DEEPi: A miniaturized, robust, and economical camera and computer system for deep-sea exploration

Short Running Title: A miniaturized deep-sea camera system

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Acknowledgements: The authors wish to thank Kaitlin Noyes (BIOS), Alan Turchik (National Geographic Society), Laura-Ashley Henderson, Roxanne Beinart, and Corrina Breusing for their assistance with field trials, and Chris Roman, David Casagrande, Rendhy Sapiie and for their assistance with field and laboratory pressure testing. We thank Corinne Quane for her assistance in refining the DEEPi assembly process. This work was supported in part by NOAA Award# NA18OAR0110288 to B. Phillips and S. Licht.

Abstract

Cameras are essential components to almost every underwater vehicle including ROV's, AUV's, manned submersibles, ocean observatories, and baited remote underwater video systems (BRUVs). Deep-sea cameras are traditionally expensive components, and are almost exclusively fabricated as one-atmosphere pressure housings made of aluminum, stainless steel or titanium, combined with custom-made optical viewports. In autonomous recording systems such as BRUVs and biologging animal tags, camera size and form factor directly influences the physical design of the entire system and limits the operational endurance. In this paper, we describe a novel design for DEEPi, a deep-sea imaging and control system based on the Raspberry Pi family of single-board computers. The DEEPi camera is an extremely compact remote head unit (~16 ml volume), can operate to depths of at least 5500m, and uses a photopolymer 3D-printed shell partially filled with epoxy as a pressure housing. A flat polished borosilicate glass disc serves as the optical viewport, and protects the lens assembly from pressure and water intrusion. The control computer is completely potted in epoxy, and is accessible through a wifi connection. The DEEPi system is described in detail, along with example imagery from deep-sea deployments to depths of up to 1096m.

Keywords: Oceans and Seas, 3D Printing, Robotics, Bermuda

Introduction

Imaging systems, either live or recorded, are a requirement for the vast majority of deep-sea vehicles and instrument platforms. Tethered ROV's often incorporate six or more cameras from different viewpoints, while power and payload restrictions often limit autonomous systems to single-camera arrangements. Due to the need to maintain digital camera optics (sensor and lens assembly) in a 1-atmosphere dry environment, all existing deep-sea cameras are completely housed inside pressure housings made of aluminum, titanium, or stainless steel that have a flat or hemispherical optical viewport. Such housings are costly to fabricate, and are large compared to the camera itself. As a result deep-sea cameras are expensive, bulky components of underwater vehicles and remote systems; this is particularly true for HD- and higher-resolution cameras. These restrictions limit the capability, system inventory, and deployment opportunities available to a growing community of marine roboticists and ocean scientists.

Recent advances in commercially-available 3D printing, specifically stereolithography-based (SLA) printing systems utilizing photopolymer resin, offer the advantage of creating completely solid parts in high resolution. This technology enables rapid prototyping of marine-relevant design features such as o-ring seals, ribbon-cable passthroughs, and complex internal geometries (Phillips et al., *in prep*). The DEEPi camera design leverages these capabilities by housing a miniature board-mounted camera inside a 3D printed shell that is designed to guide assembly and the exact placement of epoxy-filling (Figure 1A). The SLA-printed shell has the added benefit of reinforcing the entire assembly with a material that is of a higher tensile strength (65 MPa), tensile modulus (2.8 GPa), and flexural modulus (2.2 GPa) than most rigid urethane epoxy materials, allowing for an increased depth/pressure rating compared with a purely epoxy-potted design. The simple viewport design allows for quick and easy access for lens focusing, and the entire housing design is easily incorporated into larger geometries such as fairings, mounts, and multi-camera arrays. Aside from the 3D printer itself, no heavy shop machinery (lathe, mill, etc.) is necessary to fabricate the DEEPi system, making it an economically-viable deep-sea instrument design particularly appropriate for research and educational purposes. This is further enabled by the global open-source community using Raspberry Pi for technology development.

In this paper we detail the mechanical design for the DEEPi system including the 3D-printed housing/partially epoxy-filled camera unit, the epoxy-potted Raspberry Pi control computer, and waterproofed ribbon cable. Example imagery from the system operating at depth in the field is also presented. This work represents a significant reduction in the size, form factor, and cost required to obtain HD imagery from the deep ocean, with broad-ranging applications envisioned for the scientific, education, defense, and commercial sectors.

Methods

Specific electronic components used in the DEEPi system are described in detail in the Results section. 3D printed components were created using a Formlabs Form 2 SLA-based printer using standard clear resin, which were washed in >90% isopropyl alcohol and post-cured using the Form Cure unit according to manufacturer specifications. Epoxy potting was accomplished using Crystal Clear™ 202 (Smooth-On), injected into 3D-printed shells using plastic syringes, and de-bubbled using a standard vacuum/pressure chamber process. All epoxy-filled parts were left to cure for at least 5 days at ~20 C prior to pressure testing. External sealing of ribbon cable and power cable pass-throughs was made using either silicone adhesive glue or hot-melt glue. Ribbon cables were waterproofed using Scotchkast™ 2131 flame retardant electrical insulating resin (3M).

