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Review Article

Utility of 3D printing in ship repairs

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Abstract
With a growing focus on Sustainable Development Goals 2030, sustainability has become crucial in the shipping industry. Disruptive technologies like 3D printing can reduce manufacturing and operating costs, ensuring a robust spare supply chain for ships and offshore platforms. This technology can manufacture complex shapes, aiding in repairs and maintenance without requiring extensive cutting and welding. However, the unique and non-repetitive nature of ship repairs has hindered automation in this sector. This paper examines the utility of 3D printing in ship repairs, aiming to reduce repair costs and time while enhancing sustainability. The study shows that numerous advantages exist in using this technology in the shipping industry. However, its usage needs to be facilitated with adequate public awareness, preparation of procedures for manufacturing 3D printed parts, and standardization of 3D printers.

1. Introduction

In recent years, sustainability has become an important aspect in the shipping industry. Though the shipping industry is considered slow to change, due to economic considerations (Agarwala, 2022), disruptive technologies such as Information and Communication Technology (ICT), Block Chain, Artificial Intelligence (AI), Augmented Reality (AR), Internet of Things (IoT), 3D printing (Kantaros & Ganetsos, 2024), and 4D printing (material used for printing can change shape with time) (Kantaros et al., 2023a) have reduced manufacturing and operating costs and changed the way this industry operates, thereby forcing it to adopt new technologies (Jha, 2016; Tsaramirsis et al., 2022).

One such technology, 3D printing, allows individualized manufacturing using materials that are not petroleum based, thereby reducing manufacturing costs and encouraging rapid prototyping and sustainability. As a manufacturing process, 3D printing includes a number of operations and technologies that permit the production of numerous products using different materials. When used on an industrial scale, and with more advanced techniques, the procedure is called additive manufacturing (AM) (ISO, 2015). Even though the use of 3D printing has disrupted traditional manufacturing and revolutionized design due to its versatility, its true potential is still to be realized (Kantaros et al., 2023b).

The process is an 'additive' process that adds layers of material to build up products, as against the traditional method of manufacturing that involves 'subtracting' material from larger blocks of material. This makes the 3D printing process energy and material efficient, allowing the manufacture of components with intricate geometry and complex features. The final product is lighter and stronger, and hence has an improved operating life (Vafadar et al., 2021).

Greater accessibility to 3D printers has permitted the adoption of 3D printing in numerous systems, applications, and ancillaries. As a minimum, the process requires a 3D model (created by a 3D CAD model, photogrammetry, or 3D scanning). This model is then sliced to be read by a printer before layering begins, according to the design, with the process using plastics (Acrylonitrile Butadiene Styrene [ABS] or Polylactic Acid [PLA]), nylon, metals (aluminum and cobalt derivatives, stainless steel, gold, silver, and titanium), ceramics, or sand. However, in terms of materials and applications, no one solution fits all. One printer may utilize a light or heat source to melt or fuse the powder material in defined shape, while another may use light or heat from a laser to solidify the resin in thin layers. The most common process is deposition of PLA or ABS in filament form through a heated extruder to create a shape with layers. In this process, either a part or the entire object can be printed, thereby avoiding the need for assembly. Though the entire process may sound simplistic, it is not a plug-and-play process. It requires preparation prior to printing, which includes designing, file preparation, and conversion, all of which are complicated and time-consuming. Once printed, the part may require manual finishing through polishing, sanding, lacquering, and painting.

Over time, 3D printing has been tried out in various industries, such as the aerospace, medical, oil and gas, automotive, energy, architecture, rail, maritime, consumer product, and dentistry sectors, and many more (Rashid et al., 2020). In recent years, this technology has started to make inroads into the maritime industry, even though apprehension amongst stakeholders exist (Kostidi et al., 2023). It will not be long before this technology helps ensure a healthy spare supply chain management for marine assets (Kostidi & Nikitakos, 2017; Strickland, 2016). As the process can manufacture complicated shapes with ease, it can help repair and maintain complex structures without having to undertake cutting or welding, or having to maintain an extensive spare inventory.

It is with this understanding that this paper aims to look at the utility of 3D printing for the repair of ships, in an effort to reduce repair cost and time while ensuring sustainability in the shipping industry. To do justice to this discussion, the paper begins with a brief introduction. It then discusses the 3D printing technology in general, before undertaking a literature study of its use in the maritime industry. This is followed by discussing the use of the technology in ship repairs, along with a case study, followed by investigating the limitations the technology faces. A discussion and planning of the way ahead are next, before the paper is concluded.

