Image Processing and Computer Vision for Hardware Assurance

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Image Processing / Computer Vision

- **Image Processing (IP):**

  The processing of images using mathematical operations by using any form of signal processing for which the input is an image, a series of images or a video, such as a photograph or video frame; the output of image processing may be either an image or a set of characteristics or parameters related to the image. [1]

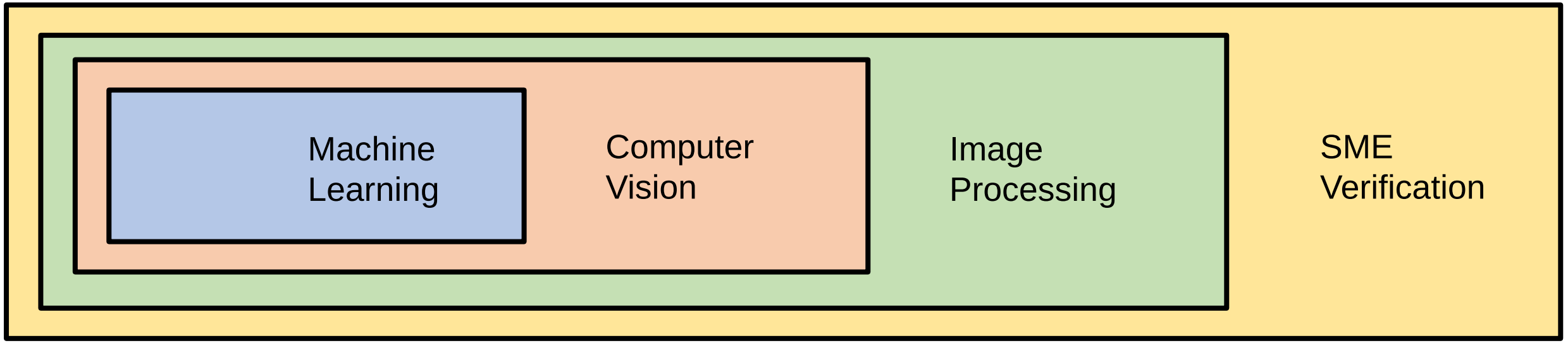
  Basically: image in, image out

- **Computer Vision (CV):**

  An interdisciplinary field that deals with how computers can be made for gaining high-level understanding from digital images or videos. From the perspective of engineering, it seeks to automate tasks that the human visual system can do. [1]

  Basically: image in, knowledge out

IP/CV Role in HW Assurance [2]



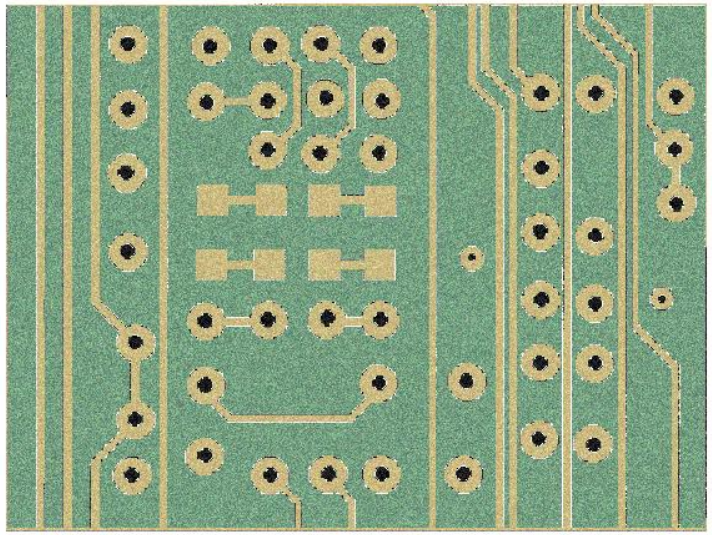
Stage Name	Machine Learning	Computer Vision	Image Processing	SME Verification
Used For	Sample Classification	Feature Extraction	Preprocessing	Multipurpose
Characteristics	• Can be fully automated • SME only needed for periodic random sampling • Widest range of applicability	• Start of automated assurance • Output no longer resembles an image • Only minor SME input required	• Clean noise in input image • Enhance appearance of defects • Still requires SME input	• Burden of assurance is completely on the human • Only useful for low-throughput supply chains • Highly prone to error

IP/CV Applications in HW Assurance [3]

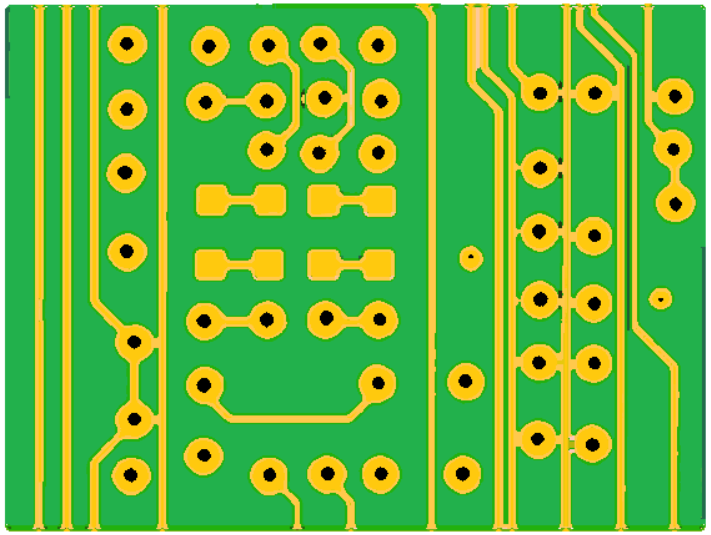
- **IC/PCB Verification Enhancement**
  - Preprocessing
  - Difference Imaging
  - Thresholding
  - Fault Detection
  - SME Verification

IC/PCB Verification: Preprocessing

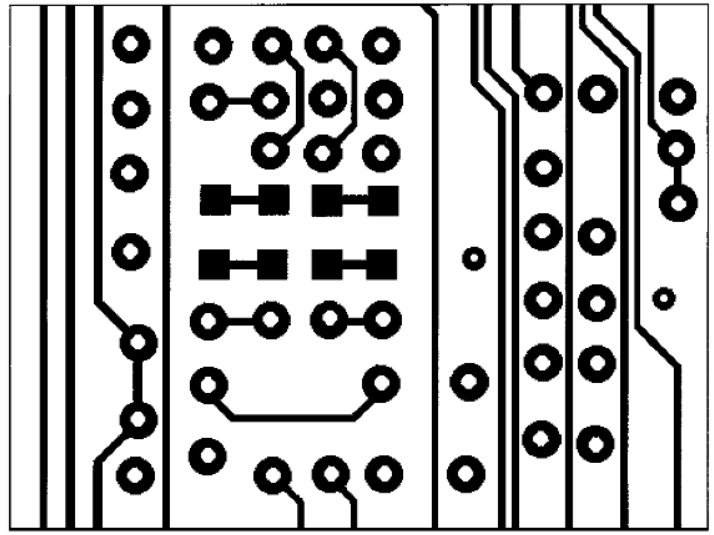
Original Image



Enhanced Image



Processed Image

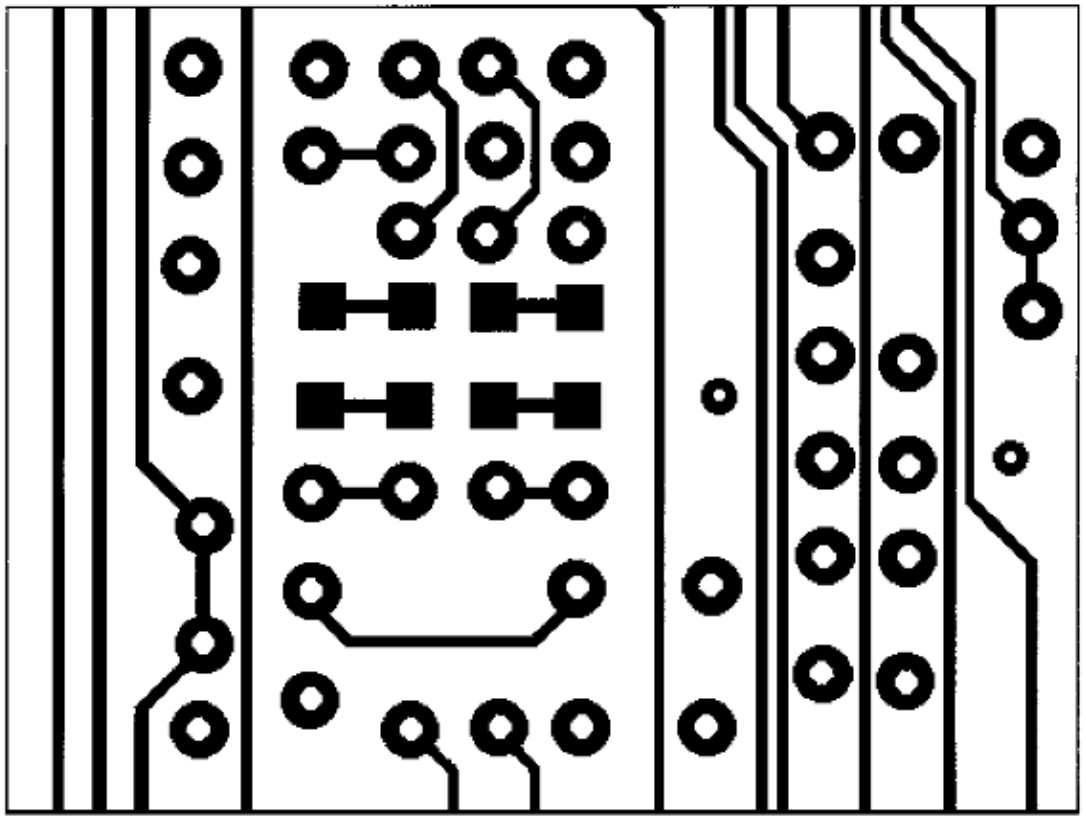


Deblurring,
Color Enhancement

Color Thresholding,
Binary Morphological
Image Processing

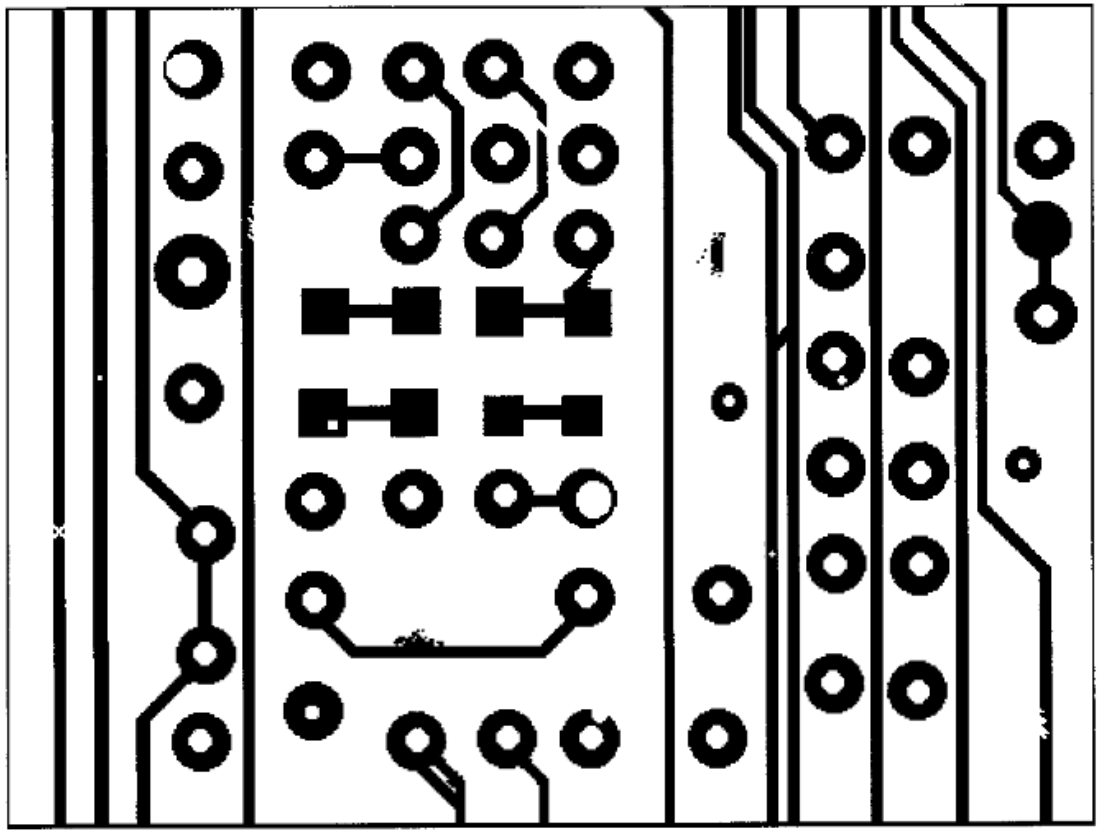
IC/PCB Verification: Difference Imaging and Thresholding

