Integration of reverse engineering and rapid tooling in foundry technology

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Abstract

The aim of this work is to present some research and development made at Institute Superior Technique (IST) of Lisbon and at Institute Polytechnic of Leiria (IPLEI) in the application of 3D-digitising and propose some practical approaches to transform by reverse engineering (RE) methods, the point cloud obtained from an object surface during digitising processes in 3D-CAD surface or solid data to manufacture rapid tooling (RT) for foundry technology. The approaches presented are also fundamental to verify prototype’s geometry for tooling and for modelling/simulation by finite element analysis (FEA), to assure the metrological accuracy of tooling geometry and optimisation of foundry process parameters. Based on four case studies presented, the paper will reach some useful conclusions for the appropriate application of 3D-digitising and RE to assist product development and RT in foundry processing technology, validating the accomplishment by the integration of these new methodologies and technologies in foundry technology.

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1. Introduction

To advance technology innovation, assisted by computational manufacturing, the use of 3D-digitising, are being integrated in the chain process of some Portuguese foundries, for applications such as: reverse engineering (RE), quality control, differential inspection, direct replication, detection of inaccuracies, redesign of parts, and manufacturing tools faster.

The rapid prototyping (RP) is a stimulating new technology for users quickly creates physical models and functional prototypes directly from CAD models. The rapid tooling (RT) generally concerns the fast production of tooling using inserts. RP and RT are means to compressing time-to-market of products and, as such, are competitiveness-enhancing technologies in foundry industry.

Since 7 years research with 3D-scanning technology has been carried out at the prototype modelling laboratory (LMP) at Instituto Superior Técnico [1–11] with 3D-scanning equipments, mainly for RE and quality control purposes integrated in the development of foundry RP patterns and RT equipment.

When a part exists but not the drawing (CAD or paper drawing) the CAD model can be generated using data from 3D-digitising (non-contact range scanner system based in laser-optical triangulation) and the RE methodology. The resulting mass of data from 3D-digitising requires RE algorithms that can efficiently and reliably generate CAD models.

The methods to digitise and reconstruct the shapes of complex three-dimensional (3D) objects have evolved rapidly in recent years. The speed and accuracy of digitising technologies owe much to advances in the areas of physics and electrical engineering, including the development of lasers, CCDs, and high speed sampling and timing circuitry. Such technologies could allow taking detailed shape measurements with precision better than 1 part per 1000 at rates exceeding 1000 samples per second. To capture the complete shape of an object, many thousands, sometimes millions of data geometry points (X–Y–Z coordinates) must be acquired.

2. RE for RT

The 3D-digitising [12,13] and reconstruction of 3D-shapes [14] by RE has numerous applications in areas that include manufacturing, virtual simulation, science, medicine [15], and consumer marketing. This is an actual research and development field that is related to the problem of processing images acquired from accurate optical triangulation [16], and is presented as a RE methodology for surface reconstructing from sets of data known as range images [17].
The standard methods for extracting range data from optical triangulation scanners are accurate only for planar objects of uniform reflectance. Using these methods, curved surfaces, discontinuous surfaces, and surfaces of varying reflectance cause systematic distortions of the range data. When using coherent illumination such as lasers, however, the laser speckle places a fundamental limit on accuracy for both traditional and space–time triangulation [18].

The range data acquired by 3D-digitisers such as optical triangulation scanners commonly consists of depths sampled on a regular grid; a sample set known as a range image. A number of techniques have been developed for reconstructing surfaces by integrating groups of aligned range images [19,20]. A desirable set of properties for such algorithms includes: incremental updating, representation of directional uncertainty, the ability to fill gaps in the re-construction, and robustness in the presence of outliers and distortions [21]. Using these methodologies one is able to merge a large number of range images yielding seamless [22,23], to assemble high-detail models to develop RT.

2.1. Integration of RE

When solving the pattern/tool making bottleneck, through the interfacing of information technologies, with RE methodologies and with RP and RT technologies, these allows reducing the lead time of manufacturing cast parts, improving the quality of parts, and assuring a better partnership with clients. The research and development of RE methodology integrated with CAD/CAE to manufacture optimised tooling (RT) is schematised in Fig. 1.

