Additive manufacturing aboard a moving vessel at sea using passively stabilized stereolithography (SLA) 3D printing

Phillips, Brennan T.[1,2*]; Allder, Josh[1]; Bolan, Grady[1], Nagle, R. Sean[1]; Redington, Allison[1]; Hellebrekers, Tess[3]; Borden, John[4]; Pawlenko, Nikolai[5]; Licht, Stephen[1]

[1]University of Rhode Island, Department of Ocean Engineering, Narragansett, RI USA
[2]University of Rhode Island, Graduate School of Oceanography, Narragansett, RI USA
[3]Carnegie Mellon University, Robotics Institute, Pittsburgh, PA USA
[4]Peace River Studios, Cambridge, MA USA
[5]NOAA Office of Exploration and Research, Narragansett, RI USA

*Corresponding Author: brennanphillips@uri.edu

Abstract

In this paper we investigate the use of passive stabilization to support stereolithography (SLA) printing aboard a moving vessel at sea. 3D printing is a useful technology onboard a seagoing vessel to support engineering development, shipboard maintenance, and other applications when land-based manufacturing resources are unavailable. SLA printed material is particularly suited for underwater applications requiring sealed housings, since SLA printers are capable of producing high-resolution models that are fully solid and impervious to water. Hydrostatic pressure can quickly compromise parts created using standard fused filament fabrication (FFF) 3D printing. However, the dynamic environment onboard a moving vessel could impact the ability of an SLA printer to selectively cure voxels in a liquid resin bath as it undergoes constant motion, and can cause spilling over the walls of the resin tank. Using passive stabilization platforms onboard moving research vessels, we successfully printed a number of parts with no discernable differences from those produced in a traditional land-based laboratory. As a practical demonstration of this capability, we printed at sea underwater pressure housings that remained sealed to 200 meters water depth with functional integrated internal electronics. No post-print machining was required to create the sealed housings. This work lays the foundation for lithographic 3D printing in seagoing oceanographic and naval applications, and additionally presents an economical approach for producing custom waterproof pressure housings in the field.

Keywords: Vat Photopolymerization; Additive Manufacturing; Oceanography; Stabilization; Pressure Housings

1. Introduction

Lithographic 3D printing can produce high-resolution, rigid prototypes that are completely sealed between print layers [1]. While several variants of laser based lithographic printing are now commercially available, stereolithography (SLA) is credited as the origin of 3D printing technology [2] and remains a commonly used form. SLA 3D printing offers a good compromise between speed, resolution, and build volume, and is now achievable using desktop-size units that cost <5000 USD. SLA printed parts can be completely solid and impervious to water intrusion [3], making them better suited to underwater applications than fused filament fabrication (FFF) printed parts that are subject to void formation [4].

3D printing methodology continues to progress at a rapid pace, but how the printers themselves perform in harsh, remote and dynamic environments is an open question. A commercial effort to conduct rapid prototyping in zero gravity led by Made In Space Inc. (www.madeinspace.us) has met success, with numerous potential applications for current and future space missions [5,6]. 3D printers have been used successfully at sea to print both soft and hard materials [7], enabling rapid prototyping during extended oceanographic research expeditions. In both of these examples FFF-based printing was employed in the dynamic environment, while the resolution and solid material properties of the parts produced was ultimately limited by the capabilities of the FFF printers. SLA-based 3D printers are currently operated exclusively in land-based laboratory, office, and production facility environments, where the printer is kept on a level surface and isolated from any significant outside forces. There is some evidence suggesting that external vibrations could benefit SLA printing by reducing the separation force required to overcome between layers [8]. While this study does not directly investigate the effects of vibration caused by the vessel itself on the printing process, we instead focus on maintaining a level environment to prevent SLA printing process errors [9] such as improperly calibrated z-level wait times, trapped volumes, inconsistencies in layering, and mitigating the risk of resin spillage.

There are many uses for 3D printers onboard seagoing vessels, but the solid and sealable nature of SLA-printed parts has unique applications for the underwater environment. Most electronic components used for ocean sensing underwater are maintained in a dry volume at 1 atm pressure inside sealed pressure housings. Such pressure housings are typically manufactured for custom applications at a premium cost using a range of materials including polymers, composites, and metals. High-pressure housings (>100 meter depth/150 psi rating) demand tight tolerances and smooth surfaces for o-ring seals and are almost exclusively custom-made. 3D printing has been proposed as a manufacturing technique for customized pressure housings, with examples including titanium and ceramic hemispheres [10] and nylon and titanium nose and tail sections for unmanned underwater vehicles [11]. However, the methods presented in the literature each rely on some form of conventional manufacturing process in order to finish the sealing surfaces after the bulk of the housing has been printed. These restrictions result in long fabrication schedules and extensive onboard spare inventories for underwater equipment that is taken to sea.

