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EVALUATION OF GEOMETRICAL UNCERTAINTY FACTORS DURING INTEGRATED UTILIZATION OF REVERSE ENGINEERING AND RAPID PROTOTYPING TECHNOLOGIES

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ABSTRACT

Rapid Prototyping Technologies (RPTs) quickly accomplish the realization of concepts related to new product designs. The integration of RPTs with Reverse Engineering (RE) is nowadays widely used in a range of applications, e.g. manufacturing of spare parts, digital reconstruction and fabrication of anatomic structures. For certain applications, the geometrical accuracy of the RE – RP-produced part is critical. Nevertheless, due to inevitable uncertainties introduced in every step of the process, the final component exhibits a variety of geometrical deviations. The paper indicates that despite the advancement in the combined use of digital RE – RP technologies for Rapid Manufacturing (RM) purposes, there are still issues to be considered in application-level before fully achieving the geometrical accuracy potential of RP and RE. Focusing on the evaluation of the geometrical uncertainties during the RP stage of mechanical components' RM process, affecting parameters are identified and to a certain extent quantified through the use of an illustrative case study.

KEYWORDS

Rapid Prototyping, Rapid Manufacturing, Reverse Engineering, Dimensional & Geometrical Accuracy

1. INTRODUCTION TO RE & RP TECHNOLOGIES

Reverse Engineering (RE) and Rapid Prototyping (RP) technologies have both grown a lot during the last decades and are nowadays very much utilised in product design, digital manufacturing, digital reconstruction and many other applications in the technical world, (Chen and Ct, 1997; Shi et al, 2000).

RE is the in depth study and analysis of an existing product or model in order to recreate the information, engineering decisions and specifications generated during the original design

(ElMaraghy, 1998). In RE, existing mechanical components, for which technical documentation is not available or accessible or do not exist, have to be reconstructed and manufactured through a variety of techniques, e.g. by the use of contact or non-contact Coordinate Measuring Machines (CMM) and dedicated software. RE techniques are obviously needed only when engineering drawings and other technical data are not available.

RP, also described as Layer Manufacturing, consists of 3D digital data utilization for object fabrication in successive layers and is performed in many ways, with several -different in principle- technologies and systems developed within the years (Pham, 2001; Salonitis et al, 2003; Yongnian et al, 2009). The most prevailing representatives of RP today are Stereolithography (SL), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), 3D Printing and UV Curing (by Multi-jetting, DLP resin flashing and droplet deposition), (Grenda, 2010).

Until recently almost all RP machines were expensive to buy (costing several tenths to hundreds of thousand of US$) and also to run, especially the laser based systems, (Wohlers and Grimm, 2002). But in the last 5 years there has been a breakthrough, with small, office-friendly, desktop scaled RP systems, often referred to as "3d Modelers" or "3d Printers", introduced to the market by almost all of the major RP Vendors (3D systems, Stratasys and others) for less than 20.000 US$ (Grenda, 2011). The "*Dimension uPrint*" machine - hosted in NTUA's RP-RE Laboratory since 2010 and used for the needs of the present work- is a fine example of a small 3d modeler, Figure-1. Recently it is also offered by Hewlett Packard as an extension to their product range of conventional printers.

Figure 1 – Dimension (Stratasys) uPrint 3d Modeler

The 3d Modeler's spread has also led to a boost of use and to the widening of the range of applications for RP, making it more accessible to small enterprises, free-lance professionals, even students and hobbyists. Within this extended applicability of RP, integrated RE-RP utilisation is now practised more often than before; mainly for the sake of artefact reproductions (spare parts, organic, medical, and cultural). In many of those cases, the *dimensional and geometrical accuracy* of the reproduced object, might be important, or critical, therefore there is a need for identification, allocation and evaluation of such factors that introduce uncertainty to the overall result, in order for the best possible quality to be obtained.

The paper reports the preliminary results of an on-going study that concerns the evaluation of the geometrical uncertainties during the integrated utilization of RE and RP technologies for the Rapid Manufacturing (RM) of mechanical components. In the scope of the paper the parameters involved in several stages of the RP process that impact the geometrical uncertainty of the fabricated component are identified and to a certain extend quantified through the use of a case study. Finally, future research directions are highlighted.

2. INTEGRATED RE – RP APPROACH: UNCERTAINTY FACTORS

In the integrated RE-RP approach the contribution to inaccuracy, or to *uncertainty* regarding the geometrical deviations of the result, is two-part. One part comes from the inaccuracies of the RE process providing the geometry for fabrication and the other part comes from the RP process followed according to the RP technology and system selected or available to perform the build. It should be noted that depending on the targeted application the overall accuracy achieved might be of none (e.g. digitizing and reproducing a concept model) to critical importance (e.g. when an assembly is reverse engineered, featuring several dimensional and geometrical fits on it). In any case, it is very useful to have a systematic approach available in order to keep inaccuracies under the best possible control, regardless of the equipment available.

Accuracy of measurement and/or digitization, as well as the overall uncertainty of the produced data is an issue of major concern in RE (Kaisarlis et al, 2006; 2007). The RE objective of remanufacturing a needed mechanical component which has to fit and well perform in an existing assembly and, moreover, has to observe the originally assigned functional characteristics of the product is rather delicate. In order to achieve that a broad range of technical specifications of the RE component, such as material specifications, heat treatment, surface treatment, surface finish, shape, size etc. and their relevant accuracy requirements, have to be assessed.

