Metrology of Rectangular Distance in Wireless Keyboard: A Repeatability Study

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Abstract

This study explores the use of metrology in manufacturing, specifically for measuring rectangular part assemblies, aims to identify the critical-to-quality (CTQ) variable features and evaluate repeatability of the measurement system when dealing with contact-based and non-contact-based measuring method. This study provides a positive implication in improving industrial quality control, minimizing production mistakes, and giving practical approache for industry practitioners and academics. The findings are vital for enhancing industrial quality control by providing methods to reduce errors and optimise production processes. This paper offers practical guidance for industry professionals and academics alike, aiming to improve operational efficiency and ensure high-quality manufacturing. The potential economic benefits underscore the significance of these advancements in advancing manufacturing practices and contributing to overall economic growth.

1. Introduction

This study focuses on the metrology of rectangular distances in wireless keyboards, emphasizing the repeatability and reproducibility of measurement systems. It identifies key quality parameters, appropriate equipment, and methodologies for assessing rectangular part assemblies. The findings will contribute to enhancing metrology practices and precision measurement skills, benefiting academic research and industrial applications.

In the manufacturing industry, quality control of precision parts or components is strongly dependent on metrology and measurement methodology. The critical-to-quality (CTQ) features are inspected specifically to ensure the parts and components satisfy the required specifications and standards. For a new industrial practitioner, measuring CTQ features is a challenging task, and it requires in-depth knowledge of metrology. Inconsistent measurements, poor selection of measuring equipment, and lack of information about gauge repeatability and reproducibility will impair the inspection result. Based on the literature review of metrology studies, there is a lack of repeatability studies comparing contact-based and non-contact-based equipment when dealing with wireless keyboard manufacturing and quality control. Thus, this study aims to conduct such an analysis as a supportive knowledge contribution in this field.

1.1 Metrology and Measurement

Metrology is the science of measurement that ensures accuracy, precision, and consistency across industrial production. It involves creating and maintaining measurement standards, calibration, and verification, which are essential for ensuring the reliability of measurement systems. Tools like coordinate measuring machines (CMM)

are widely used for precise dimensional analysis in sectors such as automotive, aerospace, and electronics. These instruments provide high-precision measurements, enabling quality control and enhancing manufacturing process. In industrial production, metrology supports in-process measurements and real-time feedback mechanisms, which improve the repeatability and reliability of measurements for components like rectangular assemblies in wireless keyboards. Advanced metrology systems, such as laser trackers and optical digitizers, are also used to measure complex geometries accurately, ensuring precise and consistent results in manufacturing processes [1, 2].

Rectangular components are widely used in manufacturing due to their simple shape and versatility across industries such as aerospace, automotive, and construction. In automotive production, sheet metal shaping and stamping are commonly used to create precise rectangular parts. Similarly, rectangular parts are integral in the electronics industry, with wireless keyboards being a key example. These keyboards, commonly used in computers and laptops, rely on rectangular components for their assembly, requiring accurate measurements for consistent performance and quality control in production [3]. Wireless keyboards allow for more flexible device use but come with security risks due to potential radio-frequency leakage. These keyboards, which consist of various keys for typing and input, are designed to provide convenience and efficiency for users. The design and production of wireless keyboards involve precise measurement of rectangular components to ensure proper functionality and user experience. Accurate dimensional measurements of these parts are critical for quality control and repeatability in the manufacturing process [4].

Metrology for rectangular parts involves precise measurements to ensure accuracy in manufacturing processes, particularly when working with components such as those used in wireless keyboards. Linear dimensions can represent the feature shape of the rectangular component.

Measurement System Analysis (MSA) is crucial in evaluating the consistency and accuracy of measurement systems in the manufacturing process, including in wireless keyboard production. It helps identify measurement variability, which can affect the overall process variability. MSA ensures that experiments, such as statistical process control or regression analyses, are based on reliable data and that measurements are reproducible. It detects errors from various sources, including part-to-part variation, gauge differences, and differences among evaluators, ensuring the reliability of the measurements used to assess the product's quality and consistency [6]. In production processes, MSA is essential for ensuring that measurement systems accurately reflect the quality of the product. Consistent and accurate measurement systems are necessary for assessing the parameters of the manufacturing process and ensuring that products meet quality standards. Variations in measurement can obscure key product deviations, so having a quality measurement system is critical for maintaining product functionality and appearance. The effectiveness of MSA directly influences customer satisfaction and profitability by improving the manufacturing process and ensuring quality control [7].

