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A Review of Geometric Reconstruction Algorithm and Repairing Methodologies for Gas Turbine Components

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Abstract

Repairing of the used gas turbine components is becoming a challenge due to continual increase in manufacturing costs and the complex geometry. This paper discusses research on the repairing solutions for the damaged ones. The various kinds of geometric reconstruction algorithm for those are introduced selectively from the cross-section of the blade because of its vital roles. However, owing to the limitation of the algorithm, it has been lack of an efficient approach for reconstructing the geometry of a blade. As a result of this study, future research directions are highlighted.

Keywords*: Gas turbine components, Geometric Reconstruction, Blade Repair*

1. Introduction

Blades, such as fan blades, compressor blades, turbine blades, propeller blades, are the most critical parts of gas turbine components [1, 2]. The geometry of the blades incorporates the disciplines of thermodynamics/aerodynamics and structural mechanics [3]. As operating in high temperature and pressure, the blades may suffer the damage of abrasive wear, distortion, impact dents and cracks. As a small change in blade geometry can directly influence the stable operation of the turbine engine, the accurate repair of these defects becomes an inevitable choice. Bearing in mind that a blade easily can be high priced, repairing these parts accurately is often profitable [4].

The repair and overhaul process of the blades involves five steps: pre-repair inspection, identification and surface reconstruction of defect area, welding, milling and grinding, post-repair inspection [5]. Pre-repair inspection is to inspect the cleaned blades by non-contacted digitizing system or contacted digitizing system, and point data is obtained with a high-accuracy and can be transferred into triangulate data automatically [6-9]. The second step is to identify the worn area of the blades and to reconstruct the geometry of the worn area [10]. Using a welding process, material is attached to the prepared areas by build-up laser welding of laser cladding [11]. Excess material is milled off, milling and grinding will restore the original shape of the blades [12]. After a post-repair inspection, if the geometry of the blade is within the specified limits, it will be returned to operate.

It should be highlighted that some steps of the repair process utilizes advanced technology, i.e. the worn areas of the blade are built-up using laser cladding, and excess material on the blade is removed by a robotic grinding and polishing system [13]. On the other hand, the step of identification and geometry reconstruction of defect area is so significant that it not only makes use of the triangulate data of the last step efficiently, but also provides NC code for welding and milling steps. Unfortunately, the algorithm of identification and geometry reconstruction of defect area is less efficient especially when reconstructing a damaged and twisted blades tip because the original surface geometry of the worn area is little valuable reference [14].

The paper is divided into three parts. In the first part the geometric reconstruction algorithm for the defect area of blade are introduced selectively. Then the repairing solutions for damaged blades are compared. Also, instead of giving full detail of the repairing method of the blades, the paper prefers to discuss the strategies from the geometry-reconstructing point of

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view. Finally, analyzing and concluding the paper, the future directions of possible research is outlined.

2. Geometry Reconstruction Algorithm for Blade Profile

A suitable blade design is a compromise of aerodynamic, structural, thermodynamic, and economic considerations; there are many parametric modeling of blade in the open literature [15]. As there are many limitations in blade geometric reconstruction, such as the errors of data acquisition, wear of the blades, the errors of particular manufacturing method, it is difficult to regenerate the geometry of blade in parameterization during the repair and overhaul of the blade. All most of the geometry reconstruction algorithms for blade profile aim to filtrate the above errors and exclude them from the geometry in order to be declined to the nominal geometry.

Monhaghegh [16] argued that the only way to capture the valid shape of a blade airfoil out of the many manufacturing deviations is to incorporate design intent. He also proposed that seven arcs that are tangent to each other, are used to define a turbine blade airfoil section, which consists of two arcs for the leading edge (LE) and the trailing edge (TE), three arcs for suction side (SS) and two arcs for pressure side (PS) (Figure 1). A segmentation and constrained fitting algorithm (SCFA) was implemented to fulfill the requirements of an airfoil consisting of seven arcs (Figure 2). The author claimed that the algorithm not only have not changed the geometry of airfoil totally, but also have filtered the waviness of the profile. Nonetheless, this paper has not presented the method how to reconstruct the surface of the turbine blade airfoil base on the accurate-reconstructed blade profiles.

