Overall indicators for comparing the performance of material extrusion printers with adaptive GBTA design

Laurent SPITAELS, Valentin DAMBLY, Édouard RIVIERE-LORPHEVRE and François DUCOBU

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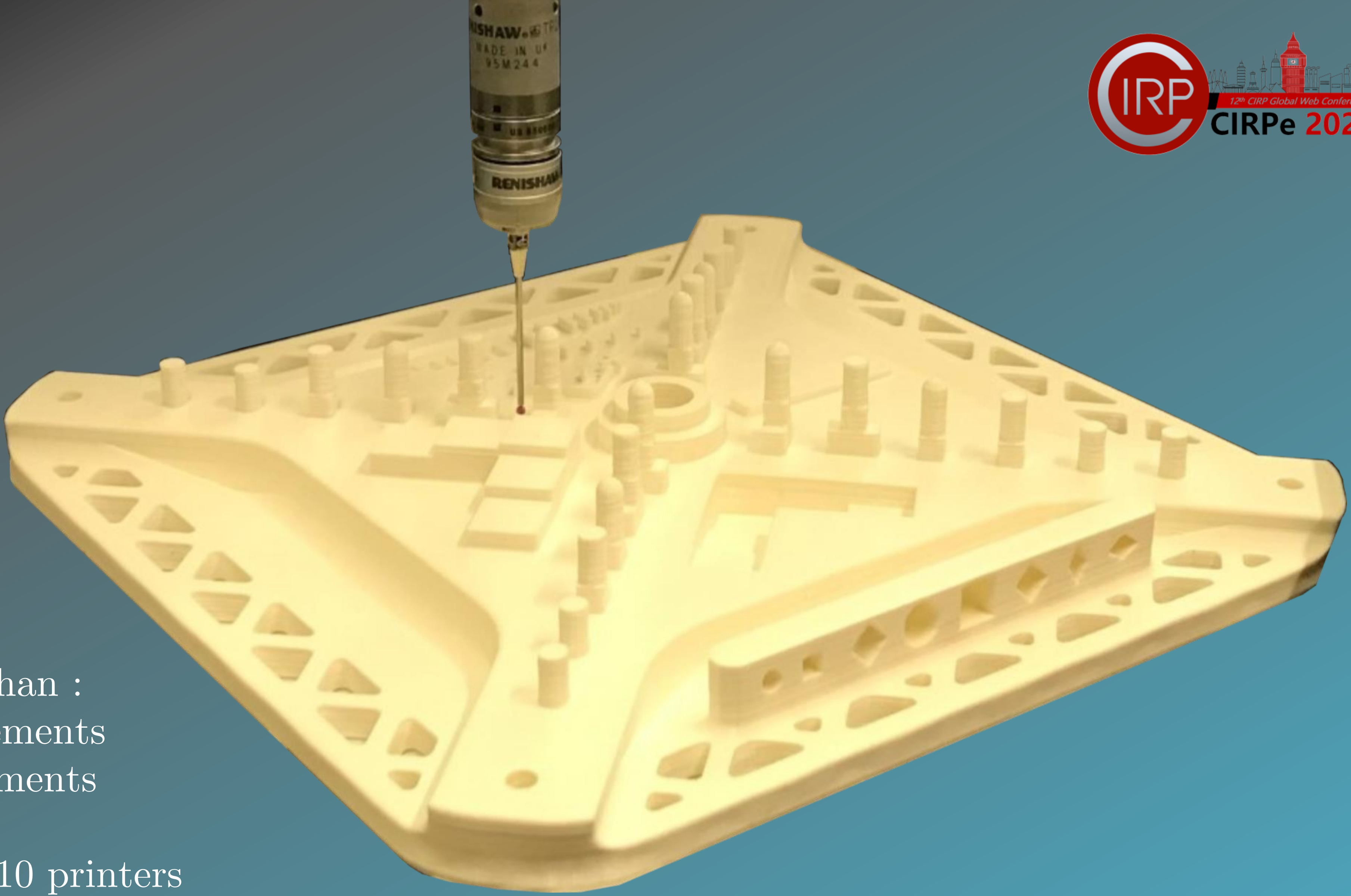


On each part, more than :

- 400 dim. measurements
- 100 geo. measurements

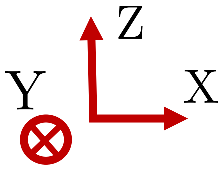
If 5 parts printed on 10 printers
→ Huge dataset !

Presentation Plan

Context and Motivations

Printers evaluated

→ 3 MEX printers using filaments



100 mm

Ultimaker 2+

PLA

Ultimaker S3

ABS PLA

Intamsys FunMat HT

ABS

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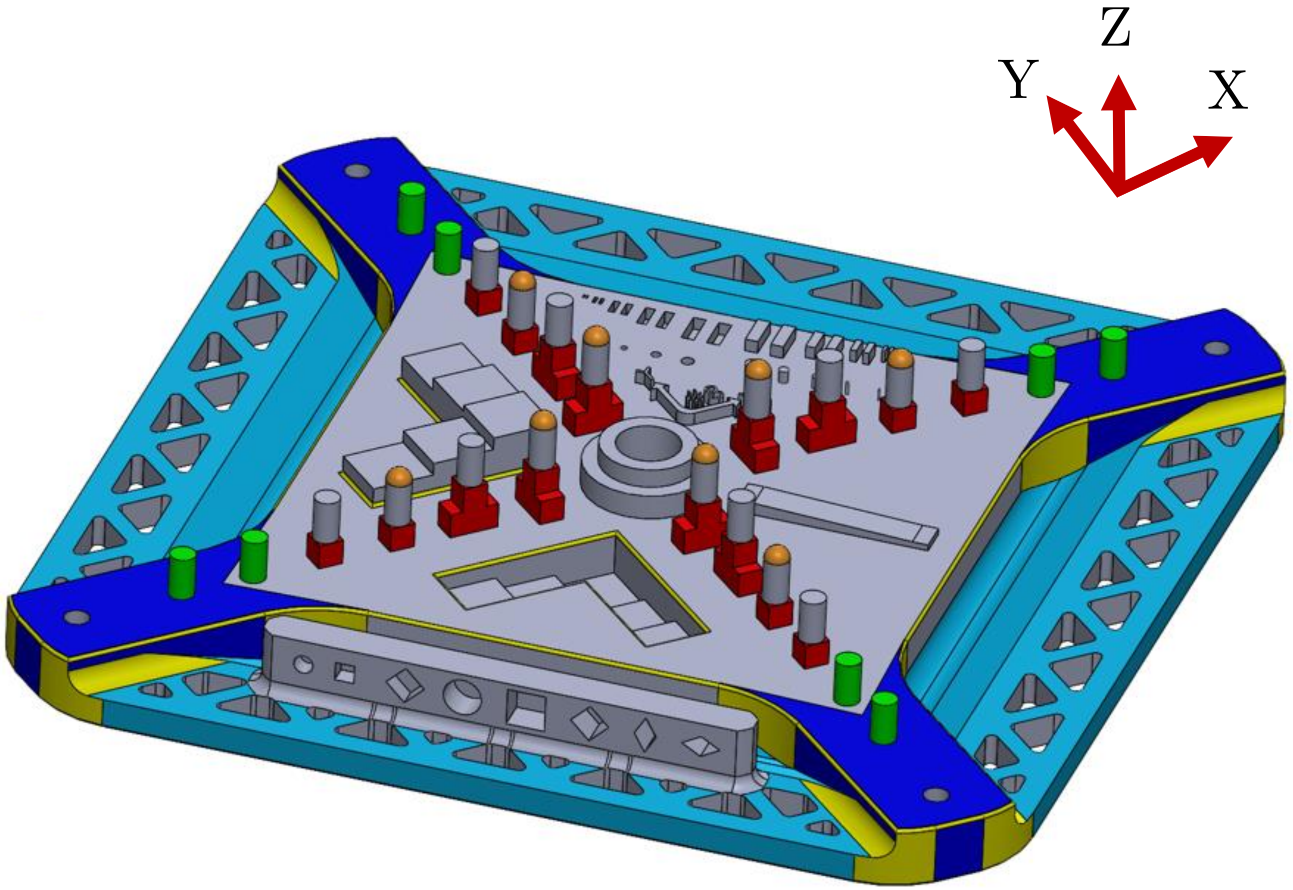
Context and Motivations

Test artifact selection

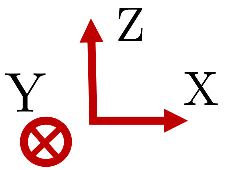
- From literature and based itself on the NIST test artifact
- Adaptive design which can be fitted into any MEX printer with a build volume larger than 132 mm x 132 mm x 17 mm (X, Y and Z)
- Systematic coverage of all achievable dimensional size ranges of ISO 286-1



