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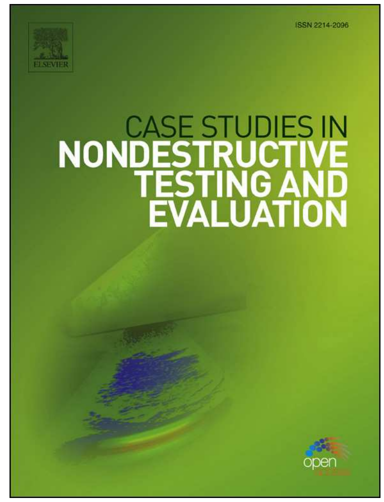

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Comparison of Different Additive Manufacturing Methods Using Computed Tomography

Paras Shah[1], Radu Racasan[1], Paul Bills[1]

The Centre for Precision Technologies, School of Computing & Engineering, University of Huddersfield, Queensgate, Huddersfield, West Yorkshire HD1 3DH, United Kingdom,

E-mail: P.Shah@hud.ac.uk, R.Racasan@hud.ac.uk, P.J.Bills@hud.ac.uk

Abstract

Additive manufacturing (AM) allows for fast fabrication of three dimensional objects with the use of considerably less resources, less energy consumption and shorter supply chain than would be the case in traditional manufacturing. AM has gained significance due to its cost effective method which boasts the ability to produce components with a previously unachievable level of geometric complexity in prototyping and end user industrial applications, such as aerospace, automotive and medical industries. However these processes currently lack reproducibility and repeatability with some 'prints' having a high probability of requiring rework or even scrapping due to out of specification or high porosity levels, leading to failure due to structural stresses. It is therefore imperative that robust quality systems be implemented such that the waste level of these processes can be significantly decreased. This study presents an artefact that is optimised for characterisation of form using computed tomography (CT) with representative geometric dimensioning and tolerancing features and internal channels and structures comparable to cooling channels in heat exchangers. Furthermore the optimisation of the CT acquisition conditions for this artefact are presented in light of feature dimensions and form analysis. This paper investigates the accuracy and capability of CT measurements compared with reference measurements from coordinate measuring machine (CMM), as well as focus on the evaluation of different AM methods.

Keywords: Additive Manufacturing, Morphological Characterisation, Dimensional Metrology, Traceability, Polymers, Artefact Design

1 Introduction

Additive Manufacturing is being used ever more widely in industrial applications such as aerospace, automotive and medical engineering from prototyping to end user parts [1-4]. In such applications use of AM allows for high geometrical complexities to be achieved with no additional cost being incurred in comparison to equivalent traditional manufacturing. Currently AM methods lack true reproducibility, meaning that in some cases large numbers of components have to be scrapped or reworked [5, 6]. Therefore there is a clamour within industry to develop a robust and reliable methodology for non-destructive evaluation of AM produced components.

Industrial Computed Tomography has been traditionally utilized to characterize material and component structures associated with traditional manufacturing processes such as moulding or casting defects, as well as organic and biological structures which can be seen to be akin to the complex network structures produced through AM to save mass.

Recently there has been a growing interest to investigate the efficacy and practicality of using CT [7-12] to both qualitatively and quantitatively analyse AM produced components, however, with both technologies at a relatively early stage a number of challenges exist in trying to achieve this.

Physically segmenting AM produced parts to verify internal dimensional accuracy is time consuming and impractical albeit not impossible. Moreover use of techniques such as optical interferometry or coordinate measuring machines (CMM) is not practical for complex internal lattice structures due both to issues of access to surfaces and time-cost due to the level of detail required. However as CMM measurements can be considered traceable such a method can be considered as a 'gold standard' for comparison to CT measurement. As such in this study CMM data will be used as a reference in the measurement comparison between AM artefacts produced using various methods and scanned using CT.

- This paper will detail the development of a CT-specific artefact, produced using representative industrial AM technologies. This has been developed with a view to encompassing the optimization of the measurement technique such that a reliable and robust comparison of the different AM methods can be accomplished.
- Deviation analysis is carried out on each of the AM artefacts and a comparison of deviations in form of AM artefacts is presented.
- 'Gold standard' feature measurements from CMM will be used as a reference and compared to features extracted from CT scanned data.
- An outline validation of the CT scanning method using CMM data is presented, uncertainty budget is determined and compensation factor calculated.

2 Additive Manufacturing Principles

The term additive manufacturing and subsequent process's shown in Table 1, termed by National Institute of Standards and Technology (NIST) & American Society for Testing and Materials (ASTM F42) committee gained wider affiliation in the early 2000s. The terminology describes a process of sequential layering of material from a digital model, to produce 3D physical objects. AM is not only used for prototyping[13] , but exceeding demands for end user products from fuel injection nozzles in aerospace [14] to orthopaedic acetabular cup implants in the medical industry [15]. Adopters of AM methods have contributed to the $3.07 billion worldwide revenue at the end of 2013 [16]. For many companies and individuals, as they try to engineer superior products, they are turning to AM for the benefits it offers over traditional techniques [17]. Custom tooling, jigs and fixtures manufactured using AM can alleviate fabrication lead times for in house machines used for production work.

