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Emerging technologies: Impact on shipbuilding

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ABSTRACT
Developments in the field of three-dimensional (3D) printing, autonomous ships and green technologies in recent times have drawn the attention of the shipping world. Each of these technologies has already been through decades of the development phase and now offers diverse applications across sectors. This paper examines each of these technologies from its inception to its impact on the shipbuilding industry, both warship and mercantile marine. Early impacts on shipbuilding are noticeable in refit and repairs, retro-fitments and logistic chain improvements. On-board/next port of call 3D-printed spare parts, tools and accessories are becoming increasingly common. Effective use of this technology to manufacture "one of a kind" steel parts or smaller and complex parts are facilitating substantial cost and time reductions during refits, repairs and retro-fitments. In the run-up to a fully autonomous ship, systems with increased autonomy are available as upgrades. Implementation of green technologies to conform to international regimes is increasing the scope of work of the refits and upgrades. Eventually, as newer hull and system designs mature and complete sea trials, the impact will be felt in new constructions and shipbuilding trends.

KEYWORDS
technology; shipbuilding; 3D printing; autonomous ships; ballast water management; LNG fuelled ships

Introduction

The technology world is abuzz with the news of the first-ever successful transplant of a three-dimensional (3D)-bioprinted thyroid gland in a mouse and the possibility of printing human organs, completion of the first round-the-world flight by *Solar Impulse 2* without the use of fuel and the debut of the world's first self-driving taxis in Singapore. Each of these is not an isolated instance of technological innovation but, rather, a manifestation of underlying emerging technologies which have been under incubation of development for decades and transcend across all sectors – shipbuilding inclusive. A small quadcopter largely made using an on-board 3D printer was flown around the hangar deck on board the USS *Essex* (LHD-2).[1] A broken wheel gear of the transmission system of the engine was repaired on the PLA Navy ship *Harbin*, a 052D-class destroyer deployed in the Gulf of Aden, utilising the on-board 3D printer.[2] The *Sea Hunter*, a 132-foot trimaran, which is the first of the class of an Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) programme of the US Navy, designed for autonomous open-seas deployment for extended duration, achieved a maximum speed of 27 knots during sea trials.

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Emerging technologies trigger clusters of innovations, introducing newer products in the global market. These products stimulate demand, increasing the volume of international trade. Sea-trade and shipbuilding follow a growth trajectory since they are major constituents of the "modern world economy" and a "globalised world order". Whilst increased demand on shipping translates to growth of the shipbuilding industry, the contemporary technologies also modify and modernise shipbuilding itself. This has been a consistent pattern in the post-industrial revolution era.

In 1913, Jacob Van Gelderen, a Dutch economist, concluded that there exist 50- to 60-year "cycles" or "periods" of long-term global economic prosperity driven by rapid growth in one or more leading sectors. The theory of major economic cycles of approximately half a century was also postulated by a Soviet economist, Nikolai Kondratieff, in 1925, and these "waves" have since been named after him. Joseph Schumpeter's subsequent study of business cycles extended and upgraded the phenomenon, linking it to temporal clustering of a number of major technological innovations contributing to the emergence of the lead sector.[3] Extensive studies ever since have deliberated the periodicity of such a phenomenon, and also whether these cycles have existed since the Song China in the twelfth century or from the modern Europe in the eighteenth century. However, the essence of these studies is that there exist periods of global economic prosperity with an approximately 55- to 60-year cycle and these are driven by clusters of technological innovation, though exact years and durations vary in different studies. When viewed in conjunction with Immanuel Wallerstein's modern world system, the economic rise leads to maximum wealth accumulation by the nation states dominating the innovation cycle.[4] Table 1 brings out the lead sectors during the Kondratieff wave periods (dates are indicative and are based on various studies) that emerged during each wave.

