EXPLORING THE POTENTIAL AND APPLICATIONS OF ADDITIVE MANUFACTURING IN REPAIRS DURING THE OPERATION OF A SHIP

MARC JOVE-BUENO
Department of Nautical Science and Engineering, UPC-Barcelona Tech, Spain
e-mail: marc.jove@upc.edu (Author for correspondence)

ROSA M. FERNANDEZ-CANTI
Department of Automatic Control, UPC-Barcelona Tech., Spain
e-mail: rosa.mari.fernandez@upc.edu
Orcid: 0000-0002-9381-6601

MONTSE VELA DEL OLMO
Department of Mathematics, UPC-Barcelona Tech, Spain
e-mail: montse.vela@upc.edu
Orcid: 0000-0003-0355-9398

CLARA BORÉN
Department of Nautical Science and Engineering, UPC-Barcelona Tech, Spain
e-mail: clara.boren@upc.edu
Orcid: 0000-0001-7666-2279

Keywords

Marine Technology, 3D Scanner, 3D Printer, Materials for 3D Printing, Additive Manufacturing

Abstract

In recent years, the naval industry has benefited from the recent advances of industry 4.0, especially with the rise of 3D printing and additive manufacturing. In particular, several shipping companies have begun to introduce the use of 3D printers on board in order to be able to perform corrective maintenance and repairs while the ship is in operation. On the one hand, one of the problems to be solved in this area is the design of the models of the spare parts to be printed in 3D when there are no original plans for these parts and the repair must be done in a very short time. The recent appearance of a portable 3D scanner model, which does not need to be connected to a computer, may be the solution so that the crew can obtain the models of the parts to be replaced in a short time and without having advanced knowledge of the 3D design tools. On the other hand, the selection of materials for repairments based on 3D printing is another important issue in the application of these technologies. This work explores the benefits of using a portable 3D scanner to obtain quick and reliable models of the parts to be replaced and considers the most suitable materials for the subsequent printing of these 3D models. The whole procedure is illustrated by the application to a case study consisting of the 3D scanning and 3D printing of a general-purpose part.

1 INTRODUCTION

Future trends in marine technology include recent v4.0 industry advances such as 3D printing and additive manufacturing. Compared to conventional manufacturing, this technology allows part optimization, weight reduction, and easier prototyping.

The main applications of 3D printing on board are corrective maintenance and repairs. If original spare parts are not available on board, it is possible to print them while the ship is in operation, thus allowing a temporary repair to be carried out until a replacement is obtained when the ship arrives in port, or even a permanent repair if the system requirements allow it.

Some shipping companies have already started to implement 3D printing technology on their ships, because many benefits can be obtained, such as better response times, inventory reduction, freedom to manufacture complex geometries and reduced transportation costs (Vujović et al., 2021; Mohammed et al., 2016).

An important issue in the use of 3D printing for corrective maintenance while a ship is in operation is that the crew themselves must select the appropriate material and print the specific part to be replaced (Kostidi et al., 2017).

Issues related to 3D printing on board have already been studied in various works. For instance, a major problem during the operation of the 3D printer on the ship is the exposure to ship movements, vibrations and marine environment. For this reason, prototypes of stabilizers are already being developed for the correct operation of on-board 3D printers, offering results without noticeable differences between land and on-board printing. For instance, see (Phillips et al., 2020), where such a prototype has been tested with an SLA (stereolithography) printer.

On the other hand, the design on board of parts models has not received the same attention. In order to print a part, its model is needed. In many cases, the shipping company provides 3D models of the most common parts. But if the model is not available, it is the crew who must design the 3D model to be printed, often with very little time to do it.

This last issue is critical, because errors in the models can arise due to the lack of training of the crew in 3D design tools and the short time to perform the designs. The final printed part may be very different from the original, which in some cases it will simply be unusable and in others it may cause the installation to malfunction.

The use of 3D scanners is a suitable solution to simplify the design procedure and to obtain the models in a short time. In the naval industry, 3D laser scanners are a feasible option when it comes to obtaining high-precision 3D files (Abbas et al., 2017). A 3D scanner can capture all the details of the part to be repaired and then, by means of a post processing with the scanner's own software, it is possible to obtain a mesh, edit the design, and finally print it using the printer installed on board.

Unfortunately, 3D scanners used in the land industry are difficult to use on a ship in operation, given the great diversity of types of parts, shapes and sizes that would have to be scanned, in addition to the fact that this type of equipment is bulky and needs to be connected to a computer. This may be a major problem in the cases where the scanning must be performed in areas that are of difficult access.

Recently, a type of a portable 3D scanner that does not need to be connected to a computer has appeared on the market. In this work, we explore the potential of this new technology in the corrective maintenance on-board of ships during the operation. The goal is to provide the crew with a tool that allows the accurate design of parts in a short time and therefore carry out reliable repairs on board. Once the part is designed, the material selection for the 3D printing is another critical issue. In this work we also analyze the materials more suitable for on-board parts. The whole procedure including 3D scanning, post processing, materials selection and 3D printing is illustrated by means of the scanning and printing of a general purpose gear.