Table 1: AM Process & Description [18]

Binder jetting	Liquid bonding agent is selectively deposited to join Powder materials.
Directed energy deposition	Focused thermal energy is used to fuse materials by melting as they are being deposited.
Material extrusion	Material is selectively dispensed through a nozzle or orifice.
Material jetting	Droplets of build material are selectively deposited.
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed.
Sheet lamination	Sheets of material are bonded to form an object.
Vat photo-polymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymerization.

AM processes will be utilised in a measurement benchmark comparison study which will determine accuracy and capability of these technologies and indicate the performance of CT for the purpose of dimensional metrology of such structures. Conformity checking and uncertainty determination will adhere to procedures used in ISO 15530[19] Each artefact will be measured 20 times on CMM and scanned once on CT. The three AM methods used in this study were chosen due to their popularity and are as follows:

1.) Direct photo-chemical alteration of liquid polymer or Stereolithography (SLA) utilises vector scanning ultraviolet laser scanning to solidify liquid photopolymer built on a lowering or hiring bed depending on machine design to produce a three-dimensional object. Material options are limited to polymers that may be photo-polymerized.

2.) High powered lasers are used to sinter chosen regions of microscopic polymeric, metallic or ceramic powder particles, in sequential two-dimensional cross sectional layers, selective laser sintering (SLS) is similar to the formation of sedimentary rocks to fabricate desired three-dimensional shape.

3.) Fused deposition modelling (FDM) used thermoplastic extrusion to build a thin tread like spool of polymer to create a cross section of the part layer by layer, similar to a hot glue gun or gas metal arc welding. Raw FDM parts have visible layer lines however various finishing processes are available including sealing and smoothing. The most popular material used in this form of AM is Acrylonitrile butadiene styrene (ABS).

2.1 Current artefacts

Benchmarking artefacts from previous studies, as shown in Figure 1, are designed to test the limits of an individual AM process; this allows users to select the most suitable process and material combination. Artefact designers incorporate multiple geometric dimensional and tolerancing (GD&T) characteristics, as shown in Table 2, in order to evaluate performance, such as form, accuracy, repeatability and surface finish. Current AM artefacts lack design optimisation for the use in CT, the sizes and shapes are not suited for evaluation using CT. Aspect ratio between thick and thin features are too high therefore leading to uneven x-ray attenuation, which produce beam effects such as; x-ray hardening and scattering [20], and scan data with low resolution due to the maximum dimension of the artefact, leading to a lack in magnification..

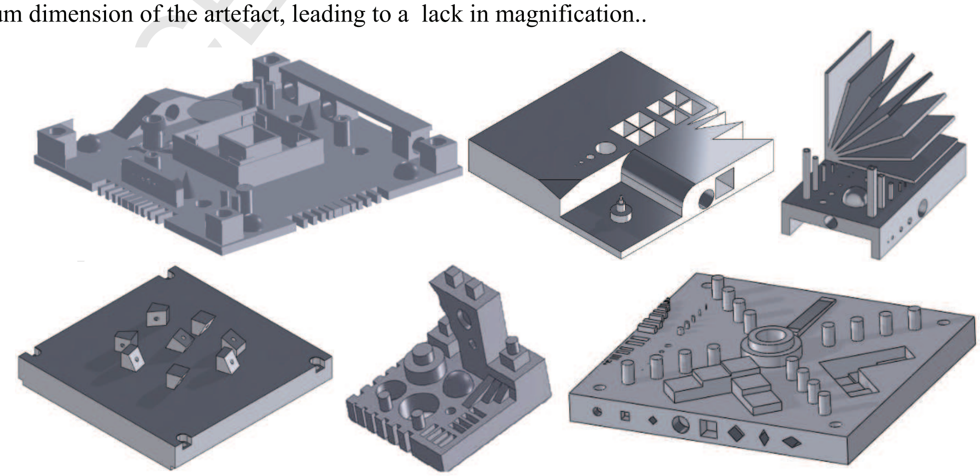

Figure 1: Additive Manufacturing Test Artefacts in order by Mahesh [21] Kruth [22] Castillo [23] Delgado[24] Johnson [25] Moylan[26] (Not to Scale)

Table 2: Geometric Features and Their Intended Purpose [27]

FEATURE	PURPOSE
Flat Base	Flatness and straightness
Cube	Squareness, parallelism, linear accuracy and repeatability
Cylindrical Hole	Roundness, cylindricity, accuracy and repeatability of radius (internal)
Sphere	Sphereness, relative accuracy and repeatability of a continuously changing sloping surface
Solid Cylinder	Roundness, cylindricity, accuracy and repeatability of radius (external)
Hollow Cylinder	Roundness, cylindricity and coaxiality of cylinders
Cone	Concity, sloping profile and taper
Angled Surfaces	Angularity, accuracy and repeatability of angled surfaces

3 X-ray Computed Tomography Principles

X-ray micro computed tomography (CT) utilises the generation of ionizing radiation to image projected geometry onto a complementary metal-oxide semiconductor (CMOS) 1000x1000 pixel flat panel detector. CT Pro (Nikon Metrology, Tring, UK) and VG Studio 2.2 (VGS) (Volume Graphics GmbH, Heidelberg, Germany) software packages are used to perform reconstruction and analysis of measurements taken place at University of Huddersfield using a Nikon XTH 225 (Nikon Metrology, Tring, UK) with a tungsten reflection target and a focal spot size of 3µm. Initial scan data is acquired using identical parameters of X-ray 200kV, 50uA, reconstruction method. Samples were placed vertically on low density foam to prevent noise/scattering from metal base plate. An initial scan was performed to check scan and reconstruction integrity and to allow the machine and samples to acclimate to the environment and scanning parameters; later leading to three scans of the samples.

