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Review

Applications of 3D printing technologies in oceanography

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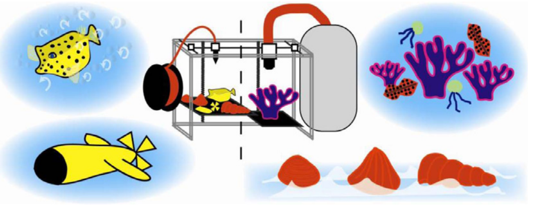
HIGHLIGHTS

- 3D printing applications for ecological monitoring and sample collection are discussed.
- 3D printing applications in hydrodynamics, biomechanics, and locomotion studies are summarized.
- 3D printing applications for tangible coral props and coral reef restoration are highlighted.
- Broad impacts of plastics and specific impact of 3D printing materials are summarized.
- A note of caution on the hazardous effects of some of the 3D printing materials has been discussed.

GRAPHICAL ABSTRACT



Abbreviations: FDM, Fused Deposition Modeling; SLA, Stereolithography; NASA, National Aeronautics and Space Administration; AUVs, autonomous underwater vehicles; USVs, unmanned surface vehicles; MUVs, micro underwater vehicles; CAD, Computer-aided design; .STL, STereoLithography or Standard Triangle Language or Standard Tessellation Language; SLS, Selective Laser Sintering; DLP, Digital Light Processing; CLIP, Continuous Liquid Interface Production; SLM, Selective Laser Melting; EBM, Electron Beam Melting; ABS, acrylonitrile butadiene styrene; GUPPIE, Glider for Underwater Problem-solving and Promotion of Interest in Engineering Education; PLA, polylactic acid or polylactide; CT, computed tomography; CSIRO, Commonwealth Scientific and Industrial Research Organization; PDMS, Polydimethylsiloxane; SOI, Sustainable Oceans International; PE, Polyethylene; PP, Polypropylene; PVC, Polyvinyl chloride; PS, Polystyrene; PET, Polyethylene terephthalate; PUR, Polyurethane.

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ABSTRACT

3D printers allow researchers to produce parts and concept models rapidly at low-cost and allow rapid prototyping of many designs from the comfort of their desk. 3D printing technologies have been explored for a wide range of applications including robotics, automobile components, firearms, medicine, space, etc. Owing to lower costs and increased capabilities of 3D printing technologies, unprecedented opportunities in the world of oceanography research are being created. Some examples include 3D printed components being employed in autonomous underwater (or surface) vehicles; 3D printed replicas of marine organisms being used to study biomechanics, hydrodynamics, and locomotion; and 3D printed coral reef replicas being used to restore damaged coral reefs. To the author's knowledge, currently there is no review covering the different 3D printing technologies applied in oceanography studies. Therefore, this review presents a summary of the different 3D printing technologies that have been used in fundamental studies or real-life applications related to oceanography. The diverse range of 3D printing applications in oceanography covered in this review has been categorized under the following sub-topics: Ecological Monitoring & Sample Collection, Hydrodynamics, Biomechanics & Locomotion, Tracking & Surface Studies, and Tangible Coral Props & Coral Reef Restoration. A detailed overview of the 3D printing technologies referred to within this review has been presented, and categorized under the following four general topics: Material Extrusion, Photopolymerization, Powder Bed Fusion, and Construction Printing. The broad impact of plastics on oceans and the specific impact of 3D printing materials on ocean life are also discussed. It is anticipated that this review will further promote the 3D printing technologies to oceanographers for a better understanding and restoration of fragile marine ecosystems.

1. Introduction

3D printing refers to additive manufacturing or rapid prototyping technologies that allow printing of 3D objects via deposition of successive layers of material in layer-by-layer arrangement (Jiang and Zhao, 2015). Based on the size and capacity, 3D printers can be broadly classified as consumer (or desktop), professional, and manufacturing (or production) 3D printers. 3D printers based on the Fused Deposition Modeling (FDM) and Stereolithography (SLA) technologies are the most commonly used commercial 3D desktop printers (Oskui et al., 2016). 3D printers give researchers the ability to produce concept models and parts rapidly at low-cost and allow rapid prototyping of numerous designs from the comfort of their desk. A new domain of 3D printers is the construction (or concrete) 3D printers (Anell, 2015; Gardiner, 2011). Since its inception, 3D printing has been explored for a wide range of applications including robotics, automobile components, firearms, medicine, space, etc. (Campbell et al., 2011; Chae et al., 2015; O'Neill, 2015; Reep et al., 2015; Stanton et al., 2015; Ventola, 2014).

National Aeronautics and Space Administration (NASA) has already begun to explore 3D printing technology for use by astronauts to print damaged parts in space under low gravity conditions (Bean et al., 2015; Kietzmann et al., 2015). In 2015, NASA and the National Additive Manufacturing Innovation Institute (known as America Makes) initiated a competition to design and build a 3D printed full-scale habitat for deep space exploration, especially, for NASA's expeditions to Mars (O'Neill, 2015).

Low-costs and increased capabilities of 3D printing technologies are creating unprecedented opportunities in the world of oceanography research. For example, 3D printed components are being employed in autonomous underwater vehicles (AUVs), unmanned surface vehicles (USVs), and micro underwater vehicles (MUVs); 3D printed replicas of marine organisms are being used to study biomechanics, hydrodynamics, and locomotion; 3D printed coral reef replicas are being used to restore damaged coral reefs. To the author's knowledge, currently there is no review covering the different 3D printing technologies applied to oceanography. Therefore, this review aims at presenting a summary of the different 3D printing technologies that have been used in fundamental studies or real-life applications related to oceanography. The broad impact of plastics on oceans and the specific impact of 3D printing materials on ocean life are also discussed. For the sake of convenience to the reader, the following section provides a detailed overview of the 3D printing technologies referred to within the subsequent section that discusses the diverse range of 3D printing applications in oceanography.

2. 3D printing technologies

Additive manufacturing processes, used in 3D printers, provide several advantages over conventional manufacturing methods including freedom to fabricate intricate geometries, optimum material usage, elimination of expensive tooling etc. (Rafi et al., 2013). The factors favoring additive manufacturing over conventional manufacturing are low production volumes, high material cost, high machining cost, capital investment, logistics costs, transportation costs, and prototyping (Frazier, 2014).

It should be noted that for all 3D printing technologies, typically there is no need of masks, molds, or dies to fabricate 3D objects. However, all 3D printing technologies need a 3D CAD (computer-aided design) model which is exported to the printer in a .STL (STereoLithography or Standard Triangle Language or Standard Tessellation Language) file format, that contains the coordinates of the vertices of triangulated sections for each surface of the 3D model. The .STL file containing the 3D information can then be interpreted and converted by the printer slicer software into a G-code (numerical control programming language) file, which contains information on 2D horizontal cross-sections for printing 3D replicas of the input 3D CAD model in a layer-by-layer fashion. The resolution of the 3D printed objects can be varied through controlling the number of triangulated sections; higher the number of triangulated sections, higher is the resolution (Gross et al., 2014; Rengier et al., 2010).

For any 3D printing technology, the speed of 3D printing objects depends on the complexity of the design and size. It should be noted that the mechanical properties of 3D printed parts vary depending on the direction the parts were printed due to the layer-by-layer approach, making it difficult to create 3D objects with isotropy (Jiang and Zhao, 2015). However, the degree of isotropic mechanical property can vary greatly based on the material used (Stansbury and Idacavage, 2016).

