Reverse Engineering of Aerospace Components Utilizing Additive Manufacturing Technology

Balakrishnan Subeshan, Abdulaziz Abdulaziz, Zeeshan Khan, Md. Nizam Uddin, Muhammad Mustafizur Rahman, and Eylem Asmatulu

Abstract Using conventional manufacturing methods for product development typically involves a relatively long lead time and cost, especially for obsolete, worn-out, or broken parts. Reverse engineering is a preferred solution for reproducing obsolete parts and has been increasingly utilized to advance additive manufacturing technology. It is a combined process of laser scanning the obsolete parts where engineering design has become unavailable. These designs are then converted into patterns for sand casting to manufacture three-dimensional (3D) prototypes for further product development. The combination of reverse engineering and additive manufacturing is being utilized to manufacture the pattern for sand casting to produce the final product faster and distribute that to the industry more rapidly. Additive manufacturing technology has had a significant impact on the manufacturing industry throughout the world. There are various application fields where additive manufacturing has had a significant impact, and one of these fields is the aerospace industry. This study presents technologies and methodologies for reverse engineering, illustrated by a stainless-steel lever part from an aircraft control assembly. It involves the reconstruction of part geometry using laser scanning, fabrication of the pattern for sand casting using material extrusion additive manufacturing technology, and reversed part fabrication using sand casting. It was found that the fabrication of patterns directly from reverse-engineered computer-aided design (CAD) data using a suitable additive manufacturing technique provides a reliable and economic path

B. Subeshan · Z. Khan · M. M. Rahman · E. Asmatulu (✉)
Department of Mechanical Engineering, Wichita State University, 1845 Fairmount St., Wichita, KS 67270, USA
e-mail: e.asmatulu@wichita.edu

M. M. Rahman
e-mail: muhammad.rahman@wichita.edu

A. Abdulaziz
Department of Industrial, Systems, and Manufacturing Engineering, Wichita State University, 1845 Fairmount St., Wichita, KS 67270, USA

Md. N. Uddin
College of Business, Engineering, and Technology, Texas A & M University, Texarkana, TX 75503, USA

TMS 2022 151st Annual Meeting & Exhibition Supplemental Proceedings,
The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-92381-5_21

for rapid product development of complicated parts for replacement purposes. The process of reverse engineering comprises of laser scanning, CAD data, and all regular manufacturing steps to make that part.

Keywords Reverse engineering · Additive manufacturing · 3D printing · Material science · Data capturing · Material extrusion · CAD reconstruction

Introduction

Reverse engineering refers to the process of generating engineering design information from existing parts. It refabricates an existing part by obtaining its surface information using a laser scanning or measurement device. It is valuable to reconstruct the three-dimensional (3D) prototype of an existing part when the engineering design data is missing or when the model has disappeared from numerous design variations, especially when the part becomes obsolete, worn-out, or broken. Furthermore, reverse engineering consists of breaking down an innovation explicitly to determine how it works and how it was designed. This breaking down draws a useful learning process [1, 2]. As a technique, reverse engineering is not set for a specific reason.

Nevertheless, reverse engineering is frequently a significant part of logical strategy for innovative product development. The way of dismantling a part and finding out how it works is frequently a fascinating method to determine how to manufacture the part or upgrade it [3]. Reverse engineering is a way of producing a prototype using a computer-aided design (CAD) model from an existing part that has already been manufactured. It allows for the reproduction of a part by understanding its physical and geometrical measurements [4]. This reverse configuration approach begins with a physical part and works backward through the procedure to plot the part's measurements and structure, which allow the part to rationally recreate the structural views that were originally produced [5]. Reverse engineering has unique characteristics in the typical design process. It takes a physical part and makes it into a CAD model to change or adjust the structure. It can similarly characterize the procedure or copy an existing part by gathering segments of the physical measurements [6]. This type of engineering is typically incorporated to upgrade the design of a product for better viability or to deliver a duplicate of a design without having access to the design plan from which the part was initially created. On many occasions, it is useful for improved maintenance, or when the technical data is misplaced, imprecise, or obsolete. Examples include handmade prototypes and the reproduction of obsolete engineering objects used in aerospace, automotive, medical, and dental applications.

