NMSA

AN INSTMC SPECIAL INTEREST GROUP

METROLOGY SKILLS FRAMEWORK
NMSA-2.1 – MANUFACTURING METROLOGY

National Metrology Skills Alliance

Version 1.0, 20th December 2023

InstMC

Foreword

The National Metrology Skills Alliance (NMSA) comprises a range of industrial and scientific companies together with educators and national bodies involved in metrology. It was formed to promote the standardisation of metrology skills, driving efficiency and consistency across UK industry. This standard framework is the result of the first phase of activity of the NMSA. Further information is available on the InstMC NMSA Special Interest Group website at:

https://www.instmc.org/sigs/national_metrology_skills_alliance

Introduction

The NMSA is structured with 2 sections as shown below in *Figure 1*. NMSA 1 defines standard skills levels for metrology and a suite of generic skills objectives that are applicable to any metrology discipline. NMSA 2 is a library of standards that define the skills objectives for a specific discipline within metrology. These are typically scoped to be relevant for a group of industrial users, rather than strictly aligned to a structure such as the SI units. In this they are flexible and can be tailored to the needs of the group. Each of the NMSA 2 standards are intended to be used in conjunction with NMSA 1.

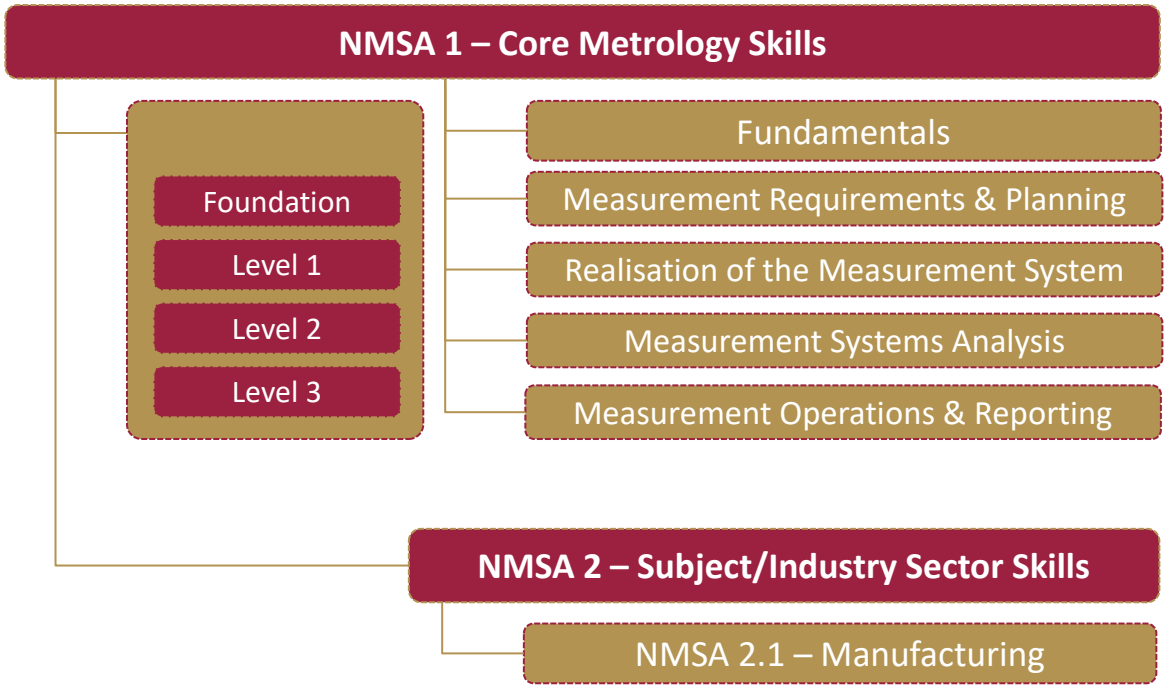

Figure 1 - NMSA Structure

This NMSA 2 standard defines the skills for manufacturing metrology, including application of measurement within the manufacturing industry. The content is not specific to any particular industrial sector and is intended to be flexible to suit application of a range of methods and technologies. The content is primarily based around dimensional measurement methods applied at a scale from microns to metres, therefore does not look to directly address nano-scale measurements or at a scale for building or surveying.

The standard has been developed by a user group of industrial metrologists working within a range of

manufacturing businesses, to focus on practical application and support key roles in deploying manufacturing metrology. The structure of the document supports the core skill levels defined in NMSA 1, to define specific skills and tasks against distinct technology or method areas, where different skills exist. Dependent on the role of the user, they may look to use all sections of NMSA 2.1 or select only those that are relevant.

Scope

In-scope

- Manufacturing Metrology methods
  - Manual Gauging
  - Surface Texture
  - Co-ordinate Metrology
  - Non-Contact/Optical
  - X-Ray/Computed Tomography

Out of Scope

- Non-Destructive Examination methods
- Visual Inspection
- Torque tightening and assembly methods
- Functional product testing

Contents

2.1.1 - Manual Measurement and Gauging

Category	Description	Foundation	Level 1	Level 2	Level 3
1. Operating Principle	**Operating principle for the measurement system, including, but not limited to:** - physical principles of operation - key elements of the system - measurement point acquisition method - type of data output, reading or scale	Describe the operating principle.	Explain the operating principle.	Evaluate and identify potential improvements to the operating principle.	Design and develop improvements to the operating principle.
2. Technology Selection	**Selection of the appropriate measurement system, including, but not limited to:** - Handheld Measurement Equipment (Micrometers, Calipers, Depth Gauges, Bore Gauges, Comparators) - Bench Top Measurement Equipment (Height Gauges, Indicators) - Measurement Standards (Gauge Blocks, Length Bars, Setting Masters, Ring Gauges) Selection of equipment to meet the measurement capability requirements Surface condition of the workpiece (texture, form, flexibility, measurement force)	List measurement systems that could be selected for an application. Describe the relative benefits and limitations of measurement systems for an application.	Explain measurement systems that could be selected for an application. Compare the relative benefits and limitations of measurement systems for an application.	Evaluate and analyse measurement systems that could be selected for an application. Justify the selection of the measurement system for an application.	Design a study to critically evaluate measurement systems that could be selected for an application. Approve the selection of the measurement system for an application.

