REVERSE ENGINEERING IN INDUSTRIAL APPLICATIONS. A COMPARATIVE STUDY

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ABSTRACT

The development of innovative products and their realisation by means of advanced manufacturing methods and process combinations is more becoming a key issue in international competitiveness. The industrial production is subsequently influenced ever more by the possibilities that Rapid Technologies - Rapid Modelling and Reverse Engineering, Rapid Prototyping and Tooling, Rapid Manufacturing can offer. Reverse Engineering (RE) is the process of digitising a physical object to obtain computerised data for further development as opposed to manufacturing a product from a digital model, e.g. CNC machining. This paper reflects experiences gained in the use of RE approaches for industrial applications, comparing specifically the use of tactile methods and digitising techniques based on photogrammetry principles. Process capabilities and the internal process chain are scrutinised. Practical case studies are presented and discussed with an emphasis on project lead times and dimensional accuracy obtained. Particular attention is paid to challenges related to surface recreation and manufacture of tooling for various components. The purpose of the paper is therefore to highlight the capabilities and wide range of applications for Reverse Engineering, while at the same time outlining pitfalls and limitations of this remarkable technology.

Keywords: Reverse Engineering, Digitising, Surface recreation

1. INTRODUCTION

A Reverse Engineering project should be viewed as a design project. Strange as it may seem, in many cases simply making a copy of an existing part is not wanted, although that may be the initial problem statement. Most of the time there are various requirements that must be addressed, such as maintaining draft angles, ensuring fitment within assemblies, minor design changes, various manufacturing issues and reconstruction of damaged parts. There may be also other issues, not necessarily related to a specific part, but rather to a client's capabilities, e.g. file transfer format, file size limitations, etc. Also, the client may have had previous experience with reverse engineered data, and will therefore have certain preferences regarding the format of the data as well as the modelling style. Simply specifying a tight tolerance and hoping that the end result will satisfy the end user is not a solution. Tolerances cannot ensure that the additional requirements are satisfied since this often leads to contradictory constraints on the project. Thus the understanding of the complete product development process chain is crucial to the success of the project.

It is therefore necessary to adapt the RE process chain to the project requirements. This may imply specifying tolerances selectively. Imaging and surface fitting may be used to a limited extent. Additional data related to the project may also be required, e.g. CAD data of the rest of the assembly or the physical assemblies. It is also important to decide early on how the data will be validated. There are various methods available for making a physical part from CAD data, e.g. a wide range of layered manufacturing (LM) methods with varying levels of accuracy or subtractive methods such as CNC machining. If CAD data of the matching parts exists, then the testing may be done in the virtual world.

A working understanding of the capabilities and limitations of the RE technology is also necessary. Often, as soon as the end user understands what the end result will look like and in what format the model will be presented, additional requirements arise. These requirements may be related to any of the issues stated above, but may not have been apparent before the client had experience with using the data or until the RE service provider understands the implications of the full product development life cycle [1].

The purpose of the paper is therefore to highlight the capabilities and wide range of applications for Reverse Engineering using optical measuring techniques based on photogrammetry principles in the RE process chain, while at the same time outlining pitfalls and limitations of this remarkable technology.

2. 3D DIGITISING FOR REVERSE ENGINEERING

Reverse engineering is the process of engineering backward to build a CAD model geometrically identical to the existing product. The process entails an object being digitised with the data being fed into the surface reconstruction software for generating the CAD model. Subsequently, the CAD model is used for manufacturing or other applications. An application example is where CAD models are unavailable, unusable, or insufficient for existing parts that must be duplicated or modified. The two key technologies in the reverse engineering chain are the 3D object digitisers and the surface reconstruction algorithms. Object digitisers can be classified into two broad categories: contact and non-contact [4]. The discussions in the paper consider only the non-contact digitisers i.e. 3D optical digitising.

The 3D digitising and reconstruction of 3D shapes has numerous applications in areas that include manufacturing, virtual simulation, science, medicine and consumer marketing. Further related applications also include, but are not limited to, tool making, product design and modification, design optimisation, rapid prototyping, mould repair, CNC-milling and others [2].

