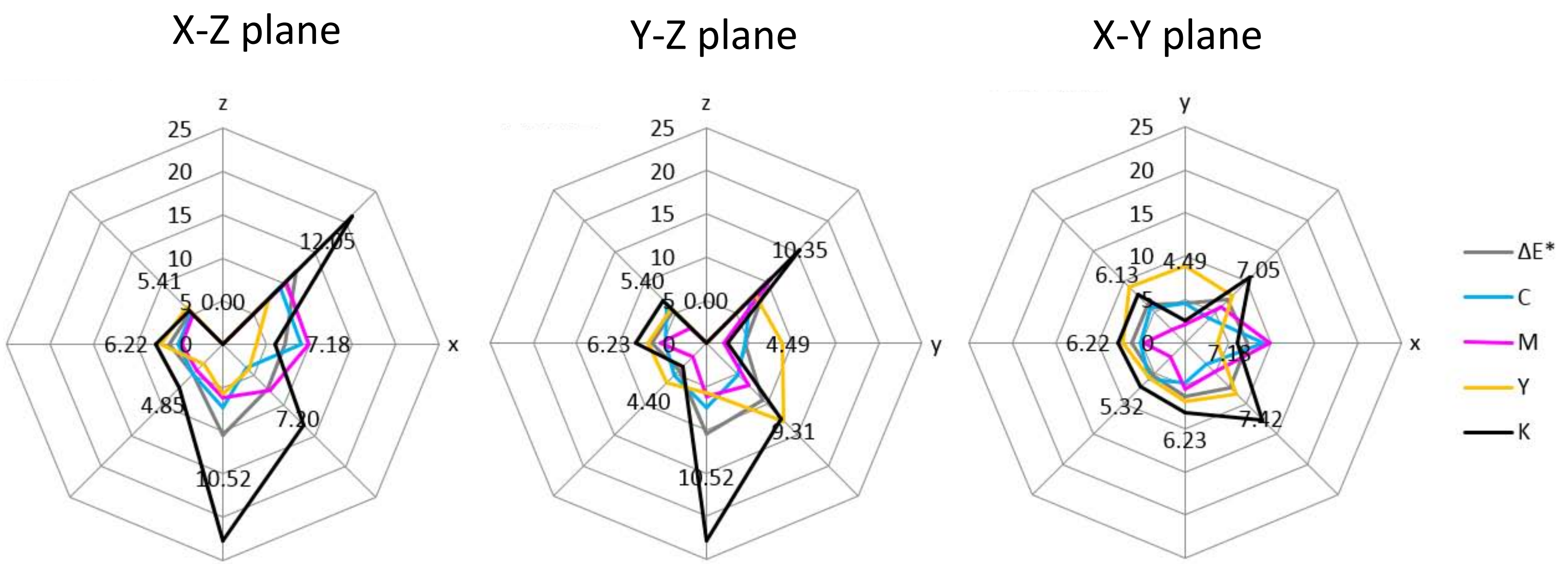
# Multi-directional color differences




## CMYK Errors

## Black is most serious

