

To the Graduate Council:

I am submitting herewith a dissertation written by Jake Dvorak entitled “Feasibility and uncertainty evaluation of sequential hybrid manufacturing using optical coordinate metrology.” I have examined the final paper copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Mechanical Engineering.

Tony L. Schmitz, Major Professor

We have read this dissertation
and recommend its acceptance:

Tony L. Schmitz

Bradley H. Jared

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Accepted for the Council:

Dixie L. Thompson

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(Original signatures are on file with official student records.)

Feasibility and uncertainty evaluation of sequential hybrid manufacturing using optical coordinate metrology

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Jake Dvorak

August 2024

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To my sunshine, Meredith.

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“It turns out to be very difficult to devise a theory to describe the universe all in one go.”

Stephen Hawking

Abstract

Hybrid manufacturing has been suggested as a solution to global manufacturing challenges including stock availability, manufacturing costs, and difficulty in production of complex parts. However, feasibility and validation of hybrid manufacturing remain open research opportunities.

This research evaluates measurement uncertainty for optical coordinate metrology (OCM) within a sequential hybrid manufacturing (SHM) framework where a primary manufacturing process, a part geometry measurement, and a secondary manufacturing process are performed sequentially on optionally separate machine tools. In this work, an additively manufactured preform is produced, the part geometry is measured using structured light optical coordinate metrology, and the final geometry is obtained using subtractive manufacturing. Quality parameters for four low to high cost OCM 3D scanning systems are found using a performance evaluation based on current ISO and VDI/VDE standards. Uncertainty of a fiducial sphere's center position is defined using the selected OCM system. This uncertainty is then propagated into the uncertainty of the coordinate system position and orientation for a coordinate system defined by three sphere centers using Monte Carlo simulation. The simulation results are validated with experimental testing. An additional function is implemented into the simulation to estimate the required overbuild to account for the coordinate system positional and rotational uncertainty. A case study with wire arc additively manufactured preforms is provided. Combined, this work represents a step towards validation, traceability, and feasibility of sequential hybrid manufacturing.

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Chapter 1

Introduction

1.1 Hybrid manufacturing

Hybrid manufacturing is defined in CIRP nomenclature in 2014 by Lauwers et al. as “the combination of processes/machine in order to produce parts in a more efficient and productive way” [1]. It is stated that the general objective of hybrid manufacturing is to exploit the “1+1=3” effect where combining processes results in double the advantages of a single process. Lauwers et al. created two groups of classifications of hybrid processes, a combination of different energy sources/tools (group I), and controlled applications of process mechanisms (group II) [1]. Examples that fall under these classifications are shown in Figure 1.1. However, Lauwers et al. make no specific mention of the hybrid manufacturing case of additive manufacturing (AM) and subtractive manufacturing (SM). More recently Webster et al. defined hybrid-AM processes as “an in-situ or series combination of an additive manufacturing process and secondary energy sources in which physical mechanisms are fundamentally altered/controlled to affect the resulting properties of the material and/or part” [2]. They proposed an “AM+X” convention where X refers to the secondary process such as forging or milling. Gibson et al. proposed an expanded map of hybrid technologies shown in Figure 1.2 [3]. They state “The secondary

process can be subtractive like milling and turning or a surface enhancement method such as shot peening, remelting, laser shock peening, rolling, or burnishing that are sequentially applied following all or part of the AM (primary) process.” Hybrid AM and SM enables robust geometrical accuracy, greater mechanical properties, and overall improved part quality and process efficiency [4, 3, 5].

Chu et al. completed a review of hybrid manufacturing at the micro/nano scale [6]. They covered main, assistive, and sequential processes combinations. Dezaki et al. completed a review of additive/subtractive hybrid manufacturing using direct energy deposition (DED) [7]. They state “hybrid manufacturing can eliminate the relevant issues in both AM and machining in producing metallic components due to its features and capabilities. However, this process is still in its infancy and extensive research works are required to improve and optimize its features.”

Most literature explores the feasibility and advantages of integrating multiple processes on a single machine tool [8, 9, 10, 11]. Benefits include reducing tool change time, improved design flexibility, and the speed of manufacture [2]. AM + SM on a single machine tool allows for inter-layer machining [8]. Additionally, part location and toolpath alignments between the two processes are simplified since they are within the same machine tool and typically on the same gantry system. However, the ability to deposit a preform that contains the desired design must still be confirmed prior to machining.

This work focuses on and proposes a clear definition for sequential hybrid manufacturing. A formal definition and description are provided in Section 1.5 and background is provided here. Formalizing a definition of SHM creates a clear distinction between traditional hybrid manufacturing on a single machine tool, and hybrid manufacturing using multiple machine tools. Both hybrid manufacturing and SHM have intrinsic benefits. SHM inherently increases productivity, as multiple machine tools can be operated simultaneously whereas a HM machine tool can typically perform either AM or SM, but not both, at any given time. HM can also affect machining accuracy. AM processes apply energy, or heat, to a part and heat has

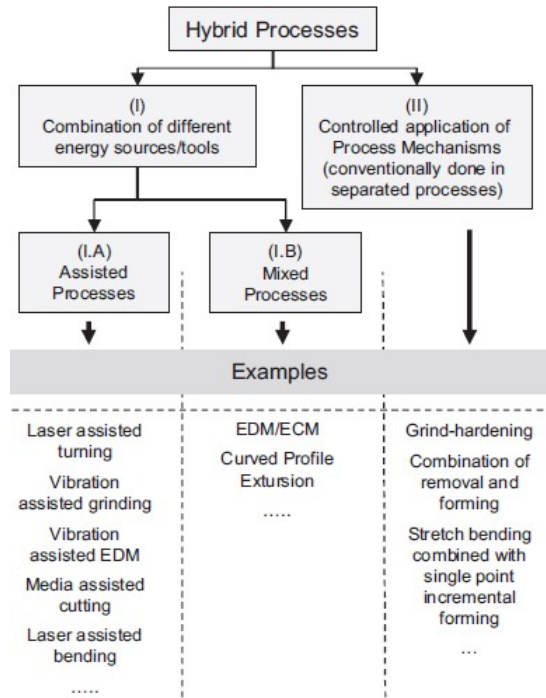


Figure 1.1: Classification of hybrid manufacturing processes according to CIRP nomenclature [1].

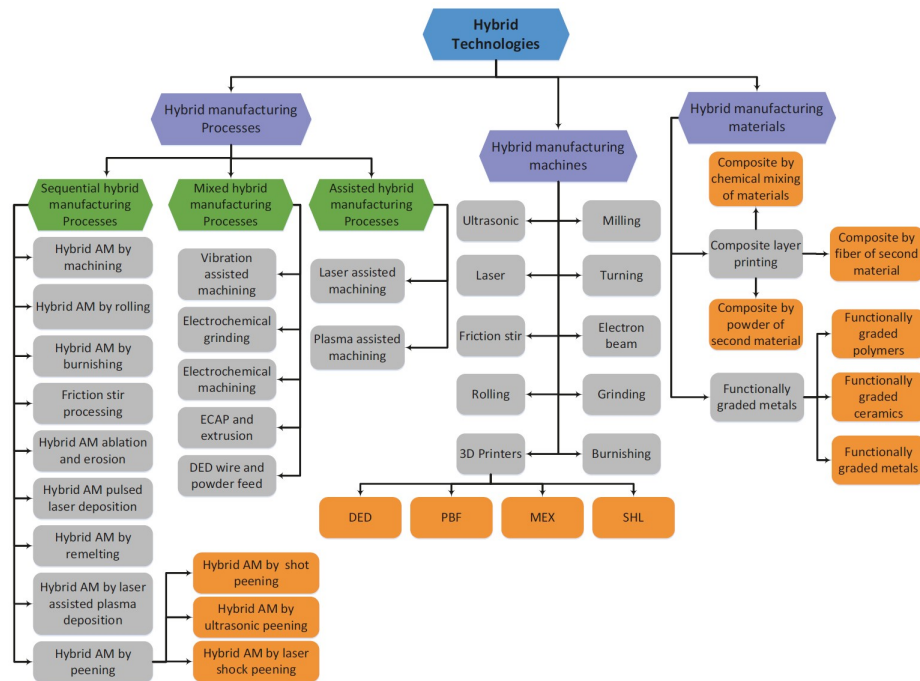


Figure 1.2: Map of hybrid technologies [3].

been well established to be one of the largest contributors to machining error (thermal errors) [12]. SHM separates the two systems and eliminates this inherent challenge. Additionally, SHM reduces machine tool complexity and the cost barrier to entry for a manufacturer. A manufacturer may already have an AM or SM system, and only needs to acquire the other as opposed to a costly and not readily available hybrid manufacturing system. Hybrid manufacturing specific systems are still specialized, expensive, and software for combined AM+SM toolpaths is in its development phase.

The key challenge associated with SHM is part transfer between machines and processes. Once a printed preform is removed from an AM system and transferred to an SM system the location of the part is unknown within the machine tool's work volume. Commonly this is addressed by approximating the printed preform as primitive shapes. Many types of AM such as wire arc AM (WAAM) produce large scale parts with rough surfaces and, potentially, significant geometric deviations from the part design; see Figure 1.3. Layer lines are clearly observed, welding spatter occurs, and parts distort [13]. Assuming these AM preforms to be primitive shapes can result in failed and unoptimized hybrid manufacturing operations due to damaged machine tooling from unexpected material and heavy tool engagement, machining with conservative machining parameters to avoid the previous point, misalignment of desired part geometry within the preform resulting in un-machined areas, and printing the preform with excessive overbuild to avoid the previous point. Modeling and managing geometric deviations is an open research topic [14, 15].

This work addresses issues with part transfer between separate machine tools in SHM by adding a metrology step and associated coordinate system. The following sections discuss the state of the art in optical coordinate metrology, measurement uncertainty, and coordinate systems in manufacturing.

1.2 Optical coordinate metrology

Optical coordinate metrology, such as structured light scanning, is well established in manufacturing environments [16, 17]. Catalucci et al. completed a review of optical metrology for digital manufacturing [18]. They discussed the advantages of optical coordinate and surface texture measurement and integration in digital manufacturing. They state geometric complexity and uncertainty evaluation as key challenges.

Structured light scanning systems use a projector to shine a structured pattern onto a test object and one or more cameras to capture the reflected, distorted pattern from the test object. The geometric shape of the object is obtained using the distorted pattern and the scanner’s calibration; see Figure 1.4. The use of optical metrology in sequential hybrid manufacturing is relatively new in literature. Cornelius et al. used structured light scanning to reacquire the form of a printed preform for milling, while also adding fiducial spheres for coordinate system definition and transfer to a milling machine [19]. Dvorak et al. proposed the benefits of using structured light for hybrid manufacturing in the form of a digital twin [20]. Dvorak et al. completed sequential hybrid manufacturing of a silicon carbide binder jet additive preform, optical coordinate metrology, and machining of a freeform surface [21].

Performance evaluations for optical coordinate metrology systems are challenging due to the complex physics and processes at hand; see Figure 1.5 [22]. Many factors impact measurement results such as temperature, vibration, data processing methods, object reflectivity, OCM system calibration, operator experience, and more. Prior research has explored its accuracy. Mendricky developed an acceptance test based on several error metrics and the VDI/VDE standard 2643—part 3 to evaluate the accuracy of optical systems [23]. Boehm et al. evaluated the accuracy of commercial sensors based on similar error metrics [24]. Dickin et al. attempted to map and correct the distortion of structured light scanners [25]. They developed a methodology for assessing scanner uncertainty and used results to compute correction mappings and reduce residual error. Eiriksson et al. showed that the system calibration parameters

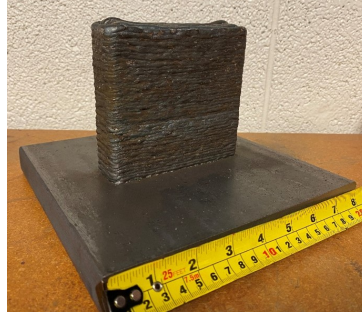


Figure 1.3: Sample of a WAAM preform printed on a baseplate.

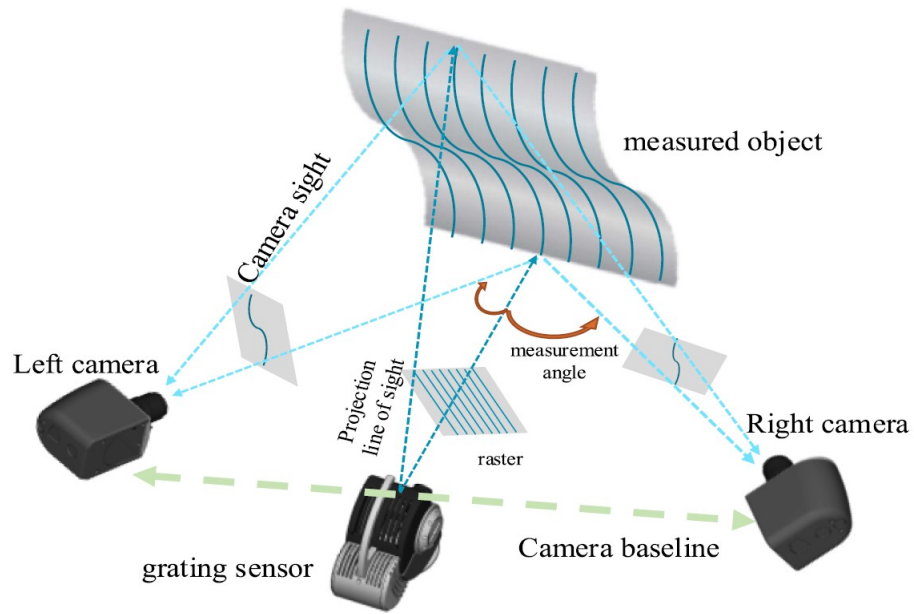


Figure 1.4: Measurement principle of structured light scanning [22].

influence measurement results [26]. They found that a custom setup with off-the-shelf, low-cost components can provide comparable and, in some cases, better results than a commercial system.

The ISO 10360 part 13 and VDI/VDE 2634 standards represent the current state of the art for performance verification of optical coordinate metrology systems [27, 28, 29]. Performance verification is “used to confirm that a measurement system meets its specification” [30]. For example, a customer that purchases a structured light scanner may perform periodic performance verification checks to verify that their system still meets original specifications, which may be part of a contract between the customer and measurement system manufacturer. VDI/VDE 2634 provides the basis for this dissertation.

1.3 Uncertainty of measurement

Measurement uncertainty is defined as “doubt about the validity of the result of a measurement” [31, 32]. NIST Technical Note 1297, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, states that “the result of a measurement is only an approximation or estimate of the value of the specific quantity subject to measurement” and that “the result is complete only when accompanied by a quantitative statement of its uncertainty” [33]. Two categories are defined for uncertainty evaluation: Type A and Type B. Type A uncertainty is evaluated by a statistical analysis of measured values under defined measurement conditions and is typically expressed as standard deviation. Some examples include standard deviation in a series of measurements, standard deviation in the mean of a series of measurements, or standard deviation from a determined calibration curve [32]. Type B uncertainty is evaluated by any other method and is typically expressed as a deviation, which may or may not be a standard deviation. Examples include calibration uncertainty of a used physical reference specimen, published uncertainty of a constant, known uncertainty of equations that approximate quantities, or a

known but uncorrected systematic error [32]. This work applies Type A uncertainty evaluations to OCM system data.

Each component that contributes to the uncertainty of a measurement can be represented by a standard deviation, called the standard uncertainty, u_i . The combined standard uncertainty, u_c is defined as the estimated standard deviation of the result of several combined measurements used to determine the value of a single measurement (such as the combination of mass and length measurements to calculate the volume of an object). It is estimated as the root sum of squares of the standard uncertainties, although correlation between the individual measurements can also be considered. The expanded uncertainty, U , is the combined standard uncertainty multiplied by a coverage factor, k . In this work $k = 2$ is used, which corresponds to a 95 percent confidence interval. For a measurement result y and a measurand Y it is confidently believed that $Y = y \pm U$.

Researchers have attempted uncertainty evaluation of optical coordinate metrology systems [34, 35, 36, 37, 38, 15]. Zhao et al. modeled uncertainty of a structured light scanner by separating Type A uncertainty sources into four categories: the instrument itself, data acquisition, data processing, and other factors [22]. They found that point cloud registration was the largest uncertainty component. Jain et al. evaluated the spatial frequency response and its uncertainty of a structured light system as a metric for resolution [39]. Sims-Waterhouse et al. determined the expanded uncertainty for form measurements using a traceable stereo-photogrammetry system [40]. They separated the contributions to the measurement uncertainty into many factors, including focal length, camera translation, temperature, and others. They found that rotation and translation between the two cameras are by far the largest influence factor for the triangulation uncertainty.

Gayton et al. developed a virtual fringe projection system to predict captured images and include major uncertainty contributors [41]. They compared experimental results to camera images built using a ray-tracing model to probe the optical field

distribution at the measurement surface boundary. Their intention was to use this model within a Monte Carlo framework to estimate uncertainty at each data point in a point cloud. Gayton et al. outlined “a method to allow the evaluation of uncertainty in a fringe projection system caused by imperfect characterisation procedures” and then apply the method to a sphere plate and flat plane artifact [42, 43].

1.4 Coordinate systems and uncertainty in manufacturing

Uncertainty associated with coordinate transformations has been explored in literature [44, 45, 46]. Che and Ni detailed an approach for uncertainty analysis of coordinate transformations based on constrained optimization uncertainty analysis and found results of a structured-light optical coordinate measurement machine [47]. Ren et al. analyzed uncertainty of coordinate transformations using the weighted total least squared adjustment [48]. Experimental results from a laser tracker validated the method.

Fiducials are often used in manufacturing for machine calibration, part location, and as a positioning method for precision manufacturing [49, 50, 51, 52]. Brunelle et al. discussed the importance of fiducials for freeform optics and stated the following: “Alignment fiducials (also) enable more precise locating of the surface during the manufacturing process.” Furthermore, the authors noted that fiducials can serve as alignment features for metrology equipment such as a coordinate measuring machine (CMM) [50]. Wang et al. defined an uncertainty analysis model of a fiducial-aided calibration and positioning system for the precision manufacturing of freeform optics [53]. They showed that the transformation uncertainty is small and that fiducial-aided calibration and positioning is most sensitive to the measurements from the on-machine measurement system. Srinivasan et al. demonstrated the use of

structured light scanning to automatically transfer a coordinate system defined by pre-machined features from a computer numerical control (CNC) machine [54]. Woody et al. showed that a fiducial calibration system can be used to transfer accuracy of a CMM to a machine tool [55, 56]. They presented an uncertainty analysis to aid in the selection of fiducials, measurement devices, and a machine tool for the desired part accuracy.

Several works have specifically considered uncertainty in manufacturing coordinate systems. Shen et al. presented an uncertainty analysis method for coordinate referencing in design and manufacturing systems, accounting for uncertainties from geometric form deviations, fixture tolerances, and measurement errors, and demonstrated its effectiveness through Monte Carlo simulations [57]. Loose et al. presented a linear model for the propagation of dimensional variation in complex, multistage manufacturing processes, accounting for fixture error, datum error, machine geometric error, and product quality [58]. The model offered potential for fault diagnosis and process design evaluation in complex machining processes. Ahn et al. developed a model to predict product tolerances due to machine tool uncertainties, addressing the stochastic nature of volumetric error in a 3D workspace [59]. Adolfo et al. used a multi-output Monte Carlo approach to evaluate uncertainty of eight link errors of a five axis machine tool [60]. Various uncertainty sources in the identification and measurement chain can be included in the model and propagated to the identified errors. Kortaberria et al. presented “a methodology for task-specific uncertainty assessment of 3D point clouds based on ISO 15530-3 and ISO 15530-4 technical specifications” [61]. Of the three major uncertainty contributors: measurement process variability, uncertainty of the CMM calibration, and uncertainty of the systematic error, they found the systematic error contribution to be the largest contributor to the uncertainty budget. Zhuang et al. studied the uncertainty propagation of measurement error on a five axis machine tool [62]. They used the kinematic chain of on machine measurement to evaluate the uncertainty

including alignment error of the workpiece, eccentricity error of the stylus tip, and positioning error.

1.5 Sequential hybrid manufacturing

Sequential hybrid manufacturing is defined as hybrid manufacturing using optionally separate machine tools where a primary manufacturing process, part measurement, and a secondary manufacturing process are performed sequentially. A flow chart with examples of processes is shown in Figure 1.6. The measurement/metrology step is necessary for linking part dimensions of the preform from the primary manufacturing process to the secondary manufacturing machine tool. This work explores the SHM case of various AM methods, optical coordinate metrology, and machining. Various fiducials are included or defined during the optical coordinate metrology step as discussed in Section 1.1. A flow chart of standard procedures for this work is shown in Figure 1.7.

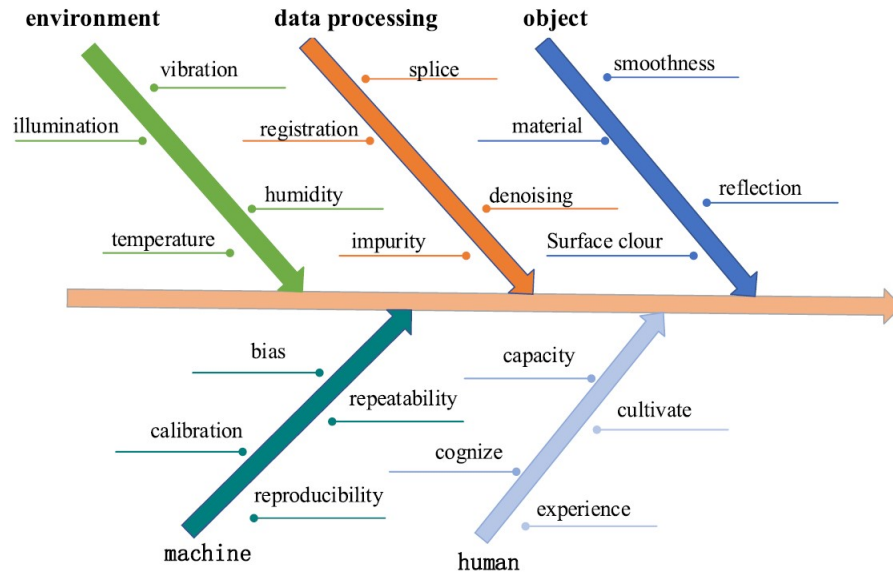


Figure 1.5: Fishbone diagram of error sources in structured light scanning [22].

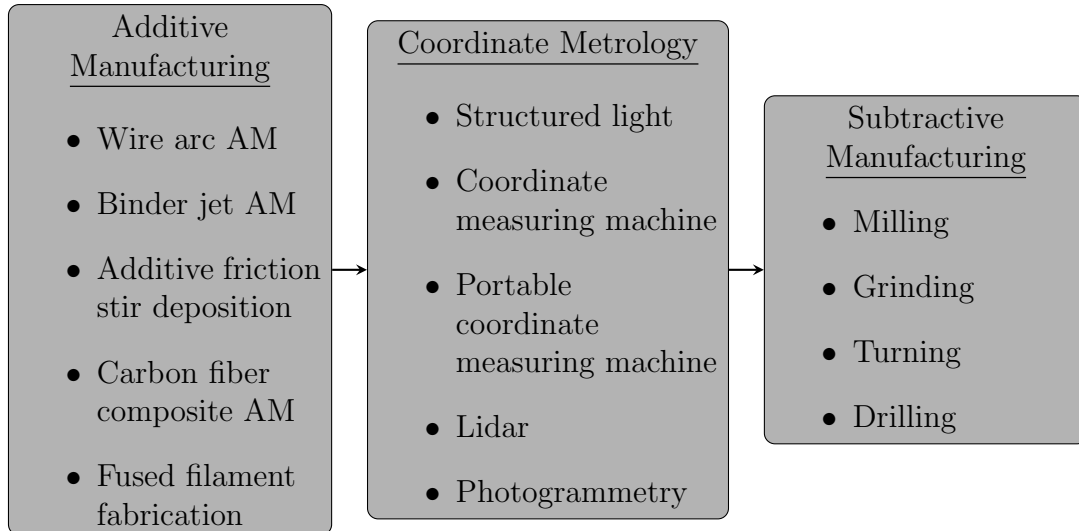


Figure 1.6: Flow chart of various SHM processes with examples of each step.

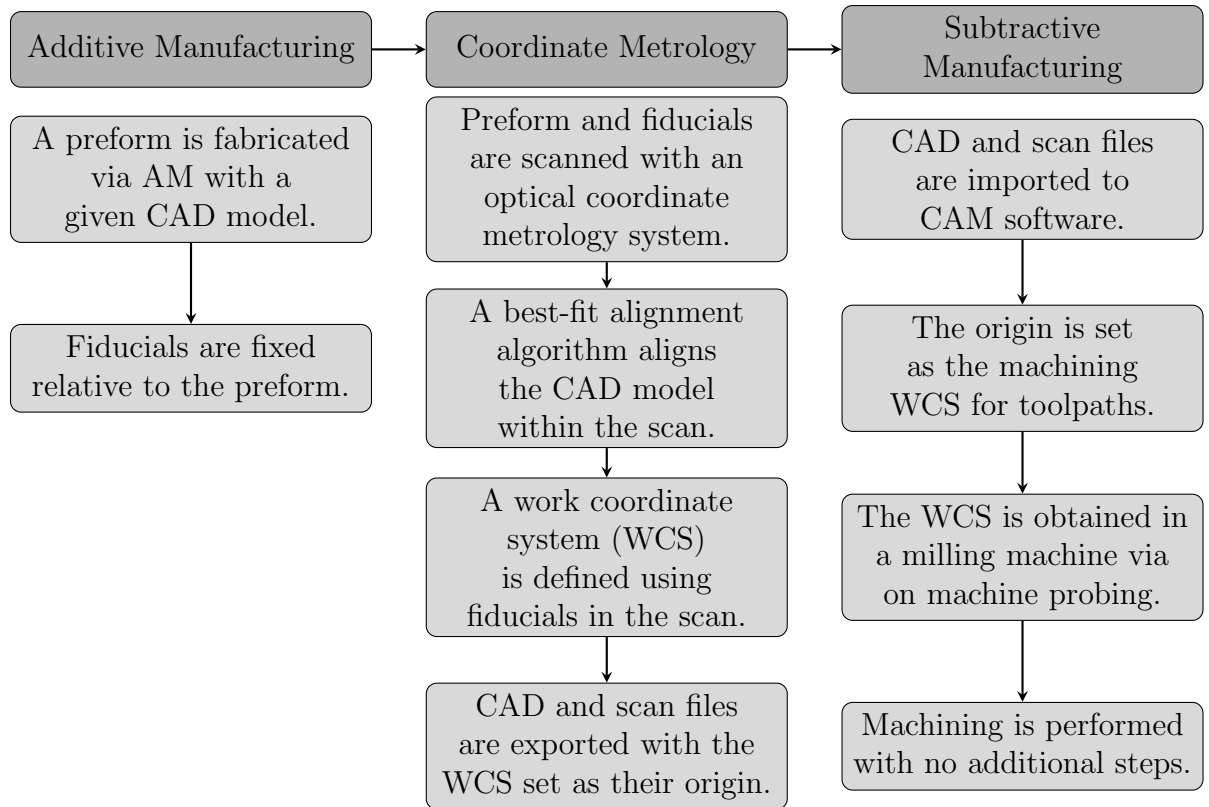


Figure 1.7: Flow chart of various SHM processes with specific tasks.

Chapter 2

Materials and methods

2.1 Optical coordinate metrology system details

First, details of the OCM systems used in this work, a GOM ATOS Q, a GOM ATOS Core 200, an Artec Spider, and an iPhone 15 Pro Max are provided; see Table 2.1. Note that GOM is now owned by Zeiss, but is referred to by GOM in this work. These systems were selected as they cover a range of initial costs, availability, intended use cases, target markets, and more. Note that, because OCM system performance is not yet well established as discussed in Section 1, the values in Table 2.1 do not necessarily provide a direct comparison. These values are likely obtained in different ways or under unrealistic idealized conditions. This concern motivates this work.

The GOM ATOS Q and ATOS Core 200 are discussed here in tandem as their characteristics and operation are mostly identical. The GOM systems capture 3D data in a series of measurement positions set by the operator. They require scanning targets be placed around or on the object to accurately register measurements to one another. 1.5 mm diameter sticker targets are used in this work. The ATOS Q is a higher cost system offered by GOM, with near double the working distance and volume and half the minimum point distance of the ATOS Core. Additionally, in this work, the ATOS Q is mounted to a mobile tripod; see Figure 2.1. This

results in measurements that can be a combination of moving the scanner or the object under test. The ATOS Core 200 is mounted to a lift table sold by GOM; see Figure 2.15. This lift table allows for fast repositioning of a rotary/tilt table with the object under test placed on it. Scanning targets are placed on the table in advance and adding targets to the object is typically not required. Overall, the ATOS Core 200 has a smaller field of view than the ATOS Q and is better suited for measurement of smaller objects. GOM markets these systems for a variety of manufacturing, inspection, manual, and automated measurement tasks.

The Artec Spider is a handheld structured light OCM system for fast measurements and high accuracy demanding tasks. Additionally, unlike the GOM systems in this work, the Spider can capture and reconstruct texture and color of the scanned object. Handheld 3D scanners typically are targeted for fast in the field measurements but may compromise accuracy and tracking ability. The Artec Spider does not require targets. However, targets were used in this work to provide optimal conditions for scanner tracking and accuracy.

The iPhone 15 Pro Max is included in this work to demonstrate a readily available and low cost OCM system. This work used an app titled Scaniverse, which uses a combination of light detection and ranging (Lidar) and photogrammetry scanning technologies. Since the iPhone is not marketed or advertised as an OCM system many details of the system are not provided from the manufacturer in Table 2.1. Many phone applications are available for 3D scanning using an iPhone. However, Scaniverse was selected for this work based on the author’s previous work in testing of accuracy of various applications, where Scaniverse provided the highest accuracy.



Figure 2.1: ATOS Q mounted to tripod for measurements.

Table 2.1: OCM system manufacturer provided details. NP represents values not provided from manufacturer.

OCM system	Technology	Measurement volume (mm)	Working distance (mm)	Minimum point distance (mm)	Field of view (deg)	Purchase price
GOM ATOS Q	Structured light	350x260x260	490	0.04	NP	\$ 109,000
GOM ATOS Core 200	Structured light	200x150x150	250	0.08	NP	\$ 30,000
Artec Spider	Structured light	90x70-180x140	200-300	0.1	30x21	\$ 24,800
iPhone 15 Pro Max	Lidar, photogrammetry	NP	NP	NP	NP	\$ 1,200

2.2 Optical coordinate metrology performance evaluation

As introduced in Chapter 1, VDI/VDE 2634 part 3, multiple view systems based on area scanning, serves as the basis for the terminology and approach implemented in this dissertation. While this standard describes performance verification and acceptance tests, the parameters it defines are used here for performance evaluation since no current standards exist specifically for performance evaluation. This serves as a baseline performance evaluation of OCM systems and provides a quantitative performance comparison between systems. The following discussion applies VDI/VDE 2634 part 3 to the OCM performance evaluation completed in this work.

2.2.1 Quality parameters

Four quality parameters defined in VDI/VDE 2634 are described here for performance evaluation. The following guidelines apply for all quality parameters with details for this work in parenthesis:

- Use spheres with a diffusely scattering surface (steel spheres with titanium dioxide coating)
- Form error of the test sphere must be much smaller than the quality parameter (see Appendix A)
- Roughness of test sphere is negligible (see Appendix A)
- Calibration certificate of artifact must be available (see Appendix A)
- Test sphere is measured on a random basis in at least three arbitrary positions within the measurement volume and from different directions (see Section 2.2.3)

- There are no restrictions to the maximum number of sensor positions, but there must be at least five positions (10 positions per test are used for this work, see Section 2.2.3)

Probing error form

The first quality parameter, probing error form, denoted PF , is the range of radial distances of measured points to a calculated fitted sphere center determined by the least-squares method; see Figure 2.3. Generally, probing error contains two influences: errors within singular measurements in the measurement volume and errors due to transformations of single measurements.

Probing error size

Probing error size, denoted PS , is the difference between the measured diameter of a fitted sphere determined by the least-squares method and the calibrated diameter of the sphere; see Figure 2.4. It is formally defined as the difference between the fitted diameter D_a and the calibrated diameter D_t where

$$PS = D_a - D_t \quad (2.1)$$

Sphere spacing error

Sphere spacing error, denoted SD , is the difference between the measured value and the calibrated value of the distance (or spacing) between the centers of two spheres; see Figure 2.5. This describes the ability of the measuring system to perform length measurements from multiple single images and is defined as

$$SD = L_{ka} - L_{kr} \quad (2.2)$$



Figure 2.2: Optical CMSs studied in this work. From left to right: GOM ATOS Core 200, GOM ATOS Q, Artec Spyder, iPhone 15 Pro Max.