The processing of images acquired from accurate optical triangulation, based on the photogrammetry principles, is presented as an added value methodology in the process chain of typical reverse engineering for surface reconstruction from sets of image data. An adaption of the RE process chain as implemented in the presented case studies is shown below (Figure 1).

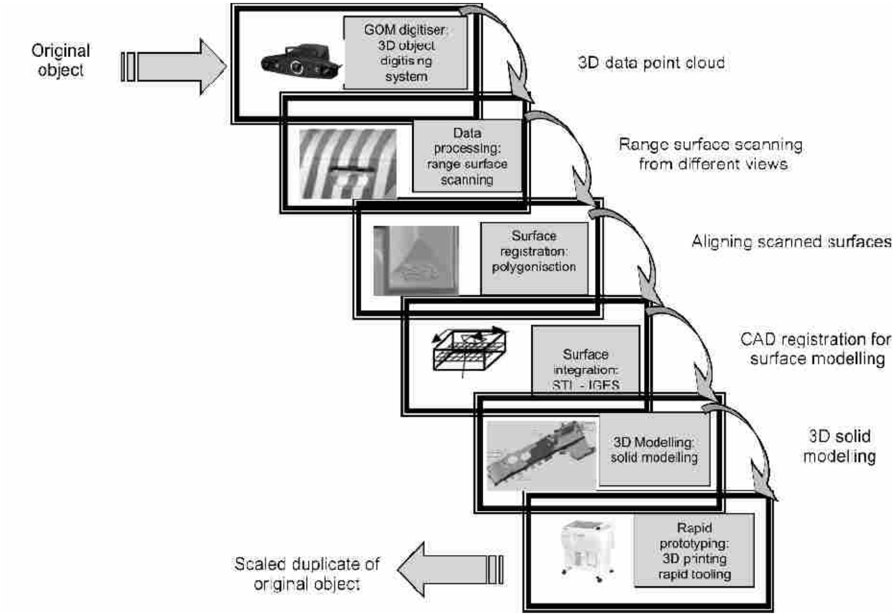


Figure 1: Optically-based Reverse Engineering process chain

As the figure depicts, the process starts by scanning the object using a digitising camera. The result is used in the sequential steps to develop a surface to solid model. The implemented RE method may be further integrated with a CAD/CAM system to produce a model, pattern or tooling (Figure 2). Such an integration may notably reduce lead times, cost, modelling hours and even inspection time.