[Spitaels2022]

Context and Motivations

Printers evaluated and their adapted GBTA designs



Intamsys FunMat HT

ABS

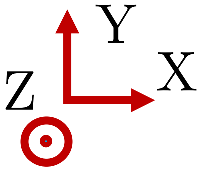
Ultimaker 2+

Ultimaker S3

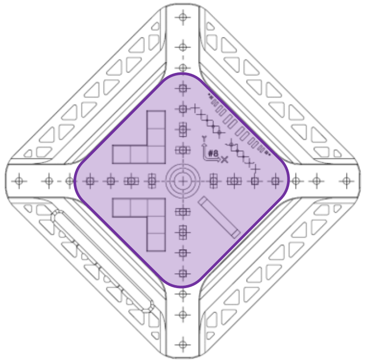
PLA

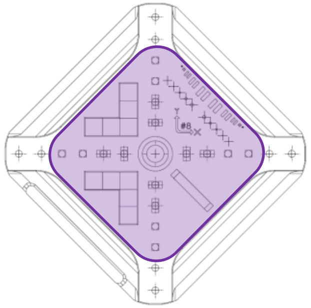
ABS

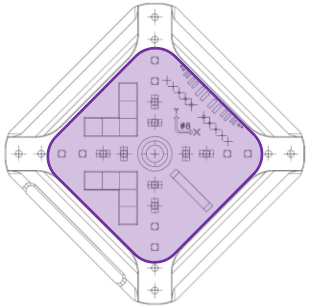
PLA

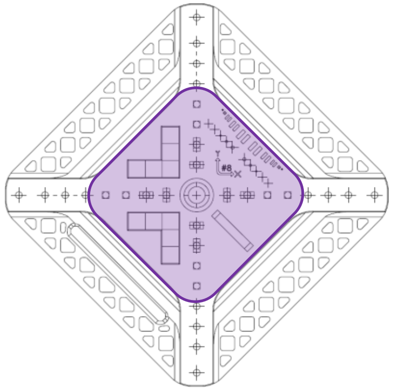


100 mm



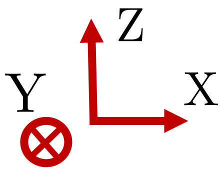






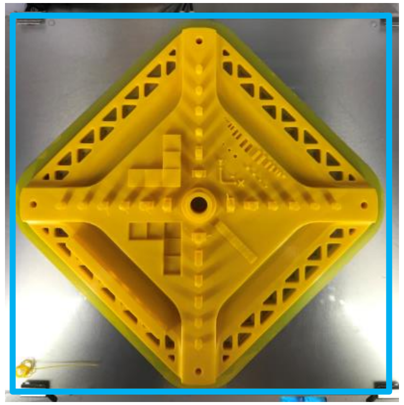
Context and Motivations

Parts manufacturing



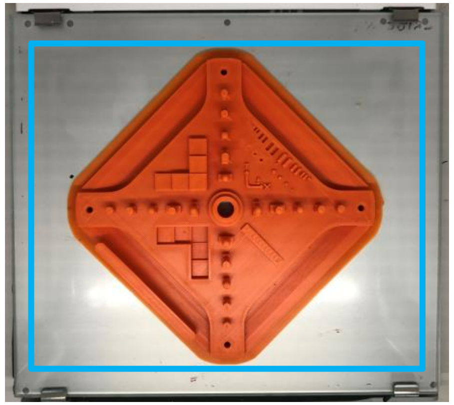
Ultimaker 2+

PLA

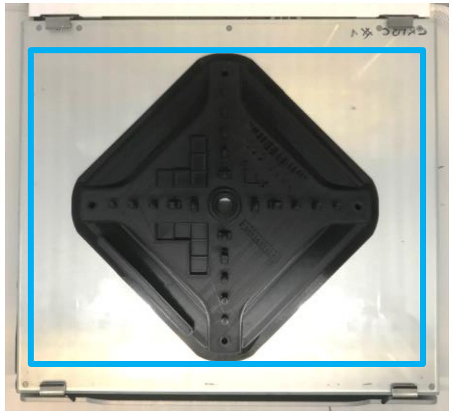


Ultimaker S3

ABS

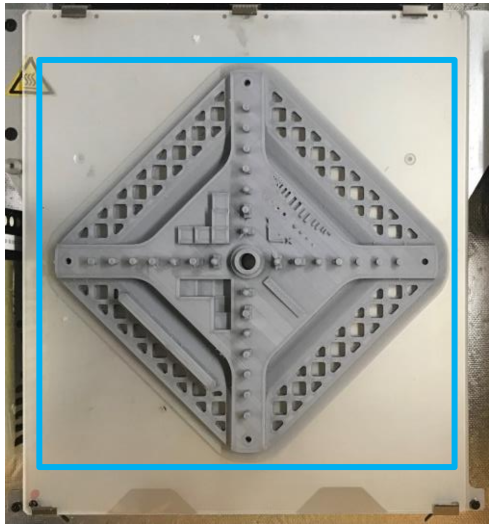


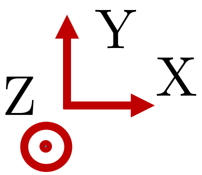
PLA



Intamsys FunMat HT

ABS



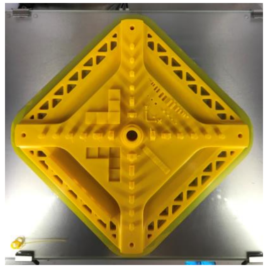
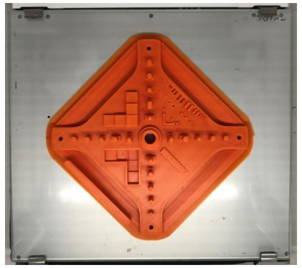
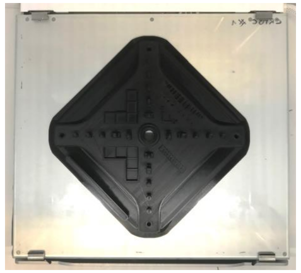
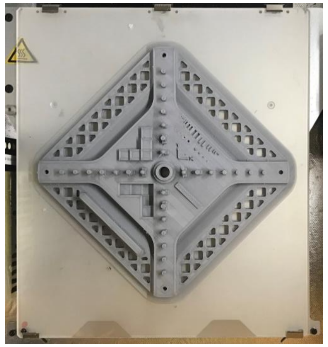


