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Original Article

Dimensional Stability of Novel Artifact and its Error Mapping with Measuring Volume of Bridge Type CMM

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Abstract - *To meet the continuous need for precision and accurate measurement, it is necessary to improve regularly the performance of three-dimensional and more flexible measuring systems (i.e., CMM). An interim check of CMM by the operator using the artifacts offers the best economical solution to verify CMM on a daily basis. There exist some limitations of the existing artifacts, especially long-term stability, the capability to detect abrupt changes in the CMM performance, and allowing different functions to share data and interact with each other. This necessitates proposing a novel artifact that will combine all the needs of the inspection process with features of uncertainty evaluation. A ball plate artifact (Novel Artifact) is designed with Dolerite as base plate material and 48 Zirconia balls to determine Geometric and Volumetric errors in different positions. The statistical performance of the artifact is verified by measuring the distance of the balls from a reference ball in the first, twelfth, and twenty-second weeks, and then by plotting the results using statistical tools. Cross-correlation is used for depicting the stability of the ball plate before dimensional stability reverification. Interim checking of the CMMs used in the production area is carried out by using this artifact, and errors such as linear, horizontal, and vertical straightness, pitch, yaw along X, Y, Z axes, and roll along Z-axis have been determined. It is evident that the estimation of error using improved novel artifact maps for measuring the volume of Bridge type CMM is more accurate and effective.*

Keywords - *Novel artifact, Coordinate measuring machines, Error mapping, Interim check, Geometric errors, Volumetric errors, etc.*

1. Introduction

In an industrial environment, CMM is the most versatile and powerful measuring equipment as well as a reliable source of the quality system, which monitors manufacturing processes according to the specifications of the quality requirements [1]. Between two verifications, the performance of a Coordinate Measuring Machine may change. Undocumented changes in the conditions of the CMM may affect the validity of all future measurements. To avoid this, CMM is periodically calibrated to verify its traceability, accuracy, compatibility between the calibrations, compatibility with existing standards, etc. Daily verification of CMM is required to check the effects on the precision of measurement. However, it is not feasible to calibrate /verify the CMM every day due to its cost [2]. Calibration is required to confirm the CMM's good performance and to validate its operative and metrological competence with high accuracy. ISO10360-2:2009 recommends interim checking as an alternate method to calibration. This method compares the part to a well-calibrated artifact, which may be identical to the actual part. This method can give good estimates of measurement uncertainty. As the artifacts are well calibrated, the results of the measurement are treated as errors.

The optimized position of the workpiece on the CMM table can be identified by an interim check using the artifacts, which gives the best economical solution. Designing and developing an artifact is a more feasible and faster approach to verify the metrological stability of CMM, which will show its operational and metrological adequacy.

Dimensional stability and accuracy of an artifact are the most important factors for the interim check of CMM, which affects uncertainty and repeatability. The work reported here discusses research carried out with an improved design of the artifact and estimated error mapping by measuring the volume of a Bridge-type CMM. The improved ball plate artifact (Novel Artifact) uses an optimally possible minimum-sized Dolerite base plate and minimum number of

Zirconia balls to determine the errors (Patent for the design of the artifact has been filed vide application no. 65459-001).

2. Research Review

Measurement productivity can be improved by finding measurement errors as a vital factor to enhance the quality and reliability of CMM measurements. To minimize the cost of measurement and to improve the accuracy, it is necessary to determine the relationship between the measured parameter and the uncertainty of measurement [3]. This section reviews research related to the need for interim checks, problems associated with calibration, processes of interim checks and monitoring, emerging approaches of interim checking, designs of ball plate artifact, types of measured errors and related standards used, and types of artifacts that have been carried out.

Measurements of the artifact or workpiece are carried out for performance verification of the CMM. The results of the interim check can be used as the basis to determine the reliability of CMM in inspecting workpieces. This reduced performance verification can be applied to examine the CMM capability. It is necessary to determine the degree of verification for the re-verification and acceptance tests [4].

In industries, the reliability of interim checks can be improved by pooled error mapping of CMM using artifact [5]. These works show the importance of the interim check of CMM. The relevant published research is synthesized for the need of interim checks, problems related to calibration, processes related to interim checks, as well as monitoring and emerging approaches, etc., are summarized in Tables 1 to 4.

Table 1. Research review related to the need for an Interim check

Key Findings	Reference Cited
Extensive adoption by the industry of interim checking of CMM	[1, 3-5]
Application-specific calibration needs and their relation to interim checking	[17]
Issues related to the use of Standards and their traceability during interim checking	[3]

Table 2. Problems related to calibration

Type of Calibration & verification problem	Reference Cited
Dominance of geometric and volumetric errors	[6-9]
Artifact-based approaches	[9, 10, 15]
Uncertainty quantification and compensation	[11, 18]
Newer data-driven approaches	[12]

Earlier researchers have reported different aspects of problems related to calibration of CMM (refer to Table 2), viz. Dominance of types of errors, uncertainty quantification and compensation, use of artifact-based approaches for calibration, different processes used for interim checks and monitoring (refer to Table 3), viz., the approach of day-to-day reliability estimation and identification of dynamic error for interim checking, etc.

Table 3. Processes related to interim checks and monitoring

Interim Checks and Monitoring Details	Reference Cited
Day-to-day reliability by Interim checks	[2, 13, 14, 19]
Material selection & dimensional stability	[19]
Identification of dynamic error	[10, 15, 16]

Different methods for the measurement of geometrical errors of a machine are discussed [6]. Geometric errors on CNC machines can be measured by using a 1D artifact [7]. Error compensation technique is used to reduce geometric error, which is the main source of inaccuracy. Its research review in measuring, modeling, and compensation of geometric errors has been reported, which is inferred as an additional process [8].

To measure volumetric errors, a hole plate artifact is designed to measure the volumetric accuracy and 21 parametric error components of CMM [9]. A calibration method for the artefact is presented to minimize the effect of geometric errors on the CMM. This method estimates the uncertainty of scale and orthogonal error. While calculating errors, the orientation of the artifact in measuring the volume of the CMM is a vital factor [10]. A cost-effective and faster method has been developed for testing the coordinate measuring machine. It needs one one-time measurement to correct the squareness error [11]. By application of neural networks and quantile regression, the errors of the CMM can be predicted. This method improved accuracy and is better than least squares regression. This reflects the trend towards hybrid data-driven models [12].