Having a significant impact in its manufacturing cost, assemblability and performance, the assignment of the dimensional and geometrical accuracy specifications of the reverse engineered component is one of the most critical RE tasks. The integrated RE-RP approach presented in the paper is based on the methodology for the designation of geometric and dimensional tolerances that match, as closely as possible, to the original (yet unknown) dimensional and geometrical accuracy specifications, published by Kaisarlis et al (2006; 2007). In RE such accuracy specifications for component reconstruction have to be reestablished, one way or the other, practically from scratch. RE tolerancing becomes even more sophisticated in case that CMM data and a few or just only one of the original components to be reversibly engineered are within reach. Moreover, if operational use has led to considerable wear/damage, then the complexity of the problem increases considerably. Although RE has an apparently significant role to play in mechanical maintenance and plant equipment availability, RE-accuracy and tolerancing issues do not seem to have been, to this date, adequately addressed. An approach to tackle with this task in a systematic way that concerns the identification and quantification of the full range of RE geometrical uncertainty factors *(equipment, software and process-related)* is currently under development by the authors.

With RP, even in its early days in the 1990s and later on, accuracy of the parts produced has always been a question, even a matter for debate between RP vendors. It has been expressed, mainly by the vendors, in absolute values of deviating dimensions, as a percentage of the dimension, even in terms closer to actual paper printing, such as DPI, often causing confusion to potential users. Consequently, several research and benchmarking works have been done to characterise and compare methods and machines in terms of their accuracy performance, e.g. Ippolito et al. (1995), Shellabear (1999). They all agree that the majority of RP methods and systems are by nature inferior to conventional machining processes in terms of accuracy, in most cases capable of achieving accuracy of a few tenths of a millimetre. They also show that there are several influencing factors introduced throughout the steps of the complete RP process chain that introduce uncertainty and have to be considered, some of them often counteracting and neutralising others. The main influencing factors related to RP geometrical uncertainty as acknowledged and proposed by the authors in the presented work are described below.

2.1 TESSELATION - STL QUALITY AND ERRORS

STL files are the de facto RP format. An STL file is practically a mesh of triangles completely surrounding the boundary surfaces of the CAD model to be fabricated, (Kumar and Dutta, 1997). In some cases STLs are directly formed from point clouds from CMM digitization. Clearly, STLs are approximations of the real geometries and they inherently introduce geometric uncertainty, especially to curved, free-form and or complex features and regions of a part, as triangles deviate more or less from the actual parts' surface. Within CAD environment, there is normally adequate control capability of the generated STL quality, through the so called "facet deviation-chordal tolerance" and "minimum triangle angle" parameters. Nevertheless, the user must always be conservative and balanced at STL generation, as very small values of these parameters can lead to very large STL files, redundant and not easily processed, while on the opposite the desired detailed and accuracy can be lost by very large values. Further, errors like inverted normals, holes, triangle overlaps can also negatively influence the final accuracy and must be kept in control. Figure-2 graphically depicts the tessellation error.

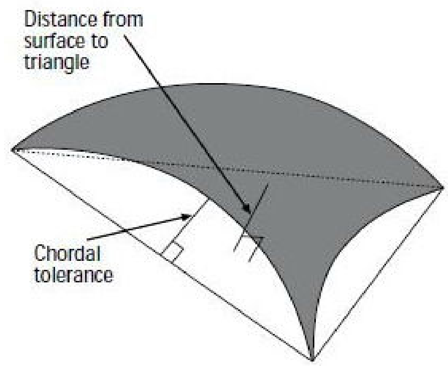


Figure 2 – Tesselation Error

2.2 STL MANIPULATION ERRORS

In order to reduce redundancy of STL files, correct or eliminate STL errors and optimize build parameters and strategies, it is quite common to utilise RP dedicated software in an independent step after CAD and before RP machines, e.g. *Magics RP* software by *Materialise*. Using such RP software several optimizations that concern, orientation, support structures, part nesting etc. can be performed. Mesh correction and STL triangle number reduction, in cases where redundancy and extreme detail is diagnosed, is also possible. Of course, errors can be generated throughout this step, such as detail and geometry deterioration and even feature eliminations.

2.3. RP SYSTEM RELATED ERRORS

Usually a very dominant factor in every RP System, systemic, process or machine-related errors, are the most likely ones to have a standardized and repetitive behaviour. They can therefore be cautiously diagnosed, investigated, registered and under specific conditions even compensated (Kechagias et al, 1999). They can further be placed under four main categories:

2.3.1 Driving, positioning and Laser beam or deposition thickness variations

In the case of laser based, or deposition based RP technologies and machines, such as the FDM uPrint examined in the present work, variation of the thickness of the beam or deposition material along the paths of each layer of the part may occur, which -regarding the inner and outer borderline paths of the part in a layer- induce errors, although compensation might have been already applied by the machine's system software. Depending on the form of each feature on the part, accuracy can vary on the same part among different form features. Driving and positioning of the X-Y and Z axes of the RP machines (often by stepper or servo-motors) during the build process, are also subject to resolution and repeatability limitations of the embedded hardware.