Recent developments in the additive manufacturing have enabled multi-material 3D printing using multiple materials, which allows fabrication of highly realistic 3D objects that closely mimic the appearance and physicochemical properties of 3D models (Begolo et al., 2014; Hardin et al., 2015; Kokkinis et al., 2015; Ready et al., 2014; Sitthi-Amorn et al., 2015). Different types of multi-material 3D printers are available in the form of Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and syringe-based extrusion 3D printers (Sitthi-Amorn et al., 2015). Applications of multi-material 3D printing are numerous; however, it is critically beneficial in biological applications (Kolesky et al., 2014; Waran et al., 2014). For a summary of commercially available 3D printers (in terms of cost, print area, print resolution) from ten leading 3D printing companies in the world, the reader is referred to a recent review (Chae et al., 2015). The following sub-sections discuss the commonly used types of 3D printing technologies under the following four general topics: Material Extrusion, Photopolymerization, Powder Bed Fusion, and Construction Printing.

2.1. *Material extrusion*

Material extrusion is an additive manufacturing process that uses a nozzle or orifice to selectively dispense a material. In FDM 3D printers (Fig. 1), a thermoplastic filament is fed through a hot extruder

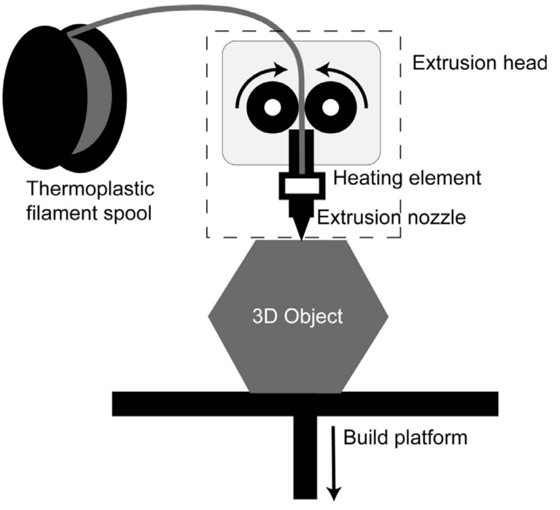

Fig. 1. Schematic illustration of a typical FDM 3D printer extruding a thermoplastic filament through a heated nozzle to build a 3D object. The extrusion head moves in the x–y plane, and the build platform moves in the z-axis.

that melts and extrudes the filament through the print head with a thickness depending on the software and hardware settings. The FDM printers deposit melted thermoplastic in a layer-by-layer format to create 3D objects (Chia and Wu, 2015; Gross et al., 2014). After the deposition of one layer (one 2D cross-section of the 3D object), the build platform of the printer moves downwards by a distance equal to one layer thickness to allow deposition of the subsequent layer. This process is repeated until the printing of the 3D object is completed. FDM technology can be used with thermoplastic filaments of various materials available in different colors. The FDM 3D printed objects have higher anisotropy compared to SLA or SLS 3D printed objects (Stansbury and Idacavage, 2016). In general, FDM printers are slower compared to SLA or SLS 3D printers.

FDM printers and thermoplastic filaments are available at lower costs compared to the SLA and SLS printers as well as their ink materials. Some cheap FDM printers are even available in the form of DIY kits. The infill of FDM printed 3D objects can be easily varied, allowing the users to print hollow 3D objects or with low or high infills. The resolution of FDM printed objects is dependent on the nozzle size and the extruder precision. One of the problems with the FDM printed 3D parts is their porosity, which prevents their direct use in applications that require air-tight or water-proof sealing. However, in order to remove the semi-porosity, epoxies can be coated onto the surfaces or infiltrated into the FDM printed 3D parts.

Other additive manufacturing technologies similar in principle to FDM use a syringe (or nozzle or orifice) to extrude liquid or semi-liquid materials. Such extrusion based additive manufacturing technologies have been extensively applied in the field of tissue engineering, commonly known as Organ 3D printing or Bioprinting (Chia and Wu, 2015; Do et al., 2015; He et al., 2016; Mironov et al., 2003), and recently being applied for food printing (Godoi et al., 2016; Sher and Tutó, 2015; Sun et al., 2015a,b).

2.2. Photopolymerization

Photopolymerization is an additive manufacturing process in which a liquid polymer is selectively cured by a polymerization process which is activated by a light source (most commonly a UV light source). Stereolithography builds 3D objects using UV curable photopolymer liquid resins. Similar to FDM printers, SLA printers (Fig. 2) build 3D objects in a layer-by-layer format. A focused source of UV light cures the liquid resin in a layer-by-layer format, while the build platform of the printer slowly pulls the printed 3D object into the liquid resin bath by a distance equal to one layer thickness (ranging

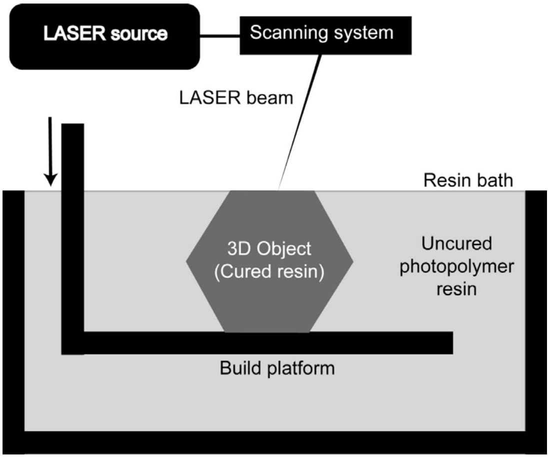

Fig. 2. Schematic illustration of a typical SLA 3D printer curing liquid photopolymer resin by scanning a laser beam to build a 3D object. The scanning system scans the laser in the *x*–*y* plane, and the build platform moves in the *z*-axis.

between 50 and 150 μm). The UV laser cures one whole 2D cross-section (of the final 3D object) based on the input 3D CAD model by scanning the laser along the 2D cross-section (Chia and Wu, 2015; Gross et al., 2014; Kumta et al., 2015). After curing of a layer, a blade loaded with resin levels the surface of the resin to ensure a uniform layer of liquid before the curing of next layer.

The initial models of SLA printers and their photopolymer resins were expensive. However, currently SLA printers and the photopolymer resins are available at costs that are comparable to FDM printers and thermoplastic filaments. A major advantage of SLA printers over the FDM printers is the ability to print high resolution intricate details of small-scale features with surface finish similar to injection molded parts (Chae et al., 2015). Also, the bonding strength between the layers is stronger in the case of SLA printed objects leading to good strength and minimal anisotropy in their structure and properties (Stansbury and Idacavage, 2016). One of the limitations with most of the SLA printers is that they use proprietary resins, and also the choices of colors are limited compared to FDM filaments.

A relatively new derivative of SLA technology is the Digital Light Processing (DLP) 3D printing that uses a DLP projector light instead of a scanned laser for the photopolymerization of liquid resins. The major difference between the SLA and DLP 3D printing technologies is that in DLP printing the DLP projector cures one whole 2D cross-section in a single shot, while in SLA printing the laser needs to be scanned across the entire 2D cross-section. Due to this major difference, the speed of DLP 3D printers is much higher compared to the SLA 3D printers (Gross et al., 2014; Stansbury and Idacavage, 2016).

Continuous Liquid Interface Production (CLIP) is a very recent continuous 3D printing technology, similar to DLP-based 3D printing, but makes use of a photochemical process allowing rapid printing of 3D objects that are much like injection-molded objects with excellent mechanical properties, feature resolution below 100 μm, and surface finish (Tumbleston et al., 2015). UV Light is projected through an oxygen-permeable window into a reservoir of UV-curable resin with a 20–30 μm oxygen-containing liquid interface (known as the dead zone) of uncured resin between the window and the printing part, curing the resin above the dead zone. As the 3D printing progresses by pulling out the printed 3D part out of the resin bath, resin flows beneath the curing resin, maintaining a continuous liquid interface. The dead zone is formed owing to oxygen inhibition of photopolymerization, allowing layer-less printing via simultaneous UV curing, resin renewal, and drawing out of printed object. CLIP 3D printing technology could draw 3D objects out of the resin at rates of hundreds of millimeters per hour, thereby fabricating objects in minutes instead of hours (Tumbleston et al., 2015).