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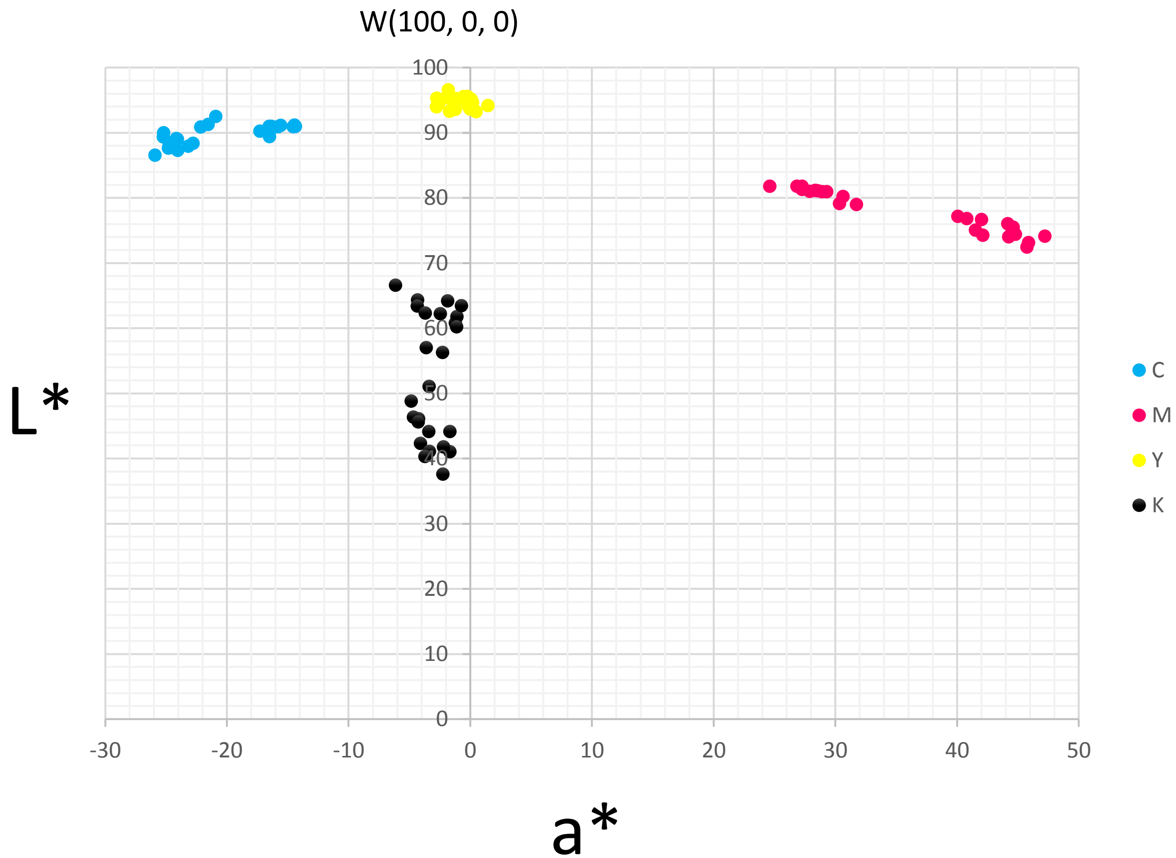
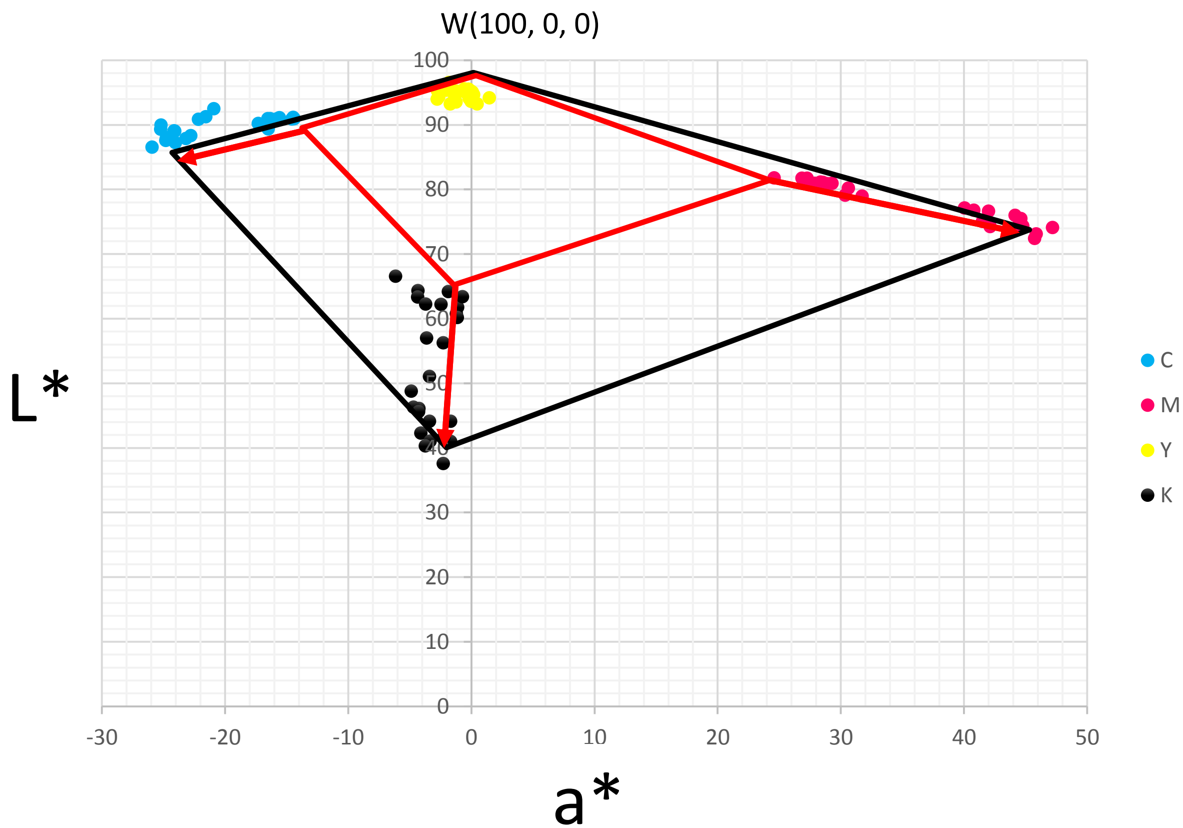
# Omnidirectional Color Correction