In this paper we present the first known attempt to conduct lithographic resin 3D printing while subjecting the operating printer to constant motion and vibration onboard a seagoing vessel, with the working hypothesis that a properly tuned stabilization platform will provide a sufficient environment to successfully produce SLA prints comparable to those done in a land-based environment. Using passive stabilization systems, various test designs and two sealed pressure housings were printed on moving offshore vessels. The printed housings were outfitted with electronic pressure sensors and tested *in situ* to 200 meters depth without any additional manufacturing processes employed for finishing. Our results validate the use of passively stabilized lithographic SLA resin printing in a dynamic environment, and we demonstrate the ability to rapidly produce customized, inexpensive, and functional deep-sea pressure housings in the field.

2. Methods

A Formlabs Form 2 3D printer (www.formlabs.com) was used to investigate SLA 3D printing under dynamic conditions. The Form 2 printer has a usable print volume of 14.5 x 14.5 x 17.5 cm, a mounting footprint of 34.5 x 33 cm, and a total height of 52 cm, making it suitable for installation in the interior laboratory spaces available on regional class oceanographic research vessels without modification to the ship. Standard clear resin was chosen from a range of print materials from the manufacturer as a compromise between print speed and mechanical strength. Formlabs' Preform print preparation software (versions 2.18.0 – 3.0.0) was used during the course of this project, with all prints run using medium (50 micron) layer thickness. Models were manually arranged in the print layout and supports automatically generated, and any supports interfering with o-ring sealing surfaces were manually removed prior to running the print. Following each print, parts were washed for approximately 10 minutes in >90% isopropyl alcohol, dried, and post-cured using the Formlabs Form Cure unit. Support structures were removed using flush-cut cutters and surfaces smoothed using 220 grit sandpaper. Two custom printed 'splash guards' were added to either side of the printer's resin tank to reduce the risk of resin overflow during wiper motion.

Field tests were conducted during two oceanographic research cruises onboard the NOAA Ship *Okeanos Explorer* (Caribbean, November 2018) and the R/V *Endeavor* (North Atlantic, April 2019). The printer and stabilization systems were operated in interior laboratory spaces located one deck above the waterline and as close as possible to the longitudinal and transverse centerlines of the vessel. In both sets of trials, mild to moderate seas were experienced while vessel navigation proceeded in accordance with normal operations.

Print trials at sea were performed with the printer mounted rigidly to a laboratory bench, and with the printer mounted on two different passive gimbal stabilization systems. The first passive gimbal system was a modified Peace River Studios GyroPro™ stabilization unit (www.peaceriverstudios.com/). The GyroPro™ was originally designed as an aid for camera operators using large-format camera systems onboard

ships, aircraft, and other moving platforms. For this effort, the printer was mounted to the gimbal platform of the GyroPro™, which provided isolation from the roll and pitch motion of the ship deck through two pairs of bearings, oriented parallel to the deck and offset from one another by 90 degrees. Vibration damping was also included in this system, through a set of six inflatable air isolation mounts. The printer was mounted in place of the active stabilization system which under normal GyroPro operation uses six spinning flywheels to resist angular motion in roll, pitch, and yaw. The yaw angle of the entire system was physically restrained to prevent rotation relative to the ship's heading.

Following initial trials with the modified GyroPro, a passive gimbal system with vibration isolation and adjustable counterweights was designed and fabricated specifically for the second set of at-sea trials with the Form 2 printer. The redesigned system lowers the Form 2 printer deeper into the gimbal, in order to align the printer's tank wiper vertically with the two axes of gimbal rotation (Figure 1B-C) in order to reduce the torque applied about the bearings during the rapid lateral motion of the wiper between print layers. The redesigned stabilization platform disassembles easily and folds flat for packing, and weighs 30 lb/13.6 kg (Figure 1D).

During all print trials, the roll and pitch angles of the printer and of the ship deck were estimated using a pair of 3-axis accelerometers (MMA8452Q Triple Axis Accelerometer, Sparkfun Electronics) recorded at 20 Hz by an embedded processor (MBED LPC1768, Sparkfun Electronics). One accelerometer was mounted to the printer itself, and the other was mounted on the stand supporting the entire system (Figure 1A-B). A set of shapes which fit together within the print volume, including a 1cm cube, three 'dogbone'-style tensile test strips, and a complex- geometry shape, were used as the sample print job for comparison across different cases, in addition to the pressure housings described in the Results section.