Processed Golden Sample



XOR

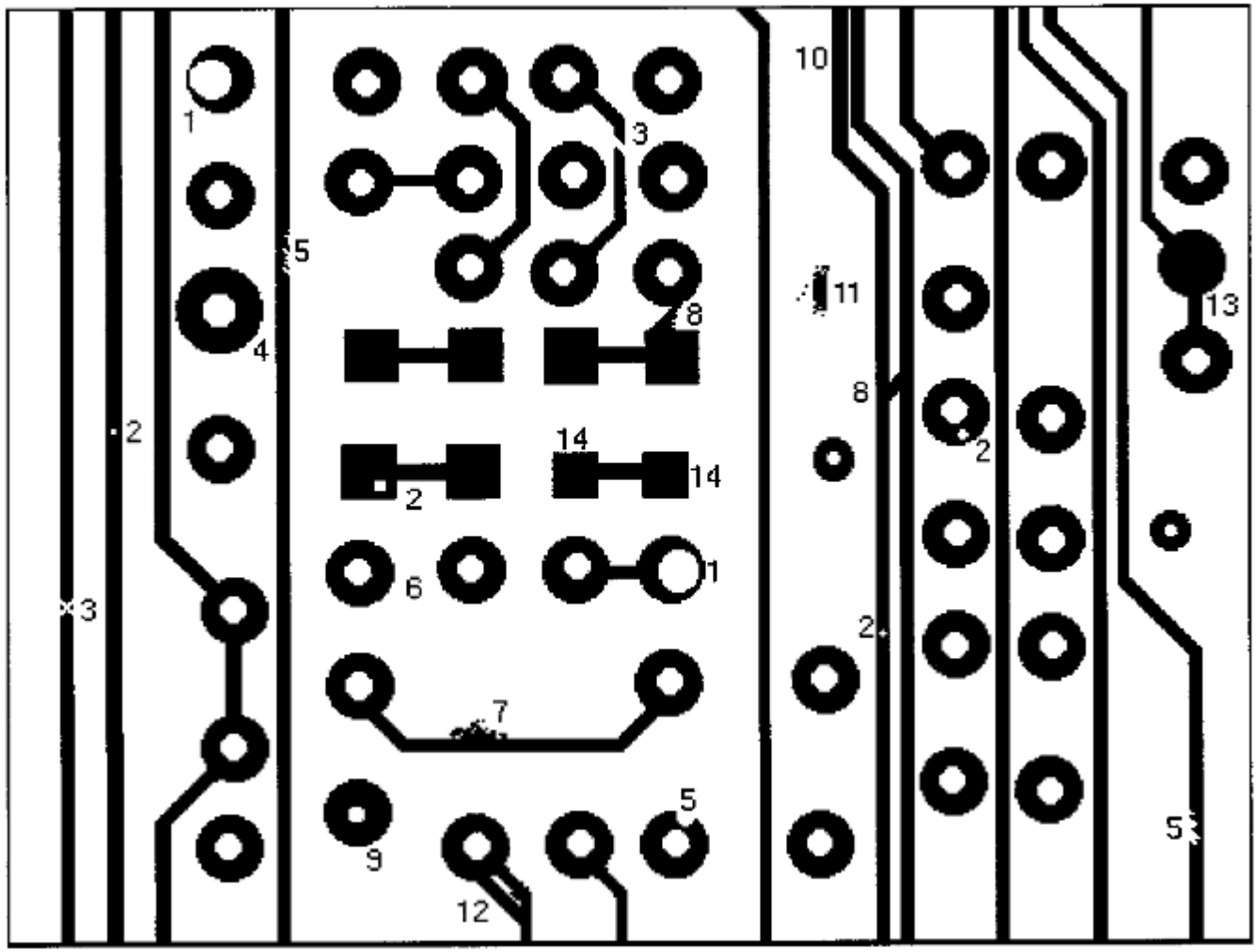
Processed Test Sample



Spot the difference!

IC/PCB Verification: Fault Detection and SME Verification

Detected Faults



SME Notes

1. Breakout
2. Pin Hole
3. Open Circuit
4. Underetch
5. Mousebite
6. Missing Conductor
7. Spur
8. Short
9. Wrong Size Hole
10. Conductors too close
11. Spurious copper
12. Excessive Short
13. Missing Hole
14. Overetch

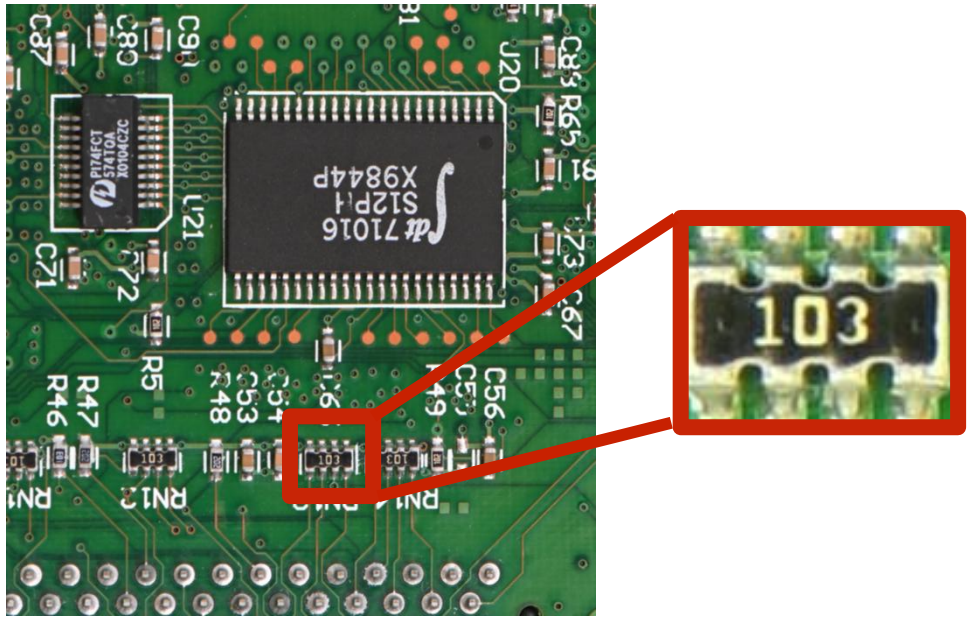
IP/CV Applications: What if there is no Golden?

- **Bill of (BoM)**
  - **Definition**: list of all components present on a PCB, such as resistors, capacitors, and Integrated Circuits (ICs) [4]
  - **Applications** [5]:
    - Hardware Assurance (e.g. detection of hardware Trojans, tampering, or other malicious modifications)
    - reverse engineering (e.g. analysis of foreign, competitor, or legacy devices)
    - industrial assessment (e.g. cost estimation, quality assurance)
    - academia (e.g. technology trend analysis)

- **Goal: Automatic BoM Extraction (AutoBoM)**

AutoBoM Idea

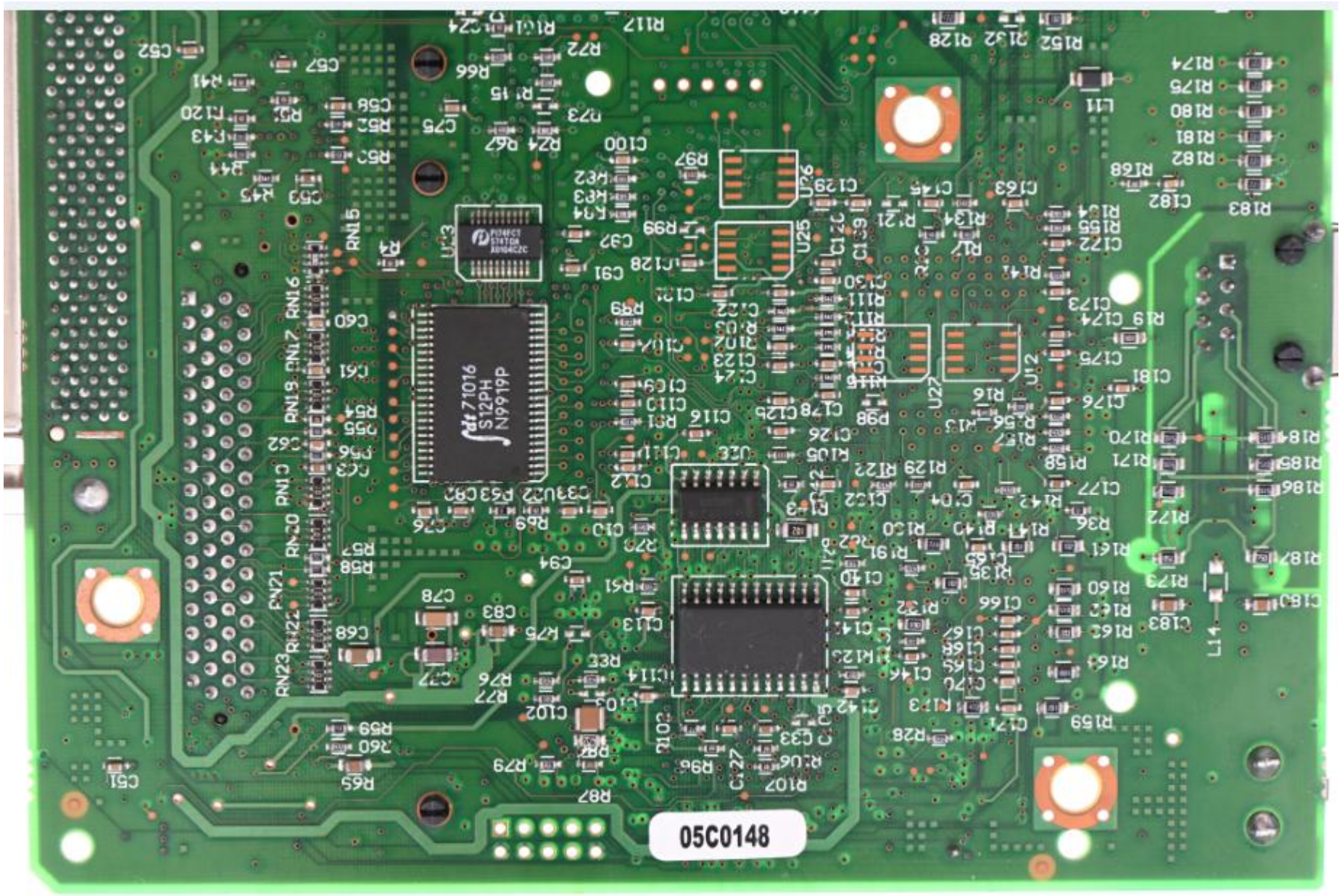
- **Component Detection**
  - Localize the components
- **Component Classification**
  - Determine what type each component is
- **Component Identification**
  - Determine enough info about each component to roughly purchase the exact materials