100 mm

Context and Motivations

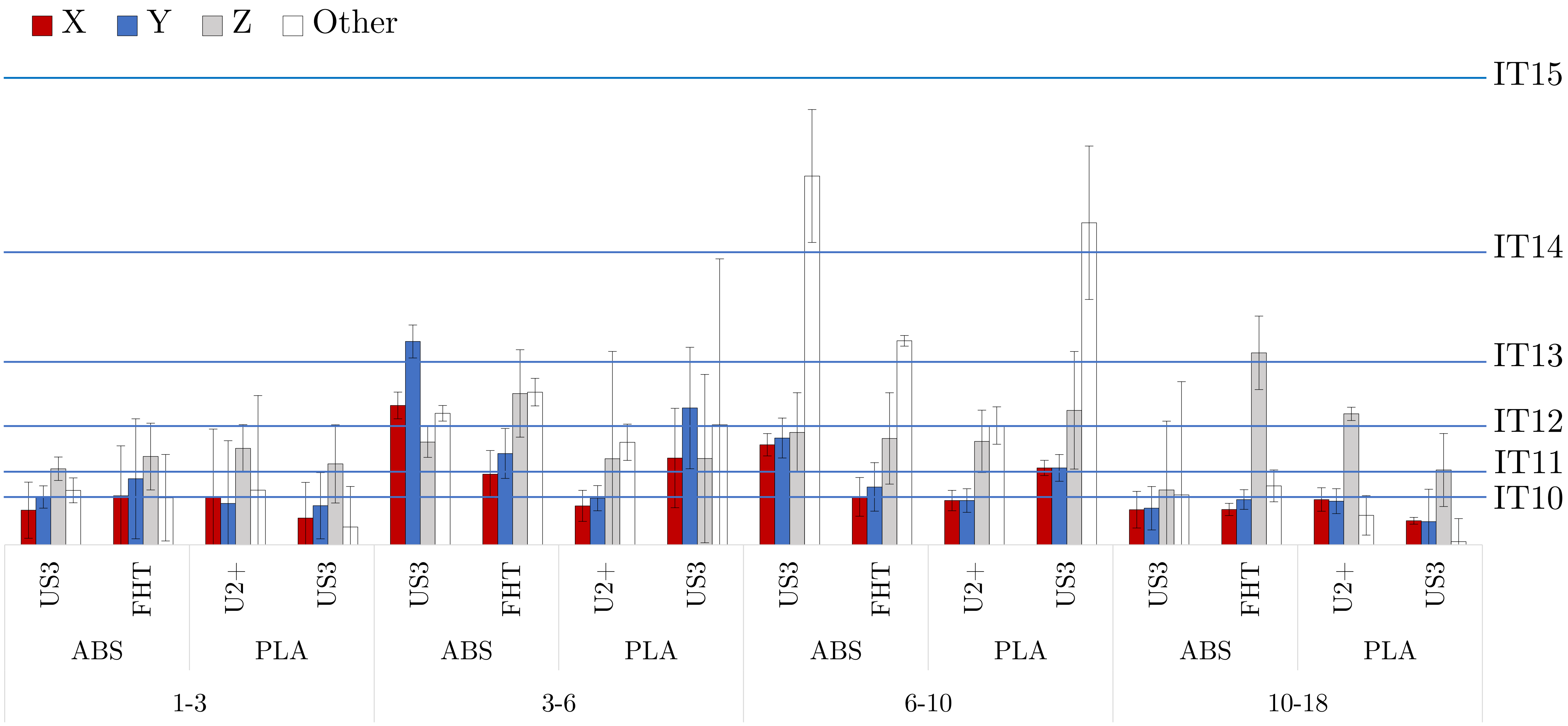
Resulting Dataset

8500 dimensional measurements and **2800** geometrical measurements

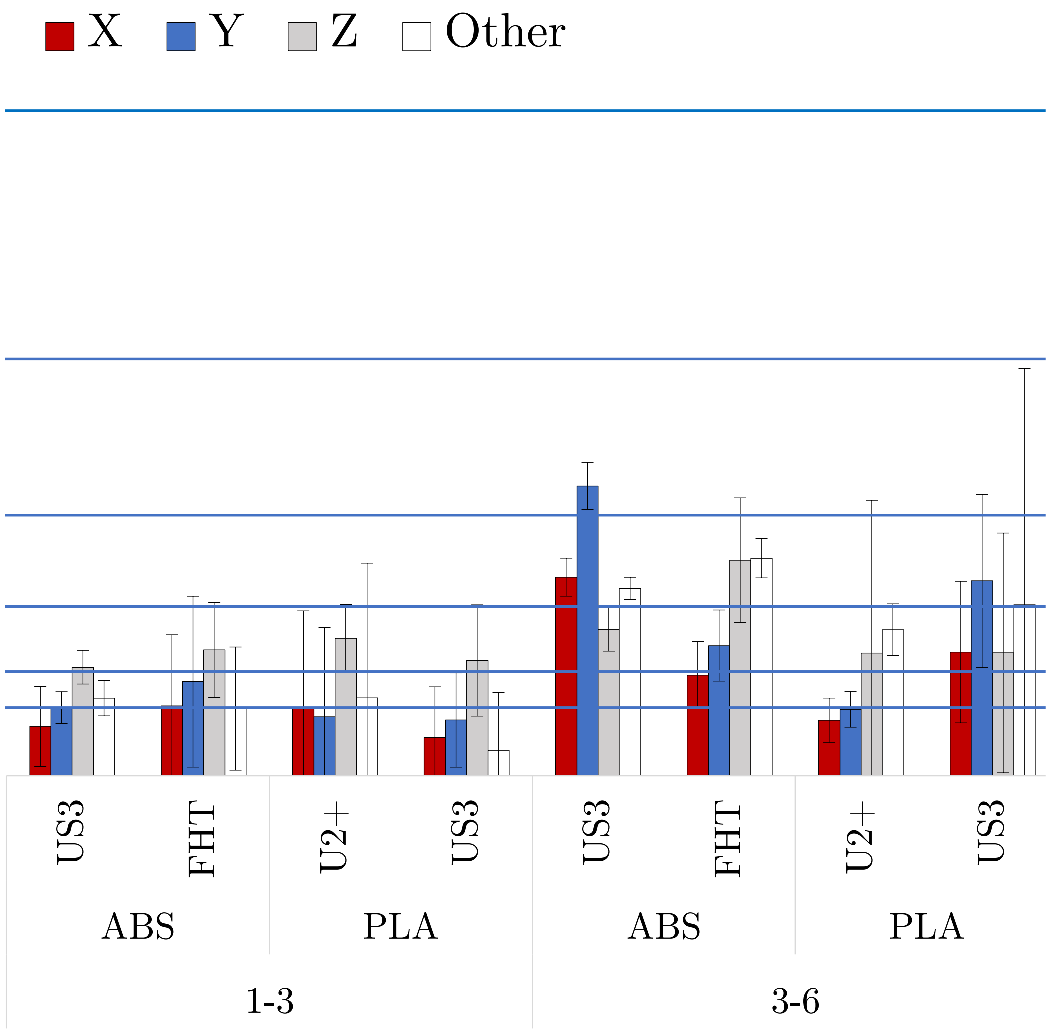





	Ultimaker 2+ PLA	Ultimaker S3 ABS	Ultimaker S3 PLA	Funmat HT ABS
Dimensional measurements	2170	1975	1975	2380
Geometrical measurements	705	685	685	725

Context and Motivations



Context and Motivations

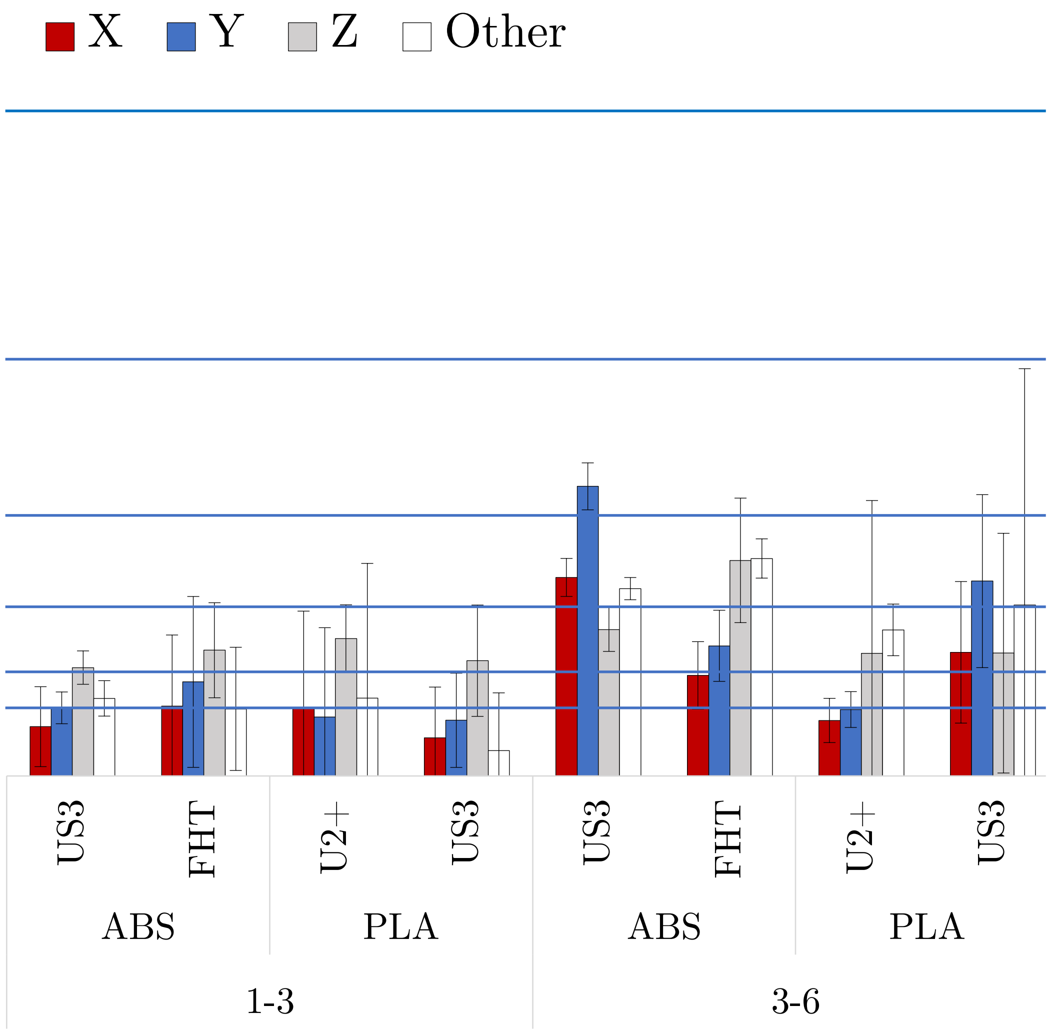


Very complete but:

- Difficult to establish direct conclusions…
- Lack of overall view

→ Introducing **overall indicators** is of prime interest and can solve this problem !