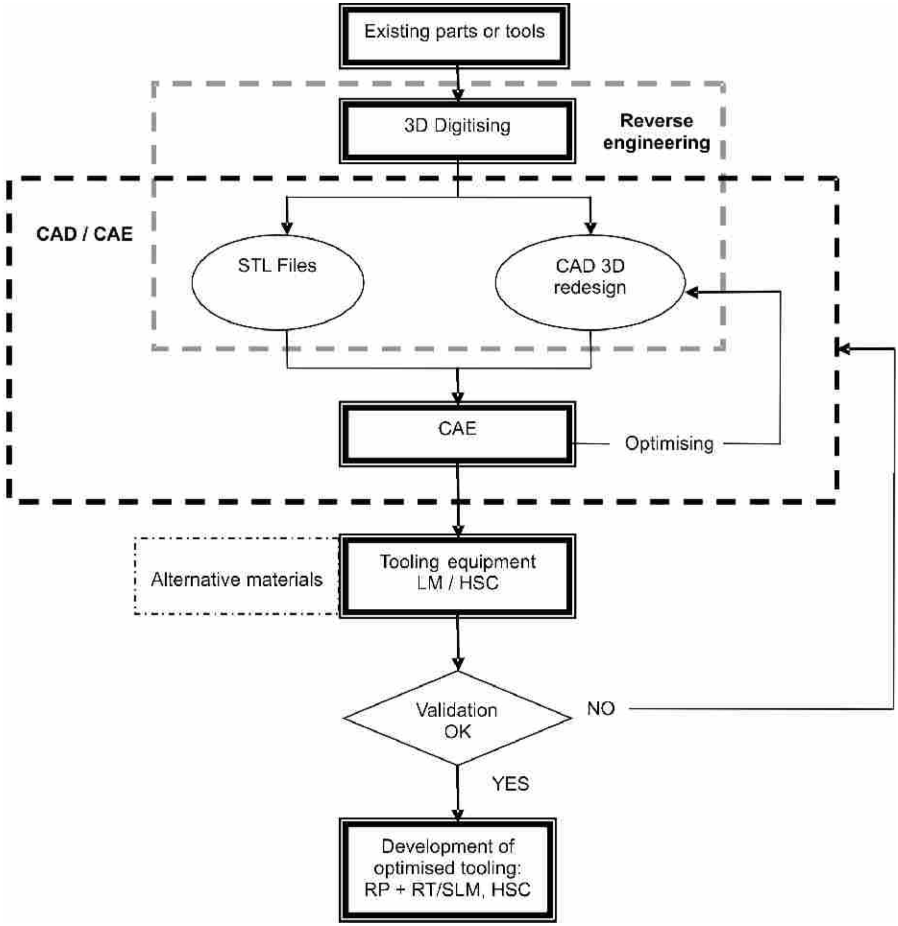


Figure 2: Schematic view of RE/CAD/CAE integrated process chain for rapid tooling

3. 3D DIGITISING SYSTEM

The 3D digitising system implemented in the case studies is a computer-aided non-contact optical system that measures both the 3D geometric shape and reflectance of a given object. It is based on the flexible, high end GOM ATOS I 3D Digitiser. Using this system, objects can be scanned quickly and with high local resolution. The system utilises the ATOS (Advanced Topometric Sensor) triangulation principle: the sensor unit projects different fringe patterns onto the object to be measured, which are then recorded by two cameras. Each single measurement generates up to 4 million data points [3].

In order to digitise an object completely, several individual measurements are required from different angles. Based on reference points (circular markers), which are applied to the object directly or to the measuring plate or fixture, ATOS transforms these individual measurements fully automatically into a common global coordinate system. The measuring data are made available as a point cloud, sections or STL data.

3.1 Fields of application

Using the ATOS I a range of field applications are stated by the OEM (GOM) [3].

- Non-contact and material-independent 3D digitising of arbitrary objects such as work pieces, models and moulds.
- Generation of STL of CAD data.
- Transfer of model modifications to CAD.
- Comparison of nominal/actual values between measured object and computer data (CAD model, point clouds or STL data).
- Quality control, e.g. measuring deformations, manufacturing defects, spring-backs.
- Verification of fitting accuracy of single components by means of virtual assembly in the software.
- Creation of control data (on the basis of freeform surfaces) for manufacturing or for copying products on NC machine tools (e.g. milling machines) and rapid prototyping systems.

3.2 ATOS I limitations

As with many new age technologies, there are confines in measuring and/or scanning of measuring objects or volumes.

- Maximum measuring volume of 500 x 400 x 400 mm with respect to camera lenses' focal length.
- Preparation of dark or transparent objects. The surface structure is important for measuring an object. If the cameras cannot record the projected fringe pattern with sufficient contrast, one can expect no data or reduced quality of the digitised data. Thus, it is recommended that the dark or transparent object be sprayed with a powder such as titan oxide.
- Reference (circular markers) point positioning should also be taken in cognisance when preparing the object. A minimum of three reference points within the measuring distance should be identified for each individual measurement.

- Related to reference point positioning is the depth perception of the camera lenses. If the no-reference points are highlighted or identifiable then no perception of depth is possible. This is to say that the measuring depth of the measuring volume automatically results from the measuring distance and the camera angle.
- Camera viewing angles to surface are not fully through 90°. On edges a viewing angle greater than 60° is not possible for the individual measurement (Figure 3). Similarly, a viewing angle greater than 30° is not possible for circles, circle segments, slotted or rectangular holes (Figure 4).

