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CGA 2016 – Las Vegas (USA)

Enhancing the dimensional accuracy of a low-cost 3D printer

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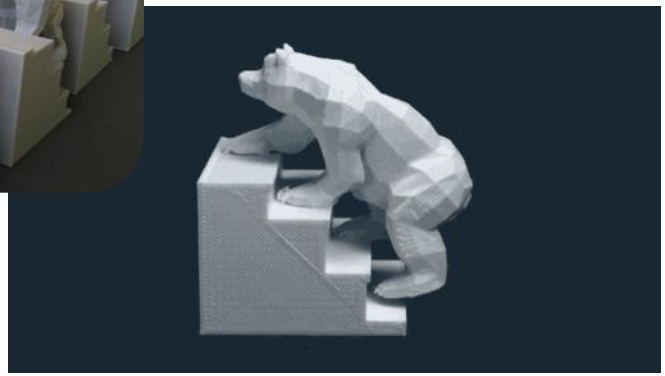
POLITECNICO
DI TORINO

Introduction

- 3D printing is widely used in the entertainment industry to easily and fast fabricate characters or objects that are first virtually modelled through Computer Graphics

- Using 3d prints in stop-motion animation, the creators do not have to mold every single facial expression of every character to be swapped from frame to frame.







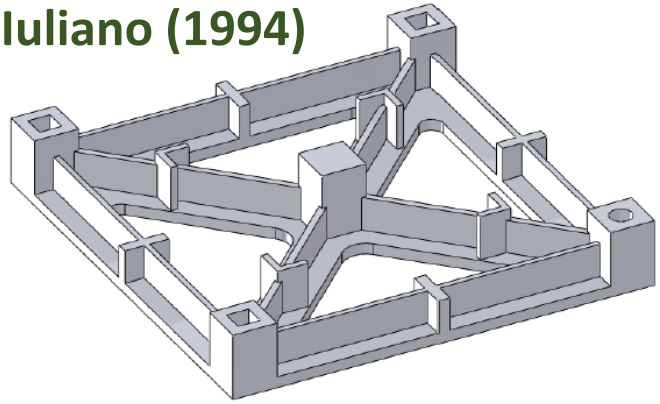
Introduction

- Recently a great number of low-cost 3D printers have been developed worldwide.
- There is the need to quantitatively compare the performances of different systems.
- Owing to the lack of an international standard guideline, the performance is evaluated upon the dimensional and geometric accuracy of manufactured parts.
- Thus several reference artifacts with different geometries were defined and proposed in the literature to be used for benchmarking.

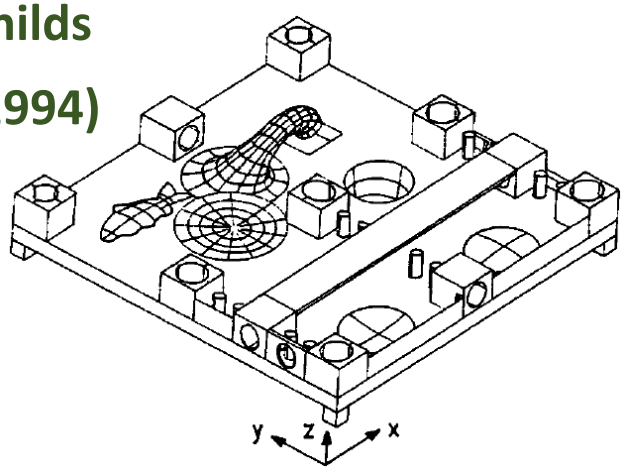
Other reference parts

Gargiulo (1992)

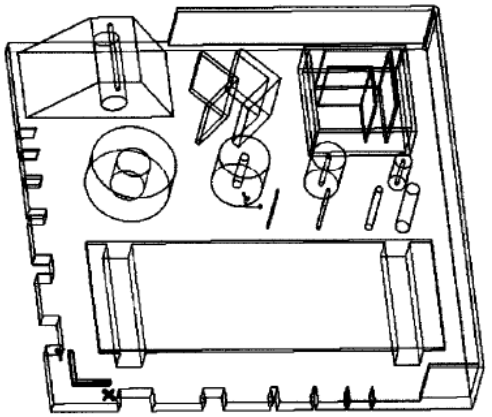
Iuliano (1994)



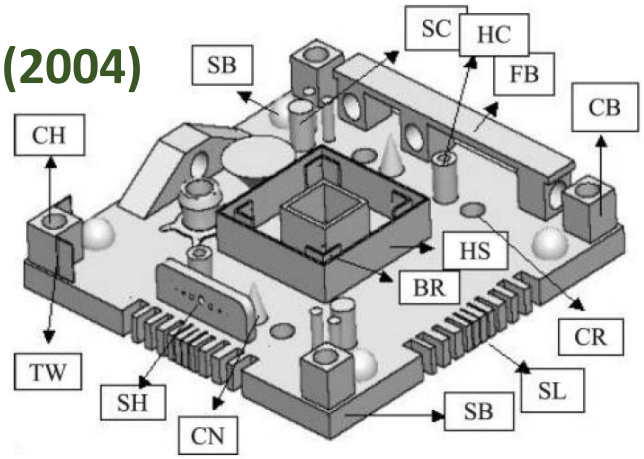
Childs (1994)



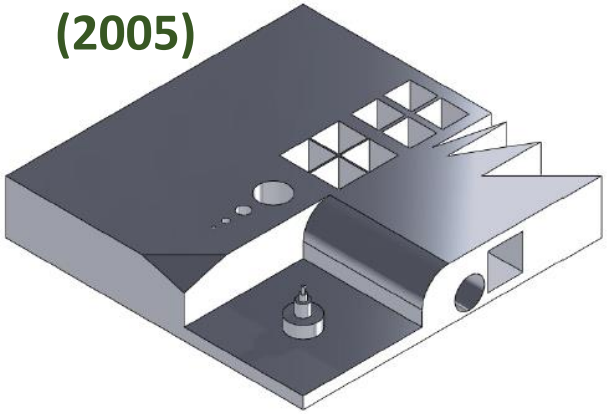
Xu (2000)



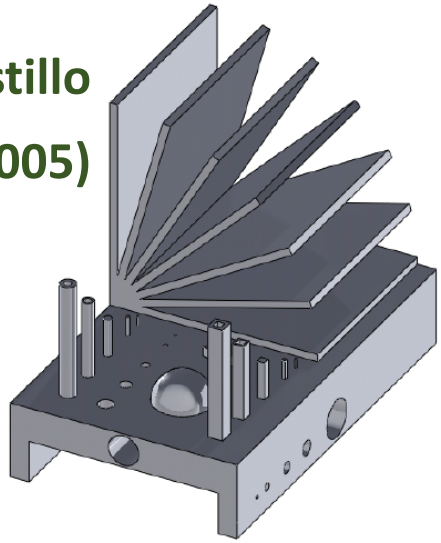
Mahesh (2004)



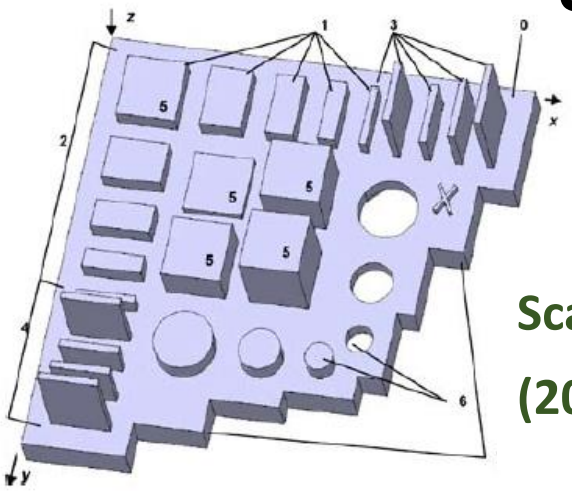
Kruth (2005)



Castillo (2005)

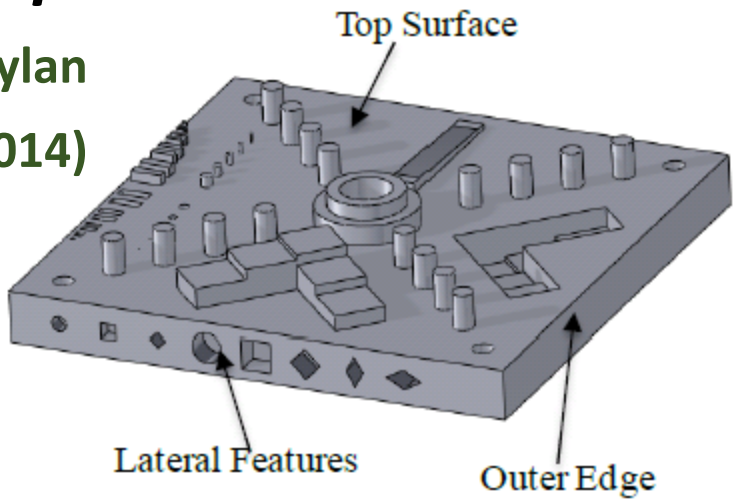


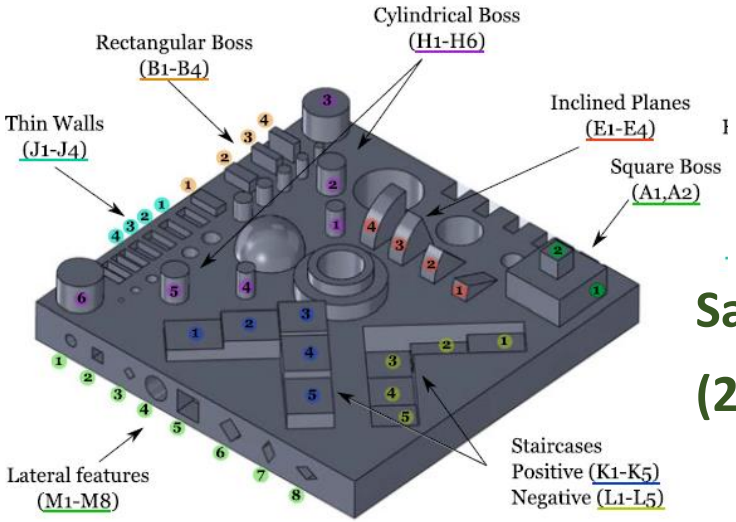
Other reference parts



Scaravetti (2008)

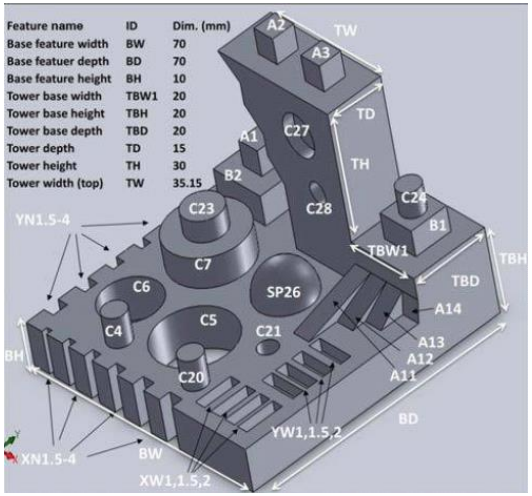
Moylan (2014)





Sanchez (2014)

Johnson (2014)



Benchmarking

- Most of the proposed artifacts present several different geometries that have similar sizes.
- When dealing with the part's dimensional accuracy and tolerances, it is particular convenient to refer to the ISO standard IT grades (ISO-286).
- Nevertheless only a few works in the literature use the IT grades to summarize the results of a benchmarking study.
- An innovative reference part is proposed in for benchmarking purposes.
- The guidelines that were defined by Moylan et al. are kept into account in the definition of the reference part's geometry.