2. Methodology

2.1 Process Flow Chart

The metrology begins with selecting and understanding the product or component. The critical-to-quality (CTQ) parameters are then identified. Once the component was identified, 3D CAD modelling and drawing ballooning are carried out. Measurement was conducted using Flexible Measurement Machine (FMM) and Vertical Profile Projector (VPP). These steps involve planning and performing Gauge Repeatability and Reproducibility (GR&R) analysis. The last phase involves analyzing data and discussing GR&R to determine the measuring capability of the measuring equipment. Fig. 1 displays a flow chart.

2.2 Selection Product

This study involves metrology of rectangular distances (critical dimension) in a wireless keyboard such as length, width, and flatness, which are essential for product quality. SolidWorks software was used to create CAD model of the wireless keyboard and perform drawing ballooning to specify dimensions and tolerances (e.g., length, edge radius, width, and flatness). This process guarantees the wireless keyboard's quality, functionality, and ensuring it meets customer expectations and performance criteria.

2.3 Identifying Measuring Equipment

Two measuring equipment were utilized to evaluate the GR&R analysis, as mentioned in Section 2.1. The VPP is capable to measure geometric and linear dimensions with high accuracy, and detecting small features like angle, with surface accuracy of 0.12% and enlargement accuracy of 0.08%. The FMM (small scale of coordinate measuring machine) is capable to assess the part quality manually, with measurements recorded and displayed on a screen. Both devices ensure precise and repeatable measurements, crucial for measuring the rectangular distances of the wireless keyboard.
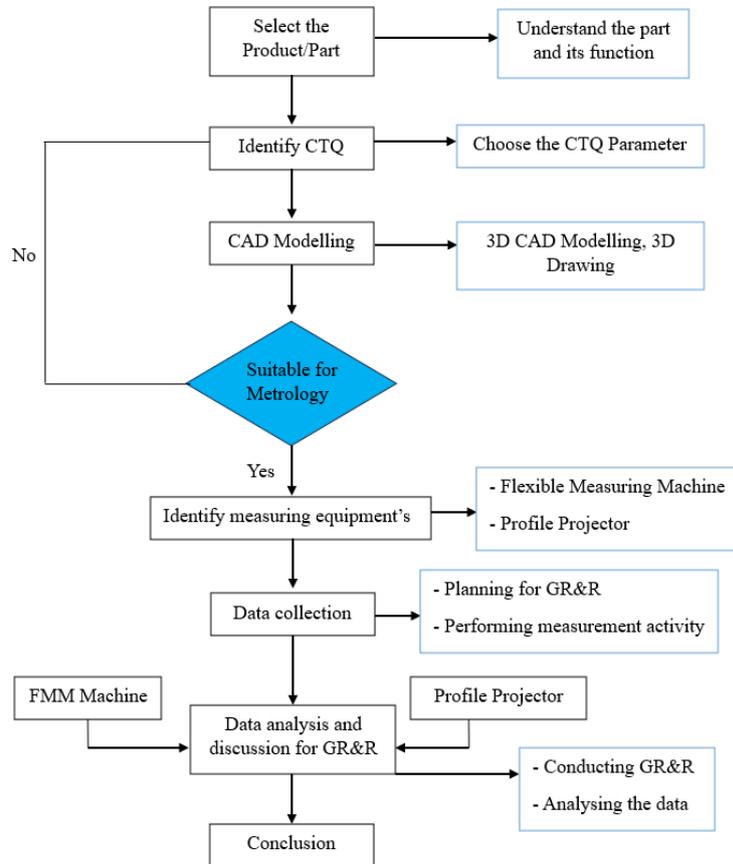

Fig 1: *Process flow chart*

2.4 GR&R Acceptance Criteria

The average range approach was used for the GR&R analysis. Three appraisers (quality inspectors A, B, C) were measured the wireless keyboard's orientation multiple times in a random order to calculate the range and average range ($\bar{R}$). The control limits (UCL and LCL) were determined based on the average range. Repeatability (EV) and reproducibility (AV) were calculated using standard equation, considering factors like appraiser differences and trials. The overall GR&R was calculated by combining repeatability and reproducibility. Additionally, process capability (Cp) analysis was performed to evaluate the measurement process competence, aiming for a Cp value of 1.33 or higher, which indicates an acceptable measurement range.