2. Understanding 3D printing

Digitalization, at the core of the disruptive technologies of Industry 4.0, has allowed the creation of physical objects using successive addition of materials (ISO, 2015), called 3D printing or additive manufacturing. Since the process directly uses computer-aided design (CAD) drawing, it permits user involvement for design refinement and easier transfer of design changes to the actual product, thus making the technology versatile. However, being easy to use, it is considered a dangerous technology, as items such as knives, guns, and counterfeit items can be printed without the knowledge of law enforcement agencies.

The technology and materials for 3D printing were developed in the 1980s using an STL file for printing software (Shellabear & Nyrhila, 2004). Subsequently, digital slicing and infill strategies were provided by Chuck Hull in 1984 (Prinz et al., 1997). Since then, numerous techniques have been proven to be effective. Today, the ASTM Standard F2792 catalogues these techniques into seven groups (ASTM, 2012), as seen in **Figure 1**. The main difference in these techniques is the way layers are built to create the final object. The widely used processes include melting and softening to produce layers, or using liquid material during printing (Wang et al., 2017). Other processes used are as seen in **Figure 2**.

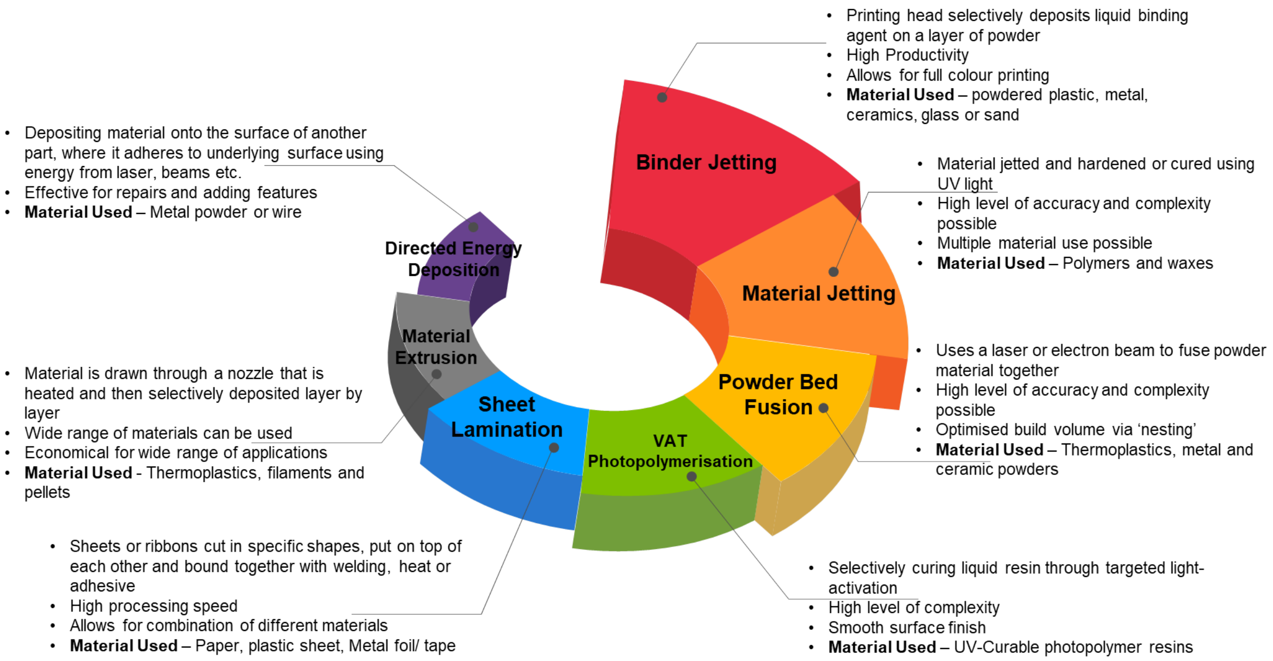


Figure 1 Standardized categories of different techniques used in 3D printing (Source: Author).