4 Coordinate Measuring Machine

Reference measurements were taken using a Zeiss Prismo CMM (Zeiss, Rugby, UK) with a calibrated maximum permissible error (MPE) = +/- (1.9 + L/300) µm. A GD&T measurement strategy of all features is produced encompassing tactile scanning methods. Sampling criteria and measurement principles are followed in accordance with ISO1101 [28]and ISO10360 [29]. A series of 20 measurements were performed on each sample with a new alignment between each to produce reliable data. A styli star arrangement with 1mm ball diameter was used with a 5mm/s scan speed at 70mN contact pressure; this allows for efficient measurement in a single fixed orientation. Measurement data is tabulated and uncertainties are determined for comparison later.

5 Measurement uncertainty

To obtain reference measurements for each sample, an average of 20 measurements for each feature per sample was determined as per ISO 15530-3. The part was taken off and realigned for each measurement to ensure unique measurements unbiased to the previous iteration. Measurements were taken in a temperature controlled environment in the range of 20ºC/±2ºC and to account for minor temperature variations Equation 1 taken from ISO 14253-2:2011 [30] is applied.

$$\Delta L = (\Delta T \times \alpha \times L)$$

Equation 1: Temperature variation

Where ΔT: the difference of temperature in the CMM laboratory, α: is linear coefficient of thermal expansion and L is measured value. Uncertainty with reference to CMM measurements per feature is determined using equations also found in [30] and can be seen in use in a previous study [31]. This allows for upper and lower acceptance boundaries to be found for individual feature measurements based on statistical analysis of measured values, factoring temperature and MPE of measurement platform. The estimation of uncertainty is calculated using Equation 2:

$$U = k\sqrt{u_{MPE}^2 + u_S^2 + u_T^2}$$

Equation 2: Uncertainty Determination

A confidence factor of 95% is used (k=2), MPE stated in CMM calibration certificate determines $u_{MPE} = \frac{MPE}{2}$. Standard uncertainty is determined using standard deviation of measured values is (s) and number of measurements taken (n) resulting in $u_s = \frac{s}{\sqrt{n}}$. Finally measurements are compensated for temperature fluctuations $u_t = (\Delta T \times \alpha) \times L$. Results have been tabulated and a graphical representation outlines that uncertainties in CMM measurements by feature in figure 2. This evaluation provides a robust method of determining accuracies with the use of statistical analysis. Results from this determination are used later for upper and lower boundary qualification, using this data to validate the measurements taken using CT. Smaller features show higher uncertainty due to capable resolution.

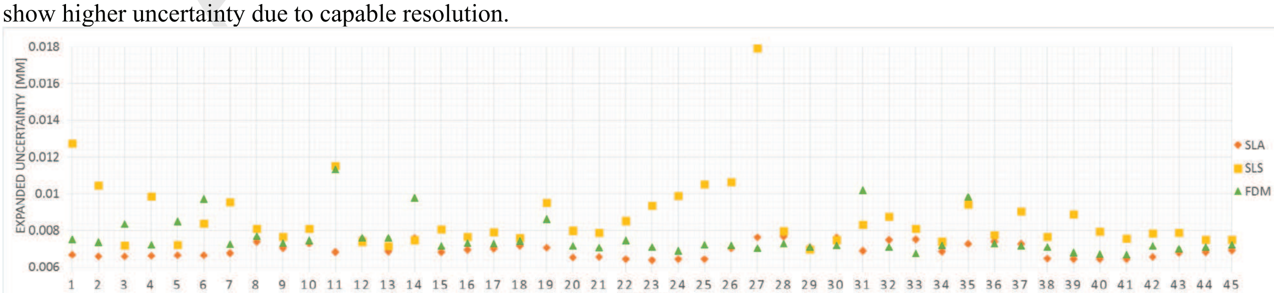

Figure 2: Expanded Uncertainty of CMM Measurements

6 Artefact Design

The layout of features to be measured is illustrated in Figure 3 and serialised in Table 3. 44 GD&T features have been designed in an arrangement beneficial to the process of CT scanning. This cylindrical artefact will provide even attenuation of x-rays in hope to maximise detail and resolution while taking a series of projection along its central axis.