Historically, the lead sector influenced the shipbuilding technology of the time and led to its evolution through the centuries. The technological transformation during each K wave impacted both merchant shipbuilding and warship-building. These branches of the shipbuilding industry share technological antecedents and many common factors in production and maintenance through their life cycle. However, shipbuilding trends and the impact of emerging technologies in each of these branches differ. A plausible explanation of this difference in shipbuilding trends can be based on the application of the industry life-cycle theory. The industry life-cycle theory defines distinct stages of the industry life cycle as inception, growth, maturity and decline.[5] The inception and growth stages are the most technologically intensive, involving innovations in process formulation and experimenting with production chains. These are the phases that demand a highly skilled and qualified workforce and intense capital investment. The industry is considered to have matured when the business processes and the production methods have been standardised, mass production has stabilised, and profits are maximised while

Table 1. Kondratieff waves and technology lead sectors.

Sl.	K wave	Start	Peak	Finish	Lead sectors
1	First	1792	1825	1847	Steam power, cotton textiles and iron
2	Second	1847	1873	1893	Railways, iron and steel
3	Third	1893	1913	1939	Electricity, chemicals and automobiles
4	Fourth	1939	1974	2000	Electronics, synthetic materials, petrochemicals and nuclear
5	Fifth	2000			Information technology and aerospace

meeting demand. Incidentally, this is the stage when the industry is most amenable to being moved to regions having abundant low-cost skilled workforce. This has been the pattern leading to the shift of merchant shipbuilding from the US and Europe to the Indo-Pacific post World War II. The warship-building industry, however, is continually upgrading technology, introducing systems to meet the capabilities desired by the nation state. It is also largely a government-controlled captive industry for security imperatives and affords higher capital investment and protection from open competition.[6]

Against this backdrop, it is important to examine some new products which have proliferated in the industry and are impacting shipbuilding trends to an extent that they may prove to be disruptive in the near future. These are 3D printing and autonomous ships. Whilst these will continue to be vital, increased global concerns over the environmental impact of technologies is already ushering in design and deployment changes incorporating green technologies. This will also have significant impact on manufacturing, construction and maintenance philosophies, thereby offering new opportunities.

3D printing – the 'additive manufacturing' process

The process of additive manufacturing is essentially a method in which the product is built up in layers of two dimensions (2D) to add up to the final product. The crucial element of this process is the precise 3D model of the product desired, the information on the material composition/constituents of the product and the capability to extrude or precisely lay out the material in a controlled environment to mould up layer by layer to manufacture the desired product. The earliest motivation for this method of manufacturing came for the application in rapid prototyping (RP) where the design can be transformed into a prototype for quick appreciation and feedback from the user. In many ways this form of manufacturing established a connection between the digital and the real world. In the last three decades the technology of 3D printing has transcended from manufacturing a prototype to making the product itself.

In 1983, Charles Hull invented the stereo-lithography apparatus (SLA) machine for which he was issued a patent in 1986. Subsequently, a number of technologies emerged such as selective laser sintering (SLS), fused deposition modelling (FDM), direct metal laser sintering (DMLS) etc.[7] Ever since its invention in the early 1980s, additive technology has gained attention, and during the last three decades of technology diffusion it has gone through the cardinal waypoints in the development cycle. One of the major developments was the ability to print using metals, and then the fusion technology to have a mix of additive materials as per the desired composition. Another prominent waypoint in the development was the introduction of RepRap (replicating rapid prototyper) technology in 2007. This technology uses open architecture, and for the first time it provided the capability for a 3D printer to replicate itself (almost 70 to 80%). Hence, by simply utilising a kit of non-printable accessories, one could re-print the 3D printer on one's own. All these developments fuelled further growth, reaching the present state of large-scale applicability.

