Training for dimensional metrology in digital manufacturing

Train4DiM

Report on development of curriculum

including syllabus cards for apprenticeships, bachelor and master degrees of studies

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Introduction

The changes that are observed from few years in the field of manufacturing and production engineering popularly known as "Fourth Industry Revolution" utilizes the achievements in the different areas of computer sciences, introducing new solutions at almost every stage of the production process, just to mention such concepts as: mass customization, cloud computing, knowledge based engineering, virtual reality, rapid prototyping or virtual models of measuring systems. To effectively speed up the production process and make it more flexible, it is necessary to tighten the bonds connecting individual stages of the production process and to raise the awareness and knowledge of employees of individual sectors about the nature and specificity of work in other stages. As an example of such diversity the training of industrial design students in field of coordinate metrology can be indicated, which allows them to design the product more consciously taking into consideration also the requirements of quality control departments. Such relations exist between all production stages. In addition to quality control demands, staff of design departments must be also aware of manufacturing-related aspects of production. Afterwards, staff of manufacturing departments should understand information given to them as technical drawings, 3d models and other relevant information given using possibilities of sophisticated engineering software by designers and also should have knowledge from the metrology field such as geometrical dimensioning and tolerancing (GD&T) framework or measurement and measuring equipment errors that are important during stating the conformity of products with their specifications. Quality control workers must know the technical documentation and rules that are used for preparing it in order to be able to prepare correct measurement routines for different inspection equipment and they also should know the basics of manufacturing using various methods (including additive manufacturing) as this will help them in deciding which specifications of the measured workpiece are crucial from the functionality point of view and in proper alignment of the workpiece in measuring volume of the inspection machine.

Due to that, finding and developing appropriate education methods adapted to the specifics of individual stages of the production process becomes extremely important issue which can be crucial to properly exploit the potential of the fourth industrial revolution.

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Curriculum for 'Dimensional metrology in digital manufacturing' including design, manufacturing and verification parts:

As decided in previous stages of the project the general structure for three different levels of learning, which include apprenticeship studies, bachelor degree studies and master degree studies, will be similar while the content at each level will differ in:

- stage of advancement of theoretical information,

- the complexity of the presented examples, practical exercises and comprehension questions,

- other specific requirements of different levels of study in relation to topics that will be dealt in the scope of individual learning modules.

The general structure of curriculum is presented below. In next sections of this report also the syllabus cards for different levels of learning are presented.

Global Masterplan			
Sign	**Title of Step/Learning Module**	**Expected Study Time**	**Learning Outcome**
GM-S1-01	Introduction to Digital Manufacturing	**0.5 h**	You can recall the distinctive elements of digital manufacturing.
GM-S1-02	Design, manufacturing and verification workflow in the digital era	**0.5 h**	You can recall the workflow of design, manufacturing and verification activities in the digital era.
GM-S1-03	Metrological aspects in design and manufacturing	**0.5 h**	You can explain the relevance of metrology throughout the design and manufacturing processes.

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Design			
Sign	**Title of Step/Learning Module**	**Expected Study Time**	**Learning Outcome**
D-S1	**Definition of the product concept and functions**		
D-S1-01	The design process	0,5 h	You can recall the design process in the digital era.
D-S1-02	Design for X guidelines	1 h	You can recall the main "design for manufacturability" guidelines.
D-S1-03	Design for Additive Manufacturing	1 h	You can recall the benefits of AM technologies and understand how to design AM parts.
D-S2	**Definition of the product specifications**		
D-S2-01	The need for Geometrical Product Specifications	0,25 h	You can understand the need for Geometrical Product Specifications.
D-S2-02	GPS concept	0,25 h	You can recall the Geometrical Product Specification (GPS) framework.
D-S2-03	Nine categories in the GPS matrix	0,25 h	You can differentiate between the nine geometrical property categories indicated in the GPS matrix.
D-S2-04	Introduction to geometrical tolerancing	1 h	You understand what is a geometrical feature and of the relationships between geometrical features.
D-S2-05	Introduction to geometrical tolerancing p. 2		You can recognize symbols of geometrical tolerances and of the rules of indication.
D-S2-06	Profile tolerancing	0,5 h	You will be able to differentiate