The article is organized as follows. Section 2 presents the concept of 3D scanning, explains what it entails, and illustrates the usefulness of the portable 3D scanner in obtaining the model of a general purpose part. Section 3 focuses on the problem of 3D printing parts in marine applications. The most suitable materials for this purpose are analyzed and their use is illustrated with the impression of the part designed in the previous section. Finally, Section 4 presents the conclusions.

2 ON BOARD 3D SCANNING

In the market we can find different types of 3D scanners, many of these present difficulties in use during the navigation of the ship, since they must be connected to a computer during the scanning process, which is a problem depending on the location of the ship where the scanning must be performed. In addition, the movements of the ship make it difficult to carry out a good scan.

Currently, new 3D scanners have come onto the market that open up a wide range of possibilities. They are scanners that do not need to be connected to a computer while being used. They allow direct scanning and meshing by means of a cell phone application or and built-in application. This is the case of brands REVOPOINT© y CREALITY©. See technical documentation and data sheets in the official websites (https://global.revopoint3d.com/en-eur, https://store.creality.com/eu/)

These portable scanners are really multipurpose scanners in the sense that they can scan parts of different sizes, even when the ship is moving, and they give the freedom to scan in locations of difficult access.

2.1 FUNDAMENTALS OF 3D SCANNING

3D scanning is the collection of data from a physical object to obtain a 3D model in digital format. This process depends on the technology that is built into the scanner. Currently on the market we can find different types of scanners depending on their technology and how they are used.

There are two main scanning technologies, *structured light* and *laser* technology. A *structured light scanner* projects light patterns onto the object and detects the shapes. It is made up of a projector that generates the patterns and cameras that capture the distance between the points. The light emitted can be *visible light* (easy to use and captures information quickly) or *infrared* (allows the colors of objects to be captured and does not cause reflections on shiny surfaces). A *laser scanner* makes projections of points or lines and a sensor measures the distance that separates it from the surface of the object. This type of technology is suitable for reflective or black surfaces.

Depending on the mode of use, 3D scanners are classified as fixed, portable or mixed. Fixed ones usually have more precision and are used for small objects. Portable units are characterized by having great versatility. Fixed-portable combinations allow for a wide range of possibilities as they combine the advantages of both modes of use.
The 3D scanning process consists of three phases:

Phase 1. Preparation of the object. In this phase, the part or geometry to be scanned is prepared with *reflective markers* or by using a *spray* to prepare the surface if the object is shiny, black or transparent. Reflective markers are small stickers or magnets with a circular reflective area in the middle with an external black ring that are placed on or around the object to facilitate the location of the object, allowing precise alignment of the scan data and providing high precision on large objects. The use of sprays allows bright, translucent or very dark objects to be prepared for scanning by applying a thin layer on the surface to prevent light distortion.

Phase 2. Scanning. During 3D scanning, massive point capture is performed to obtain a point cloud. The point cloud consists of millions of points positioned three-dimensionally, accurately forming a physical entity and representing a surface.

Phase 3. Post processing. In this phase, the point cloud is edited to correct defects, eliminate noise, fill gaps... and the mesh is edited to obtain a 3D model.

2.2 APPLICATION EXAMPLE AND RESULTS

To illustrate the use of a portable scanner in obtaining the model of an existing part we have considered the gear shown in Figure 1. It is a part of general purpose that can be found in multiple parts and systems of any marine facility. Table 1 shows the main characteristics of the part under study:

Nº Teeth	30
Material	PVC
Weight	158 g
Tooth Length	25 mm
Inner diameter	72 mm
Diametral pitch	75 mm
Outer diameter	82 mm
Addendum	3.5 mm
Deddendum	1.6 mm
Whole depth	5.1 mm
Circular pitch	7.8 mm
Space width	3 mm
Circular thickness	4.8 mm

Table 1. Gear characteristics

2.2.1 PART PREPARATION

In this stage, the gear has been placed in a rotating base (see Figure 1). Next, markers have been added on the part in order to obtain a position reference during the scanning process.

The rotating base has been used to capture as much information as possible from all the teeth of the gear. As the part has a dark finish, a spray has been used to make it easier to scan the details and markers have been added to have different references and to avoid loss of tracking (see Figure 1).