MultiJet 3D printing is a type of inkjet printing process that uses piezo printhead technology to deposit either photocurable plastic resin or casting wax materials layer-by-layer. PolyJet 3D printing is also another type of inkjet printing technology, wherein the 3D printer jets layers of curable liquid photopolymer onto a build platform and instantly UV-cures the tiny droplets of photopolymer.

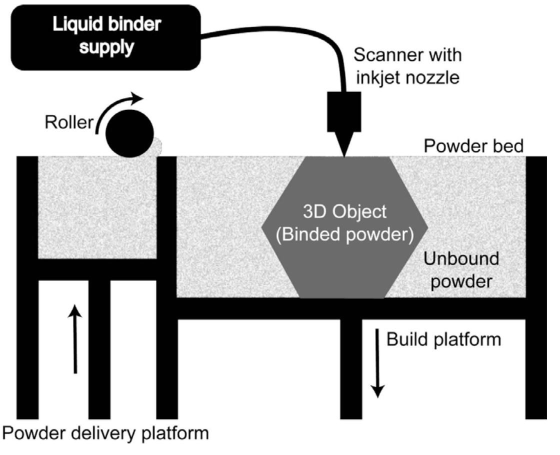

Fig. 3. Schematic illustration of a typical inkjet 3D printer binding powder by scanning an inkjet nozzle jetting liquid binder to build a 3D object. The scanner scans the inkjet nozzle in the *x*–*y* plane, and the build platform moves in the *z*-axis.

Support materials are printed if overhangs or complex shapes are to be printed (Chae et al., 2015). MultiJet or PolyJet 3D printing can achieve layer thickness down to 16 μm allowing production of high resolution smooth and accurate 3D objects that do not require post-curing (Chae et al., 2015; Stansbury and Idacavage, 2016).

2.3. Powder bed fusion

Powder bed fusion is an additive manufacturing process in which thermal energy (laser or electron beam source) is used to selectively fuse regions of a powder bed. Inkjet 3D printing technology (or binder jetting, Fig. 3) is a powder-based 3D printing technology that employs inkjet technology to selectively inject a liquid boding agent into successive layers of fine powder in order to bond the powder (Kruszyński and van Liere, 2009). The build platform is lowered, a new layer of powder is spread above the previous layer, and the process of selectively bonding the powder is repeated. Inkjet 3D printing typically uses powder particles in the size range of 0.05–0.1 mm. After the completion of 3D object printing and the complete curing of the bonding agent, the unbound powder (that inherently acts as support for overhanging structures) is removed and the printed objects are impregnated with wax or epoxy for structural strength.

Similar to inkjet 3D printing, laser sintering technologies use powders of metals, polymers, or ceramics to build 3D objects. These powders are typically in the size range of 20–150 μm (Hunt et al., 2014). Laser sintering (Fig. 4) uses a laser (usually a CO_2 laser) that selectively sinter-bonds the powder layer-by-layer to build a 3D object (Abdelaal and Darwish, 2013; Chia and Wu, 2015; Gross et al., 2014; Shirazi et al., 2016). Upon laser sintering of one thin layer of powder, the next layer of powder is spread over the previous layer and the build platform is lowered by a distance equal to one layer thickness. This process is repeated until the printing of the 3D object is completed. After completion of 3D printing of an object, the object is removed from the powder bed and the unsintered powder is removed from the object. Most SLS 3D printers use two-component powders. Unlike FDM or SLA 3D printing, SLS 3D printing typically does not require supports during the printing process as the unsintered powder provides mechanical support (Wu and Hsu, 2015). Although the surface of SLS printed 3D objects might be porous and absorb water, the whole object is not porous akin to FDM printed 3D objects. Due to the ease in fabricating intricate 3D structures, SLS technologies are now being used in manufacturing jewelry (Cooper, 2015). A 3D printing technology that uses similar principle to SLS except that high power solid-state lasers are used to melt metal powders in inert gas atmospheres is known as Selective Laser Melting (SLM) (Abdelaal and Darwish, 2013). SLM yields

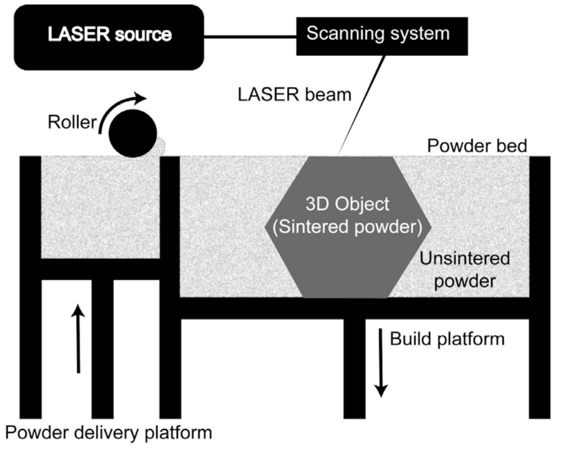

Fig. 4. Schematic illustration of a typical SLS 3D printer sintering powder by scanning a laser beam to build a 3D object. The scanning system scans the laser in the x–y plane, and the build platform moves in the z-axis.

denser metal objects compared to SLS 3D printing. In general, SLS (or SLM) 3D printing yields 3D objects with high mechanical strength and low porosity (Do et al., 2015).

An alternative powder bed fusion technology that uses high-power electron beam source (instead of a laser source) under vacuum is termed as electron beam melting (EBM) (Abdelaal and Darwish, 2013; Chia and Wu, 2015). The electron beam is focused using electromagnetic coils and deflected to desired spots using electromagnetic steering coils (Ali et al., 2014). The printing chamber under vacuum is maintained at elevated temperatures to minimize thermally induced residual stresses and formation of non-equilibrium microstructures. The penetration depth of electron beams is much higher compared to laser beams (Rafi et al., 2013). Owing to its higher energy source, the EBM 3D printers have better build rate compared to SLS (or SLM) 3D printers. Furthermore, it was found in a comparative study that with EBM technology a 35% cost reduction was achieved compared to conventional machining (Cronskär et al., 2013). Although SLS (or SLM) and EBM 3D printers provide high accuracy and strength, these 3D printers (especially the EMB 3D printers) are expensive compared to FDM or SLA 3D printers (He et al., 2016).

2.4. Construction printing

A recent additive manufacturing technology is the Construction 3D Printing, which is also known as Concrete Printing or Contour Crafting or Freeform Construction. As the name suggests, these 3D printers use construction materials such as concrete, sandstone, wood chips, sawdust, ceramics, etc. as the printing material to fabricate macro- or megascale 3D structures (Anell, 2015; Gardiner, 2011; Henke and Treml, 2013; Kariz et al., 2016; Kreiger et al., 2015; Mostafavi et al., 2015; Yossef and Chen, 2015). Some of the construction 3D printing technologies are based on the layer-by-layer deposition of extruded printing materials in the form of pastes, either from a nozzle (or orifice) controlled by a multi-axis robot or from a nozzle (or orifice) controlled by a gantry robot (Anell, 2015; Kariz et al., 2016; Mostafavi et al., 2015; Perrot et al., 2015). In this class of construction 3D printers, the deposited layers should be mechanically stable to allow subsequent deposition of layers. Also the printing materials should be sufficiently fluid in order to allow extrusion (Perrot et al., 2015).

Another class of construction 3D printers is based on the FDM principle, however, at a much larger scale compared to the desktop 3D printers. For example, the KamerMaker (RoomBuilder) by DUS Architects made use of a large scale Ultimaker FDM 3D printer for the 3D Print Canal House project (DUS Architects, 2015; Kreiger et al., 2015). A wide variety of ecofriendly filament materials are being researched for this project. Construction 3D printers based on the concept of powder bed fusion and binder jetting have also been developed, for example, the D-Shape printers (Cesaretti et al., 2014;

Gardiner, 2011). Due to large scale involved, these construction 3D printers require large amounts of printing materials to form the powder bed and also need labor intensive post-printing separation of the unused powder from the 3D printed structure.