3. Environmental Impacts	**Environmental impacts on the measurement system, including, but not limited to:** - cleanliness (environment, workpiece) - temperature - rate of change of temperature - light levels - humidity - vibration - interference (electrical, magnetic etc)	List environmental impacts that could influence the measurement system. Understand the procedure for controlling environmental impacts.	Explain environmental impacts that could influence the measurement system. Conduct the procedure for controlling environmental impacts.	Evaluate and analyse environmental impacts that could influence the measurement system. Identify and respond to potential improvements to the procedure for controlling environmental impacts. Design an asset care process.	Design a study to evaluate the environmental impacts that could influence the measurement system. Create the procedure for controlling environmental impacts. Approve the asset care process.
4. Validation	**Measurement Systems Analysis Studies (Variable), including, but not limited to:** - Repeatability Study (Type 1) - Full Gauge Repeatability & Reproducibility Study (Type 2) - Bias Study - Linearity Study - Stability Study - Evaluating the Measurement Process (EMP) - Measurement Uncertainty Analysis (MUA) - Static or dynamic study - Monte Carlo simulation **Measurement Systems Analysis Studies (Attribute), including, but not limited to:** - Attribute Agreement Analysis (% agreement, Fleiss Kappa)	Describe a validation study to prove capability of the measurement system.	Conduct a validation study to prove capability of the measurement system to a defined plan.	Design and instruct a validation study to prove capability of the measurement system.	Approve a validation study to prove capability of the measurement system.

5. Calibration	**Calibration (or verification) methods for the measurement system, including, but not limited to:** - relevant standards requirements (national, international, consensus) - limitations of the calibration/verification - calibrated parameters, characteristics or elements	Describe the calibration approach.	Explain the calibration approach. Interpret calibration results to identify pass / fail and any subsequent actions required.	Review the calibration (results, method and parameters). Instruct subsequent actions for failed calibration results. Identify trends or drift of results from the calibration and monitor adjustments.	Define the calibration specification. Evaluate non-standard situations arising from the calibrations, make and justify the appropriate decision. Approves the calibration period to ensure it is suitable based on calibration results.
6. Setup and Verification	**Best practice for setup and verification of the measurement system, including, but not limited to:** - handling - setup - calibration/verification - sanity checks	Describe best practice for setup and verification of the measurement system. Describe the relevant verification checks for the measurement system.	Carry out best practice for setup and verification, perform pre-work checks and identify presence of calibration for the measurement system. Conduct relevant verification checks for the measurement system and clearly identify if the results are pass or fail.	Review and identify improvements to the best practice for setup and verification of the measurement system. Define the verification process and pre-check routines, correct handling procedures.	Create the procedure for best practice for setup and verification of the measurement system. Approve the verification process and pre-check routines, correct handling procedures.
	Work holding influence, including, but not limited to: - distortion and deformation - free state vs clamped state - links to the design requirements	Describe best practice for work holding. Describe how work holding can influence measurement results.	Carry out best practice for work holding. Carry out verification checks on the work holding to minimise the influence on measurement results.	Review and identify improvements to the best practice for work holding. Define the verification checks on the work holding to minimise the influence on measurement results.	Create the procedure for best practice for work holding. Approve the verification checks on the work holding to minimise the influence on measurement results.
7. Programming	N/A for manual gauging	N/A	N/A	N/A	N/A

8. Execution	**Use of measurement systems, including, but not limited to:** - following setup instructions - executing approved measurement plans - identifying common measurement errors - record/evaluate results	N/A	Carry out measurement activities using the measurement system.	Modify the process for control of execution of the measurement system.	Develop the process for control of execution of the measurement system.
9. Errors and Fault Finding	**Common errors for the measurement system, including, but not limited to:** - Parallax Error - Abbe's Error - Cosine Error - technique **Workpiece effects, including, but not limited to:** - form (lobing etc) - surface texture - materials - flexible workpiece - workpiece-to-workpiece variation Tactile Specific: - plastic/elastic deformation - styli shape and material effects	List common errors and faults that could impact the measurement system. Understand the procedure for controlling common errors and faults.	Explain common errors and faults that could impact the measurement system. Conduct the procedure for controlling common errors and faults.	Evaluate and analyse common errors and faults that could impact the measurement system. Develop the procedure for controlling common errors and faults.	Design a study to evaluate common errors and faults that could impact the measurement system. Approve the procedure for controlling common errors and faults.
10. Interpretation of Results	**Results and reporting from the measurement system, including, but not limited to:** - measured units - type of values - required calculations - understand the system output - GD&T	Understand the results output from the measurement system.	Interpret and explain the results output from the measurement system.	Evaluate and analyse the results output from the measurement system.	Develop and approve the process to control the results output from the measurement system.