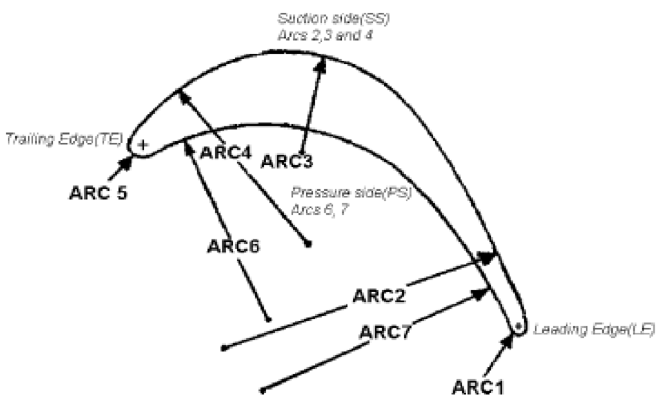


Figure 1. Airfoil cross-section nomenclature and position of seven arcs [16]

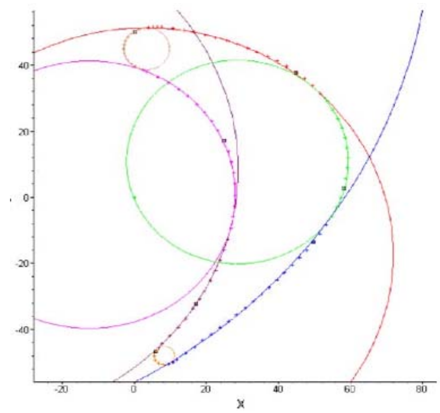


Figure 2. Final constrained fitted circles and point segments [16]

Yongqing Li [17] proposed an algorithm called constraints based nonrigid registration for 2D profile reconstruction when the relative position between the initial curve and points is worse. Once a template profile curve is obtained by slicing the nominal CAD model, the geometry of the manufacturing part is recovered with combination of the template profile curve and measured points. With two weighted correspondence matrices based on mutual distances, the algorithm is iteratively registering a template curve to the measured points by affine and free-from deformation transformation when simultaneously maintaining geometry constraints (Figure 3). Compared with constrained fitting algorithm, it is unnecessary to preprocess the measured data by sorting, segmenting and parameterization. Although it seems to show stronger robustness to noisy data than constrained fitting algorithm, the template profile curve for the used turbine blade consists of two B-spline curves with only positional and tangent constraints on both leading edge and trailing edge.

Also many researchers have used Bezier, B-spline curves or NURBS curves to reconstruct the blade for design optimization. The curve are used either as separate curves, or

as a single open or closed curve or within the addition of an arc at the leading and/or trailing edge [18-20]. Pierret [21] adopted a geometry model on Bezier curves for the definition of 2D and 3D axial turbine and compressor blades. The camber line of each 2D blade section is using a Bezier curve, and the pressure and suction sides are using two separate Bezier curve, and an arc is positioned on the trailing and trailing edge. Georgia [22] provided a toolbox to construct 3D blades in NURBS curves and surfaces. It should be highlighted that the definition of blades' cross-section is using a camber line which geometry could be controlled through the modification of the weight of its control point, and a single curve is used for the blade section surface to avoid the curvature discontinuity problems (Figure 4). However, the algorithm has to be in an interactive manner to construct the geometry of blade.
(a) definition of the camber line as a NURBS curve
(b) calculation of the normal vectors at the corresponding positions at both sides of the camber line
(c) positioning of the control points at the predefined distances normal to the camber line
(d) the corresponding NURBS control polygon
(e) construction of the blade section as a single NURBS curve

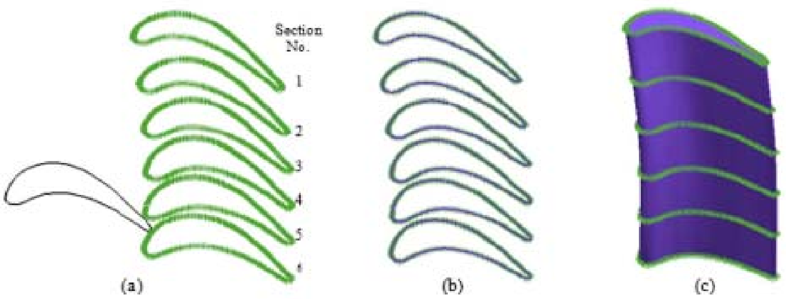


Figure 3.An example of the Nonrigid Registration method，(a) Cross sectional points of a physical turbine blade and a template curve;(b) section curve reconstructed with nonrigid registration; (c) lofted solid model based on the reconstructed curves [17]