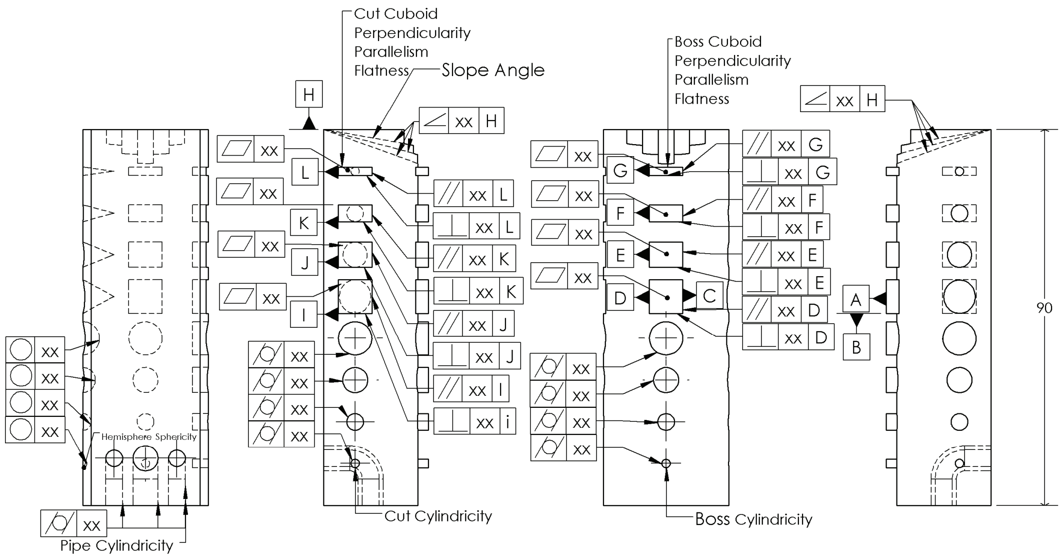

Figure 3: Additive manufactured HUDD Cylinder for Computed Tomography

This benchmarking artefact has potential to be implemented in testing some process limitations due to the feature sizes ranging from 2mm to 8mm. Methods that can be benchmarked including both metal and polymer AM, scaling of the artefact may be required. This field has been established by the means of designing test samples which encompass various GD&T characteristics [27] [32] .Current artefacts produced for the calibration of CT dimensional metrology include tetrahedron or Calotte Cube and ruby spheres in various configurations [33], these artefacts are used for geometrical characterization by measuring form and dimension. Artefacts can also be included in traceability and stability reports, allowing end users to track machine performance over time as well as suitability for prototyping or end usage. Conversely current generation AM artefacts are not optimized for the use in CT, features are designed for the intent of CMM verification and measurements. Consequently measurement of such artefacts with CT leads to lower resolution scan than desired due to the overall aspect ratio of the artefact and uneven x-ray attenuation.

Table 3: List of Features and Tolerance Allocation

Feature	I.D	U.I.D	Tolerance
Slope Angularity	SA	SA1	Angularity
		SA2	
		SA3R	
		SA3L	
		SA4	
		SA5	
Cut Cuboid Perpendicularity	CCPE	CCPE1-4	Perpendicularity
Cut Cuboid Parallelism	CCPA	CCPA1-4	Parallelism
Cut Cylindricity	CC	CCC1-4	Cylindricity
Boss Cuboid Perpendicularity	BCPE	BCPE1-4	Perpendicularity
Boss Cuboid Parallelism	BCPA	BCPA1-4	Parallelism
Boss Cylindricity	BC	BCC14	Cylindricity
Hemisphere Sphericity	HS	HS1-4	Sphericity
Pipe Cylindricity	PC	PCC1-3	Cylindricity
Cut Cuboid Flatness	CCF	CCF1-4	Flatness
Boss Cuboid Flatness	BCF	BCF1-4	Flatness

With reference to previous work by Kruth and Moylan [22, 34] an artefact for CT with both external and internal structures has been designed in order to allow for optimal detail scanning.

7 Methodology

ISO and VDI/VDE guidelines have not currently been applied widely to directly assess and characterise of AM samples using CT, so this paper details and seeks to do this, applying these principles to AM materials constructed using different methods.

All features on the AM artefact are measured and compared to CMM data to assess stability and variability, deviation is studied and CT data is re-evaluated. A comprehensive GD&T strategy is created and from this a template is generated and applied to scanned data using best fit algorithms to register samples. Through this determined method the compatibility of geometrical features including form, dimension are investigated.

A systematic approach for data acquisition is undertaken and environmental data recorded for traceability, during the scan of all samples. CT measurements were taken in environmentally controlled enclosed area with air temperature conditioning in the range of 20ºC/±2ºC. Scans typically took 3-4 hours, capturing 1044 projected images at 2000ms exposure. Raw image stacks were then reconstructed using CT Pro. Volume graphics was used for post processing. Further outline of CT procedure is depicted in figure 4.

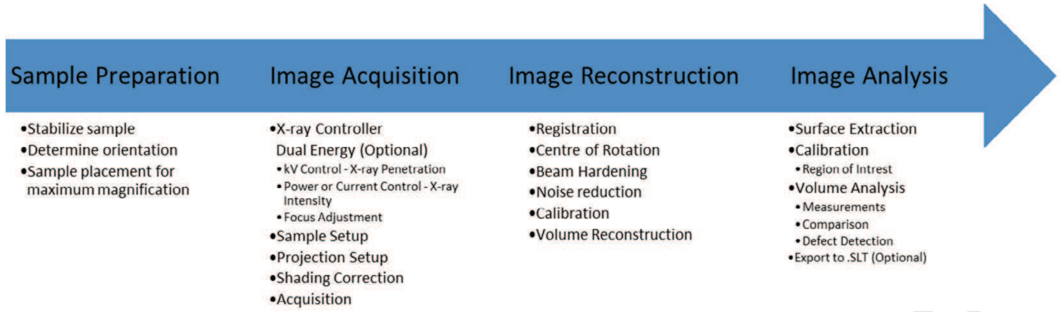

Figure 4: CT Scanning Procedure

To reduce some beam hardening and scattering effects due to uneven x-ray delivery, low energy photons are filtered out using a physical Cu filter, due to density variation between samples this ranged from 0.3-0.6mm in thickness. The size and type of filtration is determined using software simulation SpekCalc (IRC, Surrey, UK) [35, 36].