Results of CMM measurement are compared with the calibration values, which will make available information on measurement deviations and uncertainty of the measured features [13]. An experimental interim check technique is suggested for scale and orthogonal error uncertainty evaluation. Of CMM. [14]. A master artifact is developed to identify and check the dynamic properties of the CMM. This artifact takes measurements at high speed, guaranteeing the required accuracy [15].

A pitch artifact to calibrate pitch positions of the balls in radial and height positions on a circular ball plate is developed [16]. Spherical lenses are used as a reference surface to check the quality of the ophthalmic lenses [17]. In the decision-making process, consistent and reliable measurement of uncertainty is a crucial factor. For uncertainty evaluation, standard step gauges are used for verification, which is used as a workpiece [18].

From the reviewed literature, a distinct trend of CMM performance valuation using geometric and volumetric error assessment is observed. An interim check/ calibration method with the importance of orientation of the artifact within the CMM measuring volume can be devised to estimate the uncertainty of measurement. This approach can significantly reduce dependence on standards and human intervention. The use of artifacts gives real-time performance evaluation and interim checks for errors. This method also contributes to enhanced process reliability.

Different types of approaches are used for interim checking of CMM (refer to Table 4), including hybrid, self-calibration, approaches focusing on uncertainty, the material sensitivity approach, and the application-oriented diversity approach. However, the work presented herewith uses an error-finding approach by taking measurements of ball distances from the reference ball on the Novel artifact.

2.1. Use of Ball Plate as Artifact

For estimating the pooled errors and statistical performance of CMM, the Ball Plate artifact is widely used as a reference standard due to its geometric simplicity and dimensional stability. It also helps to find measurement uncertainty. Some of the research contribution from various authors detailing the number of balls used, measurement cycles performed, materials used for the plate and balls, size of the artifact, and accuracy achieved is presented in Table 5. This provides a good perspective on the effectiveness and constraints of the ball plate artifacts.

Table 4. Emerging approaches for interim checking

Emerging Approaches	Details
Hybrid Approaches [11, 12]	Integration of physical learning Models and machine learning methods
Self-Calibration Approaches [10, 16]	Decreased reliance on external standards
Approaches Focused on Uncertainty [8, 18]	Quantification and propagation of uncertainty into decision-making
Material Sensitivity Analysis approaches [19]	Recognition of thermal stability and long-term creep issues in artefact materials
Application-Oriented diversity Approach [4, 17]	Ophthalmic optics
	Multi-axis machining

Table 5. Ball plate artifact designs

Material	No of Balls	Size (mm)	Measure ment Cycles	Accuracy Achieved (µm)	Limitations *
Dolerite for base plate and Zirconia for balls [5]	52	450 × 450 × 40 thk	Not explicitly fixed	10	More balls, heavier, less accuracy
Ceramic balls glued on a cylindrical plate [16]	12	Ball circle radius 119	30	0.74	Difficulty in taking measurements, more measurement cycles,
Not mentioned [10]	36	100 x 100	Not explicitly fixed	2.1	Kinematic coupling between the base plate and ball plate may create geometric errors.
Steel for balls and Aluminum for plate [11]	25	Not mentioned	04	7.0	Less dimensional stability

Explanation of Limitations: As Ball Plate Artifacts are Mentioned in Table 5, the Results are Expressed with Respect to the (Redesigned) Novel Artifact. It is observed that, earlier Dolerite–Zirconite ball plate type artifact uses a larger number of balls and the size of the ball plate is larger, which makes it costly and heavier [5] and comparatively less accurate (10 µm). A ball plate with a cylindrical plate is difficult to manufacture and may face difficulty while taking measurements. Further, it needs more measurement cycles and is also difficult while positioning during volumetric error estimations as per ISO 10360-2 [16]. The ball plate artifact, with a spacer [10] separating the ball plate and base plate, may introduce some structural errors. Artifact with metallic balls and plate [11] will need temperature Compensation. Even after using temperature compensation, the thermal effect is a major contributor affecting accuracy and repeatability. Such experiences demand more research to improve accuracy (for correct estimation error during interim check), reduce weight, and inspection cycle time.

2.2. Types of Errors Measured

Some of the researchers measured and quantified various types of errors in line with international standards. The type of errors, the parameter used to measure error, and the standard referred to are reviewed as stated in Table 6.

2.3. Types of Artifacts and Errors

Various types of artifacts are used by different researchers to find errors. The type of artifact and the measured errors by using it, as well as the standard used, are reviewed (refer to Table 7). The present work follows the International standard ISO 10360-2, which is a general product specification for acceptance and verification of CMM.

Table 6. Types of errors and standards used

Type of Error/Test	Standards Used	Parameters Used
Length measurement error [1, 4]	NPL guidelines No. 42	Linear length
Geometric errors [2, 6, 10, 12, 18] [19, 21, 22, 23]	NPL guidelines No. 42, ISO 10360-2	Measurement uncertainty, Measurement repeatability, Local Kinematic Model, Errors due to tool wear and fixture, Measurement range, Artefact material selection, Design of Artifact, Standards for acceptance and verification of CMM, Linear, Horizontal, and vertical straightness, Pitch, roll, and Yaw errors, Multi-feature bar.
Probe form error [1, 4]	ISO 10360-2	Scanning speed, probe force
Volumetric error [3, 7, 13, 17, 21, 22, 23]	ISO 230, ISO 10360-2	Measurement of straightness and squareness errors, Self-calibration, probe positions, Self-calibration, probe positions, Deflection analysis of hole plate, measurement uncertainty
Thermo-mechanical errors [3]	ISO 230	Measurement of straightness and squareness errors
Linear error [5, 9]	ISO 10360-2, ANSI/ASME B89	Linear displacement, axis alignment
Dynamic error [8, 11]	ISO 10360-2	Regression analysis, measuring speed, Pitch, and scanning measurement of the master artefact
Angular errors [9, 14]	ISO 10360-2	Error characterization and compensation, Self-Calibration of ball plate
Squareness errors [9, 15, 16, 23]	Statistical standards	Error characterization and compensation, non-zero out of spherocity, stylus tip offset, Calibration uncertainty, and use of a telescoping ball-bar
Normality test [19, 20]	NPL guidelines No. 42, ISO 10360-2	Anderson Darling Coefficient, Univariate Normality test procedure.