Prototyping is still the largest application of 3D printing. Tooling and casting have also found great use of the 3D technologies. The added capability of this technology for customisation and personalisation has made it most suitable for medical applications such as dental implants, prosthetics, hearing aids, artificial parts, etc. It is now possible to make exact-replica models as training guides for surgeons, prior to attempting major surgeries. The technology is being developed with great success in printing skin, bone, tissue, pharmaceuticals and even human organs. Many applications have been found and implemented in aerospace, automotive, jewellery, art, design, sculpture and food industries. Like the aerospace and the automotive industry, shipbuilding also has many applications for 3D printing.[8]

There are distinct applications which have impacted both warship-building and the merchant shipbuilding industries, and specifically refits and repairs in these segments. Use of 3D technologies to prototype has also speeded up the research and development process in shipbuilding, enabling a larger number of iteration cycles. Early in the design stage, promotional models are possible for better appreciation. This technology complements lean and "just in time" processes and one-piece flow in warship constructions. Three-dimensional printing is being increasingly used to manufacture one-of-a-kind interim products, micro-panel profiles, non-standard brackets and outfitting equipment like double bottoms, side shells, single and double skins, decks and longitudinal bulkheads. A major advantage is that it provides a capability to manufacture one-of-a-kind steel parts or smaller and complex parts without having to machine or order them, reducing the cost substantially.

A major impact of 3D printing is in repairs of ships and in providing logistic support. Ships by their very nature have a longer life cycle compared to the rapidly evolving technologies in the commercial space. Accordingly, through the life cycle, logistics support often calls for complex supply chain management and large and expensive inventory costs. The issue is also complicated by the urgency of demand in the case of breakdowns and failures, and also the geographic distance of the affected ship. Three-dimensional printing offers a solution by way of capability to "print" a spare part on demand and in "just in time" mode. Items that are already being printed include gaskets, O rings, small parts of specific shape and dimension, special tools, valves of a variety of sizes and materials, etc. The advantage accrued is not only in terms of prompt repairs ashore but also freeing up space since ships may have no necessity to stock on-board spares. Whilst newer warships are already being equipped with 3D printers, merchant marines are utilising 3D printers installed in the next port of call for delivery of the spare which can be printed on demand. Options being exercised by each segment are purely on operational and commercial considerations. Although the technologies are still on trial, the trend is unambiguously clear.

Three-dimensional printing has been making waves across a large spectrum of industries due to its versatility, cost-reduction capabilities and sheer convenience. Dubbed "the third industrial revolution" by *The Economist* and "[a technology] bigger than the internet" by the *Financial Times*, 3D printing is starting to leave its mark on the shipbuilding industry.[9] As 3D technology matures further and comes closer to the mass production techniques of today, more and more goods can be produced closer to the customers. Fewer finished products, therefore, will be required to be shipped from across the globe. This may, in the distant future, mean that the bulk of shipping cargo will consist of raw materials and 3D print cartridges.[10]

Autonomous ships

Autonomous ships are those that can operate independently under the control of an on-board decision support system with a provision to control from a remote station. These have a mix of remote and automated technologies. Development of unmanned aircraft and ground and marine (surface and underwater) systems have been in progress since the early decades of the 20th century. Over the years the technology has graduated from "unmanned remotely controlled" to "partly automated" and finally to "autonomous" vehicles. This trend has been largely driven by potential military applications. For instance, since 1917 the US military has researched and employed unmanned aerial vehicles (UAVs) though actual application in a war was only during the Vietnam War and subsequently in Kosovo (1999), Iraq (since 2003) and Afghanistan (since 2001). The early applications of UAVs were limited to target practice firing, later to surveillance and then to delivery of ordinance. However, effective use of unmanned air systems (UAS) by Israel in Lebanon (1982) drew attention to the effective application of this technology, and thereafter the US utilised the initial know-how from platforms acquired from Israel.[11] Similarly, unmanned surface vehicles (USVs) were used post World War II for minesweeping and monitoring radioactivity post each atom bomb test, and unmanned underwater vehicles (UUVs) were used for mine clearing/sweeping.[12]

The rise in asymmetrical threats in recent times has increased the application of unmanned remote/automated vehicles in all three dimensions – air, surface and subsurface – as they provide a technological advantage over such threats. Globalisation and seamless connectivity in the modern world system has made it possible for non-state actors to gain access to lethal technologies which were earlier largely within the purview of the states. Unmanned systems have emerged as the most viable option against threats like nuclear weapons, sophisticated and/or bioengineered biological agents and non-traditional chemical agents. These systems reduce risks to human life and increase the standoff distance from hazardous areas.[13] The last two decades have seen an exponential rise in the development of such systems and the application of increasingly sophisticated artificial intelligence and robotics. The increased development of technologies required for making an autonomous marine vehicle has drawn the attention of the industry to develop an autonomous ship for mercantile marine, opening up a potentially disruptive technology.