3. Oceanography applications

This section discusses the diverse range of 3D printing applications in oceanography under the following topics: Ecological Monitoring & Sample Collection, Hydrodynamics, Biomechanics & Locomotion, Tracking & Surface Studies, and Tangible Coral Props & Coral Reef Restoration.

3.1. Ecological monitoring & sample collection

Researchers have been using a variety of (tethered, untethered, autonomous, etc.) underwater vehicles for ecological monitoring. With the advent of low-cost 3D printing technologies, researchers have begun to exploit this versatile technology for rapid prototyping of different components of underwater vehicles for ecological monitoring. Early examples in this domain of oceanography research dates back to almost a decade, where FDM 3D printed propellers were manufactured using a Acrylonitrile Butadiene Styrene (ABS)/polycarbonate blend for use in a high-drag AUV (D'Epagnier et al., 2007). The authors used the ABS/polycarbonate blend to make rigid propellers that would undergo less deformation. 3D printed plastic components (wings and tail) were used to develop a low-drag Stingray AUV used for ecological monitoring (Barngrover et al., 2011). The 3D printed wings and tail were coated in epoxy in order to prevent water logging. In another example, 3D printing technology was used to construct plastic propellers and motor transmission parts for an AUV (Bartolini et al., 2012).

3D printed ABS and nylon components were used to develop an USV (Goto et al., 2014). The ABS parts used to hold a camera were encased in an acrylic cylinder protecting the parts as well as the camera from water. In another demonstration, 3D printed ABS support frame was used to develop a robot launching system for underwater manipulation tasks (Yue et al., 2014). As the density of ABS is 1.05 g cm^{-3}, the robot could sink down easily. In a recent work, the authors attempted to maximize the usage of 3D printed components of a modular propulsion system for an AUV (Allotta et al., 2015). A robotic Glider for Underwater Problem-solving and Promotion of Interest in Engineering Education (GUPPIE) was recently developed (Ziaeefard et al., 2015). The GUPPIE was comprised of several 3D printed components including O-rings, acrylic tube, rack and pinion, and syringes. Using 3D printing technology instead of conventional machining, the authors were able to cut down the manufacturing time from 80 h to less than 12 h. The authors believe that using the 3D printed GUPPIE will allow students (as early as middle school) to understand the relationship between biodiversity, ecology, environmental science, and marine sustainability problems and the role engineering plays to facilitate sustainable solutions.

Owing to lower cost and improved robotic systems, better cetacean monitoring and remote sample collection in risky marine conditions is now becoming a reality. It is well known that whales indicate the health of an entire ecosystem (Bennett et al., 2015a). In recent demonstrations, custom 3D printed components (legs and frame) were used for the development of multirotor *SnotBot* UAV that would allow marine biologists to collect observational data and biological samples from living whales (Bennett et al., 2015a,b). The 3D printed frame containing the electronics was placed within the sealed chassis. In a related research, a robotic hand for underwater mobile manipulation was developed using MultiJet 3D printed (Projet 3500 3D Printer using Visijet Crystal) components (Stuart et al., 2014).

The different examples discussed in this section have been made possible due to the wider availability and lower costs of 3D printing technologies. As evident from the different examples presented here, 3D printing has been applied for developing prototypes for marine ecological monitoring and sample collection. Attempts are being made to maximize the usage of 3D printed components in surface/underwater vehicles. It is not clear from the literature as to how well the 3D printed components actually performed in service or if any challenges were faced in real-life applications of the 3D printed components. Table 1 summarizes the 3D printing applications in marine ecological monitoring and sample collection.

Table 1
Summary of 3D printing applications in marine ecological monitoring and sample collection.

3D printing application	Printer type	Material	Reference
Propellers for high-drag AUV	FDM	ABS/polycarbonateblend	(D'Epagnier et al., 2007)
Wings and tail for low-drag AUV	Unspecified	Plastic coated with epoxy	(Barngrover et al., 2011)
Propellers and motor transmission parts for AUV	Unspecified	Plastic	(Bartolini et al., 2012)
Components for USV	Unspecified	ABS & nylon	(Goto et al., 2014)
Support frame for underwater robot	Unspecified	ABS	(Yue et al., 2014)
Components of a modular propulsion system for AUV	Unspecified	Plastic	(Allotta et al., 2015)
Robotic underwater glider	Unspecified	Unspecified	(Ziaeefard et al., 2015)
Legs and frame for a multirotor UAV	Unspecified	Unspecified	(Bennett et al., 2015a,b)
Robotic hand for underwater manipulation	MultiJet (Projet 3500)	Visijet Crystal	(Stuart et al., 2014)

3.2. Hydrodynamics

Marine organisms living in the intertidal zone are subjected to large hydrodynamic forces due to high wave energy and flow velocities. The hydrodynamic forces can dislodge the marine organisms in this zone resulting in lower foraging efficiency and overall growth (Skavicus and Ditsche, 2014). The body shapes of three common benthic organisms of the marine intertidal (snail, chiton, and limpet) were replicated with polylactide (PLA, an eco-friendly thermoplastic aliphatic polyester derived from corn starch) plastic using a FDM 3D printer (ORION delta 3D printer) (Skavicus and Ditsche, 2014). A NextEngine 3D laser was used to scan the organisms into a 3D CAD program. The 3D CAD models were subsequently scaled to 1:1 and 2.5:1 sizes and finally 3D printed as polylactic acid (PLA) replicas of the marine organisms (Fig. 5). The 3D models were subjected to flume testing in order to understand how drag forces and drag coefficients change with a range of Reynolds numbers simulating currents up to 6 m s^{-1}. Using the 3D replicas in flume tests, the authors found that in higher flow velocities the snail replicas experienced significantly higher drag forces than the limpet and chiton replicas; drag coefficients for the limpet and chiton replicas were relatively high at low flow velocity and rapidly decreased at higher velocities, whereas drag coefficient for the snail replicas was lower at low flow velocity and increased at higher flow velocities; drag coefficients for the limpet and chiton replicas showed little change at higher Reynolds number, whereas drag coefficient for the snail replicas fluctuated with increasing Reynolds number. This example illustrates how 3D printing technology allows researchers to easily create scaled-up 3D models of organisms to achieve higher Reynolds number and understand how the flow forces affect the normally scaled organisms in high flow environments (Skavicus and Ditsche, 2014).

In 2014, the first study on the design, fabrication and hydrodynamic testing of a flexible 3D printed synthetic shark skin membrane was demonstrated (Wen et al., 2014). The authors used 3D models of denticles based on high-resolution micro-computed tomography (micro-CT) scans of the skin of a shortfin mako shark. Multi-material PolyJet 3D printing (Objet Connex500 3D printer capable of multi-color and multi-material printing) was used to fabricate thousands of rigid synthetic shark denticles on a flexible membrane (Fig. 6). The Young's modulus of the rigid denticles and the flexible membrane was about 1 GPa and 1 MPa, respectively. The 3D printed shark skin showed increased swimming speed with reduced energy consumption compared to control models that lacked denticles. Although the authors were able to retain the full surface complexity of natural shortfin mako shark denticles ($\sim$150 μm in size with surface features down to 5–10 μm), they could not fabricate the 3D printed replicas at the biological scale due to limitations on printing resolution using the current multi-material 3D printing technology.

The fluid flow through the complex internal skeletonized respiratory structures (hydrospires) of spiraculate blastoids is not fully understood. In a recent demonstration, the fluid flow through scaled-up (72×) 3D printed (ProJet HD3000 MultiJet 3D printer) models of the complex skeletonized respiratory structures of a blastoid echinoderm using a translucent ABS polymer was studied (Huynh et al.,

Fig. 5. 3D printed 2.5:1 scale models the chiton (*Tonicella lineata)* (left), the limpet (*Lottia pelta)* (middle), and the snail (*Calliostoma ligatum)* (right).
Source: Reprinted with permission from Skavicus and Ditsche (2014).