$$\bar{R} = Max - Min$$
$$Upper\ Control\ Limit\ (UCL) = D_4 \times \bar{R} \tag{1}$$

$$EV = \bar{R} \times K_1 \tag{2}$$

$$AV = \sqrt{(\bar{X}_{diff} \times K_2)^2 - \frac{EV^2}{nr}}$$

$$R\&R = \sqrt{(EV)^2 + (AV)^2} \tag{3}$$

The Automotive Industry Action Group (AIAG) states that a % R&R under 10% indicates a good measuring system, while values between 10% and 30% may also be acceptable in certain situations. These criteria are shown in Table 1 as follows.

Table 1: *GR&R acceptance criteria*

%R&R Decision	Decision	Comments
Under 10	Generally considered to be an acceptable measurement	This tool is highly recommended for sorting or classifying component, as well as for improving process control
10 to 30	Maybe acceptable for some applications	Consider the relevance of the application measurement, the cost of the measuring instrument, and the cost of rework or repair when making your decision. Customer approval is essential
Over 30	Considered to be unacceptable	Improving the measuring system should be a priority

2.5 Minitab Software

Minitab is the statistical process control programme utilised in this study to analyse our data. The researchers created Minitab, which uses statistics and data to optimise processes. It is used as a tool for quickly analysing research data and creating graphs. Experts use various methods, tactics, and data formats to identify process issues. To solve the problem, execute appropriate software modifications and monitor the situation.

Fig 2: Minitab Software

3.   Results and Discussion

3.1 Data Collection

The data collection process involves careful measurement to ensure accuracy and repeatability. First, a Flexible Measuring Machine (FMM) was used to measure each component at nine different points, with three measurements taken at each point. The same procedure was followed using a Vertical Profile Projector. Both machines provided three sets of data for each component. This dual-method approach generated reliable data for analysis, ensuring accurate measurements and repeatable results.

Table 2: *Measurement data (in mm)*

Point	Machine: Flexible Measuring Machine (FMM), Unit: mm					
	Set 1		Set 2		Set 3	
	Axis-X	Axis-Y	Axis-X	Axis-Y	Axis-X	Axis-Y
A	34.583	34.592	34.600	34.583	34.591	34.603
	34.640	34.689	34.590	34.613	34.625	34.583
	34.561	34.456	34.585	34.523	34.574	34.615
B	67.676	34.481	67.680	34.436	67.666	34.416
	67.719	34.397	67.670	34.455	67.712	34.483
	67.600	34.502	67.650	34.429	67.689	34.507
C	117.281	34.327	117.300	34.330	117.293	34.403
	117.271	34.596	117.305	34.501	117.280	34.475
	117.384	34.403	117.283	34.399	117.305	34.451
D	29.711	0.073	29.715	0.070	29.721	0.067
	29.715	0.084	29.720	0.063	29.717	0.055
	29.725	0.048	29.709	0.054	29.710	0.073
E	80.880	0.030	80.753	0.020	80.652	0.036
	80.638	0.023	80.555	0.029	80.559	0.032
	80.397	0.031	80.640	0.025	80.688	0.027
F	114.998	0.054	114.862	0.050	114.875	0.055
	114.751	0.052	114.812	0.058	114.697	0.051
	114.603	0.057	114.698	0.052	114.766	0.059
G	33.900	35.520	33.884	35.541	33.754	35.555
	33.730	35.653	33.750	35.467	33.717	35.509
	33.718	35.554	33.834	35.596	33.789	35.597
H	83.949	35.119	83.935	35.071	83.952	35.091
	83.956	35.030	83.951	35.039	83.941	35.053
	83.940	35.033	83.959	35.033	83.959	35.039
I	117.982	35.898	117.900	35.799	117.830	35.907
	117.746	35.822	117.912	35.837	117.768	35.722
	117.822	35.675	117.888	35.756	117.900	35.861