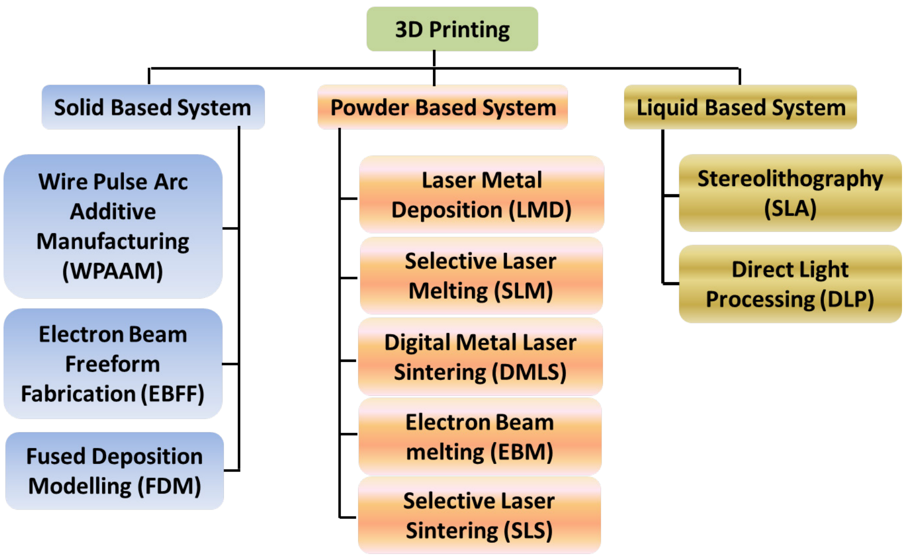


Figure 2 Types of processes used in 3D printing (Source: Author).

Like any manufacturing process, 3D printing too requires high-quality materials to build high-quality products. These may be of ceramic (Al_2O_3, ZrO_2, LiO_2, SiO_2, SiC, Si_3N_4, and PZT), metallic (gold, silver, stainless steel, and titanium), polymers (nylon, resin, polylactic acid, polyethylene terephthalate, high impact polystyrene, acrylonitrile, and butadiene Styrene), and their combinations in the form of hybrids, composites, or functionally graded materials (FGMs) (Sayed et al., 2017).

3. Comparing properties of additive manufacturing and traditional manufacturing

A general comparison of the additive manufacturing and traditional manufacturing can be seen in **Table 1**. Of these, additive manufacturing uses a combination of various process parameters, such as filler material, temperature, speed, layer thickness, power, hatch spacing, build orientation, nozzle diameter, and infill density, to name a few. Each of these parameters, individually and in combination, has a significant effect on the mechanical and tribological property of the 3D printed part (Rouf et al., 2022; Chand et al., 2021). Hence, even if one parameter is changed, the resulting properties of the printed part would be different from the previously printed part. This makes it imperative to formulate standards and set parameters for printing a specific part for a particular application that is optimized for a target application. Such an optimized set of parameters can provide a part that has better strength to weight ratio and desired mechanical, electrical, and functional properties. This factor disallows a direct comparison of the properties of a part manufactured using AM and of those of a part manufactured through traditional processes. To add to this, the 3D printed parts are subjected to post processing, such as sanding, gap filling, polishing, annealing, epoxy coating, and metal plating that significantly change their mechanical properties (Kantaros et al., 2024). In such conditions, comparing a product manufactured from AM and traditional methods become even more challenging (Zisopol et al., 2022).

Table 1 Comprehensive comparison between 3D printing technology and traditional manufacturing technology (Hadhsefat & Tingting, 2020).

	3D printing	**Traditional manufacturing**
Processing principle	Layered printing Layer by layer overlay	Traditional
Product material	Plastic, photosensitive resin, metal, etc.	Almost all materials
Processing environment	Good Environmentally friendly	Bad
Material utilization	More than 95 %	Low and wasteful
Product strength	Relatively low	Good
Input costs	Low	High
Applicable industry	Molds, toys, prototypes, etc.	Unlimited
Production cycle	Short	Long
Production scale	Single or small batch	Large-scale, high-volume
Green manufacturing	Yes	No, quite difficult to achieve
Production operation	Simple and safe	Complex and dangerous
Requirements for employees	Less demanding	Need for professional knowledge
Production equipment	No specific production environment	Need a production workshop

While this absolute definition of comparative properties is considered difficult and job specific, some studies have been reported in this area. Natali et al. (2019) in their study of the mechanical behavior of 316 thin stainless steel sheets made by using cold rolling and additive manufacturing, compared the results. For expected values of ultimate tensile strength (UTS) of about 625 MPa, Yield Strength of about 290 MPa, and elongation of about 70 %, thickness values as observed are as seen in **Table 2**. One notices that AM steel displays a higher yield strength and lower elongation, with the mechanical properties not depending on the thickness of the sheet.

Table 2 Mechanical properties of 316-stainless steel produced by additive manufacturing (3D) and cold rolling (longitudinal direction).