Context and Motivations



Very complete but:

- Difficult to establish direct conclusions…
- Lack of overall view

→ The data can be analyzed using the concepts of Trueness and Precision from ISO 5725-1:

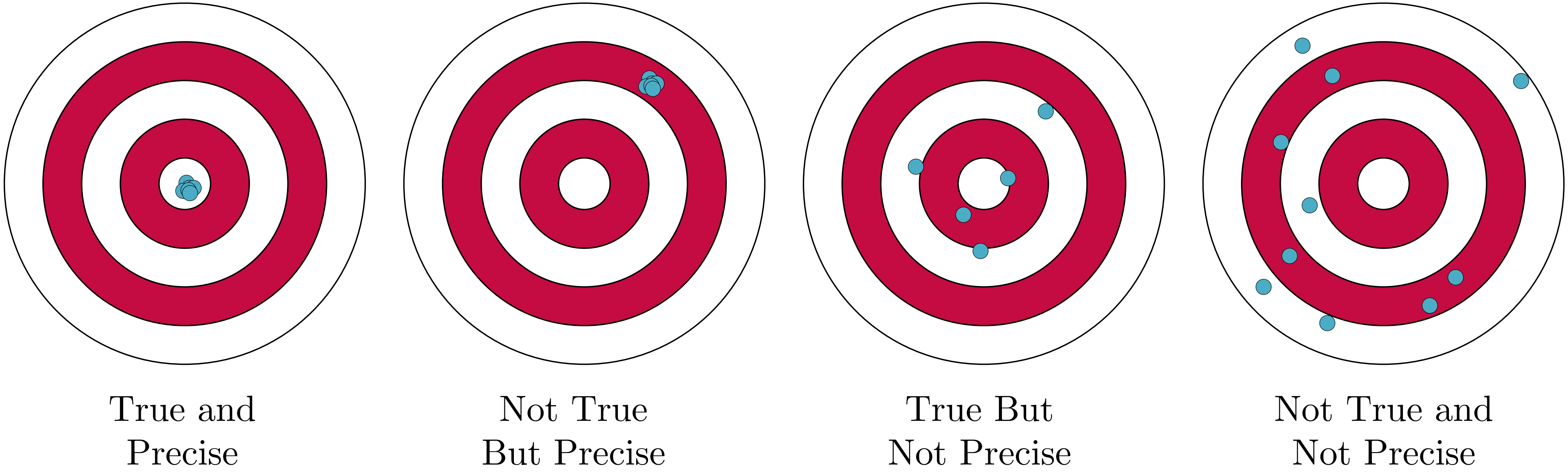
- Mean value (trueness)
- Standard deviation between the different parts (precision)

+

- Standard deviation between the different axes (axes homogeneity)

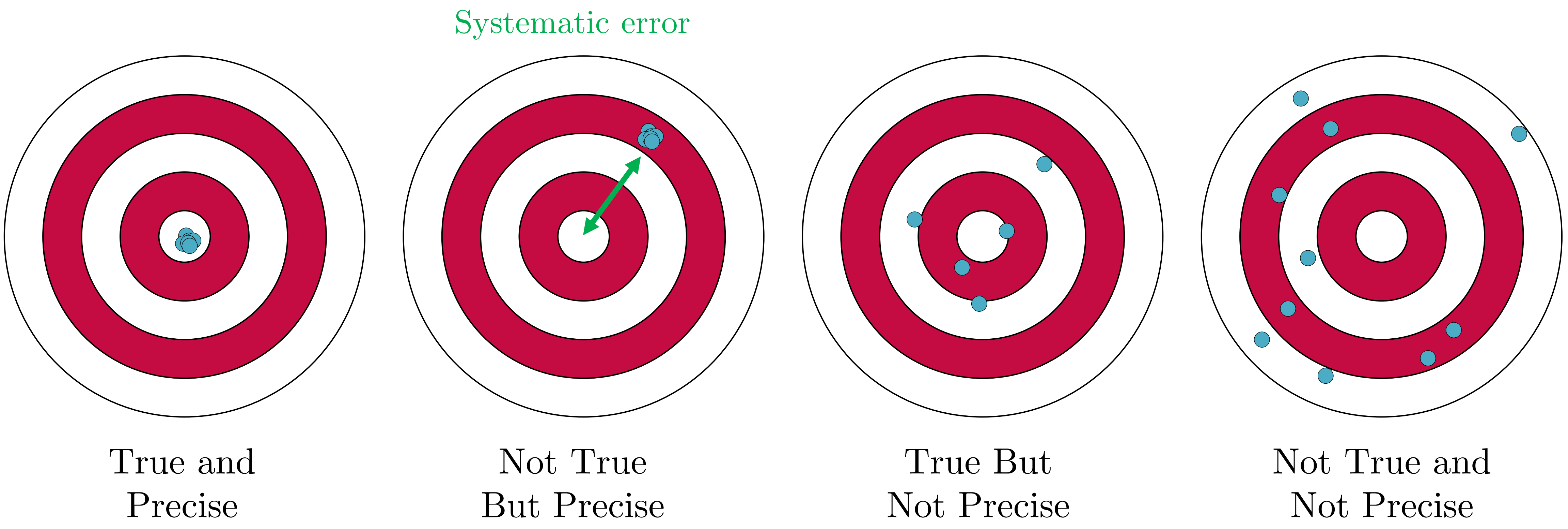
Method

Trueness and Precision – ISO 5725



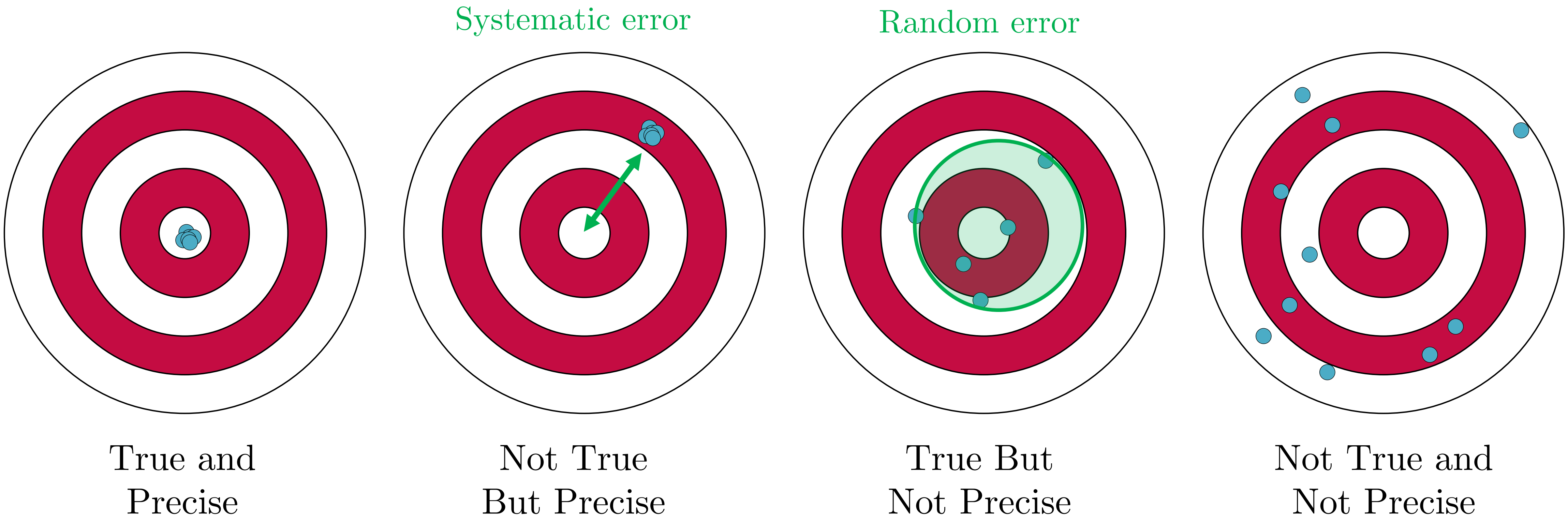
Method

Trueness and Precision – ISO 5725



Method

Trueness and Precision – ISO 5725



Method

Post treatment of the data – Dimensional measurements

ISO 286-1 method relying on the number of tolerance unit n (dimensionless)

$$n = \frac{1000 \cdot |D_n - D_m|}{i}$$

$$i = 0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D$$

$$D = \sqrt{D_1 \cdot D_2}$$

With:

- D_n the nominal dimension
- D_m the measurement
- D_1 and D_2 the lower and upper bound of the dimensional size range

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- D_1 and D_2 the lower and upper bound of the dimensional size range

Size range [mm]
1—3
3—6
6—10
10—18
18—30
30—50
50—80
80—120
120—180
180—250

Example:

- Measurement D_m = 29.430 mm while the nominal dimension D_n = 29.5 mm
- Size range: 18 mm — 30 mm → i = 1.307 µm → n = 54

Method

Post treatment of the data – Geometrical measurements

Same idea as for the dimensional measurements

→ Making them dimensionless and independent of the feature dimension

→ No method in the standards: proposal of a dimensionless number g

$$g = 1000 \cdot \frac{E_{dev}}{E_{dim}}$$

With:

- E_{dev} the measured deviation
- E_{dim} the main dimension of the measured element (def. from ISO 2768-2)

Example:

- Flatness deviation of 0.174 mm
- Plane of 50 mm x 50 mm → g = 0.174/50 = 3.48

Method

Post treatment of the data – Grouping data

Dimensional data:

- By printer, material, size range and principal axis
- Ex. U2+ PLA 18 mm – 30 mm X axis

Geometrical data:

- By printer, material, type and principal axis
- Ex. FHT ABS Flatness Z axis

Method

Post treatment of the data – Computing indicators

For a given category:

- Trueness: mean → μ_n and μ_g
- Precision: standard deviation → σ_n and σ_g
- Axis homogeneity: standard deviation between the axes X, Y and Z → $\sigma_{n,\ axes}$ and $\sigma_{g,\ axes}$

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Results

Dimensional trueness, precision scores of the printers' X axis

Size ranges [mm]	FHT ABS		U2+ PLA		US3 ABS		US3 PLA	
	μ_n	σ_n	μ_n	σ_n	μ_n	σ_n	μ_n	σ_n
1–3	67	79	65	58	47	48	37	40
3–6	96	40	53	44	191	48	119	49
6–10	66	33	61	50	137	85	105	82
10–18	48	44	62	76	48	22	33	21
18–30	73	45	57	49	95	35	86	50
30–50	93	55	60	59	105	56	90	48
50–80	108	45	65	55	155	54	124	62
80–120	149	58	147	93	193	56	207	105
120–180	184	63	26	8	328	85	341	148
180–250	298	32	215	52	/	/	/	/
Trueness	118	/	81	/	144	/	127	/
Precision	/	49	/	54	/	54	/	67

Trueness of a printer = mean of its μ_n

Example:

- FHT ABS Trueness = $\frac{\boxed{1182}}{10}$ = 118

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Results

Dimensional trueness, precision scores of the printers' X axis

Size ranges [mm]	FHT ABS μ_n	FHT ABS σ_n	U2+ PLA μ_n	U2+ PLA σ_n	US3 ABS μ_n	US3 ABS σ_n	US3 PLA μ_n	US3 PLA σ_n
1–3	67	79	65	58	47	48	37	40
3–6	96	40	53	44	191	48	119	49
6–10	66	33	61	50	137	85	105	82
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18–30	73	45	57	49	95	35	86	50
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Trueness	118	/	81	/	144	/	127	/
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Trueness of a printer = mean of its μ_n

Example:

- FHT ABS Trueness = $\frac{1182}{10}$ = 118

Precision of a printer = mean of its σ_n

Example:

- FHT ABS Trueness = $\frac{\boxed{494}}{10}$ = 49

Results

Dimensional axes homogeneity scores of the Funmat HT

Size ranges [mm]	μ_n X	Y	Z	Other	$\sigma_{n,axes}$
1–3	67	90	121	64	26
3–6	96	125	207	209	57
6–10	66	79	145	279	98
10–18	48	62	262	81	100
18–30	73	87	386	130	147
30–50	93	110	/	/	12
50–80	108	124	/	/	11
80–120	149	178	/	206	29
120–180	184	200	/	/	11
180–250	298	338	/	/	28
			Axes Homogeneity		52

Axes Homogeneity of a printer = mean of its $\sigma_{n,\ axes}$

Example:

- FHT ABS Axes homogeneity $= \frac{\boxed{519}}{10} = 52$

Results

Indicator of Dimensional Performance (IDP)

		FHT ABS	U2+ PLA	US3 ABS	US3 PLA
Trueness	X	118	81	144	127
	Y	139	67	124	109
	Z	224	164	120	134
	Other	162	107	163	137
Precision	X	49	54	54	67
	Y	56	52	86	84
	Z	184	120	108	116
	Other	49	28	57	59
Axes Homo.		52	47	58	57
IDP	Trueness	643	419	551	507
	Precision	338	254	305	326
	Axes Homo.	52	47	58	57

Each IDP is a sum of the previous scores:

- IDP Trueness FHT = sum of the FHT Trueness scores

  → 643 = 118+139+224+162

Results

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- IDP Precision and Axes Homogeneity followed the same principle

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Problem: different order of magnitude

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IDP	Trueness	643	419	551	507
	Precision	338	254	305	326
	Axes Homo.	52	47	58	57
IDP_{norm}	Trueness	0.000	1.000	0.411	0.607
	Precision	0.000	1.000	0.393	0.143
	Axes Homo.	0.546	1.000	0.000	0.091

Each IDP is a sum of the previous scores:

- IDP Trueness FHT = sum of the FHT Trueness scores

  →643 = 118+139+224+162
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Problem: different order of magnitude

→ Nomalization of the IDP following:

$$IDP_{norm} = \frac{IDP_{max} - IDP}{IDP_{max} - IDP_{min}}$$

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Results

Indicator of Geometrical Performance (IGP)

- Same principle as for the IDP.
- Indicator based on the dimensionless number g:
  - μ_g → Trueness
  - σ_g → Precision
  - $\sigma_{g,\,axes}$ → Axes Homogeneity
- Normalization, as before, to have the same order of magnitude and allow comparisons

$$\boxed{IGP_{norm} = \frac{IGP_{max} - IGP}{IGP_{max} - IGP_{min}}}$$

	Printer Material	FHT ABS	U2+ PLA	US3 ABS	US3 PLA
Trueness	X	1.671	2.804	3.365	2.598
	Y	1.275	2.695	5.229	3.918
	Z	2.088	2.153	1.960	1.941
	Other	8.392	10.243	8.051	8.550
Precision	X	1.220	1.137	2.279	1.380
	Y	0.781	1.080	4.648	2.164
	Z	0.824	1.153	1.019	1.157
	Other	6.358	7.116	6.542	5.494
Axes Homo.		0.274	1.187	1.901	1.212
IGP	Trueness	13.426	17.895	18.605	17.007
	Precision	9.183	10.486	14.488	10.195
	Axes Homo.	0.274	1.187	1.901	1.212
IGP_{norm}	Trueness	1.000	0.137	0.000	0.308
	Precision	1.000	0.754	0.000	0.809
	Axes Homo.	1.000	0.439	0.000	0.423

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Results

Overall Perfomance Indicators (OPI)

Averaging the normalized IDP and IGP:

- Obtain the OPI;
- Gives the same weight to dimensional and geometrical scores;
- Can be displayed as a radar graph to ease the read.

	Printer Material	FHT ABS	U2+ PLA	US3 ABS	US3 PLA
OPI	Trueness	0.500	0.568	0.206	0.458
	Precision	0.500	0.877	0.197	0.476
	Axes Homo.	0.773	0.719	0.000	0.257