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			between the tolerance of any line and the tolerance of any surface.
D-S2-07	Profile tolerancing p. 2		You will be able to apply the default rules and the rules using additional specification elements.
D-S2-08	Specification of AM parts	0,25 h	You will be able to provide specifications to suppliers of AM parts.
D-S3	**Preparation of the digital model of the product**		
D-S3-01	Digital model of the product	0,5 h	You can recall the 3D digital model main aspects.
D-S3-02	Methods for documenting digital models and specifications	0,5 h	You can illustrate how to document a 3D digital model including geometrical product specifications.
D-S3-03	Formats for product data exchange	0,5 h	You can recall the main formats for the exchange of product data.
Manufacturing			
Sign	**Title of Step/Learning Module**	**Expected Study Time**	**Learning Outcome**
M-S1	**Identification of manufacturing requirements**		
M-S1-01	Definition of additive manufacturing	0,5 h	You can point out key features and advantages of additive manufacturing.
M-S1-02	Characterisation of typical materials used in AM	0,5 h	You know types of materials and feedstock solutions used in additive manufacturing.
M-S1-03	Process capabilities of additive manufacturing	0,5 h	You can describe the opportunities and limits of additive manufacturing regarding complexity, surface

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			quality and tolerances.
M-S2	**Manufacturing equipment selection**		
M-S2-01	Definition of main additive manufacturing processes	1 h	You know the functional principle and pros and cons of four additive manufacturing processes.
M-S2-02	Description of typical 3d printers construction	0,5 h	You know four different 3d printers architectures.
M-S3	**Materials and manufacturing process preparation**		
M-S3-01	Digital definition of the process	0,5 h	You understand principles of additive manufacturing process planning and execution.
M-S3-02	Preparation of 3d printer	0,5 h	You know why it is important to properly set up the 3d printing equipment.
M-S4	**Manufacturing process execution**		
M-S4-01	Extrusion based additive manufacturing process execution	1 h	You know what are the main functions of 3d printers' modules in relation to material changes that happen during FDM processes execution.
M-S4-02	Power bed fusion based additive manufacturing process execution	0,5 h	You know what are the main functions of 3d printers' modules in relation to material changes that happen during SLS processes execution.
M-S4-03	Automation and supervision of additive manufacturing	0,5 h	You know the systems used for automation and diagnostics of AM.
M-S5	**Manufacturing post processing**		
M-S5-01	Finishing of the printouts - methods and requirements	0,5 h	You can select proper finishing method to each AM process.

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M-S6	Management of manufacturing environment		
M-S6-01	Management of additive manufacturing machines	0,5 h	You know how to supervise the AM machines and how to assure their constant operability.
M-S6-02	Testing of AM machines (at higher level)	0,5 h	You can recall the methods for testing of AM machines.
M-S6-03	Economic and ecological aspects of additive manufacturing	0,5 h	You can optimize the additive manufacturing process regarding costs, time and quality.

Verification			
Sign	**Title of Step/Learning Module**	**Expected Study Time**	**Learning Outcome**
V-S1	**Identification of measurement requirements**		
V-S1-01	Identification of measurement requirements	2 h	You can use information about: features to be checked, general tolerances, tolerancing principle, material, reference to cad model.
V-S1-02	Identification of measurement requirements p. 2		You can identify distances as an ambiguous specification.
V-S1-03	Identification of measurement requirements p. 3		You can implement datum, common datum and datum system into a measuring strategy.
V-S1-04	Identification of measurement requirements p. 4		You can implement position specification into a measuring strategy.
V-S1-05	Identification of measurement requirements		You can implement line- and surface profile specification into a