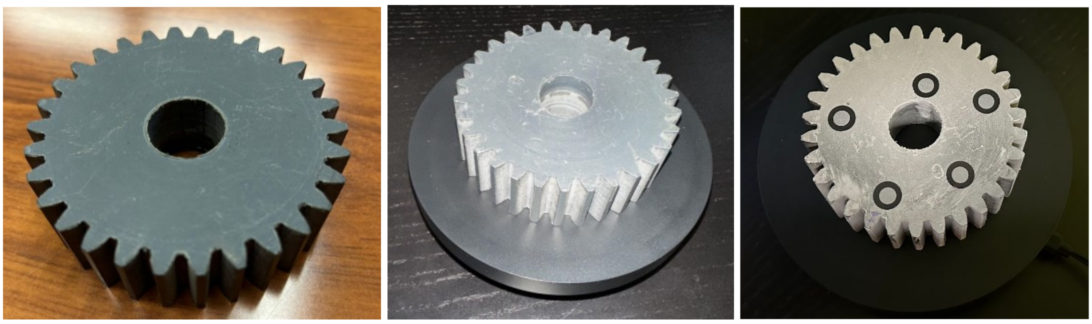

Figure 1. Study part, rotary base with 3d spray and makers

2.2.2 PART 3D SCANNING

In this work a Revopoint© Miraco 3D scanner has been used. The main features of this scanner include Quad Camera Infrared Structured Light, Fused Point Distance 0.05mm, Single-frame Accuracy 0.05mm, Scanning speed, up to 15 fps (Frame per second), Minimum Scan Volume 10 x 10 x 10 mm, Maximum Scan Volume 4000 x 4000 x 4000 mm, Working distance 100 - 1000 mm, 8k color capture (48 megapixel RGB Camera), Screen 2k AMOLED 180º, Battery 5000 mAh with fast charge, Weight 750g, 8 - core 2.4GHz Processor, 256GB Hard Drive and 32GB RAM.

For this example, the selected operation mode has been near mode with continuous scanning a general object type, high resolution and alignment by means of markers (see Figure 2).

The scanner has been placed over a tripod at a suitable distance from the part. The scanner screen shows at the top if the detection of the part is the most suitable, "excellent" in the example (see Figure 2). The scanner's near mode has been activated. The rotating base option has been activated so that it does not detect it at the time of scanning. The detection range has been adjusted, the highest accuracy and alignment by markers have been selected.

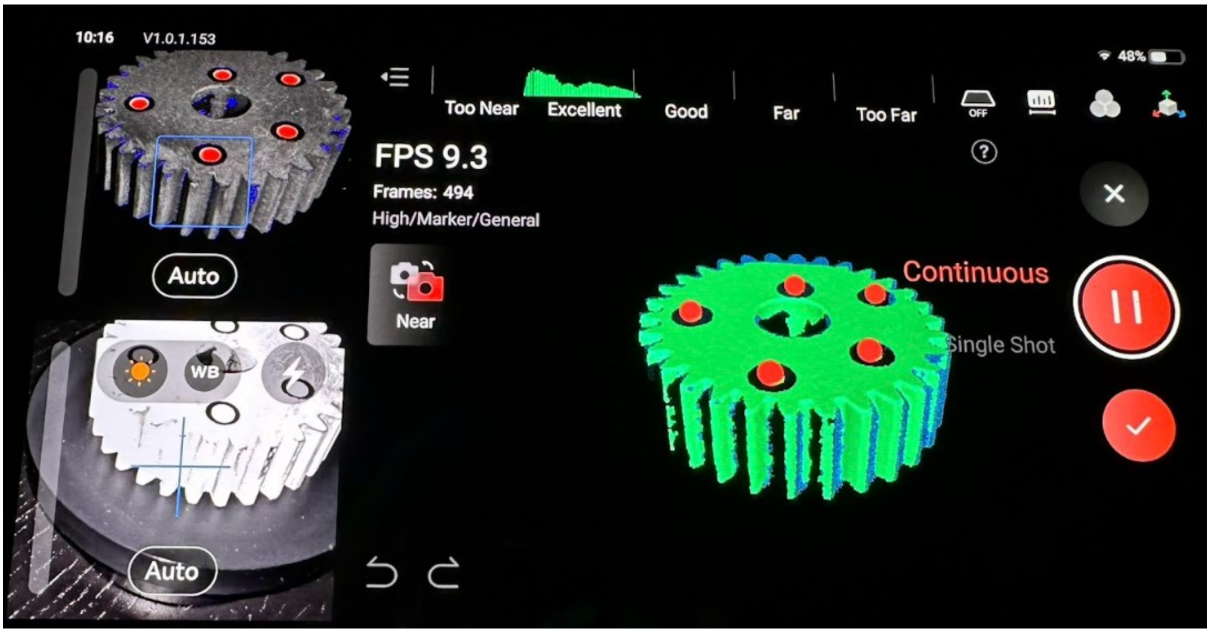

Figure 2. Scanning process of the part

As a result, a point cloud has been obtained (see Figure 3). However, in order to obtain the final mesh, a post processing stage is necessary to make the surface as uniform as possible.