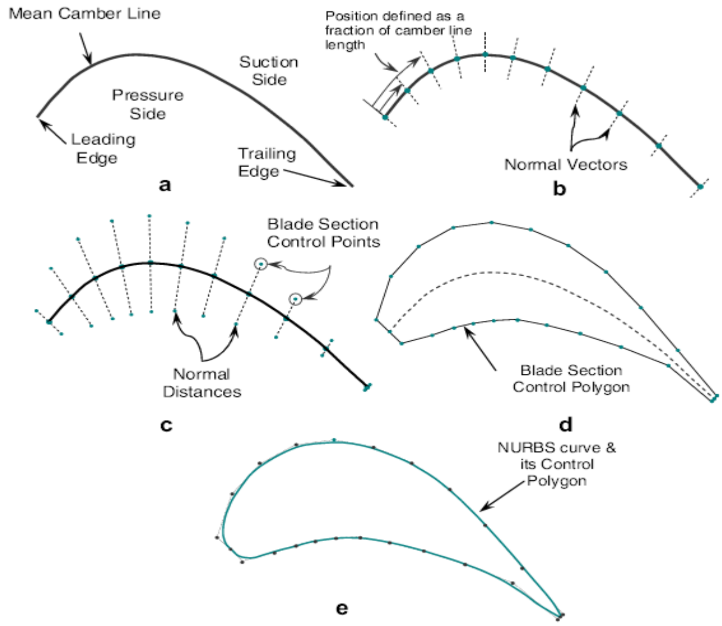


Figure 4.Schematic representation of the construction of each blade section [22]

Bryan et al [23] introduced a Robust Profile Reconstruction (RPR) algorithm, which adopted the neutral line concept and the interpretation vector method by finding the relationship between the original profile of the unused blade and the used blade under each section layers in two-dimensional plan. Due to the non-existence of the blade tip profile, the authors introduced the approach of reconstructing the used blade profile using the corresponding reference template, which is regarded as being suitable for providing the different tilting angles of turbine blade (Figure 5). Also, they assumed that the tip have the same tendency of distortion as the lower section of the used turbine blade. With these, all neutral lines of the used turbine blades are modified by extrapolation from data on the template unused turbine blade and the data on the used turbine blade (Figure 6). Although the authors claimed the profile generated by the algorithm was within the required tolerance, as the Catmull-Rom spline curve are selected to fit the convex side and the concave side of the blade, the second derivatibe of the curve is linearly interpolated with each segment, and this causes the curvature to wary linearly over length of the segment.