Laboratory pressure testing was conducted using a custom small-volume high pressure test chamber located at the University of Rhode Island. Field tests were conducted in March 2019 in deep water south of Bermuda, in collaboration with the Bermuda Institute of Ocean Sciences (BIOS). The DEEPi cameras were attached to a custom free-falling baited remote underwater video system (BRUVs) equipped with floatation, a Li-ion battery pack in a pressure housing, two potted LED lights (SiteLite, Juice Robotics, USA), a depth/temperature logger (DST centi-TD, Star-Oddi, Iceland) and an acoustic release system (Edgetech, USA) (Figure 1B).

Results

Camera Design

The DEEPi camera is based on the Raspberry Pi Camera Module v2, which is capable of capturing 8MP still images and 1080p30 video with a field of view of 62.2 degrees (https://www.raspberrypi.org/documentation/hardware/camera/). This camera module was chosen due to its high resolution, small form factor, low cost, and extensive inventory of open-source control software and documentation available for Raspberry Pi systems. The Camera Module v2 consists of a Sony IMX219PQ image sensor and lens assembly, which is mounted on a PCB containing several solid-state electronic components such as MOSFET arrays, linear and switching voltage regulators, common mode chokes, and an authentication IC chip. Aside from the image sensor and lens assembly, all of these components are considered viable for pressure-tolerant underwater packaging (Bingham 2013).

The Camera Module v2 is mounted inside a 3D-printed 'shell' consisting of two halves (Figure 2). The lower half mounts the PCB board and includes the ribbon-cable pass-through, which is dimensioned slightly larger than the ribbon cable itself. The base of the lower half is thickened purposely to increase the pressure tolerance of the unit beyond what is possible by epoxy potting alone. The upper half of the camera shell consists of the viewport mount, o-ring seal, and retaining ring. Internal dimensions of the shell assembly are designed to visually guide epoxy filling on a level surface, so that the viewport and o-ring seal are supported underneath with filled material while the lens assembly remains dry and accessible for focusing (Figure 3). An internal chamfer is also included to allow any remaining bubbles in the epoxy to float towards the viewport, where they can be released. The viewport chosen for the camera unit is a 25.4 mm diameter, 6.35 mm thick polished borosilicate disk, sealed using a standard Buna-N o-ring (Dash No. 115), and pre-loaded under light external pressure using a single-turn stainless streel spiral internal retaining ring. The overall design of the DEEPi camera head presented here is filed under US Provisional Patent Application 62/870,561.

Control Computer

The Raspberry Pi Zero W was chosen to control the camera module due to its extremely compact form factor, ability to run a full Linux operating system, wi-fi connectivity, and low cost. The Zero W is based on a Broadcom BCM2835 ARM processor and includes an array of surface-mount components, including two quartz oscillators. The oscillators are the only known components on the board to contain an air void, and so prior to epoxy-potting the entire computer, the oscillators were surface reinforced using a high-strength epoxy (JB Weld 8272 MarineWeld). This material has a higher tensile strength (27 MPa) compared with the surrounding casting epoxy material (24 MPa). A single 3D-printed shell was used to mount the computer and includes the same ribbon-cable pass-through design used in the camera module. Using an extended CSI-style ribbon cable, the camera unit can be placed up to 2m away from the control computer. The ribbon cable and CSI extender module is waterproofed using cable insulating resin that is poured directly over the cable on a flat surface, and excess is cut off using a razor blade. Power for the computer (5VDC) is provided through two single-conductor waterproof cables.

The built-in wifi modem on the Zero W allows for 'headless' control of the computer via SSH or RealVNC® Remote Desktop using a static IP address and a dedicated wifi network. A custom Python library was created to configure remote streaming of imagery from each control computer, toggle video and/or capture still imagery, and initiate/terminate recording events. Source code is provided open-source via a Github repository (https://github.com/rshom/DEEPi). Power consumption of each DEEPi system during field recordings ranged from 0.22-0.4A at 5VDC (1.1-2W). Recorded files were divided into 12-minute segments and stored in internal memory. Following each field deployment, recorded video was downloaded using standard FTP protocol.

Laboratory and Field Tests

The DEEPi camera system has been laboratory tested for functionality and physical resistance to implosion to a maximum of 59 MPa/5780 m depth. Iterative camera and computer designs were tested in the laboratory using a high-pressure hydraulic pressure chamber. Cameras were assessed for functionality before, during, and after testing to determine survival and performance, while potted Raspberry Pi computers were powered on and communicating via SSH and/or RealVNC® Remote Desktop throughout pressure cycling. Repeated pressure cycling and long-duration holds of DEEPi components under various temperature conditions remain to be conducted, while field testing has served as a viable method for determining the robustness and viability of the design.

