MMA 2024 FLEXIBLE TECHNOLOGIES

15th INTERNATIONAL SCIENTIFIC CONFERENCE
NOVI SAD, SERBIA, SEPTEMBER 24-26, 2024

Original research paper https://doi.org/10.24867/MMA-2024-02-006

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RECONSTRUCTION AND OPTIMIZATION OF COMPLEX GEOMETRIC PARTS THROUGH REVERSE ENGINEERING

Abstract: *This paper presents a case study on the repair of oldtimer parts, with a particular focus on the damaged air duct that connects the heating and cooling system to the car's cabin. The replacement of such parts is challenging due to the cessation of production, making reverse engineering a feasible solution. Using the high-resolution and high-accuracy Artec SPIDER 3D scanner, the damaged part was digitized, followed by shape reconstruction and 3D CAD modeling processes. Furthermore, the model was modified to meet modern requirements and improve its functionality. The specification and modeling of freeform features were investigated, employing constraint-based parameterization methods and prototype-driven constraint solving. These approaches enable intuitive parameterization and precise reconstruction of complex geometric shapes. The results demonstrate that the application of modern reverse engineering technologies, along with necessary modifications, can effectively address the challenges of oldtimer restoration, ensuring the preservation of the original parts' functionality and aesthetics, thereby contributing to the maintenance of cultural heritage and the technical value of these cars.*

Key words: *Reverse Engineering, CAD, Geometric Shape, Freeform feature*

1. INTRODUCTION

Automotive companies secure their survival and expand into new markets through competitive products that offer greater functionality and higher quality, achieved by implementing high levels of innovation. The backbone of the modern automotive industry is Industry 4.0, which leverages advanced digital technologies to meet contemporary demands, such as those related to mobile services [1,2].

Digital technologies are essential for reducing the need for large inventories, cutting costs associated with unsold products, and facilitating the repair and reprocessing of defective, worn-out, or damaged components [3]. These technologies enable rapid design iteration and prototyping, the production of functional end-use parts, customized components and tools, as well as the decentralized manufacturing of spare parts. In particular, digital technologies and reverse engineering are vital for the restoration and maintenance of vintage automobiles [4]. They allow owners and restorers to accurately recreate rare or discontinued parts. Vintage cars, with their unique historical significance and aesthetic appeal, often require specific components that are hard to find on the market.

Reverse engineering allows for the precise capture of surface data from existing components using scanning or measuring devices, followed by the creation of digital models and their integration into manufacturing processes. This process involves using advanced scanning and modeling technologies to reconstruct existing parts. It starts with scanning the physical object with a 3D scanner to obtain accurate digital data on the part's shape and dimensions. Then, CAD software is used to create a digital model, which can be utilized for manufacturing a new part using CNC machines or 3D printing [1,3].

The reconstruction of digital models in CAD systems uses parametric or surface methods. After reverse engineering, where physical objects are scanned and turned into digital models, the next step often involves freeform modeling. This technique offers greater flexibility and precision for designing complex geometries that are difficult to achieve with traditional methods. Freeform modeling is essential for creating parts with intricate shapes, particularly in the automotive sector for components that need high aesthetic and functional value, such as delicate artifacts and car bodies [5,6].

The aim of this paper is to apply a method for reconstructing deformed parts of vintage cars using advanced 3D scanning and modeling techniques. The focus of the paper is on the application of freeform modeling for the repair and correction of a damaged air duct. This method includes parametric modeling based on constraints and the resolution of prototype-driven constraints, enabling precise reconstruction and restoration of parts with complex geometries. By using 3D technologies, the goal is to achieve high precision and authenticity in reconstruction, allowing for long-lasting and reliable restoration of these classic cars.

2. MATERIALS AND METHODS

In this study, the reconstruction of a damaged air duct (Fig. 1) was performed. This duct connects the heating and cooling system hoses to the car's cabin. It is crucial for maintaining optimal conditions inside the vehicle cabin, and its proper functionality directly affects the comfort and safety of the driver and passengers.

The reconstruction algorithm is shown in Fig. 2. This algorithm includes three key segments in the reconstruction process: sample preparation, 3D scanning, and point cloud processing (reconstruction, modeling).

Fig. 1. Position of the air duct within the system assembly [7]

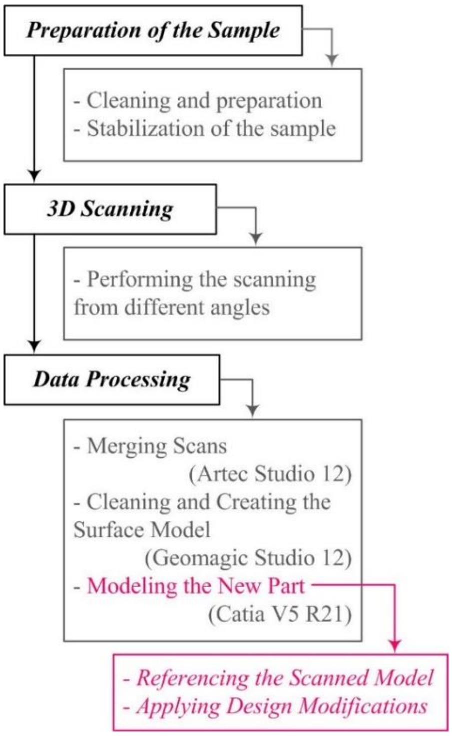

Fig. 2. Reconstruction algorithm for the air duct

2.1 Preparation of the Sample and 3D Scanning

Given that the subject of this study is a part that had already been in use, it was necessary to clean it of dirt and place it on a stable surface to eliminate possible movement during scanning. Mild detergent, soft cloths and sponges, as well as soft-bristle brushes for hard-to-reach areas, were used for surface cleaning. Compressed air was used to remove dust from cracks and openings.