Table 7. Types of artifact and error measured

Type of Artifact	Type of Error	Standards Used	Limitations*
Metallic ball plate, Ball bar, Fabricated purpose-made test piece [1]	Geometric error, Volumetric error, Squareness errors	NPL guidelines No. 42	Possible thermal expansion, High weight, Corrosion affects Long-term dimensional stability. The ball bar provides only one-D measurement, unable to measure Volumetric error. Purpose-made test piece is non-standardised, Difficult to trace to national standards
1D and 2D artefacts [3, 5, 6]	Thermo-mechanical errors, Volumetric error, Dynamic error, Vertical Straightness error along X, Y, Z, Geometric error	ISO 230, ISO 10360-2	A 1D artifact can measure errors in one direction, unable to detect squareness and volumetric errors.
3-D grid artifact of steel balls [7]	Volumetric error	ISO 10360-2	Difficult to manufacture and Calibrate precisely. High cost of calibration
Hole plate artifact [13]	Volumetric error, Length error	ISO 10360-2	Limited for volumetric error detection
Ball plate (Metallic) with spacer [10]	Geometric error	ISO 10360-2	Accuracy gets affected by mismatch of thermal expansion between plate and spacer, Increased setup complexity

*Limitations of the Artifacts, as Mentioned in Table 7, are Discussed with Respect to the (Redesigned) Novel Artifact. It is evident that metallic ball plates are higher in weight and good conductors of heat, hence thermal expansion exists. Even after thermal compensation, accuracy and repeatability are affected. Also, Corrosion affects long - term dimensional stability. A fabricated purpose - made test piece is a standardized artifact, and it is difficult to trace to national standards [1]. Ball bar or other 1D and 2D artifacts can detect the errors in one or two directions only and are unable to detect volumetric errors. Hole plate artifacts have limited volumetric error detection capabilities [3, 5, 6]. A 3-D grid artifact of steel balls is difficult to manufacture and calibrate precisely. It also requires a higher cost of manufacturing and calibration [7]. And in case of an artifact with a spacer, the accuracy of measurement gets affected by the mismatch of thermal expansion between the plate and spacer, in case of a metallic ball plate with a spacer. Such a type of artifact will increase the complexity of setup [10]. After understanding the limitations of the reported research agenda, further research is discussed next.

2.4. Research Challenges Identified and Agenda for Research

Based on published research review and field visits research gaps been identified as: (i) Interim check standardization is weak (ii) Artifact material and stability tradeoffs needs improvements, (iii) Existing artifact designs consumes more time for interim checking of CMM, (iv) Further, practically low-cost methods to use refined artifact designs for interim check purpose are needed, which needs optimization. These research gaps help us to set the research agenda as: (i) To select of appropriate material and refine the artifact design, (ii) To resolve errors issues with appropriate measurement sequences and analysis, (iii) Reduced the dependency on external standards, (iv) To improve accuracy and reduce the inspection time per calibration which can result in improved the efficiency. The next sections discuss the refined design of the Ball-Plate type artifact, testing the novel artifact, and mapping the estimations of errors to measuring the volume of Bridge type CMM with more accuracy and effectiveness.

3. Novel Artifact Design Steps

High accuracy and repeatability are some of the important considerations in CMM performance. To verify these performance characteristics of the CMM, the artifact being used for the interim check of CMM should be well calibrated with good surface finish, high-quality geometry, and dimensional stability as recommended by ISO-10360-2. The methodology adopted for the design, manufacturing, and testing of the Novel Artifact is shown in a flow chart in Figure 1.

Table 8. Data for material selection

Material	A ($10^{-6}/^{o}C$)	Σt (MPa)	ρ(kg/m3)	Hardness (BHN)	Cost (Rs)	Machinability Rating (%)
Titanium alloy	9.01	1025	4400	140	160916	45
Invar	2	445	8200	350	83731	50
SiC	4.01	336	2700	425	132555	256
Granite	6.5	60	2600	60	111854	37.5
Dolerite	2.4	399.56	3135	709	111895	443
Carbon steel	13.5	475	7850	183	121898	57
Al alloy	23.5	175	2689	50	107335	270

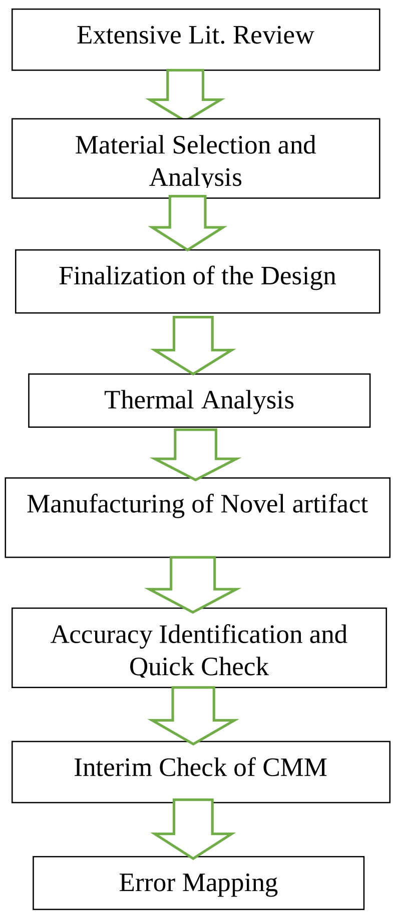


Fig. 1 Flow chart of methodology

3.1. Material Selection and Analysis

After review of the published literature, Patents, and the interactions with domain experts, the next immediate step was to finalize the material for the artifact. The main motivation for the selection of the material is to improve the accuracy of the Novel artifact. Materials among the pool of alternatives described by various attributes such as coefficient of thermal expansion (α), strength, hardness, density, machinability, and cost are considered. Multi-Aspect Decision Making (MADM) techniques, viz. Preferential Indexing and TOPSIS are utilized to finalize the material for the base plate. Dolerite is proven as a preferred material for the base plate of the artefact used for interim checks of CMM [19]. Zirconia is also a type of ceramic that depicts excellent thermal stability, chemically non-reactive to Dolerite, good resistance to corrosion and abrasion, high strength and hardness with excellent surface finish on machining. When Zirconia is subjected to impact loading, it shows transformation toughening and stops crack propagation. Hence, the material selected for the balls of the Novel artifact is Zirconia. Refer to Table 8 for the data for material selection.

3.2. Finalization of the Design

To finalize the design of the Novel artifact, four different conceptual designs are verified on the basis of measured volume, accuracy, ease of manufacturing, cost, and thermal diffusion, leading to the stability of the artifact. After studying these design concepts, a design covering 70 % of the measuring volume of the CMM table *(in line with ISO 10360-2)*, easier to manufacture, easier to handle, with good dimensional stability, and less cost has been finalized for further development. A ball plate with a Dolerite base plate and Zirconia balls is shown in Figure 2.