Results

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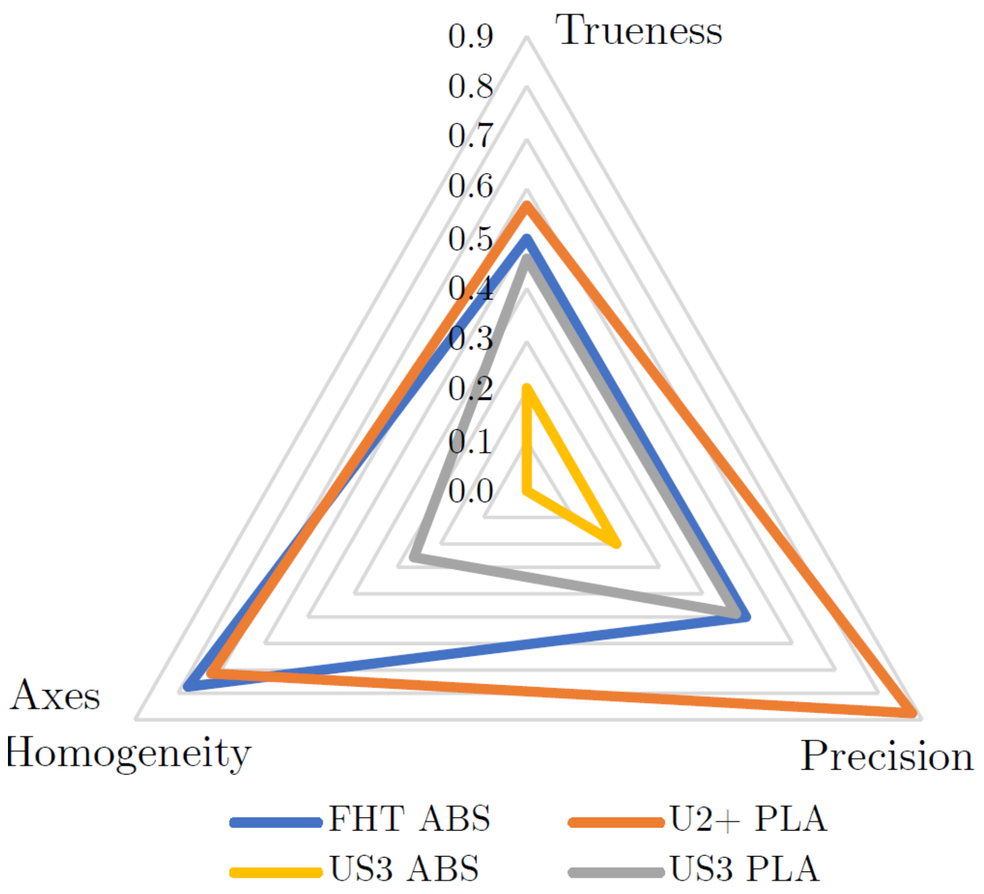

Overall Performance Indicator (OPI)

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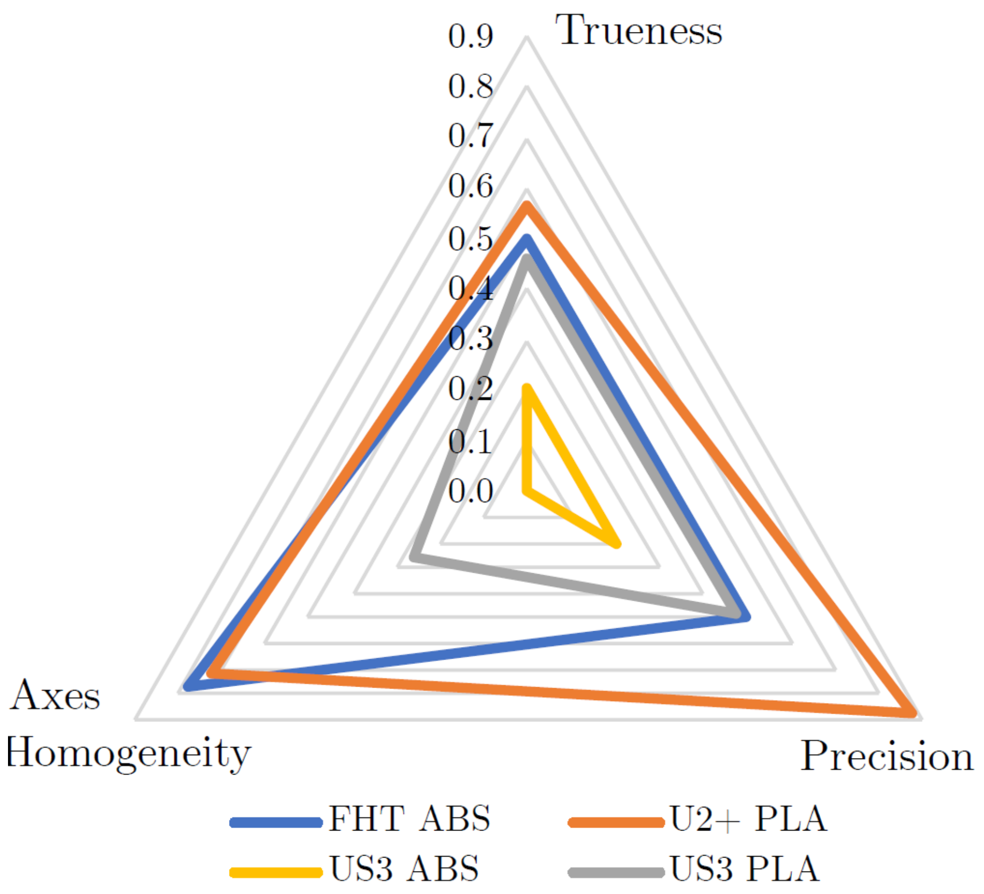
Conclusions

- The Ultimaker 2+ using PLA exhibited the best overall performance with the highest trueness and precision.
- The Funmat HT exhibited the best axes homogeneity.
- The Ultimaker S3 showed better performance using PLA than ABS

→ Significant influence of the material choice on the measured performance.



Overall Performance Indicator (OPI)

Conclusions

- The concepts of **trueness**, **precision** and **axes homogeneity** were used to rank the the tested printers.
- The *OPI* gives an image of the overall dimensional and geometrical performance in a single indicator.
- Precautions should be taken using the *OPI* since it can hide under performance that can be detected using the *IDP* and *IGP*.
- The identical weights given to the *IDP* and *IGP* performance for the computation of the *OPI* could be tuned.

Future Research Opportunities

- Measuring axis backlash and positioning repeatability to confirm the better performance of the Funmat HT and Ultimaker 2+ in terms of axes homogeneity.

- Quantifying the improvement of a printer after its modifications (firmware update for the axes stepper calibration, new printing parameters, *e.g.*) or compensation by using the proposed indicators.

- Adding other contributions into the *OPI*, such as the specific energy consumption could be interesting to evaluate the performance of the printers more comprehensively.

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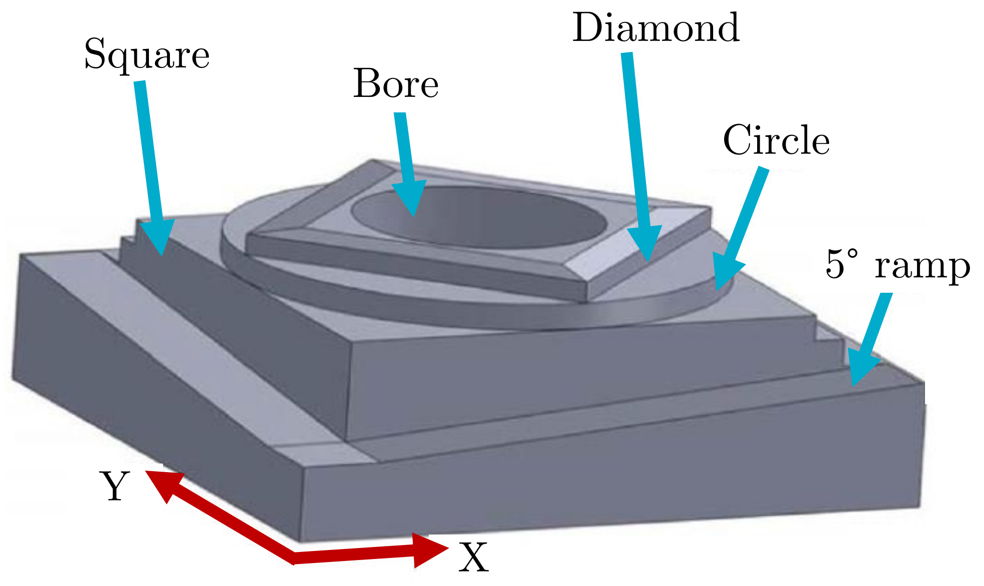
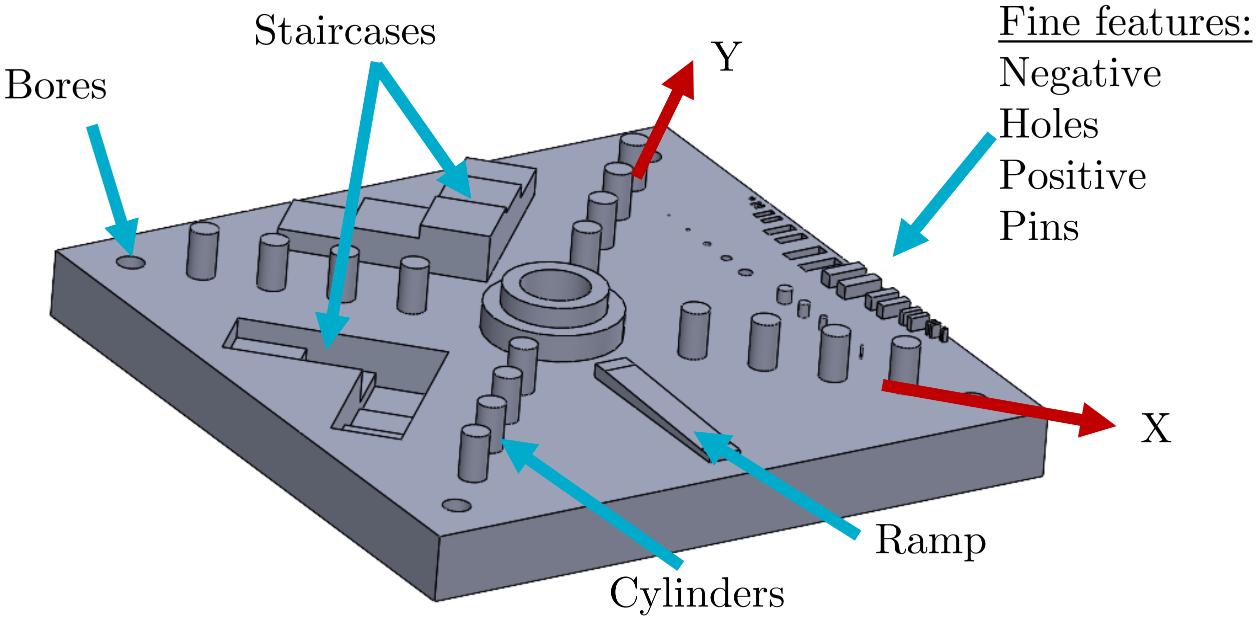
Context