Guidelines

The following indications are available in the literature:

- have a considerable number of small, medium and large features;
- not consume a large quantity of material;
- have many features of a 'real' part;
- have simple geometrical shapes;
- allow repeatability measurements;
- require no post-treatment or manual intervention (no support structures);
- not take long to build.

The proposed reference part

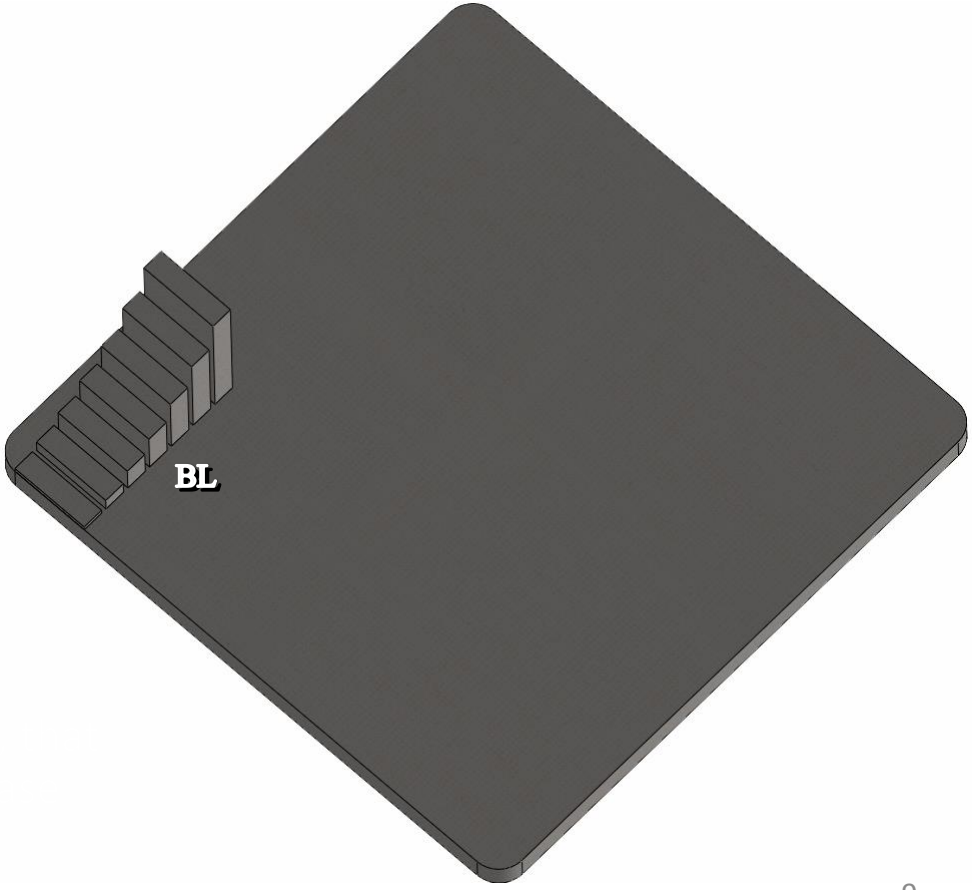
- Includes a higher number of features or dimensions for each range of basic sizes with respect to other benchmarking artifacts that have been proposed in the literature;
- Includes several classic geometries;
- Geometric features appear both in the concave and convex shapes;
- Does not require support structures for its production, allowing for manufacturing on 3D printers that come with a unique extruder.

Replicas of the reference part are printed out of ABS (acrylonitrile butadiene styrene) material by means of the compared machines using different layer thickness.

Features of the reference part

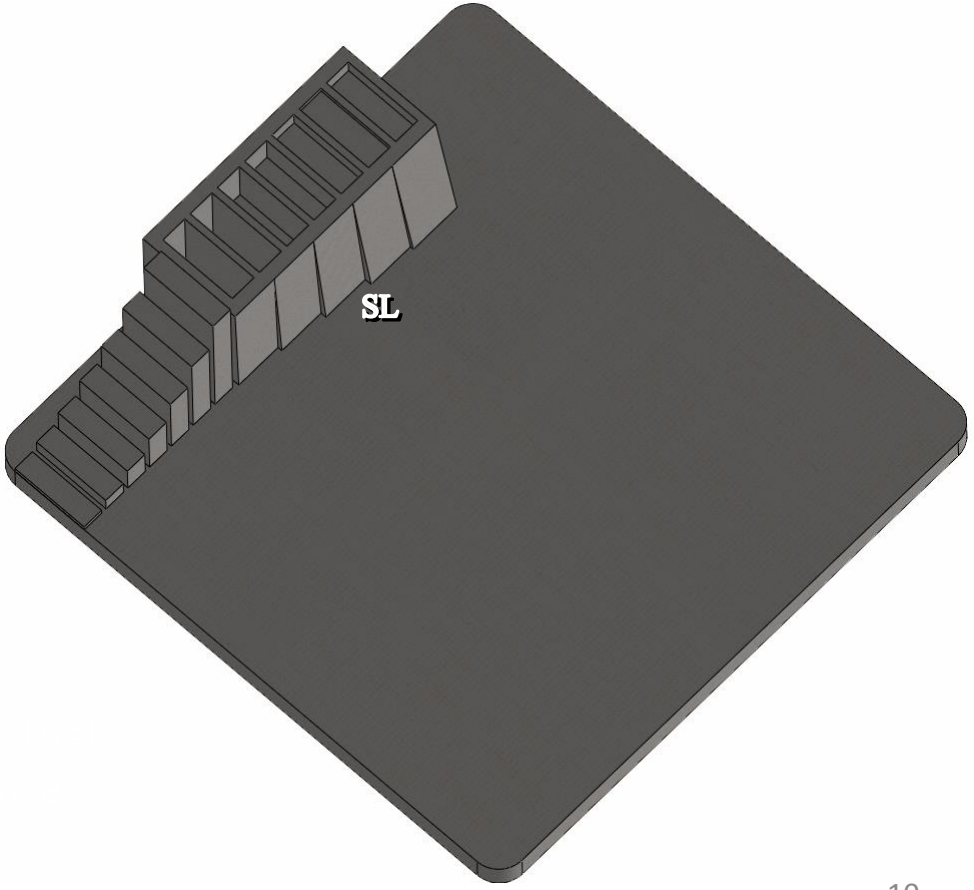
- a set of seven rectangular blocks (**BL**)

Overall dimensions
110 x 110 x 33 mm



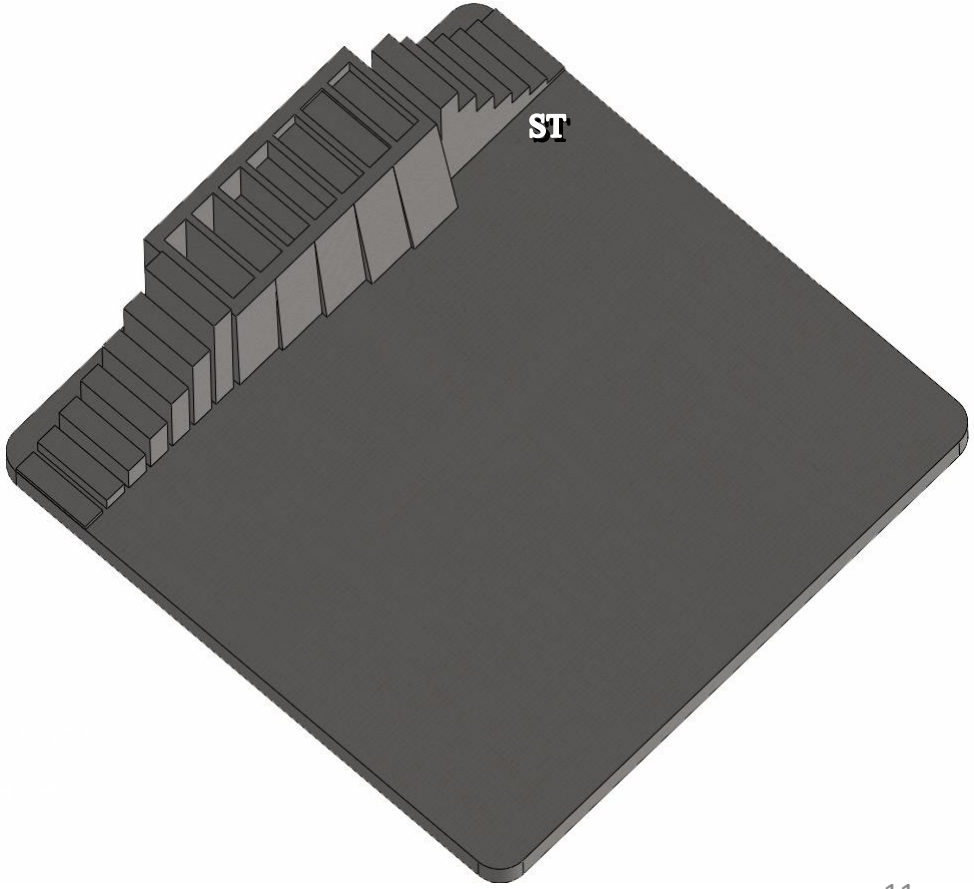
Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)