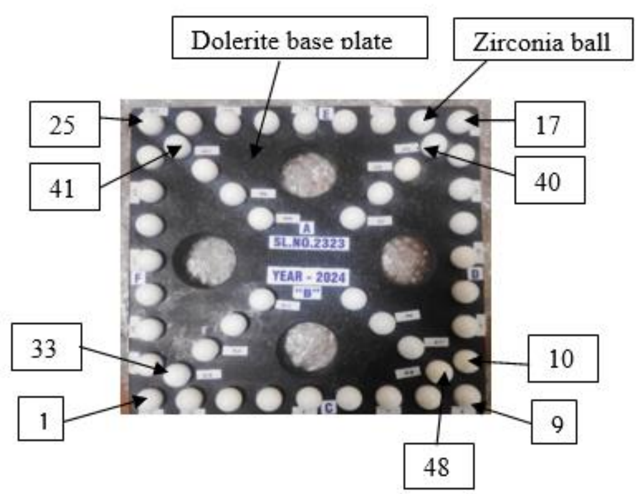


Fig. 2 Dolerite-Zirconite ball plate

3.3. Thermal Analysis

Good repeatability and accuracy are some of the important considerations in CMM performance. The thermal effect is the largest source of apparent non-repeatability and inaccuracy in most of the CMMs. Even though thermal compensation is used, the uncertainty of the measurement process is affected by the temperature stability of the artifact. Dolerite is a natural rock with very low α (2.4 x 10-6/°C) that maintains its dimensional stability. This is confirmed by carrying out thermal analysis by using ANSYS V5R21.

As the uncertainty of length measurement is lowest at 20°C, the base plate is analyzed for thermal distortion from 20°C to 24°C in steps of 0.5°C, i.e., for analysis at 20.5°C, the temperature is increased gradually to 20.5°C in 43200 seconds and kept constant for 86400 seconds.

Thus, the maximum total directional deformation observed at a temperature of 20.5 °C is 0.12248 µm, and at 24 °C, it is 0.97986 µm, which is less than 2 µm [19]. The results of the total Directional Deformation at 24°C are shown in Figure 3.

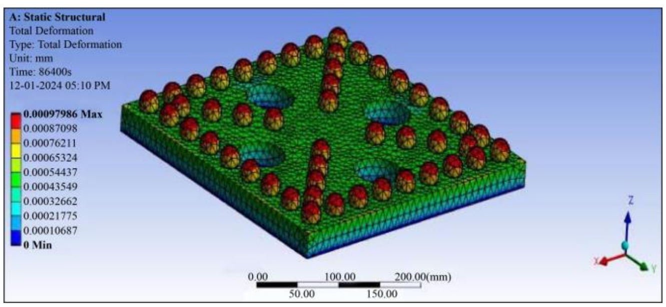


Fig. 3 Total deformation at 24°C

3.4. Manufacturing of the Novel Artifact

Dolerite base plate of size 350 mm x 350 mm x 25 mm thick for Novel Artifact is manufactured at GMT Hosur with flatness, squareness, and perpendicularity within 3 µm. 48 numbers of Zirconia balls with spherocity within 3 µm are fixed to the base plate by using structural adhesives, Resin AW 106 with Hardener HV 953 (Araldite) mixing in a 1:1 ratio as per Huntsman specification.

This Novel artifact can be handled by one person and has no moving parts. This also demonstrates its dimensional stability, computing capability in terms of geometric errors, and measuring volume for Bridge type CMM.

3.5. Accuracy Identification and Quality Check

Accuracy of the Novel Artifact is verified by checking the dimensions at NABL certified CMM using DIMS software according to the specification ISO 10360-2.
Make: Accurate Engineering, Model: Spectra,
LC = 0.0001mm,
Reference Sphere (Ceramic), dia.30.00 mm.
Traceability: Traceable to National and International Standards through NABL Lab CC-2802 vide certificate No P/97/2419, calibrated on 06/11/2024 and valid up to 05/11/2025.
Environmental conditions: 20±0.5°C, RH=45%

For estimation of the various errors, the Novel artifact was checked for its ball distances in a certified IEPL (Inspatech Engineering Pvt Ltd) situated in the western region of India, Bhosari Industrial area, Pune, India, in different orientations of the artifact on the CMM table. Ball distances were recorded in the first week and subsequently in the twelfth week and twenty-second week (refer to Table 9).

Table 9. Ball distance

Ball Distance (mm)	Nominal distance (mm)	1st week (23.11.24)	12th week (08.02.25)	22nd week (19.04.25)	D (1-12)	D (1-22)
1-2	38	38.0740	38.0781	38.0784	-0.0041	-0.0044
1-3	76	76.0932	76.0972	76.0974	-0.0040	-0.0042
1-4	114	114.0350	114.0395	114.0398	-0.0045	-0.0048
1-5	152	152.0570	152.0610	152.0612	-0.0040	-0.0042
1-6	190	190.0450	190.0489	190.0491	-0.0039	-0.0041
1-7	228	228.0520	228.0558	228.0560	-0.0038	-0.0040
1-8	266	266.0480	266.0520	266.0520	-0.0040	-0.0040
1-9	304	303.9750	303.9794	303.9796	-0.0044	-0.0046
1-25	304	304.0778	304.0812	304.0814	-0.0034	-0.0036
1-26	266	266.0010	266.0042	266.0043	-0.0032	-0.0033
1-27	228	228.0148	228.0176	228.0178	-0.0028	-0.0030