There are many different processes used to obtain data, but most of them are time-consuming. Technical information is essential for the smooth operation and continuous work of any generation of additive manufacturing, helping to manage the model of the part's computer-aided manufacturing (CAM) [7, 8]. A slight insufficiency or inaccuracy in data has repressed reverse engineering. By simplifying CAM operations of these physical models, it is essential to create their CAD models

[9]. Reverse engineering is the fastest method to get data into any system. Technical data is essential to any industry's smooth and continuous relationship with a manufacturing facility. Presently, there has been a demand for reverse engineering within many industries, such as aerospace, automotive, medical, robotics, military, and various other research environments. This study aims to minimize the knowledge gap regarding reverse engineering and achieve a complete understanding of how to deal with reverse engineering for future studies [10–13]. This study aims to cover the details of reverse engineering, showing a step-by-step process of the fabrication of patterns for sand casting a lever part from a control assembly of an aircraft using the additive manufacturing technique with polymeric materials. The study describes the various methods of creating CAD data and scanning technologies used to capture data for part geometry, a key component in the reverse engineering process. The digitized component can be manipulated in CAD modeling software to generate the files needed for additive manufacturing. This study also demonstrates the different additive manufacturing technology methods applied to create a casting pattern. Replacing older components that are no longer in production can result in substantial manufacturing costs involving complexity when using a variety of molds, machines, and tools for sand casting. Employing additive manufacturing for creating a pattern for the casting of a part has been shown to reduce these costs significantly and minimize material waste.

Experimental Procedure

Equipment and Materials

The experimental setup consisted of various pieces of equipment: HandySCAN 700 scanner, Stratasys Dimension BST 1200 printer, and Fusion 360 and VX Element 7.0 software. The HandySCAN 700 scanner was attached to a USB 3.1 connector, which facilitated getting all the cloud points faster. VX Elements 7.0 software, which is used to capture the geometry utilizing the HandySCAN 700, is fully integrated with other 3D software platforms, such as Fusion 360, and allows for the export of files. Moreover, VX Elements 7.0 is a post-processing software that integrates VX elements and enables processing of the 3D point cloud to transfer in CAD modeling software. Fusion 360 is the CAD modeling software used to edit the mesh file and finalize the 3D scanned data that is employed directly in most rapid prototyping techniques, preferably for metal 3D printing. This software allows objects to be exported in stereolithography (STL) format, which is required for 3D printing the casting pattern. HandySCAN 700 is a portable laser 3D scanner that considers multiple measurements with different speed and accuracy. It uses seven lasers, which create a grid and an additional line for increased accuracy. The scanning area is approximately 275 mm $\times$ 250 mm, the volumetric accuracy is 0.02 mm $\pm$ 0.06 mm/m, 56~60 images are scanned per second, each image collected is about 600 points, and the measurement

Fig. 1 Equipment used to perform reverse engineering of an obsolete part: **a** HandySCAN 700 laser scanner and **b** Dimension 1200es BST 3D printer

rate can meet 480,000 measures. HandySCAN 700 consists of a laser projector, and a CCD sensor triangulation system is used for self-positioning. The illuminated light emitted by the laser projector is spatially modulated by the surface of the object to be measured. Changing the angle of the imaging beam, the position of the structured light on the CCD sensor results in a change. Figure 1a displays a commercial HandySCAN 700. The Dimension 1200es BST 3D printer is based on material extrusion technology. This printer has space to build 3D designs up to 254 × 254 × 305 mm, which allows more than one model to be created at a time. Figure 1b shows a commercial Dimension 1200es BST 3D printer.