Table 2
Summary of 3D printing applications in marine hydrodynamics.

3D printing application	Printer type	Material	Reference
Replicas of benthic organisms	FDM (ORION delta)	PLA	(Skavicus and Ditsche, 2014)
Synthetic shark skin membrane	PolyJet (Objet Connex500)	Rigid material (Young's modulus 1 GPa), Flexible material (Young's modulus 1 MPa)	(Wen et al., 2014)
Models of complex skeletonized respiratory structures of a blastoid echinoderm	MultiJet (ProJet HD3000)	ABS	(Huynh et al., 2015)

2015). The 3D models replicated the distal (aboral) portion of a hydrospire, covering the first (most aboral) ten hydrospire pores. The 3D printed models helped the researchers in easy visualization of fluid flow through the hydrospires and in assessing the respiratory efficiency of the hydrospires. The authors found that the fluid flow was consistent with the effective respiratory exchange in the hydrospire folds. It was also found that the laminar fluid flow was consistent with the Reynolds numbers estimated for a living blastoid ($R_e = 0.0008 - 0.05$). This example, similar to the previous one, illustrates the limitations with current 3D printing technologies. Owing to the limits in resolution of the 3D printers and the small size of the hydrospires, the authors had to use a 72× scale factor to ensure that the internal plumbing was intact in the 3D printed model in order to allow water through it. Furthermore, due to the scale-up of the model, only part of the hydrospire pores could be printed.

Although handful in numbers, the above examples illustrate how 3D printing technologies can be applied in hydrodynamic studies in the field of oceanography. An advantage with 3D printing is that these technologies allow easy 3D model scale-up of organisms to achieve higher Reynolds number for understanding how the flow forces affect the normally scaled organisms in high flow environments. 3D printing is also allowing researchers to closely mimic miniscule details of marine creatures, for example, by including denticles to 3D printed shark skin, researchers were able to increase swimming speed with reduced energy consumption. Table 2 summarizes the 3D printing applications in the area of marine hydrodynamics.

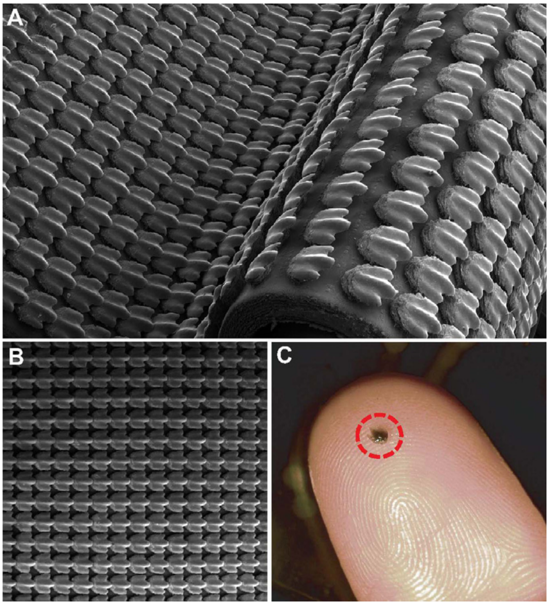

Fig. 6. SEM images of the fabricated synthetic shark skin membranes used for hydrodynamic testing. Rigid denticles were fabricated on a flexible substrate membrane using 3D printing technology. Membranes in curved and flattened states are shown in A and B, respectively. Note the changes in spacing among the denticles in the convex and concave portions of the curved membrane (A), and how denticles overlap each other in the concave region and when the membrane is flat (B). A single synthetic denticle (enclosed by the red dashed circle) on a human finger is shown in C. Each denticle measures ca. 1.5 mm in length. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: Reproduced with permission from the Journal of experimental biology (Wen et al., 2014).

3.3. Biomechanics & locomotion

Mimicking of efficient natural swimmers (e.g., boxfish) can lead to more energy efficient and maneuverable MUVs (Kodati and Deng, 2006a). Boxfish, with a rigid box-like outer body shape (known as carapace; and whose edges are known as keels) and multiple oscillating fins to cruise and maneuver, is known for its stability to swim smoothly through turbulent waters of coral reefs and demonstrate excellent maneuverability.

As early as 2002, the use of SLA 3D printing technology to study marine locomotion has been demonstrated. 3D printed models of four different species of boxfishes (spotted boxfish *Ostracion meleagris*, smooth trunkfish *Lactophrys triqueter*, scrawled cowfish *Acanthostracion quadricornis*, and buffalo trunkfish *Lactophrys trigonus*) were manufactured (Bartol et al., 2002). 3D printed models of polymerized epoxy resin fabricated using a SLA 3D printer were used to study the role of the carapace in the smooth trunkfish *Lactophrys triqueter* in the hydrodynamic stability of swimming in ostraciid fishes (Bartol et al., 2003). The authors found that the keels of the carapace of the smooth trunkfish produced leading edge vortices capable of generating self-correcting trimming forces during swimming. Furthermore, this research group demonstrated this theory using other tropical boxfishes with different carapace shapes of polymerized epoxy resin fabricated using a SLA 3D printer (Bartol et al., 2005). The 3D printed models were scaled-up in order to improve resolution of digital particle image velocimetry and force balance measurements, and to accommodate more ports in the pressure experiments. In a related work, 3D printed plastic components were used in developing a MUV propelled by an oscillating tail fin and steered by a pair of independent side fins, mimicking the boxfish (Deng and Avadhanula, 2005). SLA 3D printing technology was used to make the outer body shape (Kodati and Deng, 2006a) and an optimal tail fin (Kodati and Deng, 2006b) of a MUV by mimicking the body shape of Boxfish (Spotted boxfish, Buffalo trunkfish). Furthermore, this research group used

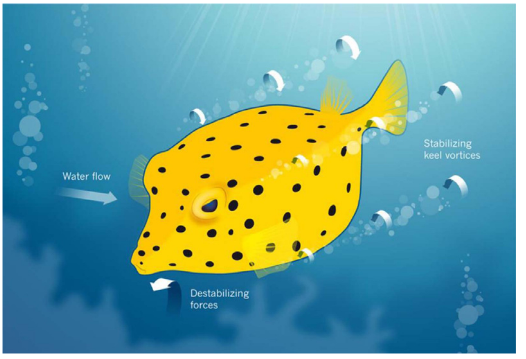

Fig. 7. Boxfish instability: The external skeleton of boxfishes (the carapace) is made up of rigid, fused scales. The edges of this carapace are called keels. Previous research had suggested that water flow leads to vortices forming around the keels that stabilize the boxfishes' movements. However, recent research shows that the effect of these stabilizing vortices is outweighed by the destabilizing forces generated by the boxy front of the boxfish carapace, and this overall instability is what gives the boxfish its remarkable maneuverability.
Source: Reprinted by permission from Macmillan Publishers Ltd: Nature (Farina and Summers, 2015), © 2015.

SLA 3D printing technology to make the outer body shape of improved versions of MUVs (Kodati et al., 2008, 2007).

Until very recently, it was believed that the body shape of Boxfish generates self-correcting trimming forces by shedding counter rotating vortices (generated around the keels) to compensate for the instabilities in turbulent water (Bartol et al., 2005, 2003, 2002; Kodati and Deng, 2006a,b). Very recently, Van Wassenbergh et al. conducted flow-tank experiments using inkjet 3D printed boxfish models (Contex Designmate CX 3D printer) and computational fluid-dynamics simulations, quantifying flow around the entire carapace, to refute the previously believed notion that water movements over the body of boxfishes are a stabilizing influence (Farina and Summers, 2015; Van Wassenbergh et al., 2015). The 3D printed plaster models were impregnated with epoxy resin to make them water resistant. The 3D printed models were also coated using a primer (Motip EAN 8711347040544) and a black paint (Motip EAN 8711347040018). The authors demonstrated that the boxfish's shape amplifies the destabilizing forces to improve maneuverability. Also, the effect of the stabilizing keel vortices was not nearly strong enough to overcome the large destabilizing forces generated by the boxy front of the boxfish carapace leading to overall instability, which provides the boxfish its remarkable maneuverability (Fig. 7).