Thickness (mm)	UTS (MPa)		Yield Strength (MPa)		Elongation (%)	
	AM	Cold rolled	AM	Cold rolled	AM	Cold rolled
0.8	578.1	638.5	471.7	300.1	24.9	67.0
0.5	569.2	619.3	440.1	266.4	24.9	65.5
0.3	569.7	645.5	428.3	298.7	18.1	61.2

4. 3D printing in the maritime industry

Serious interest of stakeholders to use 3D printing in the maritime industry was first seen in 2015, when a consortium of 27 port-related companies of the Port of Rotterdam initiated a study to determine the advantages and economic viability of the 3D printing of parts for marine applications (Port of Rotterdam, 2016). Since then, a number of researchers have studied the benefits of using 3D printing in the maritime industry. These studies have analyzed response time, inventory reduction, and reduced transportation costs (Knulst, 2016), downtime of ship systems with and without 3D printing on board (Vujovic et al., 2015), influence on spare parts management (Pour & Zanoni, 2017), and social implications (Jiang et al., 2017). In addition, they have allowed 3D printed objects to be used on an experimental basis in the marine environment. Accordingly, a titanium variable ballast tank to map the Arctic seabed, an aluminum keel for a custom built yacht, an underwater scooter, a variety of boats (Amelia, 2021), and other maritime (Nickels & Fowler, 2017) and oceanographic (Mohammed, 2016) areas have been 3D printed. Such versatile use was possible only with supporting research on stainless steel 316L (Calle et al., 2020) and composite material for inter-laminar fractures (Goh et al., 2022), tensile strength (Tanikella et al., 2017) and mechanical characteristics (Luis et al., 2019).

Research has also been undertaken on dependencies between printing time, material lengths, and infill density (Vujovic et al., 2021), the influence of infill density on microstructure and flexural behavior (Aloyaydi et al., 2019), and strength as a function of infill patterns, rather than of infill density (Saniman et al., 2020).

The feasibility study of 2015 called *3D Printing of Maritime Spare Parts* was aimed at determining the advantages and economic viability that eventually led to the development of *RAMLAB* (Rotterdam Additive Manufacturing Laboratory) to create digital manufacturing infrastructure to design, produce, and repair parts on demand and change the way ports handle spares for ships. Similarly, in an effort to reduce the number of marine parts scrapped, PJ Diesel and a group of partners studied if 3D print technology can repair and recondition such parts (Green Ship of the

Future, 2017). Recognizing that 3D printing technology is a disruptive technology, a joint industry program (JIP), along with DNV-GL, was launched in Singapore in early 2019 to develop a concept for the future supply chain of AM spare parts (Kandukuri, 2019). This study aimed at establishing the potential of 3D printing in the maritime industry using the procurement and supply data from ship owners, ship management, and ship equipment suppliers. However, issues such as the diverse nature of the maritime fleet disallowed a holistic perspective of the maritime industry, while the varying data management systems of companies created unforeseen errors in the collected data and the analysis that followed.

Though the viability of 3D printing for the maritime industry has been ongoing for over 25 years (Kostidi & Nikitakos, 2017; Strickland, 2016; Housel et al., 2015), it is still planned to be used extensively in the shipping industry. Once implemented, this technology is likely to replace several traditional manufacturing technologies, allow the development of intelligent sensors (Sullivan et al., 2020), and revolutionize the availability and delivery of marine spares by incorporation of design changes quickly. Eventually, this would help reduce the cost of spares, reduce transportation and delivery time, minimize delays and, in some cases, even personalize the part to customer needs (Mecheter et al., 2022; Kostidi et al., 2021). The related activities, however, involve expensive processes that are feasible only with trained manpower, well laid out procedures, and specific materials. Accordingly, in 2019, the University of Maine in the US showed that 3D printing could be used to manufacture boats (Carlota, 2019). Even though 3D printing technology is not well-suited for small boat manufacture, it is still being used (Peterson, 2022). Today, 3D printing is used extensively in Greece to manufacture boats at nearly three times faster a speed than conventional means (Mélanie, 2022).

5. 3D printing for ship repairs

For ships, some components can be manufactured quickly and inexpensively using 3D printing. For critical components, the process becomes complex for want of high reliability and maintainability, with the complexity being dictated by where the component is to be used.

For *merchant ships*, the major thrust in the use of 3D printing has been ashore, with several efforts by industries and academia being reported from time to time. Of these, the Netherlands-based *RAMLAB* uses a six-axis robotic arm to fabricate shipbuilding components for small and large ships, while the Danish company *Create it REAL* is looking to use 3D printing onboard using their proprietary 3D printing platform integrated with any Fused Filament Fabrication (FFF) 3D printer and sophisticated file encryption to ensure Intellectual Property (IP) rights protection (Startus, n.d). Wilhelmsen and Thyssenkrupp, duly endorsed by DNV and supported by OEMs, has created a manufacturing partners network to offer a resilient and traceable supply chain for manufacturing customized components on site using 3D printing (Wilhelmsen, n.d). To ensure minimum downtime of ships and repairs through part replacement at sea, UConn Engineers have created a device using ceramics applied to 3D printing metal parts to record degradation of the component due to overheating before producing a replacement component when failure is detected (UConn, 2017). Similarly, to ensure that Russian icebreakers remain operational while working in the Arctic Sea, the third largest Russian oil producer, *Gazprom Neft*, through their internal research, has produced metal 3D printed parts to support the repair and refurbishment of the equipment of their icebreakers and bunker vessels while at sea. The company is working to certify these components for quality and compliance under the standards of the Russian Maritime Register of Shipping (Tampi, 2020).