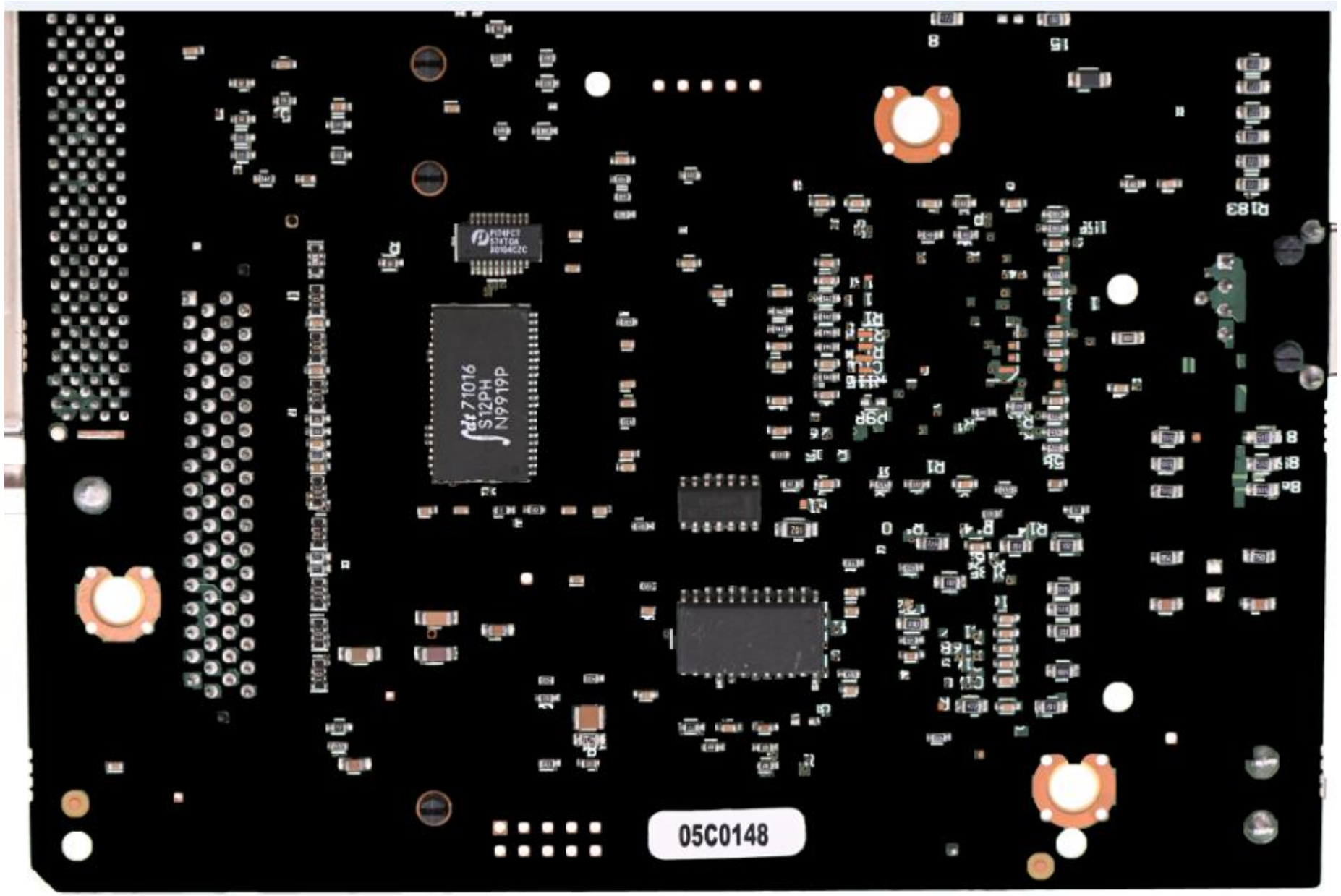
Resistor

103 Ohm Resistor Network

AutoBoM: Component Detection



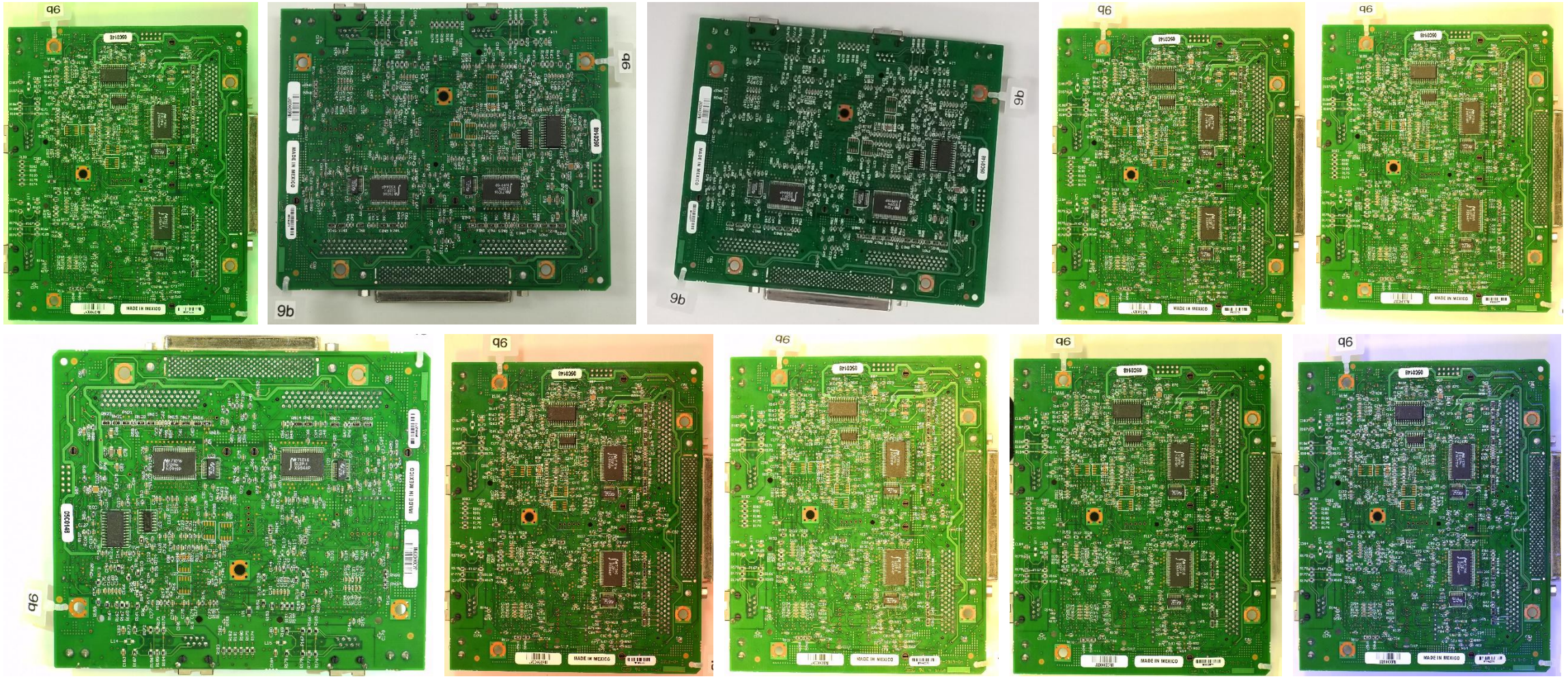
AutoBoM: Component Detection



> 99% accuracy

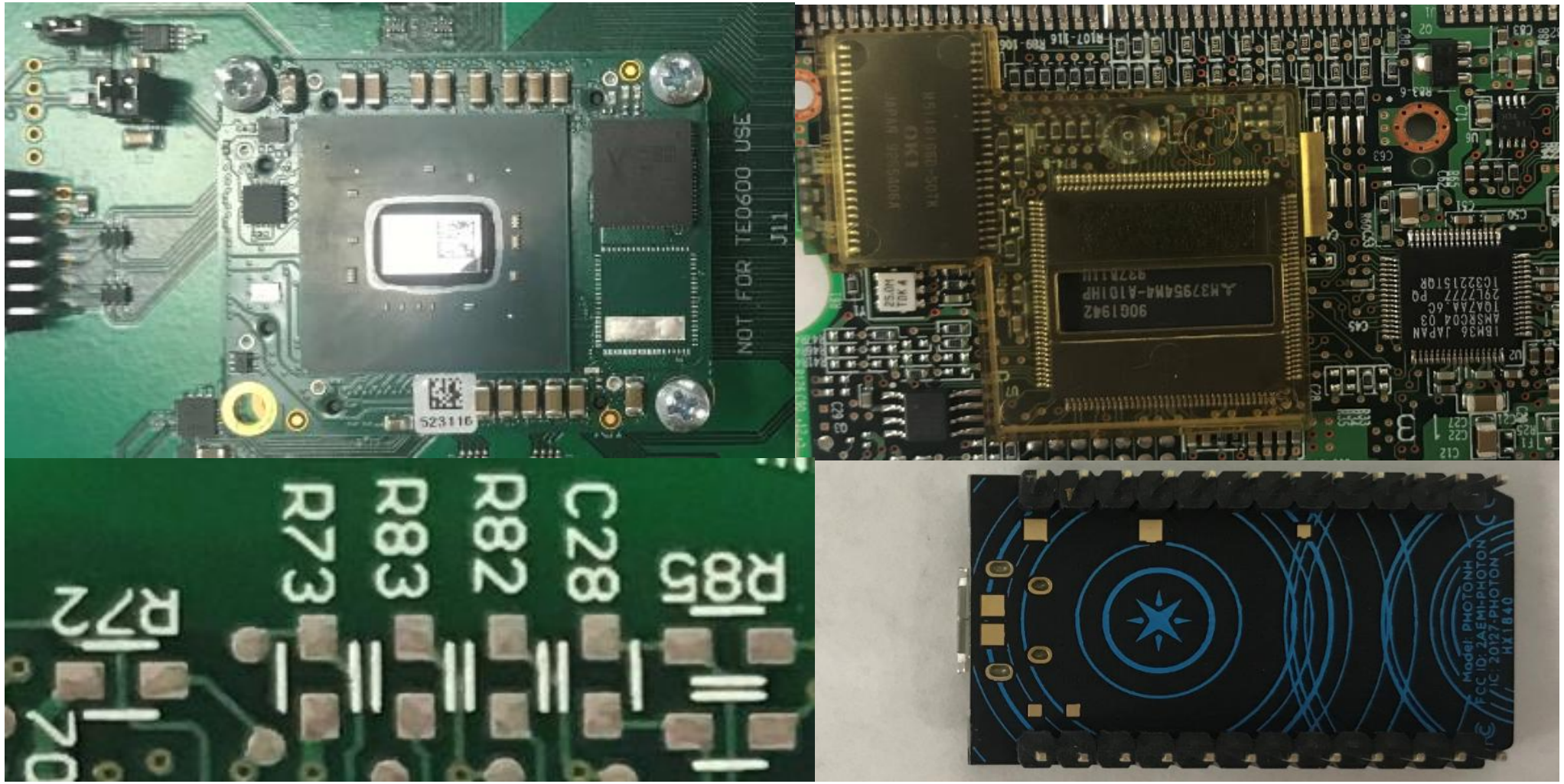
AutoBoM: Component Detection Challenges

- **Imaging Conditions:** camera type, lighting intensity, lighting color



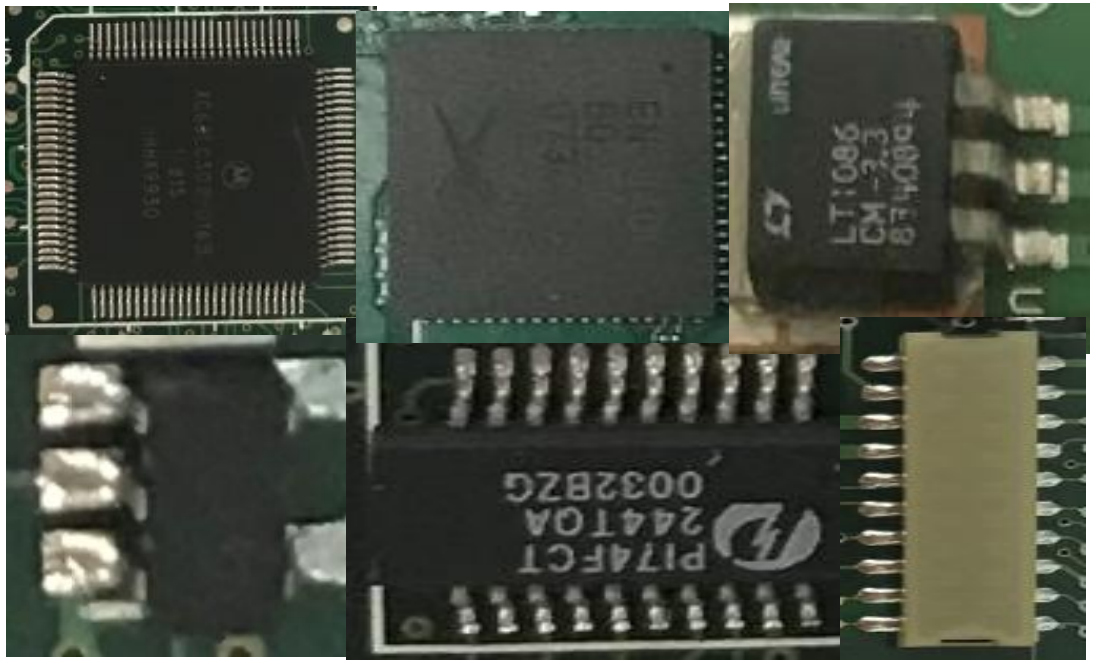
AutoBoM: Component Detection Challenges