The Artec SPIDER 3D scanner (https://www.artec3d.com/portable-3d-scanners/artec-spider) (Fig. 3) was used for product digitalization. This scanner can capture up to 1 million points per second with an accuracy of 0.05 mm and a resolution of 0.1 mm. These characteristics make it suitable for scanning objects with sharp edges, complex geometry, and fine details.

During the scanning process, the scanner was not fixed in place. In other words, the scanning was performed manually to capture all the complex surfaces that characterize this part.

Fig. 3. Artec SPIDER 3D scanner [8]

2.2 Data Processing

After the scanning was completed, the scans were merged and initially processed in Artec Studio software. This involved aligning the individual scans, removing any unnecessary data, and creating the initial 3D model. The alignment of the scans (Fig. 4) was achieved using point registration algorithms that minimize the differences between overlapping points. This process can be mathematically described as minimizing the error function E [9]:

$$E(R,t) = \sum_{i=1}^{N} \|Rp_i + t - q_i\|^2 \qquad (1)$$

where p_i, and q_i are corresponding points from two different scans, R is the rotation matrix, and t is the translation vector.

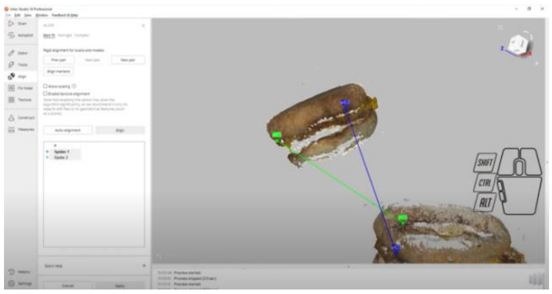

Fig. 4. Alignment of scans [10]

Further processing and reconstruction of the model were performed in Geomagic Studio 12 software. In this software, the polygonal model obtained from Artec Studio was further cleaned of irregularities and noise while maintaining its structural integrity and accuracy. The process includes [11] (Fig.5):

- Repairing polygons such as decimation (optimization that minimizes the number of polygons while preserving the geometric details of the model),
- Removing outliers and other artifacts (filtering and removing undesirable elements such as noise and irregularities), and
- Creating a smooth surface.

Once the model is prepared in this way, it is converted into a surface model in Geomagic software, which is crucial for further analysis and application in CAD software. Although the model was successfully reconstructed and imported into CATIA V5 R21, the need for re-modeling arose. Specifically, the air duct had lost its circularity in the cylindrical section (Fig. 6), and any attempt to correct the scanned model resulted in the distortion of the remaining geometry.

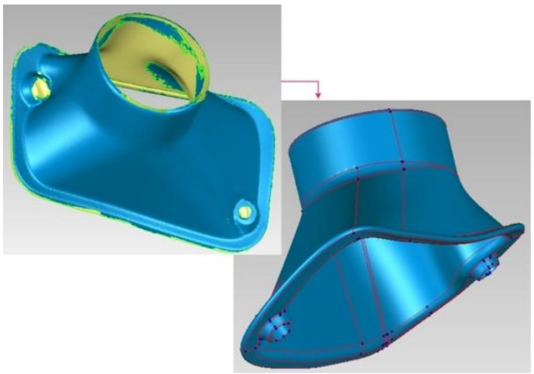

Fig. 5. Imported model from Artec Studio and adjusted model

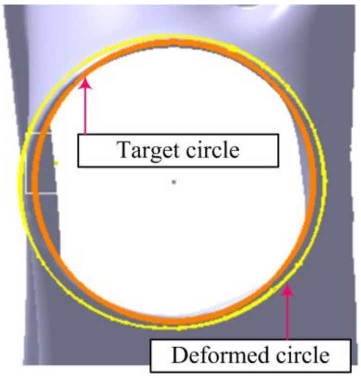

Fig. 6. Circularity deformation and desired circularity

To achieve full control over the model and its features, freeform modeling must be applied. This approach allows for the accurate creation of complex geometric shapes that are crucial for the product's functionality and integrity throughout its life cycle stages [5,6].

Freeform geometry is inherently complex and intricate. Therefore, it is essential that the shape of features can be interactively modeled during the specification of freeform classes. Furthermore, the method should allow for intuitive parametric definition of shapes and the inclusion of functional information within the class [5].