2.1.2 - Surface Texture

Category	Description	Foundation	Level 1	Level 2	Level 3
1. Operating Principle	**Operating principle for the measurement system, including, but not limited to:** - physical principles of operation - key elements of the system - measurement point acquisition method - type of data output	Describe the operating principle.	Explain the operating principle.	Evaluate and identify potential improvements to the operating principle.	Design and develop improvements to the operating principle.
2. Technology Selection	**Selection of the appropriate measurement system, including, but not limited to:** - Tactile or Non-Contact Optical - 2D or 3D (Areal) - different types of styli (tips, radius, skidded/skidless) - different types of optical system (White Light Interferometry, Confocal Microscopy, Focus Variation etc) - Surface condition of the workpiece (reflection, diffraction, transparency, specularity, sub-surface scattering)	List measurement systems that could be selected for an application. Describe the relative benefits and limitations of measurement systems for an application.	Explain measurement systems that could be selected for an application. Compare the relative benefits and limitations of measurement systems for an application.	Evaluate and analyse measurement systems that could be selected for an application. Justify the selection of the measurement system for an application.	Design a study to critically evaluate measurement systems that could be selected for an application. Approve the selection of the measurement system for an application.

3. Environmental Impacts	**Environmental impacts on the measurement system, including, but not limited to:** - cleanliness (environment, workpiece) - temperature - rate of change of temperature - light levels - humidity - vibration - interference (electrical, magnetic etc) - stray light	List environmental impacts that could influence the measurement system. Understand the procedure for controlling environmental impacts.	Explain environmental impacts that could influence the measurement system. Conduct the procedure for controlling environmental impacts.	Evaluate and analyse environmental impacts that could influence the measurement system. Identify and respond to potential improvements to the procedure for controlling environmental impacts. Design an asset care process.	Design a study to evaluate the environmental impacts that could influence the measurement system. Create the procedure for controlling environmental impacts. Approve the asset care process.
4. Validation	**Measurement Systems Analysis Studies (Variable), including, but not limited to:** - Repeatability Study (Type 1) - Full Gauge Repeatability & Reproducibility Study (Type 2) - Bias Study - Linearity Study - Stability Study - Evaluating the Measurement Process (EMP) - Measurement Uncertainty Analysis (MUA) - Static or dynamic study - Monte Carlo simulation **Measurement Systems Analysis Studies (Attribute), including, but not limited to:** - Attribute Agreement Analysis (% agreement, Fleiss Kappa)	Describe a validation study to prove capability of the measurement system.	Conduct a validation study to prove capability of the measurement system to a defined plan.	Design and instruct a validation study to prove capability of the measurement system.	Approve a validation study to prove capability of the measurement system.

5. Calibration	**Calibration (or verification) methods for the measurement system, including, but not limited to:** - relevant standards requirements (national, international, consensus) - limitations of the calibration/verification - calibrated parameters, characteristics or elements	Describe the calibration approach.	Explain the calibration approach. Interpret calibration results to identify pass / fail and any subsequent actions required.	Review the calibration (results, method and parameters). Instruct subsequent actions for failed calibration results. Identify trends or drift of results from the calibration and monitor adjustments.	Define the calibration specification. Evaluate non-standard situations arising from the calibrations, make and justify the appropriate decision. Approves the calibration period to ensure it is suitable based on calibration results.
6. Setup and Verification	**Best practice for setup and verification of the measurement system, including, but not limited to:** - handling - setup - calibration/verification - sanity checks - different types of styli - orientation of the surface (perpendicular to optics for areal systems) - selection and understanding of filtering (linear gaussian, robust gaussian etc.) - thresholding - surface curvature (filtering)	Describe best practice for setup and verification of the measurement system. Describe the relevant verification checks for the measurement system. Describe the importance of styli and probe systems and the need for qualification.	Carry out best practice for setup and verification, perform pre-work checks and identify presence of calibration for the measurement system. Conduct relevant verification checks for the measurement system and clearly identify if the results are pass or fail. Conduct the probing system qualification in line with the defined process.	Review and identify improvements to the best practice for setup and verification of the measurement system. Define the verification process and pre-check routines, correct handling procedures. Define the probing system qualification process.	Create the procedure for best practice for setup and verification of the measurement system. Approve the verification process and pre-check routines, correct handling procedures. Approve the probing system qualification process.

	Work holding influence, including, but not limited to: - distortion and deformation - free state vs clamped state - links to the design requirements	Describe best practice for work holding. Describe how work holding can influence measurement results.	Carry out best practice for work holding. Carry out verification checks on the work holding to minimise the influence on measurement results.	Review and identify improvements to the best practice for work holding. Define the verification checks on the work holding to minimise the influence on measurement results.	Create the procedure for best practice for work holding. Approve the verification checks on the work holding to minimise the influence on measurement results.
7. Programming	**Program issue and control, including, but not limited to:** - program identifiers - version control - program change management **Programming software version changes, including, but not limited to:** - changes in feature calculations - changes to evaluation methods - datum calculation methods	Describe the need for the control of programs	Carry out program issue and control using the organisations prescribed system	Design and implement a system for program issue and control Conduct process for updating programming software	Approves the process of program issue and control Design controls for updating programming software and control the effects it can have on measured results
	Translating the design requirement into feature definitions, including, but not limited to: - default evaluation methods (e.g. ISO, ASME) **Filtering Approach, including, but not limited to:** - selection of filtering methods - when filtering should be applied - filter thresholds (cut off and outlier removal) - common filtering issues **Measuring process, including**	Describe the importance of understanding/translating the design requirement. Describe good practice in programming the measurement system	Conduct programming of the measurement system, for simple activities, translating the design requirement into a program by following a predefined programming process. Carry out programming procedures that minimize or remove the common forms of error, and selecting the correct filtering method (where	Design the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Identifies potential design requirement constraints that could lead to sources of measurement error when reviewing design specifications. Conduct programming of	Approve the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Develops a process to identify potential sources of error when reviewing processes and drawings and suggest mitigation techniques.