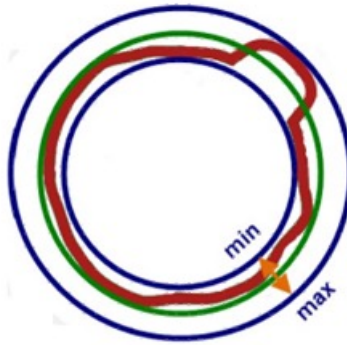


Figure 2.3: Schematic of probing error form [23].

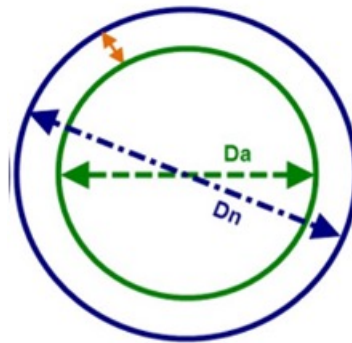


Figure 2.4: Schematic of probing error size [23].

where L_{ka} is the measured sphere spacing distance and L_{kr} is the calibrated sphere spacing distance. A sample of a sphere spacing measurement in GOM Inspect is shown in Figure 2.6.

Length measurement error

Length measurement error, denoted E , can be found when bidirectional probing is performed from two opposite points along nominally parallel faces that are vertical to one of the two surfaces. This describes the error behavior over the entire measuring volume due to a combination of various single errors. Some examples include systematic errors, random errors, and multiple scan stitching/alignment.

Method C in VDI/VDE 2634 part 3 describes correction measures for offsetting the averaging effect and compensating for systematic probing errors for the case where ball bars with only two balls are used. The length measurement error E becomes

$$E = SD + E_k \quad (2.3)$$

where SD is the sphere spacing error. E_k is a correction value defined as

$$E_k = \frac{R_1 - D_{r1}}{2} + \frac{R_2 - D_{r2}}{2} \quad (2.4)$$

where D_{r1} and D_{r2} are the calibrated diameters of the two spheres and R_1 and R_2 are spacings of two selected points to the fit sphere centers. These points are selected as outer edge points on the spheres whose spacing from the straight line through the sphere centers is minimized. R_1 is illustrated in Figure 2.8. In other words, length measurement error accounts for finding the closest point in the point cloud data so that it is truly the end to end probing length. A sample of the length measurement obtained in GOM Inspect is shown in Figure 2.9.

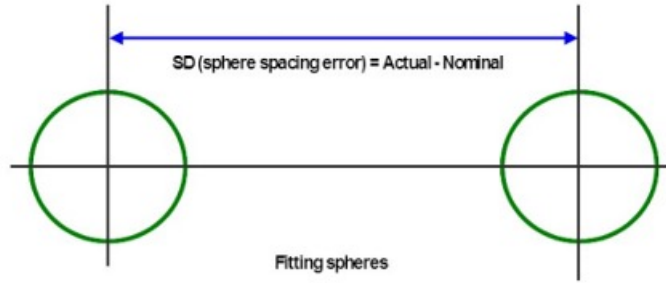


Figure 2.5: Schematic of sphere spacing error [23].

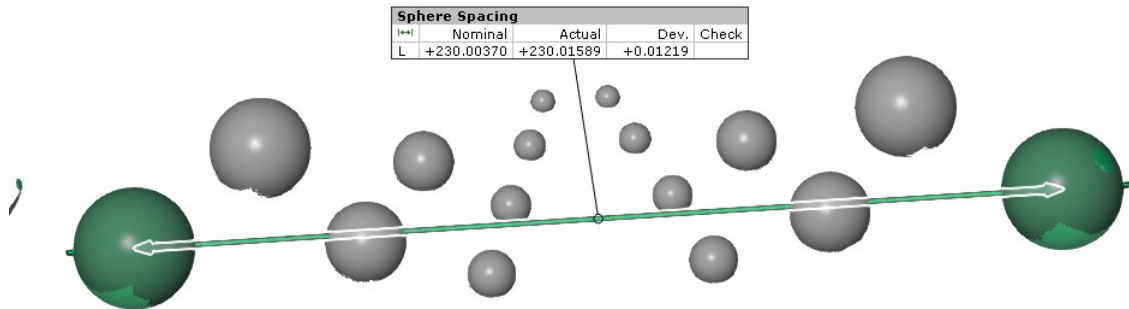


Figure 2.6: Sample measurement of sphere spacing in GOM Inspect.

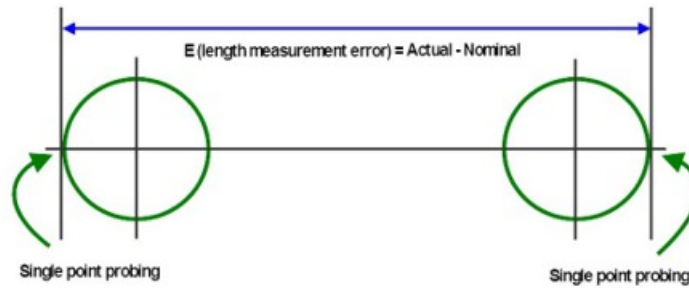


Figure 2.7: Schematic of length measurement error [23].

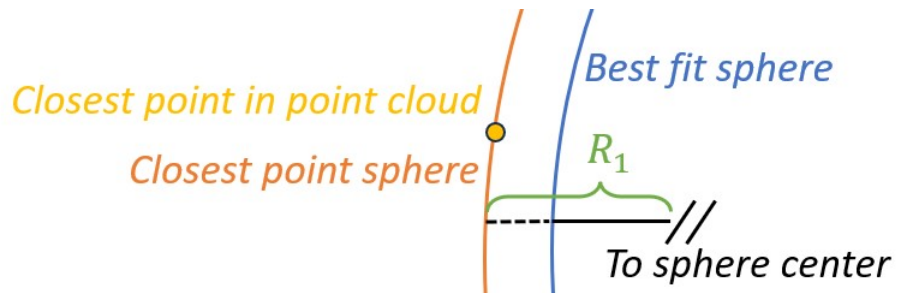


Figure 2.8: Explanation of how R_1 or R_2 are obtained for length measurement error.

2.2.2 GOM PSA400 artifact

All OCM systems were tested using a GOM probing and spacing (PSA400) artifact. The following sections detail the artifact and specific procedural considerations.

Acceptance test

GOM provides owners of their structured light metrology systems with instructions and templates for completing a purported “acceptance test” in GOM Inspect (now Zeiss Inspect)[63]. This acceptance test adheres to VDI/VDE 2634 part 3 [63]. GOM offers different sized artifacts that cover a range of scanner measurement volumes for this acceptance test. The GOM PSA400 artifact was selected for this work as it is applicable to scanners with measurement volumes ranging from approximately 35 mm x 30 mm x 20 mm to 2000 mm x 1500 mm x 1500 mm; see Figure 2.10. This artifact contains nine sphere pairs and the nominal dimensions of these pairs are tabulated in Table 2.2. A calibration report is included in Appendix A.1. Additionally, XYZ positions (with an arbitrary coordinate system) of the sphere centers were measured on a Zeiss Duramax CMM for comparison; see Appendix A.2. A top down view with sphere labels is shown in Figure 2.11. Comparisons of OCM system measuring volume widths relative to the artifact are shown in Figure 2.12. While the GOM acceptance test provides an automated script and template for executing the testing and obtaining quality parameters, it was not used for this work. Non-GOM systems cannot be used with the provided scripts and templates. Since a one to one comparison of results was desired for this work, a custom workflow was created to obtain quality parameters in a consistent manner for each system.

Airbrush spray coating

Prior to any measurements, the artifact spheres were sprayed with a titanium dioxide powder and methylated spirit mixture using a GOM airbrush system. Titanium dioxide powder is commonly used in optical coordinate metrology to coat objects

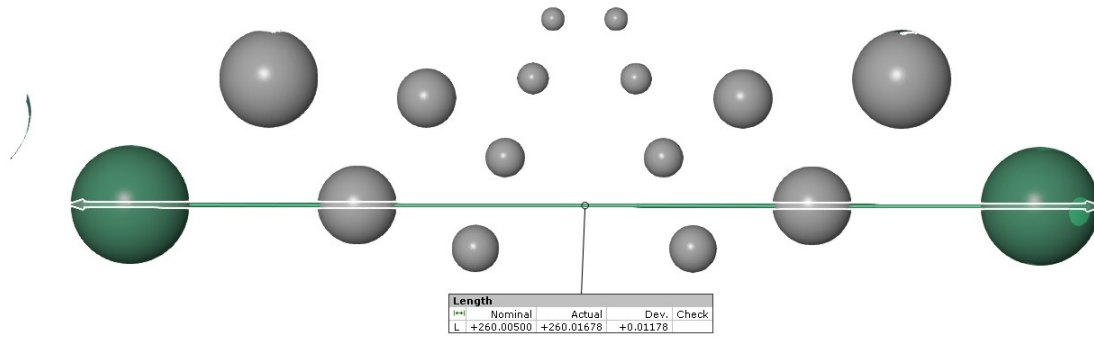


Figure 2.9: Sample of length measurement for length measurement error in GOM Inspect.



Figure 2.10: GOM PSA400 artifact in lower case.

Table 2.2: Nominal PSA400 artifact dimensions.

Sphere pair	Nominal Diameter L,R (mm)	Nominal Sphere to Sphere Distance (mm)
L1-R1	6	16
L2-R2	8	26
L3-R3	10	40
L4-R4	12	55
L5-R5	15	80
L6-R6	20	115
L7-R7	25	160
L8-R8	30	230
L9-R9	40	320

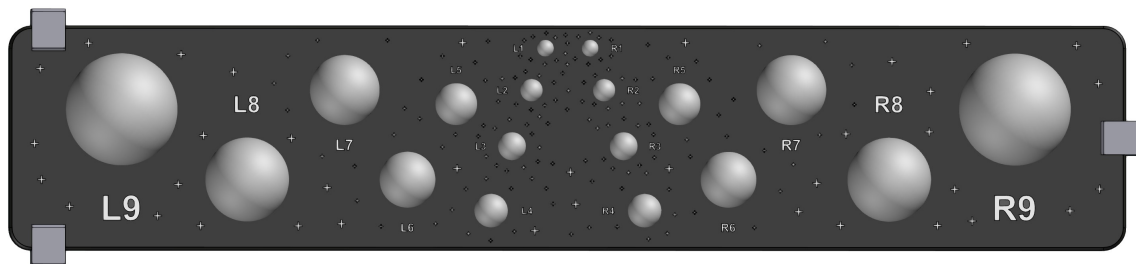


Figure 2.11: Top view of PSA400 artifact with spheres labeled.

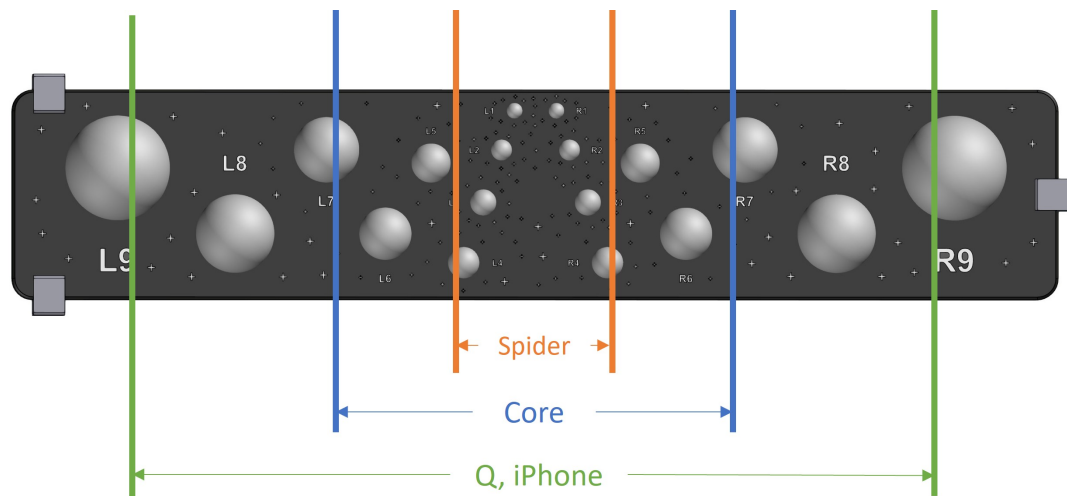


Figure 2.12: Approximate widths of OCMS maximum measurement widths for a single scan centered on the PSA400 artifact.

and reduce reflectivity. Titanium dioxide powder provides an even coating that minimizes added thickness while reducing reflectivity. A custom cover to allow spraying of the spheres without spraying scanning targets was provided with the PSA400 artifact; see Figure 2.13. Once sprayed, the spheres were not resprayed throughout this work. Therefore, sphere dimensions, coating, and reflectivity were constant for measurements using all systems.

Sensor procedural differences

The ATOS Q measurements were performed with the sensor on a tripod and the artifact on a surface plate table. The scanner angle was set on the tripod and the artifact was moved/rotated as needed; see Figure 2.14.

The ATOS Core 200 measurements were performed with the sensor mounted to a lift table. The artifact was mounted to a base that allowed for rotation and tilt; see Figure 2.15. Therefore, measurements consisted of rotating and tilting the artifact, as well as raising and lowering the lift arm as needed to maintain the optimal scanner distance.

The Spider measurements were completed similarly to the ATOS Q with some differences since the Spider is a continuous capture and typically handheld system. The Spider was mounted to a tripod and the artifact was placed stationary on the surface plate table; see Figure 2.16. The ten measurement positions were scanned by moving the scanner manually at a reasonable rate based on the operators experience with the Spider. The scanner was placed down to be stationary for several seconds at each measurement position.

An iPhone was mounted to a semi-manual DJI OM 5 stabilizing gimbal to provide smooth hand held scans; see Figure 2.17. The artifact was placed stationary on the surface plate table. Differing measurement positions were scanned by moving the scanner manually at a reasonable rate based on the operators experience scanning with the iPhone.



Figure 2.13: Cover for PSA400 artifact to enable spraying of spheres without coating scanner targets.

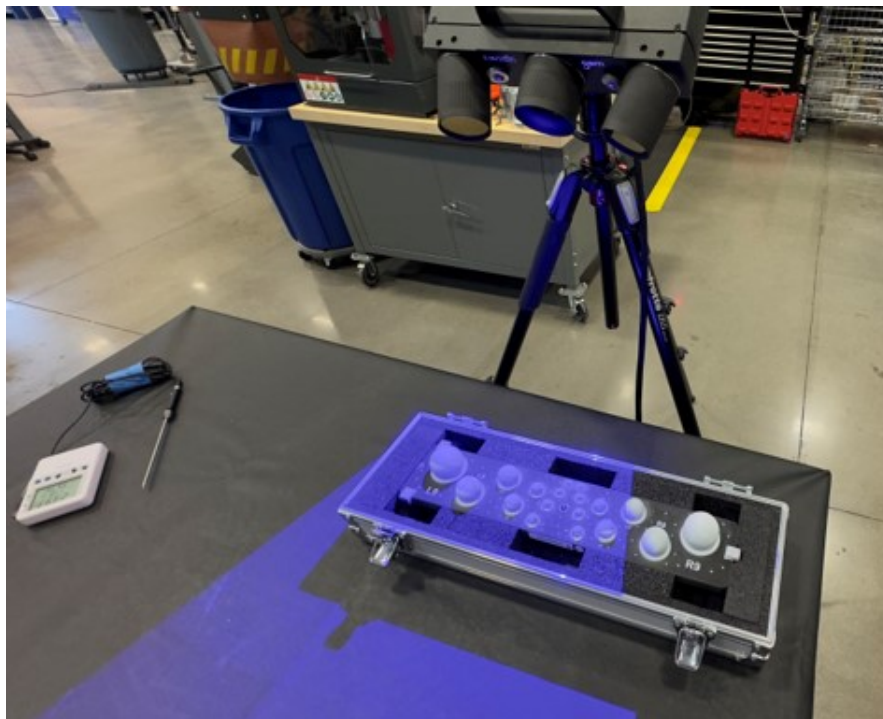


Figure 2.14: ATOS Q mounted to tripod with artifact placed on surface plate table.



Figure 2.15: ATOS Core 200 mounted to lift with artifact mounted on rotary/tilt base.

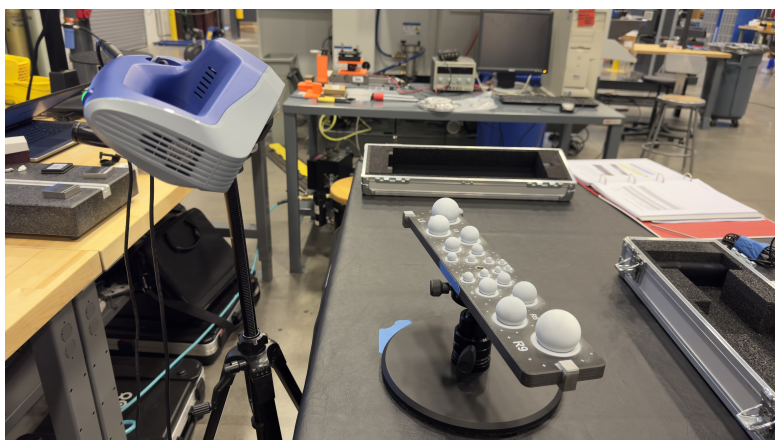


Figure 2.16: Spider mounted to tripod with artifact on surface plate table.

2.2.3 Performance evaluation procedure

This subsection describes the performance evaluation procedure for a selected OCM system.

First, the scanning measurements are performed. The sensor is calibrated according to manufacturer provided instructions, if available. The room temperature is noted prior to measurement. The artifact and room temperature must match. The measurement environment must be free of significant mechanical vibrations. Ambient light must remain consistent throughout measurement. Three sets of ten measurements are performed at ten positions, see Figure 2.18. These ten positions correspond to 45 degree increments about the midpoint between the center line of the two spheres and an additional measurement on the sides of the left and right spheres. The scanner is always tilted 45 degrees towards the artifact. The scanner is placed at the manufacturer specified optimal scanning distance from the midpoint of the center line between the two spheres, and at the center of the two spheres for the side measurements. The first set has the scanner starting parallel to the artifact, the second has the scanner tilted 90 degrees clockwise from parallel to the artifact, and the third has the scanner tilted 90 degrees counterclockwise from parallel to the artifact, all while still having the scanner tilted downwards towards the artifact by 45 degrees.

Second, the scan data is imported into GOM Inspect. The Spider and iPhone required import of .ply files, while the ATOS Q and ATOS Core scans were performed within GOM Inspect.

Third, a plane is best fit to the base of the artifact and a second plane is offset 3 mm above the fit plane. All scan data below the second plane is removed. This ensures no scanned points from the base impact the fitting of spheres. The scan data is then saved as a GOM Inspect .atos file.

Fourth, the .atos file is loaded into a GOM Inspect template that is defined to find and export all necessary parameters and dimensions based on manual surface selection



Figure 2.17: iPhone 15 Pro Max mounted to gimbal for measurements.

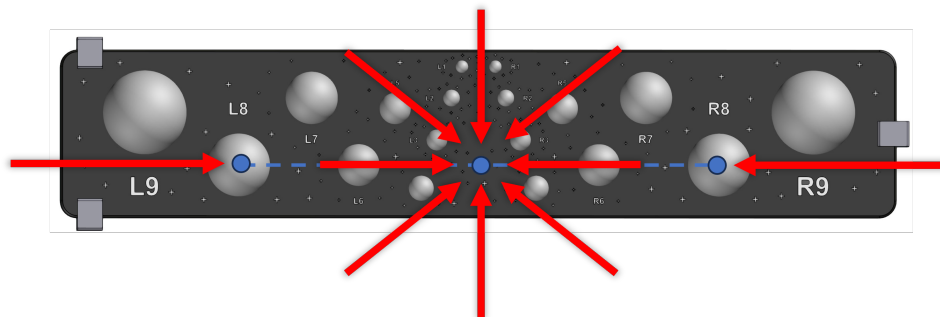


Figure 2.18: Diagram of performance measurement positions for pair L8-R8. Red arrows represent measurement directions. Blue dots show center of the spheres and the midpoint of the sphere to sphere center line.

for fitting of two spheres. Spheres are best fit to scan data using a Gaussian best-fit algorithm included with GOM Inspect. The Gaussian best-fit method squares the deviations of selected points, sums the quadratic deviations, and iterates the fitting sphere until the sum of quadratic deviations is minimized. This adheres to VDI/VDE 2634. A schematic of a sphere fit is shown in Figure 2.19. A .csv file of the identified parameters is exported.

Fifth, the .csv file is loaded into a custom MATLAB script; see Appendix C.1. This script calculates and plots length measurement error, sphere spacing error, probing error size, and probing error form for the measured range of sphere pairs for each OCM system. A basic temperature compensation for sphere diameter and spacing is included based on temperatures at the time of measurement. The compensated fitted sphere diameter D_a becomes

$$D_{a,comp} = D_a + D_a \Delta T \alpha_{spheres} \quad (2.5)$$

where ΔT is the temperature differential between at the time of measurement and the calibrated sphere diameter and $\alpha_{spheres}$ is the coefficient of thermal expansion (CTE) of the spheres as provided in the calibration report for the PSA400 artifact ($10.5 \times 10^{-6} \frac{m}{mK}$). With temperature compensation the measured sphere spacing distance becomes

$$L_{ka,comp} = L_{ka} + L_{ka} \Delta T \alpha_{plate} \quad (2.6)$$

where ΔT is the temperature differential between at the time of measurement and the calibrated sphere spacing distance and α_{plate} is the CTE of the plate as provided in the calibration report for the PSA400 artifact ($4 \times 10^{-6} \frac{m}{mK}$). Additionally, the script plots data comparing scanners to one another for their respective optimal pairs. The MATLAB script is provided in Appendix C.1.

A sample of data from GOM inspect for probing error size, adjustment residual, and adjustment residual is shown in Figure 2.20.

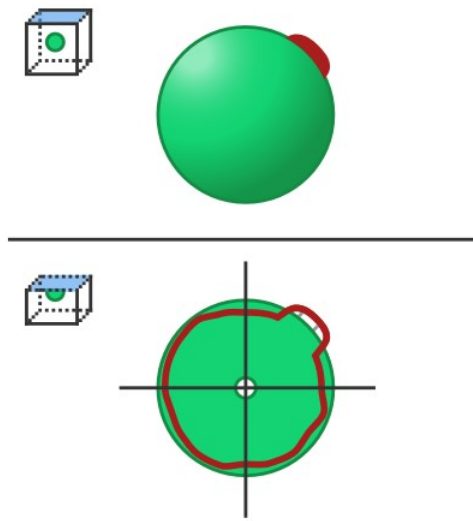


Figure 2.19: Schematic of Gaussian best fit sphere to scan data.

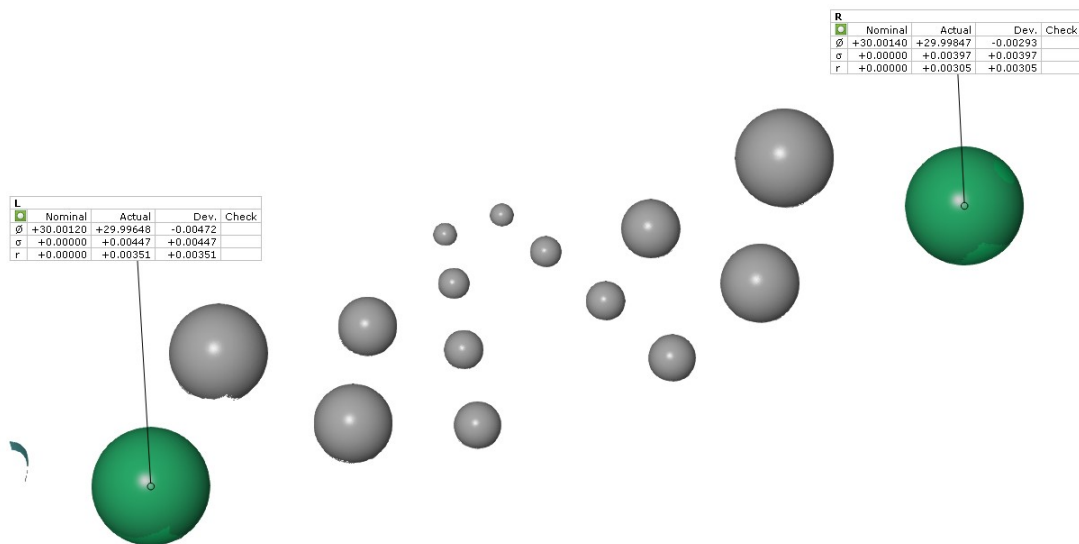


Figure 2.20: Sample data for fit left and right sphere in GOM Inspect.

2.3 Optical coordinate metrology fit sphere center positional uncertainty

The goal of this work is to quantify the uncertainty associated with coordinate systems identification using fiducial spheres that are measured and defined by OCM. Therefore, it is desired to evaluate the uncertainty of a sphere center's position in 3D space. In this work it is shown that the standard deviation of radial distances of measured points to a fitted sphere can represent the uncertainty in a sphere center's position in 3D space. Note that this standard deviation, titled adjustment residual sigma in GOM Inspect, is closely tied to probing error form. Recall that probing error form is the range of radial distances of measured points to a fitted sphere center. Additional measurements were performed to demonstrate that half of adjustment residual sigma can serve as a sphere center's positional uncertainty.

First, a sphere center positional uncertainty study was performed using the ATOS Q. This study performed five scans of the PSA400 artifact in sequence. Scans two through five were set as dependent to scan one. With this dependence, scans use identical targets (i.e., circular targets with adhesive backing attached to the artifact) throughout the five scans. Therefore, the scan coordinate system retained through the five scans. XYZ positions of each sphere center from all five scans were compared to one another to directly calculate positional standard deviation of the sphere centers. These results were compared to values reported for adjustment residual sigma found in the performance evaluation study (Section 2.2). It was observed that

$$u_{SC} \approx \sigma_{AR} \tag{2.7}$$

where σ_{AR} is the adjustment residual sigma and u_{SC} is the sphere center uncertainty for a given OCM system. For a given coverage factor, k , the expanded sphere center uncertainty is

$$U_{SC} = ku_{SC} \quad (2.8)$$

2.4 Coordinate system variation simulation

To better understand and simulate the effect of a fit sphere center's positional uncertainty on a coordinate system's position and orientation, a Monte Carlo simulation was developed in MATLAB; see Appendix C.2. Monte Carlo simulation is a powerful tool for estimating the distribution and range of possible outcomes for a given problem. It is applied here to simulate the distribution of translations and rotations for a given set of simulated sphere centers due to measurement uncertainty of an OCM system. The distribution of variation in a manufacturing coordinate system (CS) is key to fully understanding any hybrid manufacturing process chain. This work universally applies to any AM + X scenario that uses three fiducial spheres and OCM for CS definition and transfer.

The simulation inputs are adjustment residual sigma for a given scanner, nominal center positions of three fiducial spheres in Cartesian coordinates, number of Monte Carlo iterations, and the coverage factor. Each iteration, i , simulates normally distributed Cartesian positions of each of the three fiducial sphere centers based on the sphere center uncertainty.

The nominal (X,Y,Z) positions of the three fiducial sphere centers are defined as $S_{1,nominal}$, $S_{2,nominal}$, and $S_{3,nominal}$. Basis vectors of the nominal coordinate system are calculated; see Figure 2.21. The X direction is defined using sphere 2 and sphere 1 such that

$$X_{nominal,i} = \frac{S_{2,nominal} - S_{1,nominal}}{\|S_{2,nominal} - S_{1,nominal}\|} \quad (2.9)$$

A vector is defined from sphere 3 to sphere 1 such that

$$V_{S_{3,nominal}}^{S_{1,nominal}} = \frac{S_{3,nominal} - S_{1,nominal}}{\|S_{3,nominal} - S_{1,nominal}\|} \quad (2.10)$$

The Z direction is defined as the cross product of X and $V_{S_3}^{S_1}$ so that

$$Z_{nominal,i} = \frac{X_{nominal,i} \times V_{S_{3,nominal}}^{S_{1,nominal}}}{\|X_{nominal,i} \times V_{S_{3,nominal}}^{S_{1,nominal}}\|} \quad (2.11)$$

The Y direction is

$$Y_{nominal,i} = Z_{nominal,i} \times X_{nominal,i} \quad (2.12)$$

The nominal rotation matrix becomes

$$R_{nominal,i} = \begin{bmatrix} X_{nominal,i} & Y_{nominal,i} & Z_{nominal,i} \end{bmatrix} \quad (2.13)$$

The same procedure is repeated for $S_{1,simulated}$, $S_{2,simulated}$, and $S_{3,simulated}$ such that

$$S_{1,simulated,i} = S_{1,nominal} + P_{1,simulated,i} \quad (2.14)$$

$$S_{2,simulated,i} = S_{2,nominal} + P_{2,simulated,i} \quad (2.15)$$

$$S_{3,simulated,i} = S_{3,nominal} + P_{3,simulated,i} \quad (2.16)$$

where $P_{1,simulated,i}$, $P_{2,simulated,i}$, $P_{3,simulated,i} \sim N(0, (\frac{u_{SC}}{2})^2)$ meaning that $P_{1-3,simulated,i}$ are each a generated random number from the normal distribution with mean 0 and standard deviation of u_{SC} divided by two. The simulated coordinate system is defined in the same way as the nominal coordinate system.

$$X_{simulated,i} = \frac{S_{2,simulated} - S_{1,simulated}}{\|S_{2,simulated} - S_{1,simulated}\|} \quad (2.17)$$

$$V_{S_{3,simulated}}^{S_{1,simulated}} = \frac{S_{3,simulated} - S_{1,simulated}}{||S_{3,simulated} - S_{1,simulated}||} \quad (2.18)$$

$$Z_{simulated,i} = \frac{X_{simulated,i} \times V_{S_{3,simulated}}^{S_{1,simulated}}}{||X_{simulated,i} \times V_{S_{3,simulated}}^{S_{1,simulated}}||} \quad (2.19)$$

$$Y_{simulated,i} = Z_{simulated,i} \times X_{simulated,i} \quad (2.20)$$

$$R_{simulated,i} = \begin{bmatrix} X_{simulated,i} & Y_{simulated,i} & Z_{simulated,i} \end{bmatrix} \quad (2.21)$$

The rotation matrix between simulated and nominal coordinate systems can now be found with

$$R_{simulated,i}^{nominal} = \frac{R_{simulated,i}}{R_{nominal,i}} \quad (2.22)$$

where

$$R_{simulated,i}^{nominal} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \quad (2.23)$$

Translation from the nominal to simulated coordinate system origins, or translational error, is

$$\delta_i = S_{1,simulated,i} - R_{simulated,i}^{nominal} S_{1,nominal,i} \quad (2.24)$$

The Euler angles between simulated and nominal coordinate systems, or rotational errors are

$$\varepsilon_{x,i} = \alpha_i = \tan^{-1}\left(\frac{r_{21}}{r_{11}}\right) \quad (2.25)$$

$$\varepsilon_{y,i} = \beta_i = \tan^{-1}\left(\frac{-r_{31}}{\sqrt{r_{32}^2 + r_{33}^2}}\right) \quad (2.26)$$

$$\varepsilon_{z,i} = \gamma_i = \tan^{-1}\left(\frac{r_{32}}{r_{33}}\right) \quad (2.27)$$

The standard deviations of translational errors are

$$\sigma_{\delta_x} = \sqrt{\frac{1}{i-1} \sum_{j=1}^i |\delta_{x,j} - \mu_{\delta_x}|^2} \quad (2.28)$$

$$\sigma_{\delta_y} = \sqrt{\frac{1}{i-1} \sum_{j=1}^i |\delta_{y,j} - \mu_{\delta_y}|^2} \quad (2.29)$$

$$\sigma_{\delta_z} = \sqrt{\frac{1}{i-1} \sum_{j=1}^i |\delta_{z,j} - \mu_{\delta_z}|^2} \quad (2.30)$$

where

$$\mu_{\delta_x} = \frac{1}{i} \sum_{j=1}^i \delta_{x,j} \quad (2.31)$$

$$\mu_{\delta_y} = \frac{1}{i} \sum_{j=1}^i \delta_{y,j} \quad (2.32)$$

$$\mu_{\delta_z} = \frac{1}{i} \sum_{j=1}^i \delta_{z,j} \quad (2.33)$$

The standard deviations of rotational errors for each axis are

$$\sigma_{\varepsilon_x} = \sqrt{\frac{1}{i-1} \sum_{j=1}^i |\varepsilon_{x,j} - \mu_{\varepsilon_x}|^2} \quad (2.34)$$

$$\sigma_{\varepsilon_y} = \sqrt{\frac{1}{i-1} \sum_{j=1}^i |\varepsilon_{y,j} - \mu_{\varepsilon_y}|^2} \quad (2.35)$$

$$\sigma_{\varepsilon_z} = \sqrt{\frac{1}{i-1} \sum_{j=1}^i |\varepsilon_{z,j} - \mu_{\varepsilon_z}|^2} \quad (2.36)$$

where

$$\mu_{\varepsilon_x} = \frac{1}{i} \sum_{j=1}^i \varepsilon_{x,j} \quad (2.37)$$

$$\mu_{\varepsilon_y} = \frac{1}{i} \sum_{j=1}^i \varepsilon_{y,j} \quad (2.38)$$

$$\mu_{\varepsilon_z} = \frac{1}{i} \sum_{j=1}^i \varepsilon_{z,j} \quad (2.39)$$

With correlation neglected between standard uncertainties the expanded uncertainties for translation and rotation become

$$U_{\delta} = k \sqrt{\sigma_{\delta_x}^2 + \sigma_{\delta_y}^2 + \sigma_{\delta_z}^2} \quad (2.40)$$

$$U_{\varepsilon} = k \sqrt{\sigma_{\varepsilon_x}^2 + \sigma_{\varepsilon_y}^2 + \sigma_{\varepsilon_z}^2} \quad (2.41)$$

2.5 Coordinate system variation experimentation

Validation of the simulation described in Section 2.4 was completed. This required experimental testing of coordinate system variation(s). To do so, the GOM PSA400 artifact was used to define coordinate systems for multiple sphere sets within each scan of the artifact. Three coordinate system sets were defined with triplets of left and right sphere centers. These included sphere triplets 4,5, and 6 for the Spider, 5,6,

and 7 for the ATOS Core, and 7, 8, and 9 for the iPhone and ATOS Q; see Figures 2.22 to 2.24. Translation and rotation between the left and right coordinate systems were measured for each set of scan data. Translational error and rotational error were found by calculating the difference between a scanned measurement translation and rotation and CMM measurement translation and rotation. The measurements were repeated five times to obtain standard deviations of translational and rotational errors. Temperature compensation was negligible for the measurement environment.

