Comparison of Different Additive Manufacturing Methods Using Optimized Computed Tomography

Paras Shah, Radu Racasan, Paul Bills

University of Huddersfield

EPSRC Pioneering research and skills

The Centre for Precision Technologies, School of Computing & Engineering, University of Huddersfield

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

Introduction

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.

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 poster 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.

Project Outline

- 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.
- 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.

Additive Manufacturing Methods

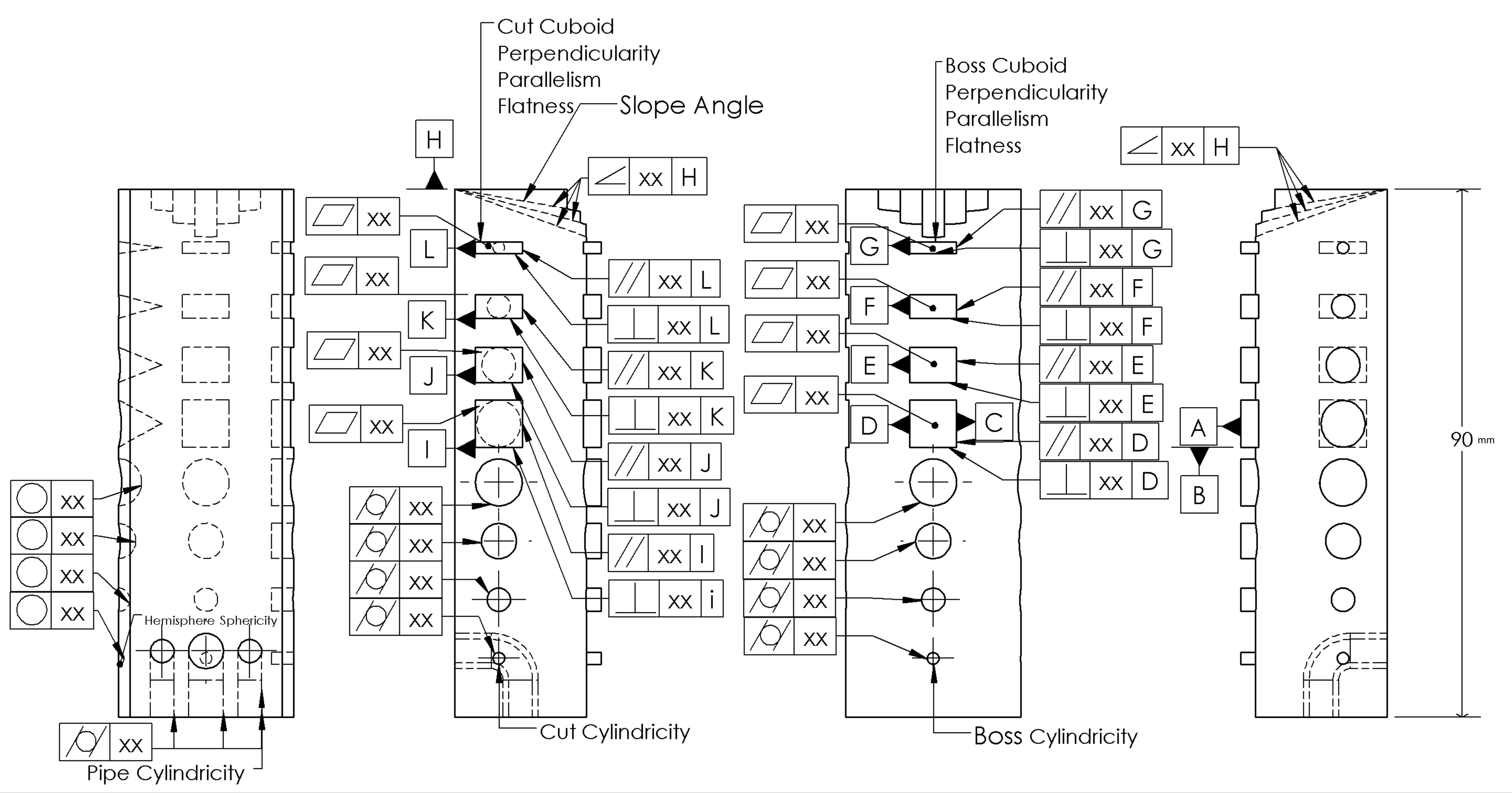
	SLA	SLS	FDM
Machine Make/ Model	3D Systems: iPro8000	3D Systems: sPro60	Hewlett Packard: Design jet 3D colour
Material	ClearvueLiquid Polymer	PA12 Powder	ABS Filament
Solid Dentistry	1.17g/cm^3	1.01g/cm^3	1.08g/cm^3
Layer Thickness	0.1mm	0.1mm	0.25mm
Thermal Expansion	70 μm/m-°C	82.6 μm/m-°C	88.2 μm/m-°C