	but not limited to: - measurement speed - sample frequency - measurement length (traverse) - positioning the styli - sample alignment		required).	the measurement system, for complex activities.	
8. Execution	**Use of measurement systems, including, but not limited to:** - following setup instructions - executing approved measurement plans - identifying common measurement errors - record/evaluate results	N/A	Carry out measurement activities using the measurement system.	Modify the process for control of execution of the measurement system.	Develop the process for control of execution of the measurement system.
9. Errors and Fault Finding	**Common errors for the measurement system, including, but not limited to:** - surface reflectivity for optical methods - stylus or radius tip size - mechanical filtering - stylus force - tracing speed - sample rate **Workpiece effects, including, but not limited to:** - form (curved surfaces) - surface texture - materials - flexible workpiece - workpiece-to-workpiece variation Tactile Specific: - plastic/elastic deformation - styli shape and material effects	List common errors and faults that could impact the measurement system. Understand the procedure for controlling common errors and faults.	Explain common errors and faults that could impact the measurement system. Conduct the procedure for controlling common errors and faults.	Evaluate and analyse common errors and faults that could impact the measurement system. Develop the procedure for controlling common errors and faults.	Design a study to evaluate common errors and faults that could impact the measurement system. Approve the procedure for controlling common errors and faults.

	Non-contact specific: - reflectivity - shallow edge contrast - transparency - specularity - sub-surface scattering				
10. Interpretation of Results	**Results and reporting from the measurement system, including, but not limited to:** - measured units - type of values - required calculations - different types of traces - interpretation of data (e.g. Abbott-Firestone curve) - GD&T for roughness, waviness & form (ISO/ASME) - Surface Texture Parameters: - (ISO/ASME) - R (Roughness) - W (Waviness) - F (Form)	Understand the results output from the measurement system.	Interpret and explain the results output from the measurement system.	Evaluate and analyse the results output from the measurement system.	Develop and approve the process to control the results output from the measurement system.

2.1.3 - Co-ordinate Metrology

Category	Description	Foundation	Level 1	Level 2	Level 3
1. Operating Principle	**Operating principle for the measurement system, including, but not limited to:** - physical principles of operation - key elements of the system - measurement point acquisition method - type of data output	Describe the operating principle.	Explain the operating principle.	Evaluate and identify potential improvements to the operating principle.	Design and develop improvements to the operating principle.
2. Technology Selection	**Selection of the appropriate measurement system, including, but not limited to:** - small, medium, large volume - construction type - absolute vs comparative - Inline measurement - machine probing Tactile specific: - bridge - gantry - cantilever - horizontal arm Non-contact specific: - laser - optical - interferometry Portable specific: - articulating arm - laser tracker **Selection of an appropriate**	List measurement systems that could be selected for an application. Describe the relative benefits and limitations of measurement systems for an application.	Explain measurement systems that could be selected for an application. Compare the relative benefits and limitations of measurement systems for an application.	Evaluate and analyse measurement systems that could be selected for an application. Justify the selection of the measurement system for an application.	Design a study to critically evaluate measurement systems that could be selected for an application. Approve the selection of the measurement system for an application.

	sensor system, including but not limited to: - benefits and limitations of different sensor options - density vs data quality choice Tactile specifics: - sensor system choice (articulating head, fixed head, tactile, active scanning, passive scanning, ultrasonic, surface finish probes) Non-Contact specifics: - scanners - photogrammetry - Surface condition of the workpiece (reflection, diffraction, transparency, specularity, sub-surface scattering)				
3. Environmental Impacts	**Environmental impacts on the measurement system, including, but not limited to:** - cleanliness (environment, workpiece) - temperature - rate of change of temperature - light levels - humidity - vibration - interference (electrical, magnetic etc) - air (contaminates, pressure, flow) - stray light	List environmental impacts that could influence the measurement system. Understand the procedure for controlling environmental impacts.	Explain environmental impacts that could influence the measurement system. Conduct the procedure for controlling environmental impacts.	Evaluate and analyse environmental impacts that could influence the measurement system. Identify and respond to potential improvements to the procedure for controlling environmental impacts. Design an asset care process.	Design a study to evaluate the environmental impacts that could influence the measurement system. Create the procedure for controlling environmental impacts. Approve the asset care process.