In an interesting recent demonstration, Porter et al. demonstrated the use of FDM 3D printing (Dimension 1200es 3D printer) technology for understanding the reason behind the square shape of a seahorse tail (Porter et al., 2015). The authors used 3D-printed models (using a rigid thermoplastic ABS*plus*) mimicking the seahorse tail in both square and cylindrical shapes. It was found that the natural square-shaped tail was better compared to the cylindrical model in terms of grasping ability as well as crushing resistance. In another interesting recent demonstration, Tiwary et al. used FDM 3D printed PLA models of two differently shaped seashells (one with diametrically converging localization of stresses and another with helicoidally concentric localization of stresses as shown in Fig. 8) and conducted mechanics-based modeling and experiments (Tiwary et al., 2015). The authors developed a mechanics-based model to explain the evolution of two complex shapes in shells as they grow in nature. It was found that the mechanical load-bearing capacity of the 3D printed PLA replicas was better compared to that of natural seashells.

Deep-sea fishes are known to have muscles that are higher in water content. Apart from watery muscles, some deep-dwelling fishes are known to have a gelatinous layer either directly below the skin or around the spine (Gerringer, 2014). The hypothesis that the gelatinous tissue surrounding the fish's muscle acts as an energetically inexpensive method of increasing swimming efficiency was tested by comparing the swimming performance (using comparative video analysis) in the deep-sea gelatinous hadal snailfish to the swimming performance in the intertidal snailfish (*Liparis florae*) which lacks the

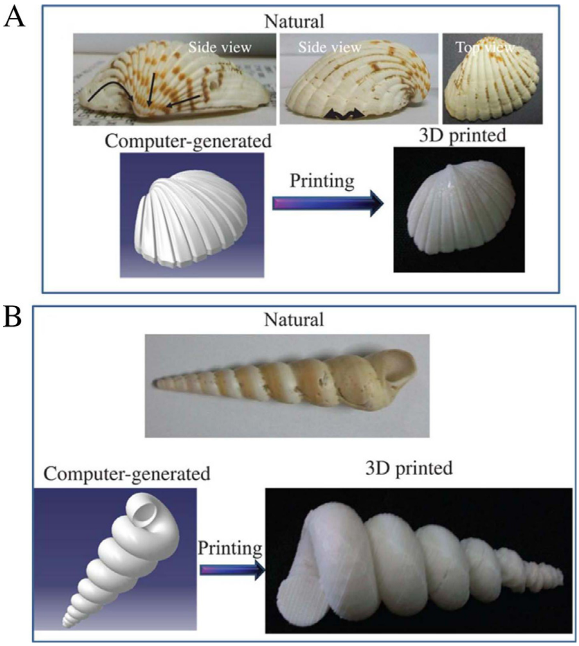

Fig. 8. The natural shells. (A and B) Digital images of (A) shell-1 and (B) shell-2 taken in their natural form at different projections. On the basis of the actual dimension, computer-generated shapes are created and 3D printed.
Source: From Tiwary et al. (2015). Reprinted with permission from AAAS.

subcutaneous gel (Gerringer, 2014). Furthermore, the authors fabricated a robotic snailfish 3D printed PLA model (ORION HB #58744 FDM 3D printer) with/without tail gel to analyze the impacts of the gelatinous layer on the locomotory performance, and found that the gelatinous layer may enhance swimming performance in the hadal snailfish.

It is clear from the above presented examples, that 3D printing technologies can prove handy in gaining better understanding of marine biomechanics and locomotion. 3D printed components that mimic parts of marine creatures are being used to develop improved MUVs. Using 3D printed square-shaped seahorse tails, researchers were able to understand that the natural square-shaped tail was better compared to the cylindrical-shaped tail in terms of grasping ability as well as crushing resistance. Using 3D printed PLA replicas researchers were able to develop a mechanics-based model to explain the evolution of two complex shapes in shells as they grow in nature. 3D printed snailfish models have helped researchers to understand that the gelatinous layer may enhance swimming performance in the hadal snailfish. Table 3 summarizes the 3D printing applications in marine biomechanics and locomotion studies.

3.4. Tracking & surface studies

One of the methods that scientists use for better understanding of the numbers and distribution of fish populations is tracking. Researchers with the Australia's national science agency Commonwealth Scientific and Industrial Research Organization (CSIRO) are using 3D printed (Arcam 3D printer) titanium tags to track big fish (Fernandez Peter, 2014). Titanium was used for printing owing to its strength, non-toxicity, and resistance to corrosion in salty waters. Using 3D printing technology, the researchers can easily optimize the surface texture of the tags to improve retention for longer time, and optimize the tag tip to achieve easiest penetration through fish skin.

Some organisms are known to resist ice formation and growth in subtidal or intertidal environments. Bioinspired 3D printed surfaces (inspired by hard-shelled benthic marine invertebrates) were

Table 3
Summary of 3D printing applications in marine biomechanics and locomotion.

3D printing application	Printer type	Material	Reference
Carapace of boxfishes	SLA	Epoxy resin	(Bartol et al., 2005, 2003, 2002)
	Inkjet (Contex Designmate CX)	Plaster impregnated with epoxy resin and coatedusing primer (Motip EAN 8711347040544) and paint (Motip EAN8711347040018)	(Van Wassenbergh et al., 2015)
Components of MUV mimicking the oscillating fin propulsion of boxfish	Unspecified	Plastic	(Deng and Avadhanula, 2005)
	SLA	Unspecified	(Deng and Avadhanula, 2005; Kodati et al., 2008, 2007; Kodati and Deng, 2006a,b)
Seahorse tail	FDM (Dimension 1200es)	ABS*plus*	(Porter et al., 2015)
Seashells	FDM	PLA	(Tiwary et al., 2015)
Robotic snailfish	FDM (ORION HB #58744)	PLA	(Gerringer, 2014)

Table 4
Summary of 3D printing applications in marine tracking and surface studies.

3D printing application	Printer type	Material	Reference
Fish tracking tags	Electron beam melting(Arcam)	Titanium	(Fernandez Peter, 2014)
Ice-retardant surfaces	MultiJet (ProJet3000)	ABS	(Mehrabani et al., 2014)
Vascularized fouling-release surfaces	PolyJet (Connex500)	VeroBlack resin	(Howell et al., 2014)

used to examine the effect of surface texture on ice formation (Mehrabani et al., 2014). The 3D surfaces were printed with ABS plastic using a MultiJet ProJet 3000 3D printer. The authors found that surface texture plays only a minor role in delaying the onset of ice formation. Further investigations are necessary in order to prepare surfaces that could delay or deter ice formation.

A variety of fouling-release coatings have been developed so far. In a noteworthy example, 3D printed (Stratasys Connex500 PolyJet 3D printer) vascularized molds were manufactured with VeroBlack polyjet photopolymer resin (Howell et al., 2014). The 3D printed mold was used to prepare vascularized silicone-oil-infused polydimethylsiloxane (PDMS) to create bioinspired self-replenishing vascularized fouling-release surfaces. Further investigations down this line could help in combating marine biofouling.

From the examples discussed above, it is clear that the application of 3D printing technologies in these avenues of research is in the budding stage and that there is plenty of room for further exploration and development. Using 3D printed surfaces, researchers were able to develop bioinspired self-replenishing vascularized fouling-release surfaces and also understand that surface texture plays only a minor role in delaying the onset of ice formation. Table 4 summarizes the 3D printing applications in marine tracking and surface studies.