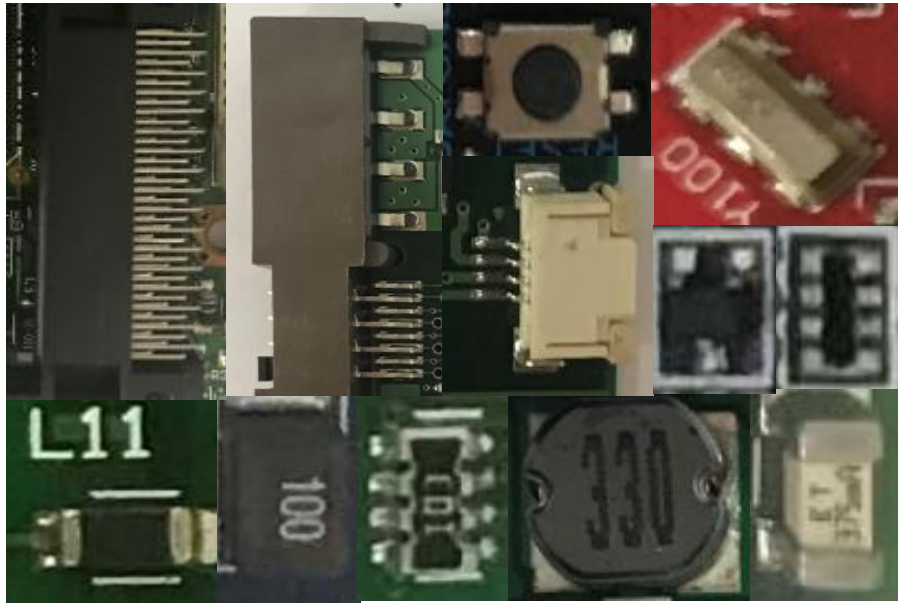
- **Inherent Board Variations**

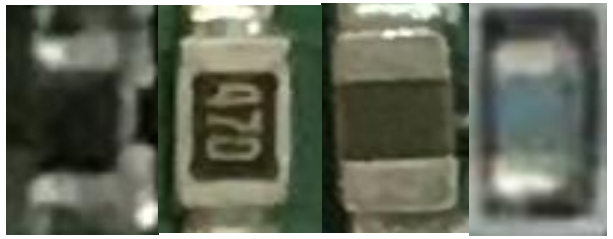


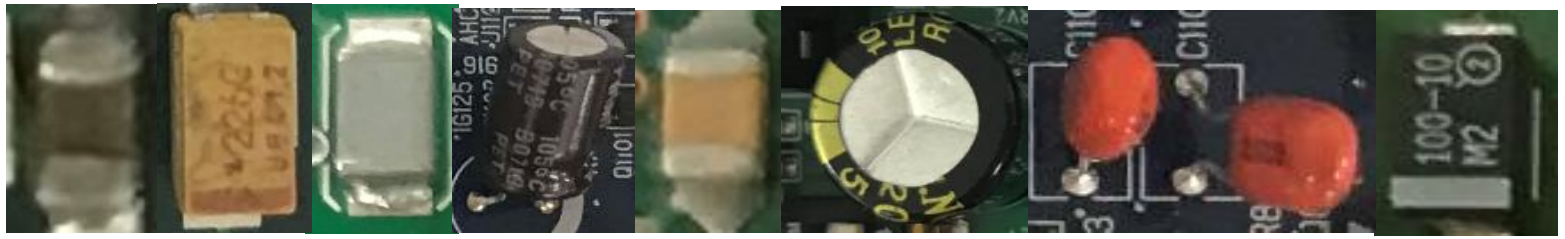
AutoBoM: Component Detection Challenges

- **Inherent Component Variations**

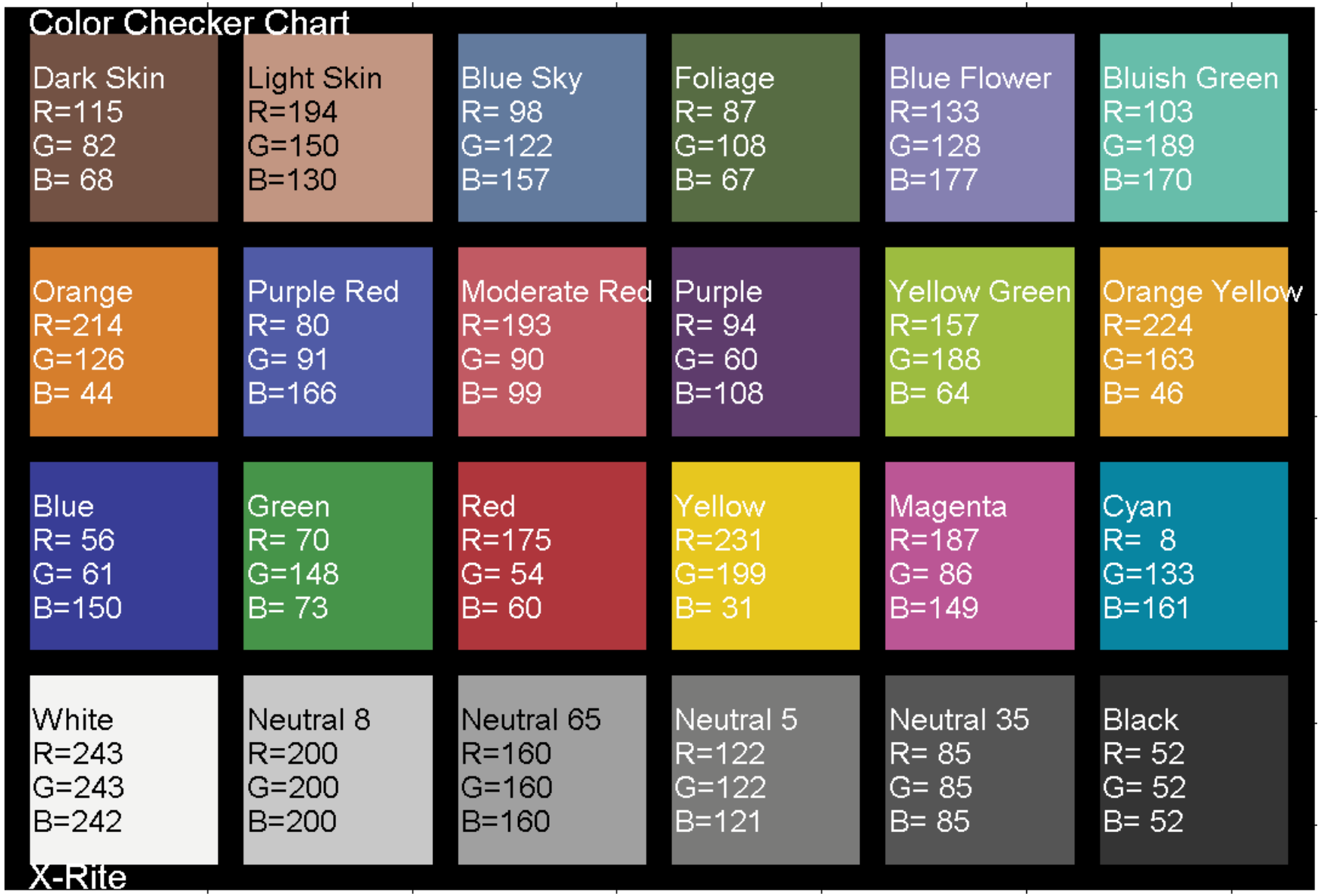




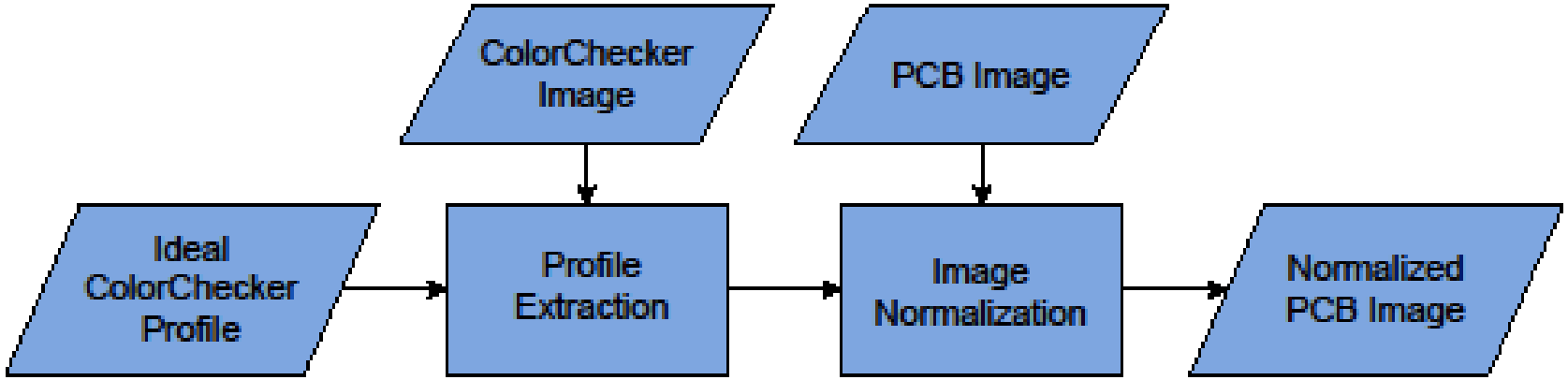


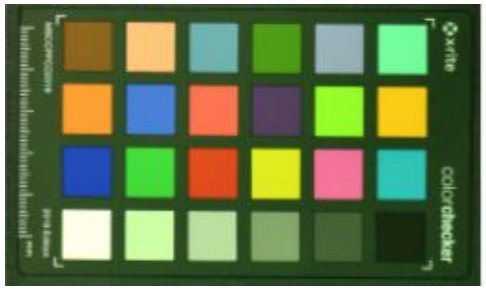


Imaging Conditions Solution: Color Checkers [6]