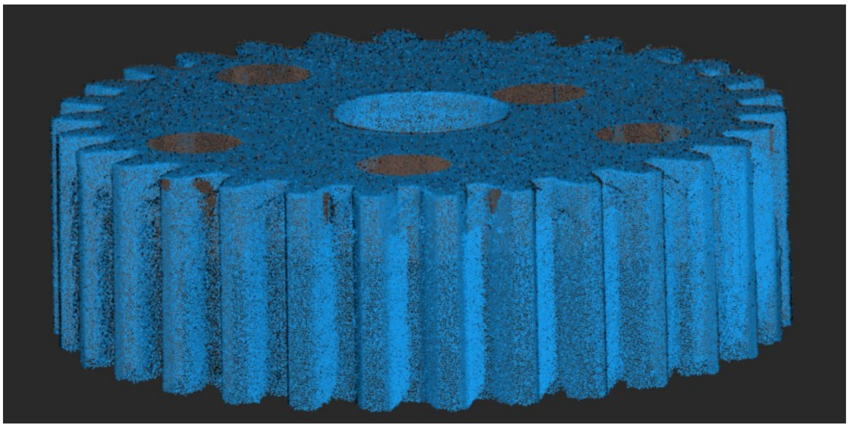

Figure 3. Gear initial point cloud

2.2.3 POST PROCESSING

For post-processing, the file is exported to the computer using the scanner manufacturer's program (Revo Scan 5), although the point cloud and mesh editing could be performed on the same scanner unit. Starting from the initial point cloud, a fusion processing is performed to obtain a more complete and accurate point cloud model. When we have the fusion done, we proceed to detect the points that do not have enough closeness to eliminate them, also overlapping points are eliminated and the point cloud is simplified to improve the processing and rendering speed. Once this procedure is done, we proceed to build the mesh of the gear (see Figure 4).

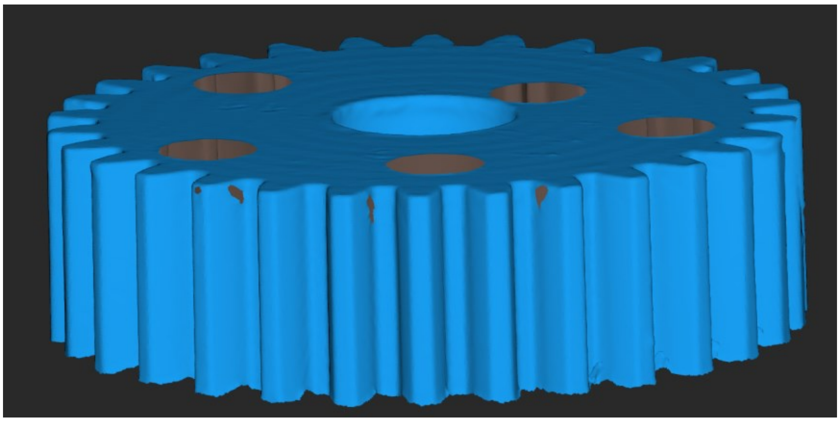

Figure 4. Gear meshing

When we have the first mesh, we proceed to eliminate the isolated faces of the model, fill the holes and missing areas of the model and simplify it to reduce the mesh size (see Figure 5). Once we have the edited mesh, we export it in OBJ format to the 3D software.

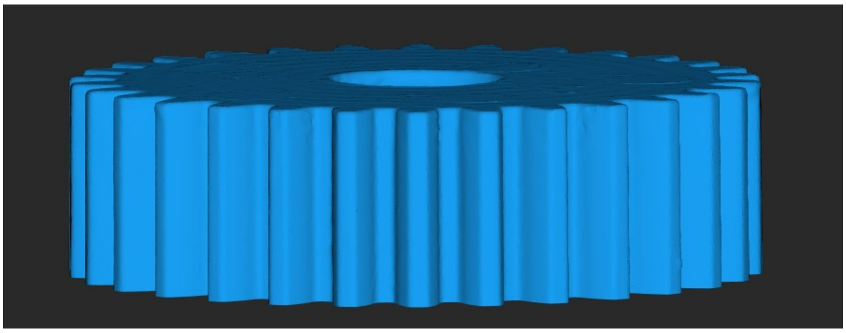

Figure 5. Edited Gear meshing

Once the final mesh has been obtained, a check of the tolerances between the original part and the obtained 3D model is performed. Then, the model can be considered valid or not. In the first case, it can be printed. In the second case, if it is decided to make any modification to the existing part, it can be exported to a 3D software to edit the existing mesh or obtain a different model from the scanned object. In the case study, we have exported the model to Rhinoceros© to finish the mesh, we have created a 2D plan of the gear and we have made an extrusion to obtain a volume (see Figure 6).