For a coordinate system, L_{abc} or R_{abc} defined by a set of sphere triplets, abc , where S_a defines the origin, S_b defines the X axis and S_c clocks rotation, the same procedure as Section 2.4 shows that

$$X_{L,abc} = \frac{S_{L,b} - S_{L,a}}{||S_{L,b} - S_{L,a}||} \quad (2.42)$$

$$V_{S_{L,c}}^{S_{L,a}} = \frac{S_{L,c} - S_{L,a}}{||S_{L,c} - S_{L,a}||} \quad (2.43)$$

$$Z_{L,abc} = \frac{X_{L,abc} \times V_{S_{L,c}}^{S_{L,a}}}{||X_{L,abc} \times V_{S_{L,c}}^{S_{L,a}}||} \quad (2.44)$$

$$Y_{L,abc} = Z_{L,abc} \times X_{L,abc} \quad (2.45)$$

$$R_{L,abc} = \begin{bmatrix} X_{L,abc} & Y_{L,abc} & Z_{L,abc} \end{bmatrix} \quad (2.46)$$

The homogeneous transformation matrix is

$$T_L = \begin{pmatrix} R_{L,abc} & R_{L,abc}S_{L,b} \\ o & 1 \end{pmatrix} \quad (2.47)$$

The positions of the right sphere centers can now be transformed into the left coordinate system with

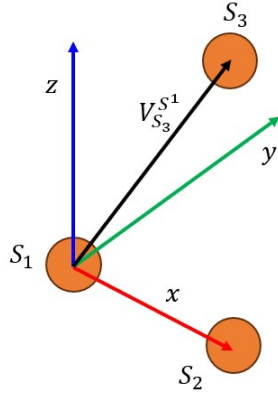


Figure 2.21: Formation of basis vectors using three spheres.

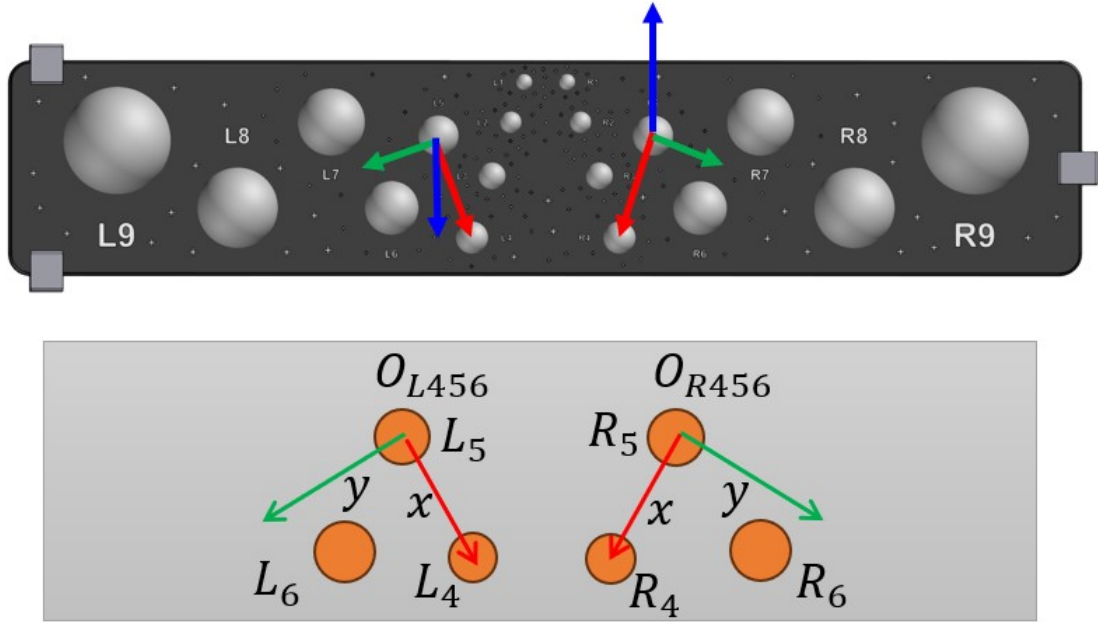


Figure 2.22: Left and right coordinate system defined on artifact by spheres four, five, and six.

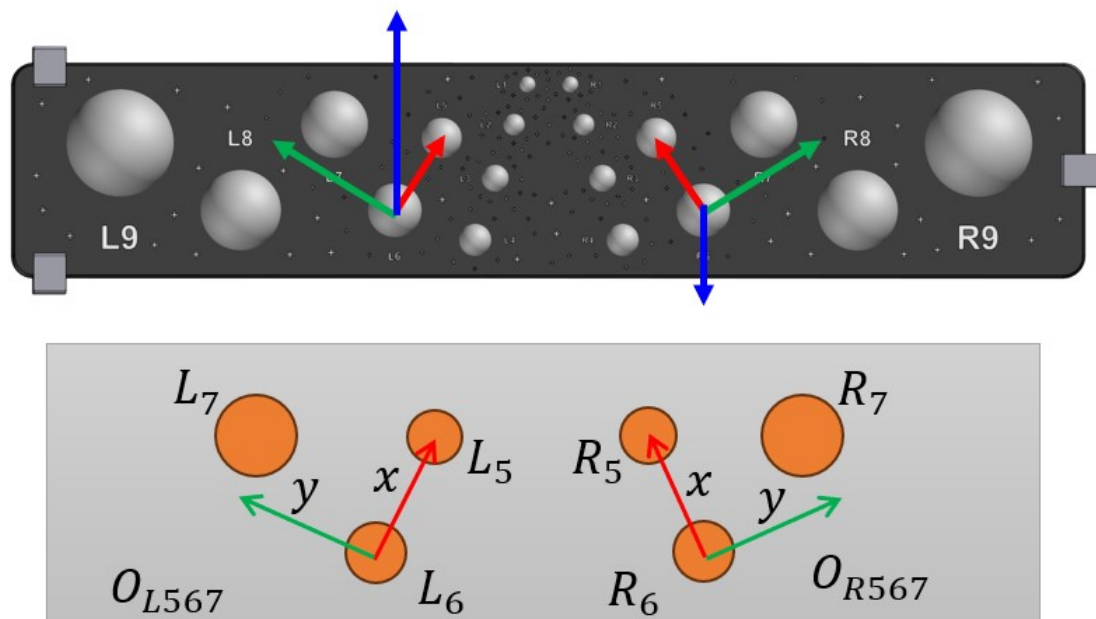


Figure 2.23: Left and right coordinate system defined on artifact by spheres five, six, and seven.

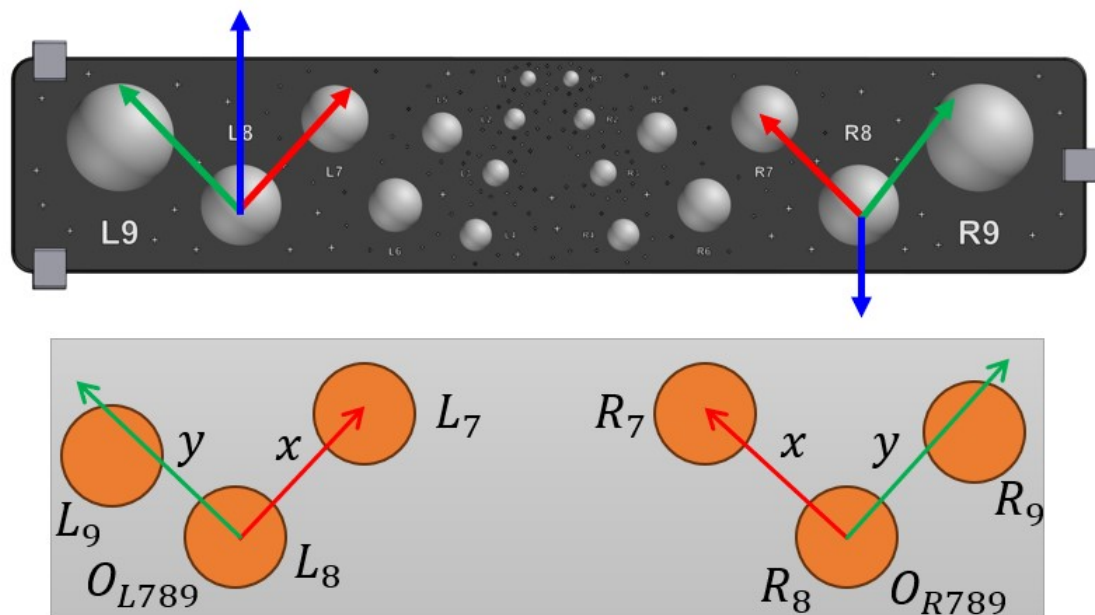


Figure 2.24: Left and right coordinate system defined on artifact by spheres seven, eight, and nine.

$$S_{LR,a} = T_L S_{R,a} \quad (2.48)$$

$$S_{LR,b} = T_L S_{R,b} \quad (2.49)$$

$$S_{LR,c} = T_L S_{R,c} \quad (2.50)$$

The LR coordinate system becomes

$$X_{LR,abc} = \frac{S_{LR,b} - S_{LR,a}}{||S_{LR,b} - S_{LR,a}||} \quad (2.51)$$

$$V_{S_{LR,c}}^{S_{LR,a}} = \frac{S_{LR,c} - S_{LR,a}}{||S_{LR,c} - S_{LR,a}||} \quad (2.52)$$

$$Z_{LR,abc} = \frac{X_{LR,abc} \times V_{S_{LR,c}}^{S_{LR,a}}}{||X_{LR,abc} \times V_{S_{LR,c}}^{S_{LR,a}}||} \quad (2.53)$$

$$Y_{LR,abc} = Z_{LR,abc} \times X_{LR,abc} \quad (2.54)$$

$$R_{LR,abc} = \begin{bmatrix} X_{LR,abc} & Y_{LR,abc} & Z_{LR,abc} \end{bmatrix} \quad (2.55)$$

From $R_{LR,abc}$ the associated Euler angles are

$$\alpha_{LR} = \tan^{-1}\left(\frac{r_{21}}{r_{11}}\right) \quad (2.56)$$

$$\beta_{LR} = \tan^{-1}\left(\frac{-r_{31}}{\sqrt{r_{32}^2 + r_{33}^2}}\right) \quad (2.57)$$

$$\gamma_{LR} = \tan^{-1}\left(\frac{r_{32}}{r_{33}}\right) \quad (2.58)$$

For two sets of sphere center data, from an OCM system measurement and a CMM measurement, where the CMM measurement is taken to represent the true (lower uncertainty), the translational errors are

$$\delta_{OCMS} = S_{OCMS,LR,a} - S_{CMM,LR,a} \quad (2.59)$$

The rotational errors are

$$\varepsilon_{OCMS,x} = \alpha_{OCMS,LR} - \alpha_{CMM,LR} \quad (2.60)$$

$$\varepsilon_{OCMS,y} = \beta_{OCMS,LR} - \beta_{CMM,LR} \quad (2.61)$$

$$\varepsilon_{OCMS,z} = \gamma_{OCMS,LR} - \gamma_{CMM,LR} \quad (2.62)$$

With repeated measurements from the OCM system and correlation between standard uncertainties neglected the expanded uncertainties of translation and rotation are

$$U_{\delta} = k\sqrt{\sigma_{\delta_x}^2 + \sigma_{\delta_y}^2 + \sigma_{\delta_z}^2} \quad (2.63)$$

$$U_{\varepsilon} = k\sqrt{\sigma_{\varepsilon_x}^2 + \sigma_{\varepsilon_y}^2 + \sigma_{\varepsilon_z}^2} \quad (2.64)$$

2.5.1 Coordinate system variation experiment procedure

This subsection describes the procedure for evaluating coordinate system variation (translational and rotational errors) from a set of OCM system data.

First, scanning measurements are performed. The sensor is calibrated according to manufacturer provided instructions if available, the room temperature is noted prior to measurement, and the artifact and room temperature must match. The

environment must be free of significant mechanical vibrations and ambient light must remain consistent throughout measurements. Five measurements are performed with sixteen positions each; see Figure 2.25. These sixteen positions correspond to two sets of 45 degree rotations about the origin sphere of the left and right coordinate systems on the artifact. This mimics the procedure for the performance evaluation study, but enables additional angles to capture spheres adjacent to the origin spheres. The scanner is always tilted 45 degrees towards the artifact and placed at the manufacturer specified optimal scanning distance from the center of the origin sphere.

Second, the scan data is imported into GOM Inspect. The Spider and iPhone required import of .ply files, while the ATOS Q and ATOS Core scans were performed within GOM Inspect.

Third, a plane is best fit to the base of the artifact and a second plane is offset 3 mm above the fit plane. All scan data below the second plane is removed. This ensures no scanned points from the base impact the fitting of spheres. The scan data is then saved as a GOM Inspect .atos file.

Fourth, the .atos file is loaded into a GOM Inspect template that reports XYZ positions for six fit sphere centers. These XYZ positions are relative to an arbitrary coordinate system in the rear top left of the artifact. The positions are exported as a .csv file and loaded into a MATLAB script; see Appendix C.4. This script performs calculations as described in the previous section.

2.6 Overbuild simulation

Each iteration of the Monte Carlo simulation described in Section 2.4 executes a “checkOverbuild” function. This function operates a loop until the minimum bounding box is found for the part’s size. This defines the AM overbuild required to compensate for the coordinate system variation due to a given OCM system’s measurement uncertainty; see Figure 2.26.

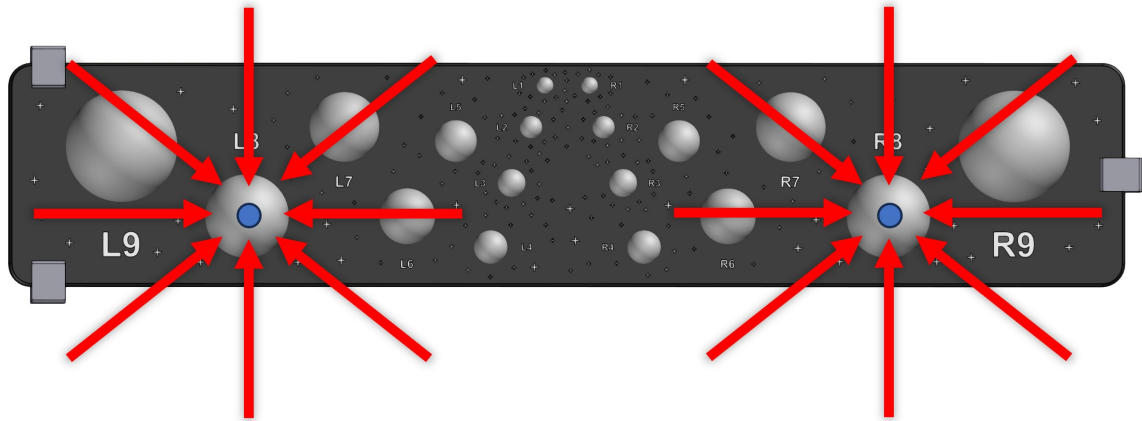


Figure 2.25: Coordinate system variation experimental measurement positions, shown for the CS defined by L789 and R789. Blue dots are the center of spheres L8 and R8.

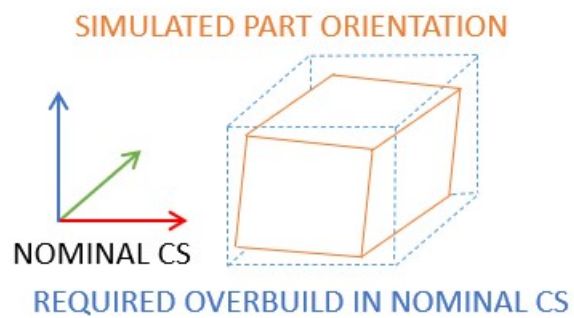


Figure 2.26: Schematic of required overbuild given a simulated part position.

The homogeneous transformation matrix calculated within each Monte Carlo simulation iteration is

$$T_i = \begin{pmatrix} R_{simulated}^{nominal} & \delta_i \\ o & 1 \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & \delta_{x,i} \\ r_{21} & r_{22} & r_{23} & \delta_{y,i} \\ r_{31} & r_{32} & r_{33} & \delta_{z,i} \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.65)$$

The required overbuild, O_b , is uniform in all directions and is initialized with a value of 0. Two additional inputs are required: $P_{min,nominal}$ and $P_{max,nominal}$ which are minimum and maximum points of the nominal part's bounding box in the nominal coordinate system. The homogeneous transformation matrix enables simple calculation of the minimum and maximum points of the bounding box in the simulated coordinate system where

$$P_{min,simulated,i} = T_i \begin{bmatrix} P_{min,x} - O_b \\ P_{min,y} - O_b \\ P_{min,z} - O_b \\ 1 \end{bmatrix} \quad (2.66)$$

and

$$P_{max,simulated,i} = T_i \begin{bmatrix} P_{max,x} + O_b \\ P_{max,y} + O_b \\ P_{max,z} + O_b \\ 1 \end{bmatrix} \quad (2.67)$$

If $P_{min,nominal} \geq P_{min,simulated}$ and $P_{max,nominal} \leq P_{max,simulated}$ then $O_{b,i} = O_b$ otherwise O_b is incremented by a set amount, 1 μm , until the previous statement is true. The result is a distribution of required overbuild quantities $O_{b,i}$ for all Monte Carlo simulation iterations. MATLAB code of the overbuild function is included in Appendix C.2.

Chapter 3

Results and discussion

3.1 Optical coordinate metrology system performance

The performance results in this section are based on three sets of results for each OCM system, where three independent scans were completed and processed for each OCM system. This provided a range of quality parameter results for all the sphere diameters that fit within a scanner's measurement volume. These results show how different sized spheres and sphere center spacings can impact the OCM system's performance. The optimal pair for each OCM system is noted, which is based on the sphere pair with the largest spacing that the scanner measurement volume can fully contain when performing measurements at the optimal distance using straight on orientation.

Figure 3.1 shows performance results for all quality parameters using the ATOS Q considering all measured sphere pairs. The optimal pair was found to be spheres L8 and R8 (30 mm diameter) based on the scanner's measurement volume at the optimal distance. This is the same pair suggested for use by GOM. All spheres were able to be measured for the ATOS Q scan volume.

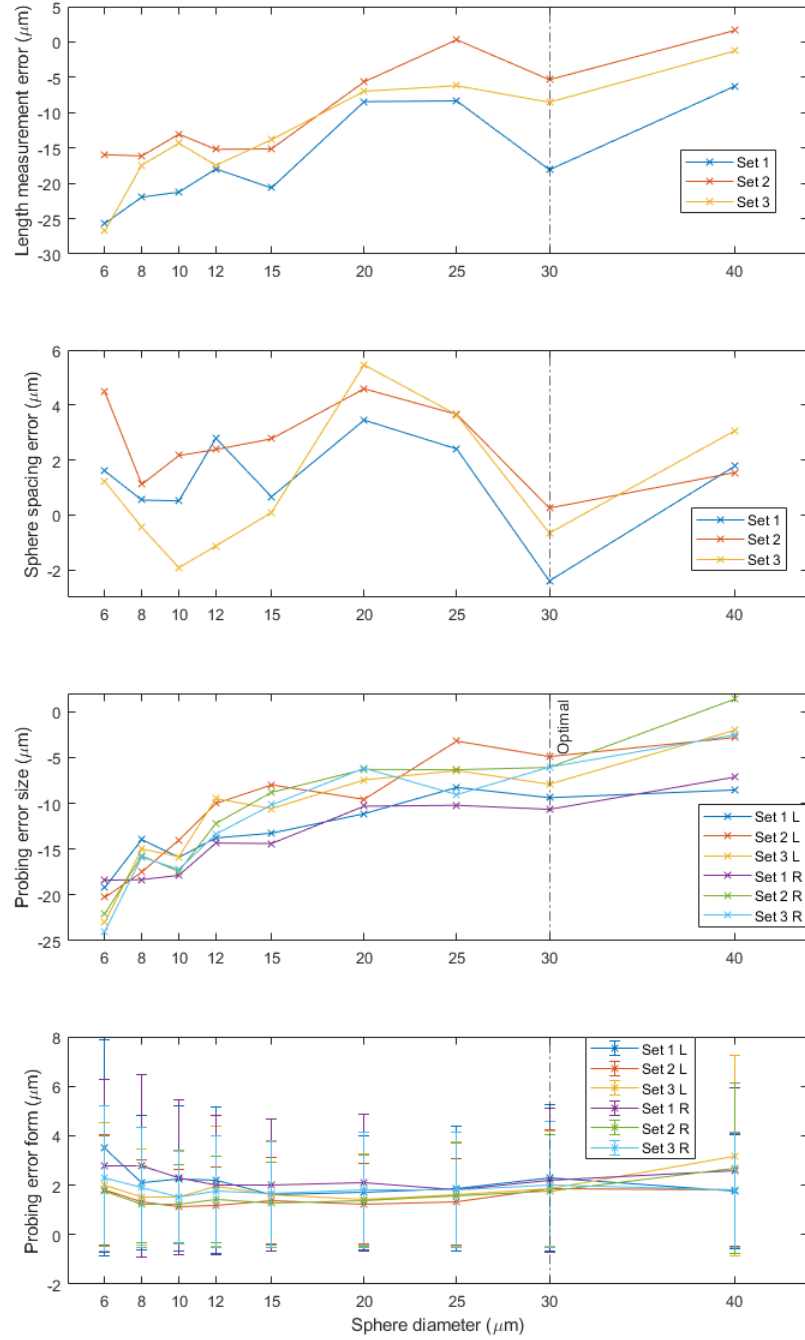


Figure 3.1: Performance evaluation results for the ATOS Q. Error bars represent adjustment residual sigma. The vertical dot dashed line represents optimal sphere pair diameter.

Figure 3.2 shows performance results for all quality parameters using the ATOS Core 200. The optimal pair was found to be spheres L6 and R6 (20 mm diameter) based on the scanner’s measurement volume at the optimal distance. This is the same pair suggested for use by GOM. Sphere pairs 1 through 8 were measured; pair 9 did not fit within the scan volume and was not measured.

Figure 3.3 shows performance results for all quality parameters using the Spider. The optimal pair was found to be spheres L3 and R3 (10 mm diameter) based on the scanner’s measurement volume at the optimal distance. Due to the Spider’s relatively limited scan volume only sphere pairs 2 through 4 were measured. All other pairs were not captured within the performance scans.

Figure 3.4 shows performance results for all quality parameters using the iPhone. The optimal pair was found to be spheres L8 and R8 (30 mm diameter) based on the scanner’s measurement volume. Results for the iPhone contain some measurements with less data points than others. This was due to issues with fitting smaller spheres; the iPhone can often not collect enough points (within a point cloud) to properly perform sphere fits.

The average performance for all quality parameters for each OCM system’s optimal pair are shown in Figure 3.5. The results quantitatively show the difference in performance between the OCM systems considered in this study. Since these results are for each scanner’s optimal pair, the metrics are approximately normalized to scanner volume. Overall, these results were anticipated. The ATOS Q and ATOS Core provide similar results, the Spider is lower (approximately five to ten times larger parameter values), and the iPhone is performance is much lower than the other OCM systems.

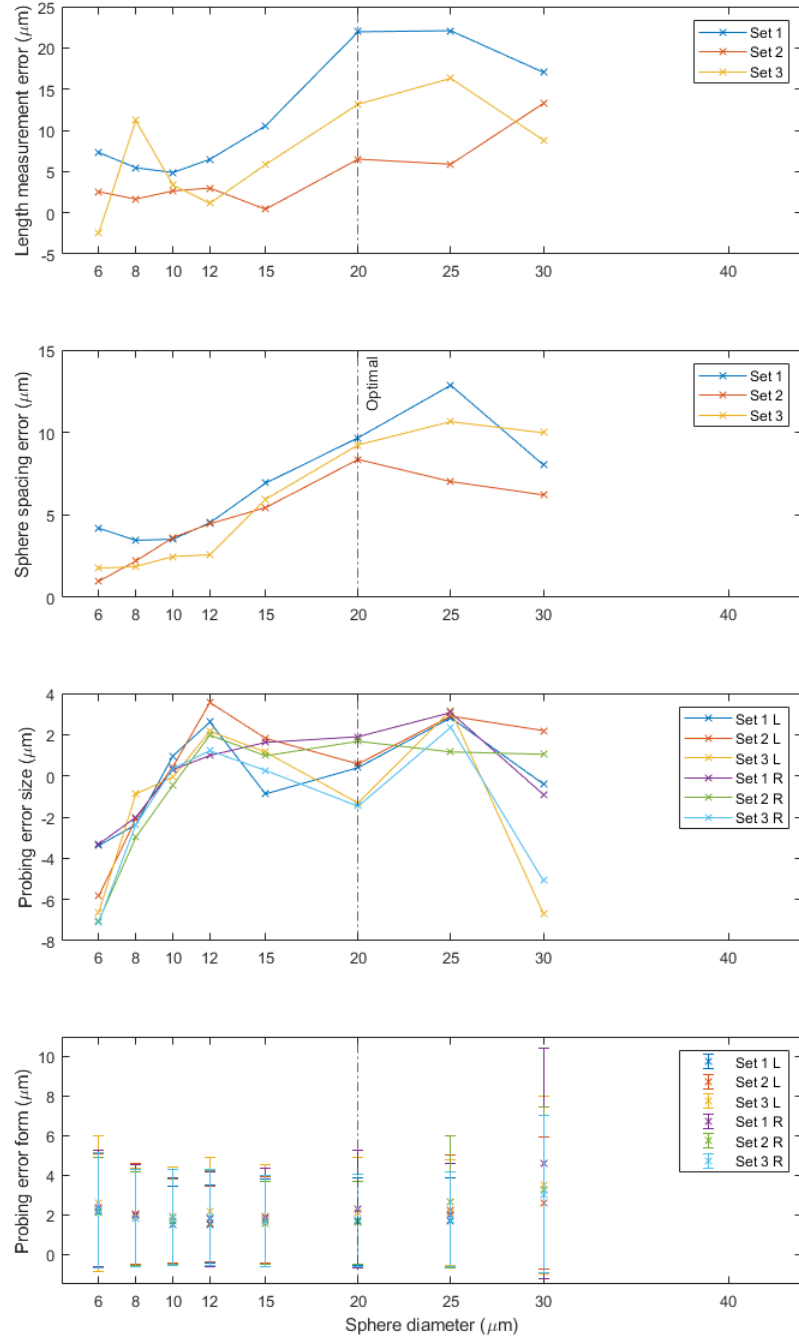


Figure 3.2: Performance evaluation results for the ATOS Core 200. Error bars represent adjustment residual sigma. The vertical dot dashed line represents optimal sphere pair diameter.

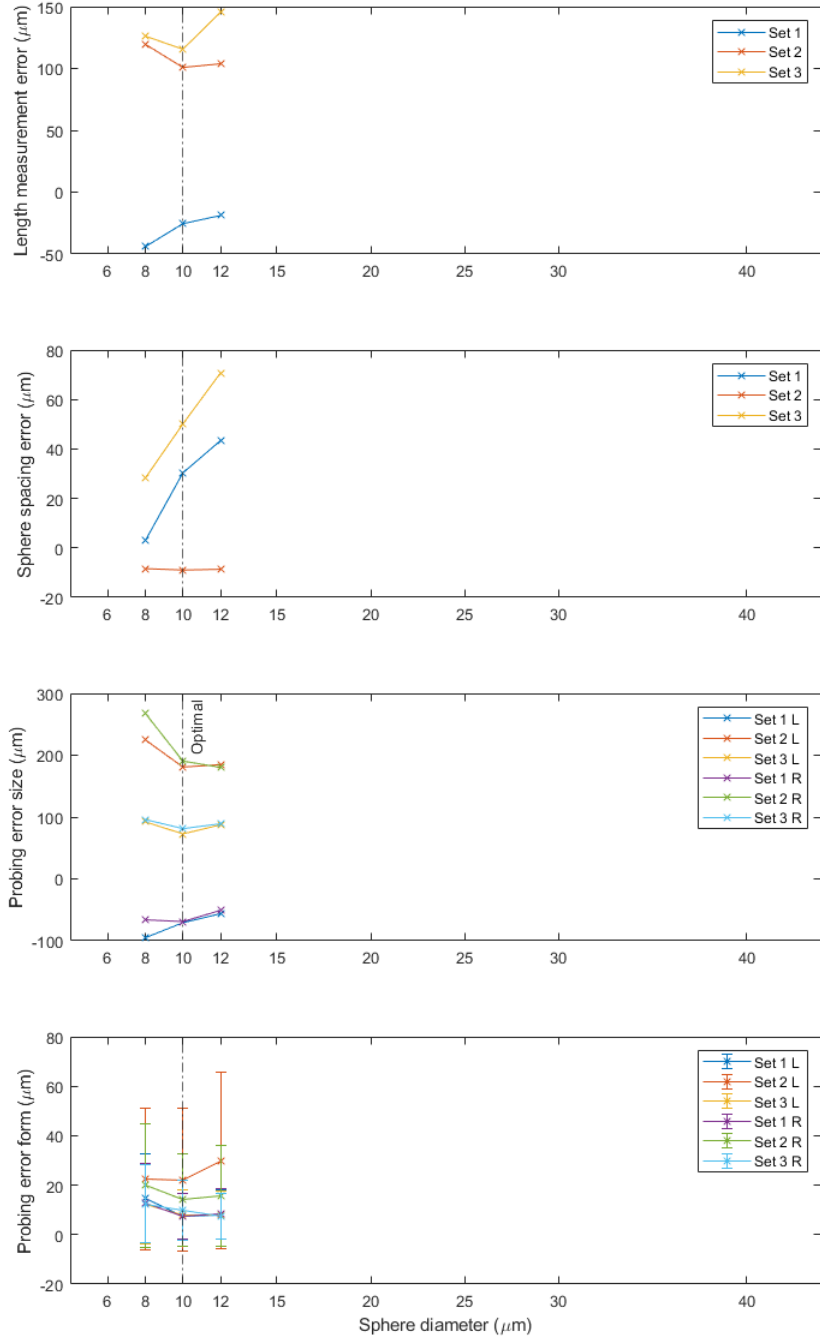


Figure 3.3: Performance evaluation results for the Artec Spider. Error bars represent adjustment residual sigma. The vertical dot dashed line represents optimal sphere pair diameter.