2.3.2 Orientation and Layer Thickness

In general, all RP technologies show a discrete difference in the XY-plane and Z-direction of the build, in a way that parts would not be characterized as uniform. Thermomechanical phenomena in almost every RP technology are different between X-Y plane and Z-axis. At the Z-axis "swelling" or "shrinking" could occur, in a different scale than in the XY plane of the layers and the stair-stepping phenomenon is always present, (Polydoras, S. and Sfantsikopoulos M., 2001). Finally, because of the fixed layer thickness of a build in an RP machine, Z-oriented dimensions of part features are always fitted by the system to their closest value that is an exact multiple of the layer thickness used by the specific RP machine; with the residue recognized as another inaccuracy. This is often described as the Z-axis "quantisation" phenomenon.

2.3.3 Filling Pattern and Supports

During solidification or deposition that occurs in each layer during an RP build, first the inner and outer boundary sections of the part are shaped. Further, in order for the final part to be dense and stable, the inner material-side of the part has also to be solidified or filled with deposited material. At the same time for proper support of the build, supporting material is placed around the part in critical support needing geometries. In many RP systems like SLA or FDM there is the option to choose between e.g. fully dense, honeycomb-like and sparse narrow shaping for the inner material, as well as for the supports. Depending on the desired material economy, part strength and application of the prototype, the way parts and supports are built internally, affects their shrinkage and dimensional-geometrical stability.

2.3.4 Material Behaviour

Different raw materials used in the RP machines, apart from their differences in chemical composition and thermomechanical properties, also undergo different processes in different RP technologies. This way, photopolymeric resins undergo solidification via photopolymerisation in SL and UV curing systems, where on the other hand, cord shaped ABS materials undergo two shifts between the solid and liquid phases through thermal melting and subsequent resolidification in the FDM process. Just after part completion, some technologies and materials might also require further secondary treatment or finishing of their parts (SLA, FDM, UV curing, SLS, LOM etc.). It is obvious that all these phenomena and process steps, coupled with contact of parts with dissolvent, water, air humidity and combined with thermal shrinkage during cooling ensure that to some extent accuracy and dimensional stability will also be affected.

3. PROPOSED APPROACH FOR GEOMETRICAL UNCERTAINTIES IN INTEGRATED RE-RP PROCESSES

The whole range of uncertainty influencing factors described in the above sections ought to be investigated by integrated RE-RP practitioners, before they are capable of fully exploiting the geometrical accuracy potential of the technologies in their applications. This can be achieved by performing Design of Experiments (DOE) and Analysis of Variance (ANOVA) on all above factors and their variables, in order to conclude which ones and how much they really affect the whole process. Nevertheless, this analytical approach is usually a major, time consuming and considerably effort-intensive task, difficult to undertake in an everyday curriculum.

Another approach, as proposed by the authors in the present work, is for RE-RP practitioners to focus on pilot parts, very similar to their regularly occurring applications and perform several complete, or partial test runs of the RE-RP process, carefully selecting and altering specific obviously or probably affecting parameters of the process in between. After assessing and evaluating each part produced in terms of accuracy and geometrical uncertainty and comparing the results with results from other parts of the same or other runs, factors of negligible effect can be omitted and the remaining strong factors can be categorized according to their magnitude of influence and to their relevance -or not- with part geometries and system parameters. This way, at the end, systematic and characteristic uncertainty influencing factors could be compensated in future parts for specific form features of interest, and the rest, characterised as erratic and non-manageable, could define the overall accuracy performance of the integrated process. The proposed approach is tested and explained in a case study within the following section of the paper, before conclusions are drawn.

4. CASE STUDY

For the case study, integrated RE-RP was attempted through the use of a direct computer controlled *Mistral 070705* (Brown & Sharpe-DEA) CMM with ISO 10360-2 max. permissible error 3,5(μm)+L(mm)/250, using *PC-DMIS v.4.2* (Wilcox Associates) measurement software and a *Dimension uPrint* 3D Modeler, a typical small scale entry level RP system very likely to be met in everyday applications.

As target parts for the process, a working couple of mechanical components were selected, sharing three different fits between them. A typical cylindrical peg-hole fit, a circumferential radial fit over an arc (section of circle) and a prismatic (distance) fit, in terms of the arc-feature's width. Apart from the working ones, several other readily measurable cylindrical features were hosted on each part, with RE tolerances prescribed to some of them. Hereafter, these parts will be named *"embolo"* and *"folia"*.

4.1 RE PROCESS STEPS

Typically, the RE process encompasses several stages including component digitization using contact or non-contact CMM, refinement of the acquired cloud of points and 3D-CAD surface/solid modelling. In the scope of this study, the above mentioned critical fits were initially recognized and the corresponding components' form features were identified. CMM measurements were performed on four intact mating pairs of *"embolo"* and *"folia"* components. In the context of *feature-based RE* (Thompson et al, 1999), the CMM measurements were focused on the dimensional evaluation of the critical features. Therefore, RE tasks such as surface digitization, curve fitting on cloud of points, etc were not considered for the case study components. The establishment of nominal dimensions and ISO standard fits for the critical features was then pursued by the application of TORE *(**TO**lerances for **R**everse **E**ngineering)* methodology (Kaisarlis et al, 2006; 2007), Figure-3 and Figure-4.