3. Results

As a control case, we attempted to print onboard a moving vessel in calm seas with no stabilization system, i.e. with the printer directly mounted to a laboratory bench. An internal software lockout on the Form 2 printer prevents the printer from initiating a new print layer when a tilt angle of greater than 1 degree is detected. The attempt to print the sample print job was aborted after a few print layers, as wait times on the order of minutes were required at the start of each layer before the level condition was sensed.

Error-free prints were completed using both passive stabilization systems, i.e. with the two-axis gimbal platform of the GyroPro and an 11 kg counterweight (Figure 1A), and with the more compact purpose built stabilization system (Figure 1B-C). The counterweights used were either standard steel barbells or lead weights, mounted directly underneath the printer mounting plate with a threaded rod and nut. In testing using counterweights ranging from 15 to 50 lb (6.8 to 22.7 kg), the printer motion was most effectively minimized with a counterweight of 35 lb/16 kg. The ultimate location of the counterweight was adjusted to allow the greatest freedom of motion within the gimbal while lowering the center of gravity of the system as much as possible; different sized weights required different positioning. The empirically-derived optimum counterweight of 35 lb/ 16 kg resulted in a natural frequency in roll of the system of approximately 0.69 Hz based on unforced oscillation trials performed on land.

Deck and printer roll motions for a 30 minute portion of a print job on board the R/V *Endeavor*, and for the duration of a single print layer, are shown in Figure 2. Data from the accelerometer mounted directly on the printer revealed deviations of <1° from level during active printing throughout all trials, despite experiencing deck tilts in excess of 7°. Between printing of vertical layers, the printer wiper induces significant printer roll motion, but this did not affect the quality of the print (Figure 3) nor does it affect the total print time, as the printer naturally returned to level after the wiper ceased moving. As a print progresses in the Form 2, resin material levels change and the build plate position progresses upwards; these variances in

the center of gravity of the system did not appear to affect stabilization performance. During both sea trials, relatively calm seas were experienced with no pitch/roll events exceeding 8°. Further work is required to determine the limits of sea state during which active printing can continue, but the geometry of the purpose-built passive stabilization system allows for up to 30° of pitch and roll motion relative to the system's base.