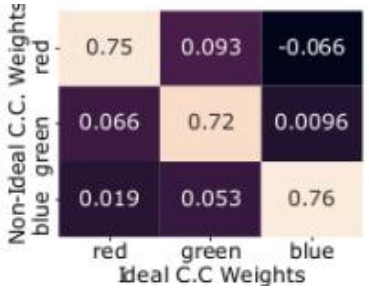


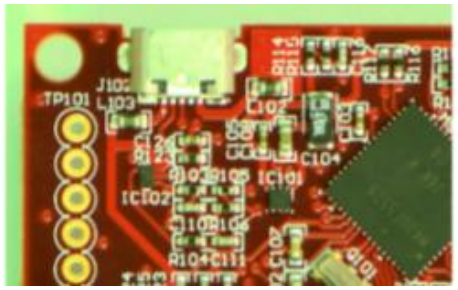
Imaging Conditions Solution: Color Checkers





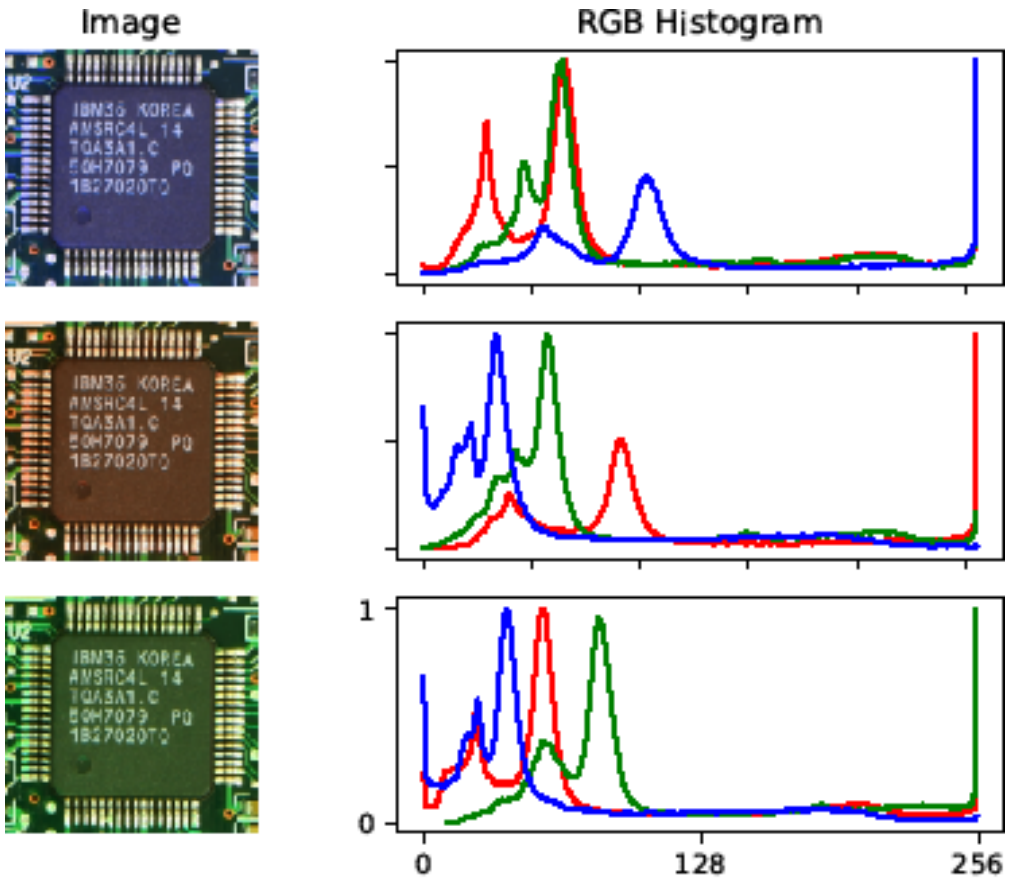
Solve Linear Regression



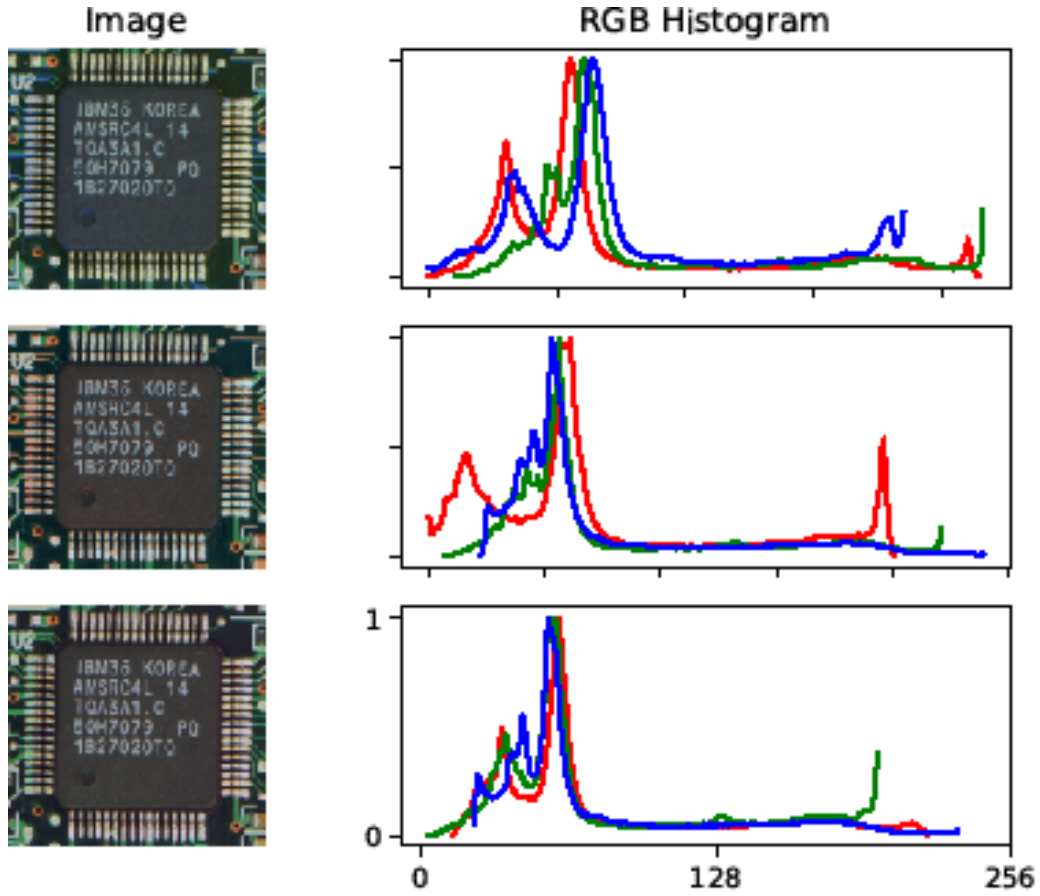


Imaging Conditions Solution: Color Checkers

Before Normalization



After Normalization



Much Better!

IP/CV Limitations

- LOTS of tuning required:
  - Color threshold
  - Enhancement parameters
  - Morphological image processing filter sizes
  - Etc. etc. etc.

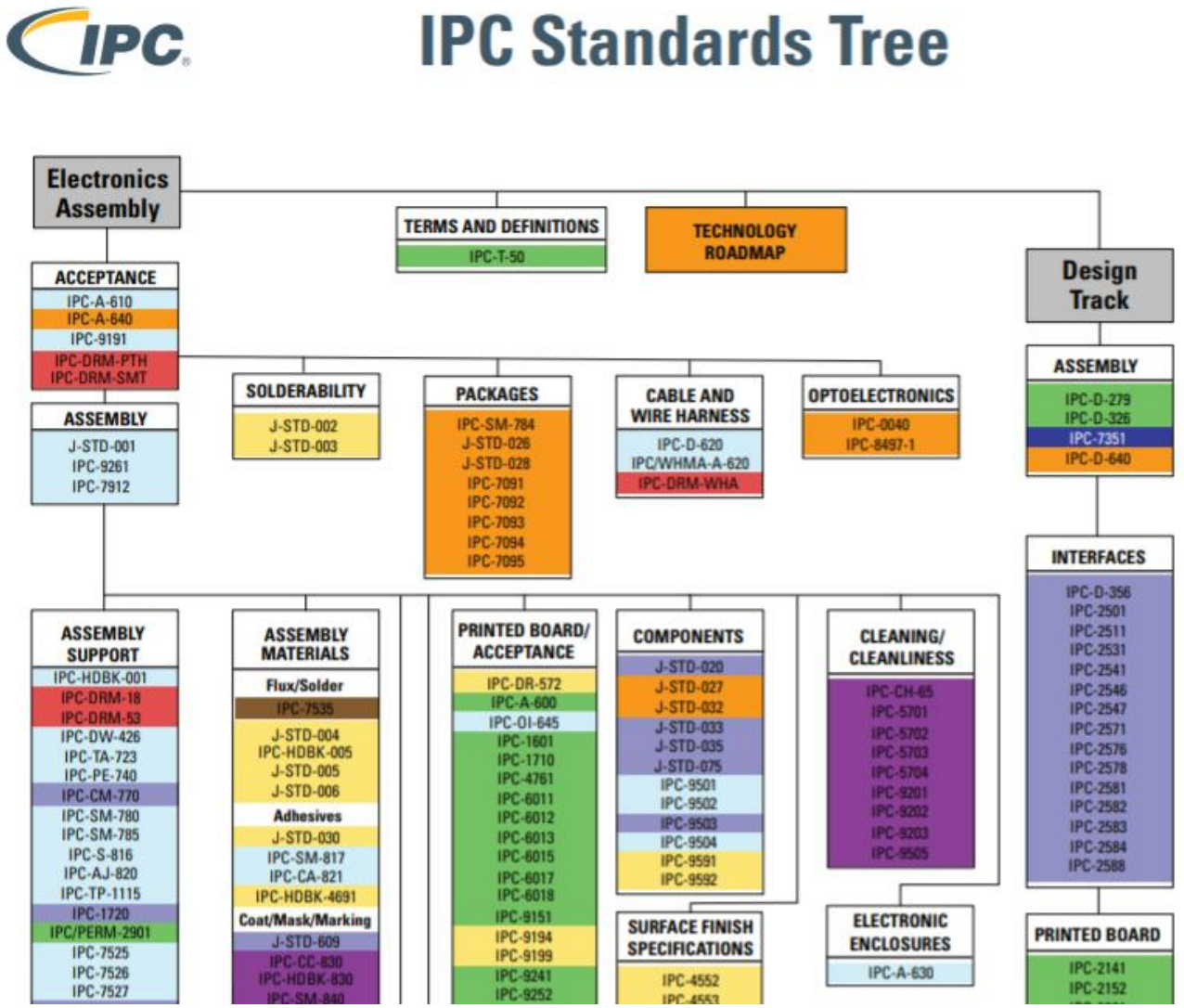
- **IP/CV, alone is not sufficient to handle inherent board or component variations. What is?**