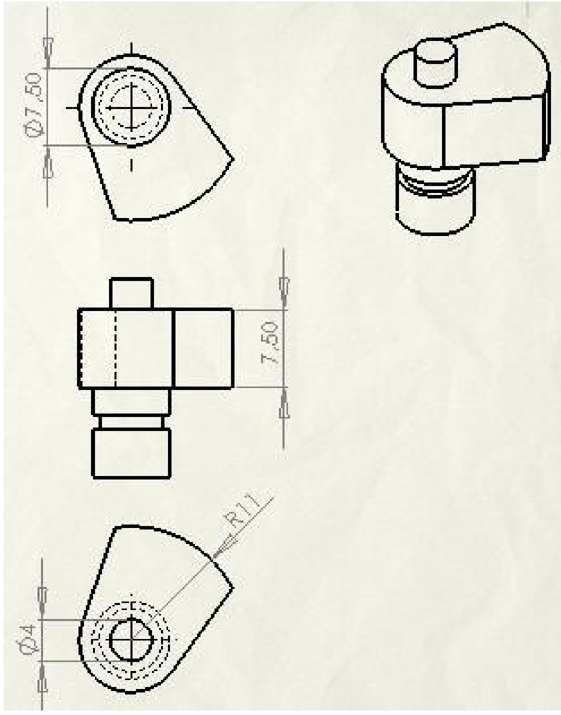


Figure 3 – ISO-E Views of the "embolo" component

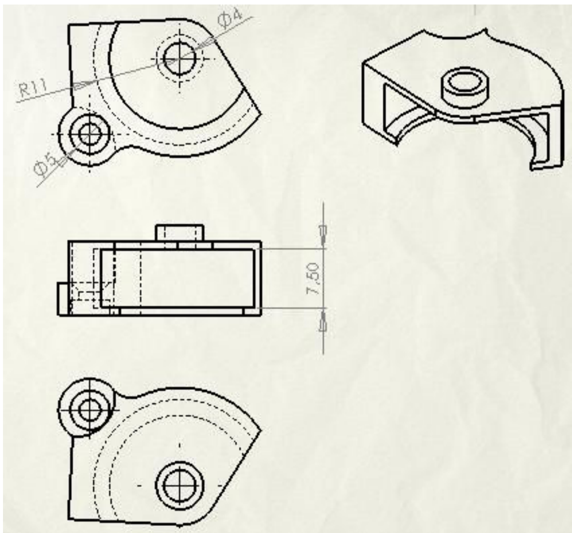


Figure 4 – ISO-E Views of the "folia" component

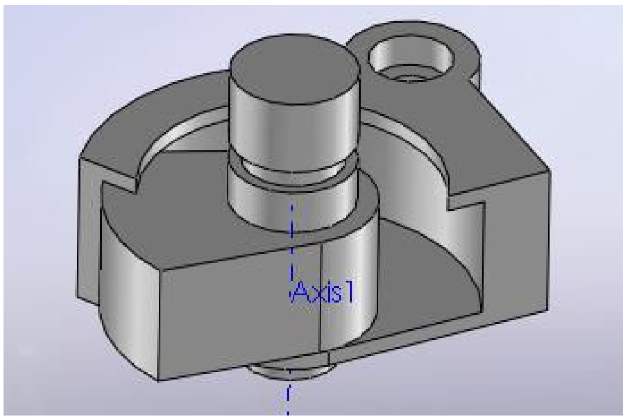


Figure 5 – Parts "embolo" & "folia" working together

4.2 PREPARATION FOR RP

After the completion of the RE steps full 3D *nominal* models for "embolo" and "folia" were available for STL extraction and RP fabrication. 2D drawings of the parts are given in Figure-3 and Figure 4. A rendered 3D representation of the working pair is given in Figure-5.

Within 3D CAD software *Solidworks 2010*, two variations of STL files with different accuracy levels of approximation were extracted for each part. They were made with the automatically regulated values of facet deviation and minimum triangle angle of the CAD software, for *"coarse"* and *"fine"* approximation presets. Moreover, the *"triangle reduction"* feature of *Magics RP* of *Materialise* RP software, was used on the "fine" version of the STLs with a setting of 0,2mm minimum feature detail and 30º triangle angle, to produce a third "relaxed" version of "fine" and check for possible accuracy declines caused by this interim RP software step. Details of the three STL versions used are given in Table-1.

Table 1- STL variations of "embolo" and "folia"

STL file	Trian gles	Kb	Facet Dev *(mm)*	Min Angle *(deg)*
emb coarse	438	22	0,035	30
emb fine tr rd	648	32	-	-
emb fine	728	36	0,013	10
fol coarse	662	33	0,040	30
fol fine tr rd	826	41	-	-
fol fine	1144	56	0,016	10

The three STL variations for "embolo" and "folia" are also graphically shown in Figure-6, where their difference in meshing density of the cylindrical features is obvious.