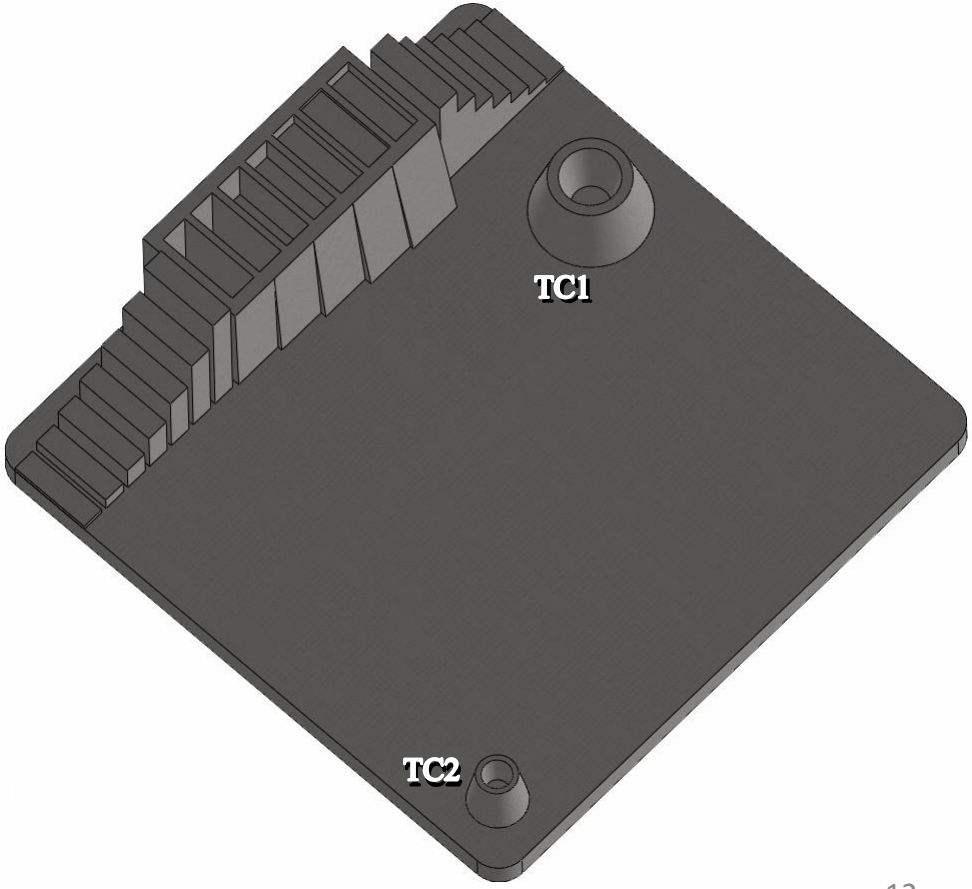
Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)
- a set of seven steps (**ST**)



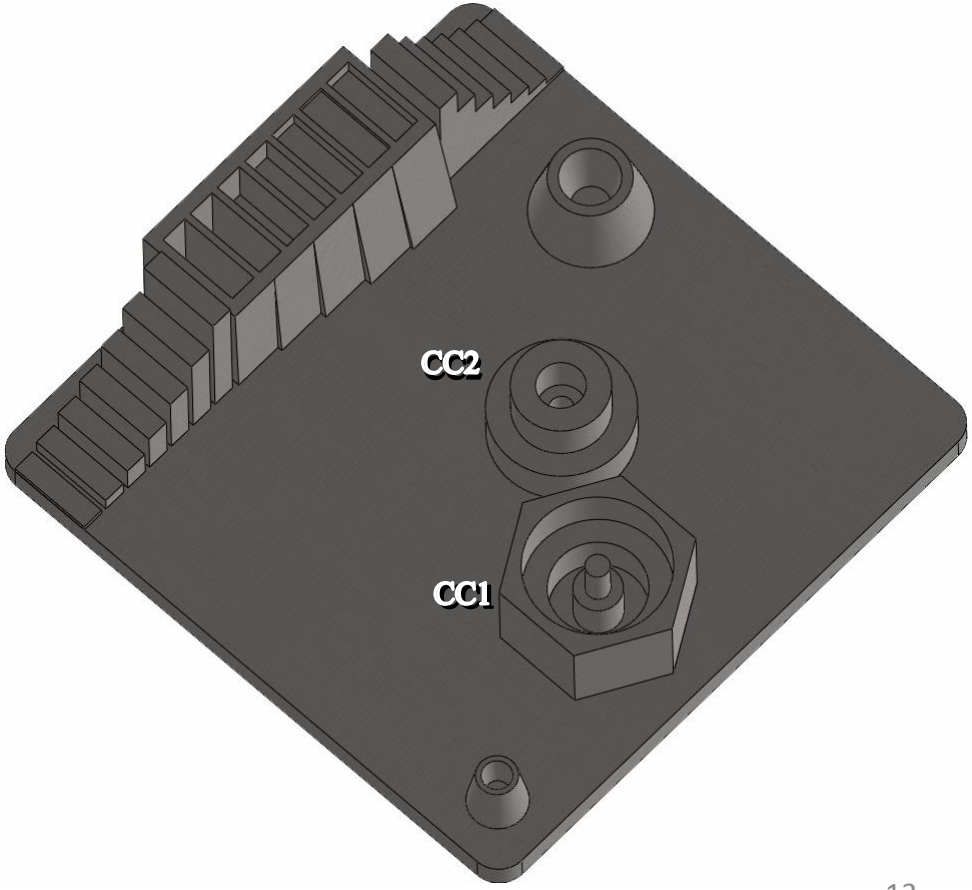
Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)
- a set of seven steps (**ST**)
- two couples of coaxial truncated cones (**TC1** and **TC2**)



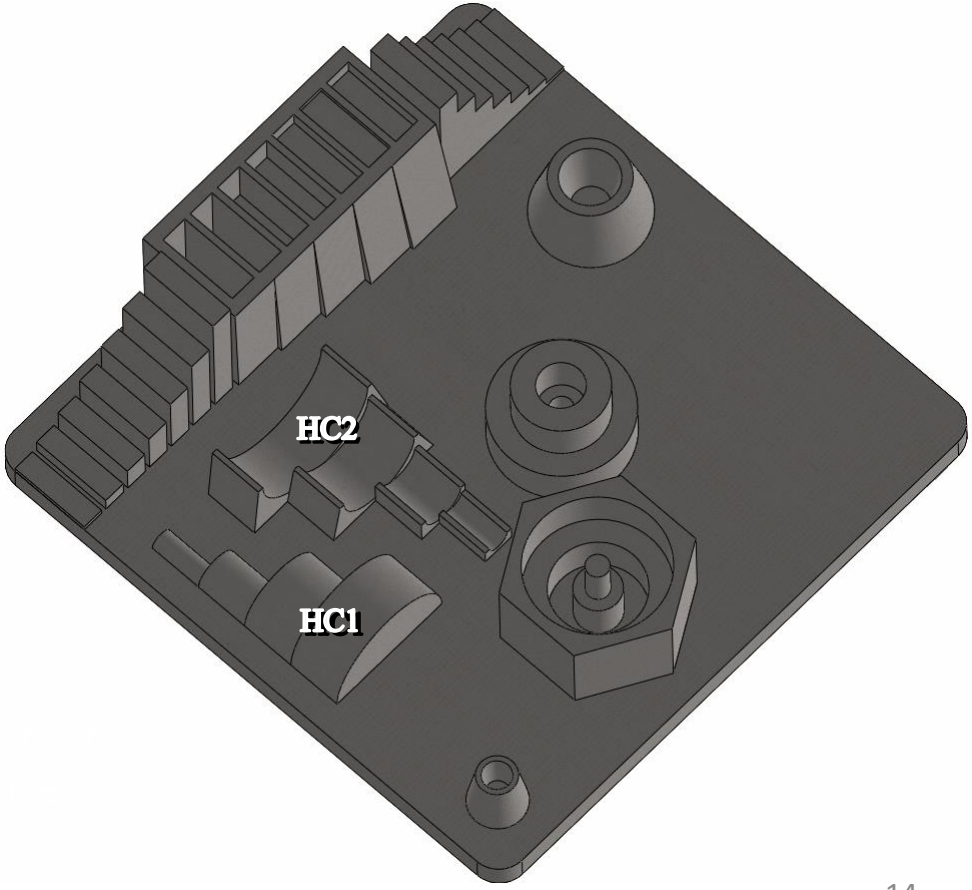
Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)
- a set of seven steps (**ST**)
- two couples of coaxial truncated cones (**TC1** and **TC2**)
- two sets of coaxial cylinders (**CC1** and **CC2**)



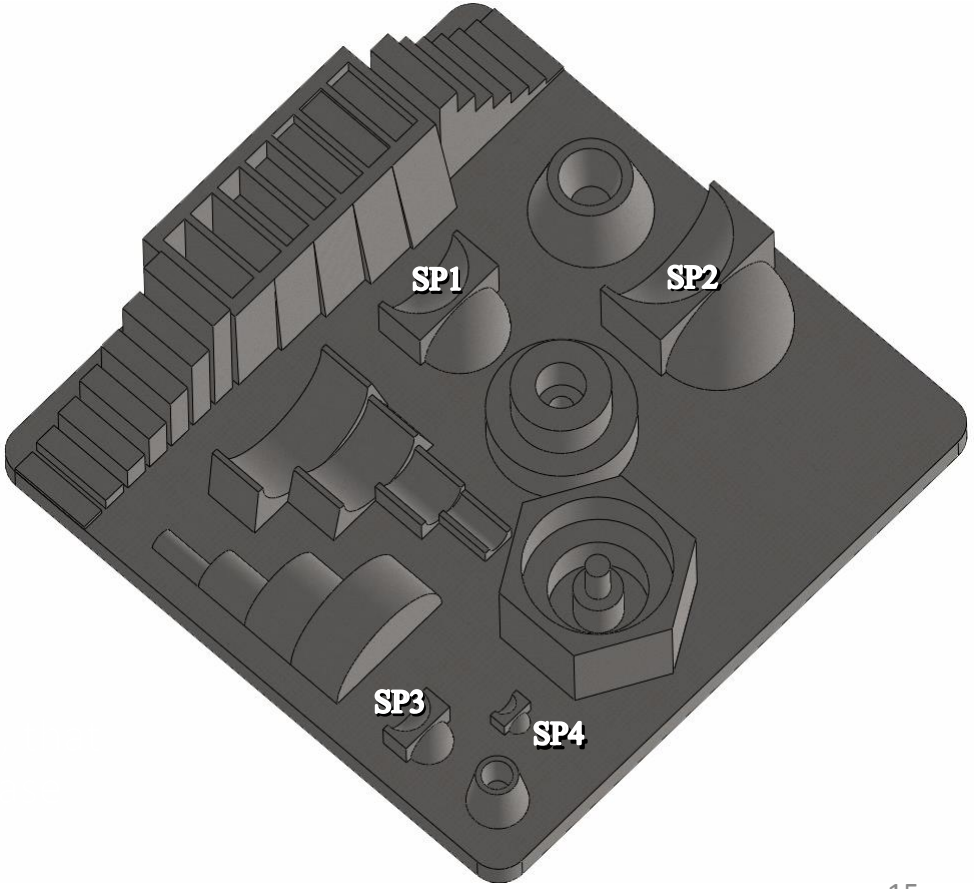
Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)
- a set of seven steps (**ST**)
- two couples of coaxial truncated cones (**TC1** and **TC2**)
- two sets of coaxial cylinders (**CC1** and **CC2**)
- two sets of hemi cylinders (**HC1** and **HC2**)