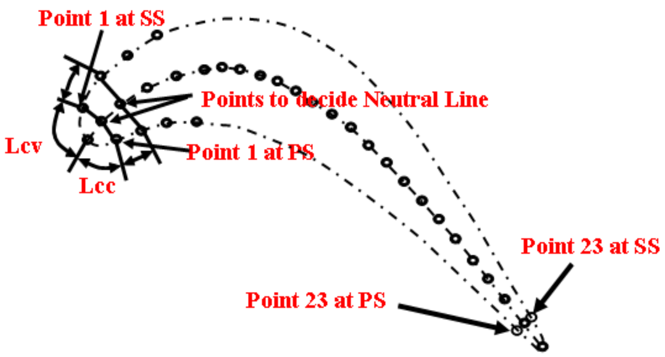


Figure 5. The neutral line after process

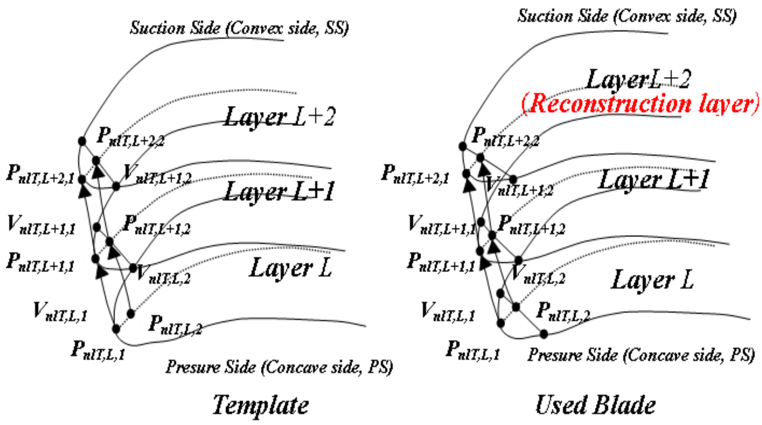


Figure 6. The profile build-up method by referring the template

3. Blade Repair Methodologies

The maintenance, repair and overhaul of aero engine components, particularly the blades, is of critical importance for the companies in aero-industrials. Repair of blades is a very competitive market and it has become an important issue in many companies, such as Rolls-Royce (UK) [24], Sifco (Ireland) [25], MTU Aero Engines (Germany) [26], Haffman Corporation (US) [27], Delcam (UK) [28], TTL (UK) [29], Geomagic (US) [30], etc. It is remarkable that Huffman Corporation has developed a multi-axis laser powder fusion welding system which features the AutoCLAD laser 2D vision software for the automatic repair of blades and vanes.

The vision system locates the part and generates a CNC program through AutoCLAD software for the welding process. Once the image is captured, the software can rapidly provide the geometry profile in the XY plane (cross section of the blade), and generate tool paths and welding parameters for the laser welding process. However due to the limitations of the 2D vision system, it is difficult to use the Huffman Machine for curved blades or blisk repairs. Moreover, MTU provides some examples of repaired RB199 HPC vanes, where the blade tip is repaired (Figure 7). Bremer [31] introduced an adaptive machining solution for blades with weld material added to repair missing volumes, which is claimed to be able to compensate for both part-to-part variation and inaccurate clamping positions of complex components. For the straight blade, two blade cross-sections below the welded bead are digitized using a tactile probe and the repair geometry of the target area is calculated. These blade repair processes are focused on straight blades and seldom consider curved blades, since the geometry of a curved blade cannot be created simply by one or two probed cross-sections. The geometric CAD model necessary for the repair of curved blades is difficult to reconstruct and therefore has been a barrier for refurbishment of curved blades.

1 Blade to be repaired

2 Welded bead on the blade tip

3 Excess material machined away

4 The repaired blade

Figure 7. Repair of a straight blade tip (RB199 HPC vanes,MTU)

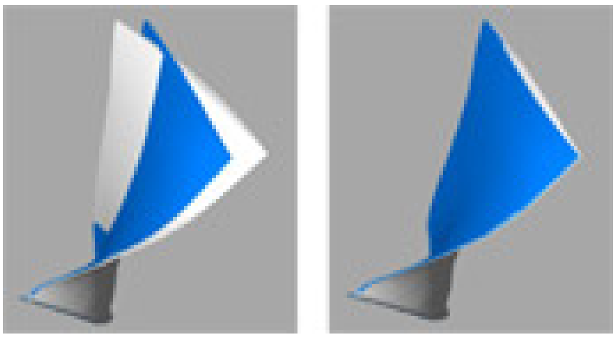


Figure 8. Adaptation of actual and nominal geometry of a Blade [34]

Considering the limitations of the above solutions, some companies and scientific research institutions attempted to use a master model or part to solve the problems. Brinksmeir et al. [32, 33] presented an adaptive repair process and machining strategy for curved blades and vanes. A master model is created from the original CAD model. Then a geometric model of the actual blade is created using a 3D optoelectronic sensor system to capture and digitize the geometry data of the part. The geometric and master models are compared and the deviation is calculated and is used to generate the tool paths. The boundary of the damaged area is calculated from the scanned data and is used to modify the milling path to blend the surfaces together. Automated Repair and Overhaul System for Aero Turbine Engine Components (AROSATEC)[34] is claimed to improving existing repair methods by adjusting the actual geometry of damaged part to eliminate the part-to-part variatio. For every type of blade, nominal geometry are required, either from CAD model or calculated based on the scanning of new or unused master part. The nominal geometry serves as reference when calculating the part to part deviations. Unlike the previous system, a major difference is the comparison when the actual geometric model is compared to the nominal geometry. Once the comparison identifies and localizes the damaged areas on the surface of the scanned part, the AROSATEC system is alleged to compensate for it (Figure 8). The advantage of the AROSATEC system is that once these data files are generated they can be used in all relevant repair steps. From the result, if the geometry and the corresponding tool path of the master part are contained in a database, the actual geometric data of the blades to be repaired can be compared with the database. The part-to-part deviation is calculated and used to generate tool path of the actual part by modifying the master part's tool path. However, due to the variations of blade geometry, especially the curved blade, it is difficult to choose such a master part.