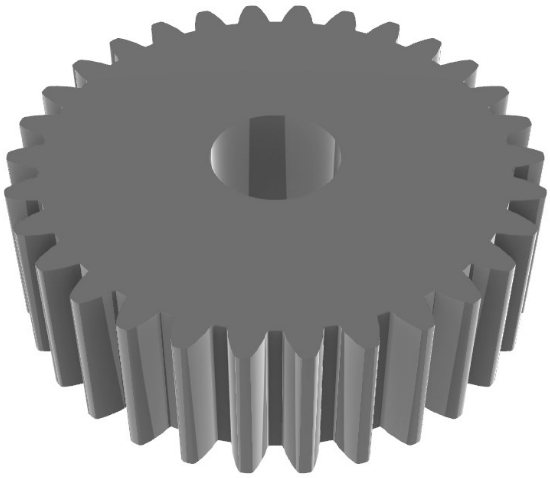

Figure 6. Render of the gear ready for 3d printing

3 ON BOARD 3D PRINTING

Once the model of the part is available, the crew can proceed with the 3D printing process. Several decisions have to be made, such as the part orientation and the material to be used. Next subsections present the printing details.

3.1 FUNDAMENTALS OF 3D PRINTING

3D printing is the process of creating objects by depositing layers of materials one on top of the other, also referred to as additive manufacturing (AM). The most common types of 3D printers are the following: Fused filament fabrication (FFF), also referred to as fused deposition modeling (FDM). continuous filament manufacturing (CFF), atomic diffusion additive manufacturing (ADAM). selective laser sintering (SLS), stereolithography (SLA), direct light processing (DLP), binder Jetting.

As the FFF process produces the part in a layered structure, mechanical properties of the part vary depending on orientation of the printing. Typically, the interlayer strength (Z) has the lowest strength in FFF.

There are materials that require post-processing at the end of printing to obtain their final properties, including *annealing*, *debinding* and *sintering*. Annealing consists in producing temperature ramps for both heating and cooling to improve the properties of the piece. To perform this procedure, a programmable oven will be required in order to program the appropriate temperature ramps for each part. Debinding is the thermal or catalytic removal of additives used in production steps. Sintering is the thermal treatment used to develop bonds between particles to obtain a solid object. In sintering, a part that is made of compressed and chemically bonded powdered material is called a green part. A brown part is created when a green part is heated and/or chemically treated to remove the binder that previously held the powder together. The brown part is then heated further to fully synthesize the part.

3.2 MATERIALS SELECTION

In the marine context, the proper material choice is of the utmost importance. In order to perform correctly it has to present adequate properties such as chemical and thermal resistance, hardness, impact resistance, and so on. Next, we present several materials that can either be used on land and in the marine environment. It should be taken into account that the technical data of each material may vary depending on the manufacturer.

Currently, the material that is most used on land is PLA (Polylactic Acid) which is a biodegradable plastic. It is very easy to print, does not produce smoke and allows very high printing speeds, so it allows to obtain prototypes in a very short time. However, it has very low resistance to impact, very low resistance to humidity and its deformation temperature is 55 ºC. For these reasons, materials with better properties will be required to withstand the marine environment to which they may be subjected.

Here we present some materials, from the great variety that can be found in the market, which can be multipurpose at the time of a repair, since during navigation there will be a limited amount of filament spools available. Each material is presented with the properties that make it adequate for marine applications. For more information see, for instance, (Ultimaker, 2023).

Plastic materials:

- CPE + (Terephthalic acid-based copolyester)
    - Excellent chemical resistance
    - Excellent temperature resistance
    - High hardness material
    - High impact resistance

- PAHT CF15 (High Temperature Polyamide carbon fiber reinforced)
    - High chemical resistance
    - High temperature resistance
    - High mechanical strength
    - Low moisture absorption

- TPU (Thermoplastic polyurethane)
    - Excellent chemical resistance
    - Low hardness
    - Good flexibility
    - High impact resistance

- PP (Polypropylene)
    - Excellent chemical resistance
    - High hardness material
    - Excellent fatigue strength
    - Low friction
    - High thermal resistance
    - High electrical resistance
    - High resistance to humidity

- PET CF (Polyethylene Terephthalate Carbon fiber-reinforced)
    - High chemical resistance
    - High temperature resistance
    - High mechanical strength
    - High stiffness

- The drawback of this material is that to achieve increased mechanical properties (+10% stiffness and +30% strength) and an improvement in temperature resistance (HDT of ~ 80 °C to HDT of ~ 180 °C.) needs annealing.

- PVA (Polyvinyl alcohol)
  - Water-soluble support material
  - Allows the creation of complex geometries facilitating the removal of supports

Thanks to its properties and flexibility, TPU is adequate for the design and printing of gaskets on a temporary basis, until a definitive replacement is obtained. On the other hand, the use of PET CF and its subsequent annealing, lead to very mechanically, thermally and chemically resistant parts. A programmable oven is required for the proper annealing.

Stainless steel materials:

- 17-4 PH stainless steel
- 316L stainless steel

The main difference between 17-4PH and 316L is that it has better mechanical properties at the cost of lower corrosion resistance.