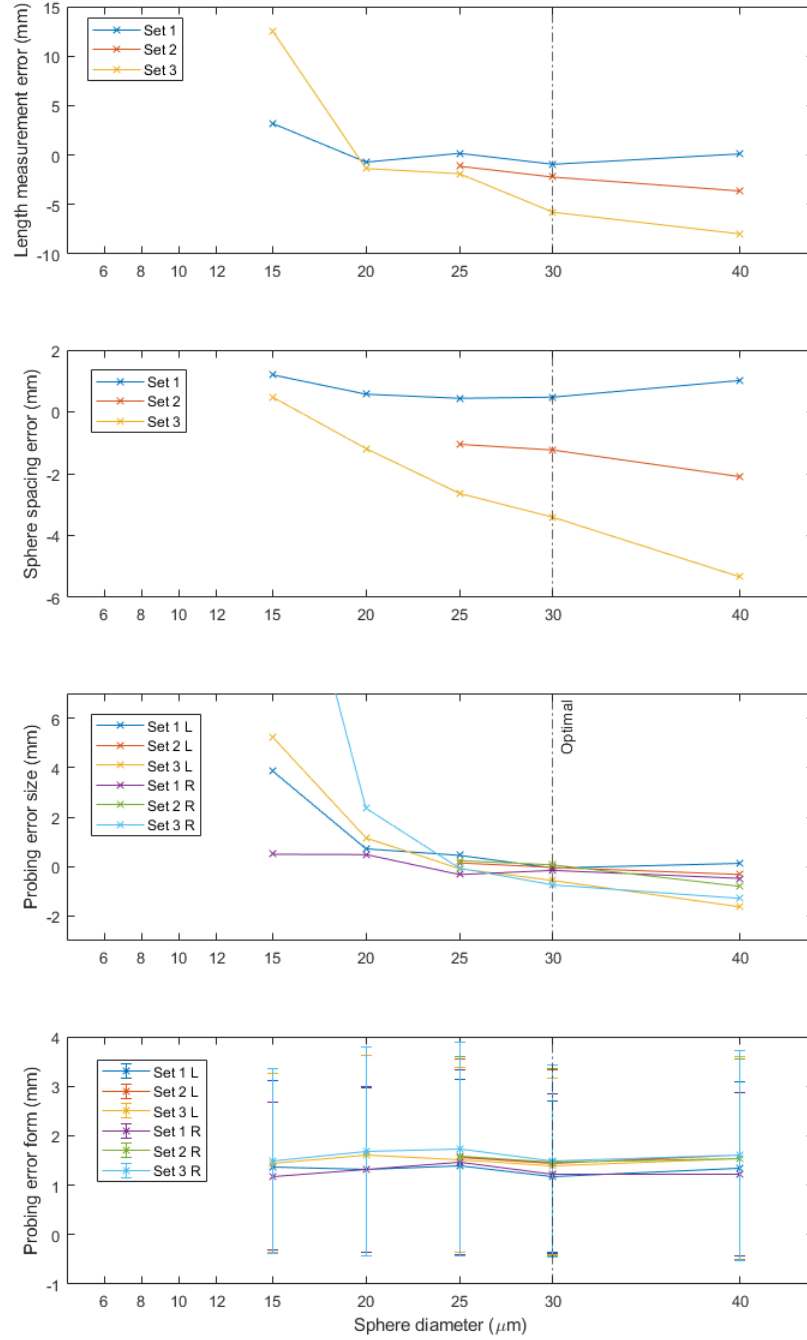


Figure 3.4: Performance evaluation results for the iPhone. Error bars represent adjustment residual sigma. The vertical dot dashed line represents optimal sphere pair diameter.

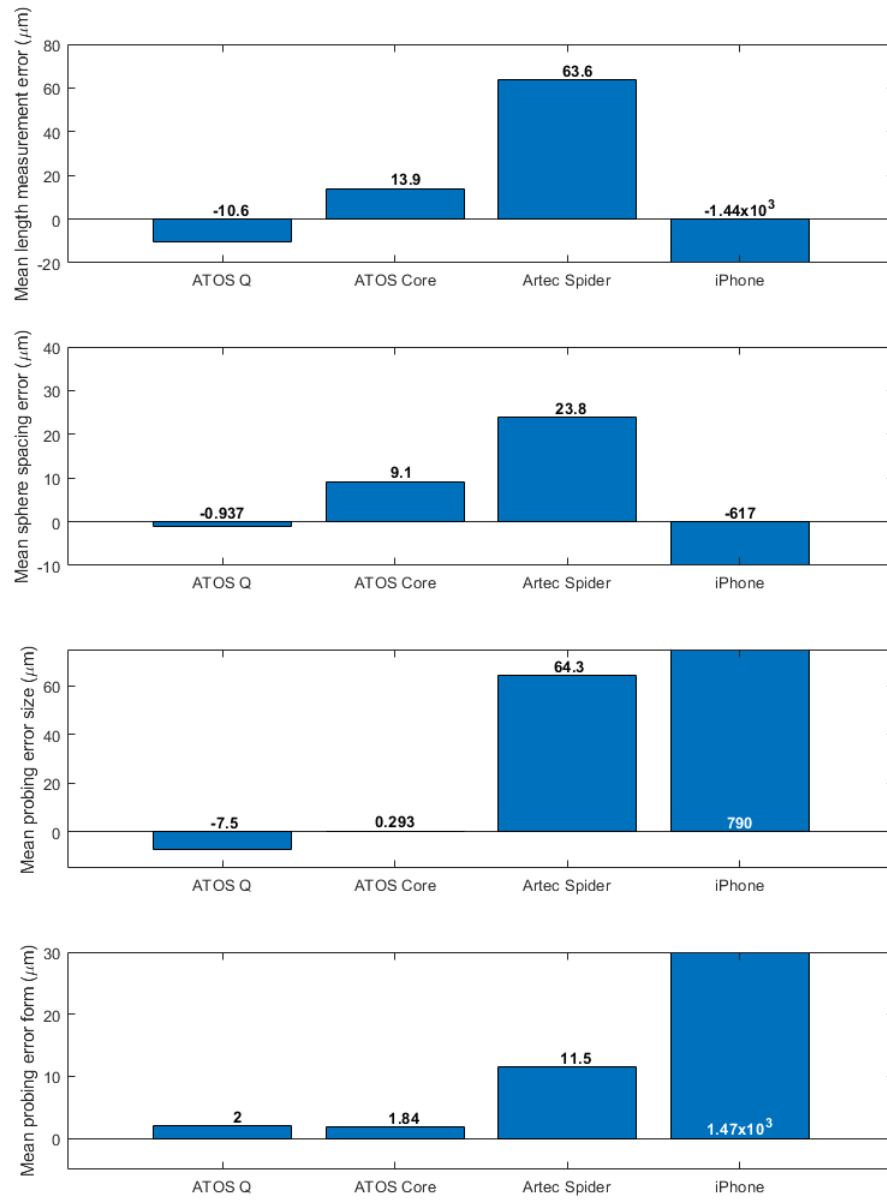


Figure 3.5: Mean performance evaluation results for all OCM systems at respective optimal pair.

3.2 Optical coordinate metrology system uncertainty

As discussed in Section 2.3, a study was first completed to verify the relationship between sphere center positional uncertainty and probing error form sigma (adjustment residual sigma). In this study, the artifact was scanned nine times with the ATOS Q with all scans using the same target-based coordinate system. The results in Figure 3.6 show standard deviations of all sphere center positions in X, Y, and Z. The uncertainty was calculated using root sum squares value of the standard deviations; it was found to be $u_{xyz} = 2.20 \mu m$. MATLAB code for the sphere center positional uncertainty study is provided in Appendix C.3.

The mean probing error form sigma, or mean adjustment residual sigma results, for all OCM system optimal pairs are shown in Figure 3.7. These values are directly reported from GOM Inspect for fit spheres. This results in a -14.4% difference from the mean adjustment residual sigma found for the ATOS Q of $2.57 \mu m$, suggesting that adjustment residual sigma is a good approximation for sphere center positional uncertainty.

3.3 Coordinate system variation simulation

The Monte Carlo simulation was completed over 500,000 iterations for each OCM system with a coverage factor of two. As discussed in Sections 2.3 and 2.4 half of the adjustment residual found for each OCM system was used for generating the distribution of sphere center positions. Simulation results are provided in Table 3.1. These simulated results are next compared to experimental results. MATLAB script for the simulation is provided in Appendix C.2.

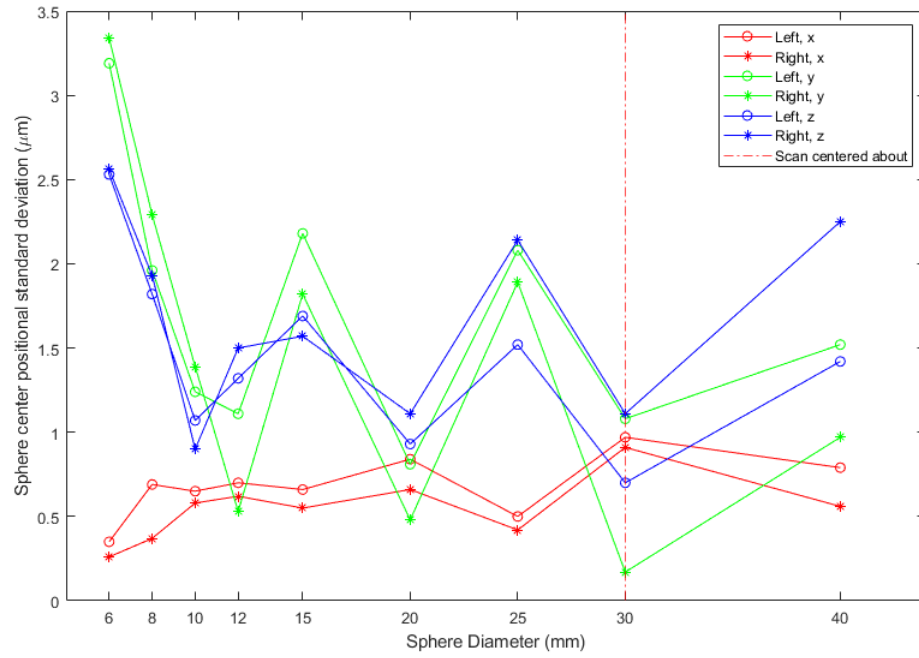


Figure 3.6: Sphere center positional standard deviation results for ATOS Q.

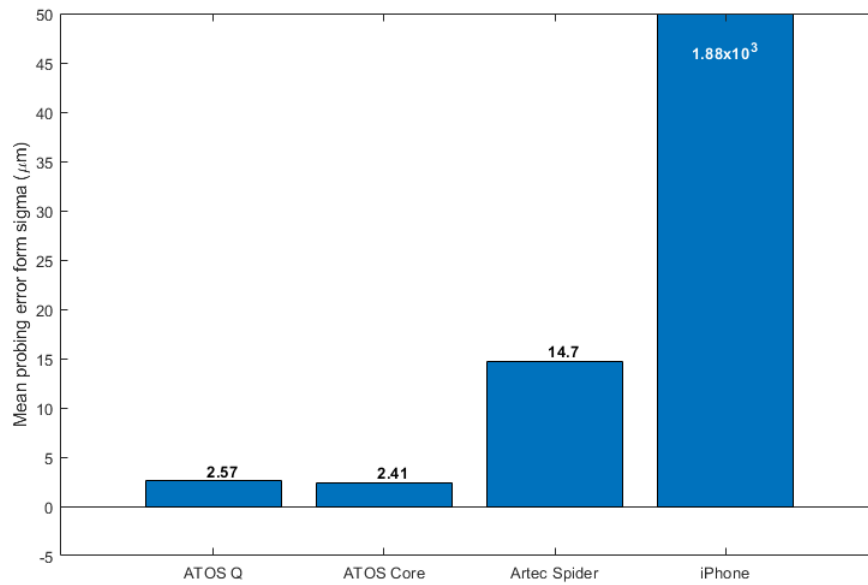


Figure 3.7: Mean probing error form sigma for each OCM system at respective optimal pair.

Table 3.1: Results of coordinate system variation simulations.

OCM system	u_{SC} (μm)	σ_{δ_x} (μm)	σ_{δ_y} (μm)	σ_{δ_z} (μm)	σ_{ε_x} (arcmin)	σ_{ε_y} (arcmin)	σ_{ε_z} (arcmin)	U_δ (μm)	U_ε (arcmin)
ATOS Q	1.30	6.09	5.69	5.60	0.155	0.131	0.132	20.1	0.484
ATOS Core 200	2.41	5.24	2.62	4.98	0.140	0.182	0.182	15.4	0.586
Spider	14.7	21.1	5.88	30.4	1.23	0.895	0.893	74.9	3.53
iPhone	1880	4450	4170	4110	113	96.3	96.4	14700	355

3.4 Coordinate system variation experimentation

Results for coordinate system variation experiments are provided in Table 3.2. The mean errors from the simulation are zero. However, in this experiment they are nonzero and are reported in Table 3.3.

Experimental results are plotted with simulation results in Figure 3.8 and 3.9. Good agreement is observed between experimental and simulated uncertainties. Note that results are shown for the ATOS Q with both spot and matrix metering, which represent two different auto-exposure approaches. The difference in results for these two metering settings demonstrate the importance of proper exposure to achieving accurate results, and that the influence of this setting on uncertainty can be substantial.

Table 3.2: Results from coordinate system variation experiments.

OCM system	σ_{δ_x} (μm)	σ_{δ_y} (μm)	σ_{δ_z} (μm)	σ_{ε_x} (arcmin)	σ_{ε_y} (arcmin)	σ_{ε_z} (arcmin)	U_{δ} (μm)	U_{ε} (arcmin)
ATOS Q	1.61	0.42	1.33	0.039	0.053	0.035	4.27	0.148
ATOS Core 200	2.51	2.03	6.39	0.166	0.186	0.103	14.3	0.540
Spider	20.7	4.16	16.1	0.947	1.07	1.15	53.2	3.59
iPhone	3240	2070	870	28.4	32.8	19.9	7890	95.5

Table 3.3: Average translational and rotational error from coordinate system variation experiments.

OCM system	$\bar{\delta}_x$ (μm)	$\bar{\delta}_y$ (μm)	$\bar{\delta}_z$ (μm)	$\bar{\varepsilon}_x$ (arcmin)	$\bar{\varepsilon}_y$ (arcmin)	$\bar{\varepsilon}_z$ (arcmin)
ATOS Q	-4.90	-14.7	1.70	-0.575	-0.064	-0.722
ATOS Core 200	0.140	-2.54	-11.8	0.644	-0.266	-0.690
Spider	9.65	-52.3	55.7	-3.64	2.52	0.330
iPhone	-1930	2120	1920	-30.6	35.8	8.02

3.5 Overbuild simulation

Figures 3.10 through 3.13 show results for overbuild simulations for all OCM systems for a 100 mm^3 part located at the distance between the left and right coordinate systems used in the previous demonstrations. This identifies the required overbuild for a constant sized part approximately normalized to each OCM system's measurement volume. It is seen that the ATOS Q and ATOS Core would require $35 \mu\text{m}$ of overbuild to fully compensate for their uncertainties. The Spider reports $150 \mu\text{m}$ of required overbuild and the iPhone over 25 mm . This shows that the Spider is likely feasible in manufacturing environments, but the iPhone is not currently practical, as 25 mm of overbuild for a 100 mm^3 part is relatively wasteful for hybrid manufacturing applications and begins to eliminate the benefits of hybrid manufacturing altogether.

3.6 Cost versus uncertainty

Cost per OCM system measurement volume is plotted versus positional and rotational uncertainty in Figure 3.14 and Figure 3.15. The bottom left of these plots represents ideal combinations. These results are informative; the ATOS Core is higher than the ATOS Q in cost per scan volume and worse in performance, but has a lower purchase price (total initial cost). The Spider is higher than both the ATOS Core and ATOS Q in cost and worse in performance, but again has a lower purchase price and is designed for other benefits such as scanning speed, no target requirements, and being handheld/portable. These factors explain its higher cost per performance. The iPhone, as expected, is off the charts.

3.7 Summary of key results

Table 3.4 shows key results across all OCM systems tested. These are average results at the optimal sphere pair for each OCM system, and the expanded uncertainty

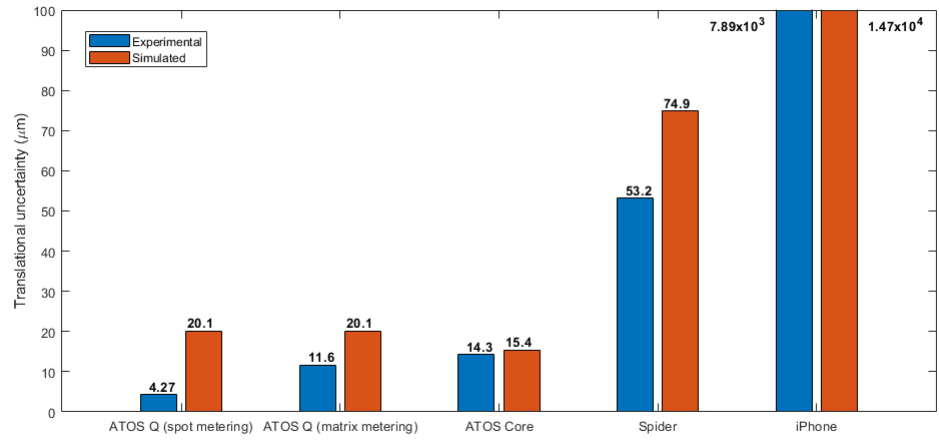


Figure 3.8: Experimental and simulated translational uncertainty results.

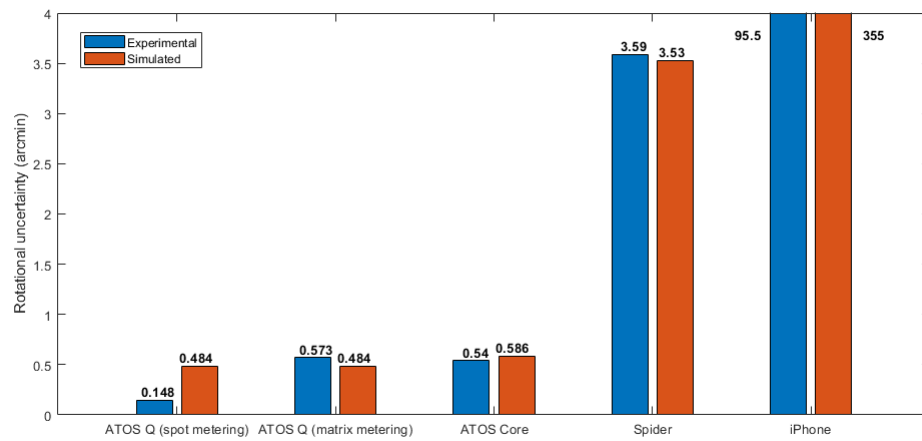


Figure 3.9: Experimental and simulated rotational uncertainty results.

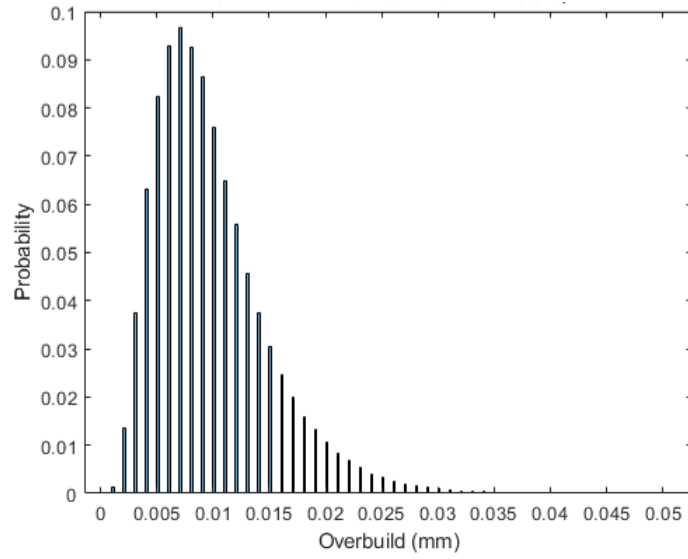


Figure 3.10: Overbuild simulation results for ATOS Q.

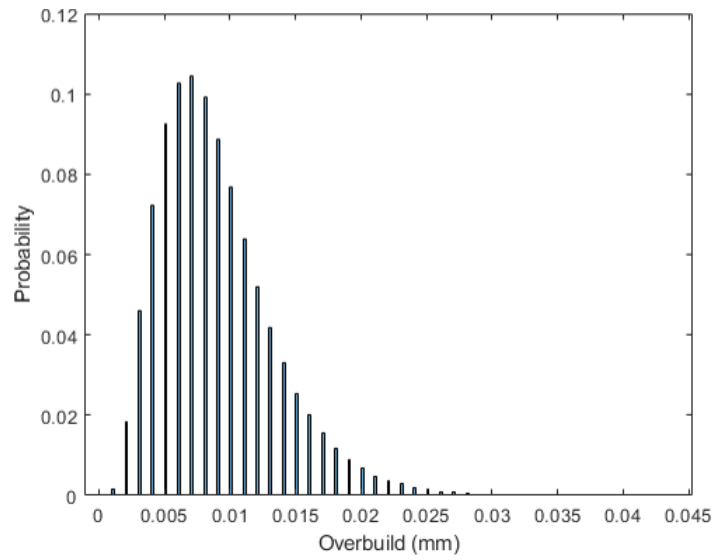


Figure 3.11: Overbuild simulation results for ATOS Core 200.

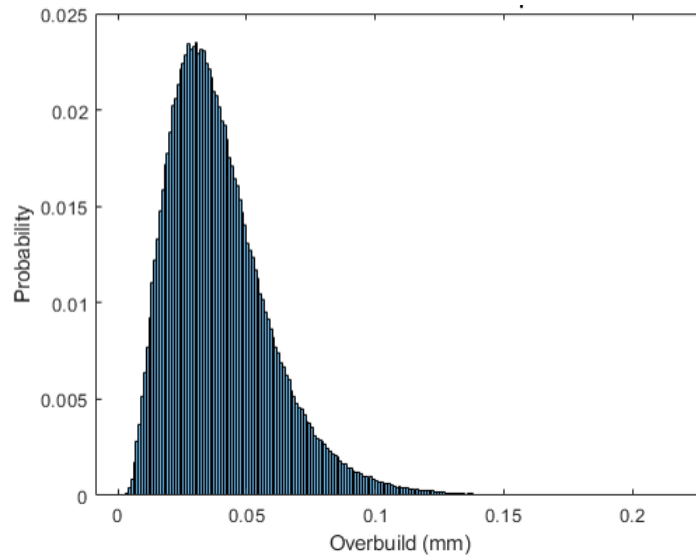


Figure 3.12: Overbuild simulation results for Artec Spider.

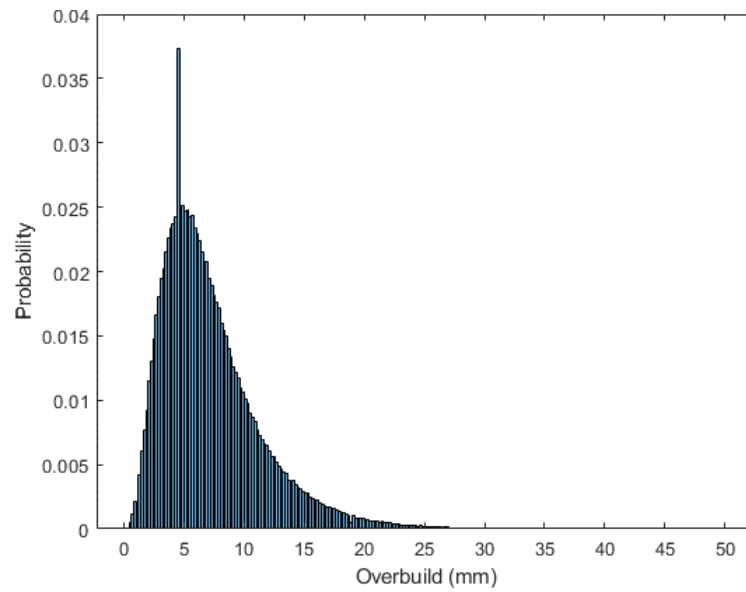


Figure 3.13: Overbuild simulation results for iPhone.

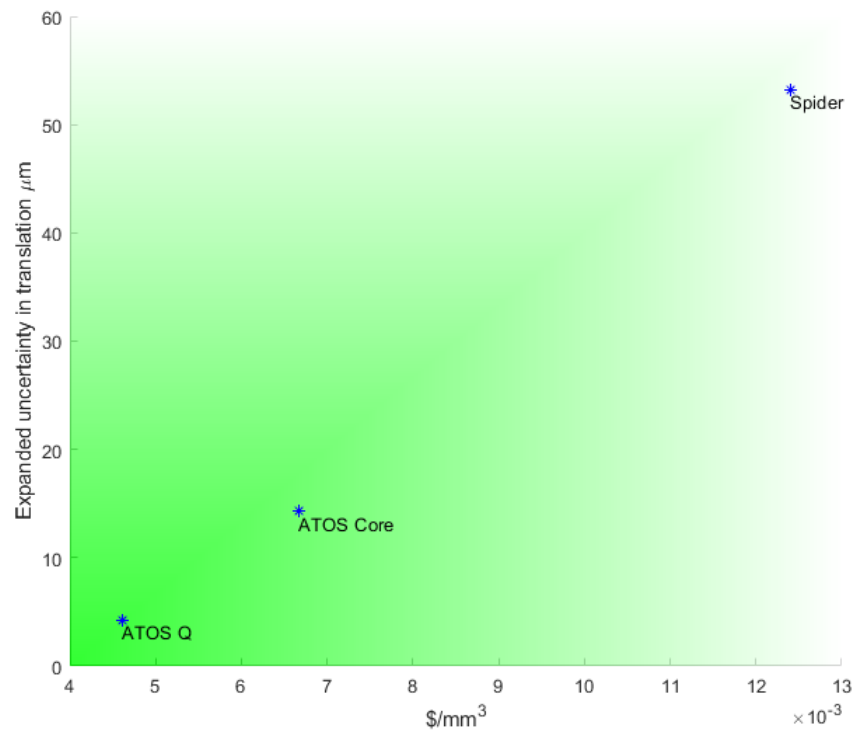


Figure 3.14: Cost normalized to scan volume vs translational uncertainty.

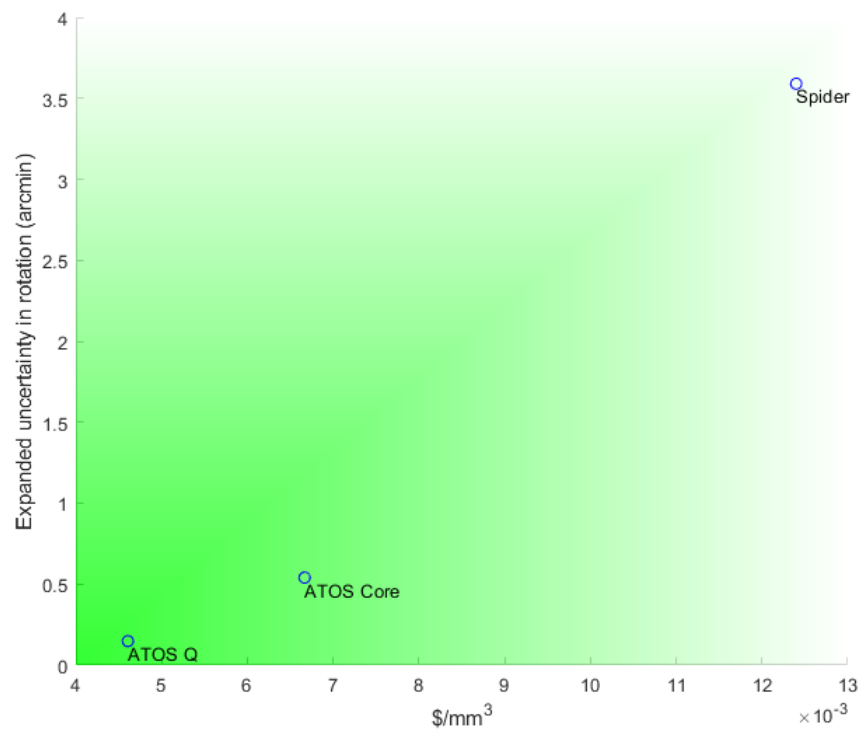


Figure 3.15: Cost normalized to scan volume vs rotational uncertainty.

results are from experimental tests reported in Section [3.4](#). The summary shows that all results fell under the manufacturer provided minimum point distance, suggesting that the minimum point distance provided may generally be a conservative estimate of performance.

Table 3.4: Summary of key results across all OCM systems tested. NP represents values not provided from manufacturer. Results are average results for optimal sphere pair. Expanded uncertainties are from experimental tests.

OCM system	Minimum point distance (μm)	Length measurement error (μm)	Sphere spacing error (μm)	Probing error size (μm)	Probing error form (μm)	σ_{AR} (μm)	U_δ (μm)	U_ϵ (arcmin)
GOM ATOS Q	40	-10.6	-0.937	-7.50	2.00	2.57	4.27	0.148
GOM ATOS Core 200	80	13.9	9.10	0.293	1.84	2.41	14.3	0.540
Artec Spider	100	63.6	23.8	64.3	11.5	14.7	53.2	3.59
iPhone 15 Pro Max	NP	-1440	-617	790	1470	1880	7890	95.5

Chapter 4

Case studies

4.1 Wire arc additive manufacturing with structured light scanning process uncertainty contributors

A case study was performed of sequential hybrid manufacturing including WAAM and structured light scanning, where machining would serve as the secondary SHM step but was not included. This study provided validation for uncertainty contributors quantified in this work, as well as insight into uncertainty contributions from the WAAM process.

Five 25.4 mm by 101.6 mm by 101.6 mm aluminum walls were printed on 203.2 mm by 203.2 mm by 6.35 mm tight tolerance (± 0.05 mm in all directions) precision ground aluminum build plates via WAAM with a Fronius TPS 4000 mounted to a KUKA KR 50 R2500; see Figure 4.1. These parts were printed sequentially with identical print parameters, part setups, and print coordinate systems. The ground build plates were placed in a repeatable location on the WAAM print table by means of minimum constraint fixturing. Each plate was aligned with three rounded locators and plates were clamped on top in identical locations with the same torque; see

Figure 4.2. One of the walls several layers into a print is shown in Figure 4.3. These efforts enable conclusions to be drawn about WAAM print uncertainty and OCM uncertainty.

Similar locating brackets and hold down clamps were mounted to a 304.8 mm x 304.8 mm x 12.7 mm precision ground aluminum CMM grade fixture plate (0.127 mm parallel tolerance, half inch spacing of 1/4-20 threaded holes); see Figure 4.4. Three 25.4 mm diameter 52100 alloy steel fiducial spheres with a $\pm 2.54 \mu\text{m}$ tolerance were mounted to the fixture plate to enable coordinate system definition. Scanning targets were attached to the fixture plate. The plate was temporarily covered while the fiducial spheres were sprayed with titanium dioxide using the airbrush system. This fixture plate setup allowed for repeatable positioning of the printed components for scanning.

A total of 14 scans were performed using the GOM ATOS Q; see Figure 4.5. Prior to these scans the sensor was calibrated. Prior to mounting to the fixture plate, the prints/ground plates were sprayed with titanium dioxide using the airbrush system. The first five scans were of a ground plate with no WAAM deposition. This enabled comparisons of the sphere center-based coordinate system and a coordinate system defined by planes fit to the ground plate. Additionally, this enabled comparison of the plate with and without deposition relative to the sphere center-based coordinate system. The next five scans were of a single mounted printed wall without removal or refixturing. This enabled insight into uncertainty of fit CAD position and translation for the same wall from five different scans, and, therefore, uncertainty associated with the scanner. An additional four scans were performed with each of the remaining four printed walls. This enabled insight into variation between the five printed walls and, therefore, the WAAM print process.

Four coordinate systems are defined and referenced. The first is defined by the three sphere centers in an identical way discussed in Section 2.4; see Figure 4.6. The second is defined by three faces of the ground build plate: the top of the plate, the front of the plate, and the left side; see Figure 4.7. Best fit geometries that define

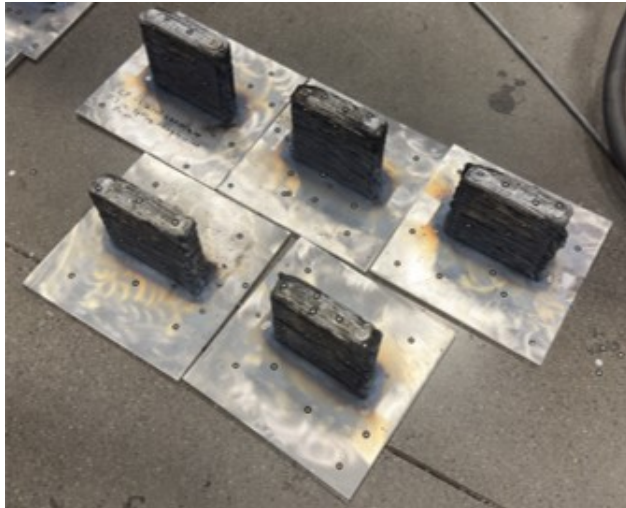


Figure 4.1: Five WAAM printed walls on ground baseplates.