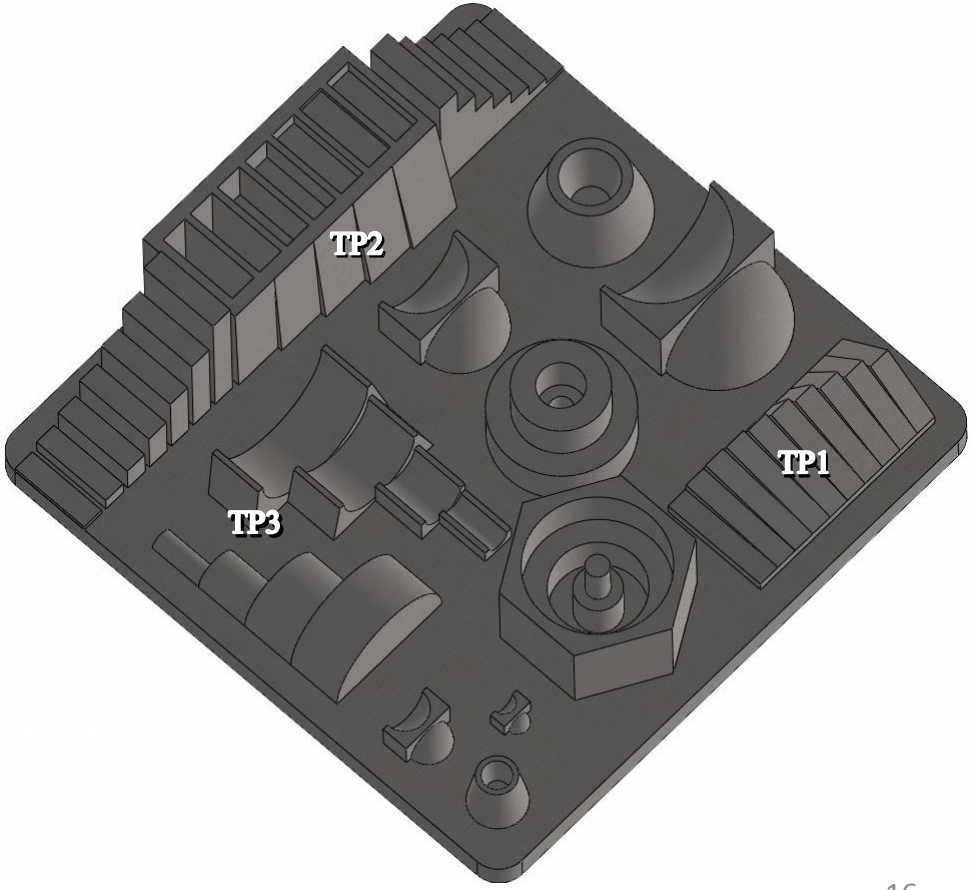
Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)
- a set of seven steps (**ST**)
- two couples of coaxial truncated cones (**TC1** and **TC2**)
- two sets of coaxial cylinders (**CC1** and **CC2**)
- two sets of hemi cylinders (**HC1** and **HC2**)
- four sets of quarters of spheres (**SP1**, **SP2**, **SP3** and **SP4**)



Features of the reference part

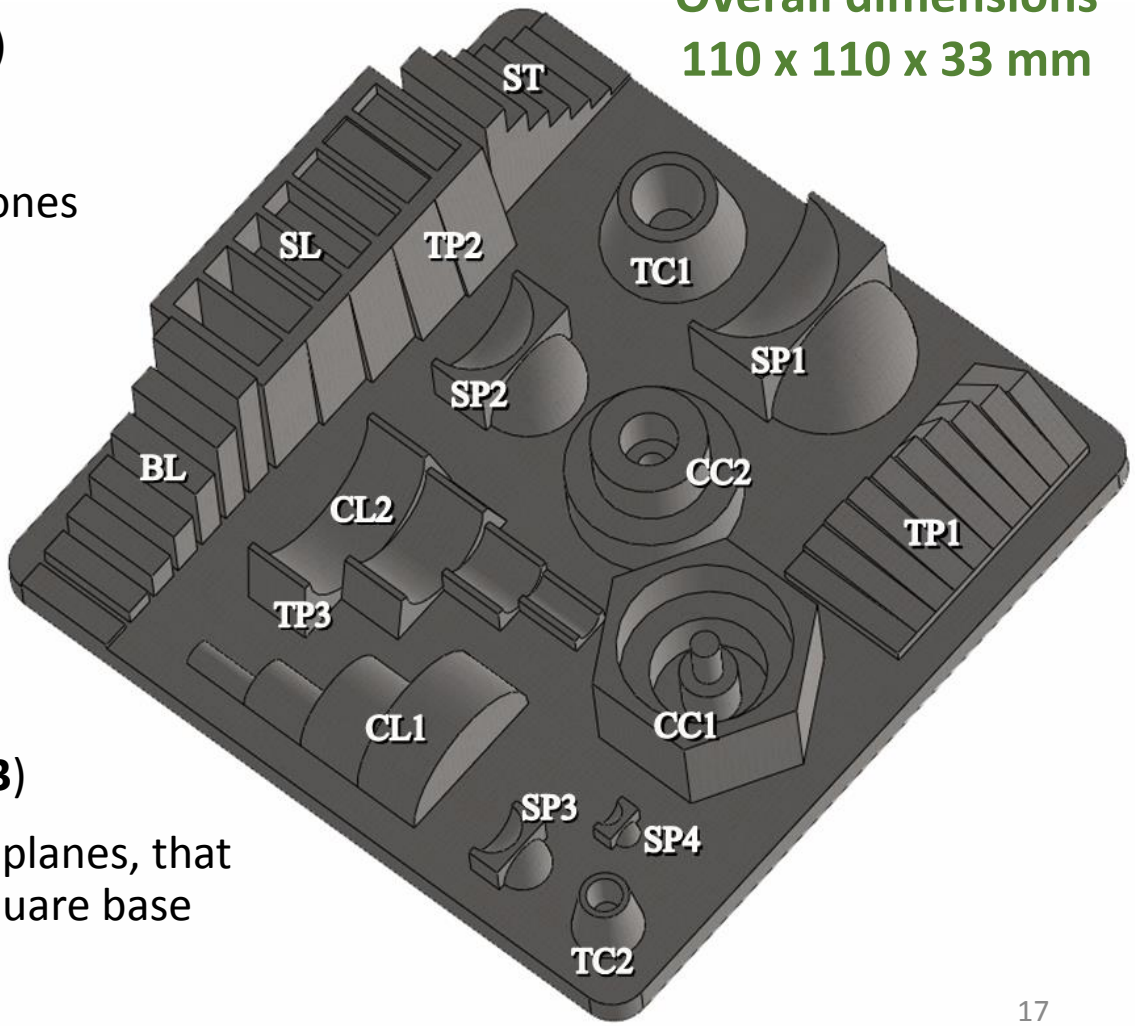
- a set of seven rectangular blocks (**BL**)
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- two couples of coaxial truncated cones (**TC1** and **TC2**)
- two sets of coaxial cylinders (**CC1** and **CC2**)
- two sets of hemi cylinders (**HC1** and **HC2**)
- four sets of quarters of spheres (**SP1**, **SP2**, **SP3** and **SP4**)
- three sets of tilted planes (**TP1**, **TP2** and **TP3**)



Features of the reference part

- a set of seven rectangular blocks (**BL**)
- a set of seven rectangular slots (**SL**)
- a set of seven steps (**ST**)
- two couples of coaxial truncated cones (**TC1** and **TC2**)
- two sets of coaxial cylinders (**CC1** and **CC2**)
- two sets of hemi cylinders (**HC1** and **HC2**)
- four sets of quarters of spheres (**SP1**, **SP2**, **SP3** and **SP4**)
- three sets of tilted planes (**TP1**, **TP2** and **TP3**)
- several other vertical or horizontal planes, that are parallel or orthogonal to the square base of the reference part.

Overall dimensions
110 x 110 x 33 mm



COMAU at a glance

A name that means tradition, competence and great experience.

Comau originally got its name from the abbreviation of COnsorzio MAcchine Utensili and now with 40 years of experience in advanced manufacturing systems, it represents a proven world-wide leader in sustainable automation and service solutions with a forward focus.

Today, Comau has a truly global presence, with 24 locations in 13 countries, which allows us to offer tailor-made solutions and localized support in a variety of fields (automotive, aerospace, petrochemical, military, shipbuilding and energy efficiency consultancy).





Specializing Master in Industrial Automation



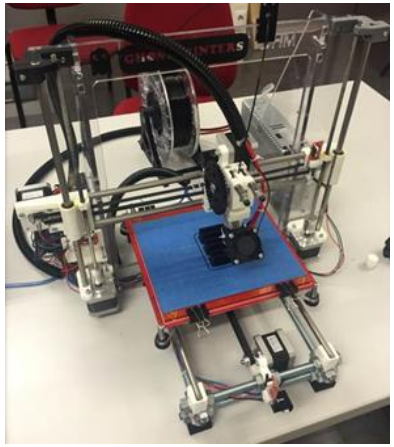
The task of enhancing the performances of the 3D printer Prusa i3, that is supplied in the assembly box, was assigned to 16 engineers attending the Master who were divided into 4 groups.

In order to assess and validate the improvements, a benchmarking activity was carried out to evaluate the dimensional accuracy of the 4 modified printers.



