UNIVERSITY OF EASTERN FINLAND dispelix COSI

Gage R&R plan

Project: Defect Detection on AR Waveguides
Group A: Júlia Pumares Benaiges, Taekyung Kim, Ann Marie Roob
Course: Industrial Project

Date of submission: 06.11.2025

Objective

The aim of this Gage Repeatability and Reproducibility (Gage R&R) study is to evaluate our measurement system used to assess the lens quality based on two Critical to Quality (CTQ) parameters:

- **CTQ1:** CIELAB mean color difference (ΔE) of the IC area
- **CTQ2:** Longest radius of the IC area

The study's objective is to quantify the variability introduced by the measurement system, including both repeatability (equipment variation) and reproducibility (operator variation).

Critical to Quality - CTQs

For this project we will focus on the following two CTQs for evaluation of our measurement system and detection of defect lenses:

*CTQ1: CIELAB mean color difference **ΔE** of IC Area*

This CTQ quantifies the color variation within the IC area of the lens. The color difference between two samples is calculated using the Euclidean distance in the CIE L*a*b* color space:

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2} \quad (1)$$

Using the results of the training data we differentiate between acceptable and defective lenses:

- **Acceptance Criteria:** ΔE ≤ 4 → Lens is acceptable
- **Defect Criteria:** ΔE > 4 → Lens is considered defective

This CTQ enables the detection of defects such as color variations, color gradients, artifacts, faulty location and smaller size of the IC area.

CTQ2: Longest radius of IC Area

This CTQ assesses the geometric shape of the lens by evaluating the **longest radius** of the IC area. The reference radius was determined to be 57 pixels**.**

The deviation from the reference radius is calculated as:

$$\Delta R = |R_{ref} - R| = |57 - r| \quad (2)$$

- **Acceptance Criteria:** ΔR ≤ 2 pixels → Lens is acceptable
- **Defect Criteria:** ΔR > 2 pixels → Lens is considered defective

With these acceptance criteria, we can filter out defects such as the wrong shape and wrong size of the IC area and even some artefacts.

Standard Operating Procedure

To ensure that measurements and analysis are performed similarly across all team members, the following SOP must be followed. This SOP defines the setup, measurement procedure, and conversion steps from captured images to CTQ values.

1. *Measurement system description*

Parameter	Description
Illumination	D65 standard lighting
Measurement device	CRI Nuance Multispectral Imaging System EX
Camera lens	Samyang 35mm F1.4 AS Ultra Multi Coating (wide-angle, manual focus prime lens)
Measurement geometry	45°/0° under D65 illumination (see Fig. 1)
Analysis software	Custom Python-based image processing and CTQ extraction tool

Figure 1: Measurement Setup

2. *Measurement procedure*

- System Calibration:
  - perform measurement of dark and white spectrum before each session to calibrate the imaging system
  - use perfect white diffuser for white spectrum, ATTENTION: surface has scratches, chose part with least artifacts!
  - ensure consistent focus and exposure settings across all measurements
- Sample Preparation:
  - place sample in lighting booth under D65 illumination
  - ensure that the sample is centered and in focus
- Image Acquisition:
  - capture a spectral cube for each sample using the CRI Nuance system (range: 450nm – 950nm, step size: 20nm)
  - create new folder for each measurement with the proper naming convention (e.g., *"d1" for Defect 1, "white" for white spectrum, "dark" for dark spectrum, "reference" for reference spectrum*)
  - save the files

3. *Conversion steps from Image to CTQ*

- Load captured spectral cube files into VS Code
- Run python code (ensure data is labeled accordingly!)
- Open output csv-file, which includes if sample number is defect or acceptable:
  - $\Delta E > 4 \rightarrow$ Defect
  - $|57 - r| > 2$ pixels → Defect

4. *Interpreting the results*

In the following table we show an example of result that we will find in the csv-file. The columns of the table are:

- Defect_id
- DE_mean: CTQ1 numerical value.
- D_radius: CTQ2 numerical value.
- CTQ1: if it's *TRUE* it means that the lens has a defect detected by CTQ1.
- CTQ2: if it's *TRUE* it means that the lens has a defect detected by CTQ2.
- Defect?: if the value is *TRUE* it means that the lens is found to be defective either by CTQ1 or CTQ2, or by both.

Defect_id	DE_mean	D_radius	CTQ1	CTQ2	Defect?
d1	4.27	0.01	TRUE	FALSE	TRUE
d2	5.70	0.21	TRUE	FALSE	TRUE
d3	10.90	0.20	TRUE	FALSE	TRUE
d4	3.09	0.10	FALSE	FALSE	FALSE
d5	8.95	0.41	TRUE	FALSE	TRUE
d6	5.67	0.33	TRUE	FALSE	TRUE
d7	5.94	0.11	TRUE	FALSE	TRUE
d8	4.81	14.63	TRUE	TRUE	TRUE
d9	3.84	4.21	FALSE	TRUE	TRUE
d10	5.78	6.09	TRUE	TRUE	TRUE
d11	4.89	0.22	TRUE	FALSE	TRUE
d12	4.98	0.34	TRUE	FALSE	TRUE
d13	10.96	0.24	TRUE	FALSE	TRUE
d14	3.71	13.95	FALSE	TRUE	TRUE

Table 1: Results of training lens samples

Gage Test

Study design:

Parameter	Description
Number of samples	12 total lenses (1 reference + 1 test lenses)
IDs of samples	CTQ1: 3, 4, 7, 10, 12 CTQ2: 13, 18, 19, 20, 21, 22
Number of operators	3 trained operators
Number of trials per operator	2 repetitions per sample
Total number of measurements	72 measurements
Measurement type	Image acquisition followed by automated CTQ extraction in python (ΔE and radius)

Data acquisition plan:

1. Each operator will capture one independent image for each lens in random order (random sample order in appendix) --> 1st trial
2. Images will be saved using the standardized file naming convention
3. Next day, step 1 and 2 will be repeated with new random sample order --> 2nd trial
4. All images will be processed using the same version of the Python analysis script to calculate:
    a. **CTQ1:** ΔE (color difference)
    b. **CTQ2:** ΔR (radius deviation)
5. The script will output both CTQ values and defect classification (defect / no defect) for each image

Data analysis plan:

The Gage R&R analysis will be performed using Python and will include:

- Calculation of total measurement variation
- Separation of **repeatability** (equipment variation) and **reproducibility** (operator variation) components

The measurement system will be evaluated in the following way [1]. If the Gage R&R variability to overall process variability is:

- **Under 10%:** acceptable Gage
- **10% to 30%:** may be acceptable
- **Over 30%:** gage is unacceptable and should be corrected or replaced

Appendix

Trial 1:

Measurement Nr.	Operator 1	Operator 2	Operator 3
1	19	10	18
2	7	20	ref
3	18	22	3
4	ref	12	20
5	4	3	7
6	20	13	12
7	22	7	21
8	3	ref	4
9	13	21	19
10	10	18	22
11	21	4	10
12	12	19	13

Trial 2:

Measurement Nr.	Operator 1	Operator 2	Operator 3
1	13	18	21
2	22	ref	3
3	4	12	7
4	10	4	ref
5	21	3	20
6	12	7	4
7	18	10	13
8	20	22	10
9	7	21	19
10	3	13	22
11	ref	19	12
12	19	20	18

Reference:

Feldman, K. (2025, January 31). *Mastering Gage R&R: Key Steps for a Successful Study*. iSixSigma. Retrieved from https://www.isixsigma.com/measurement-systems-analysis-msa-gage-rr/gage-rr/ (isixsigma.com), last visited on 04.11.2025