Point	Machine: Vertical Profile Projector, Unit: mm					
	Set 1		Set 2		Set 3	
	Axis-X	Axis-Y	Axis-X	Axis-Y	Axis-X	Axis-Y
A	33.395	33.900	33.389	33.903	33.386	33.908
	33.385	33.909	33.391	33.901	33.393	33.905
	33.394	33.900	33.396	33.906	33.389	33.905
B	66.802	33.973	66.799	33.982	66.804	33.980
	66.802	33.984	66.804	33.979	66.800	33.977
	66.797	33.972	66.803	33.984	66.802	33.984
C	116.965	34.129	116.954	34.135	116.955	34.135
	116.954	34.140	116.950	34.140	116.960	34.130
	116.950	34.140	116.959	34.135	116.958	34.130
D	28.790	0.094	28.755	0.091	28.740	0.090
	28.784	0.089	28.782	0.088	28.759	0.093
	28.736	0.090	28.780	0.093	28.755	0.089
E	79.741	0.020	79.738	0.016	79.735	0.017
	79.747	0.014	79.742	0.018	79.742	0.015
	79.701	0.016	79.749	0.014	79.735	0.020
F	113.786	0.080	113.787	0.072	113.762	0.076
	113.764	0.075	113.761	0.078	113.780	0.073
	113.768	0.076	113.782	0.076	113.780	0.078
G	32.055	35.043	32.041	35.040	32.050	35.050
	32.038	35.042	32.052	35.040	32.047	35.045
	32.067	35.051	32.057	35.044	32.041	35.044
H	82.950	34.988	82.955	34.985	82.953	34.990
	82.947	34.994	82.951	34.992	82.957	34.996
	82.957	34.985	82.949	34.989	82.950	34.992
I	116.920	34.917	116.920	34.916	116.921	34.920
	116.926	34.919	116.925	34.920	116.925	34.915
	116.922	34.923	116.927	34.915	116.920	34.912

3.2 Minitab Analysis

Flexible Measuring Machine

For Data Set 1 (X-axis) shown in Fig. 3, the 0.00% repeatability indicates no significant variation when the same operator measures the same point multiple times, demonstrating excellent measurement consistency. A low % Study Variance (0.33%) confirms minimal variation due to repeatability. Similarly, for Data Set 1 (Y-axis), the % Study Variance for repeatability is also low (0.44%), highlighting minimal measurement variation. Overall, the measurement system is highly precise, reliable, and exhibits negligible error in repeatability.
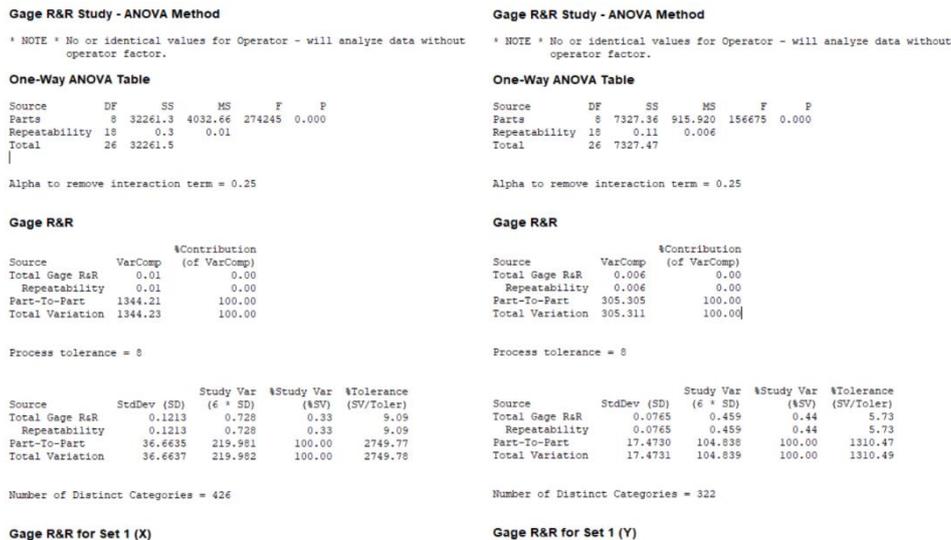
Fig 3: *Data Set 1 (FMM)*

For Data Set 2 (X-axis) as shown in Fig. 4, the % Study Variance of 0.14% for Total Gage R&R indicates that the measurement system contributes minimally to overall process variation, demonstrating high precision. The repeatability % Study Variance of 0.14% confirms consistent measurements when the same operator measures the same point multiple times. Similarly, for Data Set 2 (Y-axis), the repeatability % Study Variance of 0.24% is low, indicating the measurement system is highly reliable and consistent in repeated measurements.