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	p. 5		measuring strategy.
V-S1-06	Identification of measurement requirements p. 6		You can implement size specification into a measuring strategy.
V-S2	**Measurement equipment selection**		
V-S2-01	Architecture of Articulated Arm CMM	0,5 h	You can identify the components of an Articulated Arm CMM.
V-S2-02	Measurement equipment selection	1 h	You can distinguish two sensors available for Articulated Arm CMM.
V-S2-03	Measurement equipment selection p. 2		You can explain the principle function of a tactile probing system on an Articulated Arm CMM.
V-S2-04	Measurement equipment selection p. 3		You can explain the principle of functioning of a laserline sensor.
V-S2-05	Measurement equipment selection p. 4		You can describe the opportunities and limits of Articulated Arm CMM regarding features and tolerances.
V-S2-06	Measurement equipment selection p. 5		You can state typical artefacts for qualification used for Articulated Arm CMM.
V-S2-07	Measurement equipment selection p. 6		You can interpret basic performance indicators for Articulated arm CMM.
V-S3	**Workpiece and measuring system preparation**		
V-S3-01	Workpiece preparation process	1,5 h	You can recall the workpiece preparation process.
V-S3-02	Cleaning of workpieces		You can apply different cleaning procedures.

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V-S3-03	Fixturing of workpieces		You can recall single and modular tools for fixturing.
V-S3-04	Workpiece and measuring system preparation p. 2		You can prepare an Articulated Arm CMM ready for measurement.
V-S3-05	Workpiece and measuring system preparation p. 3		You can apply the qualification procedure of a tactile probing system on an Articulated Arm CMM.
V-S3-06	Workpiece and measuring system preparation p. 4		You can apply the qualification procedure of a laser line system on an Articulated Arm CMM.
V-S3-07	Workpiece and measuring system preparation p. 5		You can perform a suitable interim check with an ready to use Articulated Arm CMM.
V-S4	**Measurement process execution**		
V-S4-01	Number and distribution of measuring points	0,5 h	You can recall criteria for choosing number and distribution of measuring points.
V-S4-02	Measurement process execution	0,5 h	You can apply the acquisition procedure for Articulated Arm CMM.
V-S5	**Result evaluation process**		
V-S5-01	Result evaluation process	1,5 h	You can implement the measurement strategy for position specification.
V-S5-02	Result evaluation process p. 2		You can implement the measurement strategy for line- and surface profile specification.
V-S5-03	Result evaluation process p. 3		You can implement the measurement strategy for size specification.

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V-S5-04	Measurement Influences		You can recall the five groups of error sources.
V-S5-05	Documentation Overview		You can recall the need of appropriate documentation of measurements.
V-S5-06	Result evaluation process p. 4		You can prepare a measurement report.
V-S6	**Management of measurement environment**		
V-S6-01	Measurement standards	0,5 h	You can apply good practice of handling measurement standards.
V-S6-02	Performance verification of measuring systems		You can explain the terms acceptance test, reverification test and interim testing.

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Syllabus card preparation methodology

During preparation of syllabus cards for different levels of learning, following aspects were taken into account:

- as a general rule for all levels, learning modules that are related to one step (for example: D-S1, M-S3, V-S4, etc.) may be mixed in one lecture or workshop but learning modules treating about different steps are never mixed;
- syllabus card for apprenticeship level presents content with more focus on practical content realised during workshops than on theoretical information, learning outcomes defined for this level are more skills oriented then knowledge oriented, there is no deep insight into principles of operation of processes that are discussed, level of knowledge is basic, also the learning time allocated for lectures/workshops is planned in ratio of about 1:5;
- syllabus card for Master degree level presents content with more focus on theoretical content with deep insight into principles of operation of processes that are discussed, level of knowledge is advanced, there are also some workshops planned, so that students may use knowledge in practice but ratio of lectures/workshops should be at the level of 2:1;
- syllabus card for Bachelor degree level puts almost equal focus to theoretical information and practical content, level of knowledge is intermediate (above the level for apprenticeship and below the level for Master degree), principles of operation are discussed in the level that allows for understanding of cause and effect chain but without going into detailed aspects of the processes, the learning time allocated for lectures/workshops is planned in a ratio of about 1:1,5;
- assessment policy is adapted to the rules described above, for example for Master degree of studies the biggest weight during assessment is assigned to theoretical final exam, while for apprenticeship level the biggest weight is assigned to practical workshop evaluation exercise.