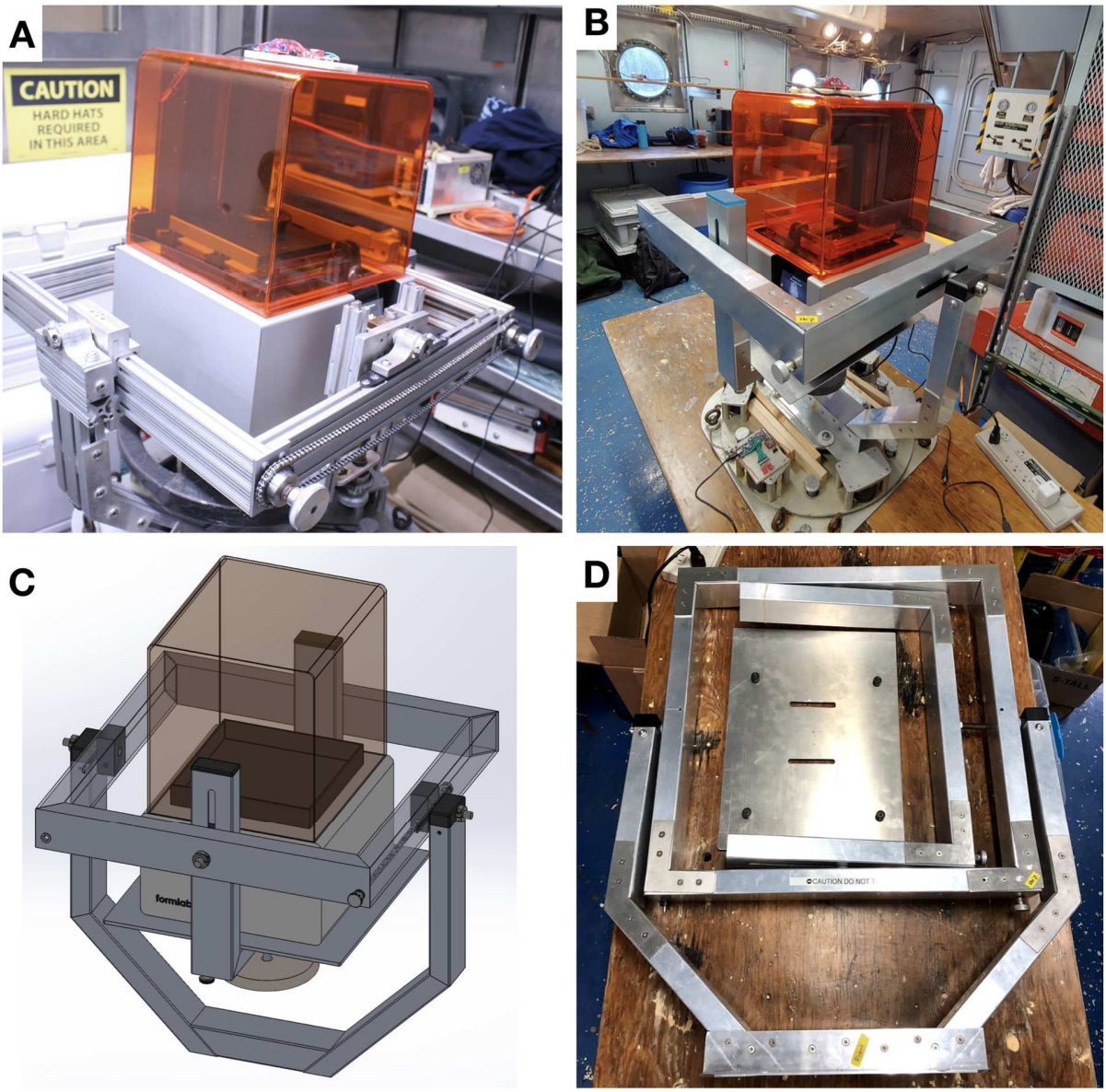

Figure 1: A) SLA 3D printer mounted on a passive gimbal platform onboard a moving research vessel. An 11 kg counterweight is mounted beneath the printer to balance the system and lower the center of gravity. B-C) Optimized 2nd-generation passive gimbal platform onboard a research vessel, designed to align printer tank wiper motion in-line with axes of rotation, along with adjustable counterweight system. D) The entire stabilization platform disassembles flat and weighs a total of 30 lb/ 13.6kg without the counterweight.