Experimental Methods

The HandySCAN 700 is an entirely handheld laser scanning device, which applies targets from its reference system to the part. These targets achieve up to 20-micron accuracy specifications. It is feasible to collect data on both sides of the part by simply moving the device around the part. A computer system connected to the device helps to virtually spin the part itself to capture data from all sides. HandySCAN 700 laser scanning is unique to previous 3D laser scanning technologies. This device uses seven laser crosses, which give a precise scanning speed of 480,000 data points per second, gathering a considerable amount of data extremely quickly and consequently minimizing scan time. Not only a seven-laser cross-system but the device can also be optionally turned into a single-line mode by simply double-clicking a button on the back of the scanner. In a single-line system, only one laser line that does not require both lenses on the scanner is used, so it only requires whichever lenses are looking at the reflecting end. These single lines quickly reflect data from the tight areas of the part, such as holes. This study used the general area coverage, which is a quick way of gathering data, and the most accurate way to map out targets and tell the scanner where it is moving around in space, thereby also assisting with a depth-of-field indicator. Holding the scanner too far away from the part indicates blue and holding the scanner too close to the part indicates red. Holding the scanner directly in the middle indicates green, which is the scanner's optical scanning distance from the part. After scanning the entire part, VX Elements 7.0 software processes the part's point cloud. The transformation of a 3D point cloud file to a CAD file is performed using Fusion 360 software, which analyzes the part geometrically and breaks it into meshes, thereby recognizing all the part's critical geometrical features. Mesh is used for extracting the surfaces to generate the CAD model. This software supports critical features to modify the CAD model to look the same as the obsolete part.

In this study, additive manufacturing was employed to manufacture the sand-casting pattern for the obsolete part. Due to accessibility, 3D printing was performed with polymeric materials, using the actual 3D part in hand to measure the geometric features and dimensions of the sand-casting pattern for the obsolete part. This technique is viable for complex parts with many geometric features. The casting pattern was fabricated using ABS plastic and PLA plastic on a Dimension 1200es BST 3D printer by incorporating the material extrusion additive manufacturing technique. This fabrication took 2 h and was followed by clearing the supports manually, using xylene for a better surface finish, and drying in an airstream for 30 min to improve the strength. The ABS plastic was closer to the more desired material used in the sand-casting process with its mechanical properties compared to the PLA plastic. The ABS P400 plastic used is a durable ABS-based material appropriate for concept models and testing of form, fit, and some function. It is impact-resistant, has a relatively high tensile strength, and is heat, scratch, and chemical resistant. The material has a relatively high thermal expansion for plastic and is lower in cost than most engineering thermoplastics. However, ABS plastic has limited weather resistance and is not very resistant to solvents. During 3D printing, the Dimension 1200es BST 3D printer operates with an extrusion system—an extrusion head with a nozzle to deposit build material onto a build platform. During material extrusion, a filament (ABS plastic) is fed through the extrusion head by a drive roll and past a heating element. The material liquefies and is then deposited by the nozzle onto a build platform. The build platform, which usually moves vertically, lowers itself automatically so the nozzle and can dispense a new material layer on top of the previous layer. To build each layer, the extrusion head deposits the layer's outline first and then fills in each layer according to master dimensions set by the operator. As each layer is deposited, it fuses to the previous one, creating a solid model. This process is repeated until the final product is completed. While adding layers, material extrusion systems sometimes dispense support material along with build material. Support material occupies negative spaces and provides stability to disconnected part features, such as overhangs or holes, during the building process. Once the part is completed and used, the support material and break-away support systems are manually removed. To remove soluble support materials, the parts are submerged in a chemical bath or a solvent, such as a xylene, which quickly dissolves the support material. 3D printing machines exclusively use thermoplastics, a group of polymers, as build materials. Thermoplastics melt or soften quickly when heated, and they retain their desired shape upon cooling.

A large variety of thermoplastics are available for use in the 3D printing additive manufacturing industry. Many modern 3D printing machines still rely on thermoplastics, usually in pellets or filaments, to build parts today. The sand-casting process is relatively simple. A sand casting of the stainless-steel lever part from an aircraft control assembly was prepared using a 3D printed ABS pattern, applying material extrusion additive manufacturing technology. The pattern-development time was reduced by speeding up the sand-casting application. The reverse-engineered part should be resistant to chemicals in the sand, abrasion-resistant, and able to withstand compaction forces applied to pack the sand. Sand casting offers an economical process for the mass production of complex metal part structures. Stainless steel was the metal used for sand casting in this study. The progression starts with the design of the cast part and the metal delivery paths in the mold. The 3D printed ABS pattern is placed in a square box called a flask. Sand is then poured into the flask and placed firmly against the 3D printed ABS pattern. Clay, which is green sand and dry sand, holds the compacted sand together. Molten metal is poured into the mold over the sprue, flowing through the path onto the part cavity. The metal correspondingly fills the riser, a reservoir that continues to supply the part cavity as the metal cools and shrinks. The metal is then allowed to cool and solidify, and the sand is separated from the part. Subsequently, the manufactured part is removed and subjected to surface treatment processes such as sanding, sealing, and painting (optional) to improve its appearance and durability. By using additive manufacturing technology for pattern creation, sand casters use an effective prototyping approach, resulting directly in production.