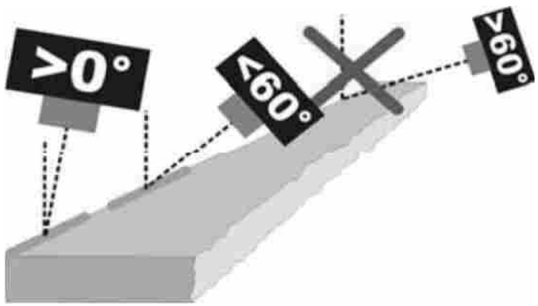


Figure 3: Camera viewing angle for border lines [3]

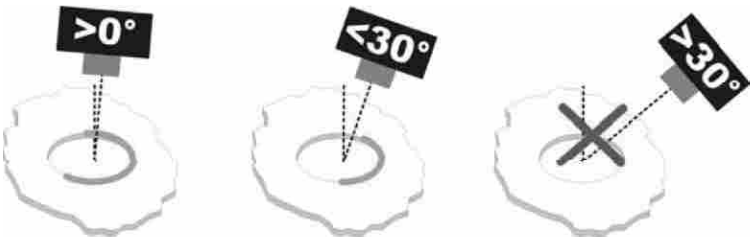
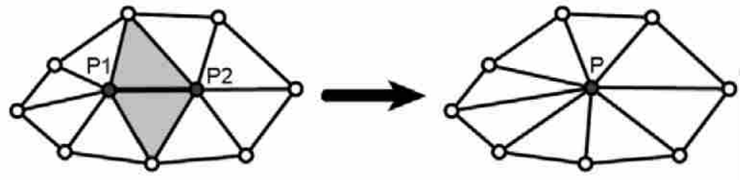


Figure 4: Camera viewing angle for circles [3]

3.3 3D digitising data pre-processing

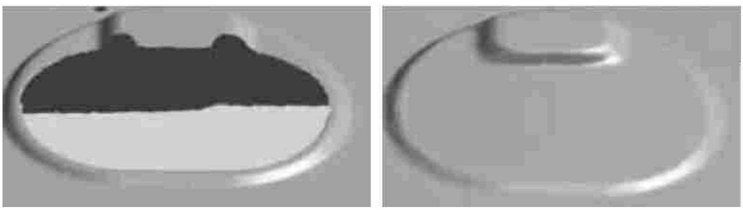
The pre-processing of range images begins by converting the range images into range surfaces by connecting the nearest neighbouring points with triangles of the range surfaces [4]. Each point of the range image is a potential vertex in the triangle mesh. And so the vertices for further triangles are created to generate a mesh. In order to do this, the measuring points need to be transformed into an editable polygon mesh. This is done by the polygonisation function, which means that the measuring point cloud is converted into a mesh of non-overlapping triangles. The complete polygonisation process comprises of [3]:

- polygonisation;
- fine alignment - all individual measurements are transformed into the same coordinate system by the reference points applied to the object or environment;
- eliminating mesh errors;
- filling reference points;
- smoothing points are shifted in such a way that they better integrate into the environment which thus appears smoother;
- thinning reduces the amount of data for certain applications. During thinning, two points of a triangle are pushed together to one point and moved in space that the resulting error is as small as possible (Figure 5).



Before thinning After thinning
Figure 5: Thinning process [3]

In addition it may occur that the user does not entirely capture all surfaces during digitising e.g. small surfaces may have been hidden by a detail of the measuring object creating gaps/holes in the polygon mesh. This may be filled using a hole-filling function with control over corresponding parameters such as surface degree and neighbourhood sizes as seen in Figure 6.



Original hole Filled hole
Figure 6: Hole filling [3]

3.4 3D digitising post-processing

Upon setting up a coordinate system for the object, using the principle of the 3-2-1 transformation (ZZZ-XX-Y) as seen in Figure 6, the respective mesh file may be exported as various files such as: G3D, STL, POL, IGES, VDA/PSET, ASCII, PLY.