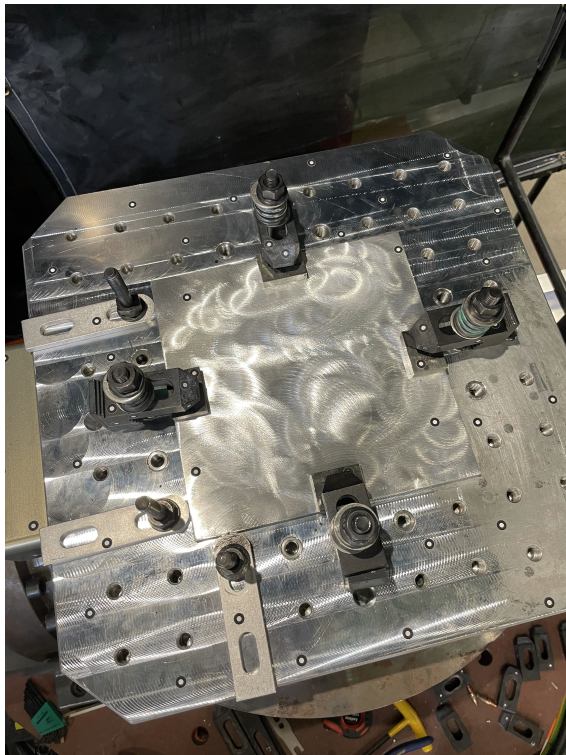


Figure 4.2: Setup for WAAM wall prints.



Figure 4.3: WAAM wall print several layers into the print.

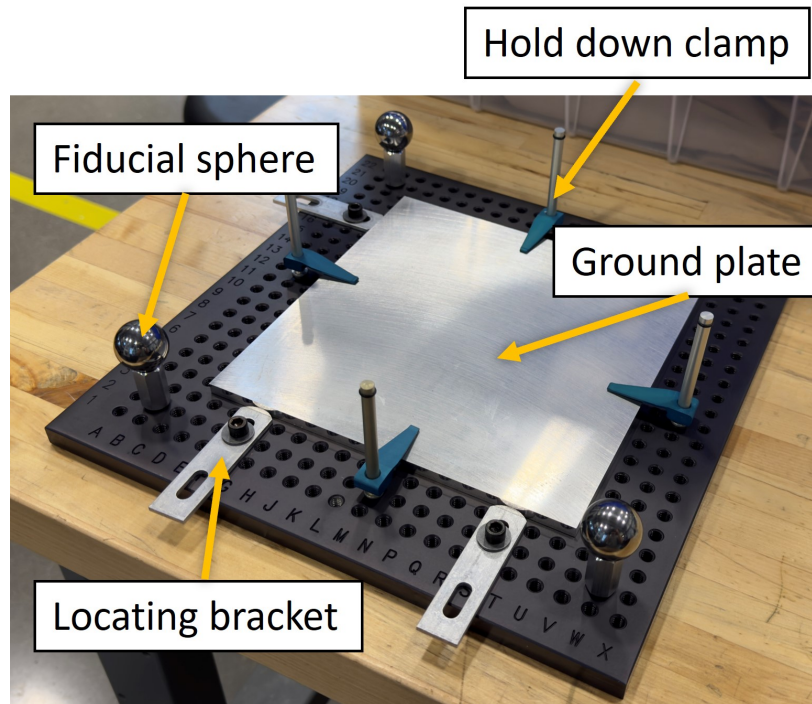


Figure 4.4: Locating brackets, hold down clamps, ground plate, and fiducial spheres mounted to fixture plate.

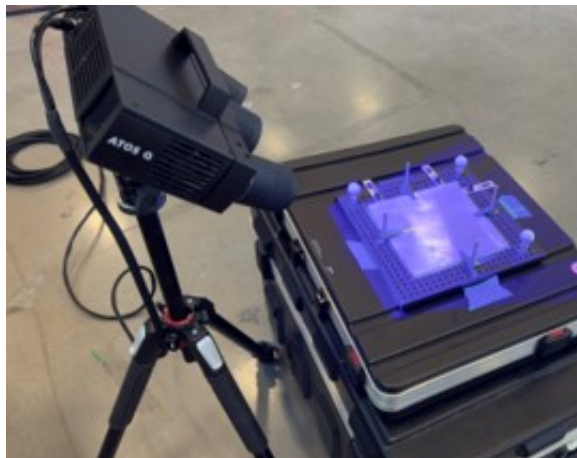


Figure 4.5: Scanning of fixture plate with ground plate mounted with ATOS Q.

coordinate system one and two are shown in Figure 4.8. The third coordinate system, the global coordinate system, was arbitrarily defined by scanning targets found in GOM Inspect; see Figure 4.9. This global coordinate system was consistent across all scans in this case study by setting the first scan as the master, and all subsequent scans as dependent. This instructs GOM Inspect to locate the same targets applied in the first scan and use the same global measurement coordinate system. The fourth and final coordinate system was defined using the top, front, and left side of the nominal CAD geometry; see Figure 4.10. CAD was best fit in all scans (except scans of the ground plate only) with a maximum search distance of 10 mm. Results show deviations in translations and rotations between these coordinate systems, and an analysis of the contribution of each to the overall uncertainty is provided.

First, results investigating the fit spheres are provided. Plots are sorted by results for the three spheres for scans involving just the ground plate, a single wall, and all five walls. Mean adjustment residual sigma results directly reported from fit spheres in GOM Inspect for all spheres are shown in Figure 4.11. The results show adjustment residual sigma to be in the range of 3 μm to 4.5 μm . In Section 3 performance tests adjustment residual sigma was found to be approximately 2.6 μm . The higher result in adjustment residual sigma is likely due to the fact that the scan was not centered about the spheres, resulting in lower quality points captured for the spheres.

The combined standard uncertainty results of the sphere center positions in X, Y, and Z are shown in Figure 4.12. In Section 3 sphere center combined standard uncertainty, u_{sc} was found to be approximately 2.2 μm . These results are noticeably higher. Similar to adjustment residual sigma results, this is attributed to scans being centered about the part and not the spheres. Additionally, it is observed that combined standard uncertainty is higher for both the single print and five print data sets, likely due to scan view blockage from the printed wall itself, removal and replacing of the walls on the fixture, and additional time between each scan.

The expanded uncertainty (coverage factor, $k = 2$) for deviation in translation and rotation between the sphere CS and base plate CS are shown in Figures 4.13 and

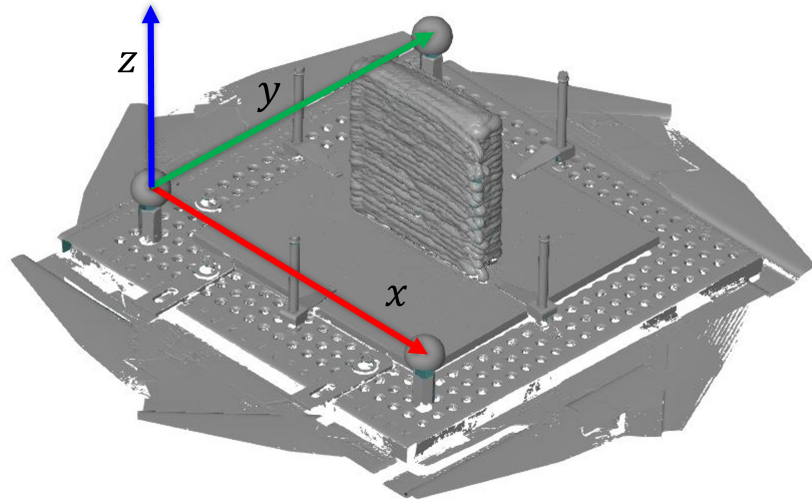


Figure 4.6: Coordinate system defined by three sphere centers mounted to plate.

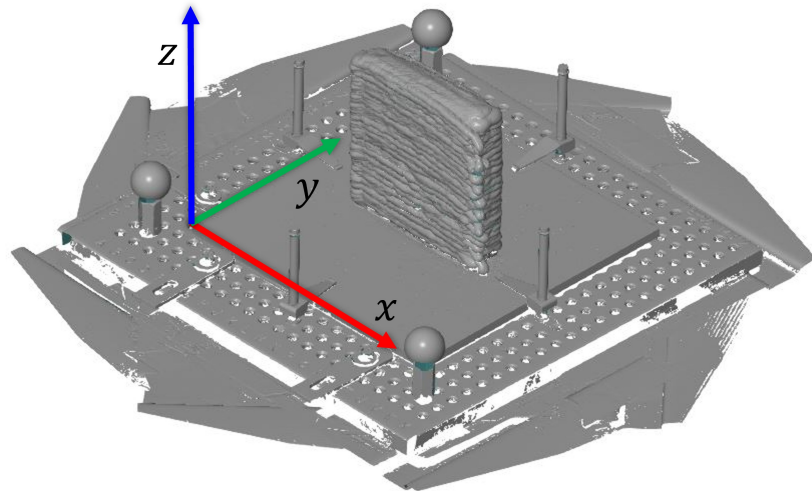


Figure 4.7: Coordinate system defined by top, front, and left side of ground plate.

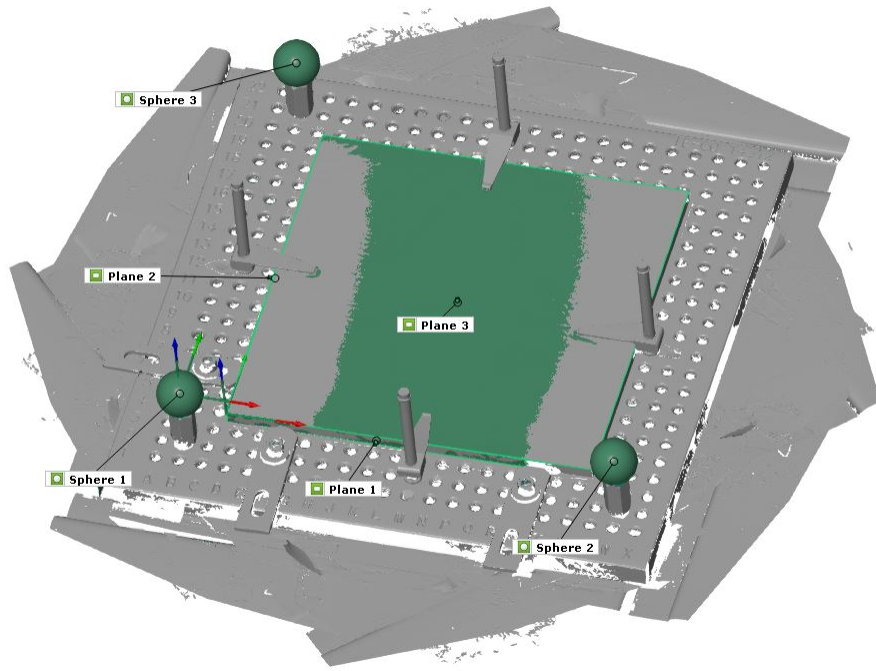


Figure 4.8: Fit geometries that define sphere and plate based coordinate systems.

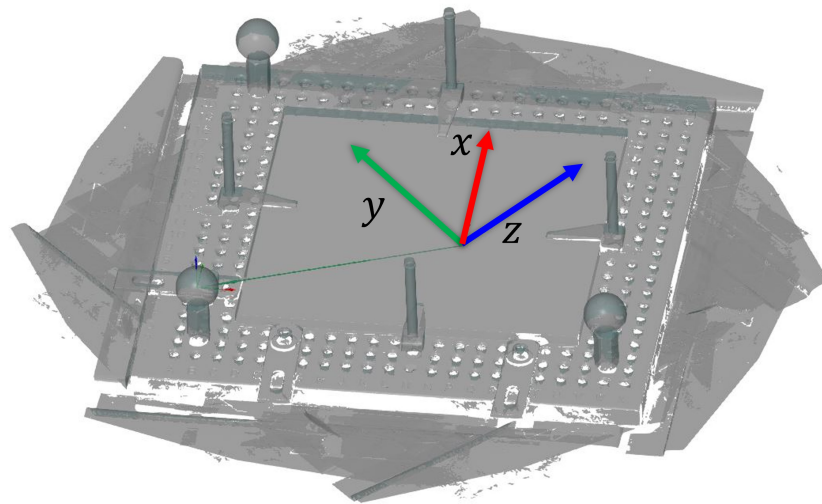


Figure 4.9: Arbitrary global coordinate system.

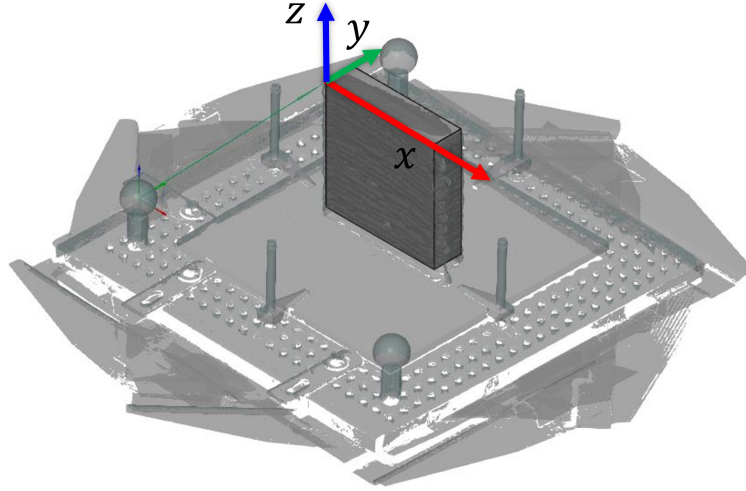


Figure 4.10: Coordinate system defined by front, top, and left sides of nominal CAD geometry.

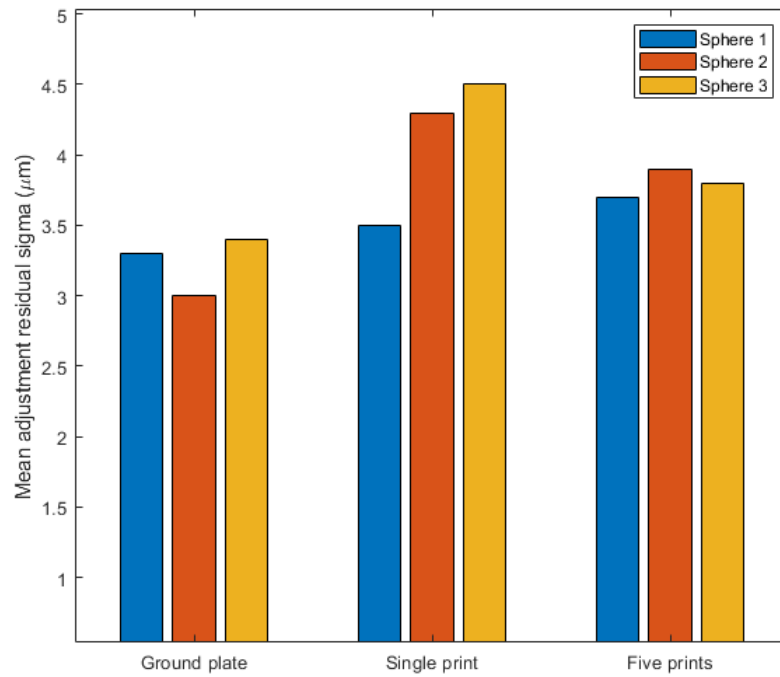


Figure 4.11: Adjustment residual sigma results for all spheres.

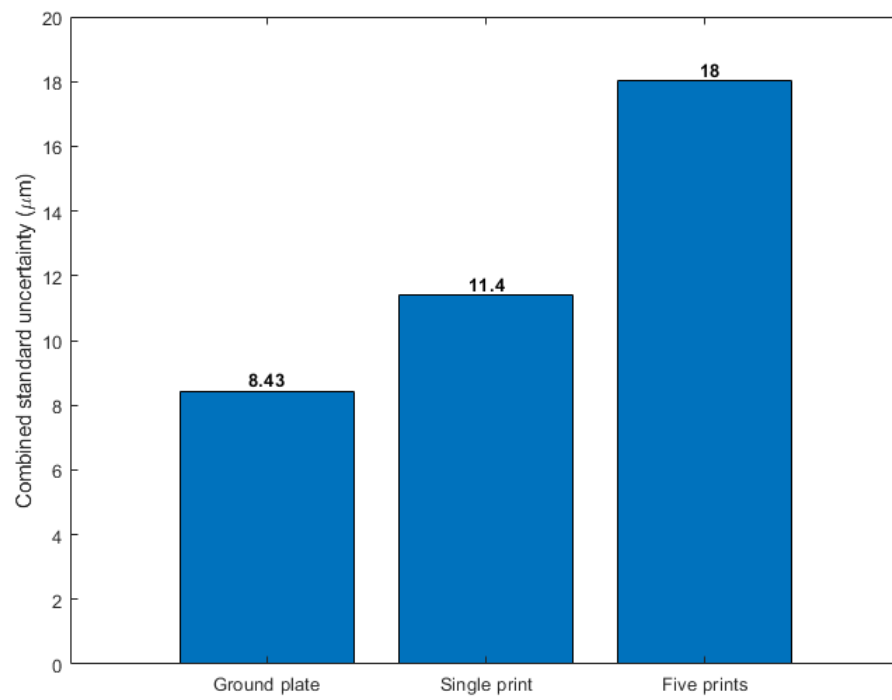


Figure 4.12: Sphere center combined standard uncertainty results.

4.14. An additional column is included for results from the Monte Carlo simulation using the three nominal sphere center positions and the adjustment residual sigma value of $2.6 \mu\text{m}$ found in performance tests in Section 3. Results for the five prints are notably higher than others due to variations in warpage of the build plate from the WAAM process. However, results for the ground plate show good agreement with the simulation results. This further validates the Monte Carlo simulation. It is also observed that the uncertainty is higher for the single print scans. This is due to the additional uncertainty associated with best fits of planes to a warped build plate, as opposed to the build plate with no deposition and associated distortion.

The expanded uncertainty for deviation in translation and rotation between the sphere CS and best fit CAD CS are shown in Figures 4.15 and 4.16. These provide insight into the uncertainty of rotation and position of the best fit CAD across repeat measurements and repeat WAAM prints. The results show that even for repeat best fits from repeat measurements of the same WAAM wall, the expanded uncertainties are an order of magnitude higher in rotation and two orders of magnitude higher in translation compared to the sphere CS to base plate CS and simulation. This indicates that the uncertainty associated with the WAAM process is one to two orders of magnitude higher than uncertainty associated with the ATOS Q. An increase in uncertainty between the single print and five print results is also seen. This demonstrates the uncertainty associated with the WAAM process in overall print size and orientation. The Monte Carlo simulation also reports overbuild required due to OCM system uncertainty for this case study at approximately $10 \mu\text{m}$; this is orders of magnitude less than associated uncertainties in the WAAM process.

4.2 Secondary hybrid manufacturing studies

Three secondary case studies are described in detail in Appendix B. These case studies were performed prior to full development of this dissertation and the primary case study described in Section 4.1. They served as demonstrations of sequential hybrid

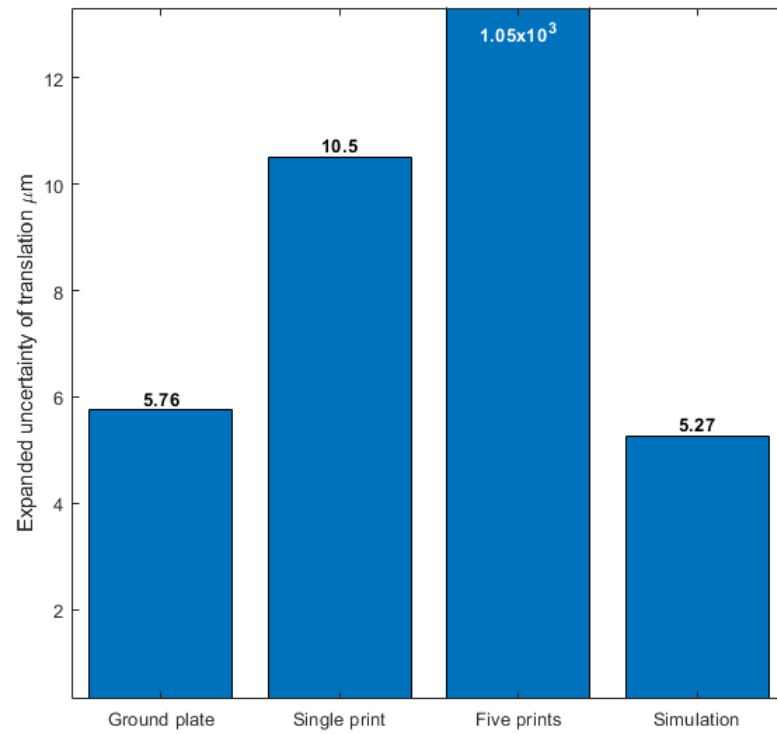


Figure 4.13: Expanded uncertainty of deviation in translation between sphere and base plate CS.

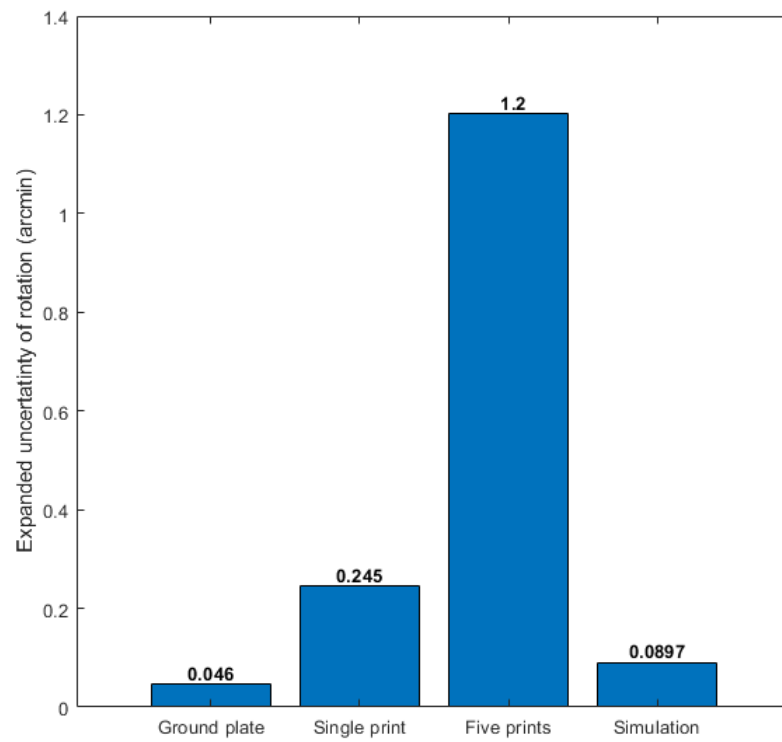


Figure 4.14: Expanded uncertainty of deviation in rotation between sphere and base plate CS.

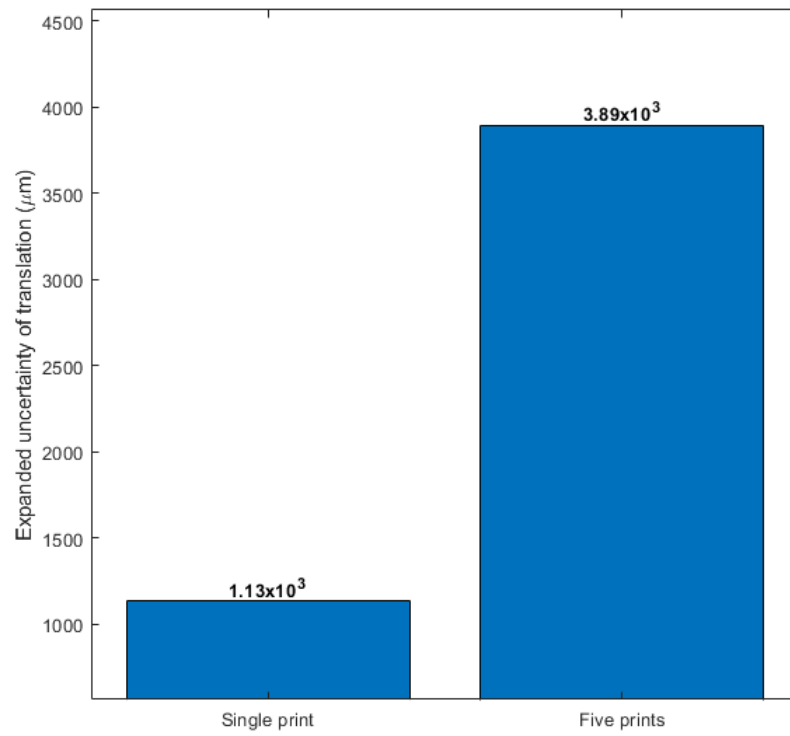


Figure 4.15: Expanded uncertainty of deviation in translation between sphere and fit CAD CS.

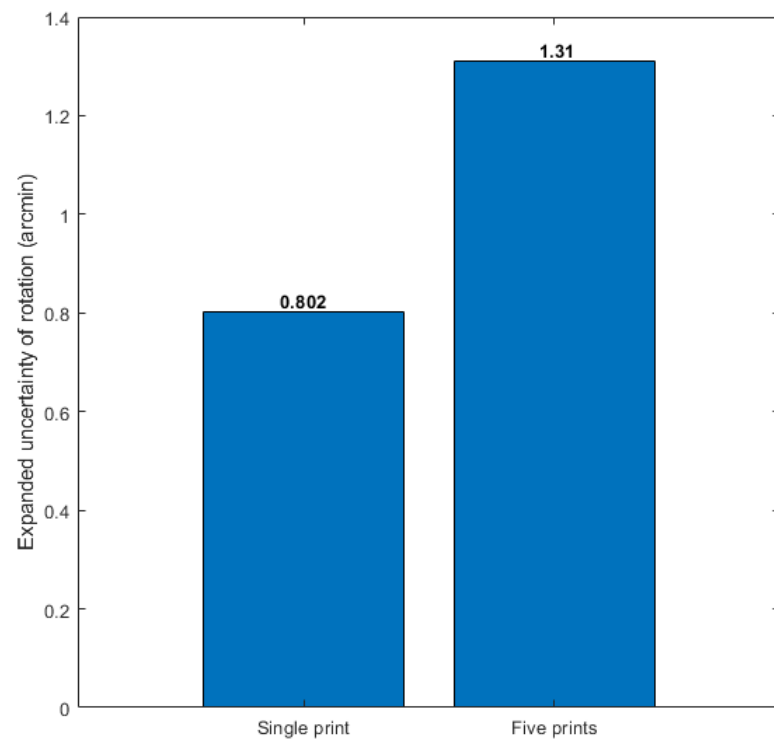


Figure 4.16: Expanded uncertainty of deviation in rotation between sphere and fit CAD CS.

manufacturing with various additive manufacturing methods and different research foci. Secondary case study [B.1](#), wire arc additive manufacturing with a digital twin focus, explored how attaching fiducials to an AM build plate post printing, structured light scanning, preform tool tip frequency response function measurements, and post machining measurements can provide a digital twin for hybrid manufacturing [\[20\]](#). Secondary case study [B.2](#), binder jet additive manufacturing with a freeform optics focus, demonstrated a hybrid manufacturing process chain for green preform infiltration, stock model identification, and machining for a freeform surface on a binder jet silicon carbide preform [\[21\]](#). Secondary case study [B.3](#), carbon-bonded carbon fiber (CBCF) with a manufacturability focus, tested geometric results for various CBCF infiltration methods against a neat sample in machining. All of these case studies were deemed successful in meeting the designer’s intent using SHM. These case studies served as demonstrations of various SHM process chains, fiducials, and OCM, but did not directly validate OCM for SHM due to the focus on other, but related, research objectives.

Chapter 5

Conclusions

Hybrid manufacturing has been demonstrated to provide a viable option for traditional manufacturing solutions that face global supply chain challenges. While hybrid processes on a single machine tool are becoming readily available, research and discussion on how to use different machine tools sequentially is still required and is defined here as sequential hybrid manufacturing. This work represents a major step forward in validation and adoption of sequential hybrid manufacturing by means of Monte Carlo simulations and experimental validations of coordinate system translational and rotational uncertainties, evaluation of fiducial sphere center positional uncertainties using optical coordinate metrology systems, and case studies with various types of additive manufacturing preforms.

New contributions to the fields of manufacturing and metrology are introduced. Statements here are made based on the literature review provided in Section [1.1](#). Previously, no literature has fully evaluated uncertainty of sequential hybrid manufacturing.

To summarize, the new contributions provided in this work are:

- A formal definition of sequential hybrid manufacturing
- Performance evaluations of low to high cost OCM systems that adhere to the latest VDI/VDE standards

- A sphere center positional uncertainty evaluation for OCM
- The resulting coordinate system positional and rotational uncertainty (based on three sphere centers) used for manufacturing coordinate system definition, transfer, and acquisition
- A Monte Carlo simulation that evaluates coordinate system positional and rotation uncertainty given sphere center positional uncertainty for a selected OCM system with a coordinate system defined by three sphere centers
- A Monte Carlo simulation that estimates the required increase in preform size, or overbuild, to account for measurement uncertainty introduced by the OCM system in sequential hybrid manufacturing, while still fully containing the desired CAD model for the secondary manufacturing process, such as machining
- A wire arc additive manufacturing case study that explores relevant uncertainty contributors for sequential hybrid manufacturing
- Secondary case studies that explore the unique benefits and feasibility of sequential hybrid manufacturing, including digital twins and preform infiltration
- A significant step towards automation and traceability of sequential hybrid manufacturing using additive manufacturing and OCM

5.1 Future work

Several areas are of interest for future work. These include performance evaluation of additional OCM system, adapting the work to apply to fit plane based coordinate systems, expanding the types of additive preforms tested and testing of castings as a preform.

Since this dissertation represents a framework for evaluating performance of an OCM system it is straightforward to evaluate performance for additional systems.

There are additional sensors readily available that are of interest, and will be added to performance, uncertainty, and cost results.

Another area of interest is alternatives to sphere-based coordinate system identification, such as plane-based coordinate systems. Preliminary research and literature review showed that precision spheres were optimal, convenient, and readily available for the efforts in this work. However, other artifacts, such as gauge blocks or 123 blocks, could also serve as a fiducial for sequential hybrid manufacturing. Research can be performed to determine how the associated uncertainty compared to the sphere center-based coordinate system identification.

It is also of interest to test additional types of additive manufacturing preforms, and other preforms altogether, such as castings or forgings. The framework proposed in this work applies universally to hybrid manufacturing applying any primary and secondary process with a metrology step in between.