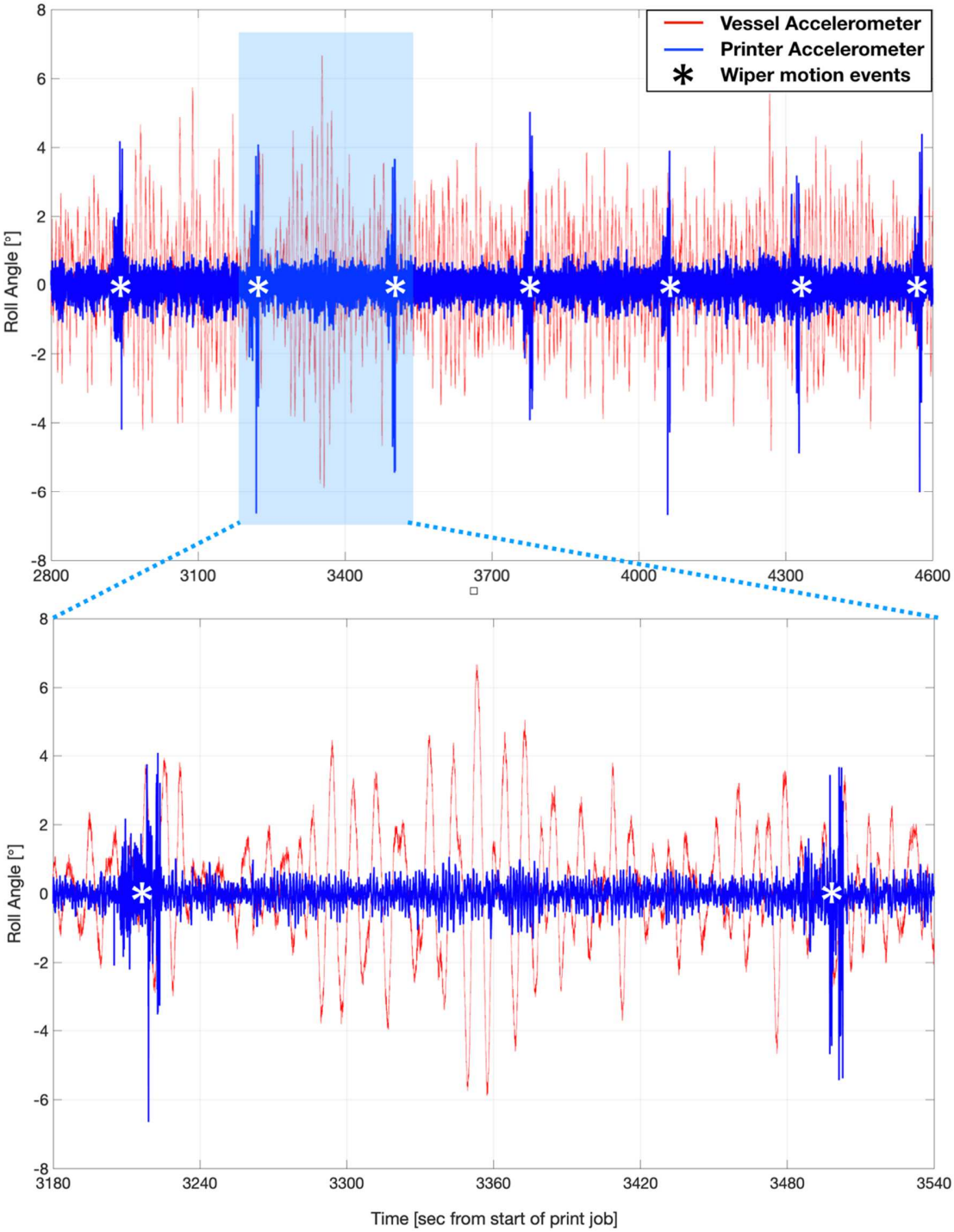

Figure 2: Example accelerometer data collected from the printer, compared against vessel motion experienced directly underneath the stabilized platform. Major roll events on the printer itself are associated with print tray wiper motion that occurs between each layer of printing.

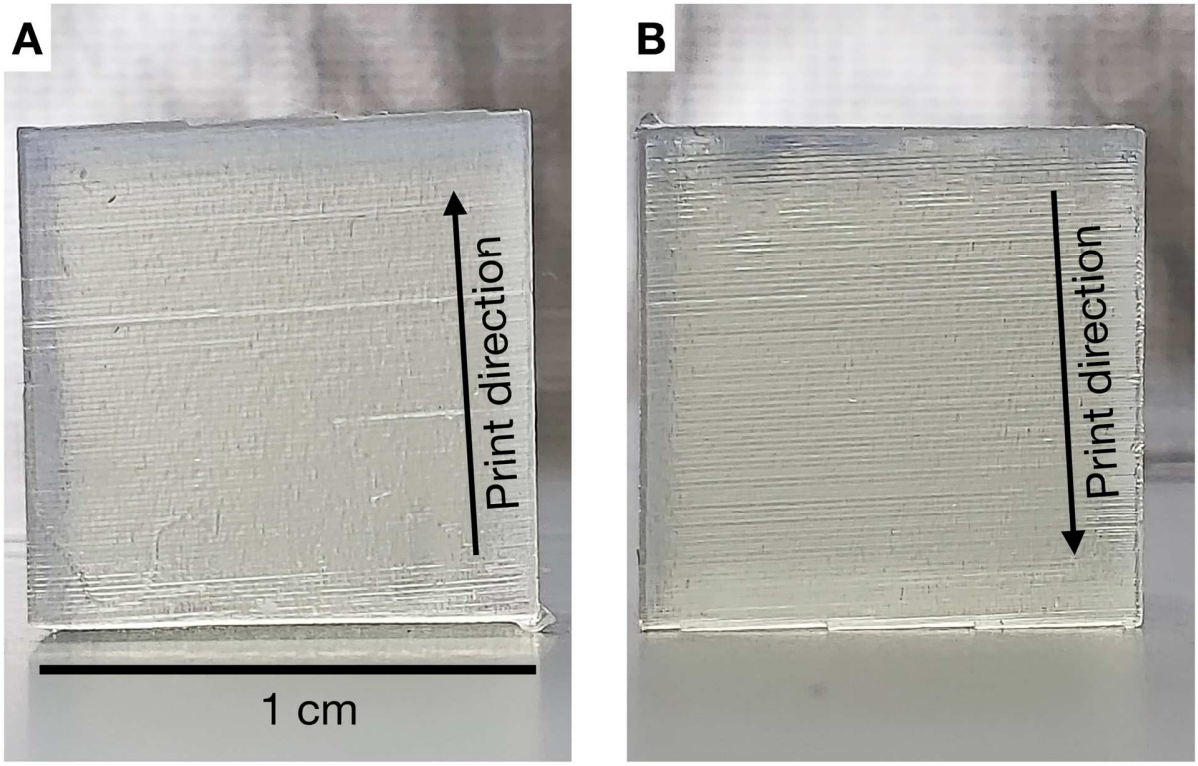

Figure 3: Visual comparison of print quality on a 1x1x1 cm cube, printed A) on land in the laboratory and B) onboard a moving vessel with passive gimbal stabilization.