Industrially sourced, a 3D CAD file of the artefact was sent with a no finish request, to be manufactured using methods and specifications listed in the table below. Manufactured samples only had support structures removed without any surface treatment, this untreated surface allows for measurement of representative capability of the machine.

Table 4: Comparison of AM methods used in experiment

	SLA	SLS	FDM
Machine Make/Model	3D Systems: iPro8000	3D Systems: sPro60	Hewlett Packard: Design jet 3d colour
Material	ClearvueLiquid Polymer	PA12 Powder	ABS Filament
Layer Thickness	0.1mm	0.1mm	0.25mm
Solid Density	1.17 g/cm^3	1.01 g/cm^3	1.08 g/cm^3
Thermal Expansion	70 µm/m-°C	82.6 µm/m-°C	88.2 µm/m-°C

Voltage, current, and filtration specification is determined using SpekCalc and exposure is finely optimised manually to achieve best possible contrast ratio between background and sample. CT operational parameters are 190-200kV, 35-50µA, at a magnification of 2.0. This resulted in a voxle size of 95.3 µm.

A comparison between CMM/CT measurements was carried out to understand the difference in process and level of capability of both measurement technologies and procedures. A measurement template was generated using the reference model file used to manufacture the samples. Representation of GD&T features are illustrated in figure 5.

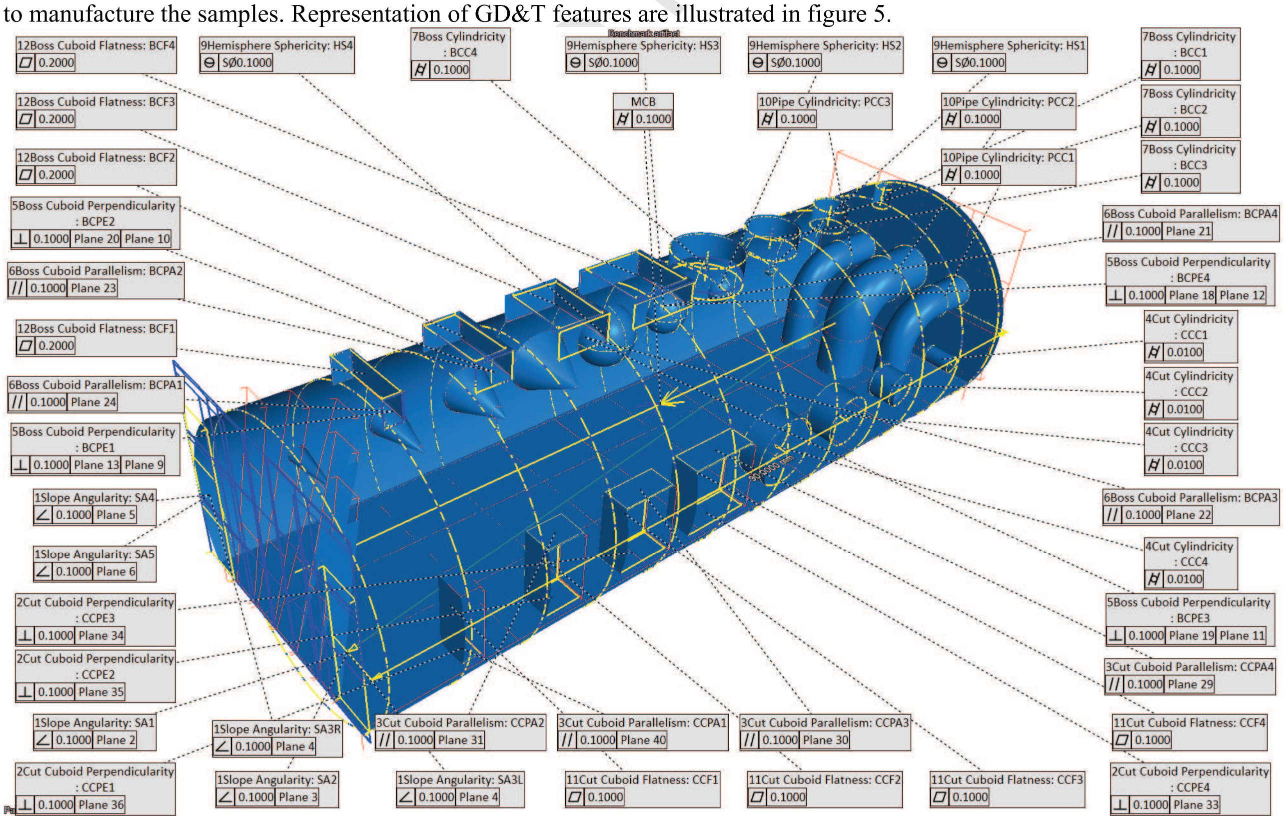

Figure 5: VGS Measurement Template

8 Results

Visual deviation analysis was performed using Catia (Dassault Systemes, etc), with the use of the digitized shape editor module the original .STL file is compared to a .STL export from VGS. With an average of 24 million fitting points and VGS best fit registration at a maximum quality level of 50, models are overlaid and form deviation was analysed. In figure 6, green areas represent deviation ±200 from original desired form. Red and purple areas depict regions that contain greater material or warping outside the desired form. Positional inaccuracy of features was found, where slope angle printed perpendicular to the print bed in all samples show deviations in excess of ±500μm. This may be due to the layering process creating a step every layer, producing a visible staircase effect rather than a smooth slope. The variation in slope angle design helps benchmark AM methods for thermal warpage and layer height accuracy.