Bibliography

- [1] B. Lauwers, F. Klocke, A. Klink, A. E. Tekkaya, R. Neugebauer, and D. McIntosh, “Hybrid processes in manufacturing,” *CIRP annals*, vol. 63, no. 2, pp. 561–583, 2014. [1](#), [3](#)
- [2] S. Webster, H. Lin, F. Carter, K. Ehmann, and J. Cao, “Physical mechanisms in hybrid additive manufacturing: A process design framework,” *Journal of Materials Processing Technology*, p. 117048, 2021. [1](#), [2](#)
- [3] I. Gibson, D. W. Rosen, B. Stucker, M. Khorasani, D. Rosen, B. Stucker, and M. Khorasani, *Additive Manufacturing Technologies*. Springer, 2021, vol. 17. [1](#), [2](#), [3](#)
- [4] KA. Lorenz, JB. Jones, DI. Wimpenny, and MR. Jackson, “A review of hybrid manufacturing,” in *2014 International Solid Freeform Fabrication Symposium*. University of Texas at Austin, 2015. [2](#)
- [5] W. Grzesik and A. Ruszaj, *Hybrid Manufacturing Processes*. Springer, 2021. [2](#)
- [6] W.-S. Chu, C.-S. Kim, H.-T. Lee, J.-O. Choi, J.-I. Park, J.-H. Song, K.-H. Jang, and S.-H. Ahn, “Hybrid manufacturing in micro/nano scale: A review,” *International journal of precision engineering and manufacturing-green technology*, vol. 1, no. 1, pp. 75–92, 2014. [2](#)
- [7] M. L. Dezaki, A. Serjouei, A. Zolfagharian, M. Fotouhi, M. Moradi, MKA. Ariffin, and M. Bodaghi, “A review on additive/subtractive hybrid

- manufacturing of directed energy deposition (DED) process,” *Advanced Powder Materials*, vol. 1, no. 4, p. 100054, 2022. [2](#)
- [8] J. M. Flynn, A. Shokrani, S. T. Newman, and V. Dhokia, “Hybrid additive and subtractive machine tools—Research and industrial developments,” *International Journal of Machine Tools and Manufacture*, vol. 101, pp. 79–101, 2016. [2](#)
- [9] B. Liu, H. Shen, R. Deng, S. Li, S. Tang, J. Fu, and Y. Wang, “Research on a planning method for switching moments in hybrid manufacturing processes,” *Journal of Manufacturing Processes*, vol. 56, pp. 786–795, 2020. [2](#)
- [10] G. Manogharan, R. Wysk, O. Harrysson, and R. Aman, “AIMS—a metal additive-hybrid manufacturing system: System architecture and attributes,” *Procedia Manufacturing*, vol. 1, pp. 273–286, 2015. [2](#)
- [11] Z. Zhu, V. G. Dhokia, A. Nassehi, and S. T. Newman, “A review of hybrid manufacturing processes—state of the art and future perspectives,” *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 7, pp. 596–615, 2013. [2](#)
- [12] R. Ramesh, MA. Mannan, and AN. Poo, “Error compensation in machine tools—a review: Part I: Geometric, cutting-force induced and fixture-dependent errors,” *International Journal of Machine Tools and Manufacture*, vol. 40, no. 9, pp. 1235–1256, 2000. [4](#)
- [13] D. Jafari, T. H. Vaneker, and I. Gibson, “Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts,” *Materials & Design*, vol. 202, p. 109471, 2021. [4](#)
- [14] B. Schleich, N. Anwer, L. Mathieu, and S. Wartzack, “Skin model shapes: A new paradigm shift for geometric variations modelling in mechanical engineering,” *Computer-Aided Design*, vol. 50, pp. 1–15, 2014. [4](#)

- [15] S. Jamiolahmadi and A. Barari, “Study of detailed deviation zone considering coordinate metrology uncertainty,” *Measurement*, vol. 126, pp. 433–457, 2018. [4](#), [8](#)
- [16] J. Xu, N. Xi, C. Zhang, Q. Shi, and J. Gregory, “Real-time 3D shape inspection system of automotive parts based on structured light pattern,” *Optics & Laser Technology*, vol. 43, no. 1, pp. 1–8, 2011. [5](#)
- [17] S. Catalucci, N. Senin, D. Sims-Waterhouse, S. Ziegelmeier, S. Piano, and R. Leach, “Measurement of complex freeform additively manufactured parts by structured light and photogrammetry,” *Measurement*, vol. 164, p. 108081, 2020. [5](#)
- [18] S. Catalucci, A. Thompson, S. Piano, D. T. Branson III, and R. Leach, “Optical metrology for digital manufacturing: A review,” *The International Journal of Advanced Manufacturing Technology*, vol. 120, no. 7-8, pp. 4271–4290, 2022. [5](#)
- [19] A. Cornelius, J. Dvorak, L. Jacobs, J. Penney, and T. Schmitz, “Combination of structured light scanning and external fiducials for coordinate system transfer in hybrid manufacturing,” *Journal of Manufacturing Processes*, vol. 68, pp. 1824–1836, 2021. [5](#)
- [20] J. Dvorak, A. Cornelius, G. Corson, R. Zameroski, L. Jacobs, J. Penney, and T. Schmitz, “A machining digital twin for hybrid manufacturing,” *Manufacturing Letters*, vol. 33, pp. 786–793, 2022. [5](#), [83](#), [101](#)
- [21] J. Dvorak, D. Gilmer, R. Zameroski, A. Cornelius, and T. Schmitz, “Freeform hybrid manufacturing: Binderjet, structured light scanning, confocal microscopy, and CNC machining,” *Journal of Manufacturing and Materials Processing*, vol. 7, no. 2, p. 79, 2023. [5](#), [83](#), [105](#), [106](#)

- [22] Y. Zhao, Y. Cheng, Q. Xu, Z. Luo, X. Wang, and H. Li, “Uncertainty modeling and evaluation of profile measurement by structured light scanner,” *Measurement Science and Technology*, vol. 33, no. 9, p. 095018, 2022. [5](#), [6](#), [8](#), [12](#)
- [23] R. Mendricky, “Determination of measurement accuracy of optical 3D scanners,” *MM Science Journal*, vol. 2016, no. 6, pp. 1565–1572, 2016. [5](#), [20](#), [22](#)
- [24] J. Boehm, “Accuracy investigation for structured-light based consumer 3D sensors,” *Photogrammetrie-Fernerkundung-Geoinformation*, vol. 2014, no. 2, pp. 117–127, 2014. [5](#)
- [25] F. Dickin, S. Pollard, and G. Adams, “Mapping and correcting the distortion of 3D structured light scanners,” *Precision Engineering*, vol. 72, pp. 543–555, 2021. [5](#)
- [26] E. R. Eiriksson, J. Wilm, D. B. Pedersen, and H. Aanæs, “Precision and accuracy parameters in structured light 3-D scanning,” *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 5, p. W8, 2016. [7](#)
- [27] “ISO 10360-13:2021 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 13: Optical 3D CMS,” Sep. 2021. [7](#)
- [28] “VDI/VDE 2634 Part 3: Optical 3D-measuring systems - Multiple view systems based on area scanning.” [7](#)
- [29] D. M. Fabris, P. Brambilla, C. Conese, M. M. Maspes, R. Sala, and M. Tarabini, “METROLOGICAL CHARACTERIZATION OF OPTICAL 3D COORDINATE MEASUREMENT SYSTEMS—COMPARISON OF ALTERNATIVE HARDWARE DESIGNS AS PER ISO 10360,” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 48, pp. 39–43, 2022. [7](#)

- [30] R. Leach, *Advances in Optical Form and Coordinate Metrology*. IOP Publishing, 2020. [7](#)
- [31] J. Jcgm *et al.*, “Evaluation of measurement data—guide to the expression of uncertainty in measurement,” *Int. Organ. Stand. Geneva ISBN*, vol. 50, p. 134, 2008. [7](#)
- [32] R. Leach and S. T. Smith, *Basics of Precision Engineering*. CRC Press, 2018. [7](#), [8](#)
- [33] B. N. Taylor, C. E. Kuyatt *et al.*, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. US Department of Commerce, Technology Administration, National Institute of . . . , 1994, vol. 1297. [7](#)
- [34] S. Li, Z. Wang, J. Guan, and J. Wang, “Uncertainty Evaluation in Surface Structured Light Measurement,” in *2021 IEEE 15th International Conference on Electronic Measurement & Instruments (ICEMI)*. IEEE, 2021, pp. 395–400. [8](#)
- [35] M.-E. Polo and Á. M. Felicísimo, “Analysis of uncertainty and repeatability of a low-cost 3d laser scanner,” *Sensors*, vol. 12, no. 7, pp. 9046–9054, 2012. [8](#)
- [36] M.-E. Polo, A. Cuartero, and Á. M. Felicísimo, “Study of uncertainty and repeatability in structured-light 3D scanners,” *arXiv preprint arXiv:1910.13199*, 2019. [8](#)
- [37] Z. Zhang, “Determining the epipolar geometry and its uncertainty: A review,” *International journal of computer vision*, vol. 27, pp. 161–195, 1998. [8](#)
- [38] J. M. Calkins, “Quantifying coordinate uncertainty fields in coupled spatial measurement systems,” Ph.D. dissertation, Virginia Polytechnic Institute and State University, 2002. [8](#)

- [39] S. Jain, A. D. Allen, and B. Zhang, “Evaluation of the spatial frequency response and the uncertainty for a commercial structured light system,” in *Applied Optical Metrology III*, vol. 11102. SPIE, 2019, pp. 226–237. [8](#)
- [40] D. Sims-Waterhouse, M. Isa, S. Piano, and R. Leach, “Uncertainty model for a traceable stereo-photogrammetry system,” *Precision Engineering*, vol. 63, pp. 1–9, 2020. [8](#)
- [41] G. Gayton, R. Su, and R. Leach, “Modelling fringe projection based on linear systems theory and geometric transformation,” in *THE 14th INTERNATIONAL SYMPOSIUM OF MEASUREMENT TECHNOLOGY AND INTELLIGENT INSTRUMENTS*, 2019. [8](#)
- [42] G. Gayton, M. Isa, R. Su, and R. Leach, “Evaluating and propagating uncertainty in digital fringe projection systems,” in *Optical Measurement Systems for Industrial Inspection XII*, vol. 11782. SPIE, 2021, pp. 302–316. [9](#)
- [43] G. Gayton, M. Isa, and R. K. Leach, “Evaluating parametric uncertainty using non-linear regression in fringe projection,” *Optics and Lasers in Engineering*, vol. 162, p. 107377, 2023. [9](#)
- [44] Z. Yan, B.-D. Yang, and C.-H. Menq, “Uncertainty analysis and variation reduction of three dimensional coordinate metrology. part 1: geometric error decomposition,” *International Journal of Machine Tools and Manufacture*, vol. 39, no. 8, pp. 1199–1217, 1999. [9](#)
- [45] Z. Yan and C.-H. Menq, “Uncertainty analysis and variation reduction of three-dimensional coordinate metrology. part 2: uncertainty analysis,” *International Journal of Machine Tools and Manufacture*, vol. 39, no. 8, pp. 1219–1238, 1999. [9](#)

- [46] Z. Yan and C.-H. Menq, “Uncertainty analysis and variation reduction of three dimensional coordinate metrology. part 3: variation reduction,” *International Journal of Machine Tools and Manufacture*, vol. 39, no. 8, pp. 1239–1261, 1999. [9](#)
- [47] C. Che and J. Ni, “A generic coordinate transformation uncertainty assessment approach and its application in machine vision metrology,” *International Journal of Machine Tools and Manufacture*, vol. 38, no. 10-11, pp. 1241–1256, 1998. [9](#)
- [48] Y. Ren, J. Lin, J. Zhu, B. Sun, and S. Ye, “Coordinate transformation uncertainty analysis in large-scale metrology,” *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 9, pp. 2380–2388, 2015. [9](#)
- [49] S. Smith, BA. Woody, and JA. Miller, “Improving the accuracy of large scale monolithic parts using fiducials,” *CIRP annals*, vol. 54, no. 1, pp. 483–486, 2005. [9](#)
- [50] M. Brunelle, J. Yuan, K. Medicus, and J. D. Nelson, “Importance of fiducials on freeform optics,” in *Optifab 2015*, vol. 9633. SPIE, 2015, pp. 325–332. [9](#)
- [51] S. Wang, C. Cheung, M. Ren, and M. Liu, “Fiducial-aided on-machine positioning method for precision manufacturing of optical freeform surfaces,” *Optics express*, vol. 26, no. 15, pp. 18 928–18 943, 2018. [9](#)
- [52] E. Olson, “Apriltag: A robust and flexible visual fiducial system,” in *2011 IEEE international conference on robotics and automation*. IEEE, 2011, pp. 3400–3407. [9](#)
- [53] S. Wang, B. Cheung, and M. Ren, “Uncertainty analysis of a fiducial-aided calibration and positioning system for precision manufacturing of optical freeform optics,” *Measurement Science and Technology*, vol. 31, no. 6, p. 065012, 2020. [9](#)
- [54] H. Srinivasan, O. L. Harrysson, and R. A. Wysk, “Automatic part localization in a CNC machine coordinate system by means of 3D scans,” *The International*

- Journal of Advanced Manufacturing Technology*, vol. 81, no. 5, pp. 1127–1138, 2015. [9](#)
- [55] B. A. Woody, K. Scott Smith, R. J. Hocken, and J. A. Miller, “A technique for enhancing machine tool accuracy by transferring the metrology reference from the machine tool to the workpiece,” 2007. [10](#)
- [56] B. A. Woody, K. S. Smith, R. J. Hocken, and J. A. Miller, “Uncertainty Analysis for the Fiducial Calibration System,” in *ASME International Mechanical Engineering Congress and Exposition*, vol. 42231, 2005, pp. 699–706. [10](#)
- [57] Y. Shen and N. Duffie, “An uncertainty analysis method for coordinate referencing in manufacturing systems,” 1995. [10](#)
- [58] J.-P. Loose, S. Zhou, and D. Ceglarek, “Kinematic analysis of dimensional variation propagation for multistage machining processes with general fixture layouts,” *IEEE Transactions on Automation Science and Engineering*, vol. 4, no. 2, pp. 141–152, 2007. [10](#)
- [59] K. G. Ahn and D. W. Cho, “An analysis of the volumetric error uncertainty of a three-axis machine tool by beta distribution,” *International journal of Machine tools and Manufacture*, vol. 40, no. 15, pp. 2235–2248, 2000. [10](#)
- [60] L. Andolfatto, J. Mayer, and S. Lavernhe, “Adaptive monte carlo applied to uncertainty estimation in five axis machine tool link errors identification with thermal disturbance,” *International Journal of Machine Tools and Manufacture*, vol. 51, no. 7-8, pp. 618–627, 2011. [10](#)
- [61] G. Kortaberria, U. Mutilba, S. Gomez, and B. Ahmed, “Three-dimensional point cloud task-specific uncertainty assessment based on iso 15530-3 and iso 15530-4 technical specifications and model-based definition strategy,” *Metrology*, vol. 2, no. 4, pp. 394–413, 2022. [10](#)

- [62] Q. Zhuang, N. Wan, Y. Guo, Z. Chang, and Z. Wang, “Uncertainty propagation and assessment of five-axis on-machine measurement error,” *Journal of Manufacturing Science and Engineering*, vol. 144, no. 10, p. 101004, 2022. [10](#)
- [63] “Process Description: GOM Acceptance Test with reference to the Guideline VDI/VDE 2634 Part 3,” Apr. 2019. [23](#)
- [64] T. L. Schmitz and K. S. Smith, *Machining Dynamics*. Springer, 2014. [102](#), [106](#)
- [65] HS. Kim and TL. Schmitz, “Bivariate uncertainty analysis for impact testing,” *Measurement Science and Technology*, vol. 18, no. 11, p. 3565, 2007. [106](#)

Appendices

Appendix A

PSA400 Artifact Calibration Reports

A.1 GOM provided calibration certificate

A calibration report for the PSA400 artifact was provided by GOM upon delivery of the artifact. This report was performed by Perschmann Calibration. See Figures [A.1-A.3](#) for pages 1-3 of the report.

A.2 Sphere center measurements

To enable coordinate system variation experimental work discussed in Section [2.5](#) sphere centers (XYZ) positions were measured in house using a Zeiss Duramax CMM. These measurements were performed at 23.8°C. These XYZ positions were relative to an arbitrarily defined coordinate system in the rear top left of the artifact. This CS

Calibration certificate no. P-7501126



Carl Zeiss GOM Metrology GmbH Customer No. : 22512
 Order No. : 6968130
 Schmitzstraße 2
 D-38122 Braunschweig

Page (1/3)

Ident. number : PSA/400/P0407 **Date of calibration** : 2023-08-17
Designation : GOM Probing/Spacing Artefact **inspection cycle** : -
Serial number : PSA/400/P0407
Size : 16mm - 320mm
Manufacturer : GOM
Model/type : PSA/400
Note : as found = as left
Calibration-result : **Actual size determination without evaluation**

Test directive : VDI/VDE/DGQ 2618 Sheet 19.1 Ü (11.2014)
 Visual inspection : Functional

The coefficient of linear expansion mounting plate : $4 \cdot 10^{-6} / K$

The coefficient of linear expansion steel spheres : $10,5 \cdot 10^{-6} / K$

Sphere L1	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	6,0000		6,0003		0,0003	1,1	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$								
Sphere R1	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	6,0000		6,0003		0,0003	1,1	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
16_L1-R1	16,0000		16,0177		0,0177	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L2	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	8,0000		8,0013		0,0013	1,1	PM 1980	
Form	0,0000		0,0006		0,0006	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R2	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	8,0000		8,0008		0,0008	1,1	PM 1980	
Form	0,0000		0,0004		0,0004	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
26_L2-R2	26,0000		25,9906		-0,0094	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L3	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	10,0000		10,0024		0,0024	1,1	PM 1980	
Form	0,0000		0,0012		0,0012	1,1	PM 1980	
$U(k=2) = 1,1 \mu m + 1,5 \cdot l \cdot 10^{-6}$; l is the length								

Perschmann Calibration GmbH
 Hauptstraße 46 d
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 Tel.: +49 5307 933-200
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Auditiertes QM-System
 gemäß:
 DIN EN ISO 9001
 DIN EN ISO/IEC 17025

QM-Dokumentation aktuell:
 www.perschmann-calibration/downloads.html



Ein Service von **Perschmann Calibration**

Figure A.1: Calibration report for PSA400 artifact used in this work, page 1 of 3.

Calibration certificate no. **P-7501126**



Ident. number : PSA/400/P0407
Designation : GOM Probing/Spacing Artefact

Page (2/3)

Sphere R3	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	10,0000		10,0038		0,0038	1,1	PM 1980	
Form	0,0000		0,0006		0,0006	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
40_L3-R3	40,0000		40,0290		0,0290	1,2	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L4	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	12,0000		12,0021		0,0021	1,1	PM 1980	
Form	0,0000		0,0006		0,0006	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R4	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	12,0000		12,0020		0,0020	1,1	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
55_L4-R4	55,0000		54,9854		-0,0146	1,2	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L5	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	15,0000		15,0013		0,0013	1,1	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R5	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	15,0000		14,9996		-0,0004	1,1	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
80_L5-R5	80,0000		80,0289		0,0289	1,2	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L6	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	20,0000		20,0046		0,0046	1,1	PM 1980	
Form	0,0000		0,0056		0,0056	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R6	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	20,0000		20,0020		0,0020	1,1	PM 1980	
Form	0,0000		0,0008		0,0008	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
115_L6-R6	115,0000		114,9955		-0,0045	1,3	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								

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Auditiertes QM-System
gemäß:
DIN EN ISO 9001
DIN EN ISO/IEC 17025

QM-Dokumentation aktuell:
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calibration/downloads.html



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Figure A.2: Calibration report for PSA400 artifact used in this work, page 2 of 3.

Calibration certificate no. **P-7501126**



Ident. number : PSA/400/P0407
Designation : GOM Probing/Spacing Artefact

Page (3/3)

Sphere L7	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	25,0000		25,0009		0,0009	1,1	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R7	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	25,0000		25,0005		0,0005	1,1	PM 1980	
Form	0,0000		0,0009		0,0009	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
160_L7-R7	160,0000		160,0000		0,0000	1,3	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L8	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	30,0000		30,0012		0,0012	1,1	PM 1980	
Form	0,0000		0,0026		0,0026	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R8	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	30,0000		30,0014		0,0014	1,1	PM 1980	
Form	0,0000		0,0008		0,0008	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
230_L8-R8	230,0000		230,0037		0,0037	1,4	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere L9	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	40,0000		40,0002		0,0002	1,2	PM 1980	
Form	0,0000		0,0007		0,0007	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
Sphere R9	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
Ø	40,0000		39,9986		-0,0014	1,2	PM 1980	
Form	0,0000		0,0008		0,0008	1,1	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								
distance of sphere centers	Setpoint (mm)	Min. (mm)	Actual (mm)	Max. (mm)	Dev. (mm)	+/- U (µm)	Standard	Meas. point pos.
320_L9-R9	320,0000		320,0445		0,0445	1,6	PM 1980	
$U(k=2) = 1,1 \mu\text{m} + 1,5 \cdot l \cdot 10^{-6}$; l is the length								

Traceability
No. Standard 1 PM 1980
Designation Coordinate measuring machine Leitz/Hexagon Reference Ultra
Traceability WO-00319017 2023-03
Ambient conditions place of calibration: Laboratory Hauptstraße 46d 38110 Braunschweig
Temperature: 20,3 °C
Person in charge
Alexander Gaus

The calibration is implemented - by comparison with reference standards and reference-standard measuring devices which are referred back to national standards for the representation of the physical units in agreement with the International System of Units (SI) - through Perschmann Calibration GmbH Labor Hauptstraße 46d 38110 Braunschweig. Decision rule P-WKai-17025-01 according to general agreement. Measured values within the limit values are evaluated as operational, measured values in the limit value area expanded by the measurement uncertainty $U(k=2)$ receive the evaluation operable with restrictions. The user decides whether it can be used. The expanded measurement uncertainty is given, which results from the standard measurement uncertainty by multiplying it by the coverage factor $k=2$. It was determined according to EA-4/02 M. The value of the measured variable lies with a probability of almost 95% in the assigned value range. A portion for the long-term instability of the calibration item is not included.

End of Calibration Certificate

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gemäß:
DIN EN ISO 9001
DIN EN ISO/IEC 17025

QM-Dokumentation aktuell:
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Figure A.3: Calibration report for PSA400 artifact used in this work, page 3 of 3.

can be arbitrary since all further work is relative distances between sphere defined coordinate systems. Sets four through nine were measured; see Table [A.1](#).

Table A.1: Sphere center (XYZ) CMM measurement results.

Sphere	X (mm)	Y (mm)	Z (mm)
L4	172.6086	-65.9504	3.6136
R4	227.5932	-65.9395	3.6078
L5	160.1047	-27.9449	4.5343
R5	240.1340	-27.9712	4.5423
L6	142.6048	-54.9459	6.1264
R6	257.6026	-54.9448	6.0963
L7	120.1136	-22.9389	7.6631
R7	280.1144	-22.9320	7.6222
L8	85.1107	-54.9361	9.2192
R8	315.1145	-54.9289	9.1501
L9	40.0903	-29.9212	12.2801
R9	360.1342	-29.9133	12.1794

Appendix B

Secondary hybrid manufacturing case studies

B.1 Wire arc additive manufacturing with a digital twin focus

This initial case study tested and outline pieces of a digital twin for SHM using WAAM, attached fiducials, and structured light scanning and is detailed in the published paper, A machining digital twin for hybrid manufacturing [20]. A 101.6 mm by 101.6 mm by 12.7 mm steel wall was printed on a 203.2 mm by 203.2 mm by 25.4 mm baseplate using WAAM. A structured light scan was completed to measure the printed wall and baseplate using a GOM ATOS Q scanner. To enable this scanning, a custom external fiducial apparatus was designed and printed using fused filament fabrication (FFF). This external fiducial apparatus housed dodecahedrons with scanner targets for the scanner to maintain tracking between scans. It also housed three satin spheres used for coordinate system definition. The bottom of the build plate defined the Z axis, fixing two rotational degrees of freedom. The line between the centers of the first and second spheres defined the X axis, fixing the final rotational degree of freedom. The center of the spheres were found using GOM

Inspect software, and used to define the coordinate system shown in Figure B.1. The scan file was then oriented to have this coordinate system as its origin. CAD of the wall and baseplate was aligned within the scan using a best fit algorithm within GOM Inspect and also oriented to the sphere center-based coordinate system. The CAD and scan were then exported in model file format to be used in computer aided manufacturing (CAM) software (Fusion 360).

An endmill was selected for machining and optimum milling parameters were found using tap testing. Both the wall (preform), and tool were tap tested. Tap testing enables measurement of a structure's response by attaching an accelerometer to the structure and hitting it with a modal hammer that measures impact force. A stability map was calculated based on a frequency-domain stability analysis that incorporates the tool tip frequency response function and force model [?]. The scan was set as a stock model for machining and the aligned CAD as the desired final model. Toolpaths were then generated based on the calculated stability maps and geometry of the scan. A coordinate rotation was performed to precisely align toolpaths by rotating toolpaths about the Z axis using built in HAAS functionality (G68 command). A Euclidian distance in the XY plane was calculated using:

$$d_{xy} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (\text{B.1})$$

where x_1 , x_2 , y_1 , and y_2 are XY positions of spheres one and two in the machine coordinate system. The angle of rotation, θ , was calculated using:

$$\theta = \cos^{-1}\left(\frac{x_2 - x_1}{d_{xy}}\right) \quad (\text{B.2})$$

Note that sphere one was set as the work coordinate system (WCS) origin and θ rotates about the WCS origin.

During machining audio of the machining sound was recorded to check for stable machining. A fast Fourier transform of steady state machining was performed

to ensure that frequency content occurred at the tooth passing frequency, integer multiples of the tooth passing frequency, or runout frequencies. After machining, the part was again scanned for comparison to intended geometry. GOM Inspect was used to generate a surface deviation map and surface roughness of the final part was compared to a theoretical expected average roughness value calculated from machining parameters. Dynamics of the final part were compared to theory by tap testing a grid of points on the wall to determine its first mode shape and corresponding natural frequency. The final machined part is shown in Figure B.2.

The following conclusions are made: In this work, multiple facets of a machining digital twin for hybrid manufacturing were shown. Temporary fiducials were attached to a WAAM preform and scanned using structured light to define a local coordinate system and CAM stock model. The scan represents a digital twin for the AM geometry and enabled the part to be located in the machine tool using standard probing cycles. The WAAM preform and tool were tap tested to generate a stability map for the machining process, which enabled milling parameter selection, including axial and radial depths of cut, spindle speed, and feed per tooth. The measurement data and models provided a digital twin for the process performance; this information augments the geometry-based CAM description with a physics-based approach for parameter selection. Audio data was recorded during machining and surface profilometry was completed post-machining to validate the absence of chatter and desired surface finish. This data provides a digital twin for the milling process that can be used to distinguish between stable and unstable (chatter) conditions for later reference. A structured light scan of the final part was completed to compare to the CAD model, surface finish measurements were performed, and dynamic testing was performed to identify the vibration response. These geometry, surface finish, and structural dynamics data give the digital twin for the part performance and agreement (or disagreement) with the design intent. The proposed machining digital twin methodology is deemed successful in accurately modeling the machining process and outcome.

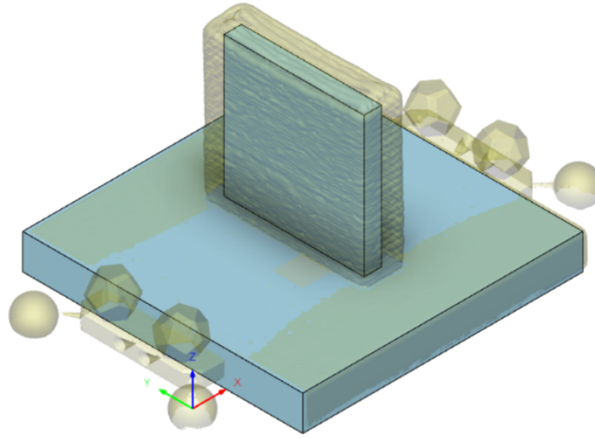


Figure B.1: CAD to scan alignment and defined coordinate system.

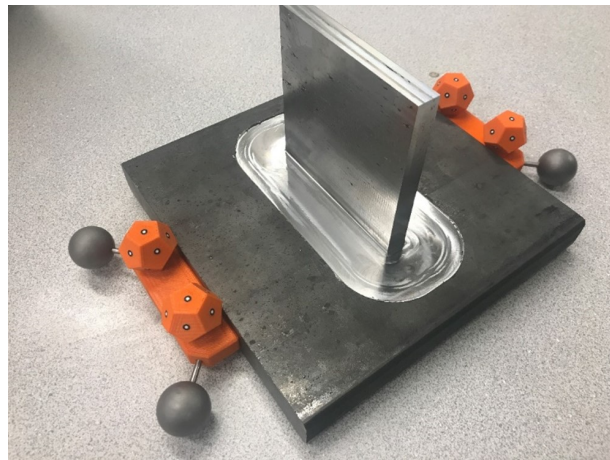


Figure B.2: Final machined wall.

B.2 Binder jet additive manufacturing with a freeform optics focus

This case study focused on freeform geometries for optics applications. These efforts have been published and titled, “Freeform Hybrid Manufacturing: Binderjet, Structured Light Scanning, Confocal Microscopy, and CNC Machining” [21]. An silicon carbide (SiC) preform with a toroidal freeform surface was fabricated using BJAM and then infiltrated with cyanoacrylate. This enabled the handling and machining of the green state preform. Structured light scanning was performed on the preform mounted in the vise. A coordinate system was defined using ground surfaces of the vise as fiducials. This coordinate system was then located in the milling machine using the on-machine probe and probing routines after the vise was mounted to the machine table. This method overcomes inherent hybrid manufacturing challenges by accurately aligning the digital design with the AM preform scan model. The structured light scan and coordinate system also enable toolpath generation and simulation.

A surface was modeled using a toroidal freeform and was printed using an Innovent binder jet printer from ExOne Company, North Huntingdon, PA, USA; see Figure B.3. The sample was infiltrated with approximately 75 mL of thin 5 cP cyanoacrylate to enable handling and reduce fragility; see right panel of Figure B.3. The sample was clamped in a 101.6 mm wide vise; see Figure B.4. A structured light scan of the preform was completed using a GOM ATOS Core 200 (ZEISS, Oberkochen, Baden-Württemberg, Germany) to establish the work coordinate system and enable stock model generation after applying 1.5 mm scanner targets directly onto the vise. Prior to scanning, AESUB (Recklinghausen, Nordrhein-Westfalen, Germany) Blue scanning spray was applied only to the vise surfaces to reduce reflectivity and improve scan quality. GOM Inspect (ZEISS, Oberkochen, Baden-Württemberg, Germany) was used to perform a best fit of the CAD to the scan as shown in Figure B.5. A maximum search distance of 0.2 mm resulted in an average deviation of 63 μm . The WCS was

defined by fitting three planes to three ground surfaces of the vise using a Gaussian best fit and 99.7% of the points from the scanned point cloud. The adjustment results for these three fitting planes showed a standard deviation of $\{19.9, 11.3, \text{ and } 7.3\}$ μm .

A Haas OM2 (Haas Automation, Inc., Oxnard, CA, USA) three-axis CNC machining center and a ball end mill were used for preform machining. The tool's dynamic response was measured by tap testing in the machine X and Y directions to ensure these parameters would result in a stable cut [?, ?]. It was found that the limiting cutting depth was larger than the desired 1 mm by a significant amount, so machining stability was not a limitation for this work. This is a primary motivation for machining prior to traditional BJAM SiC densification. Afterwards, the SiC is much harder and difficult to machine.

A parallel finishing operation was selected that maintained parallel passes in the XY plane and followed the surface in the Z direction. The scan enabled a full simulation of the programmed toolpaths; see Figure B.6. The vise with the preform still clamped was bolted to the Haas OM2 machine table and manually aligned to the machine X and Y axes using a dial indicator. This manual alignment effectively replaced the need for the coordinate rotation in Appendix B.1, as the WCS is physically aligned to the machine coordinate system. The machined SiC sample is shown in Figure B.7. Additional efforts in this work measured the surface finish, surface roughness, and geometry of the machined part. See article for full details [21].

Based on this work the following conclusions were made:

- Hybrid manufacturing of freeform surfaces on BJAM SiC samples using structured light scanning for stock model generation and WCS definition and traditional three-axis milling is possible, although final part accuracy requires additional study.
- The workpiece clamping system (a vise in this case) can provide fiducials for WCS definition and alignment in a machine tool. The strategy includes both the

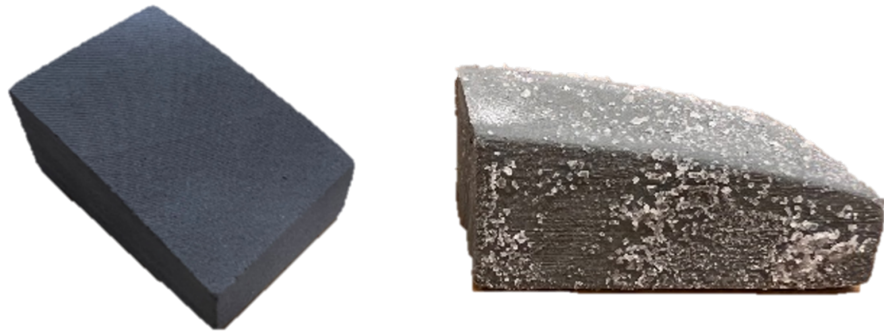


Figure B.3: Silicon carbide sample as printed (**left**) and after cyanoacrylate infiltration (**right**).

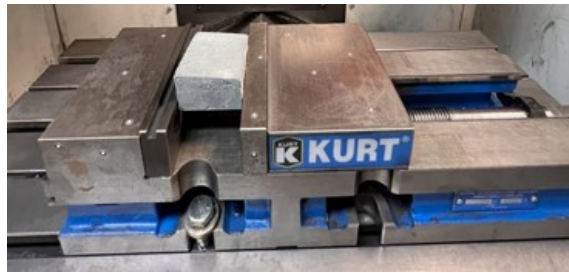


Figure B.4: Infiltrated sample clamped in milling machine vise on machine table.

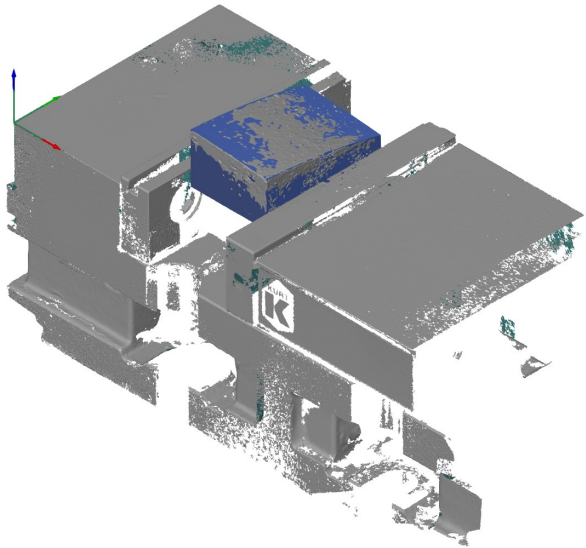


Figure B.5: CAD aligned to scan of preform with WCS defined.