Gage R&R Study - ANOVA Method

* NOTE * No or identical values for Operator – will analyze data without
    operator factor.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
Parts	8	32263.1	4032.89	1630158	0.000
Repeatability	18	0.0	0.00		
Total	26	32263.2			

Alpha to remove interaction term = 0.25

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.00	0.00
Repeatability	0.00	0.00
Part-To-Part	1344.30	100.00
Total Variation	1344.30	100.00

Process tolerance = 8

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0497	0.298	0.14	3.73
Repeatability	0.0497	0.298	0.14	3.73
Part-To-Part	36.6646	219.988	100.00	2749.85
Total Variation	36.6647	219.988	100.00	2749.85

Number of Distinct Categories = 1039

Gage R&R for Set 2 (X)

Gage R&R Study - ANOVA Method

* NOTE * No or identical values for Operator – will analyze data without
    operator factor.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
Parts	8	7321.86	915.233	513727	0.000
Repeatability	18	0.03	0.002		
Total	26	7321.90			

Alpha to remove interaction term = 0.25

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.002	0.00
Repeatability	0.002	0.00
Part-To-Part	305.077	100.00
Total Variation	305.079	100.00

Process tolerance = 8

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0422	0.253	0.24	3.17
Repeatability	0.0422	0.253	0.24	3.17
Part-To-Part	17.4665	104.799	100.00	1309.98
Total Variation	17.4665	104.799	100.00	1309.99

Number of Distinct Categories = 583

Gage R&R for Set 2 (Y)

Fig 4: *Data Set 2 (FMM)*

For Data Set 3 (Fig. 5), the % Study Variance for Total Gage R&R is 0.13% on the X-axis, indicating extremely low variability from the measurement system, showcasing high precision and capability. The % Study Variance for Repeatability is also 0.13%, confirming the measuring equipment's precision and consistency. On the Y-axis, the % Study Variance for Total Gage R&R is 0.24%, still very low, further highlighting the measurement system's minimal contribution to overall process variation and its high reliability.

Gage R&R Study - ANOVA Method

* NOTE * No or identical values for Operator – will analyze data without
    operator factor.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
Parts	8	32256.9	4032.11	1849970	0.000
Repeatability	18	0.0	0.00		
Total	26	32256.9			

Alpha to remove interaction term = 0.25

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.00	0.00
Repeatability	0.00	0.00
Part-To-Part	1344.04	100.00
Total Variation	1344.04	100.00

Process tolerance = 8

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0467	0.280	0.13	3.50
Repeatability	0.0467	0.280	0.13	3.50
Part-To-Part	36.6611	219.967	100.00	2749.58
Total Variation	36.6611	219.967	100.00	2749.59

Number of Distinct Categories = 1107

Gage R&R for Set 3 (X)

Gage R&R Study - ANOVA Method

* NOTE * No or identical values for Operator – will analyze data without
    operator factor.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
Parts	8	7331.01	916.376	519084	0.000
Repeatability	18	0.03	0.002		
Total	26	7331.04			

Alpha to remove interaction term = 0.25

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.002	0.00
Repeatability	0.002	0.00
Part-To-Part	305.458	100.00
Total Variation	305.460	100.00

Process tolerance = 8

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0420	0.252	0.24	3.15
Repeatability	0.0420	0.252	0.24	3.15
Part-To-Part	17.4774	104.864	100.00	1310.80
Total Variation	17.4774	104.864	100.00	1310.81

Number of Distinct Categories = 586

Gage R&R for Set 3 (Y)