Machine Learning: Oversimplified

- **Machine Learning (ML):**
  - Analogy: child that's really really good at math → good at seeing patterns
  - BUT, child trusts everything you tell them → information (data) you give it must be VERY helpful
- Challenge: Memorization, but cannot extrapolate (overtraining)
  - Solution 1: MORE DATA (expensive)
    - Give the ML algorithm more examples and it learns…
  - Solution 2: Incorporate domain knowledge
    - Help the ML algorithm determine what to study

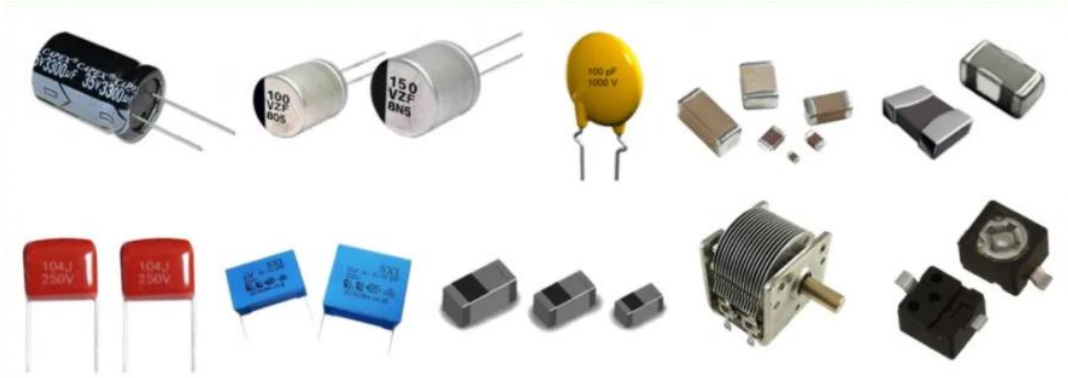
Machine Learning: Domain Knowledge

- **PCB Design Best Practices**
- **CAD Design Rule Checks**
- **Institute of Printed Circuits (IPC) Standards**
  - Participating Companies: Agilent, Apple, Boeng, Cisco, Dell, GE, Hewlett-Packard, IBM, Intel, Lenovo, Logitech, Microsoft, Motorola, Thermo Fisher, Xerox, etc. [7]



Human-Encoded Knowledge [8]

- **Example: consider just resistors and capacitors**
  - **Large variety…**



  - **BUT, >90% look like this**

Human-Encoded Knowledge [8]

- **What differences do you spot?**

Human-Encoded Knowledge [8]

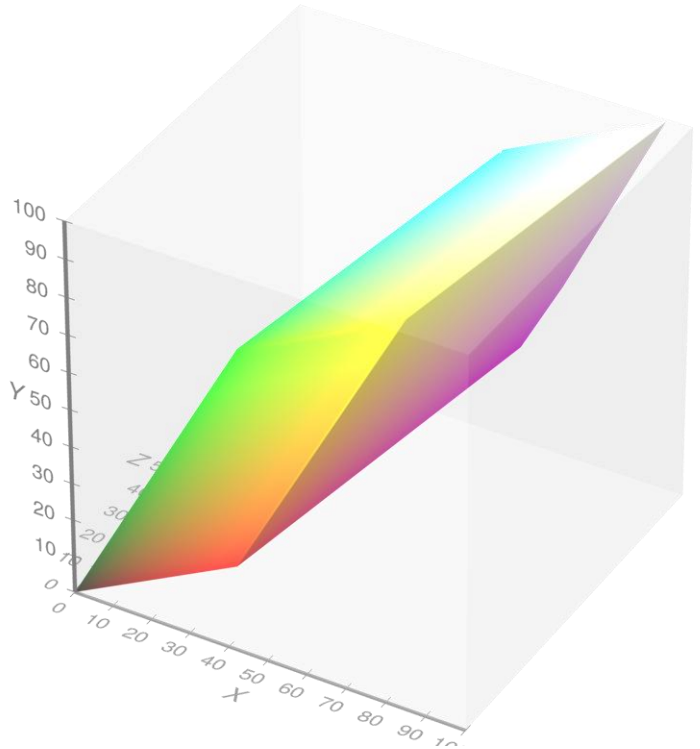
IP/CV!

- **What differences do you spot?**
  - **resistors tend to be black, capacitors tend to be brown, tan, or grey**
  - **resistors tend to have text, capacitors do not**
  - **resistors tend to be more rectangular, capacitors tend to be more rounded**

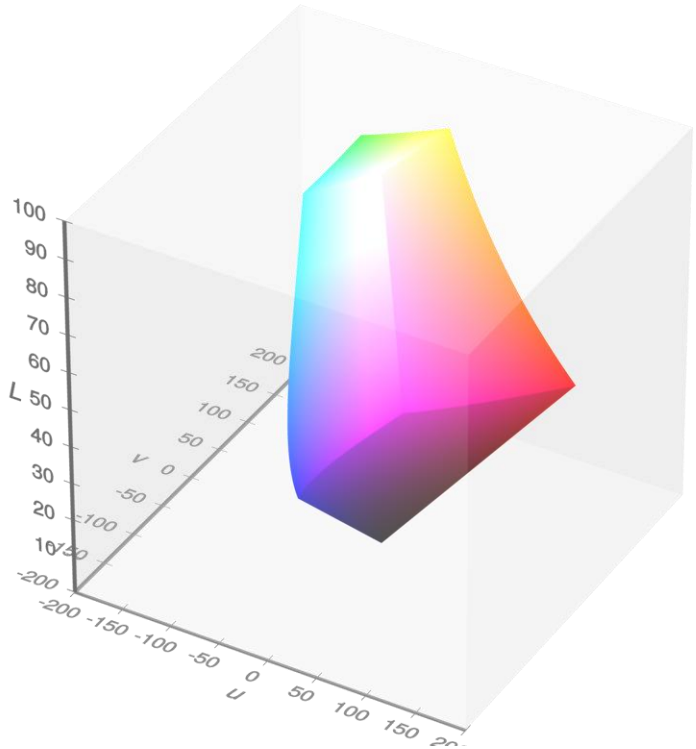
→ color
→ texture
→ shape

IP/CV: Color

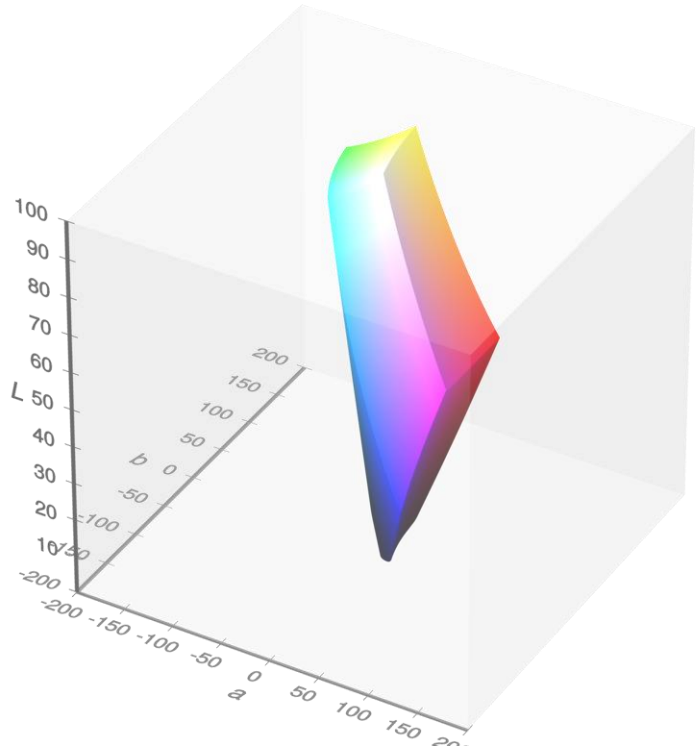
- **Color Model** = abstract numerical model that describes and organizes colors in a quantitative manner



CIE XYZ



CIE LUV

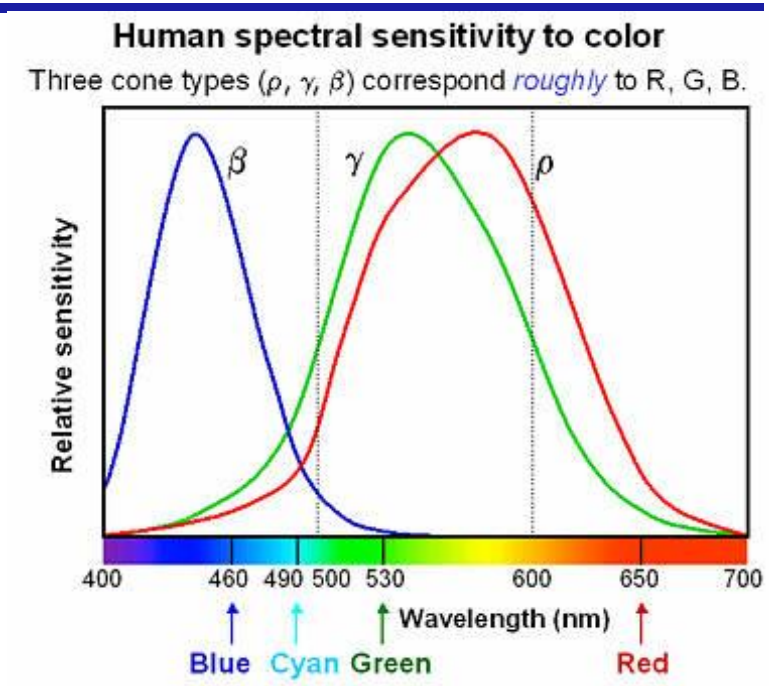


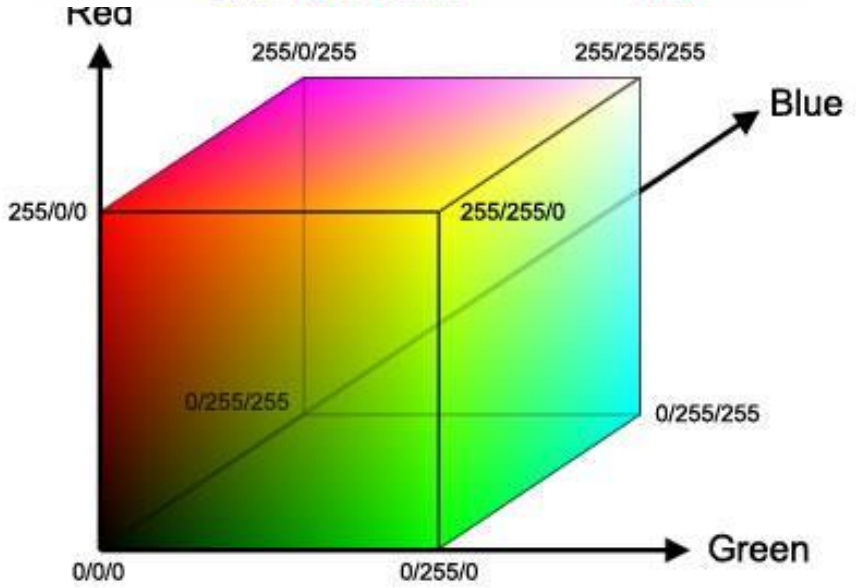
CIE LAB

IP/CV: Color - RGB [9]