Three AM methods used in this study including printing parameters and material characteristics 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.
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)
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.

Artefact Design

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. 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



Artefact Design

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 .

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. 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.

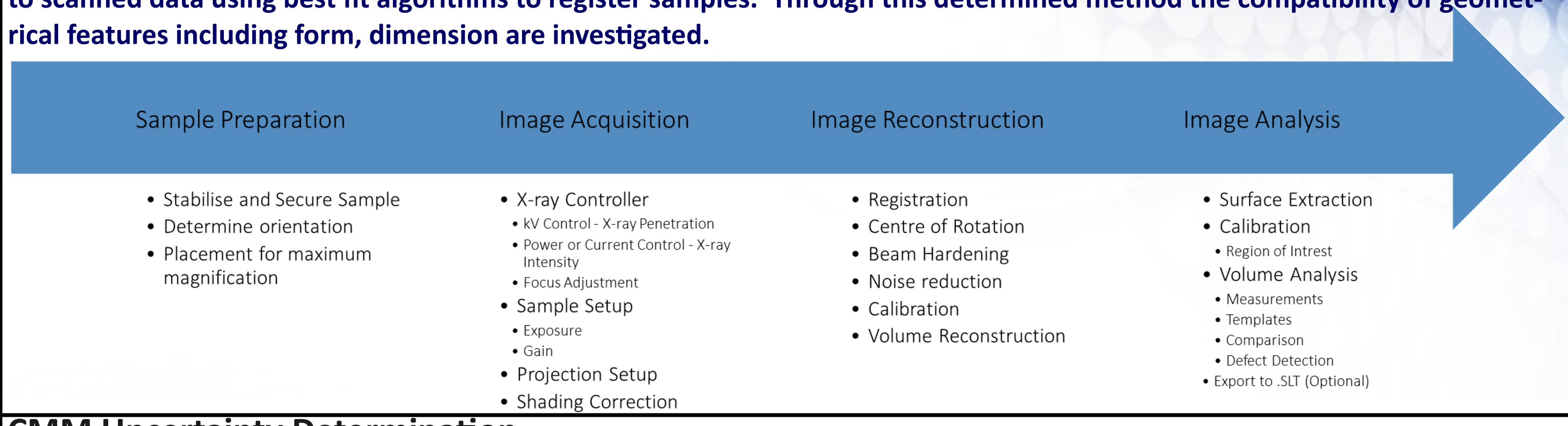
Current artefacts produced for the calibration of CT dimensional metrology include tetrahedron or Calotte Cube and ruby spheres in various configurations, these artefacts are used for geometrical characterization by measuring form and dimension. Artefacts can also be included in traceability and stability 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.