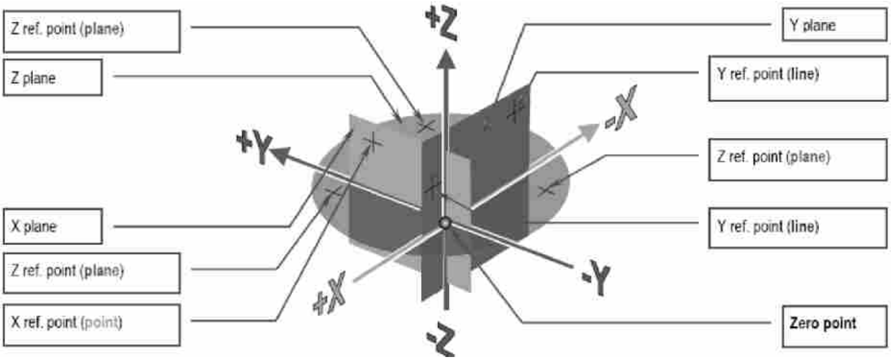


Figure 7: 3-2-1 Transformation principle [3]

4. SURFACE GENERATION FOR MODELLING

The data generated from the GOM software and the Renishaw Cyclone are most commonly STL, Ply, G3D (GOM Generic), Mod (Renishaw Generic) VDA and IGES, which are all derived from the point cloud data. These file forms are generally accepted by reverse engineering software such as GeoMagics, ProE-Wildfire REX, CopyCAD etc. However these types of forms do not conform to the capabilities of standard CAD packages such as Solidworks, ProE, UGS etc.

The files generated tend to become extremely large and require complex free-form modelling. This leads to the use of specialised packages such as CopyCAD (applied in this case) for efficient data processing. The software simplifies the process of approximating surfaces from the scan data. Features such as rounds, cylinders, holes and others can be better created rather by using a parametric modeller as most scanning methods have limitations in accurately determining geometric elements. In conjunction with CopyCAD, a parasolid modeller, PowerShape, was utilised for the refinement of the modelled data. However, the process may become tedious with larger and more intricate object volumes as the surface construction from polygons entails beginning a selection at a specific vertex and proceeding around a perimeter of the polygon in either direction until returning to the starting vertex.

The tiling of the curvature image from an initial surface consisting of a number of quadrilateral polygons is also known as boundary surface generation. The disadvantage of using this technique is that open surfaces may occur upon incorrect construction. The advantage is that should slight modifications be required on individual patches, the U-V flow lines may be manipulated easily. This is not apparent in the cases presented below as surface continuity should be as close as possible to that of the original object.

More specifically the surface should have point continuity (no gaps), and tangent continuity (no sharp angles) with the curvature continuity (no sharp radius changes) must be maintained.

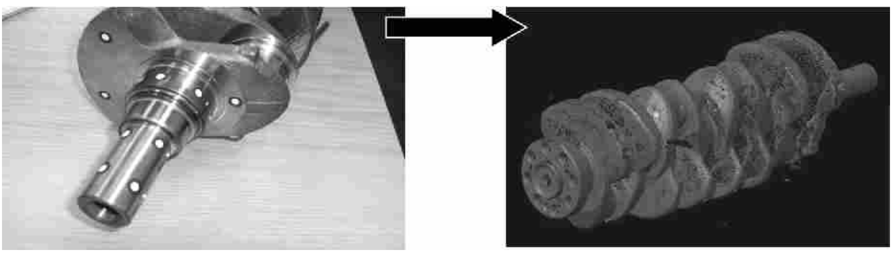
Thus, the task of surface generation in the cases discussed below would prove to be more efficient should specified sectional selection of the polygonised image data be available as a functional tool with editing parameters. Using the methodology of parametric surface generation, which entails the use of a function to map some portion of the object to a patch of the surface previously generated, would notably reduce the mesh surface solid modelling time.