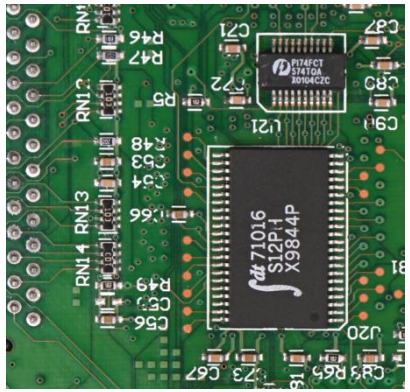
- **RGB: standard additive color model, based on human trichromacy**

- Red
  - Long wavelength, 564–580 nm
  - Range: [0, 255]
- Green
  - Med wavelength, 534–545 nm
  - Range: [0, 255]
- Blue
  - Short wavelength, 420–440 nm
  - Range: [0, 255]

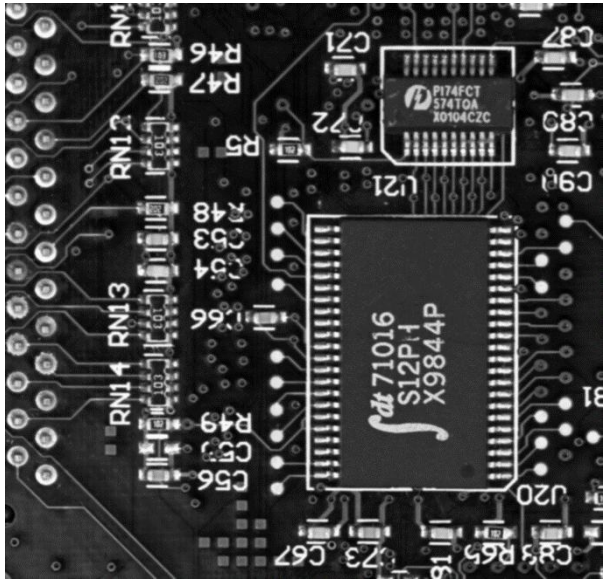




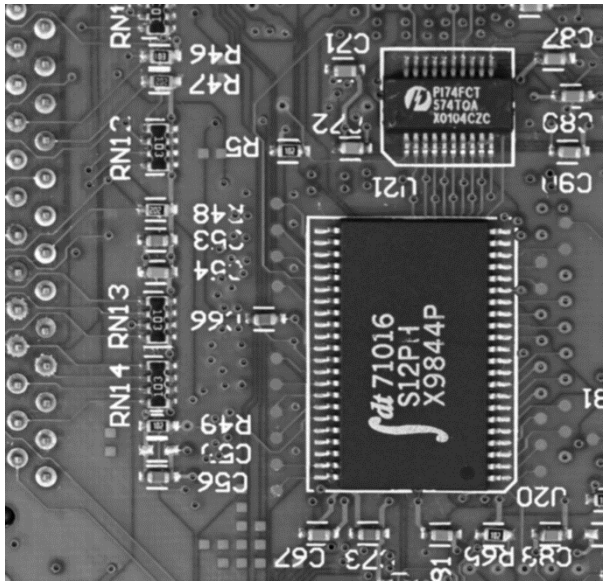
IP/CV: Color - RGB



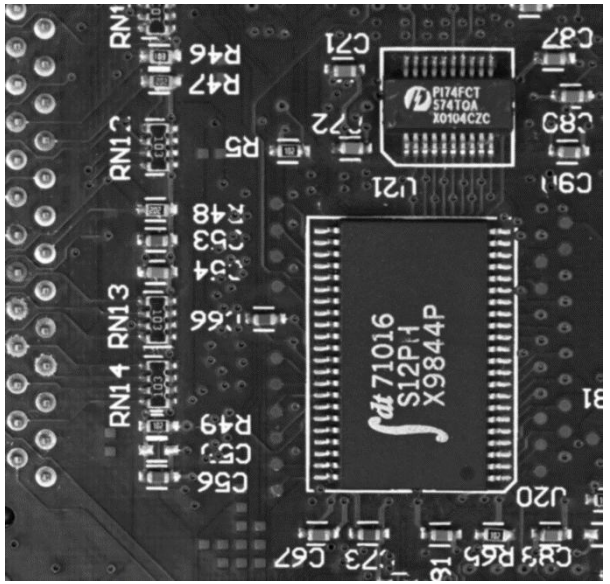
RGB



R



G

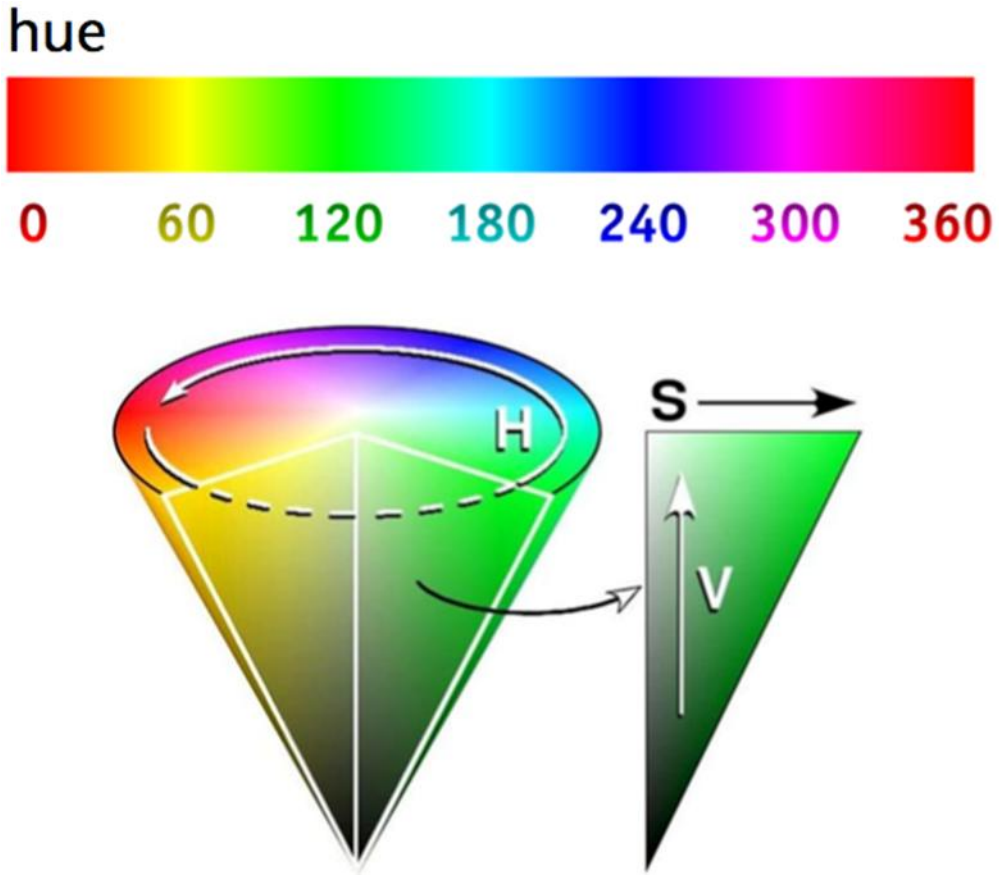


B

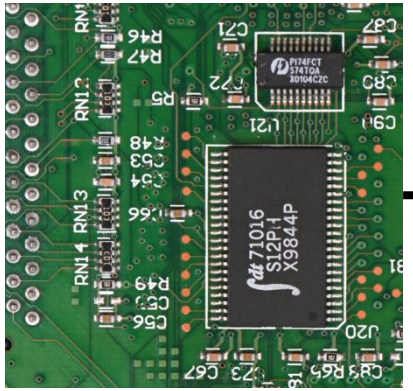
IP/CV: Color - HSV [10]

- **HSV: human-interpretable color space**

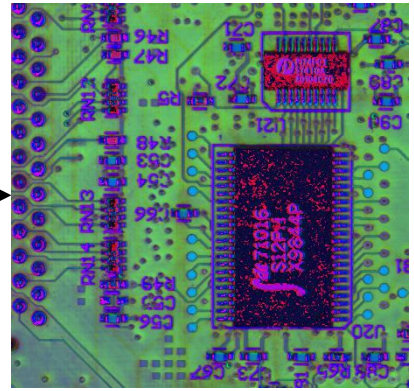
- Hue
  - color dominant wavelength
  - Range in degrees: [0, 360]
- Saturation
  - how much the color spectral distribution – colorfulness- is around a certain wavelength
  - Range: [0, 1]
- Value
  - the amount of gray, close to human perception
  - Range: [0, 1]