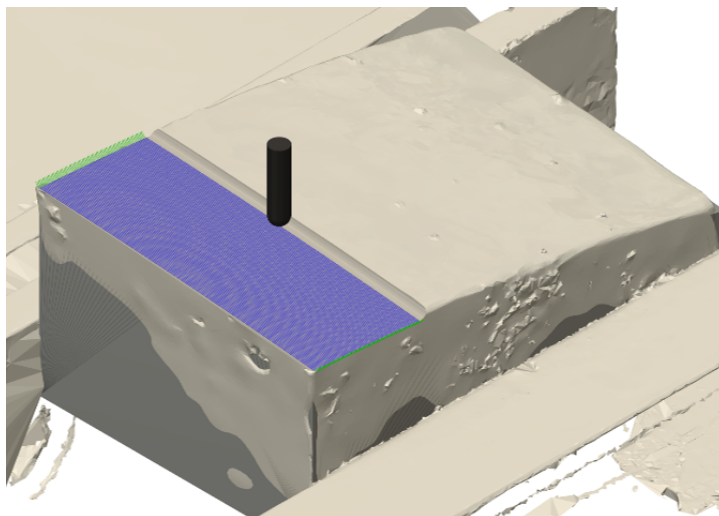


Figure B.6: CAM simulation using the scan as the stock model.



Figure B.7: Machined BJAM SiC sample.

clamping system and part in the structured light scan to enable the coordinate system to be established independently of the part design.

- The ball end milling of a BJAM SiC sample infiltrated with cyanoacrylate was not able to properly remove layer lines from the surface resulting in poor surface finish.
- The surface finish of the machined BJAM SiC sample was worse than a FFF ABS sample machined using the same parameters and toolpaths. Smaller particles or further post-processing may be required for hybrid manufacturing of SiC samples depending on the application.
- Infiltration of BJAM SiC samples can impact machining results. In this work, it is proposed that cyanoacrylate curing time can affect the final geometry of the preform.

B.3 Carbon-bonded carbon fiber with a manufacturability focus

This work, titled, Milling infiltrated carbon-bonded carbon fiber: Geometric attributed, surface characteristics, and feasibility, explored hybrid manufacturing of CBCF. Comparison and feasibility of milled parts with differing infiltration methods was of interest. The methodology used a similar technique as case study [B.2](#) where the vise served as the fiducial for hybrid manufacturing with structured light scanning.

Two methods of infiltration, cyanoacrylate, and paraffin wax were compared to a neat (non-infiltrated) sample. These three samples of CBCF were glued to aluminum bar stock and clamped in a vise. Scanning targets were added to the vise. The vise and clamped samples were scanned with a GOM ATOS Q and three ground surfaces of the vise served as fiducials for WCS definition and transfer; see Figure [B.8](#). This scan was used to align CAD within the scan and define toolpaths; see Figure [B.9](#).

Ultimately, the three samples were successfully machined in a single program; see Figure B.10. Full details of surface roughness and geometric error can be found in a soon to be published article of the same name. Based on this work the following conclusions were made:

- Infiltration of CBCF with cyanoacrylate or paraffin wax improves its machinability by creating chips, rather than dust, during material removal similar to ductile metal machining.
- Infiltration of CBCF with cyanoacrylate or paraffin wax improves its machinability by densifying the workpiece and reducing the risk of damage during handling.
- Machined wax and cyanoacrylate-infiltrated CBCF samples exhibited more accurate geometry (diameter) compared to a neat CBCF sample.
- Wax-infiltrated CBCF resulted in superior surface finish over a neat sample or cyanoacrylate-infiltrated sample.
- The vise, which serves as the workpiece clamping system, can provide reference points for defining and aligning the WCS within a machine tool. This is achieved by including both the clamping system and the part in the structured light scan. This enables the WCS to be defined independently from the part geometry.

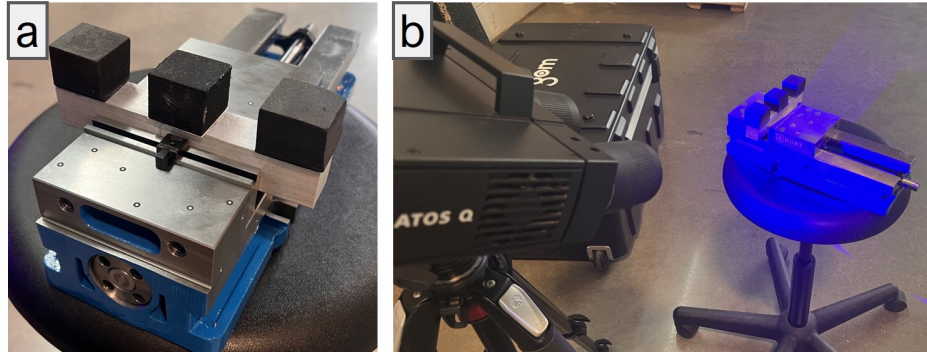


Figure B.8: (a) CBCF preforms mounted to aluminum stock in vise, (b) structured light scanning.

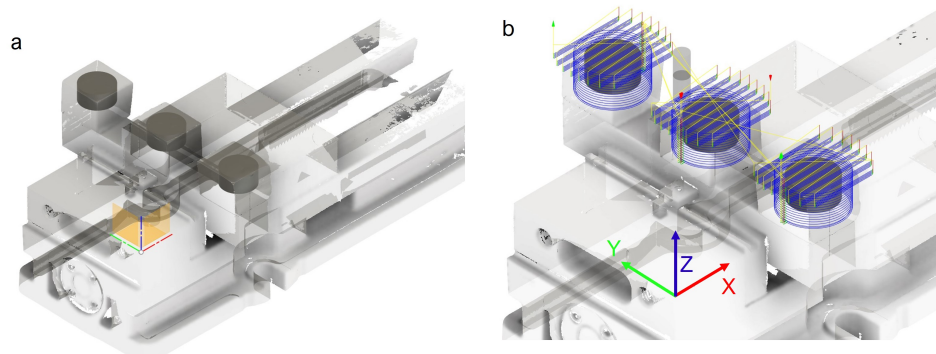


Figure B.9: (a) alignment of CAD within scan, (b) toolpaths defined for machining.

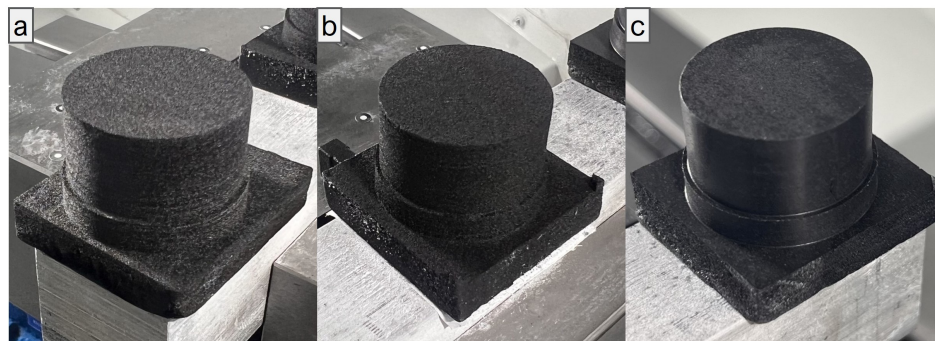


Figure B.10: Machined CBCF samples.

Appendix C

MATLAB Scripts

C.1 Performance evaluation

Contents

- Process manual PSA measurements from CSV files
- Data from GOM Inspect
- Various inputs
- Core
- Q
- iPhone
- Artec Spider
- Compare scanners to one another
- Functions

Process manual PSA measurements from CSV files

```
clear all
close all
clc
beep off
```

Data from GOM Inspect

```
load("importedPerformanceData.mat")
```

Various inputs

```
k = 2; % 95.45% coverage for expanded uncertainty
```

```
% Measurement temperatures
```

```
q_temp = 22.8; % deg C
```

```
i_temp = 21.0;
```

```
c_temp = 22.7;
```

```
s_temp = (21.7+23.3)/2;
```

```
dia = [6 8 10 12 15 20 25 30 40]; %mm, nominal
```

Core

```
% Plot core results
```

```
figure
```

```
subplot(4,1,1)
```

```
plot(dia(1:8),c_results_set1(:,1)*1e3,'-x')
```

```
hold on
```

```
plot(dia(1:8),c_results_set2(:,1)*1e3,'-x')
```

```
plot(dia(1:8),c_results_set3(:,1)*1e3,'-x')
```

```
xline(20,'-.', 'HandleVisibility','off')
```

```
legend('Set 1','Set 2','Set 3')
```

```

% xlabel('Sphere diameter')
ylabel('Length measurement error ( $\mu$ m)')
%title('Core: Length measurement error')
xticks(dia)
xlim([4,44])

subplot(4,1,2)
plot(dia(1:8),c_results_set1(:,2)*1e3,'-x')
hold on
plot(dia(1:8),c_results_set2(:,2)*1e3,'-x')
plot(dia(1:8),c_results_set3(:,2)*1e3,'-x')
xline(20,'-.','Optimal','HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
% xlabel('Sphere diameter')
ylabel('Sphere spacing error ( $\mu$ m)')
%title('Core: Sphere spacing error')
xticks(dia)
xlim([4,44])

subplot(4,1,3)
plot(dia(1:8),c_results_set1(:,3)*1e3,'-x')
hold on
plot(dia(1:8),c_results_set2(:,3)*1e3,'-x')
plot(dia(1:8),c_results_set3(:,3)*1e3,'-x')
plot(dia(1:8),c_results_set1(:,4)*1e3,'-x')
plot(dia(1:8),c_results_set2(:,4)*1e3,'-x')
plot(dia(1:8),c_results_set3(:,4)*1e3,'-x')
xline(20,'-.','HandleVisibility','off');
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')

```



```

% xlabel('Sphere diameter')
ylabel('Probing error size ( $\mu$ m)')
%title('Core: Probing error size')
xticks(dia)
xlim([4,44])

subplot(4,1,4)
errorbar(dia(1:8),c_results_set1(:,5)*1e3,c_results_set1(:,9)*1e3,'x')
hold on
errorbar(dia(1:8),c_results_set2(:,5)*1e3,c_results_set2(:,9)*1e3,'x')
errorbar(dia(1:8),c_results_set3(:,5)*1e3,c_results_set3(:,9)*1e3,'x')
errorbar(dia(1:8),c_results_set1(:,6)*1e3,c_results_set1(:,10)*1e3,'x')
errorbar(dia(1:8),c_results_set2(:,6)*1e3,c_results_set2(:,10)*1e3,'x')
errorbar(dia(1:8),c_results_set3(:,6)*1e3,c_results_set3(:,10)*1e3,'x')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R',...
'Optimal Pair')
xline(20,'-.','HandleVisibility','off')
xlabel('Sphere diameter ( $\mu$ m)')
ylabel('Probing error form ( $\mu$ m)')
%title('Core: Probing error form (adjustment residual)')
xticks(dia)
xlim([4,44])
ylim([-1.5 11])

```

Q

```

% Plot ATOS Q results
figure

```

```

subplot(4,1,1)
plot(dia(1:9),q_results_set1(:,1)*1e3,'-x')
hold on
plot(dia(1:9),q_results_set2(:,1)*1e3,'-x')
plot(dia(1:9),q_results_set3(:,1)*1e3,'-x')
xline(30,'-.','HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
ylabel('Length measurement error ( $\mu\text{m}$ )')
%title('ATOS Q: Length measurement error')
xticks(dia)
xlim([4,44])
ylim([-30 5])

```

```

subplot(4,1,2)
plot(dia(1:9),q_results_set1(:,2)*1e3,'-x')
hold on
plot(dia(1:9),q_results_set2(:,2)*1e3,'-x')
plot(dia(1:9),q_results_set3(:,2)*1e3,'-x')
xline(30,'-.','HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
ylabel('Sphere spacing error ( $\mu\text{m}$ )')
%title('ATOS Q: Sphere spacing error')
xticks(dia)
xlim([4,44])
ylim([-3 6])

```

```

subplot(4,1,3)
plot(dia(1:9),q_results_set1(:,3)*1e3,'-x')
hold on

```

```

plot(dia(1:9),q_results_set2(:,3)*1e3,'-x')
plot(dia(1:9),q_results_set3(:,3)*1e3,'-x')
plot(dia(1:9),q_results_set1(:,4)*1e3,'-x')
plot(dia(1:9),q_results_set2(:,4)*1e3,'-x')
plot(dia(1:9),q_results_set3(:,4)*1e3,'-x')
xline(30,'-.', 'Optimal', 'HandleVisibility','off')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')
ylabel('Probing error size ( $\mu\text{m}$ )')
%title('ATOS Q: Probing error size')
xticks(dia)
xlim([4,44])
ylim([-25 2])

subplot(4,1,4)
errorbar(dia(1:9),q_results_set1(:,5)*1e3,q_results_set1(:,9)*1e3,'-x')
hold on
errorbar(dia(1:9),q_results_set2(:,5)*1e3,q_results_set2(:,9)*1e3,'-x')
errorbar(dia(1:9),q_results_set3(:,5)*1e3,q_results_set3(:,9)*1e3,'-x')
errorbar(dia(1:9),q_results_set1(:,6)*1e3,q_results_set1(:,10)*1e3,'-x')
errorbar(dia(1:9),q_results_set2(:,6)*1e3,q_results_set2(:,10)*1e3,'-x')
errorbar(dia(1:9),q_results_set3(:,6)*1e3,q_results_set3(:,10)*1e3,'-x')
xline(30,'-.', 'HandleVisibility','off')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')
xlabel('Sphere diameter ( $\mu\text{m}$ )')
ylabel('Probing error form ( $\mu\text{m}$ )')
% title('ATOS Q: Probing error form (adjustment residual)')
xticks(dia)
xlim([4,44])

```

iPhone

```
% Plot iPhone results

figure
subplot(4,1,1)
plot(dia(5:9),i_results_set1(:,1),'-x')
hold on
plot(dia(7:9),i_results_set2(:,1),'-x')
plot(dia(5:9),i_results_set3(:,1),'-x')
xline(30,'-.','HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
ylabel('Length measurement error (mm)')
%title('iPhone: Length measurement error')
xticks(dia)
xlim([4,44])

subplot(4,1,2)
plot(dia(5:9),i_results_set1(:,2),'-x')
hold on
plot(dia(7:9),i_results_set2(:,2),'-x')
plot(dia(5:9),i_results_set3(:,2),'-x')
xline(30,'-.','HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
ylabel('Sphere spacing error (mm)')
%title('iPhone: Sphere spacing error')
xticks(dia)
xlim([4,44])

subplot(4,1,3)
```

```

plot(dia(5:9),i_results_set1(:,3),'-x')
hold on
plot(dia(7:9),i_results_set2(:,3),'-x')
plot(dia(5:9),i_results_set3(:,3),'-x')
plot(dia(5:9),i_results_set1(:,4),'-x')
plot(dia(7:9),i_results_set2(:,4),'-x')
plot(dia(5:9),i_results_set3(:,4),'-x')
xline(30,'-.','Optimal','HandleVisibility','off')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')
ylabel('Probing error size (mm)')
%title('iPhone: Probing error size')
xticks(dia)
xlim([4,44])
ylim([-3 7])

subplot(4,1,4)
errorbar(dia(5:9),i_results_set1(:,5),i_results_set1(:,9),'-x')
hold on
errorbar(dia(7:9),i_results_set2(:,5),i_results_set2(:,9),'-x')
errorbar(dia(5:9),i_results_set3(:,5),i_results_set3(:,9),'-x')
errorbar(dia(5:9),i_results_set1(:,6),i_results_set1(:,10),'-x')
errorbar(dia(7:9),i_results_set2(:,6),i_results_set2(:,10),'-x')
errorbar(dia(5:9),i_results_set3(:,6),i_results_set3(:,10),'-x')
xline(30,'-.','HandleVisibility','off')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')
xlabel('Sphere diameter ( $\mu$ m)')
ylabel('Probing error form (mm)')
%title('iPhone: Probing error form (adjustment residual)')
xticks(dia)

```

```
xlim([4,44])
```

Artec Spider

```
% Plot spider results
figure
subplot(4,1,1)
plot(dia(2:4),s_results_set1(:,1)*1e3,'-x')
hold on
plot(dia(2:4),s_results_set2(:,1)*1e3,'-x')
plot(dia(2:4),s_results_set3(:,1)*1e3,'-x')
xline(10,'-.', 'HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
ylabel('Length measurement error ( $\mu$ m)')
% title('Artec Spider: Length measurement error')
xticks(dia)
xlim([4,44])

subplot(4,1,2)
plot(dia(2:4),s_results_set1(:,2)*1e3,'-x')
hold on
plot(dia(2:4),s_results_set2(:,2)*1e3,'-x')
plot(dia(2:4),s_results_set3(:,2)*1e3,'-x')
xline(10,'-.', 'HandleVisibility','off')
legend('Set 1','Set 2','Set 3')
ylabel('Sphere spacing error ( $\mu$ m)')
% title('Artec Spider: Sphere spacing error')
xticks(dia)
```

```

xlim([4,44])

subplot(4,1,3)
plot(dia(2:4),s_results_set1(:,3)*1e3,'-x')
hold on
plot(dia(2:4),s_results_set2(:,3)*1e3,'-x')
plot(dia(2:4),s_results_set3(:,3)*1e3,'-x')
plot(dia(2:4),s_results_set1(:,4)*1e3,'-x')
plot(dia(2:4),s_results_set2(:,4)*1e3,'-x')
plot(dia(2:4),s_results_set3(:,4)*1e3,'-x')
xline(10,'-.', 'Optimal', 'HandleVisibility','off')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')
ylabel('Probing error size ( $\mu\text{m}$ )')
% title('Artec Spider: Probing error size')
xticks(dia)
xlim([4,44])

subplot(4,1,4)
errorbar(dia(2:4),s_results_set1(:,5)*1e3,s_results_set1(:,9)*1e3,'-x')
hold on
errorbar(dia(2:4),s_results_set2(:,5)*1e3,s_results_set2(:,9)*1e3,'-x')
errorbar(dia(2:4),s_results_set3(:,5)*1e3,s_results_set3(:,9)*1e3,'-x')
errorbar(dia(2:4),s_results_set1(:,6)*1e3,s_results_set1(:,10)*1e3,'-x')
errorbar(dia(2:4),s_results_set2(:,6)*1e3,s_results_set2(:,10)*1e3,'-x')
errorbar(dia(2:4),s_results_set3(:,6)*1e3,s_results_set3(:,10)*1e3,'-x')
xline(10,'-.', 'HandleVisibility','off')
legend('Set 1 L','Set 2 L','Set 3 L','Set 1 R','Set 2 R','Set 3 R')
xlabel('Sphere diameter ( $\mu\text{m}$ )')
ylabel('Probing error form ( $\mu\text{m}$ )')

```

```

% title('Artec Spider: Probing error form (adjustment residual)')
xticks(dia)
xlim([4,44])

```

Compare scanners to one another

```

% use function to find means across three sets per scanner
meanCore = calcMeans(c_results_set1,c_results_set2,c_results_set3);
meanQ = calcMeans(q_results_set1,q_results_set2,q_results_set3);
meani = calcMeans(i_results_set1,i_results_set2,i_results_set3);
meanS = calcMeans(s_results_set1,s_results_set2,s_results_set3);

% complete list of scanners for X axis
scanners = ["ATOS Q" "ATOS Core" "Artec Spider" "iPhone"];

% optimal sphere pairs
optQ = 8;
optCore = 6;
optS = 5-3;
opti = 8-6;

% compare optimal set LME, SSE, PES, PEF in one figure
figure
subplot(4,1,1)
bar(scanners,[meanQ(optQ,1) meanCore(optCore,1)...
meanS(optS,1) meani(opti,1)]*1e3)
Y=[meanQ(optQ,1) meanCore(optCore,1) meanS(optS,1) meani(opti,1)]*1e3;
text(1:length(Y),[0 meanCore(optCore,1) meanS(optS,1) meani(opti,1)]*1e3, ...

```



```

        num2str(Y',3),'vert','bottom','horiz','center','FontWeight','Bold');
text(4,0,num2str_custom(Y(4)),'vert','bottom','horiz','center',...
'FontWeight','Bold');
ylabel('Mean length measurement error ( $\mu$ m)')
ylim([-20,80])
% title('Mean length measurement error for optimal sphere pair')

subplot(4,1,2)
bar(scanners,[meanQ(optQ,2) meanCore(optCore,2)...
meanS(optS,2) meani(opti,2)]*1e3)
Y=[meanQ(optQ,2) meanCore(optCore,2) meanS(optS,2) meani(opti,2)]*1e3;
text(1:length(Y),[0 meanCore(optCore,2) meanS(optS,2) meani(opti,2)]*1e3,...
        num2str(Y',3),'vert','bottom','horiz','center','FontWeight','Bold');
text(4,0,num2str(Y(4),3),'vert','bottom','horiz','center',...
'FontWeight','Bold');
ylabel('Mean sphere spacing error ( $\mu$ m)')
ylim([-10,40])
% title('Mean sphere spacing error for optimal sphere pair')

subplot(4,1,3)
bar(scanners,[meanQ(optQ,3) meanCore(optCore,3)...
meanS(optS,3) meani(opti,3)]*1e3)
Y=[meanQ(optQ,3) meanCore(optCore,3) meanS(optS,3) meani(opti,3)]*1e3;
text(1:length(Y),[0 meanCore(optCore,3) meanS(optS,3) meani(opti,3)]*1e3,...
        num2str(Y',3),'vert','bottom','horiz','center','FontWeight','Bold');
text(4,0,num2str(Y(4),3),'vert','bottom','horiz','center',...
'FontWeight','Bold','Color','w');
ylabel('Mean probing error size ( $\mu$ m)')
ylim([-15,75])

```

```

% title('Mean probing error size for optimal sphere pair')

subplot(4,1,4)
bar(scanners,[meanQ(optQ,4) meanCore(optCore,4)...
meanS(optS,4) meani(opti,4)]*1e3);
Y=[meanQ(optQ,4) meanCore(optCore,4) meanS(optS,4) meani(opti,4)]*1e3;
text(1:length(Y),Y,num2str(Y',3),'vert','bottom','horiz','center',...
'FontWeight','Bold');
text(4,0,num2str_custom(Y(4)),'vert','bottom','horiz','center',...
'FontWeight','Bold','Color','w');
hold on
% errorbar([1,2,3],[meanCore(optCore,4) meanQ(optQ,4) meani(opti,4)]*1e3,...
%      [meanCore(optCore,6) meanQ(optQ,6) meani(opti,6)]*1e3);
% errorbar(1,meanQ(optQ,4)*1e3,meanQ(optQ,6)*1e3);
% errorbar(2,meanCore(optCore,4)*1e3,meanCore(optCore,6)*1e3);
% errorbar(3,meanS(optS,4)*1e3,meanS(optS,6)*1e3);
% errorbar(4,meani(opti,4)*1e3,meani(opti,6)*1e3);
ylabel('Mean probing error form ( $\mu$ m)')
ylim([-5,30])
% title('Mean probing error form for optimal sphere pair')

figure
bar(scanners,[meanQ(optQ,6)*1e3 meanCore(optCore,6)*1e3...
meanS(optS,6)*1e3 meani(opti,6)*1e3])
Y = [meanQ(optQ,6)*1e3 meanCore(optCore,6)*1e3 meanS(optS,6)*1e3...
meani(opti,6)*1e3];
text(1:length(Y),Y,num2str(Y',3),'vert','bottom','horiz','center',...
'FontWeight','Bold');
ylabel('Mean probing error form sigma ( $\mu$ m)')

```

```

ylim([-5 50])
text(4,45,num2str_custom(Y(4)),'vert','bottom','horiz','center',...
'FontWeight','Bold','Color','w')
% title('Mean probing error form sigma for optimal sphere pair')

```

Functions

```

function [data] = importCSV(c_dir)
    c_info = dir(fullfile(c_dir));
    c_info = c_info(~ismember({c_info.name}, {'.', '..'}));
    fileNames = {c_info.name};
    fileNames = cellfun(@(x) x(1:find(x=='.',1,'last')-1), fileNames,...
'UniformOutput', false);
    fileNums = str2double(fileNames);
    [~,idx] = sort(fileNums);
    c_info = c_info(idx);
    c_num = length(c_info);

    for i = idx
        filename = fullfile(c_dir,c_info(i).name);
        data{i} = readtable(filename);
    end
end

function [results] = processData(meas_temp,data,startingPair)

% rows represent sphere no 1,2,3...
% columns: Ldia Rdia distance

```

```

nominals = [6.0003 6.0003 16.0177
8.0013 8.0008 25.9906
10.0024 10.0038 40.0290
12.0021 12.0020 54.9854
15.0013 14.9996 80.0289
20.0046 20.0020 114.9955
25.0009 25.0005 160.0000
30.0012 30.0014 230.0037
40.0002 39.9986 320.0445]; %mm

for i = 1:size(data,2)
    L_dia = nominals(i+startingPair-1,1);
    R_dia = nominals(i+startingPair-1,2);
    spacing = nominals(i+startingPair-1,3);

    lme = data{1,i}(3,2).L +260.005; % comp for skew in Inspect output
    sse = data{1,i}(4,2).L +230.0037;
    pes_l = data{1,i}(1,5).x_ +30; % comp for skew in Inspect output
    pes_r = data{1,i}(2,5).x_ +30;
    % adjustment residual sigma, range, mean
    AR_s_l = data{1,i}(1,6).x__1;
    AR_s_r = data{1,i}(2,6).x__1;
    AR_range_l = data{1,i}(1,3).Range;
    AR_range_r = data{1,i}(2,3).Range;
    AR_l = data{1,i}(1,4).r;
    AR_r = data{1,i}(2,4).r;

    cal_temp = 20.3; % degC

```

```

cte_plate = 4e-6; % 1/K
cte_sphere = 10.5e-6; % 1/K

deltaT = meas_temp-cal_temp;
L_dia = L_dia + L_dia*deltaT*cte_sphere;
R_dia = R_dia + R_dia*deltaT*cte_sphere;
spacing = spacing + spacing*deltaT*cte_plate;

lme_b = lme - ((L_dia+R_dia)/2 + spacing);
pes_l_b = pes_l - L_dia;
pes_r_b = pes_r - R_dia;
sse_b = sse - spacing;

results(i,:) = [lme_b sse_b pes_l_b pes_r_b AR_l AR_r...
AR_range_l AR_range_r AR_s_l AR_s_r];
end
end

function [means] = calcMeans(set1,set2,set3)

% find means and combine left and right data
for i = 1:size(set2,1)
    mean_lme = mean([set1(i,1) set2(i,1) set3(i,1)]);
    mean_sse = mean([set1(i,2) set2(i,2) set3(i,2)]);
    mean_pes = mean([set1(i,3) set2(i,3) set3(i,3) set1(i,4)...
set2(i,4) set3(i,4)]);
    mean_AR = mean([set1(i,5) set2(i,5) set3(i,5) set1(i,6)...
set2(i,6) set3(i,6)]);
    mean_ARr = mean([set1(i,7) set2(i,7) set3(i,7) set1(i,8)...

```

```

        set2(i,8) set3(i,8)]];
        mean_ARs = mean([set1(i,9) set2(i,9) set3(i,9) set1(i,10)...
        set2(i,10) set3(i,10)]);
        means(i,:) = [mean_lme mean_sse mean_pes mean_AR...
        mean_ARr mean_ARs];
    end
end

function s = num2str_custom(x)
    if abs(x) >= 1e-3 && abs(x) < 1e3
        s = sprintf('%.2f', x);
    else
        exponent = floor(log10(abs(x)));
        mantissa = x / 10^exponent;
        s = [sprintf('%.2f', mantissa) 'x10^{ ' num2str(exponent) ' }'];
    end
end
end

```

C.2 Monte Carlo simulation

Contents

- Inputs
- Calculations
- Check desired points w function
- End statements
- Functions

```
clear all
```

```
close all
tic
```

Inputs

```
% Select system
% 1- Q
% 2- Core
% 3- Spider
% 4- iPhone
% 5 - case study
sys = 1;

if sys == 1 || 4
    % Define nominal location of three spheres
    % pair 789 (Q,iPhone)
    P1_nom = [0; 0; 0]; %mm
    P2_nom = [47.45; 0; 0];
    P3_nom = [-16.43; 48.88; 0];
    mtSize = [169.6577 -154.7016 13.5522]; % L8 to R8 (Q, iphone)
    if sys == 1
        u = 2.57e-3/2; % q mean PEF
    elseif sys == 4
        u = 1.88/2; % iphone
    end
end

if sys == 2
    % % pair 567 (Core)
```

```

    P1_nom = [0; 0; 0];
    P2_nom = [32.21; 0; 0];
    P3_nom = [14.53; 36.35; 0];
    mtSize = [62.4769 -96.1378 8.8969]; % L6 to R6 (Core)
    u = 2.41e-3/2; % core
end

if sys == 3
    % Pair 456 (Spider)
    P1_nom = [0; 0; 0];
    P2_nom = [40.0144; 0; 0];
    P3_nom = [20.1450; 25.1482; 0];
    [25.0201 -75.7094 -6.7927]; %L5 to R5 (Spider)
    u = 14.7e-3/2; % spider
end

if sys == 5
    % Pair 123 (Case study)
    P1_nom = [0; 0; 0];
    P2_nom = [241.3; 0; 0];
    P3_nom = [0.278; 241.03; 0];
    u = 2.57e-3/2; % q mean PEF
    mtSize = [69 104 77]; % Case study
end

% Iterations
loops = 500000;

% Coverage factor for expanded uncertainty

```



```

k=2; % 95%

% Overbuild check on/off
% 0- off
% 1- on
obcheck = 1;

% Overbuild increment
% raise this if code takes excessive amount of time
obinc = 0.001; % mm

% Nominal part size for overbuild check
partSize = [25.4*4 25.4 25.4*4]; % case study nominal part size

```

Calculations

```

% Preallocate
P1_sim = cell(1,loops);
X_sim = cell(1,loops);
Y_sim = cell(1,loops);
Z_sim = cell(1,loops);
R_sim = cell(1,loops);
R_nom = cell(1,loops);
R_sim_nom = cell(1,loops);
HTM = cell(1,loops);
t = cell(1,loops);
eps_z = zeros(1,loops);
eps_y = zeros(1,loops);
eps_x = zeros(1,loops);

```

```

overbuildLim = zeros(1,loops);

for i = 1:loops

% Normal distribution of XYZ for each sphere
    P1_sim{i} = P1_nom + normrnd(0,u,[3,1]);
    P2_sim = P2_nom + normrnd(0,u,[3,1]);
    P3_sim = P3_nom + normrnd(0,u,[3,1]);

% Checks
    if isequal(P1_sim{i}(),P1_nom)
        disp('S1nom and S1sim are coincident')
    end
    if isequal(P2_sim,P2_nom)
        disp('S2nom and S2sim are coincident')
    end
    if isequal(P3_sim,P3_nom)
        disp('S3nom and S3sim are coincident')
    end

% Find basis vectors for nominal CS
X_nom = (P2_nom-P1_nom)/norm(P2_nom-P1_nom);
P3_P1_nom = (P3_nom-P1_nom)/norm(P3_nom-P1_nom);
Z_nom = cross(X_nom,P3_P1_nom)/norm(cross(X_nom,P3_P1_nom));
Y_nom = cross(Z_nom,X_nom);

% Find basis vectors for simulated CS
X_sim{i} = (P2_sim-P1_sim{i})/norm(P2_sim-P1_sim{i});
P3_P1_sim = (P3_sim-P1_sim{i})/norm(P3_sim-P1_sim{i});

```

```

Z_sim{i} = cross(X_sim{i},P3_P1_sim)/norm(cross(X_sim{i},P3_P1_sim));
Y_sim{i} = cross(Z_sim{i},X_sim{i});

% Define rotation matrices
R_nom{i} = [X_nom Y_nom Z_nom];
R_sim{i} = [X_sim{i} Y_sim{i} Z_sim{i}];

R_sim_nom{i} = R_sim{i}/R_nom{i};

% Calculate translation from nominal to simulated cs
t{i} = P1_sim{i} - R_sim_nom{i}*P1_nom;

% Define homogeneous transformation matrix
HTM{i} = [R_sim_nom{i} t{i};0 0 0 1];

% Roll pitch yaw (euler) angles
eps_z(i) = atan2d(R_sim_nom{i}(2,1),R_sim_nom{i}(1,1));
eps_y(i) = atan2d(-R_sim_nom{i}(3,1),sqrt(R_sim_nom{i}(3,2)^2...
+R_sim_nom{i}(3,3)^2));
eps_x(i) = atan2d(R_sim_nom{i}(3,2),R_sim_nom{i}(3,3));

if obcheck == 4
    overbuildLim(i) = checkOverbuild(mtSize,partSize,HTM{i},obinc);
end

end
end

```

Check desired points w function

```
pt = [mtSize(1); mtSize(2); mtSize(3)];  
[pt_delta,pt_epsilon] = ptCheck(pt,HTM,loops,k);  
  
if obcheck == 4  
    figure  
    histogram(overbuildLim,'Normalization','probability')  
    title('Overbuild limit distribution')  
    xlabel('Overbuild (mm)')  
    ylabel('Probability')  
end
```