Some of the major naval applications of the autonomous ship include the *Sea Hunter*, which is the first of the class of an Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) programme. This is part of a project of the US Navy's Office of Naval Research and Defense Advanced Research Projects (DARPA) with Leidos as the prime contractor.[14] The *Sea Hunter* is a 132-foot trimaran, designed for autonomous open-seas deployment for extended duration. The vessel is meant to detect and track diesel electric submarines, and it achieved a maximum speed of 27 knots during trials.[15] Another major application is the Large Displacement Unmanned Underwater Vehicle (LDUUV) programme. It is a new class of large-displacement unmanned undersea vehicles with increased endurance, range and payload capacities. It can be launched and recovered by multiple-host platforms like the Littoral Combat Ship (LCS) and Virginia- and Ohio-class guided missile submarines.[16]

In 2015, Rolls Royce together with DNV GL, Inmarsat, Deltamarin, NAPA, Brighthouse Intelligence, Finferries and ESL Shipping started an Advanced Autonomous Waterborne Application (AAWA) initiative funded by Tekes (Finnish Funding agency for technology and innovation). It aims to produce the specifications and preliminary design for the next generation of advanced ship solutions for merchant shipping. It will develop the technological, safety, legal and economic aspects of remote and autonomous operation for a "proof-of-concept" demonstrator by 2017.[17] DNV GL supported by Transnova, Norway, has also developed an innovative shipping concept as solution in the short-sea segment. Named *ReVolt*, this vessel is 60 m long, has a maximum speed of 6 knots, is battery operated, and has a range of 100 nautical miles and a cargo capacity of 100 20-foot containers. *ReVolt* is autonomous and requires no crew.[18]

Another major initiative is the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) – a collaborative research project co-funded by the European Commission under its seventh Framework Programme.[19] The project has developed a technical concept for the operation of an unmanned merchant ship and assessed its technical, economic and legal feasibility. The central idea is to develop a ship that is completely unmanned at least for part of the voyage, and to carry out phased testing by implementation in conventional shipping. The vessel will be equipped with modular control systems and communication technology to enable wireless monitoring and control, including advanced decision support systems and capabilities for remote and autonomous operation.[20]

Plymouth University, autonomous crafts specialists MSubs and Shuttleworth Design are partnering on a project which aims to design, build and sail the world's first full-sized, fully autonomous unmanned ship across the Atlantic Ocean. The Mayflower Autonomous Research Ship (MARS) is 100 feet long, and will use state-of-the-art wind and solar technology for propulsion. After a year of testing, the Atlantic crossing is planned for 2020 to mark the 400th anniversary of the original Mayflower sailings from Plymouth, England, to Plymouth, Massachusetts, USA.[21]

Autonomous surface/underwater vehicles have seen increasing attention and investment in recent times both in the naval and the merchant marine sectors. The success and efficacy of these applications have made them an attractive option. The market sentiment is clear from a statement by Mikael Makinen, President Rolls-Royce Marine: "Autonomous shipping is the future of the maritime industry. As disruptive as the smart phone, the smart ship will revolutionise the landscape of ship design and operations". [22]

Green technologies

There are increased global concerns over global warming and greenhouse gas effects. These have influenced technology trends in the shipbuilding industry and have led to international regulations such as the International Convention for the Prevention of Pollution from Ships (MARPOL) that includes Annexure VI – Prevention of Air pollution from Ships, which entered into force in May 2005. Many of these are legally binding and mandate design changes, major outfitting alterations and fitment of equipment that will be required in addition to inherent periodic replacement of ship systems/ships. In response to these concerns, the shipping industry is reorienting its technology development strategies to contribute towards a greener marine environment.