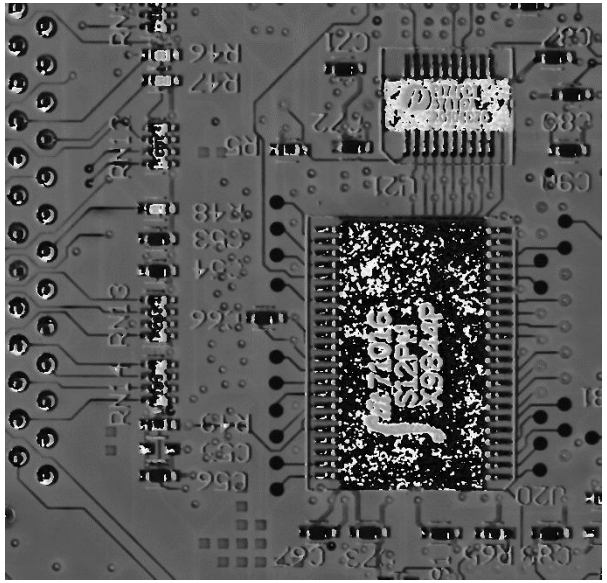
IP/CV: Color - HSV



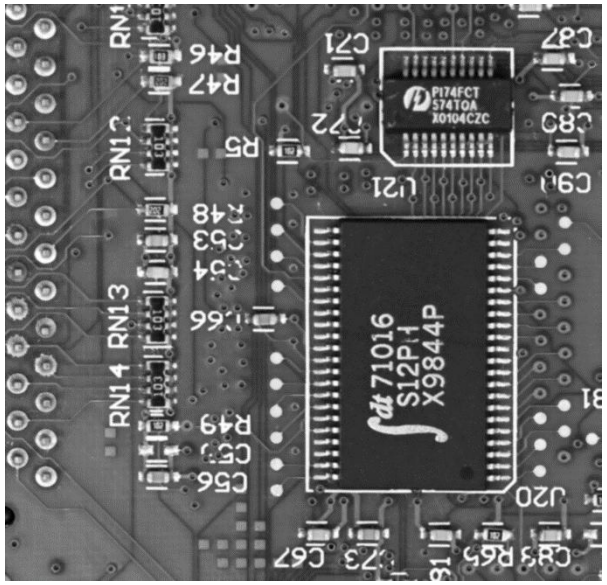
RGB



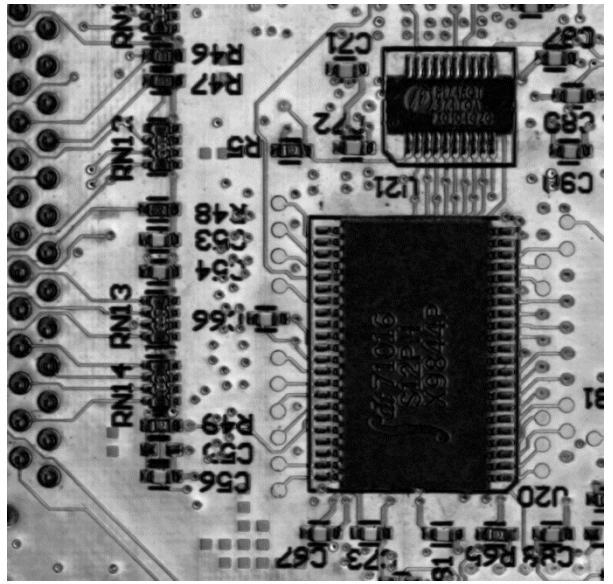
HSV



H



V

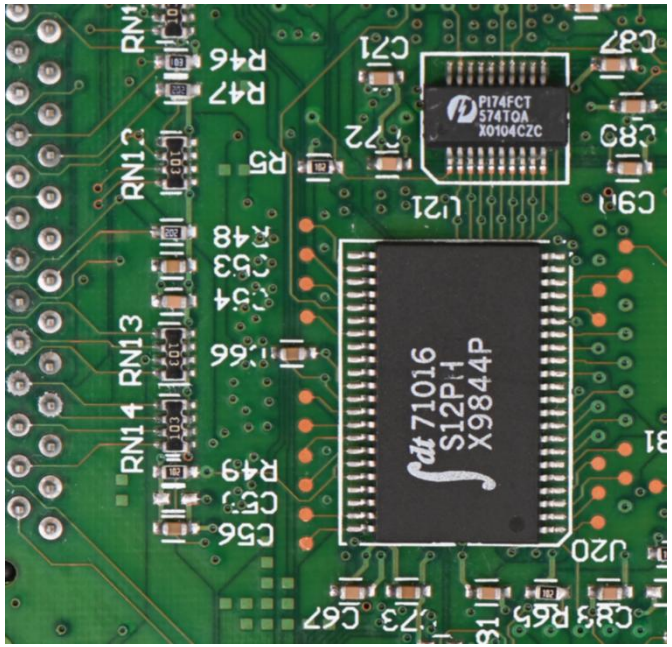


S

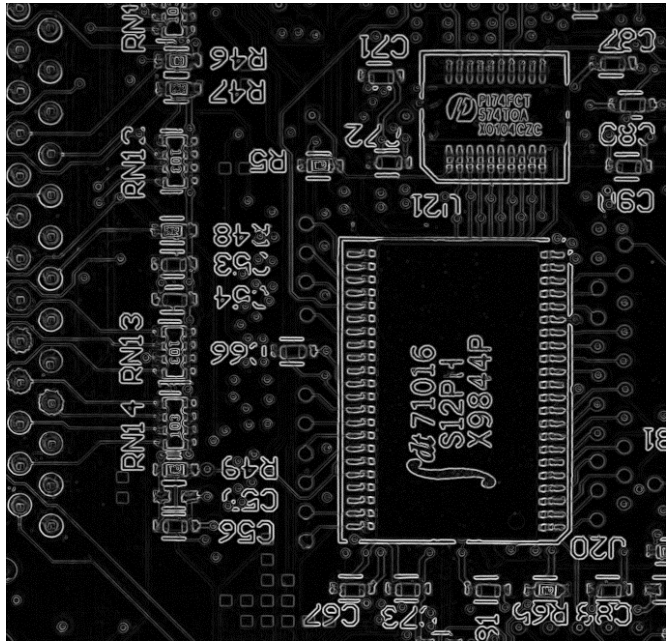
IP/CV: Shape

- **Global Shape Features**

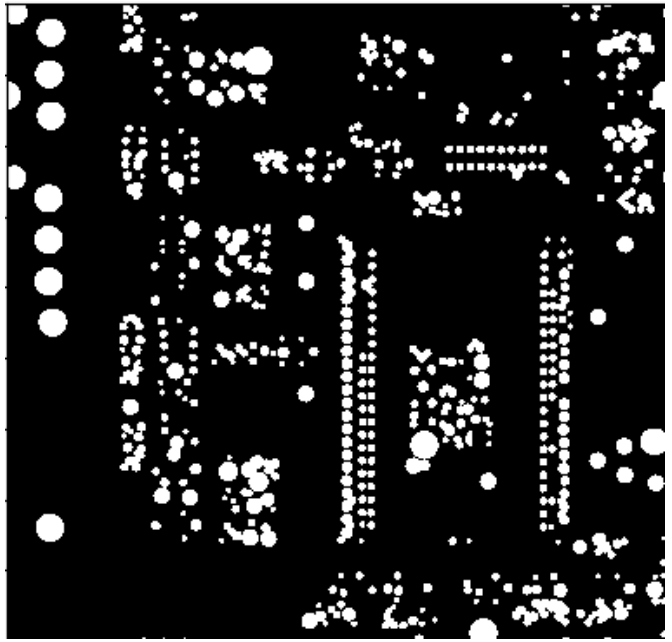
Original Image



Edge Detection

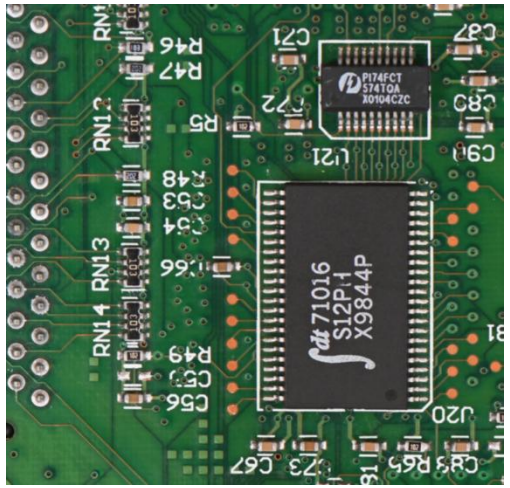


Blob Detection

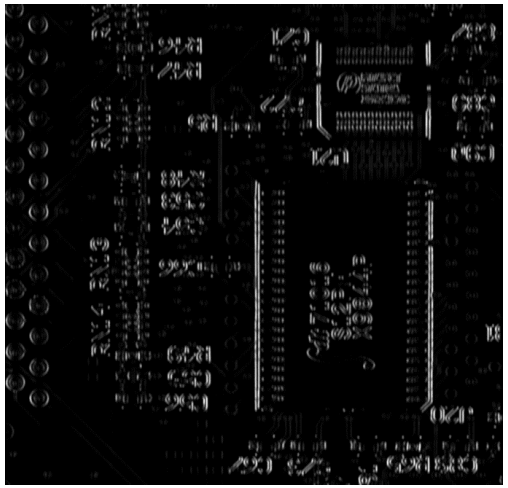


IP/CV: Texture

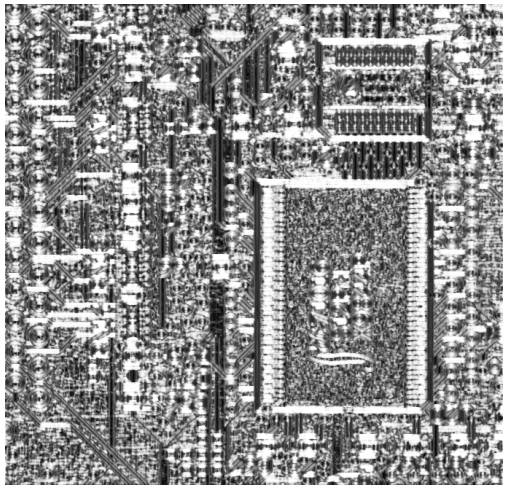
Original Image



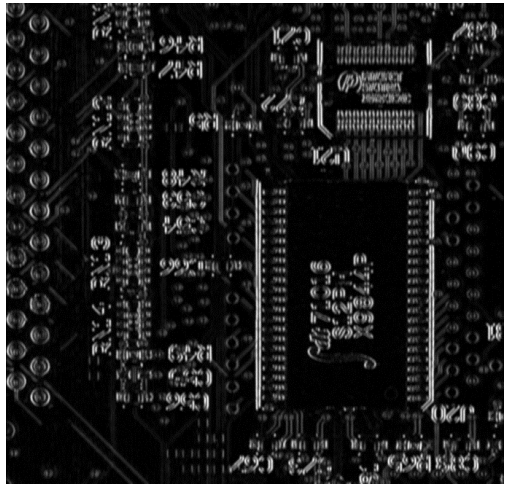
Contrast



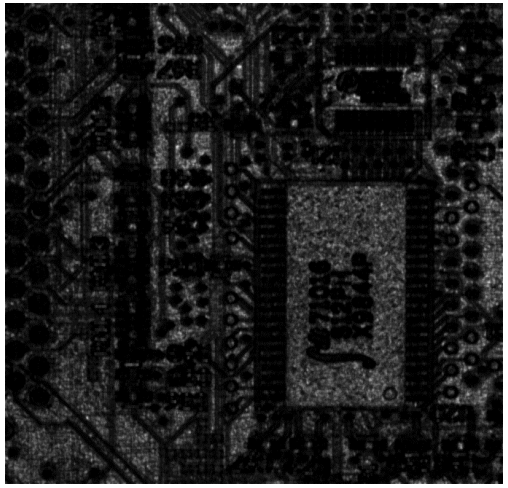
Correlation



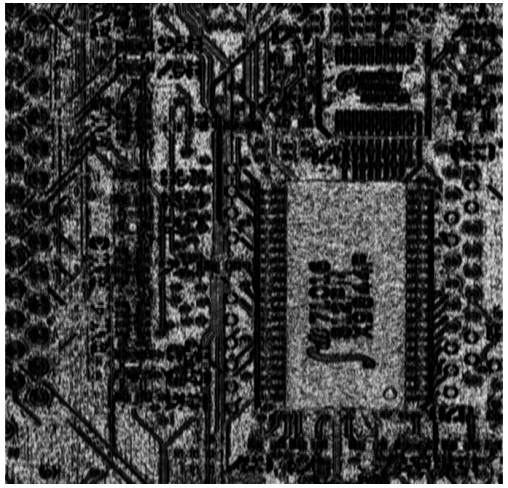
Dissimilarity



Energy



Homogeneity



Takeaways

- Image Processing (IP) vs. Computer Vision (CV)
- IP/CV role in HW Assurance
- IP/CV Applications: Verification and AutoBoM
- AutoBoM challenges:
  - imaging conditions → color checker normalization
  - board/component variations → machine learning + domain knowledge
- How to encode domain knowledge?
  - 3 types of features: color, shape, texture

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