Fig 5: *Data Set 3 (FMM)*

Vertical Profile Projector

In Data Set 1 (X-axis) as shown in Fig. 6, repeatability refers to the consistency of measurements taken by the same operator with the same instrument. The 0.00% repeatability shows no significant variation, meaning the system is highly consistent. A low study variance of 0.04% further indicates minimal variation and good repeatability. For Data Set 1 (Y-axis), the repeatability variance is also very low at 0.03%, confirming that the measurement system is precise and reliable, with almost no error.
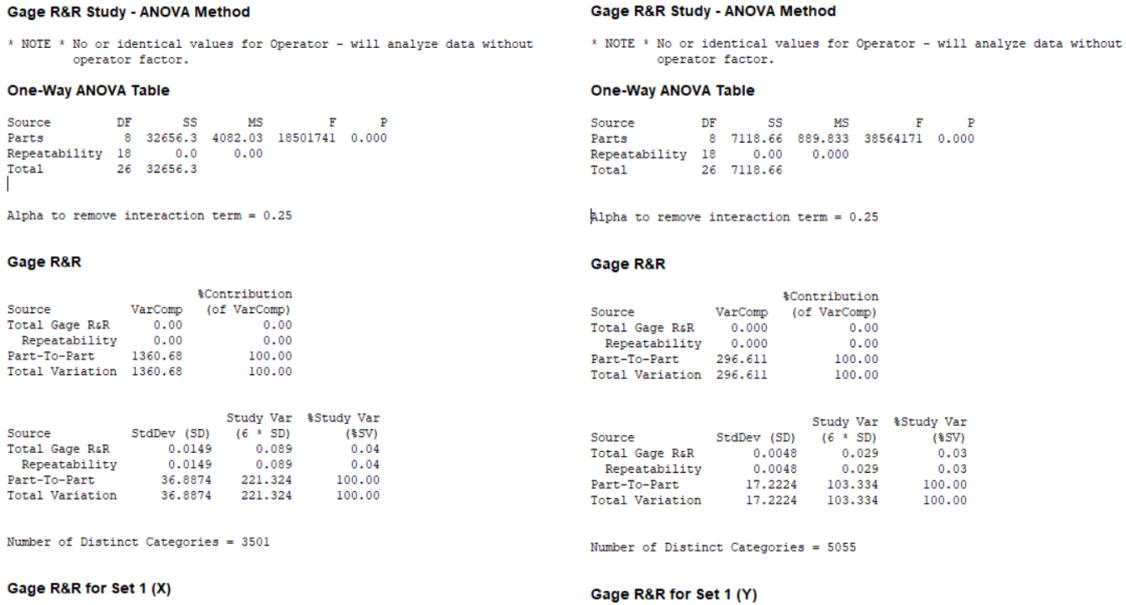

Fig 6: *Data Set 1 (VPP)*

In Data Set 2 (X-axis and Y-axis) as shown in Fig. 7, the % Study Variance for Total Gage R&R and Repeatability is extremely low at 0.02%, meaning the measurement system contributes very little to the overall variation. The main variation comes from part-to-part differences rather than measurement issues. These low values demonstrate that the system is precise, repeatable, and effective at distinguishing variations among parts. Both Data Set 2 (X-axis and Y-axis) show identical variance values, indicating the measurement system's stability and reliability.
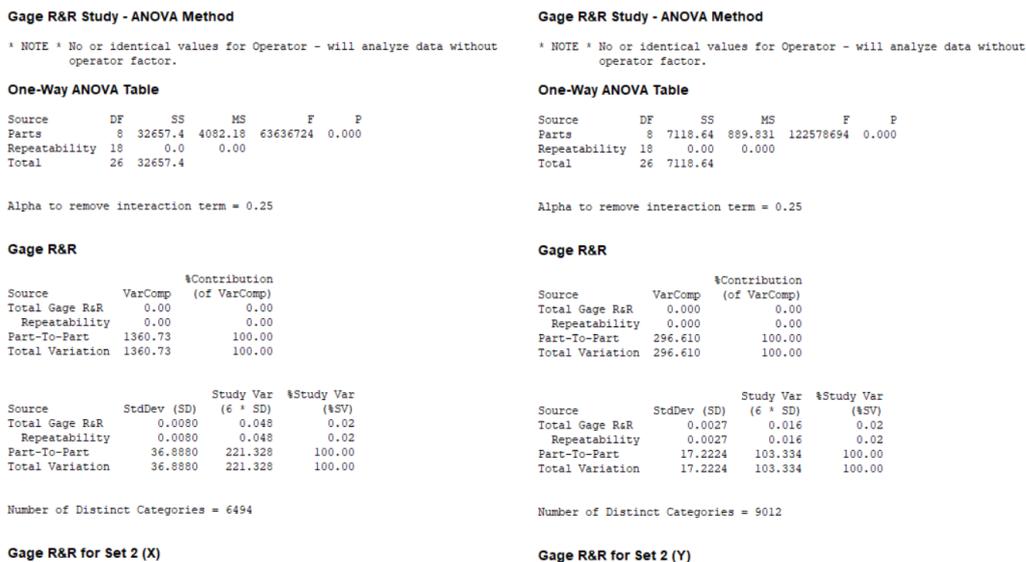