On the other hand, for *naval ships*, in an effort to shorten supply chains, reduce use of material and energy, reduce repair costs, and improve both defect identification and rectification for improved availability of ships and submarines, the use of 3D printing has been experimented with by the US Navy since 2014 (Department of Navy, 2017). Accordingly, they are working to identify components and develop procedures for the building, qualifying, and delivery of components made from metallic fillers to address the unique needs and requirements of the Navy, while ensuring the availability of the requisite infrastructure of hardware and human resources (Naval Sea Systems Command, n.d). The US Coast Guard, on the other hand, has been using onboard 3D printing since 2013. Today, five of their ships have 3D printers to create spare parts that are normally not stocked and are difficult to source (Allen, 2017). In Europe, this effort is limited to plastic components alone (EDA, 2018) and their defense sector is yet to exploit the true potential of 3D printing (EDA, 2018).

Since the components used on naval ships need to pass stringent tests for material, welding, shock, vibration, hydrostatic, and operating constraints, it becomes prudent to first create a prototype and use it on a trial basis for a stipulated time before removing it and analyzing and inspecting it for residual life and performance. This eventually provides the requisite confidence to the user and the maintainer alike, thereby ensuring a serviceable platform at sea.

It is important to mention that a component manufactured through ‘subtractive’ technology has a uniform microstructure and, hence, guarantees a uniform performance characteristic which is not the case with ‘additive’ technology, as the component is developed layer by layer, wherein the shape may be guaranteed, but the material properties may not be. To address this limitation, the USN has begun using AI to make adjustments to the 3D printing process to match the required material quality (Pappalardo, 2018).

While the efforts discussed here look impressive, they are one-off efforts, and cannot be considered an industry norm. This can be attributed to the fact that the shipping industry grapples with numerous issues and concerns for adopting 3D printing for its use. However, with a growing thrust towards Circular Economy, it is opined that the adoption may be hastened (Silva et al., 2023). How fast the adoption will be is something that will only be shown over time. Some institutes that are encouraging 3D printing in the maritime sector include (Bergsma et al., 2016):

- A 2015 feasibility study that allowed the Port of Rotterdam to develop their Wire Arc Additive Manufacturing (WAAM) 3D printer under the RAMLAB project.
- In July 2015, Hyundai Heavy Industries Co. Ltd. (HHI) opened its Hyundai Large Scale Key Parts Centre in Ulsan to produce 165 key parts through this technology.
- The China Shipbuilding Industry Corporation (CSIC), Research Centre has been researching Powder Bed Fusing since 2014. Today, they have their own version of Powder Bed Fusion, and are expanding their research facilities in the area of AM materials in Kunming and a technology center in the Yunnan province.
- The Singapore Investment and Centre for 3D Printing at Nanyang Technology University is focusing on large joints, high aspect ratio structures, and large scale repair in the Marine and Offshore industry.

To adopt 3D printing onboard ships, the process needs to be customized to meet technical specifications as mandated for ships and ensuring that the shipyards, repair yards, manufacturing partners, and associated workforce are aware of the technology, its versatility, and the possible scope of usage (Phillips et al., 2020). Subsequently, this technology will need to be extended to the platform to address defects and provide higher reliability during deployments.

While there are no short cuts to success, to ensure the use of 3D printing for ship repairs, the following steps need to be implemented.

- Develop capability to qualify and certify 3D printing components.
- Provide education, training, and certifications for the workforce.
- Enable end to end process integration of on-demand manufacturing, with integrated digital 3D printing data, infrastructure, and tools.
- Develop business practices and contracting, intellectual property, legal, and liability guidance.
- Enable manufacturing agility in maintenance and operational environments.

6. Case study

3D printing has been used for a wide range of applications that includes robotics, automobiles, firearms, medicine, space, the replication of marine organisms for conduction biomechanics, hydrodynamic and locomotion studies, and various oceanography studies (Mohammed, 2016). In the maritime domain, it has been used for manufacturing prototypes of unmanned underwater vehicles (UUV), ship models for conducting towing tests, boats, propellers for boats, and variable ballast tanks (Bayramoğlu et al., 2019). For smaller items, the technology is available for auxiliary components of ships and spare parts of pumps, valves, heat exchangers, engines, propellers, and catalyzers.