To demonstrate the potential of shipboard SLA 3D printing to serve real-world applications, a pressure housing design was printed during the sea trials (Figure 4). The design consists of a 2" ID sphere with 0.25" wall thickness, divided into two hemispheres, each with a 7/16" through hole at the apex of the hemisphere. Each hole included interior and exterior flat surfaces for washer and o-ring seating. One hemisphere was printed with an o-ring groove at the mating surface, while the other was printed with a flat surface in order to create an o-ring face seal. Matching hole patterns in exterior flanges allowed mating with standard stainless steel fasteners. The same design was also printed on land prior to sea-trials for comparison. Inside each sphere, an Arduino-based data logger (Feather M0 Adalogger; Adafruit) and lithium polymer battery (37V 350mAh; Adafruit) was installed with an external pressure sensor (Bar30; Blue Robotics) mounted in the hole at the apex of one hemisphere, and a plug mounted in the other hemisphere. A mounting pattern for the internal components was integrated into the hemisphere design, simplifying assembly.

Once assembled, the two complete pressure housings (one printed on land, the other printed at sea) with pressure data loggers were installed on a conductivity-temperature-depth rosette (CTD) frame (Figure 5A). These were lowered by cable from the ship to a depth of 200m to determine whether they remained watertight and pressure tolerant. Both 'instruments' survived the deployment and collected accurate depth data, which was consistent between the two housings (Figure 5B).