1-28	190	190.0475	190.0500	190.0502	-0.0025	-0.0027
1-29	152	151.9385	151.9358	151.9359	0.0027	0.0026
1-30	114	114.0248	114.0222	114.0223	0.0026	0.0025
1-31	76	76.0052	76.0028	76.0029	0.0024	0.0023
1-32	38	38.0672	38.0647	38.0647	0.0025	0.0025
1-33	38	37.9870	37.9857	37.9857	0.0013	0.0013
1-34	76	76.0040	76.0020	76.0020	0.0020	0.0020
1-35	114	113.9201	113.9216	113.9203	-0.0015	-0.0002
1-36	152	151.9520	151.9532	151.9521	-0.0012	-0.0001
1-37	228	227.9520	227.9534	227.9522	-0.0014	-0.0002
1-38	266	266.0070	266.0082	266.0071	-0.0012	-0.0001
1-39	304	303.9980	303.9977	303.9983	0.0003	-0.0003
1-40	342	342.0390	342.0402	342.0404	-0.0012	-0.0014
1-17	380	379.9820	379.9829	379.9830	-0.0009	-0.0010
9-10	38	38.0924	38.0934	38.0934	-0.0010	-0.0010
9-11	76	76.0065	76.0073	76.0074	-0.0008	-0.0009
9-12	114	114.0592	114.0583	114.0602	0.0009	-0.0010
9-13	152	151.9428	151.9427	151.9431	0.0001	-0.0003
9-14	190	189.9860	189.9867	189.9868	-0.0007	-0.0008
9-15	228	228.0026	228.0024	228.0028	0.0002	-0.0002
9-16	266	266.0144	266.0141	266.0147	0.0003	-0.0003
9-17	304	304.0640	304.0636	304.0641	0.0004	-0.0001
9-25	380	379.9076	379.9077	379.9078	-0.0001	-0.0002
9-41	342	341.8756	341.8757	341.8757	-0.0001	-0.0001
9-42	304	303.9200	303.9196	303.9202	0.0004	-0.0002
9-43	266	265.8790	265.8792	265.8794	-0.0002	-0.0004
9-44	228	227.8680	227.8683	227.8684	-0.0003	-0.0004
9-45	152	151.8680	151.8686	151.8688	-0.0006	-0.0008
9-46	114	113.8702	113.8698	113.8701	0.0004	0.0001
9-47	76	76.0540	76.0535	76.0536	0.0005	0.0004
9-48	38	38.0380	38.0386	38.0386	-0.0006	-0.0006
17-18	38	38.0125	38.0117	38.0120	0.0008	0.0005
17-19	76	75.9685	75.9690	75.9692	-0.0005	-0.0007
17-20	114	114.0037	114.0047	114.0049	-0.0010	-0.0012
17-21	152	152.0280	152.0289	152.0290	-0.0009	-0.0010
17-22	190	189.9969	189.9979	189.9981	-0.0010	-0.0012
17-23	228	227.9775	227.9787	227.9789	-0.0012	-0.0014
17-24	266	265.9845	265.9853	265.9855	-0.0008	-0.0010
17-25	304	303.9657	303.9671	303.9673	-0.0014	-0.0016

3.5.1. Summary for the Range of Differences (*1-22 weeks)*

Summarization of the differences in readings in the first to twelfth and twenty-second week is done graphically, indicating an overlaid normal curve, box plot, 95% confidence intervals of population, and median in Figure 4.

The null hypothesis of normality is accepted for a smaller sample size and may be rejected even for small violations. Thus, its assessment with statistical tests is profound to the sample size. Hence, to study normality violation in light of sample size, graphical methods are used [20]. This graphical method shows statistics of Anderson-Darling (AD) Normality tests to define the normal distribution of data, or else [21]. In the present work, the P-value is obtained by Minitab software with the AD test statistic. It is the possibility of gauging evidence against the null hypothesis. The higher the value of the AD statistic, the less likely the data will follow a normal distribution. Anderson Darling Normality Test (A-Squared 1.70, P-Value <0.05) shows that the data for the twenty-second week follows a normal distribution curve.

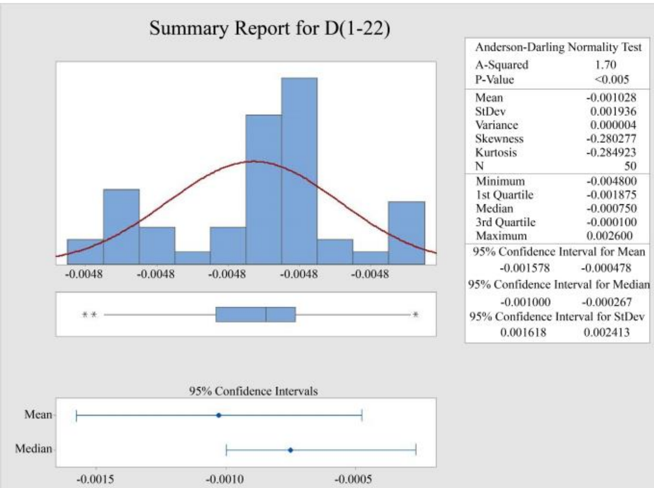


Fig. 4 Graphical summary for the range of difference (1-22 weeks)

3.5.2. Coefficient of Pearson Correlation

The correlation coefficient is used to examine the association between the X and Y series. Selective co-variance is obtained by using the following formula:

$$C_{xy} = \frac{1}{n-1}\left[\sum_{i=1}^{n} X_i Y_i - n\overline{x}\overline{y}\right] \tag{1}$$

Where Yi Xi - Reading values

$\overline{x}, \overline{y}$ -

Measured values mean

Between the series correlation exists and grows stronger if $C_{xy} \neq 0$. Pearson's Correlation coefficient is used to determine correlation strength,

$$r_{xy} = \frac{C_{xy}}{S_x S_y} \tag{2}$$

Where S_x and S_y are selective random variance.

Correlations between first and twelfth D (1-12) and first and twenty-second week D (1-22):

Difference in values of 1st to 12th week and 1st to 22nd week shows a positive relationship as Pearson correlation of D (1-12) and D (1-22) = 0.969,
Correlation: D (1-12), D (1-22)
Pearson correlation of D (1-12) and D (1-22) = 0.969
P-Value = 0.000
Hence, it is necessary to decide the recalibration period of the Ball Plate.

3.5.3. Cross Correlation

Cross-correlation is the generalization of standard linear correlation analysis. When the coefficient of correlation of two variables approaches or is equal to 1, it indicates a strong positive linear correlation where all the readings will be around a line having a positive slope; otherwise, if the coefficient of correlation is near the least attainable value of 1, then the two variables indicate a strong negative linear correlation [22]. Constancy of retaining dimensions by the ball plate is ensured with the help of cross correlation with difference (lag of 6 weeks). This is the standard method for measuring the degree of correlation between two rows.

Cross correlation r_{xy} with lag d is obtained by using the formula:

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\left(y_{i-d} - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_{i-d} - \overline{y}\right)^2}} \tag{3}$$

Where lag is to d =1, 2…n

A cross-correlation plot with differences in readings of 1st to 12th and 1st to 22nd weeks is shown in Figure 5.