While information on initiatives for the use of 3D printing exists, there are no published case studies of real time use of this technology in the maritime sector, especially onboard while at sea. Though there are many success stories of this technology from the aerospace and other industries, they cannot be replicated in the maritime industry, owing to this industry's peculiarity (Green Ships of the Future, 2016). Information available for the maritime industry shows that this technology has been used for non-load bearing parts such as plastic syringes, oil tank caps, model planes required for flight deck mock-ups, nozzles for powder fire extinguishers, lever knobs for lathes, or handrail brackets (Kostidi & Nikitakos, 2017; Ziółkowski & Dyl, 2020), with the manufacture of some bigger components to study the possibility of implementing 3D in shipbuilding (Ziółkowski & Dyl, 2020).

Case study. While case studies of actual use of 3D printing for repairs in ships are elusive, one case study, published in the Russian language, discussing the use of 3D printing in ship repair (Dektyarev et al., 2019) is deliberated here. The study pertains to the repair of a ship's automatic firefighting system- 'BARK-M'- used in the Project 11356 class of ships. The BARK-M uses a sensor which has increased moisture resistance and has sealed cable entries to allow its use in the marine environment. However, the sensor consists of delicate parts which are susceptible to damage during transportation and installation, especially the cap (the transparent part in **Figure 3**). This cap is not available as a spare, and is available only along with the full sensor. Hence, if this part is damaged, the entire assembly would need to be dismantled. Statistics show that one out of 5 - 6 such protective caps get damaged, and the cost of replacement of the sensor is nearly 4,000 rubles. To save money and replace the broken part, the JSC PSZ, Yantar shipyard decided to use 3D printing, since the part was not load bearing and did not require certification from a classification society. Accordingly, the drawing was prepared and the cutting of layers was defined before manufacturing the part on a Tevo Tornado 3D Printer using two materials, SBS and PLA plastics, as seen in **Figure 4**. The printing of one sample took about 60 minutes with 15 g or 4 m of plastic thread. The cost per sample, without cost of electricity or wear of machinery, was calculated as 23 rubles for SBS, and 32 rubles for PLA plastic.

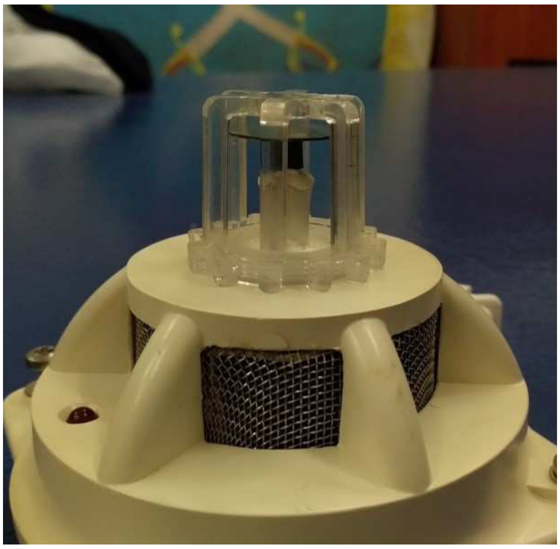
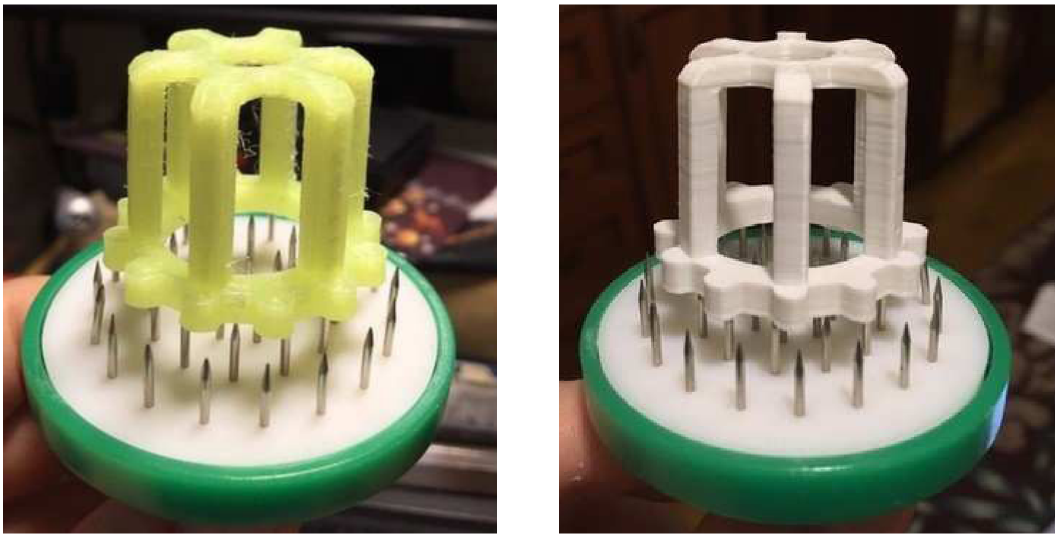


Figure 3 BARK-M sensor.