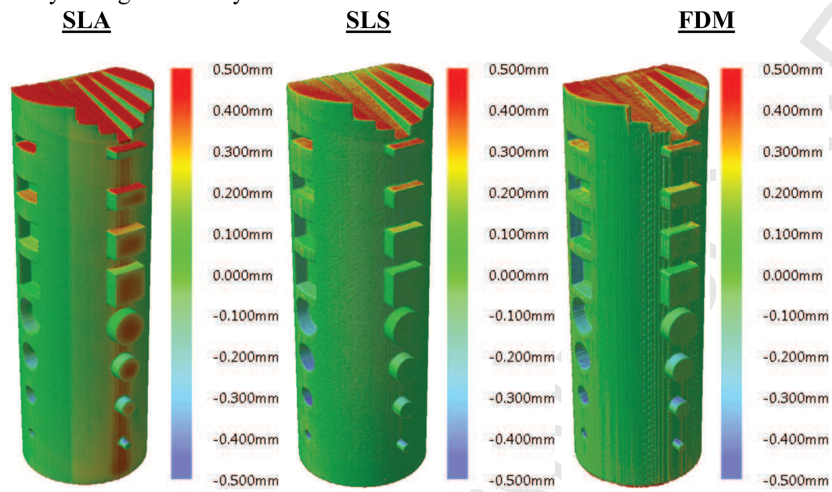

Figure 6: SLA SLS FDM Deviation Analysis

8.1 Measurement Comparison CMM vs CT

Measurement using CMM are taken as reference and compared to CT scans. This was evaluated using VGS figures 7-9 where nominal deviation from each feature of each AM sample is presented. A comparison of surface determination methods were also evaluated to analyse variation in results, comparing impact and implications. CT1 represents Automatic surface determination, and CT2 shows iterative surface determination mode with calculated edge threshold. Initial results show good conformance to reference measurements with high percentage of results are within boundary limits of determined uncertainty thresholds calculated previously. It is evident that minor adjustments in surface determination have considerable impact on results; some measurements have wavered in and outside of expanded uncertainty determination boundaries calculated in section 5. VGS automatic surface determination takes an ISO 50 approach where a surface is configured mid-way between object and background material. Usually between the two material peaks resides an area where the determined surface can be expanded or contracted slightly causing variation in measured tolerances.

Interestingly with the application of iterative surface detection, some results are not consistent with CMM results for example internal pipes PCC1-3 showing higher accuracy in SLA for CT2 but having no change in SLS and FDM. This suggests inconsistencies or incompatibility within the iterative method as this method according to VGS extends the search distance depending on the local grey value gradient. As there is visual but no technical feedback during determination it is difficult to assess, each features requires individual assessment of plain matching integrity. A time consuming methods which can be easily solved with enhancements in software analysis methods.

In terms of accuracy of AM methods, SLA is shown to have a variety of fluctuating tolerances in areas such as bossed cube perpendicularity and parallelism, showing the most accurate from all, conversely the highest internal pipe deviation was recorded on SLA, suggesting accuracy issues with internal structures or improper cleaning and removal of liquid photo polymer. Results of SLS were found to have higher stability between features, with a difference in deviation of 50 μm which is far less from 225 μm for SLA and 350 μm for FDM. SLS was the most difficult to measure using CMM, as after each measuring small powder deposits would form, implying material loss due to scanning and probing of stylus; this is also backed up by higher measurement uncertainty figures recorded in section5. FDM sample indicate that features have a worse accuracy and unstable feature measurement deviation than that of SLA and SLS samples, this can be backed by the inaccuracies of deposing molten filament through a heated nozzle, as resolution of manufacturing is determined by layer height and nozzle diameter and in this case the layer high was 0.25mm; which was clearly visible in CT scan data. Other factors involved in manufacturing accuracy include varying temperature and build speed during the build process could affect the accuracy of the parts. These parameters might help minimize the amount of warpage that the part undergoes due to the amount of time it is exposed to heat.[37].