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

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

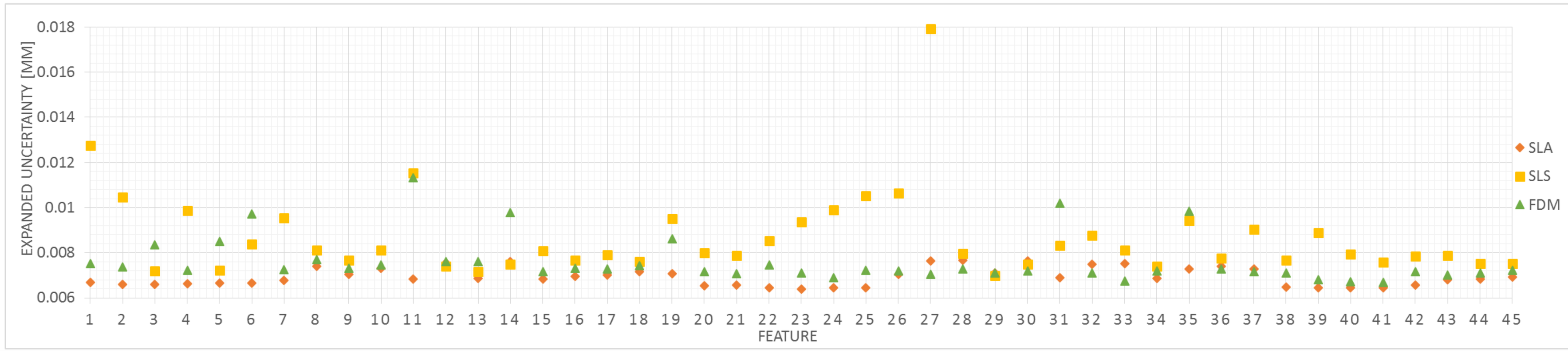
Methodology

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.