Reverse engineering starts with a manufactured part and produces a geometric model using a 3D optoelectronic sensor system to capture and digitize the geometry data of the part [35]. As the scanned data of the worn blade can be saved in the STL file format, it is possible to reconstruct the original geometry of defect area based on the non-defective area through various RE applications. Gao [14, 36]states that the repair of curved blade faces two problems: 1) the geometry of the original specification CAD model is different from the geometry of the used blade due to the defects of distortion and wear. 2) The orientation of the cross-section varies along the length of the blade due to the twist (Figure 9). The author proposes a repair solution which integrates a non-contact digitizing system, reverse engineering (RE) application software and CAD/CAM software (Figure 10). A RE tool (Polyworks) is used to reconstruct a reference blade tip model through the surface extension approach (Figure 11). The paper also gives details of experimental trials on curved blade tip repair to verify the solution. Perhaps due to the complex procedure and manual operations required, the model reconstruction process is time consuming and the quality of the reference model created also limited the repair accuracy. Yilmaz [37, 38] claimed that it is crucial to maintain the original blade shape and to achieve maximum efficiency for the restored blade, such as chord and thickness dimensions. The author presents a repair and overhaul methodology for aeroengine components, which is an integrated approach of 3D optical measurement, free-form surface reconstruction and machining operations. In this work, The Rhinoceros 3D modelling package was chosen to reconstruct the target blade, a swept cross section was chosen to approximate the blade tip (Figure 12). Using the Matlab, the sweep surface is split into four areas by surface mean curvature analysis, which was considered as the best at maintaining the original blade shape. Once the data is transformed into IGES file, Polywork RE software was used for inspection and comparison to calculate the excess weld material. The Five-axis Hermle C-800-U CNC machine was used to remove the excess welding material and CATIA V5 was chosen as the CAD/CAM environment for tool path generation (Figure 13). In brief, these solutions through RE application are more effective than those who use the master model to create the blade tip. However, it requires complex procedures and interactive operations when the RE software is used to reconstruct the geometry of the turbine blade.

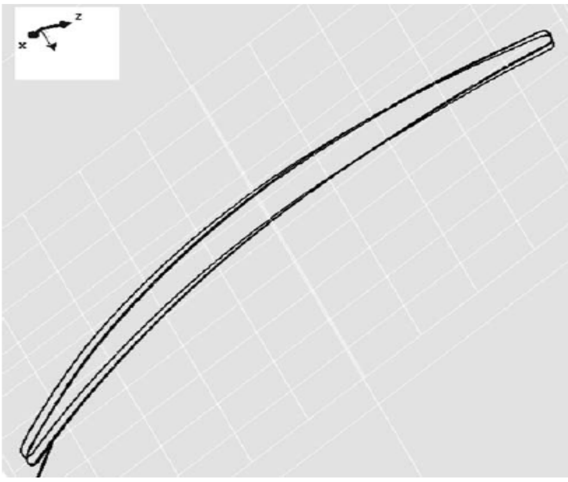


Figure 9. Two profiles on nominal model [36].