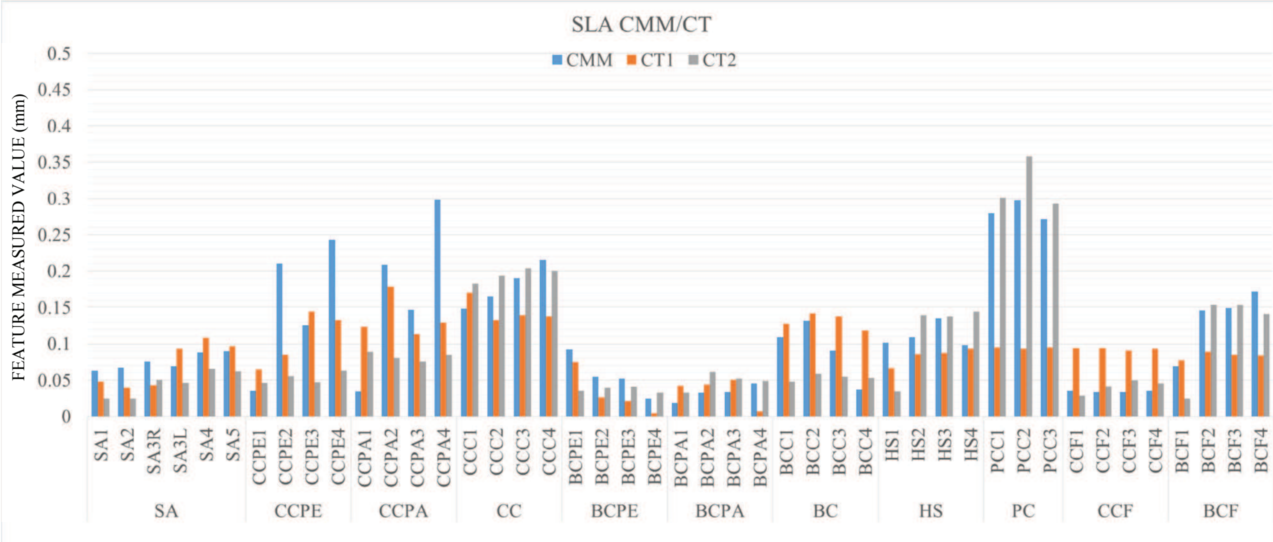

Figure 7: SLA CMM/CT Measurements

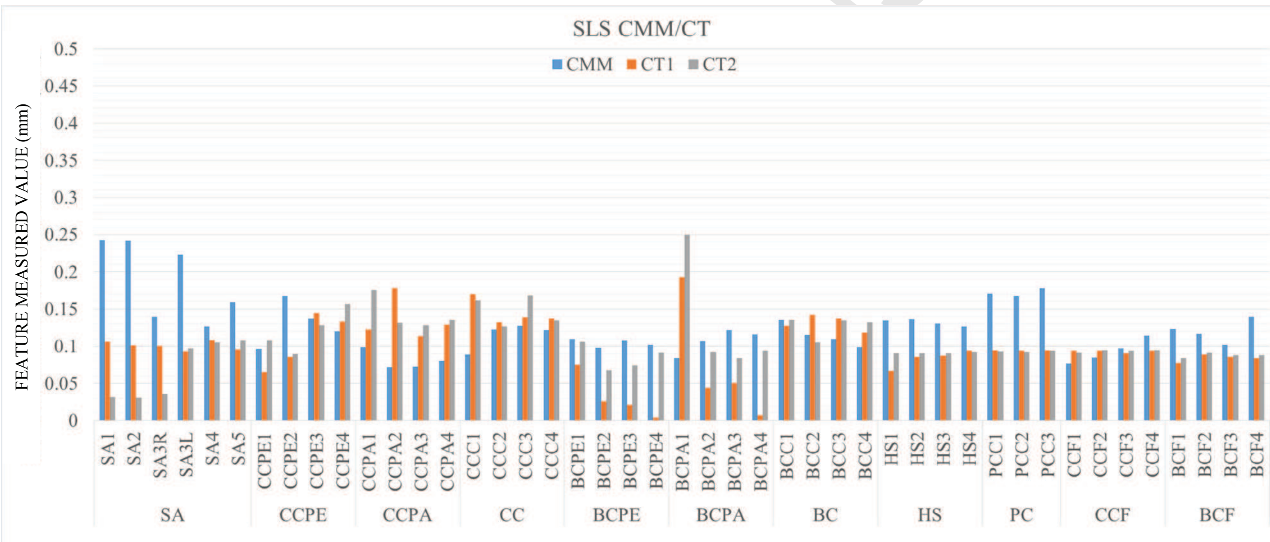

Figure 8: SLS CMM/CT Measurements

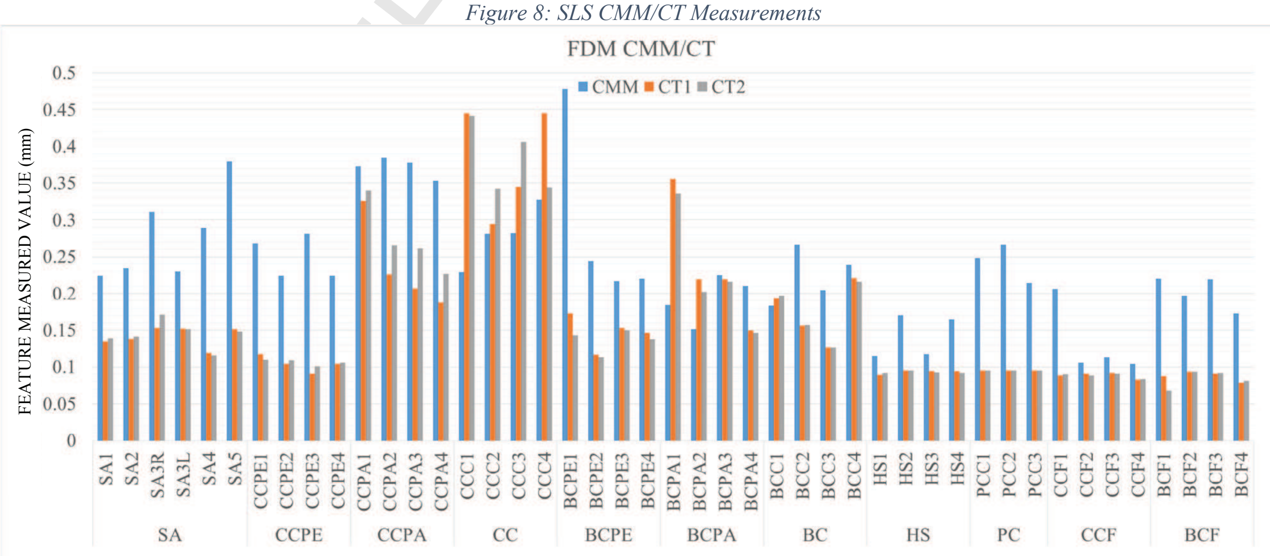

Figure 9: FDM CMM/CT Measurements

9 Discussion

This study uses AM designed artefact which were evaluated for measurement and form using CT and comparing to CMM reference measurements. The premise concentrated on different methods of production available in industrial AM. Analysing internal features using CT has great significance as intricate cooling systems for injection moulding allowing for faster cooling and quicker ejection and heat exchangers with increased performance are being developed using AM technology, intricate advance features which are near impossible to verify using traditional gold standard CMM methods[38]. The CT measurements are less accurate and the level of uncertainty is greater than that taken using CMM. Furthermore any influencing factor contributing to the inaccuracy of a CT measurement is in this case usually lower than the voxel size of the scan; this includes thermal drift, mechanical stability, magnification and object orientation to name a few [39], these factors when combined contribute to the overall noise of the measurement system and is difficult to compensate for.

Visual deviation, using software to superimpose scanned CT data to original CAD models allowed for visual comparison of a variety of AM methods, which provided a means to preliminary analyse the form that is created as well as its differences in feature position. As the layer height for both SLA and SLS are the same, they can be compared like for like but as the layer height differs for FDM, this has to be considered when comparing results. This artefact was designed to be optimised for maximum achievable resolution, scanned using CT but also allowing for single plan CMM measurements to be taken efficiently and effectively. Scans have provided higher resolution scan data than that of the NIST standard due to smaller aspect ratio and size, while adhering to the fundamentals of GD&T offering a myriad of features for comparison.

Every feature was visually checked for anomalies such as insufficient points collected for fitting, occlusion of plains causing instability in plain fixing. VGS provides little indication whether or not a plain is correctly fixed but by checking each individual feature provides ample validation. Difficulties were faced in surface determination, just as zooming in to a digital image causes pixilation, voxelation is caused when determining a surface on a volume reconstruction of a CT scan, and this resulted in a surface determination comparison study. Results suggest trends in results from both CMM