Compared printers

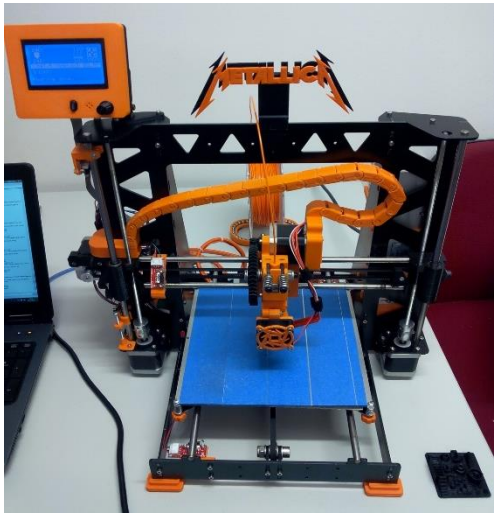


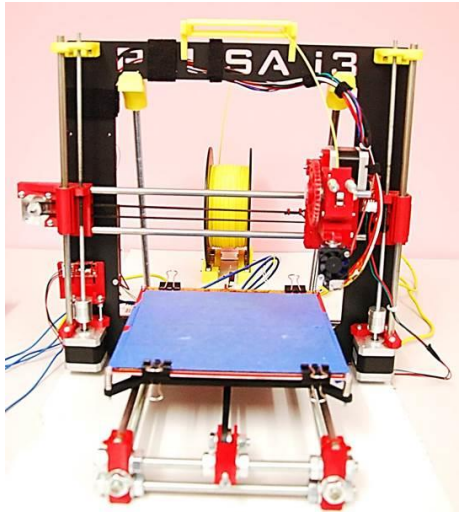


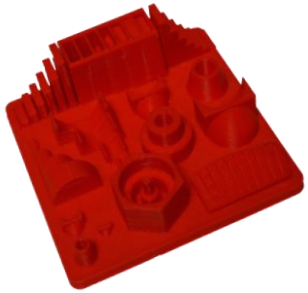








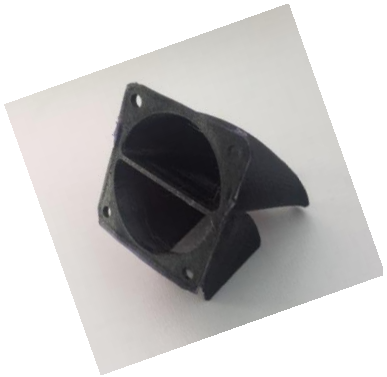




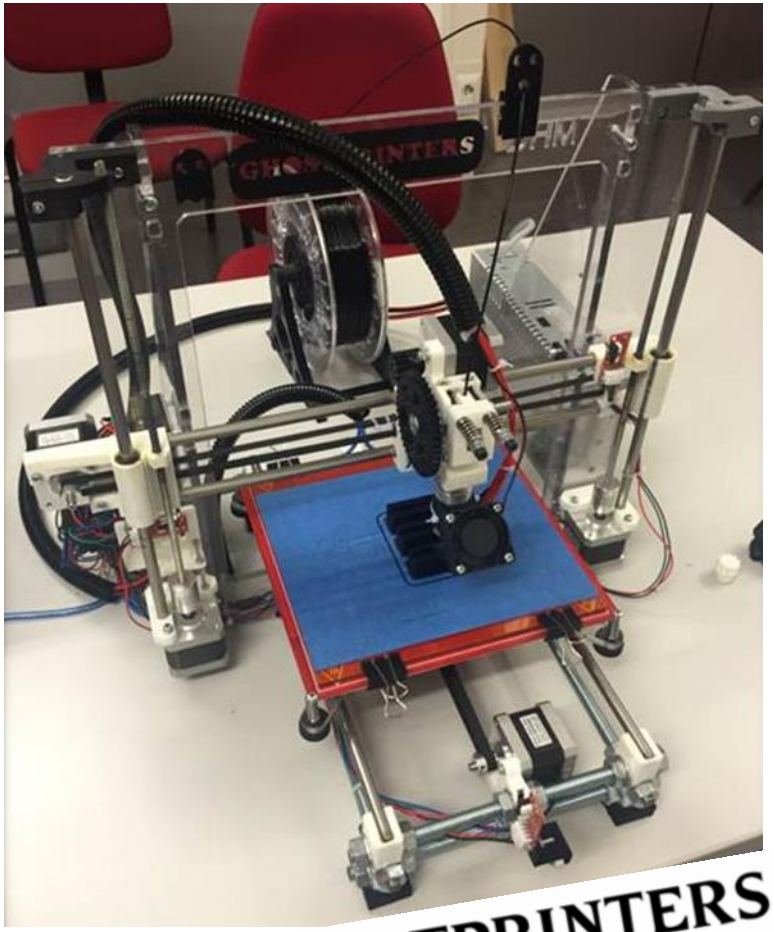
Ghostprinters

List of main improvements:

- anti-vibration feet
- Z axis holder
- Y axis end course riser
- bed adjust striped nuts
- power supply holder
- double fan duct
- spool rotating holder
- filament guide
- extruder gears



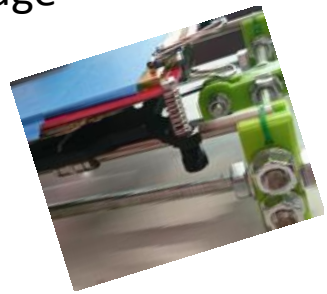


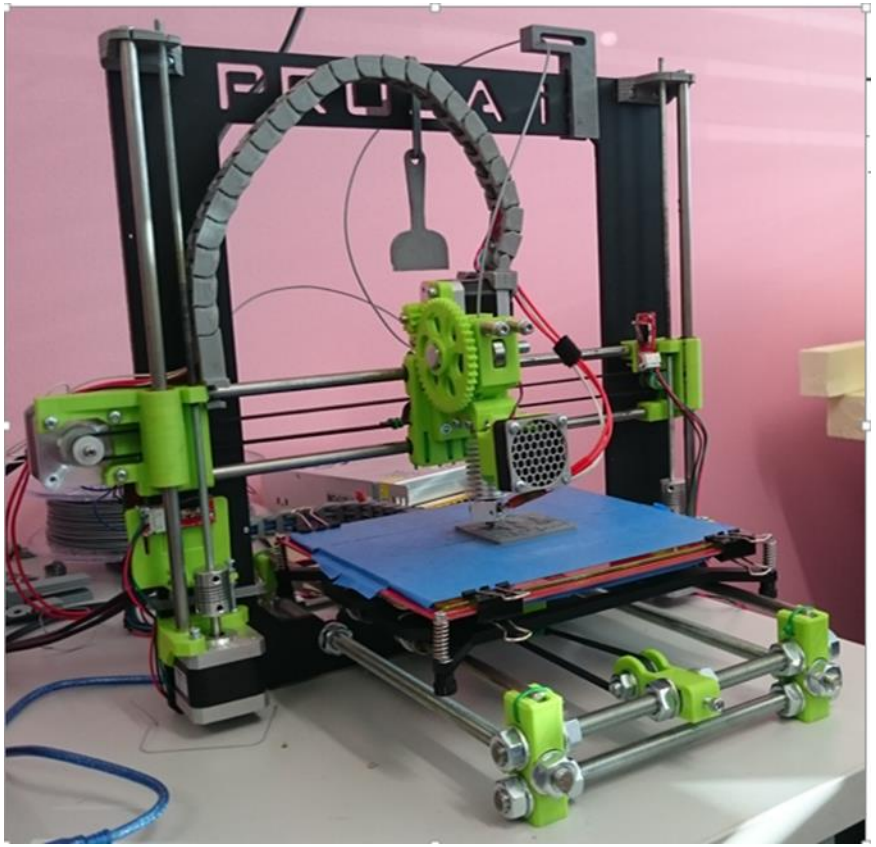


Fluo

List of main improvements:

- Y axis endstop leverage
- filament holder
- Y axis chain
- X axis chain
- fan protection grid
- adjustable heated bed device
- filament guide +z axis ending







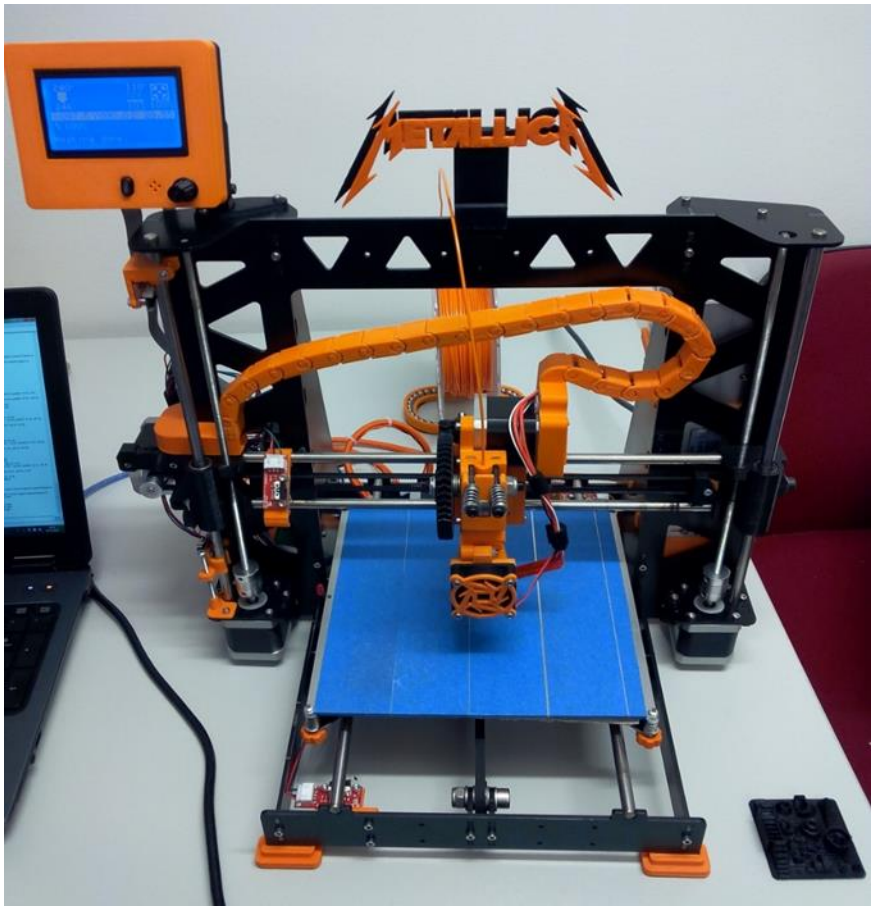
Metallica

List of main improvements:

- motor protection
- fan guard
- catenary
- extruder holder
- X-axis and Y-axis belt tensioner
- X-axis and Y-axis carriage
- power supply cover
- spool holder
- bed leveling knob
- anti-wobble