NAS 979 for machining centers



Square base: 100 mm x 100 mm

NIST Test artifact for AM printers

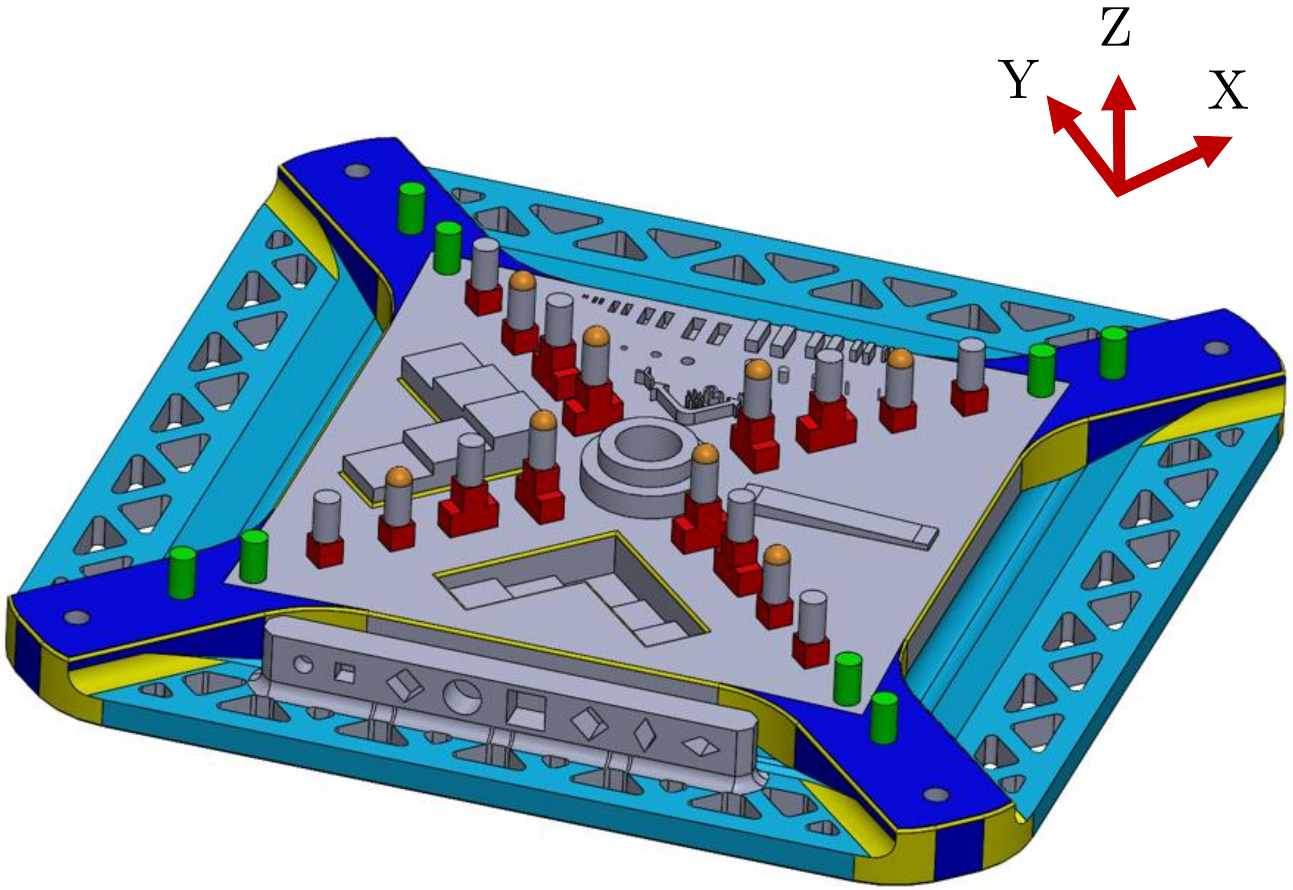


Square base: 100 mm x 100 mm

Method

Test artifact selection

- From literature and based itself on the NIST test artifact
- Adaptive design which can be fitted into any MEX printer with a build volume larger than 132 mm x 132 mm x 17 mm (X, Y and Z)
- Systematic coverage of all achievable dimensional size ranges of ISO 286-1

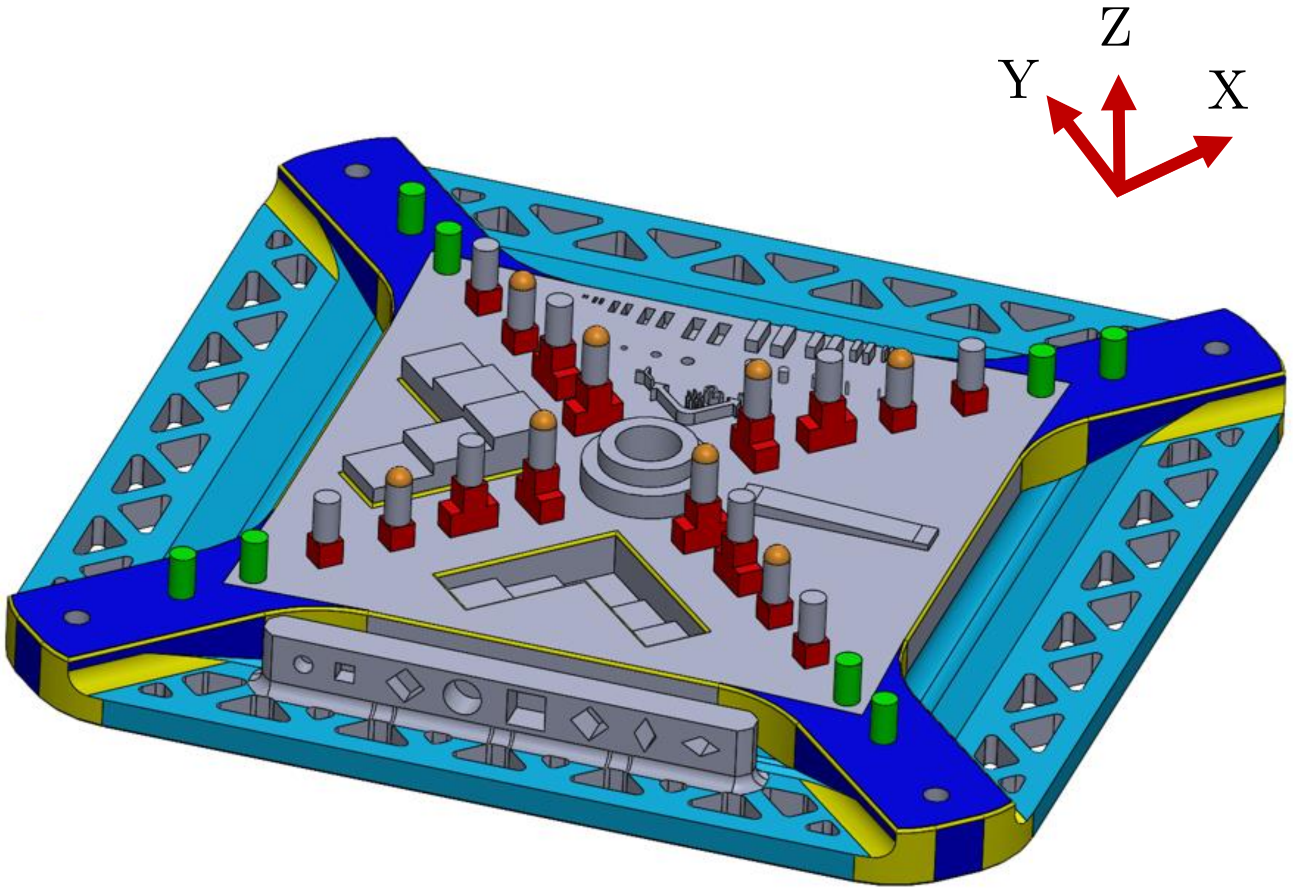


[Spitaels2022]