Some of the new technologies which are gaining prominence in designing green ships of the future include a low- or no-ballast system, Liquefied Natural Gas (LNG) fuel for propulsion and auxiliary systems, exhaust gas scrubber systems to reduce Sulphur Oxide (SO_x) emissions (up to 98% reduction), exhaust gas recirculation systems and addition of water in fuel prior injection into the combustion chamber for reduction of Nitrogen Oxide (NO_x) emissions (up to 80% reduction). Increased efficiency to reduce fuel consumption can also result in contributing towards environmental protection. This can be achieved by an advanced and streamlined rudder and propeller system, speed nozzle designs in smaller vessels, appropriate paint schemes, a waste heat recovery system, fuel and solar cell propulsion systems, etc.[23] Major shipbuilding companies are strategising to adapt to respond to these requirements.

Ballast-free ship design

Ever since steel-hull ships were built, ballast water has been used for weight compensation, stabilisation, maintenance of safe regimes, management of hull stresses, maximisation of propulsion efficiency and manoeuvrability. However, marine organisms like bacteria, microbes, small invertebrates, eggs, cysts and larvae are carried in the ballast water. The interaction of these species with the native marine ecosystems poses ecological and health issues. Biological invasion through ballast water is a major concern in the marine ecosystem and has led to species extinction and biotic homogenisation worldwide.[24] International efforts to address the issue of transfer of invasive aquatic species (IAS) started in 1991 and culminated in the adoption of the International Convention for the Control and management of Ships Ballast Water Sediments (BWM Convention) by International Maritime Organization (IMO) in February 2004. The convention requires all ships to implement a ballast-water management plan as per a given standard and guidelines. A technical group of experts has to approve various technologies being proposed for effective ballast-water management. The convention will enter into force 12 months after ratification by 30 states, representing 35% of world merchant shipping.[25]

The last state to ratify the BWM convention was Peru on June 10, 2016, making the total number of states which have ratified the convention 51 and bringing the percentage of world tonnage to 34.87%.[26] Considering that the convention will come into force 12 months post ratification by 35% of the world tonnage, the convention is very close to being implemented. The convention's entry into force will require the retrofit of expensive new treatment equipment (over a 5-year period) on around 70,000 ships.[27] This has brought into focus the treatment technologies available and the retro fitment requirements and also shore-based infrastructure that will need to be set up, and ballast-water management system manufacturers are already experiencing possible bottlenecks.

A variety of ballast-water treatment technologies are available. The mechanical treatment methods include filtration and separation, and the physical treatment methods include sterilisation by ozone, ultraviolet light, electric currents and heat treatment. Chemical treatment methods include the addition of biocides to ballast water to kill organisms.[28] In addition to these technologies, a number of ballast-free ship design concepts are being developed which can potentially revolutionise future hull designs.

The ballast-free concept designed by DNV GL is likely to carry less or no ballast water and is less complex compared to a ballast-water treatment system, while offering high fuel savings and reduced emissions. The design incorporates a prismatic hull to enable bow and propeller immersion and longitudinal tanks to neutralise bending moments during loading and discharging. The spectrum of design concepts includes a Very Large Crude Carriers (VLCC) Triality concept, ballast-free bulk carriers (the Ecore concept) and ballast-free car carriers (the Momentum concept).[29] The hybrid ship design minimises the transfer of organisms by enabling a ship to sail with reduced ballast. This design has an electrically driven duct propeller in addition to a conventionally driven main propeller. The retractable duct propellers are deployed for low marine speed-ballast voyages that carry about one tenth of the ballast water typically required. The two different modes of sailing lead to reduced fuel consumption because less energy is needed. This is achieved without impairing the operational safety of the ship.[30] Some of the other initiatives towards a ballast-free design include the Non Ballast Water Ship (NOBS) design by the Shipbuilding Research Centre of Japan (SRC), the Monomaran hull design by the Delft University of Technology (DUT), the flow-through concepts of Prof. Michael Parson, ballast-free bulk carriers and the solid-ballast ship having a 25-tonne solid ballast container.