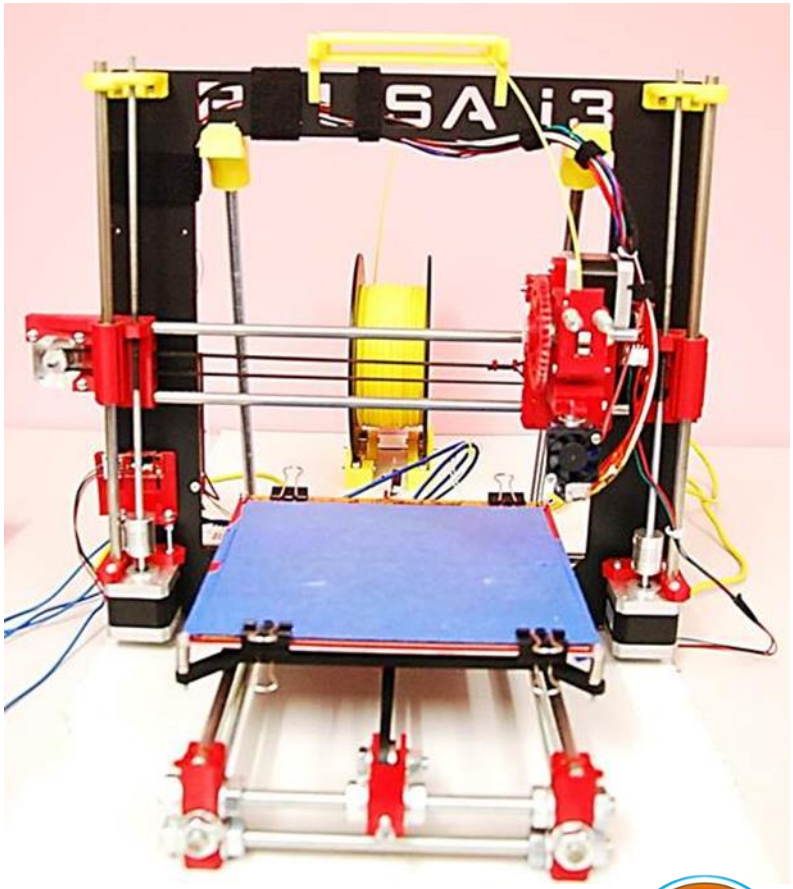
Print-Doh

List of main improvements:

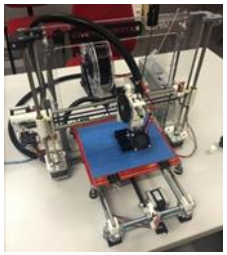
- Z axis support
- filament guide
- spool holder
- stiffener rods
- X axis chain
- auto bed leveling kit
- bowden kit
- auto bed leveling kit







The manufactured replicas



Ghostprinters



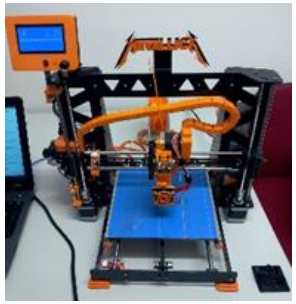
Nozzle size: 0.20 mm
Layer thickness: 0.15 mm
Printing time: 9.5 hours



Fluo



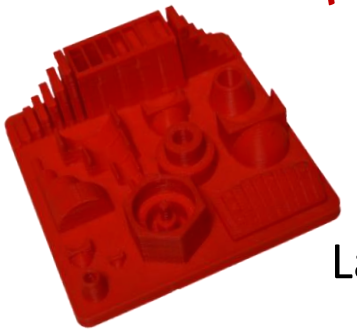
Nozzle size: 0.40 mm
Layer thickness: 0.20 mm
Printing time: 5.5 hours



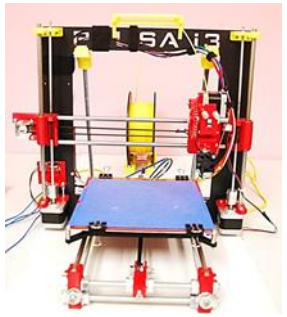
Metallica



Nozzle size: 0.30 mm
Layer thickness: 0.20 mm
Printing time: 6 hours



Print-Doh



Nozzle size: 0.40 mm
Layer thickness: 0.25 mm
Printing time: 5 hours

Dimensional inspection



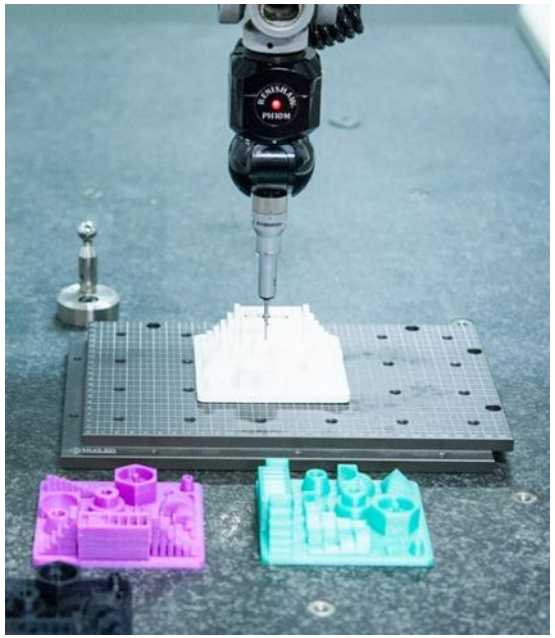
The CMM machine declared volumetric length measuring uncertainty MPE_E according to ISO-10360/2 is

$$1.5 + L/333\ \mu m$$

Three replications were made for the inspection of each part.

At least 10 inspection points were measured on each geometric feature.

A unique configuration of the CMM probe with the axis orthogonal to the part base plane is required.



ISO 286 Guideline

The dimensional quality of a part is defined by IT grades.

For each range basic size, the IT grade is related to the maximum admitted deviation with respect to the nominal dimension.

Table 1 — Numerical values of standard tolerance grades IT for basic sizes up to 3 150 mm [1)]

Basic size mm		Standard tolerance grades																	
		IT1 [2)]	IT2 [2)]	IT3 [2)]	IT4 [2)]	IT5 [2)]	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14 [3)]	IT15 [3)]	IT16 [3)]	IT17 [3)]	IT18 [3)]
Above	Up to and including	Tolerances																	
		µm											mm						
—	3 [3)]	0,8	1,2	2	3	4	6	10	14	25	40	60	0,1	0,14	0,25	0,4	0,6	1	1,4
3	6	1	1,5	2,5	4	5	8	12	18	30	48	75	0,12	0,18	0,3	0,48	0,75	1,2	1,8
6	10	1	1,5	2,5	4	6	9	15	22	36	58	90	0,15	0,22	0,36	0,58	0,9	1,5	2,2
10	18	1,2	2	3	5	8	11	18	27	43	70	110	0,18	0,27	0,43	0,7	1,1	1,8	2,7
18	30	1,5	2,5	4	6	9	13	21	33	52	84	130	0,21	0,33	0,52	0,84	1,3	2,1	3,3
30	50	1,5	2,5	4	7	11	16	25	39	62	100	160	0,25	0,39	0,62	1	1,6	2,5	3,9
50	80	2	3	5	8	13	19	30	46	74	120	190	0,3	0,46	0,74	1,2	1,9	3	4,6
80	120	2,5	4	6	10	15	22	35	54	87	140	220	0,35	0,54	0,87	1,4	2,2	3,5	5,4

Standard tolerance factor

The values of standard tolerances corresponding to IT 5 – IT 18 grades for nominal sizes up to 500 mm are evaluated through the standard tolerance factor ***i*** that is expressed in micrometres by the following formula:

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

Where ***D*** is the geometric average of the range of nominal sizes in millimeters:

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

Range		**Basic sizes**							
Above	**D_1 (mm)**	**1**	**3**	**6**	**10**	**18**	**30**	**50**	**80**
Up to and including	**D_2 (mm)**	**3**	**6**	**10**	**18**	**30**	**50**	**80**	**120**
Standard tolerance factor	i (μm)	0.542	0.733	0.898	1.083	1.307	1.561	1.856	2.173

ISO IT grades

The IT grades are classified by the number ***n*** of times that the tolerance factor ***i*** fits into the dimensional deviation.

For a generic nominal dimension D_{jn}, the number n_j of tolerance units is computed as follows:

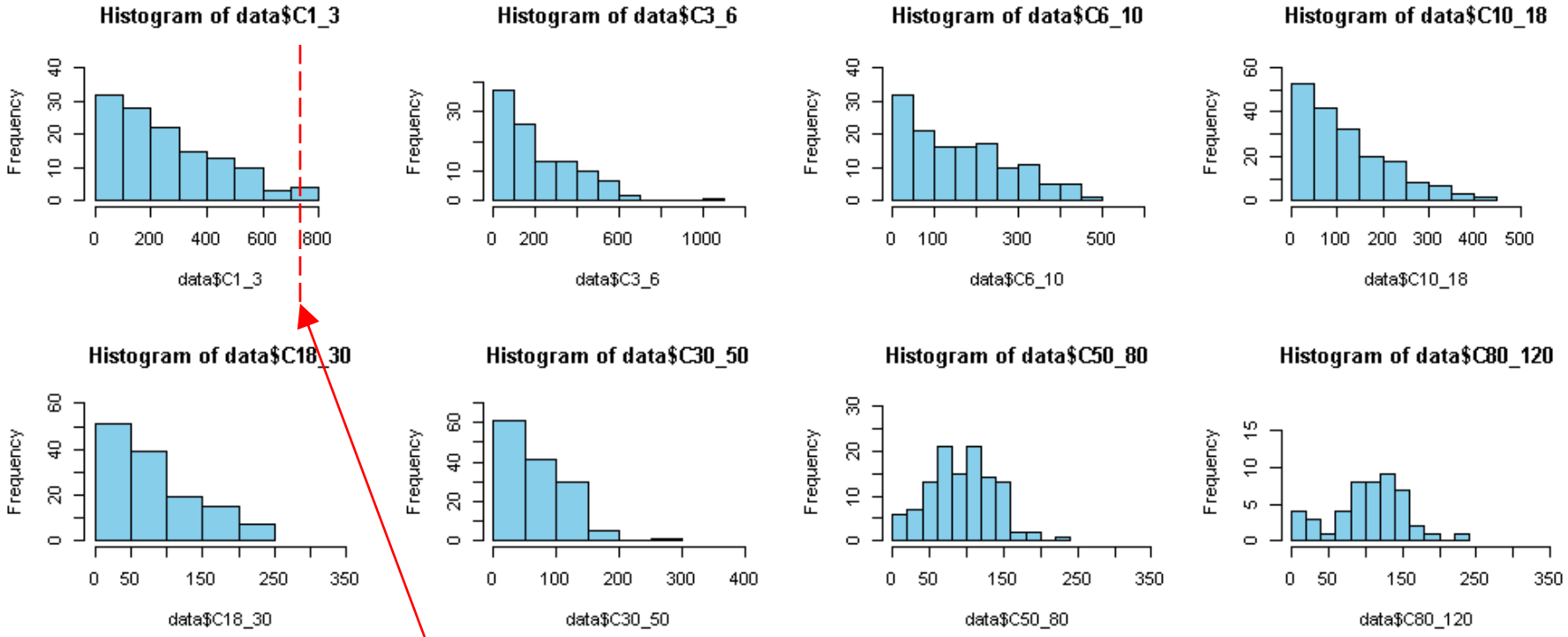
$$n_j = \frac{1000 \left| D_{jn} - D_{jm} \right|}{i}$$

where D_{jm} is the corresponding measured dimension.