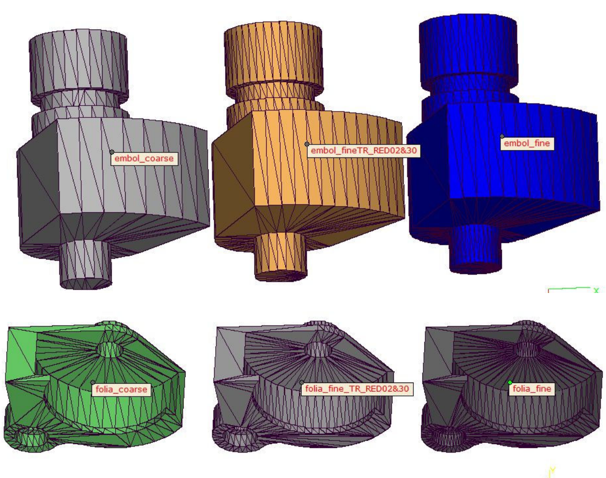


Figure 6 – Parts "embolo" & "folia" STLs

4.3 RP PROCESS STEPS

The three STL files of "embolo" and "folia", before their build in NTUA's *Dimension uPrint* 3D Modeler, were processed with *Dimension's* operating software *CATALYST v.4.2*, in order for orientation, placement, fill style and support material method to be selected. The authors decided that ***(i)*** all cylindrical features to be examined would be placed parallel to the X-Y plane, ***(ii)*** parts would be oriented for minimum support material, ***(iii)*** low approximation accuracy "coarse" STLs would be built both with "sparse - low density" and "solid" fills to investigate the difference, the "triangle reduced fine" STLs with "sparse high – density" fill and the "fine" STLs with "solid" fill, and ***(iv)*** all supports would be built with the automated "SMART" setting, which is the most common choice. The four different pairs of "embolo" and "folia" parts that were actually built in the case study are summarized in Table-2.

Table 2- Parts "embolo" and "folia" built

Part	No	Description	Fill Pattern
embolo	1	coarse	Sparse Low density
embolo	2	coarse	Solid
embolo	3	fine triangle reduced	Sparse High density
embolo	4	fine	Solid
folia	1	coarse	Sparse Low density
folia	2	coarse	Solid
folia	3	fine triangle reduced	Sparse High density
folia	4	fine	Solid

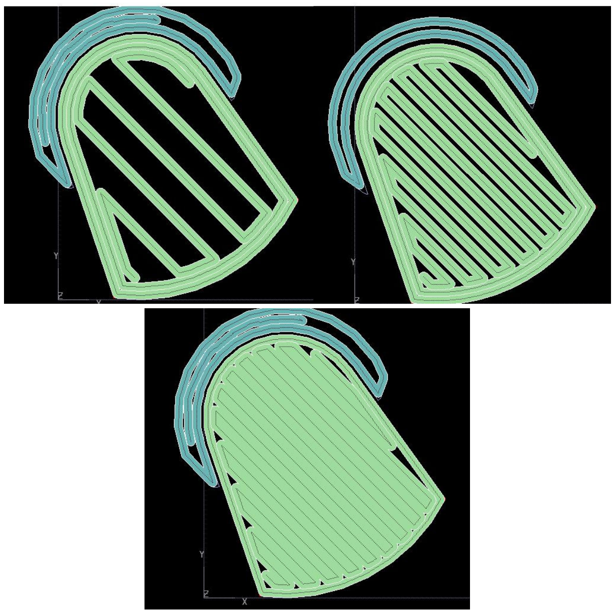


Figure 7 – Different fill patterns on "embolo"

A graphic example of “sparse – low density”, “sparse-high density” and “solid” fill patterns in the area of the arc cylinder section of “embolo” is given in Figure-7. All parts were symmetrically packed and evenly placed in the build area and fabrication was started on NTUA’s uPrint machine, running the latest *Version 9.1 Build 3550 System Software* (Released May 2011). Parts were complete in less than two hours.

After removing the build platform, a first set of CMM measurements on accessible cylindrical features, before the ultrasonic alkali solution support removal process step, was performed on all parts, to acquire some intermediate accuracy results for comparison with the finished parts after support removal. A picture of the CMM measurements on the “raw” parts is provided in Figure-8. Parts were then marked and placed in an alkali solution ultrasonic cleaning tank, for approximately 3 hours for support removal. The fully cleaned parts were subsequently analytically measured again with the CMM machine, on all their critical features and dimensions of interest.

Figure 8 – “Raw” Parts measured with the CMM

4.4 MEASUREMENT RESULTS

The critical features that are associated with the assembly fits were CMM measured on the finished parts. They are described and named in Table-3.

Table 3- Features measured on “embolo” and “folia”

Part	Name	Descript.	Nominal *(mm)*	Fitted
embolo	A	External Cylinder	Ø7,5	-
embolo	B	External Cylinder	Ø4	to C´
embolo	C	External Cylinder Arc Sector	Ø22	to D ´
embolo	D	Cylinder Arc Sector’s Width external	7,5	to E´
folia	A´	Internal Cylinder	Ø 2,7	-
folia	B´	Internal Cylinder	Ø 5	-
folia	C´	Internal Cylinder	Ø4	to B
folia	D´	Internal Cylinder Arc Sector	Ø22	to C
folia	E´	Cylinder Arc Sector’s Width internal	7,5	to D

In all measured cylindrical features a significant form error was found (deviation from the form of a perfect circle), ranging up to 0,2mm and with an average of app. 0,1mm in external features and ranging up to 0,45mm and with an average of app. 0,15mm in internal ones. In some of them it is even visible to the naked eye on the RP parts, Figure-9.