Currently, FFF technology allows the printing of metal 17-4 PH and 316L parts. The only drawback of these materials is that the dimensions are limited (100x100x100 mm^3) since they require debinding and sintering to obtain the final properties of the part.

For this reason, in order to print in metal with its maximum resistance, we have two options: (1) to print a green part and send it to post-processing on arrival at port until its completion; and (2) to make the design on board and send it to a company specialized in 3D printing to be printed and post-processed.

Finally, with the use of the stainless metal filament, spare parts for gears, supports, hinges, etc., could be obtained in a certain period of time although it takes much longer compared to printing composite or plastic materials.

3.3 APPLICATION EXAMPLE AND RESULTS

In order to illustrate the details of the 3D printing procedure, in this section we present the procedure to obtain a duplicate of the gear shown in Figure 1.

The selected material has been CPE+ as it has very good mechanical, thermal and impact properties, allowing its use in applications that must resist wear. For the use of the case study part, its properties satisfy the necessary requirements for good performance. Since it is a material that adheres very strongly to the hot bed, a 3DLAC layer is added to prevent delamination of the glass bed.

The printing of the gear could also have been done with 17-4PH plus a post processing to obtain the desired properties as explained in the previous section. In such a case, the print cores should be changed, the ceramic support material should be added and the part should be oversized (the software does it automatically) since in debinding and sintering the parts end up shrinking.

The printing of the gear has been done with the Ultimaker S5 printer which has the following specifications: Dual extrusion for composites, 330 x 240 x 300 mm build volume, FDM printing technology (Fused Deposition Modeling), compatible filament diameter of 2.85mm, layer resolution (0.25mm nozzle: 150 - 60 microns, 0.4 mm nozzle: 200 - 20 microns, 0.6 mm nozzle: 300 - 20 microns 0.8 mm nozzle: 600 - 20 microns), Double gear feeder, reinforced for composite materials, print cores interchangeable, nozzle temperature 180-280 ºC, active leveling, heated glass plate.

The settings for gear printing are as follows: Layer height 0.15 mm, wall line count 5, top / bottom thickness 1.2 mm, filling density 100%, filling pattern grid, printing temperature 270 ºC, printing plate temperature 110 ºC, printing speed 30 mm/s, print cooling activated, adhesion type (edge).