4. Validation	**Measurement Systems Analysis Studies (Variable), including, but not limited to:** - Repeatability Study (Type 1) - Full Gauge Repeatability & Reproducibility Study (Type 2) - Bias Study - Linearity Study - Stability Study - Evaluating the Measurement Process (EMP) - Measurement Uncertainty Analysis (MUA) - Static or dynamic study - Monte Carlo simulation	Describe a validation study to prove capability of the measurement system.	Conduct a validation study to prove capability of the measurement system to a defined plan.	Design and instruct a validation study to prove capability of the measurement system.	Approve a validation study to prove capability of the measurement system.
5. Calibration	**Calibration (or verification) methods for the measurement system, including, but not limited to:** - relevant standards requirements (national, international, consensus) - limitations of the calibration/verification - calibrated parameters, characteristics or elements - trumpet diagrams	Describe the calibration approach.	Explain the calibration approach. Interpret calibration results to identify pass / fail and any subsequent actions required.	Review the calibration (results, method and parameters). Instruct subsequent actions for failed calibration results. Identify trends or drift of results from the calibration and monitor adjustments.	Define the calibration specification. Evaluate non-standard situations arising from the calibrations, make and justify the appropriate decision. Approves the calibration period to ensure it is suitable based on calibration results.
6. Setup and Verification	**Best practice for setup and verification of the measurement system, including, but not limited to:** - handling - setup - calibration/verification (reference part, artefact, 'gold' part) - sanity checks	Describe best practice for setup and verification of the measurement system. Describe the relevant verification checks for the measurement system. Describe the importance of	Carry out best practice for setup and verification, perform pre-work checks and identify presence of calibration for the measurement system. Conduct relevant verification checks for the measurement	Review and identify improvements to the best practice for setup and verification of the measurement system. Define the verification process and pre-check routines, correct handling procedures.	Create the procedure for best practice for setup and verification of the measurement system. Approve the verification process and pre-check routines, correct handling procedures.

	Non-contact specifics: - resolution - intensity **Probing system and styli maintenance, including, but not limited to:** Generic: - Reference spheres and qualification - qualitative checks - maintenance of probes and sensors Tactile Specifics: - material selection - styli shape - stiffness/rigidity - Size, Length, Alignment, Tightness - diameter - standard deviation Non-contact Specifics: - working range - resolution - frequency	styli and probe systems and the need for qualification.	system and clearly identify if the results are pass or fail. Conduct the probing system qualification in line with the defined process.	Define the probing system qualification process.	Approve the probing system qualification process.
	Work holding influence, including, but not limited to: - distortion and deformation - free state vs clamped state - links to the design requirements	Describe best practice for work holding. Describe how work holding can influence measurement results.	Carry out best practice for work holding. Carry out verification checks on the work holding to minimise the influence on measurement results.	Review and identify improvements to the best practice for work holding. Define the verification checks on the work holding to minimise the influence on measurement results.	Create the procedure for best practice for work holding. Approve the verification checks on the work holding to minimise the influence on measurement results.

7. Programming	**Program issue and control, including, but not limited to:** - program identifiers - version control - program change management **Programming software version changes, including, but not limited to:** - changes in feature calculations - changes to evaluation methods - datum calculation methods	Describe the need for the control of programs	Carry out program issue and control using the organisations prescribed system	Design and implement a system for program issue and control Conduct process for updating programming software	Approves the process of program issue and control Design controls for updating programming software and control the effects it can have on measured results
	Translating the design requirement into a Co-ordinate system/datum structure and definitions, including, but not limited to: - degrees of freedom - co-ordinate system types - alignment methods - best fit Portable specifics: - bundling Techniques **Translating the design requirement into feature definitions, including, but not limited to:** - minimum point density for features - minimum point density for form - AD-HOC approach - scientific approach - feature coverage - default evaluation methods (e.g. ISO, ASME) - Monte Carlo Simulations	Describe the importance of understanding/translating the design requirement. List some important aspects of programming a co-ordinate measuring system.	Conduct programming of the measurement system, for simple activities, translating the design requirement into a program by following a predefined programming process. Carry out programming procedures that minimise or remove the common forms of error, and selecting the correct filtering method (where required).	Design the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Identifies potential design requirement constraints that could lead to sources of measurement error when reviewing design specifications. Conduct programming of the measurement system, for complex activities.	Approve the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Develops a process to identify potential sources of error when reviewing processes and drawings and suggest mitigation techniques.

	Approach Vectors and Velocity, including, but not limited to: - effects of cosine - calculation of normal vectors **Filtering Approach, including, but not limited to:** - selection of filtering methods - when filtering should be applied - filter thresholds (cut off and outlier removal) - common filtering issues				
8. Execution	**Use of measurement systems, including, but not limited to:** - following setup instructions - executing approved measurement plans - identifying common measurement errors - record/evaluate results	N/A	Carry out measurement activities using the measurement system.	Modify the process for control of execution of the measurement system.	Develop the process for control of execution of the measurement system.
9. Errors and Fault Finding	**Common errors for the measurement system, including, but not limited to:** - programming errors - projection errors - ineffective strategy selection - datum selections - Abbe's Error - Cosine Error - collisions **Workpiece effects, including, but not limited to:** - form (lobing etc) - surface texture - materials - flexible workpiece	List common errors and faults that could impact the measurement system. Understand the procedure for controlling common errors and faults.	Explain common errors and faults that could impact the measurement system. Conduct the procedure for controlling common errors and faults.	Evaluate and analyse common errors and faults that could impact the measurement system. Develop the procedure for controlling common errors and faults.	Design a study to evaluate common errors and faults that could impact the measurement system. Approve the procedure for controlling common errors and faults.

	- workpiece-to-workpiece variation Tactile Specific: - plastic/elastic deformation - styli shape and material effects Non-contact specific: - reflectivity - shallow edge contrast - transparency - specularity - sub-surface scattering				
10. Interpretation of Results	**Results and reporting from the measurement system, including, but not limited to:** - measured units - type of values - required calculations - understand the system output (point cloud, colourmap, numerical) - GD&T	Understand the results output from the measurement system.	Interpret and explain the results output from the measurement system.	Evaluate and analyse the results output from the measurement system.	Develop and approve the process to control the results output from the measurement system.