and CT but also opening up more questions than answers, such as the high comparison accuracy and conformity of some features for example bossed cube and cut cube flatness with percentage error as low as 18.6% compared to pipe cylindricity and cut cube parallelism, reaching 86% error from CMM results. Nevertheless the focus CT for AM has investigated the suitability of such technologies for the verification and acceptance AM parts. Conformity and correlation between measurements taken using CT was visible. Table below shows percentage error of CT results compared to reference CMM results. The use of iterative surface determination shows marginal improvements and certain sets of features but results are nominal and inconclusive, further statistical analysis is required to accurately determine CT scan surface.

Table 5: Percentage Error % of CT Measurements Using Reference Results (Lower is Better)

Feature	FDM		SLS		SLA	
	CT1	CT2	CT1	CT2	CT1	CT2
SA	47.43	46.27	42.55	59.15	28.33	41.53
CCPE	57.86	56.92	24.56	23.97	50.81	60.14
CCPA	36.61	26.71	72.17	76.17	88.88	86.05
CC	39.52	40.88	30.50	31.81	24.49	13.64
BCPE	44.69	48.02	70.63	18.89	53.84	37.04
BCPA	42.34	37.52	85.21	65.28	74.81	55.77
BC	23.12	24.18	18.59	16.39	73.81	47.92
HS	32.46	32.74	36.82	31.30	24.23	35.34
PC	60.81	60.75	45.44	46.22	66.77	11.87
CCF	27.56	27.89	14.48	13.02	69.06	29.99
BCF	56.53	58.37	29.31	26.15	36.07	22.90

10 Conclusion

This paper explores the application of deviation analysis of an AM artefact optimised for the use in CT with error comparison to CMM reference measurements. Three AM methods were analysed for form and dimensional accuracy, with a goal to assess the capability of CT scanning and software reconstruction and measurement abilities to the gold standard CMM method. The comparison evidently demonstrates colorations between different measurement techniques with few outliers, with a comparison of surface determination methods explored. The next step would be to investigate CT scanning statistically while exploring the black box potential of the contributing uncertainty factors.

11 Further work

Image correction of CT using calibrated ball bars and ball palates to readjust reading, account for scanning errors and will look at scan orientation and whether or not thermal focal drift, 3D scaling errors, machine manipulator geometrical errors are greater than the voxel size of the scan to make definitive differences to measurements. Artefact design for the manufacturing with metallic materials will provide unique obstacles, which will be explored in the future. Further studies will look at a single AM method such as metal manufacturing with varying machine parameters in more detail.

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