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Syllabus card for 'Dimensional metrology in digital manufacturing' (including design, manufacturing and verification part) for Apprenticeship studies:

Course description

1 General information

Course name	Dimensional metrology in digital manufacturing
Level of study (App., B.Sc, M.Sc., Ph.D.)	App.
ECTS	-
Course length	One (1) semester
Developed in the scope of	Erasmus+ Train4DiM project

2 Prerequisites

- none

3 Program

Type	Lectures	Classes	Workshops	Computer labs	Project	Seminar
Hours	4	0	20	0	0	0

4 Contents

Lectures		
No.		Hours
1	Introduction to Digital Manufacturing. Metrological aspects in design and manufacturing.	1,0
2	The need for Geometrical Product Specifications. GPS concept. Nine categories in the GPS matrix. Specification of AM parts.	1,0
3	Definition of additive manufacturing. Characterization of typical materials used in AM.	1,0

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4	Workpiece and measuring system preparation.	1,0

Workshops		
No.		Hours
1	Design, manufacturing and verification workflow in the digital era.	0,5
2	Introduction to geometrical tolerancing. Profile tolerancing.	1,5
3	The design process. Design for X guidelines. Design for Additive Manufacturing.	2,5
4	Digital model of the product. Methods for documenting digital models and specifications. Formats for product data exchange.	1,5
5	Process capabilities of additive manufacturing.	0,5
6	Definition of main additive manufacturing processes. Description of typical 3d printers construction.	1,5
7	Digital definition of the process. Preparation of 3d printer.	1
8	Extrusion based additive manufacturing process execution. Power bed fusion based additive manufacturing process execution. Automation and supervision of additive manufacturing.	2
9	Finishing of the printouts - methods and requirements.	0,5
10	Management of additive manufacturing machines. Economic and ecological aspects of additive manufacturing.	1,5
11	Identification of measurement requirements.	2
12	Architecture of Articulated Arm CMM. Measurement equipment selection.	1,5
13	Workpiece preparation process. Cleaning of workpieces. Fixturing of workpieces.	0,5
14	Number and distribution of measuring points. Measurement process execution.	1
15	Result evaluation process. Measurement influences. Documentation overview.	1,5
16	Measurement standards. Performance verification of measuring systems.	0,5

5 Learning Outcomes (skills and knowledge):

- The student can recall the distinctive elements of digital manufacturing.
- The student can implement workflow of design, manufacturing and verification activities in the digital era.

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- The student can explain the relevance of metrology.
- The student can explain the design process in the digital era.
- The student can apply the main "design for manufacturability" guidelines.
- The student can demonstrate the benefits of AM technologies and understand how to design AM parts.
- The student can understand the need for Geometrical Product Specifications.
- The student can use the Geometrical Product Specification (GPS) framework.
- The student can differentiate between the nine geometrical property categories indicated in the GPS matrix.
- The student understand what is a geometrical feature and of the relationships between geometrical features.
- The student can interpret symbols of geometrical tolerances and of the rules of indication.
- The student can differentiate between the tolerance of any line and the tolerance of any surface.
- The student can apply the default rules and the rules using additional specification elements.
- The student can provide specifications to suppliers of AM parts.
- The student can use the 3D digital model.
- The student can document a 3D digital model including geometrical product specifications.
- The student can use the main formats for the exchange of product data.
- The student can point out key features and advantages of additive manufacturing.
- The student can use materials and feedstock solutions used in additive manufacturing.
- The student can describe the opportunities and limits of additive manufacturing.
- The student demonstrate the functional principle and pros and cons of four additive manufacturing processes.
- The student can use four different 3d printers architectures.
- The student understand principles of additive manufacturing process planning and execution.
- The student can properly set up the 3d printing equipment.
- The student can use main functions of 3d printers' modules in relation to material changes that happen during FDM processes execution.
- The student can apply the main functions of 3d printers' modules.
- The student classify the systems used for automation and diagnostics of AM.
- The student can select proper finishing method to each AM process.
- The student can supervise the AM machines and how to assure their constant operability.
- The student can optimize the additive manufacturing process regarding costs, time and quality.
- The student can use information about: features to be checked, general tolerances, tolerancing principle, material, reference to cad model.
- The student can identify distances as an ambiguous specification.
- The student can implement datum, common datum and datum system into a measuring strategy.
- The student can implement position specification into a measuring strategy.
- The student can implement line- and surface profile specification into a measuring strategy.
- The student can implement size specification into a measuring strategy.
- The student can identify the components of an Articulated Arm CMM.
- The student can distinguish two sensors available for Articulated Arm CMM.
- The student can explain the principle function of a tactile probing system on an Articulated Arm CMM.
- The student can explain the principle of functioning of a laserline sensor.
- The student can describe the opportunities and limits of Articulated Arm CMM.
- The student can use typical artefacts for qualification used for Articulated Arm CMM.