The specification of freeform shapes commenced with the creation of prototype shapes, referred to as freeform definition points (Fig. 7). These points, located in 3D space, are utilized to construct the model by connecting them with curves to establish the initial shape of the features. Mathematically, each point Pi on the model's surface is defined by its coordinates (x_i,y_i,z_i) in three-dimensional space. The points are strategically positioned on the imported model to delineate key geometric characteristics. Subsequently, these points serve as reference markers for the generation of more complex shapes [12]. Splines are then used to interpolate these points, ensuring the desired spatial configuration.

The main directions along which the geometry of the model develops define the axes that pass through the three holes on the model itself (Fig.8).

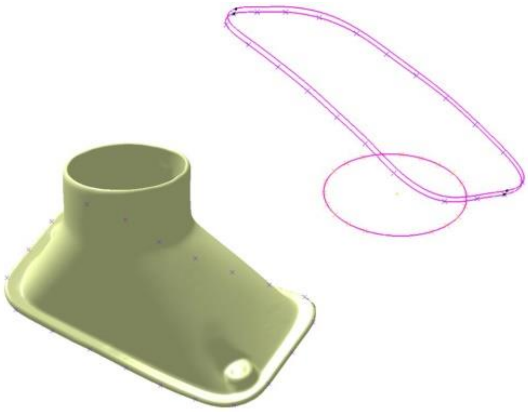

Fig. 7. Freeform definition points

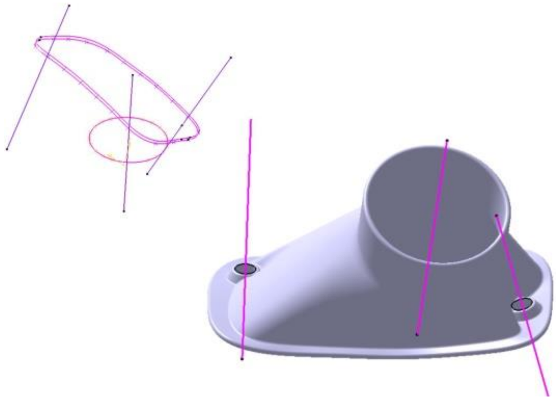

Fig. 8. Axis directions on the model

Following the definition of the basic geometry using splines and points, the next step involves the creation of surface shapes. These shapes impart either additive or subtractive characteristics to the model [5,6,12]. This process enables the formation of smooth and continuous surfaces, which are integrated into a unified model to ensure proper connectivity and continuity (Fig. 9).

All defined features are parametrically linked through geometric and dimensional constraints, with validation conditions precisely determining the relationships between model instances. The introduction of parameters and the establishment of validation conditions for the position and orientation of individual surfaces, as well as their directional extensions, facilitate the accurate positioning of the model within the assembly (Fig. 8 and 9) [5].

3. RESULTS

The application of this methodological approach results in efficient model management, facilitating not only the creation of technical drawings but also the preparation of the model for 3D printing and other essential manufacturing processes (Fig. 10). This approach ensures high precision and functionality of the model, enabling its successful integration into various stages of the production process.

This method optimizes all aspects of modeling, from initial design to final production, significantly enhancing the efficiency and quality of the final product.

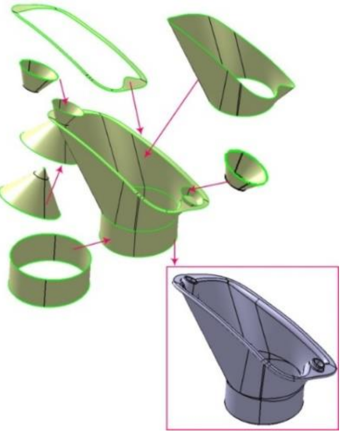

Fig. 9. Surface creation

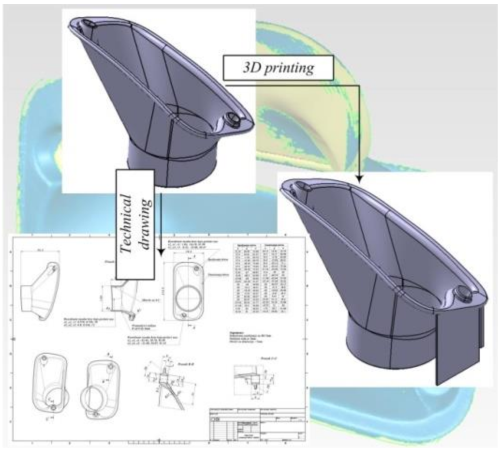

Fig. 10. Technical drawing and model for 3D printing

4. CONCLUSION

The results of this study demonstrate the successful integration of advanced 3D scanning, freeform modeling, and constraint-based parametric modeling techniques in reconstructing deformed vintage automobile parts. This modern reverse engineering approach preserves the functionality and aesthetics of original parts while enabling precise replacement and restoration. Consequently, the study aids in preserving the cultural and technical value of these historical vehicles, underscoring the importance of innovative restoration methods.

Future research should refine freeform modeling techniques to enhance reconstruction accuracy and efficiency. Additionally, integrating artificial intelligence and machine learning into reverse engineering could improve precision and automation. Expanding these methods to other vintage automobile components and fields requiring precise restoration also warrants exploration.

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