LNG-fuelled ships

Liquefied natural gas (LNG) is natural gas in liquefied form and is produced as a result of lowering the temperature of natural gas to below its boiling point of approximately −162° C (about −260°F). LNG consists mainly of methane (CH_4), with minor amounts of other hydrocarbons (ethane, propane, butane and pentane). It has emerged as the best alternative to conventional fuels since it leads to virtual elimination of SO_x emissions and particulate matter, and substantial reduction of NO_x (~90%) and carbon dioxide (CO_2) emissions (~20%). The *LNG World Shipping Report* data reveals that as of March 2016, total LNG fuelled ships in service numbered 80 and 106 more ships are on order. The corresponding figures for 2015 were 66 and 81, necessarily giving an increase of 21% for those in service and nearly 31% for tonnage on order. Though these figures are below the earlier predicted growth in demand, the momentum is expected to pick up once four of the new generation LNG bunker supply ships are put into service, later in 2016.[31]

In December 2015, DNV GL granted an approval in principle to Dalian Shipbuilding Industry Company (DSIC) for a new VLCC design in which the LNG fuel tanks are located on the open deck, necessitating minimal changes to conventional layout and cargo capacity. The LNG fuel tanks give the vessel the capability of performing a round trip from the Middle East to the US without refuelling. The duel fuel design also gives flexibility in bunkering options. The vessel meets the IMO's NO_x Tier III requirements while operating in gas fuel mode.[32]

In March 2016, Wartsila was awarded a contract by Gdansk Ship repair yard "Remontowa" S.A. to supply a comprehensive scope of engines, propulsion machinery, integrated automation systems, and gas-handling systems required for the mid-life upgrade of two RoPax ferries and their conversion to operate on LNG fuel. The ferries, the *Spirit of British Columbia* and the *Spirit of Vancouver*, are the flagship vessels of British Columbia Ferry Services based in Victoria, Canada. The work will be carried out in the Remontowa ship repair yard in Poland during 2017/2018.[33] In August 2016, MSC cruises placed an order for two LNG-fuelled 200,000 gt-plus cruise ships on STX France, with a plus-two option. The contract value is US$ 4.1 billion, and expected delivery is from 2022 onwards.[34]

Japan's first LNG-fuelled ship, *Sakigake*, a tugboat owned by NYK, emits about 30% less carbon dioxide, 80% less nitrogen oxide and absolutely no sulphur oxide when using LNG fuel. NYK has been focussing on construction of LNG-fuelled car carriers and LNG bunkering vessels.[35] Similarly, the South Korean Ministry of Trade, Industry and Energy announced plans to dominate the LNG propulsion and bunkering market, and it expects to secure 70% of world's orders for dual-fuel vessels by 2020.[36]

Conclusion

Three-dimensional printing, autonomous vehicles and green technologies have evolved from inception through decades of development to the present levels of diverse applications. The pace at which new products are introduced stands as testimony to the heightened research and development efforts and funding both at the state level and from business entities. These technologies have the potential to fuel the next wave of global economic growth, with high gains for those who dominate the innovation cycle. Early impacts on shipbuilding are noticeable in refit and repairs, retro-fitments and logistic chain improvements. On-board/next port of call 3D-printed spare parts, tools and accessories are becoming increasingly common. Similarly, the effective use of 3D technology to manufacture steel parts or smaller and complex parts is facilitating substantial cost and time reductions during refits, repairs and retro-fitments. In the run-up to a fully autonomous ship, systems with increased autonomy are available as upgrades. Implementation of green technologies to conform to international regimes is increasing the scope of work of the refits and upgrades. Eventually, as newer hull and system designs mature and complete sea trials, the impact will be felt in new construction ships.

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