![Fig. 1. Developed RE methodology integrated with CAD/CAE and FEA for optimised RT.](image)

2.2. 3D-scanning laser digitiser principle

Laser 3D-scanning digitisers bring more automation to data gathering. These devices scan without contact by a striped laser beam the profile of a physical model and CCD cameras capture profile images that by triangulation algorithms generate digital data (Fig. 2). By exploiting the laser stripe by triangulation the “Reversa” sensor, guided by a “Replica” NC machine, measures hundreds of surface points per second, taking only a few minutes to digitise typical objects, no matter how complex their surface geometry.

This 3D-scanning system (at LMP-IST) could stripe coordinate point data at a standard scanning speed of 6000 points/min, with an accuracy on \( \pm 25 \) \( \mu \text{m} \). Some actual limitations concerns scan surface preparation of RP prototypes that must be sprayed with matt white paint and for this reason the scanning accuracy is reduced for about \( \pm 20 \) \( \mu \text{m} \) in \( X-Y-Z \) axes.

3. Case studies

3.1. Case study 1—3D-digitising of RP-SLS for RE and FEA optimisation before casting

A preliminary set of non-optimised RP tools for sand casting have been manufactured by RP-selective laser sintering (RP-SLS) technology with powder Duraform glass-filled
material, i.e., two half patterns and a core-box to compact sand moulds and sand cores, as shown in Fig. 3.

The digitising of 3D-shapes (Fig. 4a), as the foundry pattern and core-box made by RP-SLS, allows getting surface data and representing it as range images, as shown in Fig. 4b–c.

Accurate numerical methods, based on geometric triangulation, calculate coordinates and advanced software transform this on the surface of models. The captured data was inspected using planar 2D-viewing profiles, from “Ri-tools” software (3D scanners), and in almost all transverse sections was been found a high metrological quality.

The link that connects digitised 3D-models to physical models for manufacturing comes from RE process in which a 3D-scanner digitises points from the surface of a physical model and specialised software transform that into CAD surfaces or solids. At LMP (prototype modelling laboratory at IST) the CopyCAD RE software is used for a range of RE operations. Such operations allow creating 3D-CAD models from rebuilt models for finite element analysis (FEA) and engineering operations (Fig. 5a–c). The RE software have a complete control over the selection of boundaries to optimise surfaces for subsequent modelling and have also the option to maintain tangent continuity between adjacent Bézier curves, or to preserve sharp discontinuities between surface edges. When necessary is generated an error map that compute the variations between the original data and the surface data produced in terms of specified tolerances.

To optimise the casting part, from the generated 3D-CAD, the mechanical behaviour simulated by FEA allows to verify
the stress/strain limits and to correct the geometry if necessary. The optimising was performed with FEA software ("ANSYS") with the aim of part mass reduction and reducing the stresses in critical part zones maintaining or increasing the warranty of mechanical performances.

After the 1st simulation by finite element method (FEM), it is verified that the main stresses concentration are located in the A, B and C zones (Fig. 6 a) and the limit factors are described in Table 1. The B and C zones present acceptable stresses, but in A zone the stress is critical. To reduce the maxim stress in A zone it is necessary to increase the concordance radius from 1.5 to 2.5 mm. From a 2nd simulation by FEM the new values are also listed in Table 1.

Table 1
Sesful–strain results from FEM analysis (“ANSYS”)

<table>
<thead>
<tr>
<th></th>
<th>1st simulation</th>
<th>2nd simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum stress (MPa)</td>
<td>479</td>
<td>294</td>
</tr>
<tr>
<td>Maximum strain (mm)</td>
<td>0.127</td>
<td>0.116</td>
</tr>
<tr>
<td>Mass (N)</td>
<td>30.37</td>
<td>30.40</td>
</tr>
<tr>
<td>Radius A, r (mm)</td>
<td>1.5</td>
<td>2.5</td>
</tr>
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The increased radius A (+1 mm) has allowed a reduction of 185 MPa in the maxim stress making the stress field more uniform. To reduce the part weight some internal cavities and enlarged holes to uniform casting thickness have been redesigned and the casting present in the final FEA iteration only 25.46 N (−16% of mass), maintaining its mechanical performances and increasing the trust coefficient in 40% (Fig. 6b).