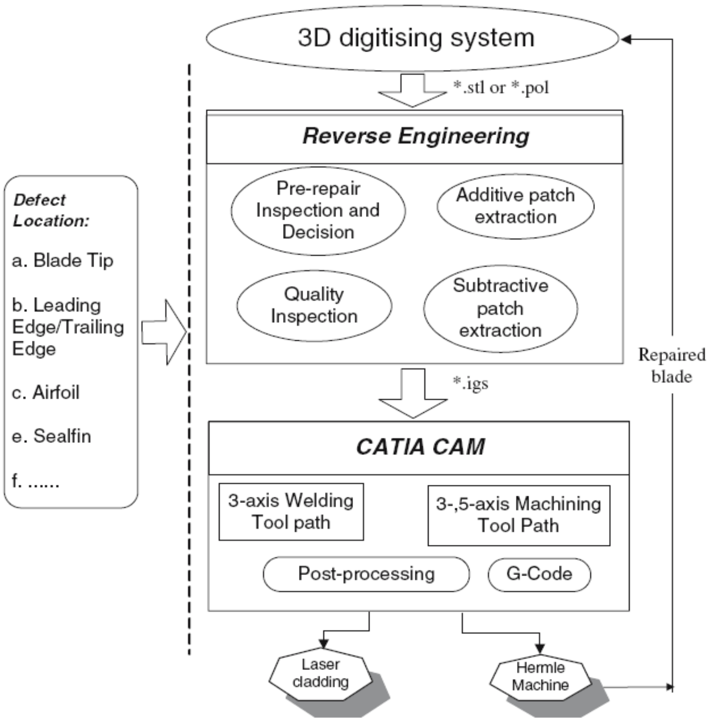
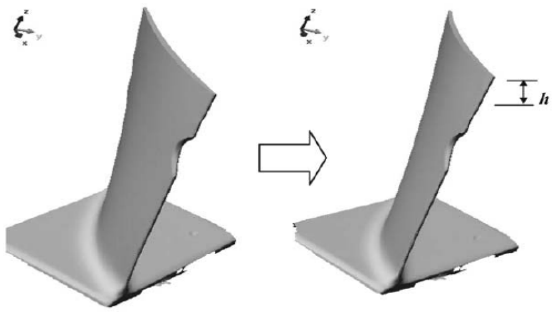


Figure 10. Repair system structures [36]



a) Model of the worn blade tip b) The reconstructed blade model

Figure 11. Blade tip geometry reconstruction [36].

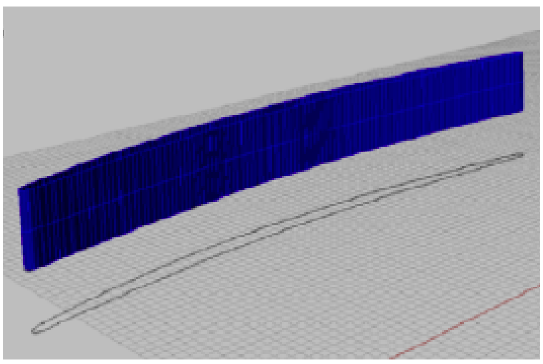


Figure 12. Reconstructed swept volume at the blade tip [38]

Figure 13.Blades after and before repair process [38]

4. Discussion and Conclusion

There has been a lot of work in the field of repair methodologies for the blades in recent years. From the point of view of the geometry reconstruction of the worn or damaged blade, the repair and overhaul methodologies for the turbine components are implemented by offsetting the cross-section (with no defects) along the length of the straight blade, or by using the master model, or by using the RE applications. No matter what method is used, its purpose is to improve fitting accuracy and efficiency of blade repair process. The progress of the geometric reconstruction algorithm could establish a stable foundation for repair of the damaged area of the blades. Based on the review study of current achievement and problems existed in the repair techniques, future research on this field will be involved in following aspects:

Geometry reconstruction algorithm with higher efficiency and accuracy. Since the blade surface reconstructed in the RE software is not unique, how to create the blade geometry accurately and efficiently is an important issue. After scanning and triangulating the surface geometry of the worn blade, the basic theory and approach of computer-aided geometrical design might be utilized to identify the boundary between the worn area and the non-defect area, and to regenerate the geometrical shape of the worn area through the recreated surface of the non-defect area. Especially, once the blade tip is worn and twisted, the nominal surface geometry of the worn area is no reference values and the fitting accuracy of the non-defect area of the blade becomes essential. Perhaps more attention is paid for How to combine the characteristic of the blade tip and the accurate fitting model of the non-defect area of the blade. Of course, the higher accuracy and less time-consuming operation of the reconstructed surface should be first ensured and the continuity and fairness of the regenerated surface for the worn area should be also guaranteed.

Data share between repair processes. It is necessary to integrate the repair processes including build-up process, machining process and inspection process. The constructed geometric model should be shared by each individual repair cell. Once the data standard is united, it will allow the definition of the open data formats, which could serve directly as the input file for machines as well as the original for translation to specific file formats.

Acknowledgements

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