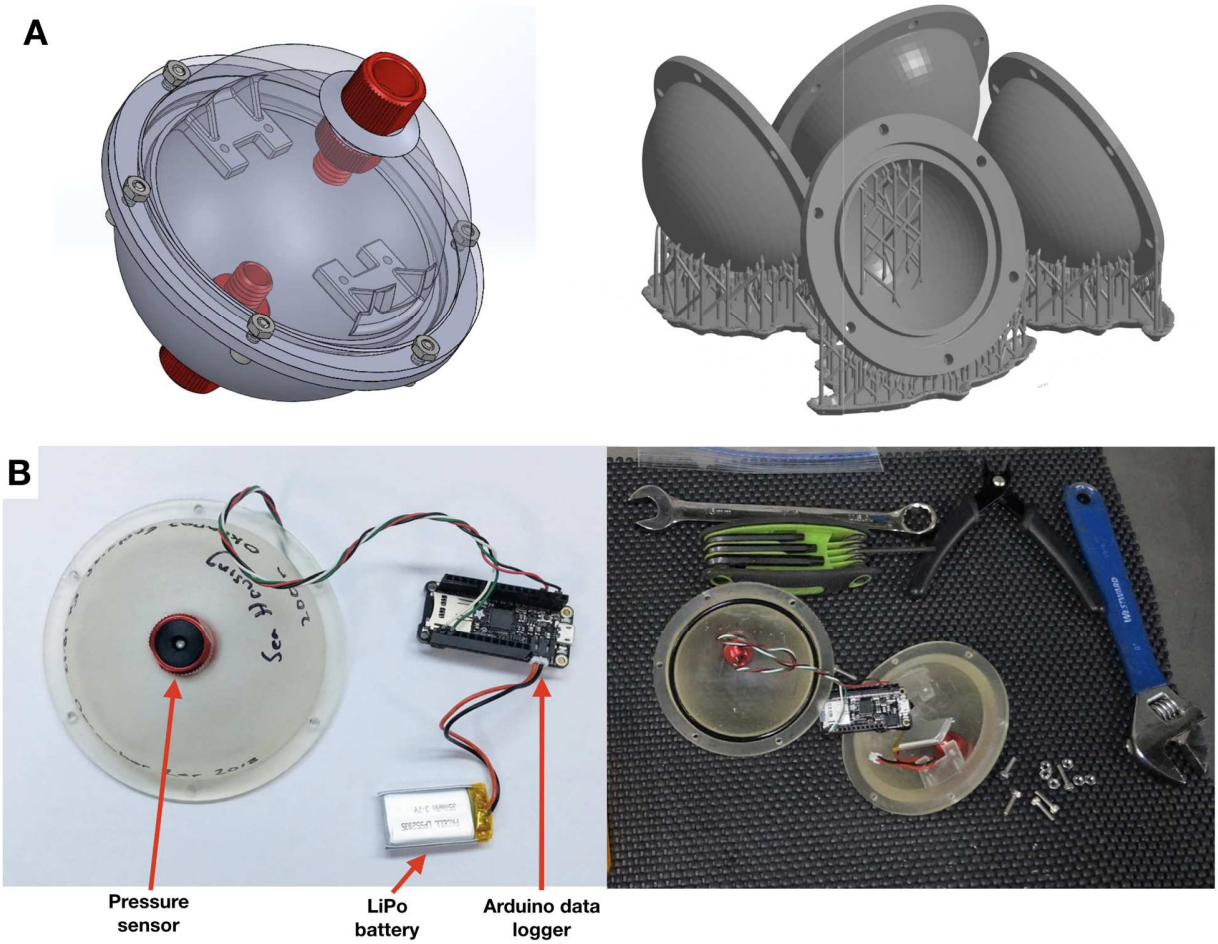

Figure 4: A) 3D model/print layout of 3D-printed pressure housing design, as shown in Solidworks and Formlabs' Preform software. Note support structures in the print layout are restricted to non-sealing surfaces. B) Pressure housings under assembly at sea, with pressure data logger system installed.

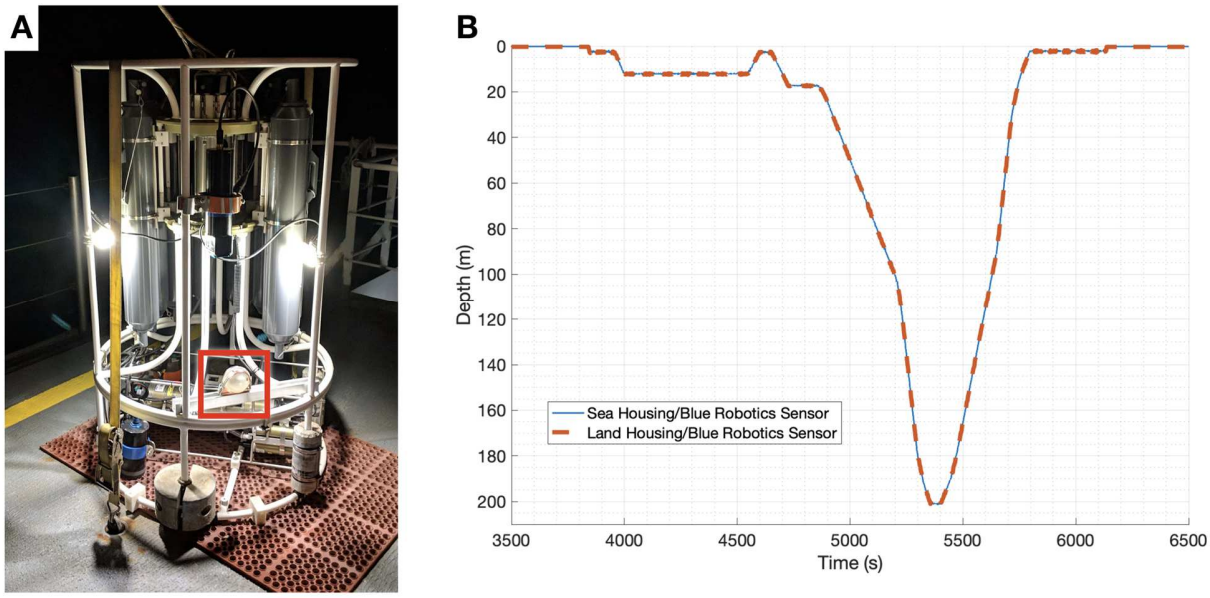

Figure 5: A) 3D printed pressure housing mounted onboard an instrument frame, prior to deployment in the ocean. The housing location is shown in the blue inset. B) Deployment profile, measured using electronic pressure sensors mounted inside the pressure housings. A pressure housing printed on land in the laboratory was tested for comparison.

4. Discussion

Rapid prototyping in dynamic environments, including seagoing vessels and aerospace platforms, has growing potential for a wide range of purposes. As additive manufacturing research advances, the physical size, resolution, mechanical properties, and overall functionality of printed designs will continue to deliver new applications. Aside from the demonstration in this study to produce functional underwater housings, 3D-printed parts produced in the field can be used to replace faulty mechanical components of many existing systems, and can allow for rapid adaptation to changing objectives as demonstrated by Vogt et al. [7]. SLA 3D printing can be used in dentistry for applications such as molds, braces, and crowns [12, 13] and as a result extended research cruises and naval vessel deployments will directly benefit from stabilized SLA printing.