The study of casting solidification simulation has been also performed with the objective to optimise the casting with risers and gating system before manufacturing the necessary foundry tools. With casting simulation software (AFS—American Foundrymen’s Society) one performs thermal analysis for cooling and solidification process. The AFS solidification system uses the finite difference method (FDM) to calculate heat transfer during cooling and solidification of the cast material. This software gave useful information on the progression of cooling and solidification. During solidification could be generated porosity located in casting “hot spots” zones. The material density (MD) in the casting and risers are calculated based on the shrinkage curve for the casted alloy. This criterion can be used to analyse how risers pipe and where internal porosity is located. A sample of MD plot is shown in Fig. 6c.

The optimised 3D-CAD model from RE can be sent to different RP machines to create re-engineered RP-SLS casting tools allowing the production of enhanced castings, as the one shown in Fig. 7.

3.2. Case study 2—non-contact metrology of core-box made by RP-LOM

After create a computer model to manufacture an impeller casting part of an water pump, either by interactive 3D-CAD design (Fig. 8) or through shape digitisation of a physical model, there are a possibility to produce the castings integrating tooling technology, i.e., manufacturing a core-box for sand casting with RP-laminated object manufacturing (RP-LOM) technology, as a starting direct working prototype-tool for a pre-production of castings, as shown in Fig. 9.

The dimensions of the final manufactured part must fall within tolerances of the original computer model. In this case, 3D-scanning can assist in determining where and to what extent the computer model of the casting part and the
The non-contact metrology could be made with 3D-digitising apparatus that have dedicated software for data processing. The data translation with replication software ("Ri-tools" from 3D-scanners) allows manipulating the digitised point data from the 3D-scanning. Manipulation features in 2D by sections provide a range of point that makes it easier to measure usable point data. Teaming up the replication software lets one construct 3D-splines from point data, wire frame triangular mesh models from splines, and finally surface models, as shown in Fig. 10.

The image processing utilises accurate numerical methods, based on geometric triangulation to calculate co-ordinates and advanced software for RE ("CopyCAD" from Delcam UK) transform this data on the surface of models (Fig. 11a). Capabilities in the replication software let one define cutting planes that pass through the object’s surface and capture 3D co-ordinates that fall on the intersection of two planes and detect maximum and minimum points, as reference surface points, allowing quality control.

To look for inaccuracies the shape of prototypes was checked by comparing the physical tool surface digitised by 3D-scanning against the corresponding 3D-CAD reference points (Fig. 11b). The benefits of this technique is the
immediate visualisation and identification of shape errors in a shorter time when comparing with conventional CMM metrology techniques.

The background at LMP and made labours have permit to correct shape inaccuracies of the physical LOM core-box by transforming it in a rebuilt 3D-CAD via RE, and the time spanned was only 4 days. The 3D-scanning of the two core-box parts (drag and cope) for digitising collected data took 2 days, leaving the rest of the time for the core-box re-modelling via RE with 3D-CAD (“AutoCAD R14” software). The sand cores manufactured inside the RP-LOM core-box (Fig. 12 a) have allowed producing a pre-series (10 parts) of impeller castings (Fig. 12 b) for foundry process validation.

3.3. Case study 3—3D-digitising an auto-casting part to make RP-SLA/SLS

When a casting part must be re-engineered one could utilise the 3D-digitising technique to capture range images of its 3D-shape.

For surface reconstruction each range image provides a detailed description of an object as seen from one point of view. Before attempting to reconstruct the entire shape of an object, one requires assembling multiple range images. A single range image generally cannot acquire all sides of an object (Fig. 13), thus requiring multiple range images to be taken. In fact, many objects are too complex to be captured by a small number of range images taken. For instance, from mutually orthogonal directions and their opposites (i.e., from the six faces of a cube). Due to self-occlusions, an object may require a large number of range scans to see every visible point. Taking many range images offers two additional advantages: noise reduction and improved sampling rate.

With RE methodology, in order to merge a set of range images into a single description of an object, it is necessary to place them all in the same coordinate system, i.e., they must be registered or aligned with respect to each other. The alignment may arise from prior knowledge of the pose of the rangefinder when acquiring the range images.

The reworked 3D-CAD model (Fig. 14) from RE can be converted in a surface triangulated mesh (STL format) for FEA simulation or RP.