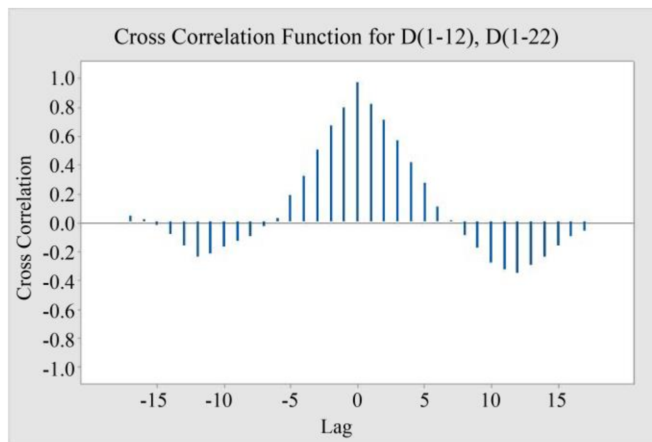


Fig. 5 Cross correlation for difference (1-12 weeks), and (1-22 weeks)

3.6. Interim Check of CMM

Different types of geometric errors occurring in CMM are shown graphically in Figure 6, and a detailed description of the same is given in Table 10.

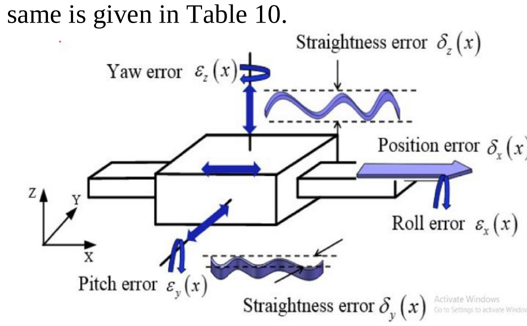
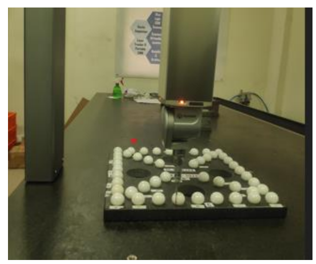


Fig. 6 Geometric errors

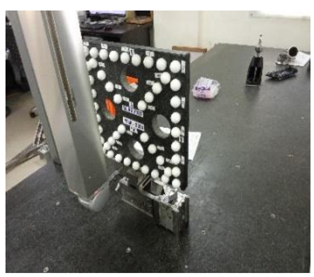
Table 10. Types of errors

Sr. No	Type of Errors	Description
1	Linear Displacement	CMM Scale error. Resultant of the difference between calibrated value and measured value.
2	Horizontal Straightness	Deviation from the true line of travel perpendicular to the direction of travel in horizontal plane.
3	Vertical Straightness	Deviation from the true line of travel in vertical plane perpendicular to the direction of travel.
4	Roll Angular	Rotation around an axis parallel to the direction of travel in the horizontal plane.
5	Pitch Angular	Rotation around an axis perpendicular to direction of travel in the horizontal plane.
6	Yaw Angular	Rotation around an axis perpendicular to direction of travel in the vertical plan.

Setup 1. Ball plate in XY Plane



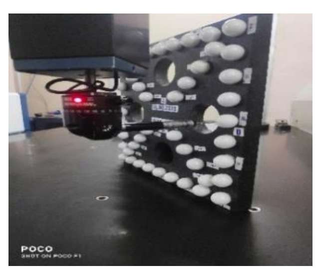
Setup 2. Ball plate at the best height position in the XY Plane



Setup 3. Ball plate in XZ plane

Setup 4. Ball plate in YZ plane

Setup 5 : Ball plate along the diagonal of the machine table



Setup 6: Ball plate in perpendicular position to set up 5.

Fig. 7 Different orientations of the novel artifact on the CMM table

Table 11. Ball plate orientation and setup

Setup No. (Ball plate Position)	**Measurement Strategy: Ball Positions**	**Outcome of Measurement**
Setup 1 (Ball plate in XY Plane)	'Measure the distance between balls 1-2,1-3,1-4,1-5,1-6,1-7,1-8,1-9 on the straight edge side along X axis'.	X- Horizontal straightness
	'Measure the distance between balls 1-25,1-26,1-27,1-28,1-29,1-30,1-31,1-32 on the straight edge side along the Y axis'.	Y- Horizontal straightness
	'Angle between straight edges along Y and X axes'.	XY squareness
Setup 2 (Ball plate at best height position in the XY Plane)	'Measure distances between balls 9-10, 9-11,9-12,9-13,9-14,9-15,9-16, 9-17'.	Y- linear
	'Find the difference values from right deviations to left deviations'.	Pitch X-Axis
	'Measure distances between balls 1-2, 1-3, 1-4, 1-5, 1-6, 1-7, 1-8, 1-9'.	X- linear
	'Find the difference values from bottom deviations to top deviations'.	Pitch Y-Axis.
Setup 3 (Ball plate in XZ plane)	'Measure distances between balls 9-10, 9-11,9-12,9-13,9-14,9-15,9-16,9-17 along Z axis'.	Z- linear
	'On surface E, measure ball distance 17-18, 17-19,17-20, 17-21, 17-22,17-23,17-24, and 17-25'.	X vertical straightness
	'On the surface F, measure distance of balls 1-25,1-26,1-27,1-28,1-29,1-30,1-31,1-32'.	Z- Vertical straightness
	'Measure squareness of surface F w.r.t. C'	ZX squareness
	'On the surface, D measures the distance of balls 17-18,17-19,17-20,17-21,17-22,17-23,17-24,17-25'.	Z-horizontal Straightness.
	'Measure distances between balls 25-24,25-23,25-22,25-21,25-20,25-19,25-18,25-17(with minimum and maximum probe extensions) Find the difference values between the maximum and minimum.	Yaw of X-Axis.
Setup 4 (Ball plate in YZ plane)	'Measure distances between balls 17-18,17-19,17-20,17-21,17- 22,17-23,17-24,17-25'.	Y –vertical straightness
	'Measure squareness of surface F w.r.t. C'.	ZY squareness
	'Measure points on surface F with horizontal probe with minimum extension in X negative direction. Again, measure the same points with maximum extension.'	The difference is roll of the Z Axis.
Setup 5 (Ball plate along the diagonal of the machine table)	'Measure distances between balls 1-33,1-34,1-35,1-36,1-37,1-38,1-39,1-40,1-17' 'Measure distances between balls 9-25, 9-41,9-42,9-43,9-44,9-45,9-46,9-47,9-48'	Volumetric errors
Setup 6 (Ball plate in perpendicular position to set up 5)	'Repeat the method of measurement as stated in the previous step (i.e., set up 5)'.	Volumetric errors

Geometrical errors in measuring the volume of the CMM are mapped with the ball plate. For the orientation of the workpiece on the CMM table, measuring volume should be a good indication. For the given reference location, all three-dimensional position error components (in X, Y, and Z) are measured with the ball plate artifact.