Stabilization systems vary widely in functionality and complexity, ranging from feedback-based active stabilization platforms to simple passive gimbal systems. The work demonstrated here using a passive gimbal to successfully achieve SLA printing presents an economical pathway forward for developers and consumers to produce resin-based parts in active environments. The system is also fairly compact, and can be mobilized using air-shipment methods along with the printer itself. New lithographic 3D printers are continually being introduced to the commercial market, including improved SLA-based systems and digital light projection (DLP) printers. We expect that passive stabilization systems will also be applicable to these new printers, scaled only in physical size and the required amount of counterweight.

Conclusion

In this paper we demonstrate the use of a passive stabilization system to achieve SLA 3D printing onboard a seagoing vessel. When properly stabilized, the performance of the printer at sea was the same as

observed on land. Fully functional underwater pressure housings were also printed at sea, as an example of a practical application of this new capability. Numerous other applications of this method are foreseen for oceanographic, naval, and commercial purposes.

Acknowledgements

The authors wish to thank David Taggart, Jim Miller, Stephan Grilli, Raymond Wright and Jared Abdirken for their support in providing materials and travel funding for this project. In addition, we wish to thank James LeBlanc and Chris Ambrosini from NUWC-Newport for their advisement, and Gail Paolino, Krystal Hazard, and Robin Freeland for their administrative and technical support. We thank Lora Van Uffelen, Catalina Martinez, the crew of the R/V *Endeavor* and the NOAA Ship *Okeanos Explorer* for their logistical support.

Funding: This work was supported by NOAA Award# NA18OAR0110288 to B. Phillips and S. Licht and was partially supported by ONR grant N000141712722. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research.

References

[1] R.L. Truby, J.A. Lewis, Printing soft matter in three dimensions, Nat. 540 (2016) 371-378, https://doi.org/10.1038/nature21003

[2] C.W. Hull, Apparatus for production of three-dimensional objects by stereolithography, U.S. Patent No. 4,575,330 (1986).

[3] J.S. Mohammed, Applications of 3D printing technologies in oceanography, Methods in Oceanog. 17 (2016) 97-117, https://doi.org/10.1016/j.mio.2016.08.001

[4] T.D. Ngo, A. Kashani, G. Imbalzano, K.T. Nguyen., D. Hui, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Composites, Part B 143 (2018) 172-196, https://doi.org/10.1016/j.compositesb.2018.02.012

[5] N. Leach, 3D printing in space, Archit. Des. 84(6) (2014) 108-113, https://doi.org/10.1002/ad.1840

[6] E. Goldstein, Just hit print, Aerosp. Am. 52(6) (2014) 38-42.

[7] D.M. Vogt, K.P. Becker, B.T. Phillips, M.A. Graule, R.D. Rotjan, T.M. Shank, E.E. Cordes, R.J. Wood, D.F. Gruber, Shipboard design and fabrication of custom 3D-printed soft robotic manipulators for the investigation of delicate deep-sea organisms, PloS One 13(8) (2018) e0200386, https://doi.org/10.1371/journal.pone.0200386

[8] J. Jin, J. Yang, H. Mao, Y. Chen, A vibration-assisted method to reduce separation force for stereolithography, J. Manuf. Process. 34 (2018) 793-801, https://doi.org/10.1016/j.jmapro.2018.03.052

[9] A.P. West, S.P. Sambu, D.W. Rosen, A process planning method for improving build performance in stereolithography, Comput.-Aided Des. 33(1) (2001) 65-79, https://doi.org/10.1016/S0010-4485(00)00064-6

[10] K. Breddermann, P. Drescher, C. Polzin, H. Seitz, M. Paschen, Printed pressure housings for underwater applications, Ocean Eng. 113 (2016) 57-63, https://doi.org/10.1016/j.oceaneng.2015.12.033

[11] J. Manley, J. Smith, Taking UUV's Faster, Further & Deeper, Mar. Technol. Report. 61:5 (2018) 42-46.

[12] J.W. Stansbury, M.J. Idacavage, 3D printing with polymers: Challenges among expanding options and opportunities, Dent. Mater. 32(1) (2016) 54-64, https://doi.org/10.1016/j.dental.2015.09.018

[13] V.N.V. Madhav, R. Daule, Rapid prototyping and its application in dentistry, J. Dent. Allied Sciences 2(2) (2013) 57-61, http://dx.doi.org/10.4103/2277-4696.159285