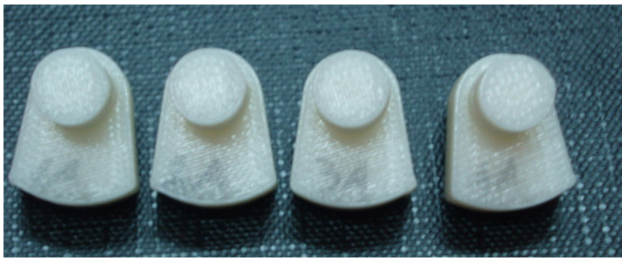


Figure 9 – Form Error on RP cylindrical features

Therefore it was decided that apart from the CMM measured deviations of the dimensions of the cylindrical features, based on measurements calculated by the least squares fitting method, an extra “correction” value equal to half the form error of the corresponding feature would be added by the authors to the deviations measured, thus leading to the *“worst deviation”* found in each measured feature. In this way, a more “realistic” approach of the functional uncertainty of the features would be obtained, since the test parts would be primarily tested for fit in accordance with the maximum material boundary conditions *(Maximum Material bore – Minimum Material shaft)* as standardized by ASME Y14.5M (2009). The same does not apply for dimensions D and E´ that are linear widths. Nevertheless, for these width dimensions, a Z-orientation “quantization” of the dimension applies, which practically alters the nominal values from 7,5mm to 7,366mm for D and to7,62mm for E´, as verified with the help of the *CATALYST 4.2 uPrint* operating software.

All “worst deviations” of cylinders and the width deviations measured for the features of Table-3, are graphically depicted in Figure-10 for “embolo” and Figure-11 for “folia”. At the width deviation graphs the theoretically calculated value expected due to z-layer quantization is also depicted.

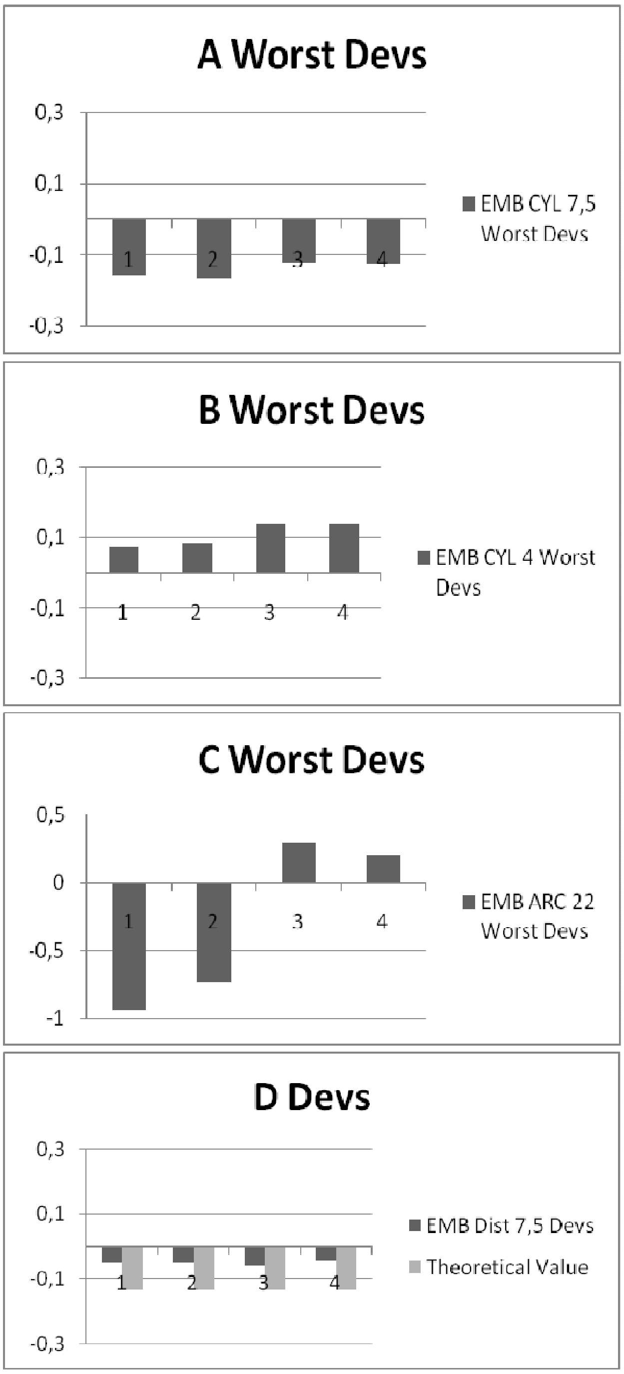
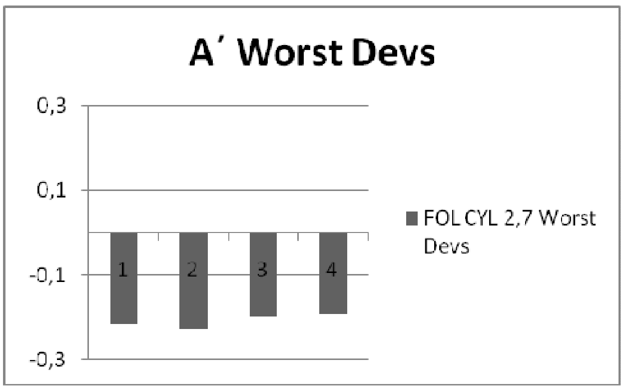