Developed a Novel (ball plate) Artifact that is used for interim checking of CMM in IEPL (Inspatech Engineering Pvt Ltd), Bhosari, Pune, Maharashtra, India. Inspection is carried out for measuring the distance between balls (the distance between the reference ball and other balls), and errors have been estimated. Each distance is measured three times as specified in standard ISO 10360-2 [23]. Different orientations of Novel Artifact on CMM table as experimental setups (positions as per ISO 10360-2) for estimation of errors are shown in Figure 7.

For the measurement of distances between balls, the Novell Artifact is placed on the CMM table in different orientations. The setup adopted, measurement strategy, and the outcome of the same are depicted in Table 11.

Table 12. Error values X-axis

	Geometrical Error Values of X-Axis				
Position	**Linear**	**Pitch**	**Yaw**	**V-Straightness**	**H-Straightness**
0	0	0	0	0	0
38	0.0000	0.0003	0.0022	-0.0001	0.0006
76	-0.0005	-0.0012	0.0012	-0.0003	0.0007
114	0.0018	-0.0032	0.0012	-0.0010	0.0009
152	-0.0005	-0.0009	0.0025	-0.0006	0.0009
190	0.0001	-0.0005	0.0009	-0.0003	0.0009
228	-0.0003	-0.0002	0.0014	-0.0005	-0.0026
266	0.0004	-0.0023	0.0024	0.0006	0.0007
304	-0.0011	-0.007	0.0023	0.0022	-0.0021

Table 13. Error values Y-axis

	Geometrical Error Values of Y-Axis				
Position	**Linear**	**Pitch**	**Yaw**	**V-Straightness**	**H-Straightness**
0	0	0	0	0	0
38	0.0004	-0.0002	0.0022	0.0014	0.0003
76	-0.0007	-0.0001	0.0017	0.0025	0.0002
14	0.0013	-0.0002	0.0012	0.0020	0.0004
152	0.0001	0.0000	0.0024	-0.0009	0.0011
190	0.0008	-0.0005	0.0023	0.0026	0.0002
228	-0.0006	-0.0009	-0.0024	-0.0018	-0.0013
266	0.0019	0.0004	0.0014	-0.0028	0.0000
304	-0.0032	-0.0001	-0.0005	-0.0029	-0.0009

3.7. Error Mapping

Vertical Straightness: Vertical straightness errors are obtained by keeping the ball plate in a vertical position, and readings are taken. Vertical Straightness error is obtained by using the formula.

$$V(xi) = Zi - Zfit(xi) \tag{4}$$

Horizontal Straightness: Horizontal straightness errors are obtained by keeping the ball plate in a horizontal position, and readings are taken. Error is obtained by using the formula,

$$H(xi) = Yi - Yfit(xi) \tag{5}$$

Pitch errors are obtained by taking the difference of the deviation.

Yaw and rolling errors are obtained by taking the difference of readings with maximum and minimum probe extensions. Taking the readings along the diagonal of the machine, volumetric errors can be obtained.

3.7.1. Experimental Results

Geometrical errors such as linear, Pitch, Yaw, Vertical, and horizontal straightness values along X, Y, and Z axes, and Roll error along Z are estimated (Refer to Tables 12, 13, and 14).

Table 14. Error values Z-axis

	Geometrical Error Values of Z-Axis					
Position	**Linear**	**Pitch**	**Yaw**	**Roll**	**V-Straightness**	**H-Straightness**
0	0	0	0		0	0
38	0.0005	0.0002	0.0011	0.0027	0.0019	0.0004
76	0.0007	0.0004	0.0017	0.0014	0.0042	-0.0002
114	0.0002	0.0000	0.0016	0.0012	0.0018	0.0003
152	0.0000	-0.0002	0.0026	0.0021	-0.0026	0.0015
190	0.0008	-0.0001	0.0007	0.0011	-0.0023	0.0018
228	-0.0008	0.0001	0.0017	0.0013	0.0003	-0.0023
266	-0.0006	0.0029	0.0007	0.0020	-0.0015	0.0009
304	-0.0008	-0.0004	0.0024	0.0029	-0.0017	-0.0023

3.7.2. Graphical Representation of the Evaluated Errors

Graphical representation of errors along the X-axis is shown in Figure 8.

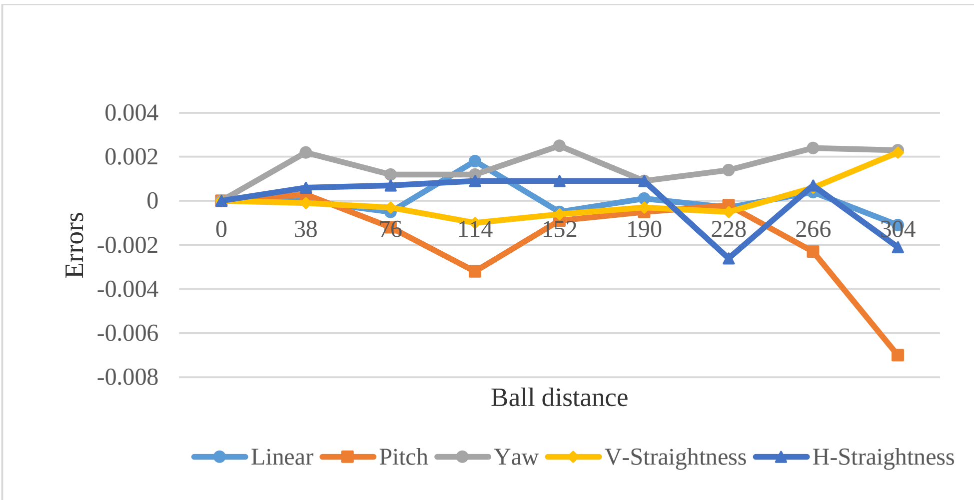


Fig. 8 Errors along X-axis

Graphical representation of errors along the Y-axis is shown in Figure 9.