Basic size		Standard tolerance grades													
Above	Up to	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11	IT 12	IT 13	IT 14	IT 15	IT 16	IT 17	IT 18
1 mm	500 mm	7*i*	10*i*	16*i*	25*i*	40*i*	64*i*	100*i*	160*i*	250*i*	400*i*	640*i*	1000*i*	1600*i*	2500*i*

In this study, the ***n*** value corresponding to the 95th percentile of the distribution within each range is assumed as the maximum dimensional error.

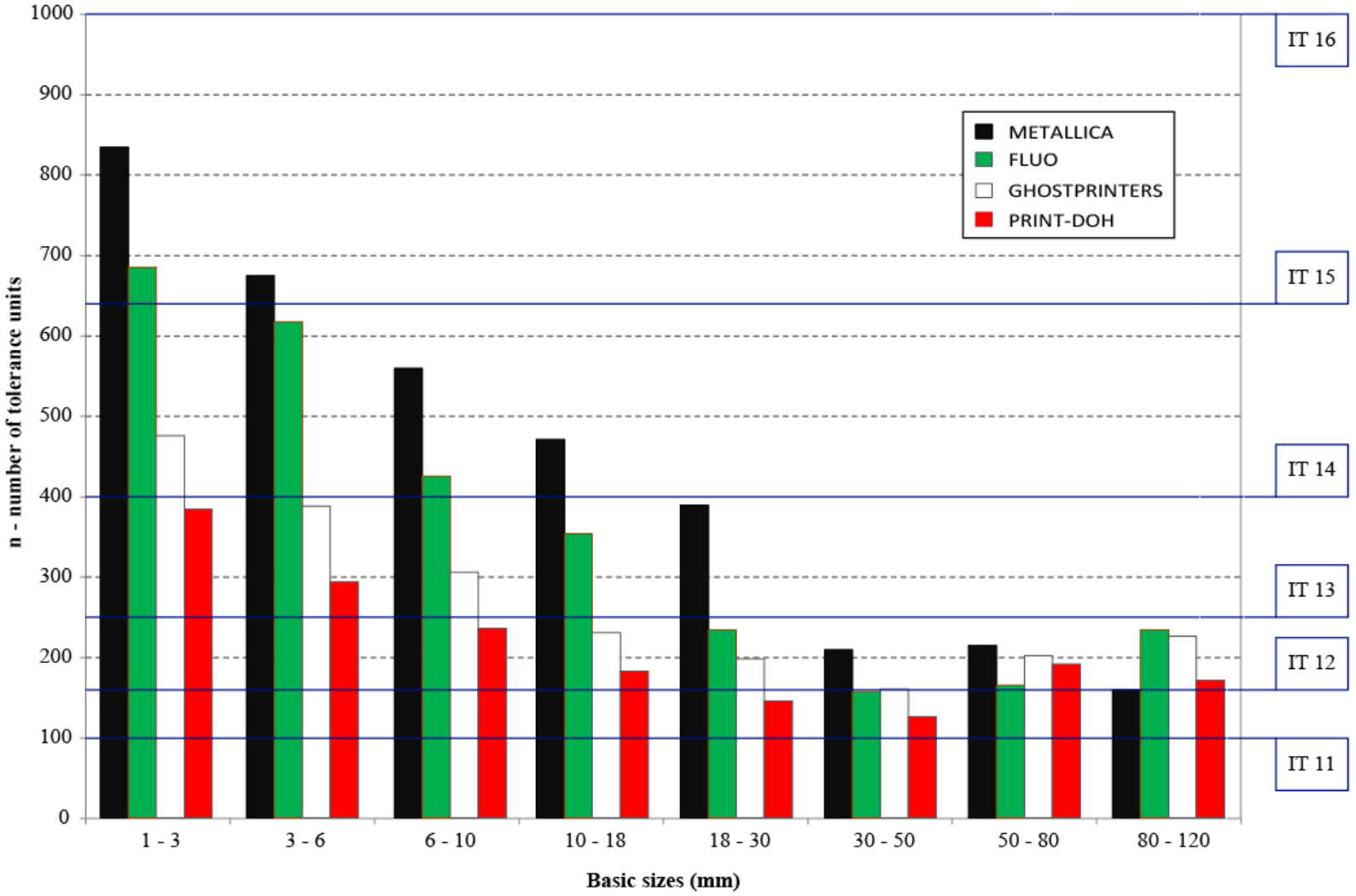
Distribution of n for different ISO ranges



5% out

Confidence level is set to 95%

Comparison of results



Comparison of results

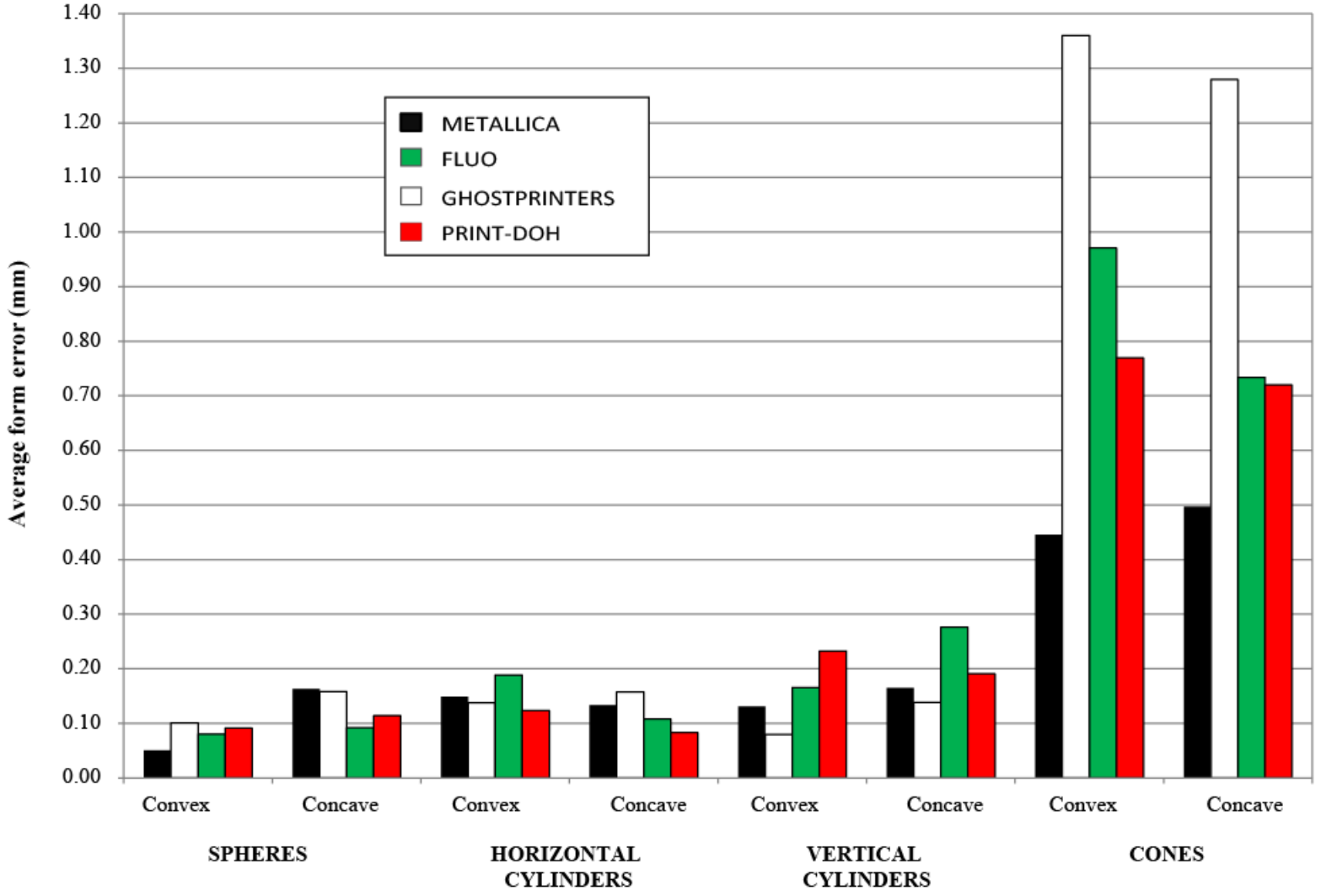
Part quality ranges from IT11 to IT16.

Smaller features have lower dimensional accuracy.

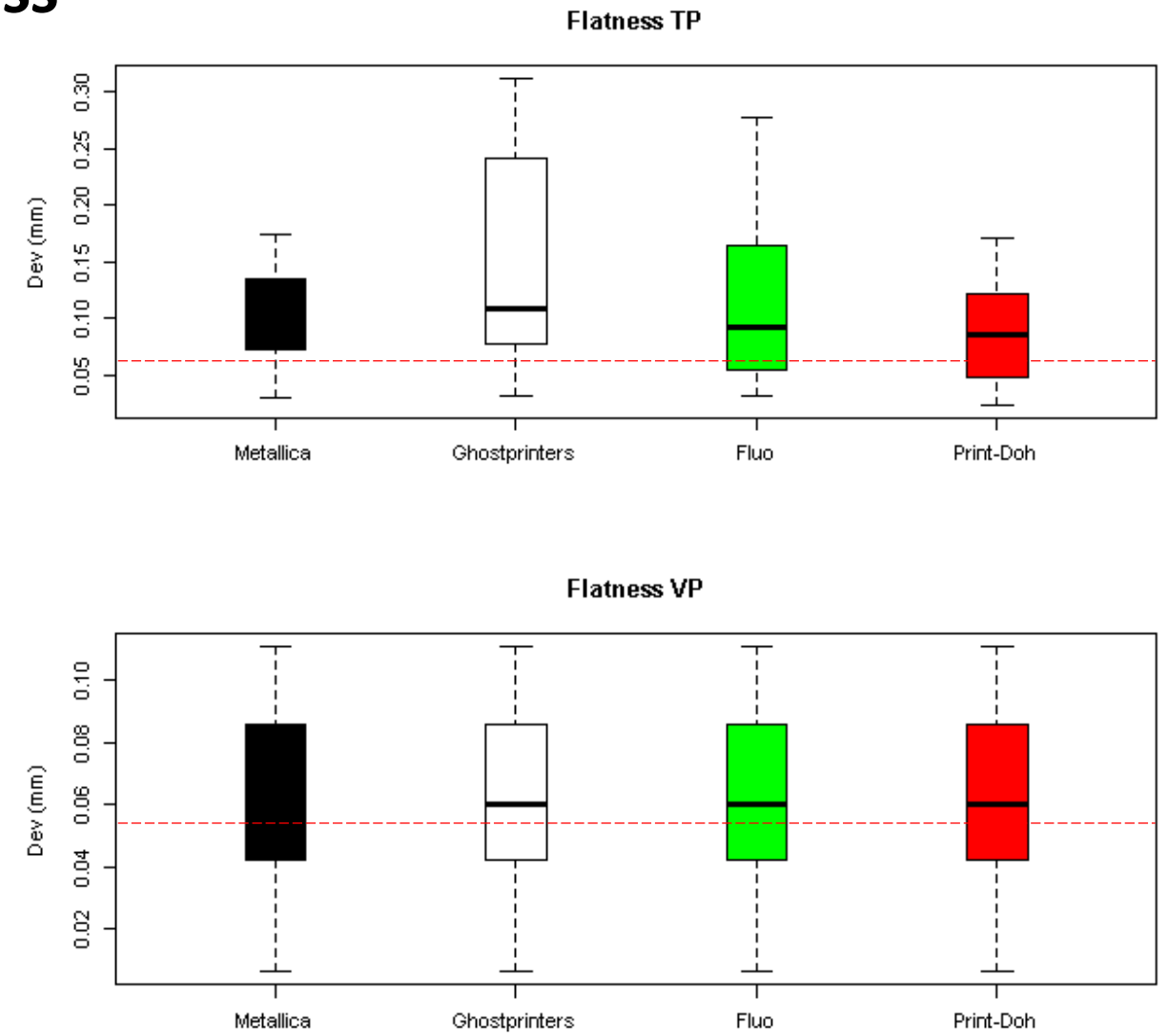
Table 1 — Numerical values of standard tolerance grades IT for basic sizes up to 3 150 mm [1)]