# Color variations in (L*, a*) plot



# Gamut scaling toward the white point



# Generate a 2D LUT for compensation

Measure the multi-directional L*a*b* values for CMYK primaries

↓

Averaging the ΔE between the white point and the CMYK primaries

↓

Calculate the ratio of the mean ΔE of orientation (α,θ) to the mean ΔE of the top direction.

↓

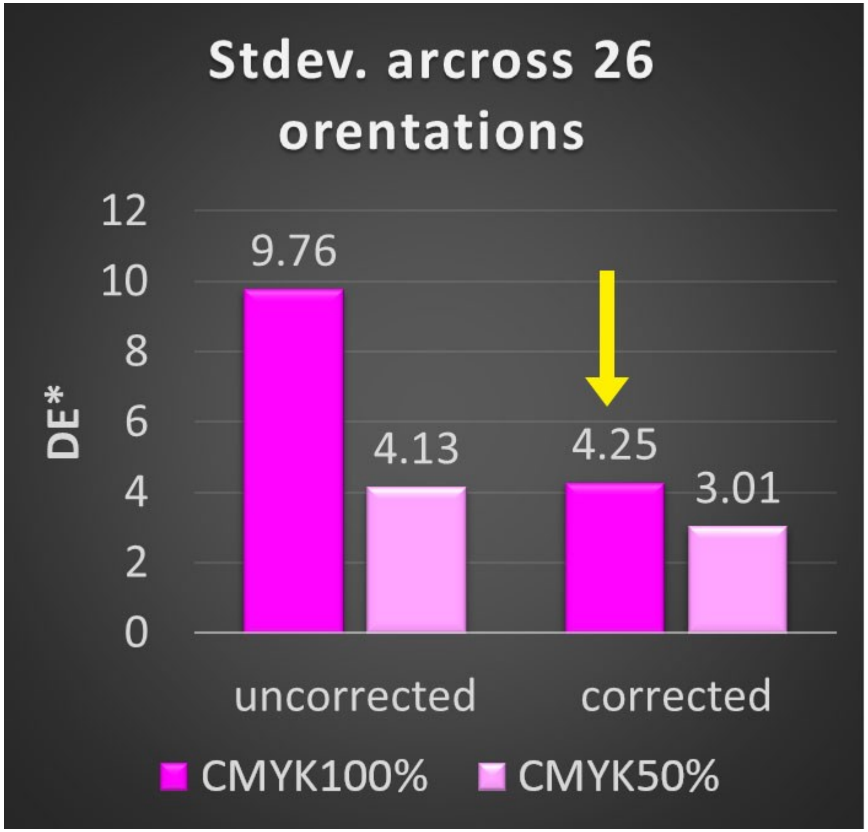
Generate a 5x9 2D LUT to store the ratio **S** for each of the direction.

# Omnidirectional Color Correction

1. Calculate the (α,θ) from the surface normal of the input voxel.
2. Obtain the S value by interpolating the 2D (α,θ) LUT.
3. Modify its LAB value based on the following equation:

$$\begin{bmatrix} L^{*\prime} \\ a^{*\prime} \\ b^{*\prime} \end{bmatrix} = \begin{bmatrix} 100 - s \cdot (100 - L^{*}) \\ s \cdot a^{*} \\ s \cdot b^{*} \end{bmatrix}$$

# Results


Stdev. arcross 26 orentations
DE*
12
10
8
6
4
2
0
9.76
4.13
4.25
3.01
uncorrected
corrected
CMYK100%
CMYK50%

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# Conclusions

# Conclusions

- A **hybrid 3D color dithering method** is proposed to improve image quality of a UV-curing photopolymer 3D inkjet system.
- It uses two different sizes of optimal threshold matrices to perform color halftoning in **KMCYW** order.
- A **Multi-directional Color Target** was designed to estimate color performance of surfaces in 26 directions.
- A **omnidirectional color correction method** also is proposed to improve the color consistency of the color across different faces of a 3D print.

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Thank you for your listening

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