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- The student can interpret basic performance indicators for Articulated arm CMM.
- The student can apply the workpiece preparation process.
- The student can apply different cleaning procedures.
- The student can use single and modular tools for fixturing.
- The student can prepare an Articulated Arm CMM ready for measurement.
- The student can apply the qualification procedure of a tactile probing system on an Articulated Arm CMM.
- The student can apply the qualification procedure of a laser line system on an Articulated Arm CMM.
- The student can perform a suitable interim check with an ready to use Articulated Arm CMM.
- The student can use in practice criteria for choosing number and distribution of measuring points.
- The student can apply the acquisition procedure for Articulated Arm CMM.
- The student can implement the measurement strategy for position specification.
- The student can implement the measurement strategy for line- and surface profile specification.
- The student can implement the measurement strategy for size specification.
- The student can recall the five groups of error sources.
- The student can create appropriate documentation of measurements.
- The student can prepare a measurement report.
- The student can apply good practice of handling measurement standards.
- The student can differentiate the terms acceptance test, reverification test and interim testing.

6 Assessment policy (examination):

- Passed final exam
- Attended all workshops
- Passed workshop evaluation exercise
- The final grade is evaluated as the weighted average of grades from: the final exam (0.3) and workshop evaluation exercise (0.7)

7 Literature

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Syllabus card for 'Dimensional metrology in digital manufacturing' (including design, manufacturing and verification part) for Bachelor degree studies:

Course description

1 General information

Course name	Dimensional metrology in digital manufacturing
Level of study (App., B.Sc, M.Sc., Ph.D.)	B.Sc.
ECTS	3
Course length	One (1) semester
Developed in the scope of	Erasmus+ Train4DiM project

2 Prerequisites

- knowledge of basics of metrology and Industry 4.0 concept

3 Program

Type	Lectures	Classes	Workshops	Computer labs	Project	Seminar
Hours	10	0	14	0	0	0

4 Contents

Lectures		
No.		Hours
1	Introduction to Digital Manufacturing. Metrological aspects in design and manufacturing.	1,0
2	The need for Geometrical Product Specifications. GPS concept. Nine categories in the GPS matrix. Introduction to geometrical tolerancing. Profile tolerancing. Specification of AM parts.	2,5
3	Definition of additive manufacturing. Characterization of typical materials used in AM. Process capabilities of additive manufacturing.	1,5

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4	Description of typical 3d printers construction.	0,5
5	Finishing of the printouts - methods and requirements.	0,5
6	Management of additive manufacturing machines. Economic and ecological aspects of additive manufacturing.	1
7	Architecture of Articulated Arm CMM. Measurement equipment selection.	1,5
8	Workpiece preparation process. Cleaning of workpieces. Fixturing of workpieces. Workpiece and measuring system preparation.	1,5