Figure 10 – "Worst Deviations" on "embolo"



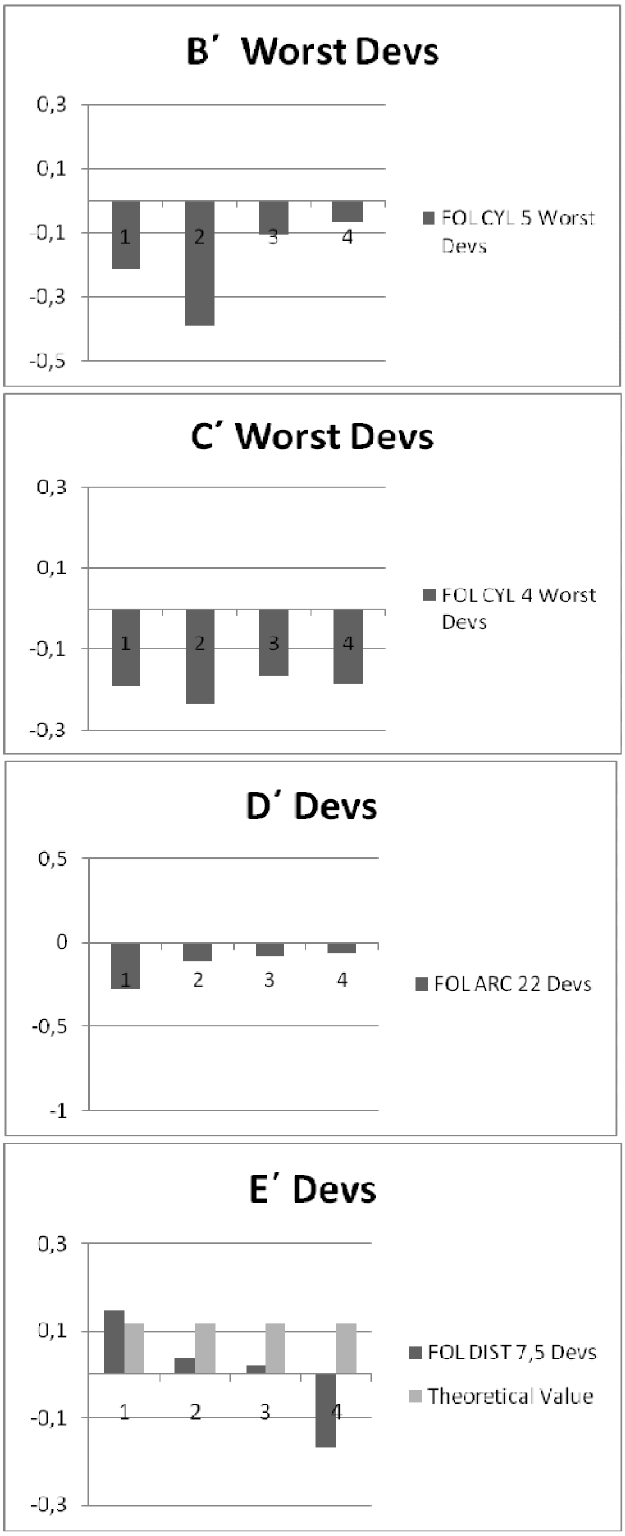


Figure 9 – "Worst Deviations" on "folia"

The deviations of dimensions on features that have a fit on the working couple of "embolo" and "folia" are separately shown in Figure-12, with the graphs placed according to parts' assembly hierarchy.