With SBS plastic With PLA plastic

Figure 4 Spare manufactured using 3D technology.

It is important to mention that, while the product has been successfully manufactured at a much lower cost and with ease, it was only possible due to it not being a load bearing member and not requiring a mandatory classification certificate.

7. Limitations

While 3D printing is a disruptive technology with a huge potential, digitization of spare parts is a challenge as there is *no defined procedure* to make a 3D printed version of an original part. This thus makes the entire process complicated. Though van Oudheusden et al. (2023) have provided a framework to produce spare parts, using literature review and experimental study, the process is iterative and prone to incorrect implementation. In general, for using 3D printing successfully in repairs, first, the fault has to be identified. Then, multiple iterations are performed to produce a part with the correct performance and fit. Since a 3D part performs differently than the original part, it cannot be merely replicated, and requires iterations to arrive at the correct requirements for the required performance. To define what can be replicated and what cannot be with 3D printing is yet another challenge. Similarly, while use of incorrect steps results in a failed part, it is not necessarily correct that following the correct step would provide a part with the acceptable standards to be a successful replacement.

The potential and the downside notwithstanding, *understanding and acceptance* by the maritime industry of 3D printing is still in its nascent stages. While the concerns are appreciated, it is essential that the limitations of this technology are understood by all to appreciate the current bounds of this technology, to avoid discarding it as ineffective. It is important that efforts to overcome limitations are channelized appropriately to improve the technology, and make it the future go-to technology for repairs.

Currently, with *limited development of additive technologies* such as 3D printing, the traditional reductive technologies are considered to be at least one magnitude superior (3D Hubs, n.d). However, additive technology, when combined with other technologies, can achieve the required specifications desired by the industry, as seen in **Table 3**. Yet another limitation of the additive technology is that the cost of the material, consumption of energy, and the time required for processing and post-processing are all high and need to be addressed. Despite this, 3D printing can be effectively used in the following cases.

- To manufacture the first parts/ products to reduce the high initial investment involved in traditional manufacturing technologies.
- To achieve similar benefits when the volume of product to be manufactured is small.
- When the product is custom made or personalized.
- When it is impossible to manufacture a product being developed by conventional technologies.

Table 3 Characteristics of additive technology (Source: Author’s compilation).

	Advantages	**Disadvantages**
Complexity	Can render geometries of great complexity, including with cavities and other forms.	Lack accuracy Accuracy is ± 0.X00 mm for additive and 0.XX0 mm for subtractive
Lead time	Short lead time, especially for first time manufacturing, as part can be generated from a 3D file.	Are slower and, hence, expensive.
Customization	Can manufacture modified/ customized parts with ease.	Range of available materials that can be used for manufacturing is limited.
Initial cost	Low fixed cost associated with product development and for the first manufactured product.	Lacks quality and procedures and rules for certification.

8. Discussions and way ahead

'But for the nail, the war was lost' is a well-known proverb. It goes without saying that non-availability of the correct spare at the right time can hamper the operational availability of a platform at sea, be it for trade or for war. It is because of this that ship-operators ensure that the required spare is made available to the seagoing platform at the earliest, even if it requires extensive transportation. To encourage easier and timely availability of spares, technologies such as 3D printing represent a paradigm shift by providing greater capability and flexibility. The task at hand becomes simpler with advanced scanning technologies without the need for original manufacturing drawing. Such flexibility allows not only repairs, but development of new products, thereby bringing about a disruptive change in the existing design and manufacturing industry. In effect, this technology has provided unprecedented capacity and autonomy to the maintainer, without depending on the supply structure and logistics that invariably are cost and time prohibitive. Today, the maintainer has the option to not only manufacture a new part, but can also look at refurbishing a worn out part using 3D printing, thereby encouraging adoption of Circular Economy in the shipping industry.