Workshops		
No.		Hours
1	Design, manufacturing and verification workflow in the digital era.	0,5
2	The design process. Design for X guidelines. Design for Additive Manufacturing.	2,5
3	Digital model of the product. Methods for documenting digital models and specifications. Formats for product data exchange.	1,5
4	Definition of main additive manufacturing processes	1
5	Digital definition of the process. Preparation of 3d printer.	1
6	Extrusion based additive manufacturing process execution. Power bed fusion based additive manufacturing process execution. Automation and supervision of additive manufacturing.	2
7	Testing of AM machines.	0,5
8	Identification of measurement requirements.	2
9	Number and distribution of measuring points. Measurement process execution.	1
10	Result evaluation process. Measurement influences. Documentation overview.	1,5
11	Measurement standards. Performance verification of measuring systems.	0,5

5 Learning Outcomes (skills and knowledge):

- The student can recall the distinctive elements of digital manufacturing.
- The student can recall the workflow of design, manufacturing and verification activities in the digital era.
- The student can explain the relevance of metrology throughout the design and manufacturing processes.

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- The student can recall the design process in the digital era.
- The student can apply the main "design for manufacturability" guidelines.
- The student can demonstrate the benefits of AM technologies and understand how to design AM parts.
- The student can understand the need for Geometrical Product Specifications.
- The student can use the Geometrical Product Specification (GPS) framework.
- The student can differentiate between the nine geometrical property categories indicated in the GPS matrix.
- The student understand what is a geometrical feature and of the relationships between geometrical features.
- The student can interpret symbols of geometrical tolerances and of the rules of indication.
- The student can differentiate between the tolerance of any line and the tolerance of any surface.
- The student can apply the default rules and the rules using additional specification elements.
- The student can provide specifications to suppliers of AM parts.
- The student can recall the 3D digital model main aspects.
- The student can illustrate how to document a 3D digital model including geometrical product specifications.
- The student can use the main formats for the exchange of product data.
- The student can point out key features and advantages of additive manufacturing.
- The student know types of materials and feedstock solutions used in additive manufacturing.
- The student can describe the opportunities and limits of additive manufacturing regarding complexity, surface quality and tolerances.
- The student know the functional principle and pros and cons of four additive manufacturing processes.
- The student know four different 3d printers architectures.
- The student understand principles of additive manufacturing process planning and execution.
- The student know how properly set up the 3d printing equipment.
- The student can use main functions of 3d printers' modules in relation to material changes that happen during FDM processes execution.
- The student know what are the main functions of 3d printers' modules in relation to material changes that happen during SLS processes execution.
- The student classify the systems used for automation and diagnostics of AM.
- The student can select proper finishing method to each AM process.
- The student can supervise the AM machines and how to assure their constant operability.
- The student can recall the methods for testing of AM machines.
- The student can optimize the additive manufacturing process regarding costs, time and quality.
- The student can use information about: features to be checked, general tolerances, tolerancing principle, material, reference to cad model.
- The student can identify distances as an ambiguous specification.
- The student can implement datum, common datum and datum system into a measuring strategy.
- The student can implement position specification into a measuring strategy.
- The student can implement line- and surface profile specification into a measuring strategy.
- The student can implement size specification into a measuring strategy.
- The student can identify the components of an Articulated Arm CMM.
- The student can distinguish two sensors available for Articulated Arm CMM.
- The student can explain the principle function of a tactile probing system on an Articulated Arm CMM.

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REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL ESTABLISHING "ERASMUS+": THE UNION PROGRAMME FOR EDUCATION, TRAINING, YOUTH AND SPORT AND REPEALING DECISIONS No 1719/2006/EC, No 1720/2006/EC AND No 1298/2008/EC