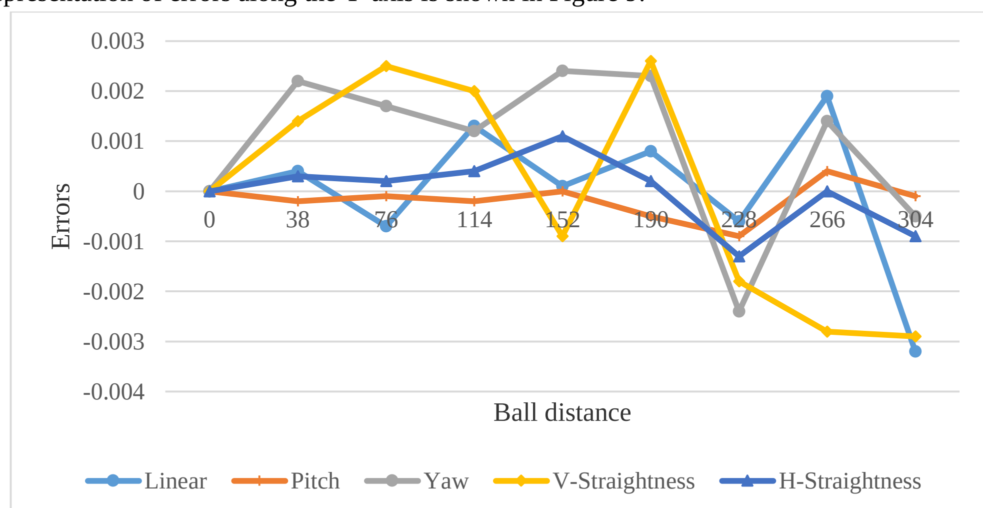


Fig. 9 Errors along Y-axis

Graphical representation of errors along the Z-axis is shown in Figure 10.

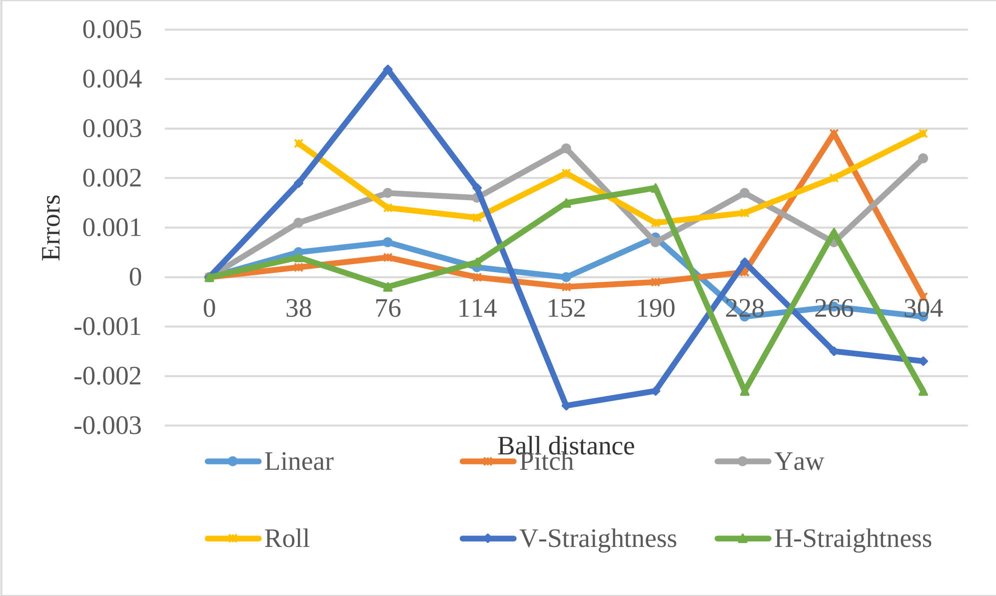


Fig. 10 Errors along Z-axis

4. Results, Discussion, and Conclusion

In order to minimize the time to perform the interim test, an abbreviated test procedure is focused on those test positions that most commonly reveal a problem with the CMM. This is taken up for further research, and the solution is reported here as a redesigned ball-plate type artifact. Design and development of the Novel artifact is as recommended by the international standard ISO 10360-2. The results obtained for testing the artifacts are summarized here.

From the analysis for dimensional stability of the Novel Artifact, it is observed that the Anderson Darling Normality Test (A-Squared value 1.70, P-Value <0.05) shows readings follow a normal distribution curve. It indicates random measurement variations with negligible systematic errors. Hence, it can be concluded that the manufacturing precision and material stability of the ball plate produce consistent measurement data over time (Refer to paragraph 3.5.1.).

Further, the Pearson correlation coefficient for the difference in readings of 1st-12th and 1st-22nd week is 0.969 (very close to 1), indicating a strong affirmative relationship. This shows that readings in the 1st week vary, the later readings vary in the same direction and magnitude, which means no significant dimensional drift (Refer to paragraph 3.5.2.). A correlation plot is used to prove the recalibration period of the Novel artifact. Correlation is high, and no phase shift is observed for a period of one year. This confirms that a Novel artifact requires no dimensional verification for one year. Artifact exhibits long-term dimensional stability, making it low maintenance, a high standard for interim checks of CMM (Refer to paragraph 3.5.3.). Geometric errors and the Probing system errors are the main contributors to the CMM errors. Geometric errors are due to the structural imperfections of the machine itself.

These are a total of 21 types of errors (18 measured along X, Y, Z axes and 03 squareness errors). Straightness, linear, yaw, pitch, and roll errors, etc. During actual interim checking of CMM used for inspection of the jobs in production line by using developed Novel Artifact, it is observed that the maximum deviation along X-axis is 0.0032 mm (pitch) in the distance range 76 mm to 114 mm; maximum deviation along Y-axis is 0.0029 mm vertical straightness, and maximum deviation along Z-axis is 0.0029 (Pitch and Roll) clearly indicates the improved accuracy w.r.to accuracy reported till date which shows capability of Novel Artifact to estimate all types of errors (Refer to paragraphs 3.7.1. and 3.7.2.). By using this Novel artifact, it is possible to measure the total 19 geometric and volumetric errors of the CMM out of 21 types of errors.

The study presents an approach to use a Novel artifact for interim calibration of Bridge type CMM. This Novel artifact is recommended for an interim check of CMM working in the temperature range of 20°C to 24°C. Maximum deformation at 24°C is 0.00097986 mm (0.97986 µm), which is much less than 2 µm (Refer to paragraph 3.3.). Hence, the use of the artifact can also be extended until deformation reaches 2 µm, particularly for shop floor utilization. This can also be used as a measurement standard for assessing the measuring accuracy and repeatability of the CMM used in an Industrial environment. However, this Novel artifact needs periodic dimensional verification, careful handling, specified working conditions, and appropriate mounting on the CMM table.

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