The objective of casting solidification simulation by FEA is to validate a casting with riser and gating system before manufacturing the prototype casting tools. The normal procedure to operate casting simulation (“AFS” software) is to

![Fig. 12. (a) Sand core made in the direct RT-LOM core-box, (b) steel casting impeller for water pump.](image1)

![Fig. 13. 3D-scan lines from the part top for re-engineering.](image2)

![Fig. 14. 3D-CAD models (“Pro-Engineer” software) generated from RE.](image3)
elaborate a 3D virtual prototyping of the casting in a surface triangulated structure (STL format) and to attribute parameters for mould materials and graphical curves concerning solidification and shrinkage for casting alloys. The casting simulation software has algorithms that allow simulate the progression of cooling and solidification. One could analyse the resulting graphics for: liquidus time (LT), critical fraction of solid (CFS), MD, and solidus time (ST). The graphical plot for ST is exemplified in Fig. 15, showing the risers accomplishing its mission in the final of casting solidification stage.

The optimised geometry data from FEA simulation could be sent to different RP machines to create re-engineered physical RP models, as the examples RP-SLA (made with Stereo Lithography Apparatus in Somos 5170 polymeric resin) and RP-SLS (made with Selective Laser Sintering in Duraform glass-filled plastic powder), shown in Fig. 16.

The described methodologies and technologies allows reducing the lead time and after validate the optimised re-engineered casting design of the compressor-support for autos, the mass production started in a sand casting moulding machine (“DISAmatic” process) improving the quality of casting parts, as the sample shown in Fig. 17.

3.4. Case study 4—non-contact metrology to select the best RP pattern accuracy before casting

Some scanning tests for evaluate the accuracy of RP patterns have been carried out at LMP with the 3D-scanning equipment. A 3D digitised plot representing the casting pattern scan lines is represented in Fig. 18.
The reworked model in 3D-CAD ("Pro-Engineer" software) is composed by two sand core shape to define the inside of the two castings ("mechanical clamps") made in pairs with sand mouldings (Fig. 19).

To estimate the capabilities of different RP processes, in the manufacture of sand casting patterns, three pairs of RP-models manufactured by SLA (photocurable resin SOMOS 3100); SLS (Nylon powder); and LOM (paper material one side with thermo-glue), Fig. 20, have been measured by non-contact 3D-scanning at LMP.

After measurements the dimensional analysis have allowed to plot the error distribution functions (EDFs) for each RP-model (Fig. 21). For each pair of RP-models have been registered 118 measurements per bin. Upon analysis of each EDF histogram it is recognised that for the RP-models the $X-Y-Z$ dimensions peaks within the tolerance $\pm 0.1\,\text{mm}$ with frequencies of 75% for RP-SLA, 70% for RP-LOM, and 25% for RP-SLS.

The cumulative error distribution (CED) for each RP model measured, i.e., the normalised integral of the EDF from zero error to infinity has been also calculated for a graphical representation. A CED plot of the percentage of accurate casting in nodular iron moulded from direct RP-SLA pattern.
measurements falling within a given error versus the magnitude of the error (steps = 0.1 mm) is shown in Fig. 22.

After metrology validation the RP-SLA patterns have demonstrated the greater accuracy, then the other two RP-LOM and RP-SL patterns. The RP-SLA patterns have produced sand moulds in a sand casting moulding machine (‘DISAmatic’ process) and a series of 1250 castings have been manufactured inside the requested design tolerances, as the sample shown in Fig. 23.

4. Conclusions

The RE via 3D-digitising is a methodology to make virtual prototyping (VP) models for FEA by computer simulation. The FEA allows optimising cast parts to manufacture improved RT (patterns and core-boxes) for foundry.

The RE methodology aided by 3D-digitising make available a faster shape metrology control of prototype tools for foundry by calculating the deviation between 3D-digitising data and 3D-CAD model, before manufacturing processes.

The RE methodology starting from 3D-digitising of physical parts allows to rebuild promptly physical casting models (3D-CAD) and to manufacture faster rapid prototypes and/or tools for foundry.

The 3D-digitising and RE enhance the metrological accuracy in product development and RT for foundry processing technology and marketing competitiveness. The integration of RE with RT technology reduces lead-time and associated costs in foundry industry.

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