Context and Motivations

Test artifact selection

- From literature and based itself on the NIST test artifact
- Adaptive design which can be fitted into any MEX printer with a build volume larger than 132 mm x 132 mm x 17 mm (X, Y and Z)
- Systematic coverage of all achievable dimensional size ranges of ISO 286-1



[Spitaels2022]

Context

Off-machine metrology

Measuring the part after its fabrication

Advantages:

- Non-invasive for the machine
- Affordable
- Conventional means (CMM, *e.g.)*) can be used for the parts measurement
- Comparison of several machines possible and eased

Disadvantages:

- No direct link between a deviation and its cause
- Design of the part conditioned by the measuring device foreseen

→ Adapted for the industrial context with limited measuring means and machine modifications

→ Already used since decades for the performance assessment of machining center (NAS 979)

Method

Parts manufacturing

Parameters	Units	Ultimaker 2+ (U2+)	Ultimaker S3 (US3)	Funmat HT (FHT)
Build volume (XYZ)	[mm]	$223 \times 223 \times 205$	$230 \times 190 \times 200$	$243 \times 243 \times 260$
Feedstock	/	⌀ 2.85 mm Filaments	⌀ 2.85 mm Filaments	⌀ 1.75 mm Filaments
Nozzle temperature	[°C]	220 (PLA)	215 (PLA), 240 (ABS)	255 (ABS)
Build platform temperature	[°C]	60 (PLA)	60 (PLA), 85 (ABS)	85 (ABS)
Nozzle diameter	[mm]	0.4	0.4	0.4
Layer thickness	[mm]	0.1	0.1	0.1
Infill density	[%]	20	20	20
Infill pattern	/	Cubic	Cubic	Cubic
Brim	[mm]	8	8	8
Print time	[h]	30	24 (PLA), 29 (ABS)	54

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Print time	[h]	30	24 (PLA), 29 (ABS)	54

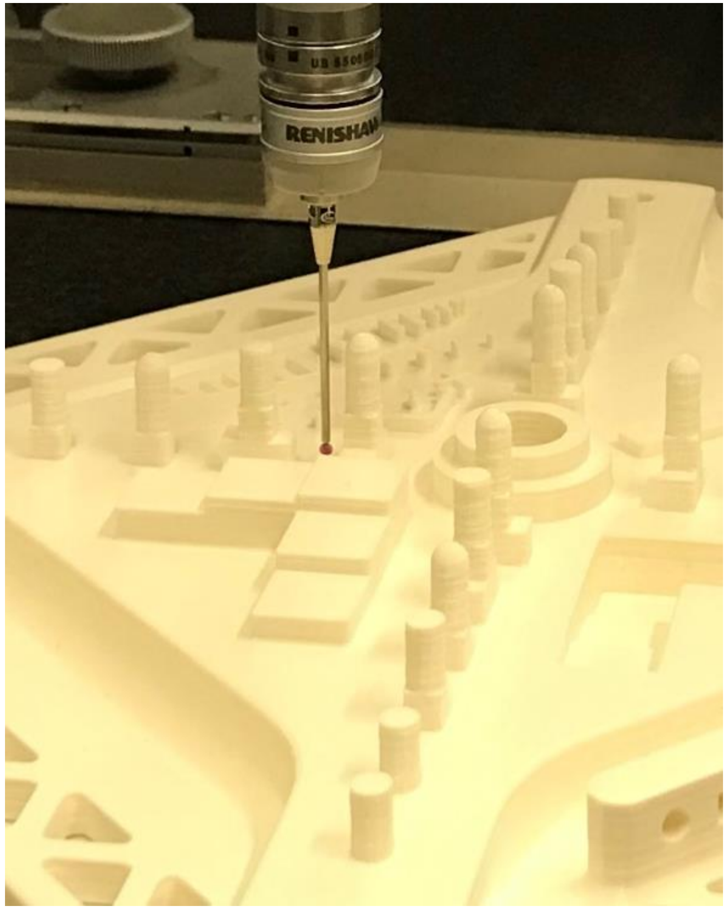
Common printing parameters

Method

Measurement of the parts

- CMM Wenzel LH 54 with a PH10M Renishaw Head
- Probe diameter: 1.5 mm
- Part and skirt removed from the build platform

Geometrical features	Number of probed points
Cylinders	8 distributed over 2 circles
Hemispheres	9 distributed over 3 circles
Planes in general	6
Top planes	39 (U2+), 40 (US3) and 47 (FHT)



Results

Geometrical trueness, precision and axes homogeneity scores

Type of measurement	Axis	FHT ABS	U2+ PLA	US3 ABS	US3 PLA
Cylindricity	Other	10.464	12.420	11.121	13.222
Flatness	X	1.056	0.435	2.257	1.115
	Y	0.594	0.864	3.585	2.191
	Z	1.547	1.461	1.893	1.843
	Other	1.132	2.572	0.874	1.931
Parallelism	X	3.526	7.803	7.633	6.189
	Y	2.873	7.027	11.945	9.267
	Z	2.629	2.845	2.026	2.039
	Other	3.081	2.979	3.110	4.498
Profile	Other	22.813	26.981	16.223	13.673
Perpendicularity	Other	4.470	6.266	8.927	9.426
Straightness	X	0.430	0.174	0.205	0.491
	Y	0.359	0.195	0.156	0.295

Mean value of g : μ_g

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Mean value of g : μ_g

	Printer Material	FHT ABS	U2+ PLA	US3 ABS	US3 PLA
Trueness	X	1.671	2.804	3.365	2.598
	Y	1.275	2.695	5.229	3.918
	Z	2.088	2.153	1.960	1.941
	Other	8.392	10.243	8.051	8.550
Precision	X	1.220	1.137	2.279	1.380
	Y	0.781	1.080	4.648	2.164
	Z	0.824	1.153	1.019	1.157
	Other	6.358	7.116	6.542	5.494
Axes Homo.		0.274	1.187	1.901	1.212

→ Same principle as before,
→ Idem for precison and axes homogeneity

CIRP 12th CIRP Global Web Conference CIRPe 2024

Results

Indicator of Geometrical Performance (IGP)

Each IGP is a sum of the previous scores:

- IGP Trueness FHT = sum of the FHT Trueness scores

  →13.426 = 1.671 + 1.275 + 2.088 + 8.392

- IGP Precision and Axes Homogenneity followed the same principle

	Printer Material	FHT ABS	U2+ PLA	US3 ABS	US3 PLA
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Axes Homo.		0.274	1.187	1.901	1.212
IGP	Trueness	$\boxed{13.426}$	17.895	18.605	17.007
	Precision	9.183	10.486	14.488	10.195
	Axes Homo.	0.274	1.187	1.901	1.212

12th CIRP Global Web Conference CIRPe 2024

Results

Indicator of Geometrical Performance (IGP)

Each IGP is a sum of the previous scores:

- IGP Trueness FHT = sum of the FHT Trueness scores

  →13.426 = 1.671 + 1.275 + 2.088 + 8.392

- IGP Precision and Axes Homogenneity followed the same principle

→ Normalization, as before, to have the same order of magnitude and allow comparisons

$$IGP_{norm} = \frac{IGP_{max} - IGP}{IGP_{max} - IGP_{min}}$$

	Printer Material	FHT ABS	U2+ PLA	US3 ABS	US3 PLA
Trueness	X	1.671	2.804	3.365	2.598
	Y	1.275	2.695	5.229	3.918
	Z	2.088	2.153	1.960	1.941
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IGP_{norm}	Trueness	1.000	0.137	0.000	0.308
	Precision	1.000	0.754	0.000	0.809
	Axes Homo.	1.000	0.439	0.000	0.423