5. CASE STUDIES

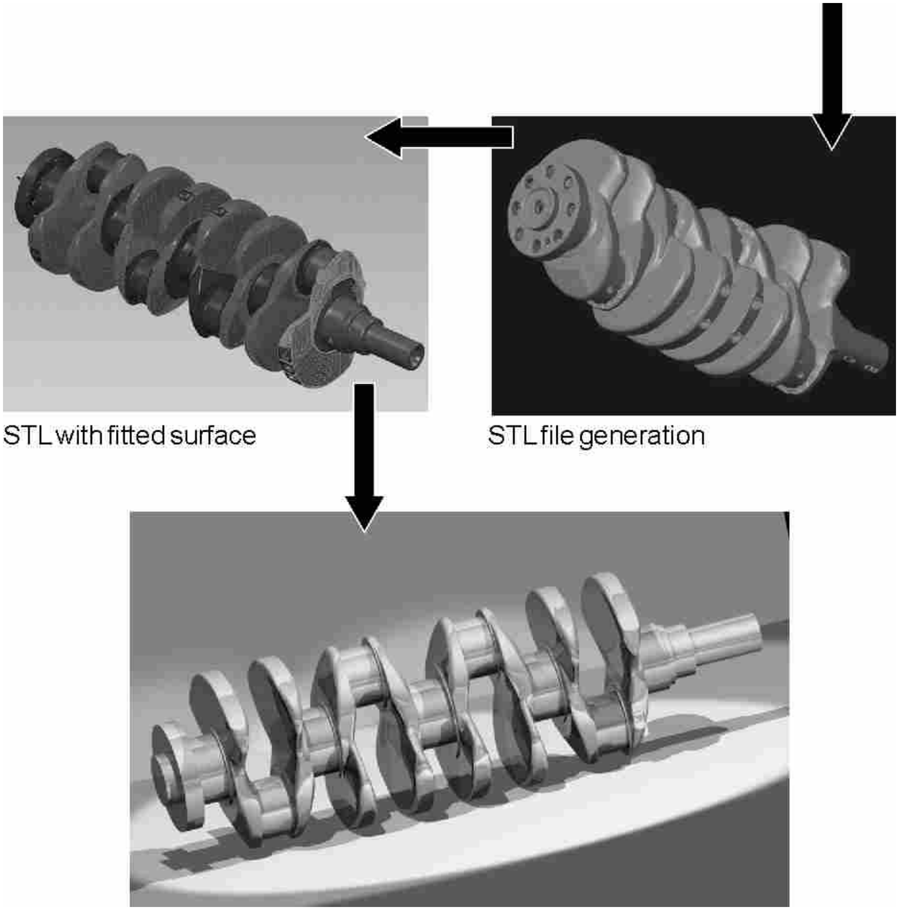
5.1 Reverse engineering of a new crankshaft

In this example a new crankshaft had to be digitised and modelled. Due to the shape of the crankshaft, it is virtually impossible to digitise the component in an entirety using the Renishaw Cyclone tactile scanner. The only possible solution in this case was to cut the crank at the journals and digitise them individually. Matching of this data would require a great deal of time and give rise to alignment error. The estimated time for the completion of the project in this way was around four to five weeks. This was not acceptable; thus the only feasible option was to use devices with photogrammetric work principles such as the GOM system as described above.

The process starts by applying reference points to the physical model. The points serve as the alignment base for each photo that is taken as shown in the chart below, which represents the process chain (Figure 8). A total of 80 images were taken to attain the required data.



Preparation of component | Point cloud data



Final surface model
Figure 8: Crankshaft modelling process - from scanned data to final surface model

The raw data is a point cloud which is polygonised to generate an STL file. This creates connectivity between the points and allows the user to apply surfaces to this shaded image i.e. mesh [1]. The data acquired was of high standard and ready in this form to start the modelling. One day was spent on the scanning, which was approximately 25% of the estimated time for using the Renishaw scanner. The image data on the casting surfaces of the component was more than adequate. However, machined areas i.e. ground and milled surfaces provided data that could only be used to approximate features such as holes, shafts etc., which would not be suitable for the final model. A Coordinate Measuring Machine (CMM) was used to measure the position and size of the various features and conventional modelling methods were used to create them in combination with the scan data.

