

# METROLOGY SKILLS FRAMEWORK NMSA-2.1 – MANUFACTURING METROLOGY

National Metrology Skills Alliance

Version 1.0, 20<sup>th</sup> December 2023



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#### 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

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## 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.

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

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

	<b>but not limited to:</b> - 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.
	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	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.
9. Errors and Fault Finding	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				

	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	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.

	<ul> <li>sensor system, including but not limited to: <ul> <li>benefits and limitations of different sensor options</li> <li>density vs data quality choice</li> </ul> </li> <li>Tactile specifics: <ul> <li>sensor system choice</li> <li>(articulating head, fixed head, tactile, active scanning, passive scanning, ultrasonic, surface finish probes)</li> </ul> </li> <li>Non-Contact specifics: <ul> <li>scanners</li> <li>photogrammetry</li> <li>Surface condition of the workpiece (reflection, diffraction, transparency, specularity, sub- surface scattering)</li> </ul> </li> </ul>				
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:	styli and probe systems and	system and clearly	Define the probing	Approve the probing system
- resolution	the need for qualification	identify if the results	system qualification	qualification process
- intensity	the need for quaincation.	are pass or fail	nrocess	quaineation process.
incensity			process.	
Prohing system and styli		Conduct the probing		
maintonance including but not				
limited to:		System quanication in		
Conorici		line with the defined		
Deference enhance and		process.		
- Reference spheres and				
- qualitative checks				
- maintenance of probes and				
sensors				
l'actile Specifics:				
- material selection				
- styli snape				
- stiffness/rigidity				
- Size, Length, Alignment,				
lightness				
- diameter				
- standard deviation				
Non-contact Specifics:				
- working range				
- resolution				
- frequency				
Work holding influence,	Describe best practice for	Carry out best practice	Review and identify	Create the procedure for best
including, but not limited to:	work holding.	for work holding.	improvements to the	practice for work holding.
- distortion and deformation	-	-	best practice for work	5
- free state vs clamped state	Describe how work holding	Carry out verification	holding.	Approve the verification
- links to the design requirements	can influence measurement	checks on the work	C C	checks on the work holding to
	results.	holding to minimise the	Define the verification	minimise the influence on
		influence on	checks on the work	measurement results.
		measurement results.	holding to minimise the	
			influence on	
			measurement results.	

	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
7. Programming	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 - 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 - 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 - lnline 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 - lnline 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.

Destation for the second sec	
Best practice for setup and Describe best practice for Carry out best practice Review and identify Create the proce	dure for best
verification of the measurement setup and verification of the for setup and improvements to the practice for setu	p and
system, including, but not measurement system. verification, perform best practice for setup verification of th	e
limited to: pre-work checks and and verification of the measurement sy	stem.
- handling Describe the relevant identify presence of measurement system.	
- setup verification checks for the calibration for the Approve the veri	fication
- calibration/verification measurement system. measurement system. Define the verification process and pre-	check
(reference part, artefact, 'gold' process and pre-check routines, correct	handling
part) Describe the importance of Conduct relevant routines, correct procedures.	
- sanity checks styli and probe systems and verification checks for handling procedures.	
the need for qualification. the measurement Approve the pro	bing system
Non-contact specifics: system and clearly Define the probing qualification pro	cess.
- resolution identify if the results system qualification	
- intensity are pass or fail. process.	
Probing system and styli Conduct the probing	
maintenance, including, but not	
limited to:	
6. Setup and Generic: process.	
Verification - Reference spheres and	
qualification	
- gualitative checks	
- maintenance of probes and	
sensors	
Non-Contact / Ontical Specifics:	
- material selection	
- stiffness/rigidity	
- Size Length Alignment	
Tightness	
- diameter	
- standard deviation	
Non-contact Specifics:	
- working range	
- resolution	
- requercy	

	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.
	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
7. Programming	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.	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:		method (where	the measurement	
	- minimum point density for		required)	system for complex	
	features		required).	activities	
	minimum point donsity for form			activities.	
	- AD-NOC approach				
	- leature coverage				
	(e.g. ISO, ASIVIE)				
	- Monte Carlo Simulations				
	Annuarch Masters including but				
	Approach vectors, including, but				
	not limited to:				
	- effects of cosine				
	- calculation of normal vectors				
	Filtoring Approach including				
	Filtering Approach, including,				
	but not infiled to:				
	- selection of filtering methods				
	- when filtering should be applied				
	- filter thresholds (cut off and				
	outlier removal)				
	- common filtering issues		_		
	Use of measurement systems,	N/A	Carry out measurement	Modify the process for	Develop the process for
	including, but not limited to:		activities using the	control of execution of	control of execution of the
	- following setup instructions		measurement system.	the measurement	measurement system.
8. Execution	<ul> <li>executing approved</li> </ul>			system.	
0. Excedition	measurement plans				
	- identifying common				
	measurement errors				
	<ul> <li>record/evaluate results</li> </ul>				