While this manufacturing technology has made numerous advances, for the shipping industry, it has begun making inroads in recent years. For use onboard ships, especially for critical components, additional work to conform to the required material properties is a work-in-progress which will need to be refined with adequate support from the classification societies to ensure the acceptance of the part manufactured using this process. The technology is here to stay, and would only make further improvements. Hence, in order to ensure its adoption, it is essential that requisite and appropriate standards and rules be defined for both the process and the tests to prove efficacy of the manufactured product. To date, DNV-GL (Junghans & Govindaraj, 2022), RINA, Lloyds Register, and ABS have developed classification rules for acceptance of parts made using additive manufacturing. In doing so, a well laid out procedure to be adhered to while manufacturing 3D printed parts for use onboard needs to be laid out to ensure adherence of the required properties and seamless grant of approvals by the classification societies.

When using onboard, there are some inherent limitations that need to be adequately addressed. These limitations include the slow printing speed, the necessity to carry sufficient and correct type of print material, the inherent weakness of printed parts, and the sensitivity of the printer to power fluctuations (Gardner, 2021). Furthermore, the available 3D printing techniques are not suitable for all materials, as specific materials need specific printers (Kantaros & Dimitrios, 2021). Eventually, when the technology is ripe, a variety of industrial 3D printers may be required for various jobs. In order to avoid a large inventory of printers and their obsolescence management, it is essential that some broad policy guidelines are developed and promulgated, as done in the IT industry.

Today, when comparison of the additive technology is made with traditional technology, it is done without considering the overall cost of operation impacted. If the latter is considered, it will provide an improved comparison of the advantages additive technology provides over traditional manufacturing. It is prudent to mention that, as the additive technology improves, the cost of manufacture will go down exponentially, wherein it will become a serious contender for the existing norms and systems of design and manufacture. While this happens, there is a need for greater awareness about the process for greater acceptance of this technology.

Some areas that need greater scholarship include study of speed adaptation algorithms to account for horizontal changes, the nature of trajectory to be followed, and the additional distance to be covered while printing to optimize the surface quality and mechanical resistance of the part being manufactured (Silva et al., 2021). Additionally, influence of actual ship motions and vibrations in a seaway on the 3D printing process, especially when vibration dampers in printers cater for printer-generated vibrations and not environmental ones, is considered essential (Vujovic et al., 2021). These future study areas are, however, not considered absolute, as the technology is developing on a daily basis, and new study areas are bound to spring up regularly. With a major thrust towards sustainability, especially in the shipping industry, technologies such as 3D printing will find support from policymakers, developers, users, and the industry.

To facilitate adoption of 3D printing in ship repairs, understanding and acceptance of this technology is considered critical. Such awareness will emerge only if the industry and the stakeholders invest in training programs, establish partnerships with 3D printing technology providers, and conduct pilot projects to demonstrate the viability of this technology. This awareness would encourage greater realization of the unsustainability of current subtractive manufacturing technologies and the need of adopting sustainable technologies such as 3D printing for a healthier planet.

Some specific actionable recommendations to encourage adoption of 3D printing in ship repairs are:

(a) Increase public awareness by providing avenues and opportunities for training.

(b) Classification societies to develop procedures for manufacturing 3D printed parts. This will create greater confidence in users to print and use these parts.

(c) Increase scholarship to optimize surface quality and mechanical resistance of printer products.

(d) Industry standards for 3D printers to be defined to ensure compatibility and interoperability for easier maintenance and upkeep.

9. Conclusions

Use of 3D printing for ship repair would impact the need to procure spares from foreign OEMs, thus reducing reliance on foreign supply chains. In some cases, OEM involvement may still be necessary for drawings and filler materials, which will eventually encourage greater innovation to manufacture impossible shapes through 3D printing. In addition, 3D printing will facilitate maintenance of obsolete products, for which OEM support and spares is an issue. However, concerns regarding piracy of Intellectual Rights (IR) rights may need to be addressed (Ballardini et al., 2018). The technology will encourage new businesses and opportunities in the form of professional services such as production of 3D printers, product designers, printer operators, material suppliers, and legal help for IP issues. All in all, it will encourage local manufacturing to make the nation self-reliant, while creating an imbalance of export and import between countries and loss of manufacturing jobs in countries where outsourcing happens.

In order to make the use of this technology a reality, the most critical requirement is to ensure that the owners, users, and maintainers of ships are able to adapt their supply chain to incorporate this technology. This adoption needs to be adequately supported with awareness, training, and knowledge of users and operators in the field of 3D printing and AI. As this technology looks to diversify into a 4D technology, using nanotechnology and robotics, the focus will shift to sustainability and environment friendly products. Eventually, autonomous ships identifying a malfunction, printing and replacing a spare using robotics without human intervention, is not far off. To realize such a future, development of technologies such as 3D printing are considered a must.

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