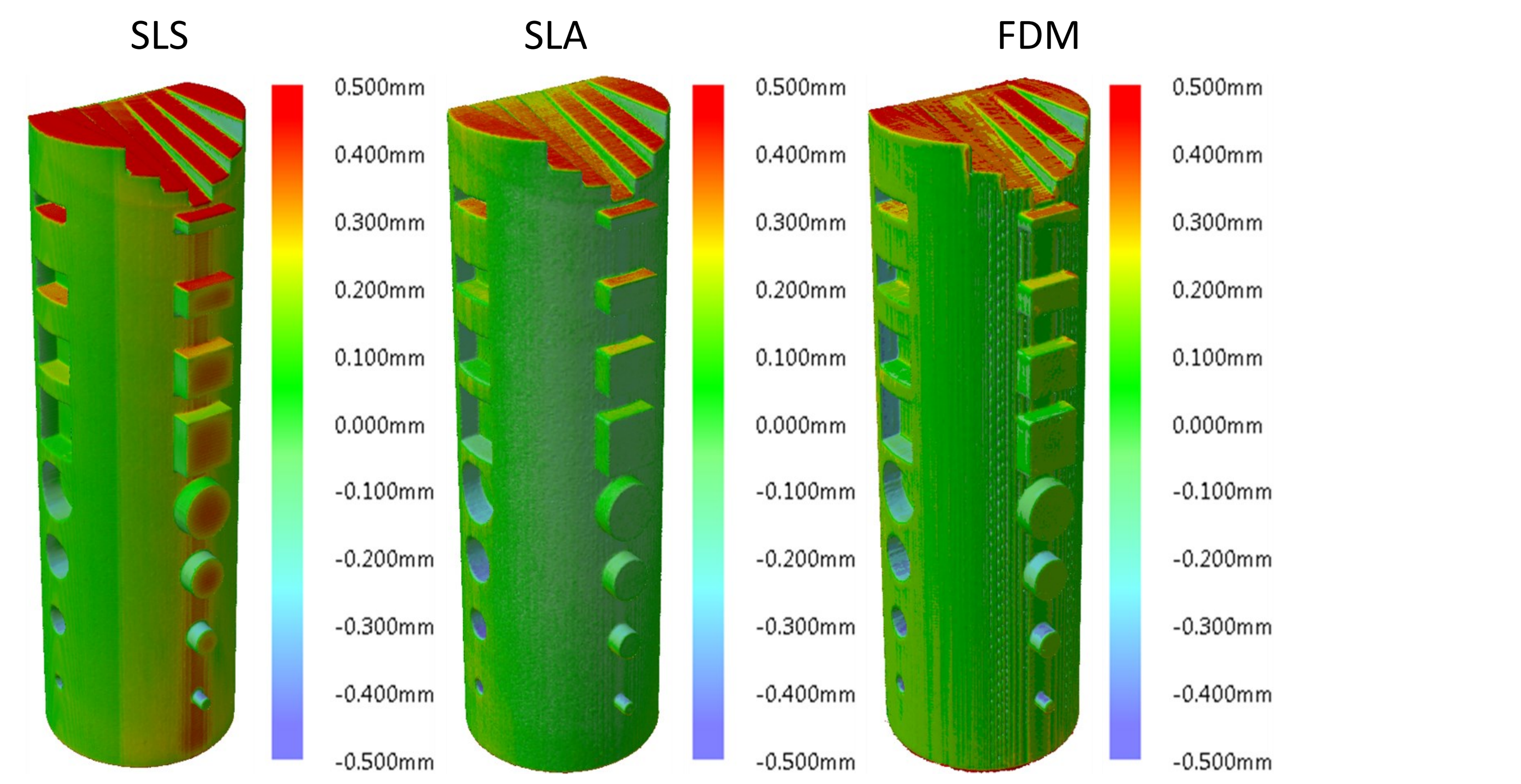
CMM Uncertainty Determination

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.