This in itself presented difficulties in matching of the modelled surfaces to the surfaces created of the scan data, affecting the modelling time.

5.2 Cylinder head

In this example a cylinder head's intake and exhaust ports were to be reverse engineered. An existing method of achieving this involved using a Renishaw Cyclone to scan the port to the most ultimate position without the stem of the probe coming into contact with the component. Once this position is reached, the area already scanned is milled down and rescanned. This process is repeated several times until all the necessary detail are achieved. As one may imagine this is a lengthy and tedious method, taking up to 2 to 3 weeks. The removal and replacement of the component on the machine may also result in mismatching of scans.

Another method of digitising intake and exhaust ports is to take a silicon print of the ports. This was found not to be reliable, as the silicon proved to be too flexible and did not deliver accurate results [5].

The project was conducted applying the GOM system. The initial attempt proved to be fruitless as the lenses used were set for a measuring area of 500 x 400 mm^2 and did not capture a high level of detail (Figure 9). A smaller set of lenses was used with a measuring volume of 65 x 50 x 30mm. This proved to be highly accurate, aligning each image taken in the region of 3-15µm. It allowed for higher resolution in each image, but required many more images to capture all necessary details totalling 427. This procedure took just over 7 hours for all 8 ports (4 intakes, 4 exhausts).

The modelling took one week to complete, of which a considerable amount of time was spent on modelling the areas not captured in the images as discussed below, thus pushing the completion time of the project to just over a week.

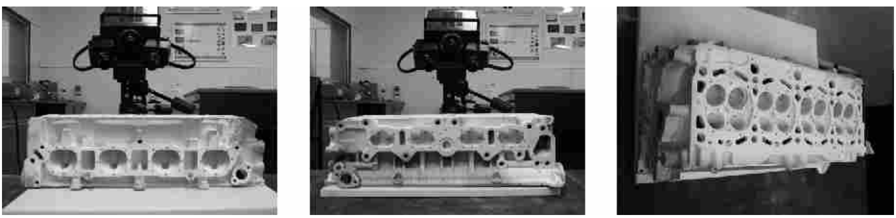


Figure 9: Cylinder head volumes of ports and valve seats

The limitation of this method was a hardware issue - the camera lenses could not capture all details of the port section, where the air intake side almost bends through 90 degrees to join the valve seating side as this was a “blind spot”. This data had to be corrected using the surrounding data to fill the holes that the camera could not capture (Figure 10).

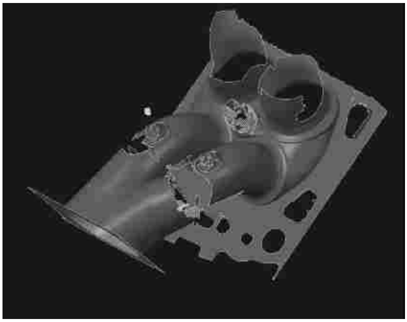


Figure 10: Section of the cylinder head exhaust port showing blind spots

6. CONCLUSION

This paper reflects experiences gained in using a photogrammetric approach for surface recreation as opposed to the use of tactile measuring probe methods. Depending on the application, the reduction of scanning and modelling time can be remarkable as demonstrated in the presented case studies. Some difficulties related mainly to data processing and hardware configuration were also highlighted.

The implementation of this technique in the industrial environment is still in its initial stages. Although there is obvious potential and advantages, further experience should be accumulated before a technologically solid analysis could be made and proper capability profiles of the various RE process chains and configurations are drawn with regard to achievable accuracy, modelling time, cost issues, user friendliness, software compatibility, geometric and topological complexity of the object and others.

7. REFERENCES

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