Basic size mm		Standard tolerance grades																
		IT1 [2)]	IT2 [2)]	IT3 [2)]	IT4 [2)]	IT5 [2)]	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14 [3)]	IT15 [3)]	IT16 [3)]	IT17 [3)]	IT18 [3)]
Above	Up to and including	Tolerances																	
		µm											mm						
—	3 [3)]	0,8	1,2	2	3	4	6	10	14	25	40	60	0,1	0,14	0,25	0,4	0,6	1	1,4
3	6	1	1,5	2,5	4	5	8	12	18	30	48	75	0,12	0,18	0,3	0,48	0,75	1,2	1,8
6	10	1	1,5	2,5	4	6	9	15	22	36	58	90	0,15	0,22	0,36	0,58	0,9	1,5	2,2
10	18	1,2	2	3	5	8	11	18	27	43	70	110	0,18	0,27	0,43	0,7	1,1	1,8	2,7
18	30	1,5	2,5	4	6	9	13	21	33	52	84	130	0,21	0,33	0,52	0,84	1,3	2,1	3,3
30	50	1,5	2,5	4	7	11	16	25	39	62	100	160	0,25	0,39	0,62	1	1,6	2,5	3,9
50	80	2	3	5	8	13	19	30	46	74	120	190	0,3	0,46	0,74	1,2	1,9	3	4,6
80	120	2,5	4	6	10	15	22	35	54	87	140	220	0,35	0,54	0,87	1,4	2,2	3,5	5,4

Form error


Average form error (mm)
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
METALLICA
FLUO
GHOSTPRINTERS
PRINT-DOH
Convex
Concave
Convex
Concave
Convex
Concave
Convex
Concave
SPHERES
HORIZONTAL CYLINDERS
VERTICAL CYLINDERS
CONES

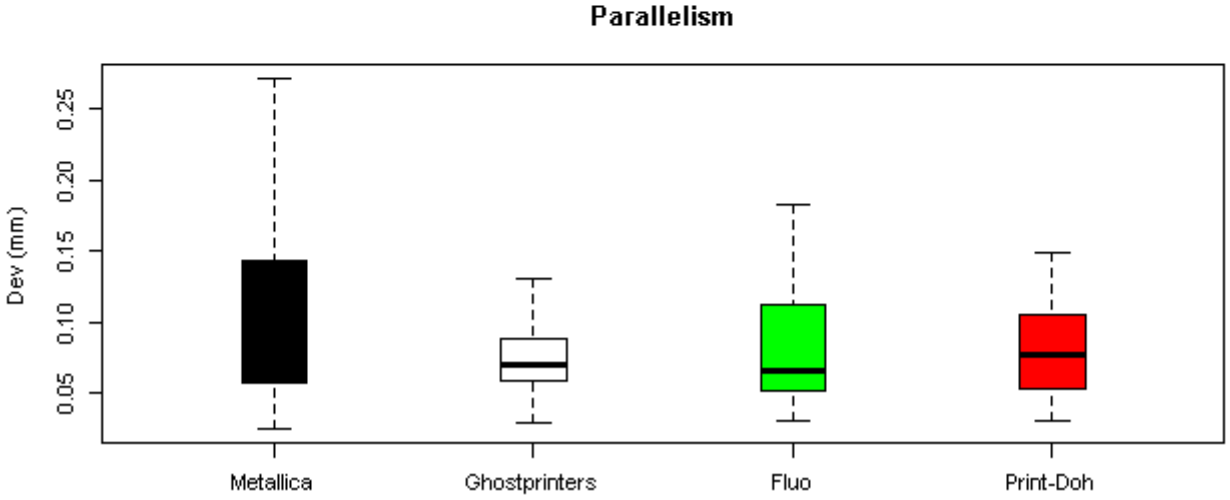
Flatness



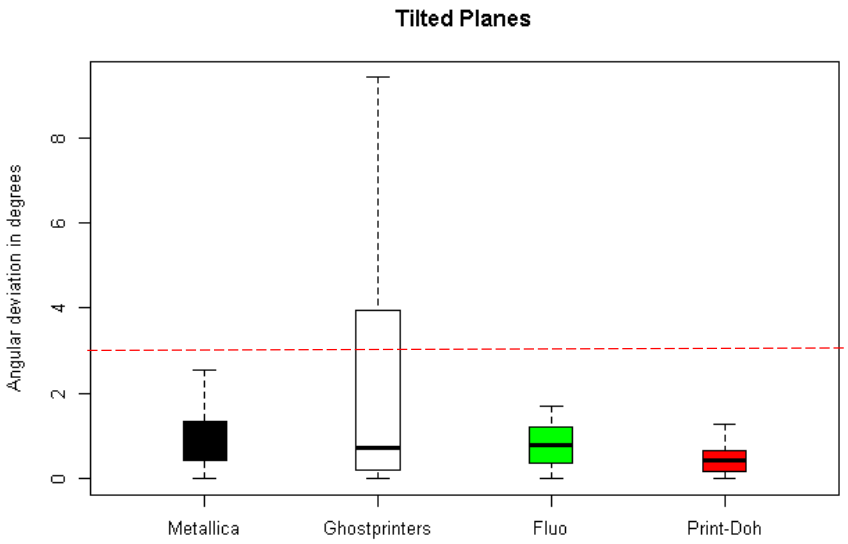
Maximum range for HP

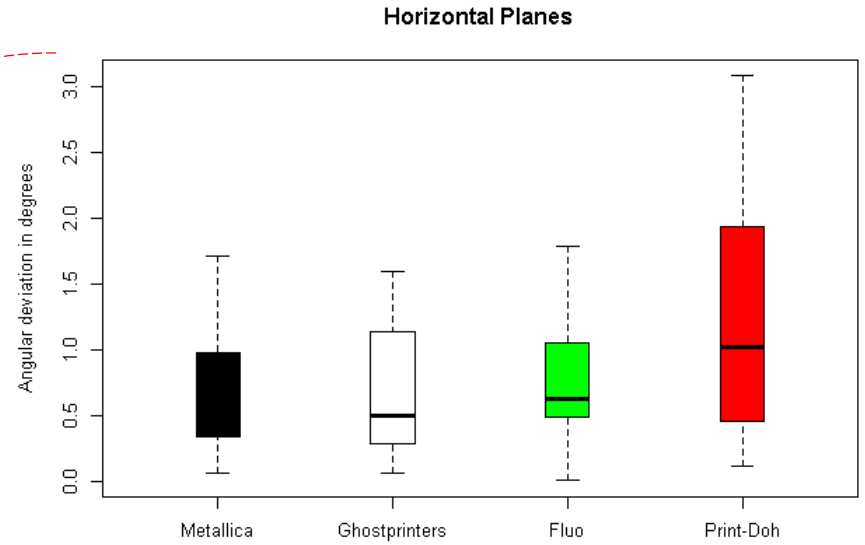
Flatness

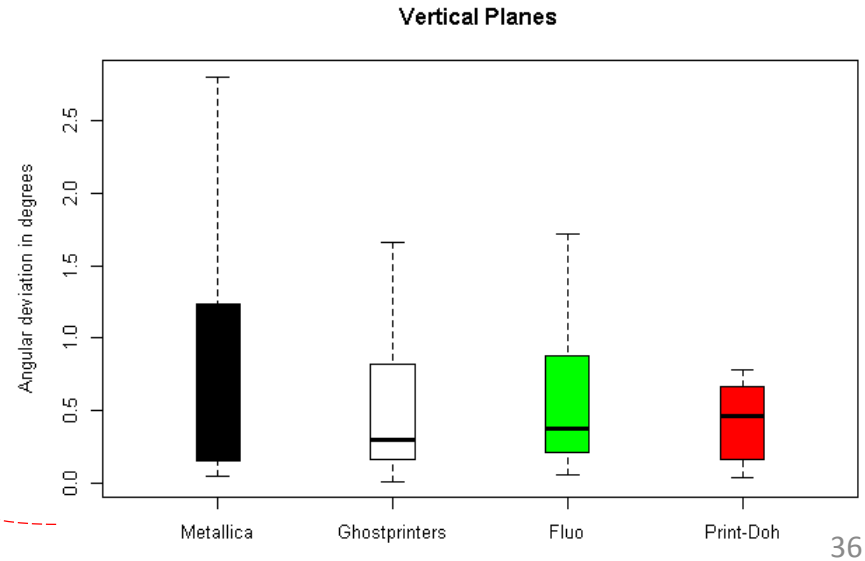

Flatness HP
Dev (mm)
0.02
0.03
0.04
0.05
Metallica
Ghostprinters
Fluo
Print-Doh


Parallelism
Dev (mm)
0.05
0.10
0.15
0.20
0.25
Metallica
Ghostprinters
Fluo
Print-Doh

Angular errors







Conclusions

- Greater geometric accuracy for the Ghostprinters and Print-Doh devices. However

GHOSTPRINTERS

Nozzle size: 0.20 mm
Layer thickness: 0.15 mm
Printing time: 9.5 hours

Print-Doh

Nozzle size: 0.40 mm
Layer thickness: 0.25 mm
Printing time: 5 hours

- The difference in the performance can be ascribed to the improvements, but also to the optimized printing parameters.
- Over the first benchmarking results presented, the reference part will be used for comparing other FDM machines by fabrication of new replicas.
- The proposed methodology has a general applicability and could also be extended to other AM systems that are used for production of metal parts.

Enhancing the dimensional accuracy of a low-cost 3D printer

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Thanks for your attention!



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