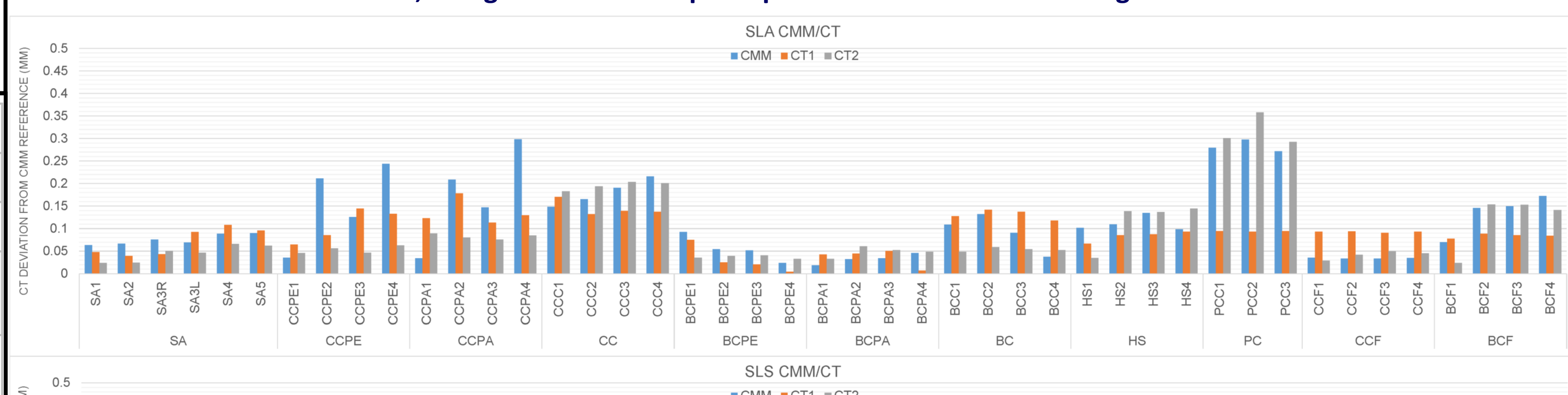
Results

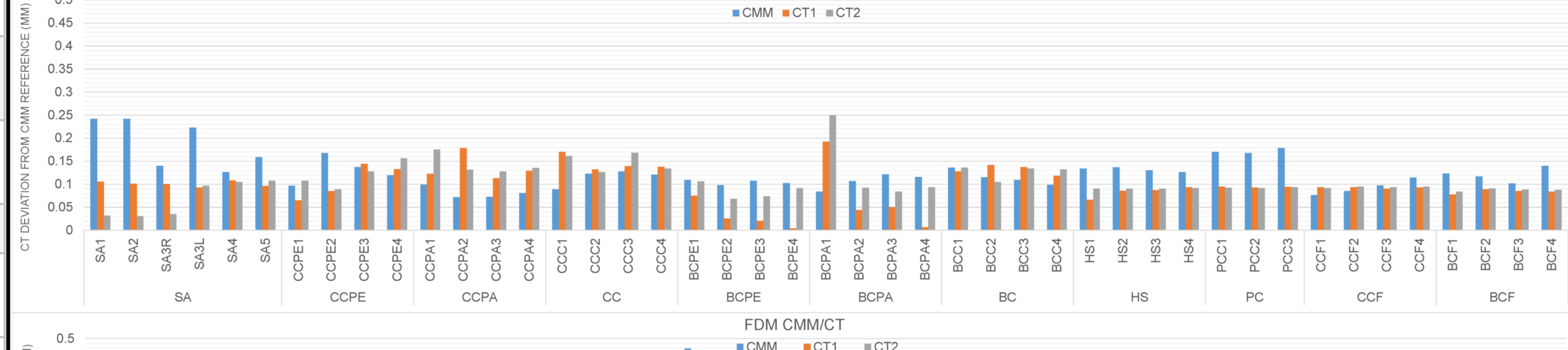
Visual deviation analysis was performed using Catia (Dassault Systemes, etc), with the use of the digitized shape editor module the original .STL file is compared to a .STL export from VGS. With an average of 24 million fitting points and VGS best fit registration at a maximum quality level of 50, models are overlaid and form deviation was analysed. 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.

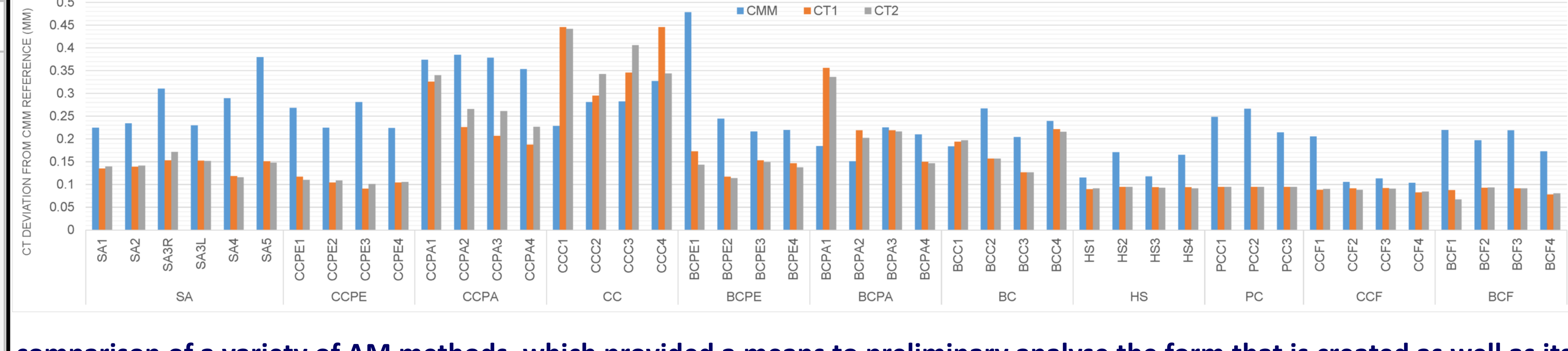


Results

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, these factors when combined contribute to the overall noise of the measurement system and is difficult to compensate for. 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. 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. 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.

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.

Acknowledgements

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