3.5. Tangible coral props & coral reef restoration

Coral reefs are fragile diverse underwater ecosystems. Several studies have documented the decline in the abundance of reef-building corals over the last several decades. In 2009, inkjet 3D printing technology (Z Corporation Spectrum Z510 3D printer) was used to create tangible props for interactive measurement of branching marine coral data (Kruszyński and van Liere, 2009). Computed Tomography scanning (Matsuoka et al., 2012) of specimens (10–15 cm) collected from coral reefs was performed to extract the coral 3D surface data, which was subsequently used to 3D print tangible plaster props Fig. 9(a). A stylus was used for interaction with the props Fig. 9(b). The 3D printed tangible props allowed more efficient and natural interaction in both virtual reality mode

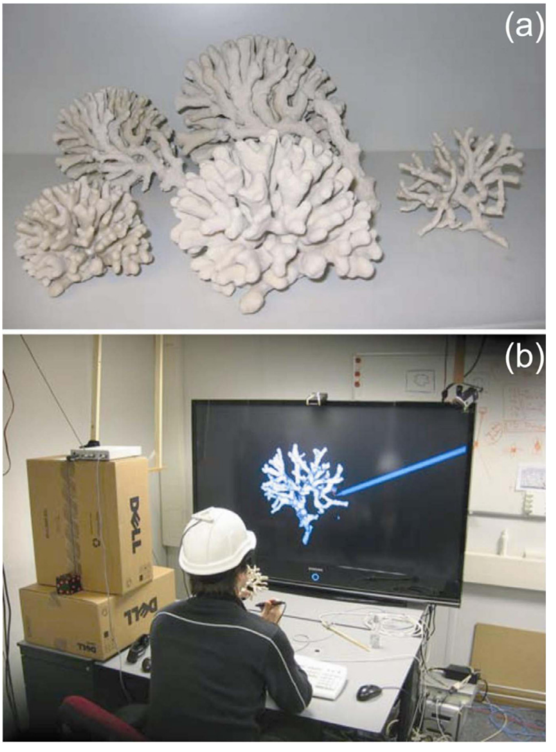

Fig. 9. (a) Tangible props printed from coral data. The front left prop has a diameter of 10 cm. (b) Interactive coral measurement application. The user interacts with the small prop in his hand, while a greatly enlarged virtual representation is seen on the large 67-in. stereoscopic display.
Source: Reprinted from Kruszyński and van Liere (2009) with permission of Springer.

(for magnified visualizations of coral structures) and augmented reality mode (using the 3D printed coral replicas). The 3D printed tangible coral props provide several advantages over using the original corals including avoiding the need for handling the fragile coral, enabling handling of small corals via scaled-up models, and allowing remote collaboration. More recently, 3D imaging of a radiolarian was performed using high-resolution micro-CT. The 3D image data was used to create 3D printed (ZPrinter 450 Inkjet 3D printer) plaster models of the specimen (Ishida et al., 2015). Researchers studying the numerical growth simulation of corals can use 3D printed corals for better understanding of how the simulated coral models compare to the real corals (Kruszyński and van Liere, 2009).

Ocean acidification, decrease in the pH of the oceans caused due to the uptake of carbon dioxide, is estimated to have partially caused millions of dollars of loss to the oyster industry in the United States and estimated to cost the global economy US$1 trillion per year by the end of the century (Cressey, 2015). Albright et al. have very recently presented the results from the first seawater chemistry manipulation experiment of a natural coral reef community (Albright et al., 2016). The results from the study show that ocean acidification may be already damaging coral reef growth. The world is facing coral reef loss at a rapid rate all around the globe. Several steps are being taken towards conserving and restoring coral reefs. The use of construction 3D printing technology was studied for a speculative design for an artificial reef in the Red Sea (Gardiner, 2011). In first of its kind example in 2012, the Australian organization Sustainable Oceans International (SOI) made use of a construction-scale 3D printer (D-Shape) based on powder bed fusion and binder jetting to construct 3D printed reef units containing non-toxic patented sandstone material (SOI, 2012). The first reef units were about 1 m tall and weighed around 500 kg each (Fig. 10). The 3D printed reefs had natural pH surfaces favorable for growth of coral larvae. The use of 3D printing technology allows mimicking the natural complexity

Fig. 10. 3D printed reef unit from a patented sandstone material.
Source: SOI (2012).

(caves and connecting tunnels) and creating diversity in the artificial coral reefs. The 3D printed artificial reef units were put to use for real-life application in the coasts of Bahrain; with about 3000 pre-cast concrete Reef Balls and 3D printed reef units submerged near the coasts (Pardo, 2013; SOI, 2012). In September 2015, it was reported that a New England based Shellfish Company (Woodbury Shellfish, USA) in collaboration with a ceramic 3D printing services company (Tethon 3D, USA) has started to develop 3D printed artificial reefs using inkjet 3D printed ceramic (naturally occurring clay) structures (Grunewald, 2015). The companies hope to boost oyster populations along with restoration of the local marine environment.

It can be seen from the above examples that 3D printing is not only being used in conducting fundamental marine biology studies, but also being applied to real-life applications. 3D printed tangible props allowed more efficient and natural interaction in both virtual reality and augmented reality modes, while avoiding the need for handling the fragile coral and enabling handling of small corals via scaled-up models. 3D printing technologies are allowing researchers to mimic the natural complexity and creating diversity in the artificial coral reefs. 3D printed artificial corals from sandstone and ceramics are being put to use in real-life applications to restore the local marine environment. Recently, the use of FDM 3D printing (3D Touch printer) was explored to create 3D PLA specimens for studying rock mechanics through compressive and tensile strength tests (Jiang and Zhao, 2015). The authors found that the FDM 3D printing of PLA was not suitable for direct simulation of rock, and suggested that an alternative suitable material using FDM 3D printing or a different 3D printing technology need to be explored in order to print 3D grains with arbitrary shapes. The different 3D printed artificial coral reef units can similarly be investigated in order to more closely mimic their real counterparts. Table 5 summarizes the 3D printing applications in tangible coral props and coral reef restoration.

4. 3D printing materials: a note of caution

From the diverse range of examples presented in the previous section, it is evident that 3D printing technologies are opening new avenues in the field of oceanography. Nevertheless, the 3D printed products need to be carefully evaluated. It is estimated that 60%–80% of all marine litter is plastic. In a recent study, Bejgarn et al. presented an initial screening of the marine environmental hazard properties of leachates from different weathering plastics to the marine harpacticoid copepod

Table 5
Summary of 3D printing applications in tangible coral props and coral reef restoration.

3D printing application	Printer type	Material	Reference
Tangible props	Inkjet (Spectrum Z510)	Plaster	(Kruszyński and van Liere, 2009)
	Inkjet (ZPrinter 450)	Plaster	(Ishida et al., 2015)
Coral reef units	Construction-scale powder bed fusion (D-Shape)	Sandstone powder	(Gardiner, 2011; Pardo, 2013; SOI, 2012)
	Inkjet	Ceramic clay	(Grunewald, 2015)

[Crustacea] *Nitocra spinipes* (Bejgarn et al., 2015). The different plastics tested in this study included Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), Polystyrene (PS), Polyethylene terephthalate (PET), Polyurethane (PUR), Bioplastics, Polyisoprene rubber, and PLA (a commonly used FDM 3D printer filament). The authors found that leachates from different plastics differed in toxicity to *N. spinipes* and that the toxicity varied under simulated weathering. In another recent study, Sussarellu et al., exposed adult oysters to virgin polystyrene microspheres (2 and 6 μm) for 2 months during gametogenesis (Sussarellu et al., 2016). It was found that the consumption of microalgae and absorption efficiency were significantly higher in the exposed oysters. Furthermore, at the end of 2 months, the exposed oysters displayed significant decreases in oocyte number, diameter, and sperm velocity. These examples highlight the broader ecological impacts in marine ecosystems due to plastics.