Results and Discussion

The CAD model obtained from laser scanning consists of many points on the surface, stitched together on the cloud data. It is very tedious to make a complete whole volume model due to unavoidable discontinuities among the stitched surfaces. However, some reverse engineering software facilitates surface evaluation and model inspection by measuring the difference between the surface model and cloud data, automatically filling and correcting gaps. Overall, the results of models created using 3D CAD modeling software are better than those obtained through reverse engineering. Reverse engineering is suitable when drawings are not available, and the part has a complex geometry. The lever part, when reversed, is a medium-complexity part due to the holes and fillets on the top portion and its curved geometry. CAD modeling with traditional CAD software typically takes at least a week. In contrast, it took only 3 h for laser scanning and 2 h for 3D printing this pattern for casting the part. Figure 2a–c show the results of the study. Figure 2a shows the obsolete physical part, and Fig. 2b shows the CAD model of the obsolete part, which was obtained using the HandySCAN 700 laser scanner. The pattern for sand casting of the reversed part was created using the material extrusion additive manufacturing technique. Figure 2c shows the 3D printed part, which is the pattern for sand casting of the reversed part

Fig. 2 Reverse engineering process: **a** obsolete physical part, **b** CAD model of obsolete part, and **c** pattern for sand casting of the reversed part using material extrusion additive manufacturing

manufactured with the Dimension 1200es BST 3D printer, an affordable process with low energy usage. Figure 3 shows a visual comparison of the obsolete part and the 3D printed part, a fabricated pattern for sand casting. The 3D printed fabricated pattern for sand casting was made precisely like the actual obsolete part, which incorporated the dimensional analysis. All figures display a complete understanding of the reverse engineering progression. When the feature extraction of the five major characteristic designators on the obsolete part was tested, the design value of the hole distance varied, depending on the location. A comparison of the measured value and design value of the hole distance is shown in Table 1, which also includes the deviation of the pattern manufactured using the material extrusion system from the original obsolete part.

Dimensional accuracy measures the fabricated pattern's closeness for sand casting to the corresponding obsolete part. For dimensional comparison, Fig. 3 shows the three locations measured on both the obsolete and 3D printed parts fabricated for sand casting. Each dimension was measured twice. The absolute deviation was calculated relative to the obsolete part's dimensions since the same model was used for all reverse

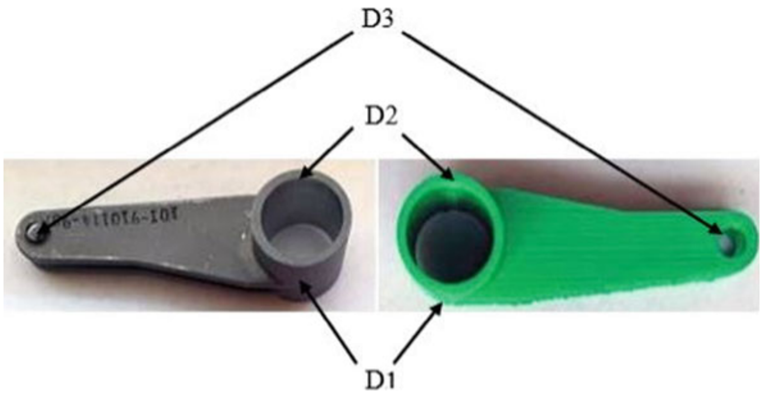

Fig. 3 Dimensional comparison of three locations measured on both obsolete part (left), and 3D printed part (right), a fabricated pattern for sand casting

Table 1 Comparison of measured values and characteristic designator values

Reference location	Original obsolete part value (mm)	Fabricated part value (mm)	Deviation value (mm)	Error (%)
D1	5	4.9	0.1	0.02
	5	4.4	0.6	0.12
D2	60	62.4	2.4	4.00
	60	54.4	5.6	9.30
D3	15	11.9	3.1	20.60
	15	12.3	2.7	18.00