	Commence from the	List sources and sources and	Fundation and an annual	Further and an alway	Design a study to such sta
	Common errors for the	List common errors and	Explain common errors	Evaluate and analyse	Design a study to evaluate
	measurement system, including,	faults that could impact the	and faults that could	common errors and	common errors and faults
	but not limited to:	measurement system.	impact the	faults that could impact	that could impact the
	- programming errors		measurement system.	the measurement	measurement system.
	- projection errors	Understand the procedure	Construct the survey of dump	system.	A management the summer of the second s
	- Ineffective strategy selection	for controlling common	Conduct the procedure	Develop the proceedure	Approve the procedure for
	- datum selections	errors and faults.	for controlling common	bevelop the procedure	controlling common errors
	- Abbe S Error		errors and faults.	for controlling common	and faults.
	- Cosine Error			errors and faults.	
	- consions				
	Workpiece effects including				
	but not limited to:				
	- form (lobing etc)				
9. Errors and	- surface texture				
Fault Finding	- materials				
i duit i manig	- flexible workpiece				
	- workpiece-to-workpiece				
	variation				
	Tactile Specific:				
	- plastic/elastic deformation				
	- styli shape and material effects				
	Non-contact specific:				
	- reflectivity				
	<ul> <li>shallow edge contrast</li> </ul>				
	- transparency				
	- specularity				
	<ul> <li>sub-surface scattering</li> </ul>				
	Results and reporting from the	Understand the results	Interpret and explain	Evaluate and analyse the	Develop and approve the
	measurement system, including,	output from the	the results output from	results output from the	process to control the results
10.	but not limited to:	measurement system.	the measurement	measurement system.	output from the
Interpretation	- measured units		system.		measurement system.
of Results	- type of values				
ornesuits	- required calculations				
	- understand the system output				
	(point cloud, colourmap,				

graysca	ale, numerical)		
- GD&T	Т		

# 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.

	Calibration (or verification)	Describe the calibration	Explain the calibration	Beview the calibration	Define the calibration
	methods for the measurement	approach	annroach	(results method and	specification
	system including but not			(results, method and	specification.
	limited to:		Interpret calibration	parameters).	Evaluate non standard
	rolovant standards		results to identify pass	Instruct subcoquent	cituations arising from the
			/ fail and any	instruct subsequent	situations ansing norm the
5. Calibration	limitations of the		/ Idil dilu dily	actions for falled	the enprenriate decision
	- limitations of the		subsequent actions	calibration results.	the appropriate decision.
	calibration/verification		requirea.		
	- calibrated parameters,			Identify trends or drift of	Approves the calibration
	characteristics or elements (e.g.			results from the	period to ensure it is suitable
	kinematics and detector panel			calibration and monitor	based on calibration results.
	error correction)			adjustments.	
	Best practice for setup and	Describe best practice for	Carry out best practice	Review and identify	Create the procedure for best
	verification of the measurement	setup and verification of the	for setup and	improvements to the	practice for setup and
	system, including, but not	measurement system.	verification, perform	best practice for setup	verification of the
	limited to:		pre-work checks and	and verification of the	measurement system.
	- handling	Describe the relevant	identify presence of	measurement system.	
	- setup	verification checks for the	calibration for the		Approve the verification
	<ul> <li>calibration/verification</li> </ul>	measurement system.	measurement system.	Define the verification	process and pre-check
	(reference part, artefact, 'gold'			process and pre-check	routines, correct handling
	part)	Describe the importance of	Conduct relevant	routines, correct	procedures.
6. Setup and	- sanity checks	sensor systems and the	verification checks for	handling procedures.	
Verification	- surface determination ISO value	need for qualification.	the measurement		Approve the sensor
	- qualitative checks		system and clearly	Define the sensor	qualification process.
	- maintenance of sensors		identify if the results	qualification process.	
			are pass or fail.		
	Non-contact specifics:				
	- resolution		Conduct the sensor		
	- intensity		qualification in line		
	- power		with the defined		
			nrocess		
			p. 00035.		

	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.
	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
7. Programming	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.	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		method (where	the measurement	
	definitions, including, but not		required).	system, for complex	
	limited to:			activities.	
	- 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				
	<ul> <li>filter thresholds (cut off and</li> </ul>				
	outlier removal)				
	- common filtering issues				
	Use of measurement systems,	N/A	Carry out measurement	Modify the process for	Develop the process for
	including, but not limited to:		activities using the	control of execution of	control of execution of the
	<ul> <li>following setup instructions</li> </ul>		measurement system.	the measurement	measurement system.
9 Execution	<ul> <li>executing approved</li> </ul>			system.	
o. Execution	measurement plans				
	<ul> <li>identifying common</li> </ul>				
	measurement errors				
	<ul> <li>record/evaluate results</li> </ul>				

	Common orrors for the	List common errors and	Evolain common orrors	Evaluate and analyse	Design a study to evaluate
	monocurrement system including	faults that could impact the	and faults that could	common orrors and	common orrors and faults
	het a st lissite d to a			fourthe thest sound imposed	that sould impose the
	but not limited to:	measurement system.	Impact the	faults that could impact	that could impact the
	- programming errors		measurement system.	the measurement	measurement system.
	- projection errors	Understand the procedure		system.	
	<ul> <li>ineffective strategy selection</li> </ul>	for controlling common	Conduct the procedure		Approve the procedure for
	- datum selections	errors and faults.	for controlling common	Develop the procedure	controlling common errors
	- Abbe's Error		errors and faults.	for controlling common	and faults.
	- Cosine Error			errors and faults.	
	- collisions				
	Workpiece effects, including,				
	but not limited to:				
	- form (lobing etc)				
9. Errors and	- surface texture				
Fault Finding	- materials				
i duit i munig	- flexible workpiece				
	- workpiece-to-workpiece				
	variation				
	Tactila Spacific:				
	nlactic olastic deformation				
	- plastic/elastic deformation				
	- styll shape and material effects				
	Non-contact specific:				
	- reflectivity				
	- shallow edge contrast				
	- transparency				
	- specularity				
	- sub-surface scattering				

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

## Version History

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