- The student can explain the principle of functioning of a laserline sensor.
- The student can describe the opportunities and limits of Articulated Arm CMM regarding features and tolerances.
- The student can state typical artefacts for qualification used for Articulated Arm CMM.
- The student can interpret basic performance indicators for Articulated arm CMM.
- The student can apply the workpiece preparation process.
- The student can apply different cleaning procedures.
- The student can use single and modular tools for fixturing.
- The student can prepare an Articulated Arm CMM ready for measurement.
- The student can apply the qualification procedure of a tactile probing system on an Articulated Arm CMM.
- The student can apply the qualification procedure of a laser line system on an Articulated Arm CMM.
- The student can perform a suitable interim check with an ready to use Articulated Arm CMM.
- The student can recall criteria for choosing number and distribution of measuring points.
- The student can apply the acquisition procedure for Articulated Arm CMM.
- The student can implement the measurement strategy for position specification.
- The student can implement the measurement strategy for line- and surface profile specification.
- The student can implement the measurement strategy for size specification.
- The student can recall the five groups of error sources.
- The student can create appropriate documentation of measurements.
- The student can prepare a measurement report.
- The student can apply good practice of handling measurement standards.
- The student can differentiate the terms acceptance test, reverification test and interim testing.

6 Assessment policy (examination):

- Passed final exam
- Attended all workshops
- Passed workshop evaluation exercise
- The final grade is evaluated as the weighted average of grades from: the final exam (0.5) and workshop evaluation exercise (0.5)

7 Literature

7. Tom Vaneker, Alain Bernard, Giovanni Moroni, Ian Gibson, Yicha Zhang – Design for additive manufacturing: Framework and methodology, CIRP Annals – Manufacturing Technology 69 (2020) 578 – 599.
8. Giovanni Moroni, Stefano Petro, Wilma Polini – Geometrical Product Specification and Verification in Additive Manufacturing, CIRP Annals – Manufacturing Technology 66 (2017) 157-160.
9. Ian Gibson, David Rosen, Brent Stucker – Additive Manufacturing Technologies, Springer, 2015.
10. Richard Leach, Simone Carmignato - Precision Metal Additive Manufacturing, CRC Press, 2021.
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12. Wei Gao - Metrology, Springer, 2020.

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Syllabus card for 'Dimensional metrology in digital manufacturing' (including design, manufacturing and verification part) for Master degree studies:

Course description

1 General information

Course name	Dimensional metrology in digital manufacturing
Level of study (App., B.Sc, M.Sc., Ph.D.)	M.Sc.
ECTS	3
Course length	One (1) semester
Developed in the scope of	Erasmus+ Train4DiM project

2 Prerequisites

- knowledge of basics of metrology and Industry 4.0 concept

3 Program

Type	Lectures	Classes	Workshops	Computer labs	Project	Seminar
Hours	16	0	8	0	0	0

4 Contents

Lectures		
No.		Hours
1	Introduction to Digital Manufacturing. Design, manufacturing and verification workflow in the digital era. Metrological aspects in design and manufacturing	1,5
2	The design process. Design for X guidelines.	1,5
3	The need for Geometrical Product Specifications. GPS concept. Nine categories in the GPS matrix. Introduction to geometrical tolerancing. Profile tolerancing. Specification of AM	2,5

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	parts.	
4	Definition of additive manufacturing. Characterization of typical materials used in AM. Process capabilities of additive manufacturing.	1,5
5	Definition of main additive manufacturing processes. Description of typical 3d printers construction.	1,5
6	Power bed fusion based additive manufacturing process execution. Automation and supervision of additive manufacturing.	1
7	Finishing of the printouts - methods and requirements.	0,5
8	Management of additive manufacturing machines. Economic and ecological aspects of additive manufacturing.	1
9	Identification of measurement requirements.	2
10	Architecture of Articulated Arm CMM. Measurement equipment selection.	1,5
11	Workpiece preparation process. Cleaning of workpieces. Fixturing of workpieces. Workpiece and measuring system preparation.	1,5

Workshops		
No.		Hours
1	Design for Additive Manufacturing.	1
2	Digital model of the product. Methods for documenting digital models and specifications. Formats for product data exchange.	1,5
3	Digital definition of the process. Preparation of 3d printer. Extrusion based additive manufacturing process execution.	2
4	Testing of AM machines.	0,5
5	Number and distribution of measuring points. Measurement process execution.	1
6	Result evaluation process. Measurement influences. Documentation overview.	1,5
7	Measurement standards. Performance verification of measuring systems.	0,5

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- The student can distinguish two sensors available for Articulated Arm CMM.
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