2.1.4 - Non-Contact/Optical

Category	Description	Foundation	Level 1	Level 2	Level 3
1. Operating Principle	**Operating principle for the measurement system, including, but not limited to:** - physical principles of operation - key elements of the system - measurement point acquisition method - type of data output	Describe the operating principle.	Explain the operating principle.	Evaluate and identify potential improvements to the operating principle.	Design and develop improvements to the operating principle.
2. Technology Selection	**Selection of the appropriate measurement system, including, but not limited to:** - small, medium, large volume - construction type - absolute vs comparative - Inline measurement Non-contact specific: - structured light - laser - optical - photogrammetry - interferometry Portable specific: - articulating arm laser line probe - laser tracker with non-contact accessory Multi-sensor systems - small, medium, large volume - construction type - absolute vs comparative - Inline measurement	List measurement systems that could be selected for an application. Describe the relative benefits and limitations of measurement systems for an application.	Explain measurement systems that could be selected for an application. Compare the relative benefits and limitations of measurement systems for an application.	Evaluate and analyse measurement systems that could be selected for an application. Justify the selection of the measurement system for an application.	Design a study to critically evaluate measurement systems that could be selected for an application. Approve the selection of the measurement system for an application.

	Sensor system selection, including but not limited to: - benefits and limitations of different sensor options - density vs data quality choice Selection of equipment to meet the measurement capability requirements Surface condition of the workpiece (reflection, diffraction, transparency, specularity, sub-surface scattering)				
3. Environmental Impacts	**Environmental impacts on the measurement system, including, but not limited to:** - cleanliness (environment, workpiece) - temperature - rate of change of temperature - light levels - humidity - vibration - interference (electrical, magnetic etc) - air (contaminates, pressure, flow) - stray light	List environmental impacts that could influence the measurement system. Understand the procedure for controlling environmental impacts.	Explain environmental impacts that could influence the measurement system. Conduct the procedure for controlling environmental impacts.	Evaluate and analyse environmental impacts that could influence the measurement system. Identify and respond to potential improvements to the procedure for controlling environmental impacts. Design an asset care process.	Design a study to evaluate the environmental impacts that could influence the measurement system. Create the procedure for controlling environmental impacts. Approve the asset care process.

4. Validation	**Measurement Systems Analysis Studies (Variable), including, but not limited to:** - Repeatability Study (Type 1) - Full Gauge Repeatability & Reproducibility Study (Type 2) - Bias Study - Linearity Study - Stability Study - Evaluating the Measurement Process (EMP) - Measurement Uncertainty Analysis (MUA) - Static or dynamic study - Monte Carlo simulation	Describe a validation study to prove capability of the measurement system.	Conduct a validation study to prove capability of the measurement system to a defined plan.	Design and instruct a validation study to prove capability of the measurement system.	Approve a validation study to prove capability of the measurement system.
5. Calibration	**Calibration (or verification) methods for the measurement system, including, but not limited to:** - relevant standards requirements (national, international, consensus) - limitations of the calibration/verification - calibrated parameters, characteristics or elements - trumpet diagrams	Describe the calibration approach.	Explain the calibration approach. Interpret calibration results to identify pass / fail and any subsequent actions required.	Review the calibration (results, method and parameters). Instruct subsequent actions for failed calibration results. Identify trends or drift of results from the calibration and monitor adjustments.	Define the calibration specification. Evaluate non-standard situations arising from the calibrations, make and justify the appropriate decision. Approves the calibration period to ensure it is suitable based on calibration results.

6. Setup and Verification	**Best practice for setup and verification of the measurement system, including, but not limited to:** - handling - setup - calibration/verification (reference part, artefact, 'gold' part) - sanity checks Non-contact specifics: - resolution - intensity **Probing system and styli maintenance, including, but not limited to:** Generic: - Reference spheres and qualification - qualitative checks - maintenance of probes and sensors Non-Contact / Optical Specifics: - material selection - stiffness/rigidity - Size, Length, Alignment, Tightness - diameter - standard deviation Non-contact Specifics: - working range - resolution - frequency	Describe best practice for setup and verification of the measurement system. Describe the relevant verification checks for the measurement system. Describe the importance of styli and probe systems and the need for qualification.	Carry out best practice for setup and verification, perform pre-work checks and identify presence of calibration for the measurement system. Conduct relevant verification checks for the measurement system and clearly identify if the results are pass or fail. Conduct the probing system qualification in line with the defined process.	Review and identify improvements to the best practice for setup and verification of the measurement system. Define the verification process and pre-check routines, correct handling procedures. Define the probing system qualification process.	Create the procedure for best practice for setup and verification of the measurement system. Approve the verification process and pre-check routines, correct handling procedures. Approve the probing system qualification process.