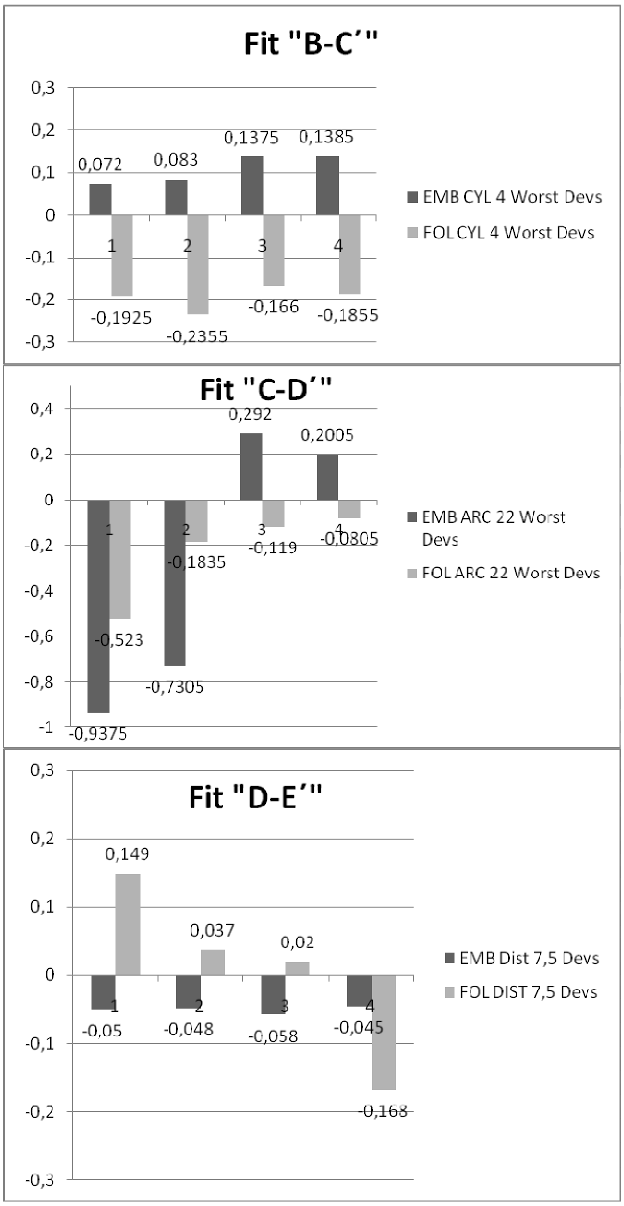


Figure 12 – Measurements related to fits between parts

4.5 ASSESEMENT & EVALUATION OF RESULTS

The analysis of CMM measurements and the observation of all graphs produced from the measured data have lead to some remarkable findings. They can be summarized to the following:

- The overall accuracy of the parts produced lies in very respectable levels for a low cost entry level RP machine, since all "worst" deviations calculated, average as absolutes very closely to a value of 0,25mm. It must be noted that this would be a typical accuracy value for most of the larger and more expensive RP machines a decade ago. Also, if "form errors" were not considered for correction, the overall inaccuracies would then average closely to 0,15mm.
- A form error is always constant on all cylindrical features, in most cases around 0,1mm, but with peak values of about 0,45mm in some features. It seems RP-systemic, related to the way FDM heads reach in and out of the deposited circles.
- Almost all XY-oriented dimensions measured on the parts appear some 30 to 40μm smaller if the parts originate from the "coarse" STL files compared to the ones made with "fine" STLs. On features C and D΄ though, the deviations were much higher than the theoretically expected by the tessellation error calculated on them. This difference is RP system related, as repetitive measurements excluded CMM uncertainty. It is advised to use "fine" STLs.
- External features generally seem to deviate less than internal ones. There seems to be a shift in their trend in a dimension value of app. 5mm, above which measured dimensions seem to lack from their nominals, while below they seem to exceed them.

Internal features are mostly less than nominal. Compensation seems applicable to a certain extent.

- For the Z-axis aligned D and E΄ dimensions, although at first glance D seems to be less than nominal and E΄ to exceed it, with the adjusted nominals after quantization, on one hand D (external dimension) values are clearly greater than the expected "new" nominals and E΄ (internal dimension) smaller, with the exception of the first value of part "folia" No1. This is an indication of part "swelling".
- Parts made with the "coarse" STL files presented far worse results compared to the ones made with "fine" and "fine – triangle reduced" STLs. Furthermore, the triangle reduction with the values used for it, appeared to have very little to negligible effect regarding accuracy.
- As for the fill patterns, it seems that poor STLs built with SOLID fill patterns are the worst accuracy combination, while fine STLs with sparse-high density fill patterns are a little better than their respective solid filled ones and possibly the best combination. This can probably be explained by the assumption that a solid filled part, although stronger, would nevertheless shrink-expand more than a sparsely filled one.
- The finishing process of support removal in alkali solution seems to have an effect of 50μm by maximum, reducing most external and increasing most internal feature dimensions. Since this step in the majority of parts cannot be omitted, the difference is just noted as a partial influence.
- Finally, as for the fits examined, although the measured values only, indicate that 5 out of 12 fits would be succeeded, practically the full failure of a loose fit on all four pairs of the fit B-C΄, which is the first in the assembly hierarchy, dictates that a fit of prototypes of the working couple "embolo"-

“folia” would not be possible at all, without a secondary finishing step on the prototypes produced. This of course was verified on the actual FDM pars. The graphs, also indicate that in order for the fits to be attainable right from the start, external dimensions should be reduced and internal ones increased about 0,3mm each, in CAD level prior to the build.

5. CONCLUSIONS

RP equipment, especially with the addition of small, cheap 3d modellers, combined with RE methodologies and equipment, indeed vastly increase the abilities of designers and engineers and increase the range of their applications. The full potential of such integrated processes, especially in terms of accuracy can only be reached by experimentation and methodological approaches.

The work presented in this paper is in such a direction and has so far produced encouraging and exploitable results. It is part of an on-going study that concerns the overall evaluation of the geometrical uncertainties during the integrated utilization of RE and RP technologies for RM of mechanical components and assemblies. Apparently, it needs to be further extended by future study on more types of characteristic features and parts, possibly also made by combinations of several RE and RP technologies. New runs on the existing equipment, focused on the “grey areas” of results of the present work will also further highlight the factors of uncertainty and inaccuracy and their effect in the integrated RE-RP process and propose specific ways for their handling.

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