Figure 9. Preview the gear in the Ultimaker Cura before printing with CPE+

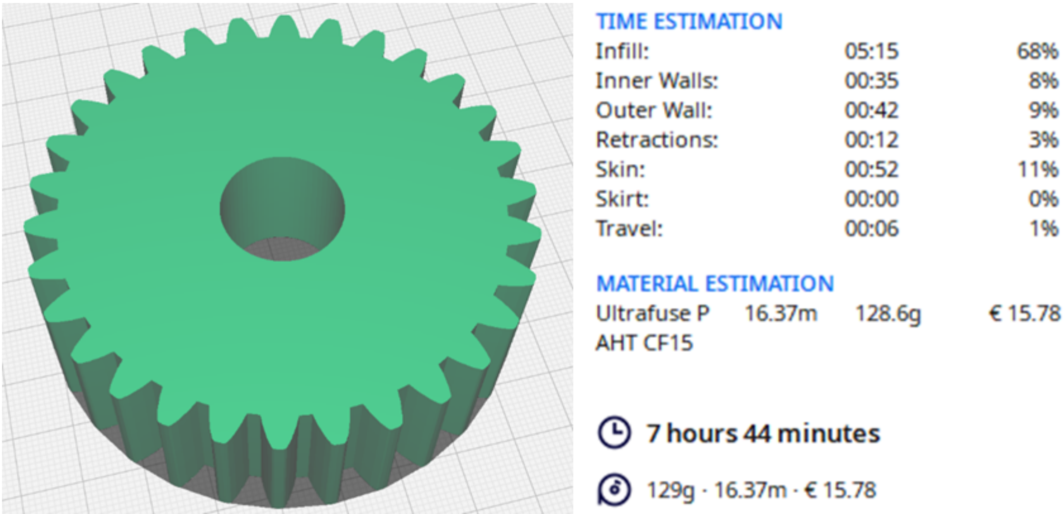

Figure 10. Preview the gear in the Ultimaker Cura before printing with PAHT CF15

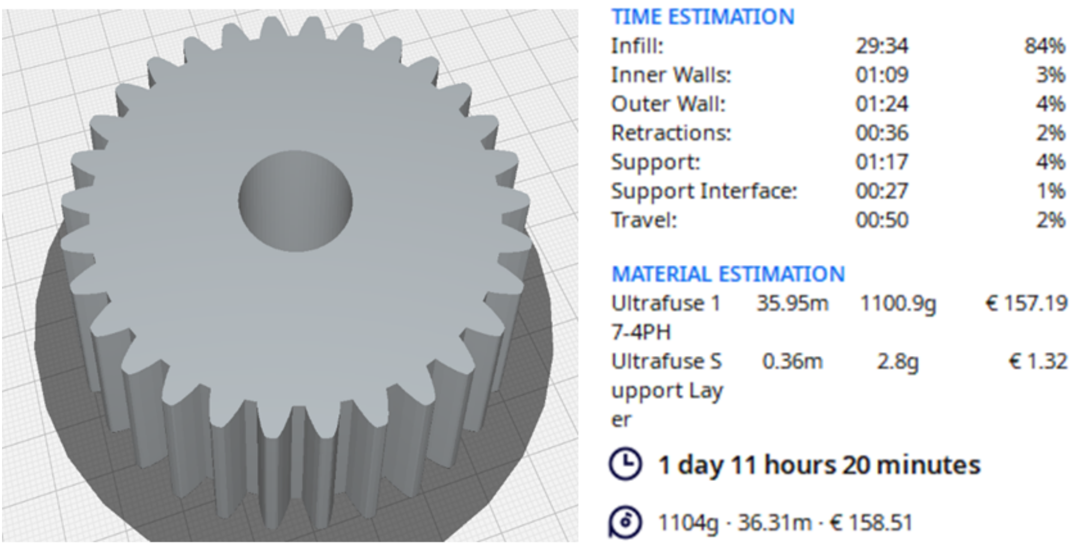

Figure 11. Preview the gear in the Ultimaker Cura before printing with Ultrafuse 17-4PH and Ultrafuse support Layer

Table 2 shows the print settings (profile, layer height, wall thickness, infill density, speed, support…). Depending on the material, whether it is plastic or metal, the costs and printing times vary significantly.

Material	Printing time	Estimated Cost (Material only)	Post Processing
CPE+	17h 25m	12€	-
PAHT CF15	7h 44m	15.8€	-
17-4PH	1d 11h 20m	158.6€	Debinding and sintering

Table 2. Comparison of gear printing with different materials

Apart from the final costs, in this case, if it is made of metal, a post-processing would be needed, which increases the manufacturing cost and the time to obtain the spare part. It should be taken into account that the costs mentioned above are only estimations of what the material would cost, not including the cost of the power needed for printing, wear of accessories, adhesive necessary for proper printing ...

In order to validate the result, a comparison has been made between the gear obtained by 3D printing and the original part (see Figure 10).

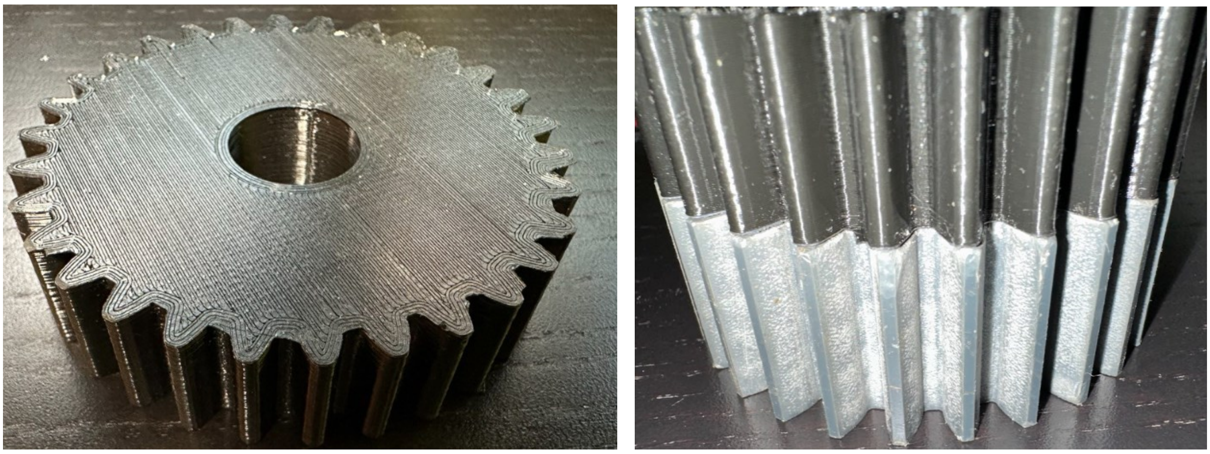

Figure 10. 3D printed part and comparison with the original gear.

As can be seen, the results obtained (except for the color since in this case it has been printed with black filament) are almost identical. To validate the result, once the printing is finished, it is important to perform a visual inspection to determine that there are no imperfections that may affect the operability of the part and check the dimensions to ensure that the difference between them is acceptable. In case the differences of the printed part are not acceptable, the model should be exported to a 3D software to make the necessary adjustments to ensure its correct operation.

4 CONCLUSION

The use of 3D portable scanners provides great versatility since combined with a 3D printing system allows them to perform on board repairs in a very short period of time. The use of a 3D scanner reverse engineers the components that need to be repaired and obtain a printable design for proper maintenance.