Very recently, Oskui et al. assessed the toxicity of printed parts from two different classes of commercial 3D printers (FDM-based Dimension Elite and SLA-based Form 1+) using zebrafish (*Danio rerio*) embryos (Oskui et al., 2016). The authors fabricated cylindrical 3D test objects using ABS with the FDM 3D printer and using a proprietary photopolymer resin (combination of methacrylated oligomers and monomers and photoinitiators) with the SLA 3D printer. It was found that the 3D printed parts from both classes of printers displayed measurable toxicity, with the SLA-printed parts being more toxic compared to the FDM-printed parts. However, the toxicity of the SLA-printed parts diminished after undergoing a post-printing ultraviolet light treatment Fig. 11(a). In another recent study, Macdonald et al. assessed the biocompatibility of four commercially available 3D printing photopolymers (VisiJet Crystal EX200, WaterShed 11122XC, Dreve Fototec 7150 Clear and ABSplus P-430) using zebrafish embryos (Macdonald et al., 2016). 3D printed test substrates were fabricated with HD3500+ MultiJet 3D printer using VisiJet Crystal EX200 (and VisiJet S300 support), Viper Pro SLA 3D printer using WaterShed 11122XC and Dreve Fototec 7150 Clear, DesignJet FDM 3D printer using ABSplus P-430. Similar to the results from the previously discussed report, the authors found that the 3D printed parts made using all the photopolymers were highly toxic to the zebrafish embryos Fig. 11(b). However, the authors were able to reduce the toxicity of the Fototec 7150 3D printed parts by a post-printing treatment with 99% ethanol. These examples illustrate the negative effects of different 3D printing materials on marine creatures.

5. Conclusions and prospective

Overall, this review has discussed a diverse range of 3D printing applications in oceanography and presented examples under the following subtopics: Ecological Monitoring & Sample Collection, Hydrodynamics, Biomechanics & Locomotion, Tracking & Surface Studies, and Tangible Coral Props & Coral Reef Restoration. Under most of the subtopics, there exist only single-digit examples indicating that plenty more opportunities exist for applying 3D printing technologies in oceanography. Majority of the 3D printing applications have been found in the areas of 3D printed components for use in ecological monitoring vehicles, hydrodynamics or biomechanics or locomotion studies, and coral reef replica construction. A detailed overview of the 3D printing technologies referred to within this review has also been presented, and categorized under the following four general topics: Material Extrusion, Photopolymerization, Powder Bed Fusion, and Construction Printing.

It is clear from the different examples presented in this review that 3D printing technologies are being exploited for a wide variety of applications ranging from fundamental oceanography studies to

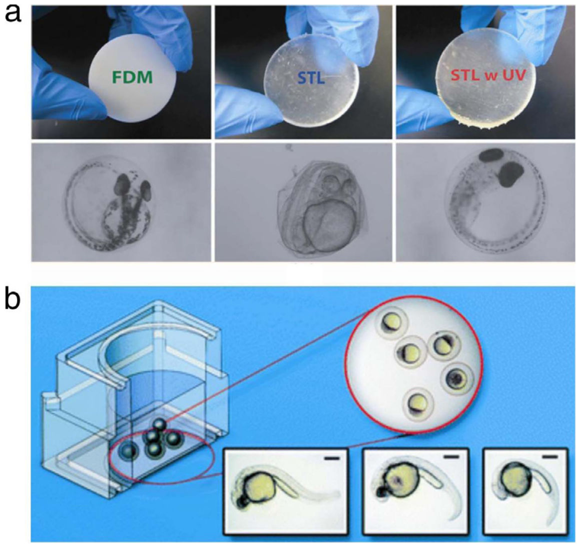

Fig. 11. (a) Examples of the FDM- and STL-printed test parts along with STL-printed part treated with ultraviolet light (STL w UV) to reduce its toxicity (40 mm diameter and 4 mm height) (*Top*), Zebrafish embryos exposed to FDM-, STL-, and (STL w UV)-printed parts. Embryos exposed to (STL w UV)-printed parts developed normal levels of melanophores that were comparable to those of embryos exposed to FDM-printed parts (*Bottom*), (b) Illustration showing a single-well culture device that contains zebrafish embryos at the bottom of the well. Stereomicroscopy images of dechorionated zebrafish embryos immobilized in agar. Control zebrafish embryo cultured in a 24-well plate development is normal (*Bottom-left*). Zebrafish cultured with Watershed material has stunted development (about 2–3 h behind control) along with darkening of yolk sac indicating toxicity as well as roughing and widening yolk extension (*Bottom-center*). Zebrafish cultured on VisiJet Crystal has stunted development (by ca. 5 h). Eyes and brain have not developed, pigmentation is not present, unusual yolk sac and yolk extension shape; all show retardation. Scale bar is 500 μm.
Source: Reprinted from Macdonald et al. (2016). Published by The Royal Society of Chemistry. Reprinted with permission from Oskui et al. (2016). Copyright (2016) American Chemical Society.

real-life applications. Researchers are attempting to maximize the use of 3D printed components in surface/underwater vehicles. 3D printing technologies are also allowing marine biologists to collect observational data and biological samples from marine creatures. An inherent advantage with 3D printing technologies is that they allow easy 3D model scaling-up of organisms to achieve higher Reynolds number, thereby allowing a better understanding of how the flow forces affect the normally scaled organisms in high flow environments. 3D printing is also allowing researchers to closely mimic miniscule details of marine creatures. Such studies could allow researchers to develop marine vehicles with increased swimming speeds and reduced energy consumption. 3D printed models are allowing researchers to easily visualize fluid flow through different internal parts of aquatic creatures. 3D printed components that mimic parts of marine creatures are being used to develop improved MUVs. Using 3D printed square-shaped seahorse tails, researchers are beginning to understand that the natural square-shaped tail are better compared to cylindrical-shaped tail in terms of grasping ability as well as crushing resistance. 3D printed snailfish models are helping researchers to understand that the gelatinous layer may enhance swimming performance in the hadal snailfish. 3D printed tangible props are allowing more efficient and natural interaction in both virtual reality and augmented reality modes, while avoiding the need for handling the fragile coral and enabling handling of small corals via scaled-up models. 3D printing technologies are allowing researchers to mimic the natural complexity and creating diversity in the artificial coral reefs. 3D printed artificial corals from sandstone and ceramics are being put to use in real-life applications to restore the local marine environment.

With studies indicating that ocean acidification may be damaging the coral reef ecosystems, future 3D printed objects intended to be applied to oceanography could incorporate materials with basic pH, especially in the case of artificial coral replicas used for coral restoration. Furthermore, nanotechnologies could be exploited to incorporate slow-release materials that could maintain a basic pH in the micro-environment surrounding the 3D printed artificial coral replicas; contributing towards faster coral reef restoration (Norzagaray-López et al., 2015). Another avenue where nanotechnologies could be exploited is in making 3D printed artificial coral replicas using slow dissolving materials that could eventually create nano-/micro-pores in the artificial coral replicas mimicking the natural porous corals. In calm waters, porous corals have the advantage of possessing fast growth rates. Therefore, porous artificial coral replicas could potentially contribute towards faster coral restoration by allowing living coral to penetrate the porous structures.

In summary, 3D printing technologies offer exciting opportunities for rapid prototyping of complex and customized models at low cost. Nevertheless, thorough investigations similar to the examples discussed in previous section should be conducted for the different 3D printing materials applied to oceanography studies in order to avoid further damage to fragile marine ecosystems (Galloway and Lewis, 2016). It is anticipated that 3D printing technologies will be further exploited for a variety of fundamental studies in oceanography due to the ease, low cost and short time required for evaluating several different 3D models. It is also anticipated that this review will further promote the 3D printing technologies to oceanographers for a better understanding and restoration of fragile marine ecosystems.

Notes. The author declares no competing financial interest.

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