	Work holding influence, including, but not limited to: - distortion and deformation - free state vs clamped state - links to the design requirements	Describe best practice for work holding. Describe how work holding can influence measurement results.	Carry out best practice for work holding. Carry out verification checks on the work holding to minimise the influence on measurement results.	Review and identify improvements to the best practice for work holding. Define the verification checks on the work holding to minimise the influence on measurement results.	Create the procedure for best practice for work holding. Approve the verification checks on the work holding to minimise the influence on measurement results.
7. Programming	**Program issue and control, including, but not limited to:** - program identifiers - version control - program change management **Programming software version changes, including, but not limited to:** - changes in feature calculations - changes to evaluation methods - datum calculation methods	Describe the need for the control of programs	Carry out program issue and control using the organisations prescribed system	Design and implement a system for program issue and control Conduct process for updating programming software	Approves the process of program issue and control Design controls for updating programming software and control the effects it can have on measured results
	Translating the design requirement into a Co-ordinate system/datum structure and definitions, including, but not limited to: - degrees of freedom - co-ordinate system types - alignment methods - best fit Portable specifics: - bundling Techniques **Translating the design requirement into feature definitions, including, but not**	Describe the importance of understanding/translating the design requirement. List some important aspects of programming a co-ordinate measuring system.	Conduct programming of the measurement system, for simple activities, translating the design requirement into a program by following a predefined programming process. Carry out programming procedures that minimise or remove the common forms of error, and selecting the correct filtering	Design the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Identifies potential design requirement constraints that could lead to sources of measurement error when reviewing design specifications. Conduct programming of	Approve the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Develops a process to identify potential sources of error when reviewing processes and drawings and suggest mitigation techniques.

	limited to: - minimum point density for features - minimum point density for form - AD-HOC approach - scientific approach - feature coverage - default evaluation methods (e.g. ISO, ASME) - Monte Carlo Simulations **Approach Vectors, including, but not limited to:** - effects of cosine - calculation of normal vectors **Filtering Approach, including, but not limited to:** - selection of filtering methods - when filtering should be applied - filter thresholds (cut off and outlier removal) - common filtering issues		method (where required).	the measurement system, for complex activities.	
8. Execution	**Use of measurement systems, including, but not limited to:** - following setup instructions - executing approved measurement plans - identifying common measurement errors - record/evaluate results	N/A	Carry out measurement activities using the measurement system.	Modify the process for control of execution of the measurement system.	Develop the process for control of execution of the measurement system.

9. Errors and Fault Finding	**Common errors for the measurement system, including, but not limited to:** - programming errors - projection errors - ineffective strategy selection - datum selections - Abbe's Error - Cosine Error - collisions **Workpiece effects, including, but not limited to:** - form (lobing etc) - surface texture - materials - flexible workpiece - workpiece-to-workpiece variation Tactile Specific: - plastic/elastic deformation - styli shape and material effects Non-contact specific: - reflectivity - shallow edge contrast - transparency - specularity - sub-surface scattering	List common errors and faults that could impact the measurement system. Understand the procedure for controlling common errors and faults.	Explain common errors and faults that could impact the measurement system. Conduct the procedure for controlling common errors and faults.	Evaluate and analyse common errors and faults that could impact the measurement system. Develop the procedure for controlling common errors and faults.	Design a study to evaluate common errors and faults that could impact the measurement system. Approve the procedure for controlling common errors and faults.
10. Interpretation of Results	**Results and reporting from the measurement system, including, but not limited to:** - measured units - type of values - required calculations - understand the system output (point cloud, colourmap,	Understand the results output from the measurement system.	Interpret and explain the results output from the measurement system.	Evaluate and analyse the results output from the measurement system.	Develop and approve the process to control the results output from the measurement system.

	grayscale, numerical) - GD&T				

2.1.5 - X-Ray/Computed Tomography

Category	Description	Foundation	Level 1	Level 2	Level 3
1. Operating Principle	**Operating principle for the measurement system, including, but not limited to:** - physical principles of operation - key elements of the system - measurement point acquisition method - type of data output	Describe the operating principle.	Explain the operating principle.	Evaluate and identify potential improvements to the operating principle.	Design and develop improvements to the operating principle.
2. Technology Selection	**Selection of the appropriate measurement system, including, but not limited to:** - X-Ray / CT - 2D or 3D - Detector types (CLDA/Flat Panel) - Power Generation (e.g. 125 kV / 225kV / 450 kV / MeV) - Spot size - Filters - Scan area size - Material of the workpiece	List measurement systems that could be selected for an application. Describe the relative benefits and limitations of measurement systems for an application.	Explain measurement systems that could be selected for an application. Compare the relative benefits and limitations of measurement systems for an application.	Evaluate and analyse measurement systems that could be selected for an application. Justify the selection of the measurement system for an application.	Design a study to critically evaluate measurement systems that could be selected for an application. Approve the selection of the measurement system for an application.

3. Environmental Impacts	**Environmental impacts on the measurement system, including, but not limited to:** - cleanliness (environment, workpiece) - temperature - rate of change of temperature - light levels - humidity - vibration - interference (electrical, magnetic etc) - air (contaminates, pressure, flow) - stray light	List environmental impacts that could influence the measurement system. Understand the procedure for controlling environmental impacts.	Explain environmental impacts that could influence the measurement system. Conduct the procedure for controlling environmental impacts.	Evaluate and analyse environmental impacts that could influence the measurement system. Identify and respond to potential improvements to the procedure for controlling environmental impacts. Design an asset care process.	Design a study to evaluate the environmental impacts that could influence the measurement system. Create the procedure for controlling environmental impacts. Approve the asset care process.
4. Validation	**Measurement Systems Analysis Studies, including, but not limited to:** - Repeatability Study (Type 1) - Full Gauge Repeatability & Reproducibility Study (Type 2) - Bias Study - Linearity Study - Stability Study - Evaluating the Measurement Process (EMP) - Measurement Uncertainty Analysis (MUA) - Static or dynamic study - Monte Carlo simulation	Describe a validation study to prove capability of the measurement system.	Conduct a validation study to prove capability of the measurement system to a defined plan.	Design and instruct a validation study to prove capability of the measurement system.	Approve a validation study to prove capability of the measurement system.