Fig 7: *Data Set 2 (VPP)*

For both Data Sets (X-axis and Y-axis) in Fig. 8, the % Study Variance for Total Gage R&R is 0.02%, indicating that the measurement system has minimal impact on overall variation and is highly precise. Likewise, the % Study Variance for Repeatability percentage is also 0.02%, showing excellent consistency in repeated measurements. These results confirm that the measurement system is both precise and reliable, with most of the variation coming from Part-to-Part differences rather than the measurement process.

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Gage R&R Study - ANOVA Method                          Gage R&R Study - ANOVA Method

* NOTE * No or identical values for Operator - will analyze data without    * NOTE * No or identical values for Operator - will analyze data without
         operator factor.                                      operator factor.

One-Way ANOVA Table                                    One-Way ANOVA Table

Source        DF     SS      MS         F       P      Source        DF     SS      MS         F       P
Parts          8  32664.5  4083.06  127743557  0.000   Parts          8  7118.72  889.840  104459481  0.000
Repeatability 18    0.0      0.00                       Repeatability 18    0.00     0.000
Total         26  32664.5                               Total         26  7118.72


Alpha to remove interaction term = 0.25                Alpha to remove interaction term = 0.25


Gage R&R                                                Gage R&R

                         %Contribution                                          %Contribution
Source        VarComp   (of VarComp)                   Source        VarComp   (of VarComp)
Total Gage R&R    0.00        0.00                      Total Gage R&R   0.000        0.00
  Repeatability   0.00        0.00                        Repeatability  0.000        0.00
Part-To-Part   1361.02      100.00                      Part-To-Part   296.613      100.00
Total Variation 1361.02     100.00                      Total Variation 296.613     100.00


                           Study Var  %Study Var                                Study Var  %Study Var
Source        StdDev (SD)  (6 * SD)     (%SV)           Source        StdDev (SD)  (6 * SD)     (%SV)
Total Gage R&R   0.0057     0.034       0.02            Total Gage R&R   0.0029     0.018       0.02
  Repeatability  0.0057     0.034       0.02              Repeatability  0.0029     0.018       0.02
Part-To-Part    36.8920   221.352     100.00            Part-To-Part    17.2225   103.335     100.00
Total Variation 36.8920   221.352     100.00            Total Variation 17.2225   103.335     100.00


Number of Distinct Categories = 9200                    Number of Distinct Categories = 8320


Gage R&R for Set 3 (X)                                  Gage R&R for Set 3 (Y)
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Fig 8: *Data Set 3 (VPP)*

3.3 Gauge Repeatability Result

The values of 0.253 and 0.025 indicate that the variation in measurements is mainly due to repeatability errors, such as equipment variation, operator consistency, or environmental factors. A % study variance below 10% is considered good, and between 10-30% is acceptable. The value of 0.253 for the Flexible Measuring Machine (FMM) is considered low, while the Vertical Profile Projector shows very high precision, with only 0.025% of the variation due to repeatability errors. A lower % repeatability indicates better measurement consistency, while a higher value suggests the need for improvements in equipment calibration, operator training, or environmental controls.

Table 3: *Gauge repeatability results*

Machine	Lowest % Variance	Highest & Variance	Average % Variance
FMM	0.13	0.44	0.253
VPP	0.02	0.04	0.025

Conclusion

The conclusion drawn from the study underscores precision of the measurement systems employed. Through a meticulous analysis using Minitab software, both precision machines have been proven suitable for measuring rectangular distance of wireless keyboard product. Based on its consistent results, that are, the % variance of gauge repeatability 0.253% and 0.025% for FMM and VPP respectively, prove that both measuring equipment are highly precise to measure an intended linear dimension. The results also represent the variability as indicated by the measurement systems themselves is very minimal, below the acceptable limit of 10%. This underscores their reliability in accurately assessing CTQ variables. Generally, the findings provide confidence in terms of measurement consistency and effectiveness of the measurement system for quality control of precision products.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

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