Additive manufacturing development has opened a wide range of materials with which we could work on board to make either new designs or repairs for corrective maintenance since we can work with a wide variety of plastics, composite materials and metal filaments. In this way, maintenance costs are reduced and the time it takes to affect the vessel's operability is reduced. With the use of the metal kit it is possible to reduce the costs of making small series compared to the existing traditional methods such as Computer Numerical Control (CNC), injection.... In this way the application of 3D printing on board a ship allows us to obtain spare parts with freedom at the time of designing the part, wasting less material at the time of manufacture.

In this work, once the scanning and 3D printing of the gear has been done, it has been found that it would require personnel with training in design, 3D printing and materials (since it is important to select the material depending on the use to be made of the printed part) because once the part has been scanned, it is possible that it may require some modification of the 3D model. These training could be done in the same training centers where the studies to become a ship's engineer officer are done.

In further studies it would be interesting to verify the correct operation of a FDM (Fused Deposition Modeling) printer on board, including the more suitable adjustments for its correct operation, how the vibrations and movements of the ship affect and how the marine environment will affect the components of the printer.

5 REFERENCES

Abbas, M. A.; Lichti, D. D.; Chong, A. K.; Setan, H.; Majid, Z.; Lau, C. L.; Idris, K. M.; Ariff, M. F. M. Improvements to the accuracy of prototype ship models measurement method using terrestrial laser scanner. *Measurement* [online]. 2017, vol. 100, p. 301–310. [Accessed: May, 2024]. Available at: https://doi.org/10.1016/J.MEASUREMENT.2016.12.053

Breddermann, K.; Drescher, P.; Polzin, C.; Seitz, H.; Paschen, M. Printed pressure housings for underwater applications. *Ocean Engineering* [online]. 2016, vol. 113, p. 57–63, [Accessed: May, 2024]. Available at: https://doi.org/10.1016/J.OCEANENG.2015.12.033

Heikkinen, I. T. S.; Kauppinen, C.; Liu, Z.; Asikainen, S. M.; Spoljaric, S.; Seppälä, J. V.; Savin, H.; Pearce, J. M. Chemical compatibility of fused filament fabrication-based 3-D printed components with solutions commonly used in semiconductor wet processing. *Additive Manufacturing* [online]. 2018, vol. 23, p. 99–107. [Accessed: May, 2024]. Available at: https://doi.org/10.1016/j.addma.2018.07.015

Kostidi, E.; Nikitakos, N. Exploring the Potential of 3D Printing of the Spare Parts Supply Chain in the Maritime Industry: Marine Navigation and Safety of Sea Transportation. In book: *Safety of Sea Transportation. Proceedings of the 12th International Conference on Marine Navigation and Safety of Sea Transportation* (TransNav 2017), June 21-23. 2017, Gdynia, Poland: CRC Press, 2017, p.171-178. [Accessed: May, 2024]. Available at: https://doi.org/10.1201/9781315099088-29

Mohammed, J. S. Applications of 3D printing technologies in oceanography. *Methods in Oceanography* [online]. 2016, vol. 17, p. 97–117. [Accessed: May, 2024]. Available at: https://doi.org/10.1016/j.mio.2016.08.001

Paoli, A.; Razionale, A. V. Large yacht hull measurement by integrating optical scanning with mechanical tracking-based methodologies. *Robotics and Computer-Integrated* Manufacturing [online]. 2012, vol. 28, no. 5, p.592–601, [Accessed: May, 2024]. Available at: https://doi.org/10.1016/J.RCIM.2012.02.010

Phillips, B. T.; Allder, J.; Bolan, G.; Nagle, R. S.; Redington, A.; Hellebrekers, T.; Borden, J.; Pawlenko, N.; Licht, S. Additive manufacturing aboard a moving vessel at sea using passively stabilized stereolithography (SLA) 3D printing. *Additive Manufacturing* [online]. 2020, vol. 31, article no. 100969, [Accessed: May, 2024]. Available at: https://doi.org/10.1016/j.addma.2019.100969

Ultimaker. UltiMaker PET CF annealing instructions: Annealing PET CF 3D printed parts. In: *Support.ultimaker.com* [online]. Jun 27, 2023, [Accessed: May, 2024]. Available at: https://support.ultimaker.com/s/article/000002925

Vujović, I.; Šoda, J.; Kuzmanić, I.; Petković, M. Parameters evaluation in 3D spare parts printing. *Electronics* [online]. 2021, vol. 10, no. 4, article no.365, [Accessed: May, 2024]. Available at: https://doi.org/10.3390/electronics10040365

Ziółkowski, M.; Dyl, T. Possible applications of additive manufacturing technologies in shipbuilding: a review. *Machines* [online]. 2020, vol. *8, no.* 4, article no.84, [Accessed: May, 2024]. Available at: https://doi.org/10.3390/machines8040084