Fig. 4 Final reverse-engineered part using sand casting from 3D printed pattern

engineering processes. The percentage deviation for measuring the dimensional accuracy of the fabricated pattern for sand casting is defined as the percentage ratio of deviation from the obsolete part's corresponding dimension. Dimensional errors may be introduced during laser scanning, point-data processing, solid modeling, and manufacturing pattern casting. Figure 4 shows the final sand-casted part, which is similar in geometry to the obsolete lever from the aircraft's control assembly.

Conclusion

There has been an increasing interest in reverse engineering of obsolete parts to replace parts that are worn out or whose original drawings (geometric, material, and manufacturing details) are not available. With reverse engineering, the obsolete part is measured to obtain new data and permit remanufacture of the part, which is possible in several ways with today's modern techniques of using point cloud data from the obsolete part in digital CAD data files. This study showed how to overcome product development issues for traditional metal sand casting by combining reverse engineering and additive manufacturing technologies. This approach has been successfully demonstrated by conducting an industrial case study on an obsolete stainless-steel lever from an aircraft control assembly. Every step in the reverse engineering process, such as data capturing, refining the CAD model, and manufacturing the casting pattern, was achieved correctly. The comparative analysis of several routes for pattern fabrication yielded valuable data regarding dimensional accuracy and surface quality. Material extrusion additive manufacturing was used to make the part with sufficient quality to be used as a pattern for sand casting. By using additive manufacturing instead of traditional manufacturing methods, time and money can be saved. The proposed approach is particularly suited to the urgent replication of worn-out parts with complex shapes and those needed only once or in small quantities. Additive manufacturing is pertinent to the aerospace industry when the manufacturing of engineering products and tooling is involved. Innovation in additive manufacturing technology is expected to bring benefits in terms of accuracy and cost soon, especially for small and complex components.

Acknowledgements The authors gratefully acknowledge Wichita State University for the technical and financial support for this research study.

References

1. Bhatti A, Syed NA, John P (2018) Reverse engineering and Its applications. In: Omics technologies and bio-engineering. Academic Press, pp 95–110
2. Buonamici F, Carfagni M, Furferi R, Governi L, Lapini A, Volpe Y (2018) Reverse engineering of mechanical parts: a template-based approach. J Comput Des Eng 5:145–159
3. Samuelson P, Scotchmer S (2002) The law and economics of reverse engineering. Yale Law J 111:1575–1663
4. Payal H, Tomer R (2020) Review on reverse engineering. J Crit Rev 7:1408–1412
5. Chilton J, Chuang CC (2017) Rooted in nature: aesthetics, geometry and structure in the shells of Heinz Isler. Nexus Netw J 19:763–785
6. Potabatti NS (2019) Photogrammetry for 3D Reconstruction in solidworks and its applications in industry (Doctoral dissertation)
7. Jiménez M, Romero L, Domínguez IA, Espinosa MDM, Domínguez M (2019) Additive manufacturing technologies: an overview about 3D printing methods and future prospects. Complexity. https://doi.org/10.1155/2019/9656938
8. Tong W, Chen M (2021) A sufficient condition for 3D typical curves. Comput Aided Geom Des 87:101991
9. Wang X, Bi Z (2019) New CAD/CAM course framework in digital manufacturing. Comput Appl Eng Educ 27:128–144
10. Subeshan B, Baddam Y, Asmatulu E (2021) Current progress of 4D-printing technology. Prog Addit Manuf 1–22
11. Asmatulu E, Alonayni A, Subeshan B, Rahman MM (2018) Investigating compression strengths of 3D printed polymeric infill specimens of various geometries. In: Nano-, Bio-, Info-Tech Sensors, and 3D Systems II, p 21
12. Baddam Y, Uddin MN, Don TN, Asmatulu E (2019) Integrating 4D printing processes into STEM education. ASEE Midwest Section Conference, Wichita, KS
13. Chen Z, Chen W, Guo J, Cao J, Zhang YJ (2018) Orientation field guided line abstraction for 3D printing. Comput Aided Geom Des 62:253–262