End statements

```
format short  
disp('Loop 1 HTM:')  
disp(HTM{1})  
toc  
disp('Code complete')
```

Functions

```
function [pt_delta_error,pt_epsilon_error] = ptCheck(pt,HTM,loops,k)  
    pt_component = [pt;1];  
    pt_delta_error = zeros(4,loops);  
    pt_epsilon_error = zeros(3,loops);  
    for i = 1:loops  
        pt_delta_error(:,i) = pt_component-HTM{i}*pt_component;  
        pt_epsilon_error(:,i) = 60*rad2deg([atan2(HTM{i}(3,2),HTM{i}(3,3));  
                                              atan2(-HTM{i}(3,1),sqrt(HTM{i}(3,2)^2...
```

```

+HTM{i}(3,3)^2));
atan2(HTM{i}(2,1),HTM{i}(1,1))]);

end

std_delta = [std(pt_delta_error(1,:))*1e3 std(pt_delta_error(2,:))*1e3...
std(pt_delta_error(3,:))*1e3];
std_epsilon = [std(pt_epsilon_error(1,:)) std(pt_epsilon_error(2,:))...
std(pt_epsilon_error(3,:))];
U_delta = k*norm(std_delta);
U_epsilon = k*norm(std_epsilon);

% plot distribution of results
f = figure;
tiledlayout(3,2)

nexttile
histogram(pt_delta_error(1,:)*1e3,'Normalization','probability')
ylabel('Probability')
lim = axis;
xmax = lim(2);
ymax = lim(4);
title('Distribution of \delta_x')
text(0.99*xmax,0.99*ymax,"\sigma_\delta_x = " + ...
std_delta(1),'HorizontalAlignment','right','VerticalAlignment','top');
text(0.99*xmax,1.1*ymax,"U_\delta = " + U_delta,'HorizontalAlignment'...
,'right','VerticalAlignment','top');

nexttile
histogram(pt_epsilon_error(1,:), 'Normalization', 'probability')

```

```

ylabel('Probability')
lim = axis;
    xmax = lim(2);
ymax = lim(4);
title('Distribution of \epsilon_x')
text(0.99*xmax,0.99*ymax,"\sigma_\epsilon_x = " + ...
std_epsilon(1),'HorizontalAlignment','right','VerticalAlignment','top');
text(0.99*xmax,1.1*ymax,"U_\epsilon = " + U_epsilon,'HorizontalAlignment'...
,'right','VerticalAlignment','top');

nexttile
histogram(pt_delta_error(2,:)*1e3,'Normalization','probability')
ylabel('Probability')
title('Distribution of \delta_y')
lim = axis;
    xmax = lim(2);
ymax = lim(4);
text(0.99*xmax,0.99*ymax,"\sigma_\delta_y = " + ...
std_delta(2),'HorizontalAlignment','right','VerticalAlignment','top');

nexttile
histogram(pt_epsilon_error(2,:), 'Normalization','probability')
ylabel('Probability')
lim = axis;
    xmax = lim(2);
ymax = lim(4);
title('Distribution of \epsilon_y')
text(0.99*xmax,0.99*ymax,"\sigma_\epsilon_y = " + ...
std_epsilon(2),'HorizontalAlignment','right','VerticalAlignment','top');

```

```

nexttile
histogram(pt_delta_error(3,:)*1e3,'Normalization','probability')
ylabel('Probability')
title('Distribution of \delta_z')
lim = axis;
    xmax = lim(2);
ymax = lim(4);
text(0.99*xmax,0.99*ymax,"\sigma_\delta_z = " + ...
std_delta(3),'HorizontalAlignment','right','VerticalAlignment','top');
xlabel('\mu_m')

nexttile
histogram(pt_epsilon_error(3,:),'Normalization','probability')
ylabel('Probability')
lim = axis;
    xmax = lim(2);
ymax = lim(4);
title('Distribution of \epsilon_z')
text(0.99*xmax,0.99*ymax,"\sigma_\epsilon_z = " + ...
std_epsilon(3),'HorizontalAlignment','right','VerticalAlignment','top');
xlabel('\mu_{\epsilon}')

f.Units = 'normalized';
f.OuterPosition = [0 0 1 1];
end

function [overbuildLim] = checkOverbuild(mtSize,partSize,HTM,obinc)
    overbuild = 0;

```

```

partSizeMin = mtSize;
partSizeMax = mtSize + partSize;
while 1
    % assign latest Min / Max in terms of nominal CS
    partOverbuildMin = HTM * [partSizeMin'-overbuild; 1];
    partOverbuildMin = partOverbuildMin(1:3);
    partOverbuildMax = HTM * [partSizeMax'+overbuild; 1];
    partOverbuildMax = partOverbuildMax(1:3);
    % check if partSize is inside of partOverbuild
    if all(partSizeMin' >= partOverbuildMin) && all(partSizeMax'...
        <= partOverbuildMax)
        overbuildLim = overbuild;
        break
    end

    % increment until above is true
    overbuild = overbuild + obinc;
    overbuildLim = overbuild;
end
end

```

C.3 Positional uncertainty

Contents

- Find xyz uncertainty from sphere data
- Input data
- Plots

Find xyz uncertainty from sphere data

jake dvorak april 2024

```
clear all
```

```
close all
```

Input data

```
L_x_sigma = [0.00035
```

```
0.00069
```

```
0.00065
```

```
0.0007
```

```
0.00066
```

```
0.00084
```

```
0.0005
```

```
0.00097
```

```
0.00079]; %mm
```

```
R_x_sigma = [0.00026
```

```
0.00037
```

```
0.00058
```

```
0.00062
```

```
0.00055
```

```
0.00066
```

```
0.00042
```

```
0.00091
```

```
0.00056];
```

```
L_y_sigma = [0.00319
```

```
0.00196
```

```
0.00124
```

```
0.00111
0.00218
0.00081
0.00208
0.00108
0.00152];
R_y_sigma = [0.00334
0.00229
0.00139
0.00053
0.00182
0.00048
0.00189
0.00017
0.00097];
L_z_sigma = [0.00253
0.00182
0.00107
0.00132
0.00169
0.00093
0.00152
0.0007
0.00142];
R_z_sigma = [0.00256
0.00193
0.0009
0.0015
0.00157
```

```

0.00111
0.00214
0.00111
0.00225];

k = 2;

sphere_dia = [6; 8; 10; 12; 15; 20; 25; 30; 40];

```

Plots

```

ref = 8;
figure
plot(sphere_dia,L_x_sigma*1e3,'ro-')
hold on
plot(sphere_dia,R_x_sigma*1e3,'r*-')
plot(sphere_dia,L_y_sigma*1e3,'go-')
plot(sphere_dia,R_y_sigma*1e3,'g*-')
plot(sphere_dia,L_z_sigma*1e3,'bo-')
plot(sphere_dia,R_z_sigma*1e3,'b*-')
xline(sphere_dia(ref),'r-.')
ylabel('Sphere center positional standard deviation (\mum)')
xlabel('Sphere Diameter (mm)')
xticks(sphere_dia)
% title('Sphere center positional standard deviations: ATOS Q')
legend('Left, x','Right, x','Left, y','Right, y','Left, z',...
       'Right, z','Scan centered about')
xlim([4 44])

```

```

L_xyz_sigma = sqrt(L_x_sigma.^2+L_y_sigma.^2+L_z_sigma.^2);
R_xyz_sigma = sqrt(R_x_sigma.^2+R_y_sigma.^2+R_z_sigma.^2);

u_xyz = sqrt(L_x_sigma.^2+L_y_sigma.^2+L_z_sigma.^2+R_x_sigma.^2 ...
    +R_y_sigma.^2+R_z_sigma.^2)*1e3

sigma_xyz_mean = mean([L_x_sigma(ref),R_x_sigma(ref),L_y_sigma(ref) ...
    ,R_y_sigma(ref),L_z_sigma(ref),R_z_sigma(ref)])

```

C.4 Experimental coordinate system variation

Contents

- function to process sphere XYZ data r4
- Data
- Primary script
- Functions

function to process sphere XYZ data r4

jake dvorak march 2024

```

clear all
clc
beep off
close all

```

Data

```

% iPhone data
Lxyz_i{1} = [0 0 0

```

```

0 0 0
1.4268 -114.0201 62.3926
-20.7894 -90.9106 84.1286
-55.2144 -115.8862 64.7918
-99.8542 -99.0971 82.6629];
Rxyz_i{1} = [0 0 0
0 0 0
115.8272 -114.7716 63.7112
138.0088 -92.2463 86.6824
172.4621 -118.0436 68.4660
216.9808 -101.4826 87.4002];

Lxyz_i{2} = [0 0 0
0 0 0
4.5377 -60.6281 94.0962
-17.5931 -29.1927 96.0758
-51.7558 -60.3126 98.7406
-95.2384 -36.2921 102.0149];
Rxyz_i{2} = [0 0 0
0 0 0
117.8006 -61.0552 92.6862
139.7413 -29.4073 95.2445
173.9605 -60.5170 97.5128
218.2834 -36.1283 99.9485];

Lxyz_i{3} = [0 0 0
0 0 0
0.9859 -64.5556 95.3758
-21.9156 -32.4066 97.8199

```

```

-57.0028 -64.5237 100.2043
-101.7726 -40.0439 103.9090];
Rxyz_i{3} = [0 0 0
0 0 0
117.0839 -63.9748 92.0261
139.3823 -31.6351 96.8239
174.6831 -63.0762 97.8547
220.0972 -38.0847 101.0842];

```

```

Lxyz_i{4} = [0 0 0
0 0 0
7.4967 -72.8465 92.4213
-14.2371 -42.0337 94.1930
-47.7388 -72.9069 96.3474
-90.7684 -49.0863 99.5279];

```

```

Rxyz_i{4} = [0 0 0
0 0 0
118.8252 -73.0479 91.5342
140.3638 -42.1445 94.0730
174.0750 -72.7557 95.7010
217.8896 -48.8074 98.4200];

```

```

Lxyz_i{5} = [0 0 0
0 0 0
7.6495 -67.3312 94.1068
-14.8734 -35.4827 96.3797
-49.4730 -67.3113 98.3749
-94.1358 -42.9402 101.6576];

```

```

Rxyz_i{5} = [0 0 0

```

```
0 0 0
122.9707 -67.0146 92.5557
145.1695 -34.9596 95.4820
179.9532 -66.5679 97.1743
224.7334 -41.5738 99.8912];
```

% Core data

```
Lxyz_core{1} = [90.2955 -59.3460 7.5808
77.8165 -21.3563 9.1581
60.3669 -48.3843 10.9620
37.9200 -16.4053 13.3555
2.9741 -48.7372 15.5305
0 0 0];
```

```
Rxyz_core{1} = [145.2651 -59.3072 6.1592
157.8196 -21.3455 7.1023
175.3251 -48.3300 7.9693
197.8641 -16.3274 9.1918
232.8951 -48.3245 9.5315
0 0 0];
```

```
Lxyz_core{2} = [90.2948 -59.3473 7.5849
77.8158 -21.3581 9.1562
60.3662 -48.3845 10.9645
37.9189 -16.4052 13.3519
2.9734 -48.4364 15.5325
0 0 0];
```

```
Rxyz_core{2} = [145.2645 -59.3098 6.1623
```

```
157.8208 -21.3466 7.1013
175.3258 -48.3312 7.9718
197.8648 -16.3277 9.1892
232.8967 -48.3248 9.5328
0 0 0];
```

```
Lxyz_core{3} = [90.2964 -59.3481 7.5817
77.8168 -21.3572 9.1588
60.3664 -48.3859 10.9627
37.9191 -16.4067 13.3551
2.9738 -48.4388 15.5306
0 0 0];
```

```
Rxyz_core{3} = [145.2668 -59.3088 6.1602
157.8227 -21.3467 7.1029
175.3288 -48.3311 7.9698
197.8677 -16.3285 9.1912
232.8986 -48.3259 9.5305
0 0 0];
```

```
Lxyz_core{4} = [90.2950 -59.3495 7.5841
77.8164 -21.3589 9.1629
60.3649 -48.3870 10.9655
37.9182 -16.4081 13.3595
2.9721 -48.4404 15.5333
0 0 0];
```

```
Rxyz_core{4} = [145.2654 -59.3106 6.1619
157.8206 -21.3481 7.1061
```



```

175.3271 -48.3327 7.9712
197.8653 -16.3291 9.1938
232.8966 -48.3259 9.5310
0 0 0];

Lxyz_core{5} = [90.2995 -59.3466 7.5767
77.8196 -21.3579 9.1520
60.3694 -48.3847 10.9583
37.9218 -16.4050 13.3526
2.9762 -48.4374 15.5308
0 0 0];

Rxyz_core{5} = [145.2674 -59.3081 6.1571
157.8218 -21.3462 7.0986
175.3276 -48.3315 7.9678
197.8659 -16.3278 9.1882
232.8990 -48.3253 9.5304
0 0 0];

% ATOS Q data
qset = 1; % 1 is matrix metering 2 is spot metering

if qset == 2
    Lxyz_q{1} = [-142.39206 -16.42358 -7.2856
-154.38723 12.05436 -32.71718
-172.28274 -6.71801 -13.59261
-194.35864 17.7528 -34.71811

```

```

-229.81888 -4.74889 -12.61859
-274.5419 15.57279 -28.37967];
Rxyz_q{1} = [-87.41812 -16.28854 -6.05839
-74.37785 12.22669 -30.88967
-57.31183 -6.46807 -11.02474
-34.3934 18.10348 -31.15038
0.1328 -4.25433 -7.4966
45.43078 16.26289 -21.25092];
Lxyz_q{2} = [-142.39227 -16.42357 -7.28866
-154.38767 12.05949 -32.71388
-172.28292 -6.71708 -13.59346
-194.3588 17.75761 -34.71518
-229.81994 -4.74871 -12.61958
-274.54283 15.57596 -28.37714];
Lxyz_q{3} = [-142.3935 -16.4213 -7.28746
-154.38873 12.05833 -32.71675
-172.28469 -6.71595 -13.59323
-194.35977 17.75664 -34.71716
-229.82139 -4.74635 -12.61965
-274.54397 15.57655 -28.38045];
Lxyz_q{4} = [-142.39263 -16.42419 -7.28665
-154.38825 12.05809 -32.71338
-172.28325 -6.71746 -13.59149
-194.35877 17.75658 -34.71441
-229.81971 -4.74882 -12.61832
-274.54237 15.57516 -28.37755];
Lxyz_q{5} = [-142.39358 -16.42352 -7.28864
-154.38874 12.05984 -32.71492
-172.28415 -6.71645 -13.5939

```

```

-194.35946 17.75808 -34.71542
-229.82076 -4.74789 -12.61987
-274.54315 15.5763 -28.37807];
Rxyz_q{2} = [-87.41778 -16.28892 -6.0614
-74.37745 12.23135 -30.88706
-57.31113 -6.46713 -11.02565
-34.39307 18.10826 -31.14754
0.13348 -4.25463 -7.49767
45.43166 16.26461 -21.24896];
Rxyz_q{3} = [-87.41805 -16.28803 -6.05948
-74.37815 12.22996 -30.88843
-57.31254 -6.46678 -11.0249
-34.3938 18.10616 -31.14804
0.13264 -4.25461 -7.49626
45.43096 16.26369 -21.24917];
Rxyz_q{4} = [-87.41868 -16.28934 -6.05913
-74.37754 12.23025 -30.8855
-57.31176 -6.46749 -11.0227
-34.39368 18.1072 -31.14468
0.13232 -4.25425 -7.49458
45.43098 16.26511 -21.24551];
Rxyz_q{5} = [-87.41934 -16.28918 -6.06187
-74.37881 12.23079 -30.8873
-57.31277 -6.46739 -11.0249
-34.39418 18.10772 -31.14611
0.13102 -4.25443 -7.49635
45.43009 16.2651 -21.24617];
elseif qset == 1
Lxyz_q{1} = [146.7912 -55.4497 9.6709

```

136.6509 -17.0797 4.5362
 117.5073 -42.4266 9.9460
 97.0187 -9.2888 6.1645
 60.1030 -38.5234 12.0038
 16.6865 -10.7064 10.4112];

Rxyz_q{1} = [201.6733 -58.7142 10.6193
 216.5215 -21.8757 5.9391
 232.2793 -49.2843 11.9141
 256.7098 -18.8222 8.9043
 289.6548 -52.2360 15.9296
 336.1039 -29.7860 15.8766];

Lxyz_q{2} = [146.7883 -55.4510 9.6625
 136.6502 -17.0778 4.5476
 117.5056 -42.4289 9.9421
 97.0187 -9.2843 6.1771
 60.1023 -38.5220 12.0008
 16.6885 -10.7015 10.4211];

Rxyz_q{2} = [201.6744 -58.7150 10.6071
 216.5235 -21.8708 5.9487
 232.2802 -49.2834 11.9077
 256.7104 -18.8160 8.9157
 289.6575 -52.2308 15.9214
 336.1043 -29.7761 15.8779];

Lxyz_q{3} = [146.7907 -55.4468 9.6645
 136.6477 -17.0747 4.5489

117.5046 -42.4266 9.9460
 97.0153 -9.2860 6.1806
 60.0997 -38.5284 12.0055
 16.6820 -10.7113 10.4244];

Rxyz_q{3} = [201.6755 -58.7094 10.6128
 216.5213 -21.8663 5.9486
 232.2805 -49.2765 11.9121
 256.7084 -18.8122 8.9183
 289.6574 -52.2257 15.9280
 336.1050 -29.7715 15.8826];

Lxyz_q{4} = [146.7892 -55.4515 9.6652
 136.6488 -17.0770 4.5557
 117.5036 -42.4297 9.9468
 97.0147 -9.2876 6.1886
 60.0981 -38.5310 12.0066
 16.6811 -10.7122 10.4325];

Rxyz_q{4} = [201.6734 -58.7162 10.6122
 216.5202 -21.8708 5.9579
 232.2784 -49.2844 11.9141
 256.7090 -18.8189 8.9274
 289.6552 -52.2342 15.9322
 336.1067 -29.7800 15.8943];

Lxyz_q{5} = [146.7905 -55.4543 9.6624
 136.6483 -17.0782 4.5602
 117.5059 -42.4318 9.9472

```

97.0161 -9.2890 6.1954
60.0995 -38.5333 12.0069
16.6845 -10.7141 10.4384];

Rxyz_q{5} = [201.6758 -58.7182 10.6082
216.5213 -21.8726 5.9591
232.2799 -49.2870 11.9102
256.7098 -18.8193 8.9261
289.6578 -52.2372 15.9237
336.1060 -29.7844 15.8864];
end

% Artec Spider pairs 4 to 7
% actually pairs 2 to 5? no this was a different set.
Lxyz_s{1} = [-3.5808 -66.5976 14.1469
-15.4894 -28.9941 7.2596
-33.5083 -55.409 11.4185
-55.5537 -23.6397 5.0122
0 0 0
0 0 0];

Rxyz_s{1} = [51.1145 -66.438 20.2232
64.0924 -28.8005 16.1303
80.8642 -55.0942 24.1219
103.6233 -23.2054 22.6854
0 0 0
0 0 0];

Lxyz_s{2} = [15.7925 -69.3375 16.4669

```

```

6.0018 -30.8218 11.5721
-13.4567 -56.2039 15.7005
-33.668 -22.9152 11.603
0 0 0
0 0 0];

```

```

Rxyz_s{2} = [70.5996 -72.8586 19.7165
85.7764 -35.9793 16.3112
101.1774 -63.5736 22.467
125.868 -33.1596 21.003
0 0 0
0 0 0];

```

```

Lxyz_s{3} = [10.2953 -63.3974 13.8935
-0.1311 -24.7555 12.9355
-19.1611 -50.7358 14.3743
-39.9422 -17.5232 13.6262
0 0 0
0 0 0];

```

```

Rxyz_s{3} = [65.1508 -66.3077 16.9425
79.703 -29.0281 17.3733
95.561 -56.8374 20.7328
119.6991 -26.0204 22.5235
0 0 0
0 0 0];

```

```

Lxyz_s{4} = [27.9763 -69.6209 18.1369
18.2549 -31.0038 14.0162

```

```

-1.257 -56.438 17.4066
-21.4138 -23.0299 13.8757
0 0 0
0 0 0];

```

```

Rxyz_s{4} = [82.7468 -73.2696 21.7993
97.9769 -36.34 19.341
113.3066 -64.0776 25.0319
138.0071 -33.6579 24.5008
0 0 0
0 0 0];

```

```

Lxyz_s{5} = [21.1166 -72.8746 16.9332
9.0502 -34.701 16.4914
-8.8201 -61.4708 18.4233
-30.9697 -29.1353 18.5061
0 0 0
0 0 0];

```

```

Rxyz_s{5} = [76.1053 -73.5084 18.2016
89.1034 -35.6589 18.3268
106.2057 -62.7949 21.0394
129.0815 -31.0086 22.1442
0 0 0
0 0 0];

```

```

% CMM data

```

```

% Left spheres

```



```
% rows are xyz per sphere from spheres 4 to 9
Lxyz_CMM{1} = [172.6086 -65.9504 3.6136;
               160.1047 -27.9449 4.5343;
               142.6048 -54.9459 6.1264;
               120.1136 -22.9389 7.6631;
               85.1107 -54.9361 9.2192;
               40.0903 -29.9212 12.2801]; %mm
```

```
% Right spheres
% rows are xyz per sphere from spheres 4 to 9
Rxyz_CMM{1} = [227.5932 -65.9395 3.6078;
               240.1340 -27.9712 4.5423;
               257.6026 -54.9448 6.0963;
               280.1144 -22.9320 7.6222;
               315.1145 -54.9289 9.1501;
               360.1342 -29.9133 12.1794]; %mm
```

Primary script

One block of code for each scanner

```
disp('Units: delta is micrometers and epsilon is arcminutes')
disp('First row: mean')
disp('Second row: standard deviation')
disp('Left to right: X Y Z')
% Core
[~,Rxyz_CMML] = leftCS567(Lxyz_CMM,Rxyz_CMM);
[~,Rxyz_coreL] = leftCS567(Lxyz_core,Rxyz_core);
[euler_core] = rightCS567(Rxyz_coreL);
[euler_cmm] = rightCS567(Rxyz_CMML);
```

```

[delta_core,epsilon_core,Ud_core,Ue_core] = ...
    findError567(Rxyz_coreL,Rxyz_CMML,euler_core,euler_cmm)

% ATOS Q
[~,Rxyz_CMML] = leftCS789(Lxyz_CMM,Rxyz_CMM);
[~,Rxyz_qL] = leftCS789(Lxyz_q,Rxyz_q);
[euler_q] = rightCS789(Rxyz_qL);
[euler_cmm] = rightCS789(Rxyz_CMML);

[delta_q,epsilon_q,Ud_q,Ue_q] = ...
    findError789(Rxyz_qL,Rxyz_CMML,euler_q,euler_cmm)

% iPhone
[~,Rxyz_CMML] = leftCS789(Lxyz_CMM,Rxyz_CMM);
[~,Rxyz_iL] = leftCS789(Lxyz_i,Rxyz_i);
[euler_i] = rightCS789(Rxyz_iL);
[euler_cmm] = rightCS789(Rxyz_CMML);

[delta_i,epsilon_i,Ud_i,Ue_i] = ...
    findError789(Rxyz_iL,Rxyz_CMML,euler_i,euler_cmm)

% Artec Spider
[~,Rxyz_CMML] = leftCS456(Lxyz_CMM,Rxyz_CMM);
[~,Rxyz_sL] = leftCS456(Lxyz_s,Rxyz_s);
[euler_s] = rightCS456(Rxyz_sL);
[euler_cmm] = rightCS456(Rxyz_CMML);

[delta_s,epsilon_s,Ud_s,Ue_s] = ...

```

```
findError456(Rxyz_sL,Rxyz_CMML,euler_s,euler_cmm)
```

Functions

```
function [Lxyz2,Rxyz2] = leftCS456(Lxyz,Rxyz)
```

```
L = length(Lxyz);
```

```
for i = 1:L
```

```
    origin = Lxyz{i}(2,:); %
```

```
    x_axis = Lxyz{i}(1:2,:)-origin;
```

```
    x_axis = x_axis/norm(x_axis);
```

```
    z_axis = cross(x_axis,Lxyz{i}(3,:)-origin);
```

```
    z_axis = z_axis / norm(z_axis);
```

```
    y_axis = cross(z_axis,x_axis);
```

```
    rotation_matrix = [x_axis', y_axis', z_axis'];
```

```
    HTM = [rotation_matrix', -rotation_matrix'*origin'; 0 0 0 1];
```

```
    for j = 1:6
```

```
        Lxyz2{i}(j,:) = transformPosition(HTM,Lxyz{i}(j,:));
```

```
        Rxyz2{i}(j,:) = transformPosition(HTM,Rxyz{i}(j,:));
```

```
    end
```

```
end
```

```
end
```

```

function [Lxyz2,Rxyz2] = leftCS567(Lxyz,Rxyz)

L = length(Lxyz);

    for i = 1:L
        origin = Lxyz{i}(3,:); %
        x_axis = Lxyz{i}(2,:)-origin;
        x_axis = x_axis/norm(x_axis);

        z_axis = cross(x_axis,Lxyz{i}(4,:)-origin);
        z_axis = z_axis / norm(z_axis);

        y_axis = cross(z_axis,x_axis);

        rotation_matrix = [x_axis', y_axis', z_axis'];

        HTM = [rotation_matrix', -rotation_matrix'*origin'; 0 0 0 1];

        for j = 1:6
            Lxyz2{i}(j,:) = transformPosition(HTM,Lxyz{i}(j,:));
            Rxyz2{i}(j,:) = transformPosition(HTM,Rxyz{i}(j,:));
        end
    end
end

function [Lxyz2,Rxyz2] = leftCS789(Lxyz,Rxyz)

L = length(Lxyz);

    for i = 1:L

```

```

origin = Lxyz{i}(5,:); %
x_axis = Lxyz{i}(4,:)-origin;
x_axis = x_axis/norm(x_axis);

z_axis = cross(x_axis,Lxyz{i}(6,:)-origin);
z_axis = z_axis / norm(z_axis);

y_axis = cross(z_axis,x_axis);

rotation_matrix = [x_axis', y_axis', z_axis'];

HTM = [rotation_matrix', -rotation_matrix'*origin'; 0 0 0 1];

for j = 1:6
    Lxyz2{i}(j,:) = transformPosition(HTM,Lxyz{i}(j,:));
    Rxyz2{i}(j,:) = transformPosition(HTM,Rxyz{i}(j,:));
end
end
end

function [euler] = rightCS456(Rxyz)
L = length(Rxyz);
for i = 1:L
    origin = Rxyz{i}(2,:); %
    x_axis = Rxyz{i}(1,:)-origin;
    x_axis = x_axis/norm(x_axis);

    z_axis = cross(x_axis,Rxyz{i}(3,:)-origin);
    z_axis = z_axis / norm(z_axis);

```

```

        y_axis = cross(z_axis,x_axis);

        rotation_matrix = [x_axis' y_axis' z_axis'];
        euler{i} = rad2deg(rotm2eul(rotation_matrix,'ZYX'));
    end
end

```

```

function [euler] = rightCS567(Rxyz)
L = length(Rxyz);
    for i = 1:L
        origin = Rxyz{i}(3,:); %
        x_axis = Rxyz{i}(2,:)-origin;
        x_axis = x_axis/norm(x_axis);

        z_axis = cross(x_axis,Rxyz{i}(4,:)-origin);
        z_axis = z_axis / norm(z_axis);

        y_axis = cross(z_axis,x_axis);

        rotation_matrix = [x_axis' y_axis' z_axis'];
        euler{i} = rad2deg(rotm2eul(rotation_matrix,'ZYX'));
    end
end

```

```

function [euler] = rightCS789(Rxyz)
L = length(Rxyz);
    for i = 1:L
        origin = Rxyz{i}(5,:); %

```

```

        x_axis = Rxyz{i}(4,:)-origin;
        x_axis = x_axis/norm(x_axis);

        z_axis = cross(x_axis,Rxyz{i}(6,:)-origin);
        z_axis = z_axis / norm(z_axis);

        y_axis = cross(z_axis,x_axis);

        rotation_matrix = [x_axis' y_axis' z_axis'];
        euler{i} = rad2deg(rotm2eul(rotation_matrix,'ZYX'));
    end
end

function transformed_position = transformPosition(HTM,position)
    position = [position, 1];
    transformed_position = HTM * position';
    transformed_position = transformed_position(1:3)';
end

function [delta,epsilon,U_delta,U_epsilon] = ...
    findError456(Rxyz1,Rxyz2,eul1,eul2)
k = 2;
L = length(Rxyz1);

for i = 1:L
    delta_ans{i} = (Rxyz1{i}(2,:) - Rxyz2{1}(2,:))*1e3;
    epsilon_ans{i} = eul1{i}-eul2{1};
end
for i = 1:L

```

```

        delta_x(i) = delta_ans{i}(1,1);
        delta_y(i) = delta_ans{i}(1,2);
        delta_z(i) = delta_ans{i}(1,3);
        epsilon_z(i) = epsilon_ans{i}(1,1);
        epsilon_y(i) = epsilon_ans{i}(1,2);
        epsilon_x(i) = epsilon_ans{i}(1,3);
    end

    delta = [mean(delta_x) mean(delta_y) mean(delta_z)
             std(delta_x) std(delta_y) std(delta_z)];
    epsilon = [mean(epsilon_x) mean(epsilon_y) mean(epsilon_z)
              std(epsilon_x) std(epsilon_y) std(epsilon_z)].*60;
    U_delta = k*norm(delta(2,:));
    U_epsilon = k*norm(epsilon(2,:));
end

function [delta,epsilon,U_delta,U_epsilon] = ...
    findError567(Rxyz1,Rxyz2,eul1,eul2)

k = 2;
L = length(Rxyz1);

for i = 1:L
    delta_ans{i} = (Rxyz1{i}(3,:) - Rxyz2{1}(3,:))*1e3;
    epsilon_ans{i} = eul1{i}-eul2{1};
end

for i = 1:L
    delta_x(i) = delta_ans{i}(1,1);
    delta_y(i) = delta_ans{i}(1,2);
    delta_z(i) = delta_ans{i}(1,3);

```



```

        epsilon_z(i) = epsilon_ans{i}(1,1);
        epsilon_y(i) = epsilon_ans{i}(1,2);
        epsilon_x(i) = epsilon_ans{i}(1,3);
    end

    delta = [mean(delta_x) mean(delta_y) mean(delta_z)
             std(delta_x) std(delta_y) std(delta_z)];
    epsilon = [mean(epsilon_x) mean(epsilon_y) mean(epsilon_z)
              std(epsilon_x) std(epsilon_y) std(epsilon_z)].*60;
    U_delta = k*norm(delta(2,:));
    U_epsilon = k*norm(epsilon(2,:));
end

function [delta,epsilon,U_delta,U_epsilon] = ...
    findError789(Rxyz1,Rxyz2,eul1,eul2)
k = 2;
L = length(Rxyz1);

for i = 1:L
    delta_ans{i} = (Rxyz1{i}(5,:) - Rxyz2{1}(5,:))*1e3;
    epsilon_ans{i} = eul1{i}-eul2{1};
end
for i = 1:L
    delta_x(i) = delta_ans{i}(1,1);
    delta_y(i) = delta_ans{i}(1,2);
    delta_z(i) = delta_ans{i}(1,3);
    epsilon_z(i) = epsilon_ans{i}(1,1);
    epsilon_y(i) = epsilon_ans{i}(1,2);
    epsilon_x(i) = epsilon_ans{i}(1,3);
end

```

```

end

delta = [mean(delta_x) mean(delta_y) mean(delta_z)
         std(delta_x) std(delta_y) std(delta_z)];
epsilon = [mean(epsilon_x) mean(epsilon_y) mean(epsilon_z)
           std(epsilon_x) std(epsilon_y) std(epsilon_z)].*60;
U_delta = k*norm(delta(2,:));
U_epsilon = k*norm(epsilon(2,:));
end

```

Vita

Jake Dvorak obtained his bachelor's degree in Mechanical Engineering from the University of Tennessee in 2017. He became a graduate research assistant under Dr. Chad Duty and a graduate teaching assistant under Dr. Matthew Young. While working his teaching assistantship in the MABE Maker Lab he conducted research for Dr. Duty and the Manufacturing Demonstration Facility. He completed his thesis titled "Measurement and Analysis of Pressure Profile for Nozzle Based Single Screw Extrusion Systems" in fall of 2020 to earn a master's degree in Mechanical Engineering. He continued on in graduate school at University of Tennessee under Dr. Tony Schmitz. He began working full time for the MABE department directing the MABE Maker Lab while pursuing his PhD in Mechanical Engineering specializing in hybrid manufacturing. After working to improve the MABE Maker Lab and helping it grow to become a UT core facility, the Manufacturing Core at University of Tennessee, he stepped down from the director role in early 2024 to complete his dissertation and work towards a post-doc role in manufacturing research.