5. Calibration	**Calibration (or verification) methods for the measurement system, including, but not limited to:** - relevant standards requirements - limitations of the calibration/verification - calibrated parameters, characteristics or elements (e.g. kinematics and detector panel error correction)	Describe the calibration approach.	Explain the calibration approach. Interpret calibration results to identify pass / fail and any subsequent actions required.	Review the calibration (results, method and parameters). Instruct subsequent actions for failed calibration results. Identify trends or drift of results from the calibration and monitor adjustments.	Define the calibration specification. Evaluate non-standard situations arising from the calibrations, make and justify the appropriate decision. Approves the calibration period to ensure it is suitable based on calibration results.
6. Setup and Verification	**Best practice for setup and verification of the measurement system, including, but not limited to:** - handling - setup - calibration/verification (reference part, artefact, 'gold' part) - sanity checks - surface determination ISO value - qualitative checks - maintenance of sensors Non-contact specifics: - resolution - intensity - power	Describe best practice for setup and verification of the measurement system. Describe the relevant verification checks for the measurement system. Describe the importance of sensor systems and the need for qualification.	Carry out best practice for setup and verification, perform pre-work checks and identify presence of calibration for the measurement system. Conduct relevant verification checks for the measurement system and clearly identify if the results are pass or fail. Conduct the sensor qualification in line with the defined process.	Review and identify improvements to the best practice for setup and verification of the measurement system. Define the verification process and pre-check routines, correct handling procedures. Define the sensor qualification process.	Create the procedure for best practice for setup and verification of the measurement system. Approve the verification process and pre-check routines, correct handling procedures. Approve the sensor qualification process.

	Work holding influence, including, but not limited to: - distortion and deformation - free state vs clamped state - links to the design requirements	Describe best practice for work holding. Describe how work holding can influence measurement results.	Carry out best practice for work holding. Carry out verification checks on the work holding to minimise the influence on measurement results.	Review and identify improvements to the best practice for work holding. Define the verification checks on the work holding to minimise the influence on measurement results.	Create the procedure for best practice for work holding. Approve the verification checks on the work holding to minimise the influence on measurement results.
7. Programming	**Program issue and control, including, but not limited to:** - program identifiers - version control - program change management **Programming software version changes, including, but not limited to:** - changes in feature calculations - changes to evaluation methods - datum calculation methods	Describe the need for the control of programs	Carry out program issue and control using the organisations prescribed system	Design and implement a system for program issue and control Conduct process for updating programming software	Approves the process of program issue and control Design controls for updating programming software and control the effects it can have on measured results
	Translating the design requirement into a Co-ordinate system/datum structure and definitions, including, but not limited to: - degrees of freedom - co-ordinate system types - alignment methods - best fit - slave datums for 2DCT Portable specifics: - bundling Techniques **Translating the design**	Describe the importance of understanding/translating the design requirement. List some important aspects of programming a co-ordinate measuring system.	Conduct programming of the measurement system, for simple activities, translating the design requirement into a program by following a predefined programming process. Carry out programming procedures that minimise or remove the common forms of error, and selecting the correct filtering	Design the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Identifies potential design requirement constraints that could lead to sources of measurement error when reviewing design specifications. Conduct programming of	Approve the organisations programming process to cover the specific design requirement needs to minimise or remove the common forms of error. Develops a process to identify potential sources of error when reviewing processes and drawings and suggest mitigation techniques.

	requirement into feature definitions, including, but not limited to: - minimum point density for features - minimum point density for form - AD-HOC approach - scientific approach - feature coverage - default evaluation methods (e.g. ISO, ASME) - Monte Carlo Simulations **Approach Vectors, including, but not limited to:** - effects of cosine - calculation of normal vectors **Filtering Approach, including, but not limited to:** - selection of filtering methods - when filtering should be applied - filter thresholds (cut off and outlier removal) - common filtering issues		method (where required).	the measurement system, for complex activities.	
8. Execution	**Use of measurement systems, including, but not limited to:** - following setup instructions - executing approved measurement plans - identifying common measurement errors - record/evaluate results	N/A	Carry out measurement activities using the measurement system.	Modify the process for control of execution of the measurement system.	Develop the process for control of execution of the measurement system.

9. Errors and Fault Finding	**Common errors for the measurement system, including, but not limited to:** - programming errors - projection errors - ineffective strategy selection - datum selections - Abbe's Error - Cosine Error - collisions **Workpiece effects, including, but not limited to:** - form (lobing etc) - surface texture - materials - flexible workpiece - workpiece-to-workpiece variation Tactile Specific: - plastic/elastic deformation - styli shape and material effects Non-contact specific: - reflectivity - shallow edge contrast - transparency - specularity - sub-surface scattering	List common errors and faults that could impact the measurement system. Understand the procedure for controlling common errors and faults.	Explain common errors and faults that could impact the measurement system. Conduct the procedure for controlling common errors and faults.	Evaluate and analyse common errors and faults that could impact the measurement system. Develop the procedure for controlling common errors and faults.	Design a study to evaluate common errors and faults that could impact the measurement system. Approve the procedure for controlling common errors and faults.

10. Interpretation of Results	**Results and reporting from the measurement system, including, but not limited to:** - measured units - type of values - required calculations - understand the system output (point cloud, colourmap, grayscale, numerical) - GD&T	Understand the results output from the measurement system.	Interpret and explain the results output from the measurement system.	Evaluate and analyse the results output from the measurement system.	Develop and approve the process to control the results output from the measurement system.

Version History

Version	Reason for Issue	Date
1.0	First Issue	20/12/2023