Following successful laboratory testing, two field deployments of DEEPi cameras were conducted in deep water approximately 7km due East of Castle Harbor, Bermuda. Two DEEPi cameras and control computers were attached to a free-falling BRUV lander system equipped with lights and a depth/temperature logger. In this original configuration, the Raspberry Pi Zero W computers were not epoxy potted; ribbon-cable pass-throughs were 3D printed into a custom, thick bulkhead attached to a standard 1 atmosphere titanium housing (Figure 1B). During the first deployment to 715m depth (ambient temperature 10.8 C) both cameras recorded video for approximately 2 hours at depth. The second deployment to 1096m depth (ambient temperature 5.3 C) recorded successfully for approximately 6 hours at depth. The BRUVs recorded HD video of several deep-sea fish species including dogfish sharks, a cutthroat eel, and sixgill sharks (Figure 4, Supplementary Material).

A second field test was conducted in September 2019 using DEEPi cameras and completely potted DEEPi control computers, configured to stream live video to the surface via wifi and an ethernet-to-fiber media converter (Figure 1C). Wifi and Bluetooth connectivity is possible through seawater over very short (centimeter-scale) distances; taking advantage of this possibility, we demonstrated the ability to livestream multiple DEEPi camera feeds to the surface using an ethernet-to-fiber converter and fiber-optic cable to the surface. This imagery was used to visually guide deep-sea benthic grabs at depths of 395m in Baltimore Canyon, located due East off the coast of Maryland, USA on the continental shelf break.

Discussion

The DEEPi camera is a ~25 mm cube, operates to at least 5500m depth, and is capable of recording HD video and 8-megapixel still images, making it the smallest form factor HD deep-sea camera system available present-day. As a remote unit, the camera can be located up to 2m away from the control computer allowing for a wide range of mounting configurations. The camera can also be physically combined with the control computer as a single unit. The total cost of materials required to produce each DEEPi system (separate of battery) is <$100USD; this value is subject to options such as SD card size and can be further reduced when produced in quantity. Since no specialized tools are required to build the DEEPi camera and control computer (3D-printed parts can be ordered online from a number of services), the design we present here is viable for sharing with a broad research and educational community. This open-source framework is envisioned to be similar to that described by Cazenave et al. (2014) for the 300m-rated SeeStar camera system.

In recent years several miniaturized deep-sea cameras have been developed for biologging/animal-borne sensor packages (e.g. Marshall et al. 2007, Calambokidis et al. 2007, Rosen et al. 2015, Goldbogen et al. 2017) and some are commercially available (e.g. Little Leonardo Co., Japan; CATS Cam, Australia). The deepest-rated of these is the DVL1300M-VD3GT unit by Little Leonardo Co., a completely epoxy-potted video and data logger rated for 2000m. These video logging tags cost thousands of dollars per unit, and none offer the benefits of the Raspberry Pi open source programming architecture for user development, along with wireless programming, live-stream video capability, and potential expansion into time-synced multi-camera arrays. The DEEPi camera also derives a significantly increased depth rating by incorporating the 3D-printed shell along with precisely controlled epoxy filled volumes. The depth rating for DEEPi could be further increased through printing with various materials as they are made available to the commercial market, including sapphire viewports, rigid photopolymers and metals such as aluminum, stainless steel, and titanium. The camera design described in this paper is easily scaled for other 'cellphone'-style camera modules, which are anticipated to be released to the user development market in the near future.

BRUV systems are regularly employed in shallow-water teleost fish and elasmobranch studies (Brooks et al. 2011, Goetz et al. 2012, Bond et al. 2012) and are increasingly being adopted for deep-water research (Jamieson et al. 2009; Friedlander et al. 2014; Phillips et al. 2016, 2019; Devine et al. 2018). These relatively low-cost imaging platforms can be launched and recovered using almost any size vessel in any oceanic region, and allow for multiple simultaneous deployments. The DEEPi camera system presented here offers to further reduce the cost and form factor of deep-sea BRUV systems, along with creating a broad user and development base who can take advantage of the open-source architecture of the Raspberry Pi and Python hardware and software architecture.

Because Raspberry Pi Zero W computer boards include wifi and network connectivity, it is relatively straightforward to sync and livestream multiple camera feeds. We foresee advanced applications of this capability manifested as multi-view, stereo/quantitative imagery, and virtual reality systems. The field deployment of DEEPi systems in Baltimore Canyon, USA (Figure 1C) demonstrates the possibility of using multiple, self-powered DEEPi systems to live-stream and record imagery while synced through a single wireless network. We anticipate improving on this work in the near future.

Conclusion

In this paper we have described the DEEPi camera system, a novel, affordable deep-sea imaging system based on the Raspberry Pi computer and camera encased in 3D-printed epoxy-filled housings. The camera can operate as a remote head unit and the hardware design of the pressure housing is described in detail. The DEEPi system has been laboratory tested for operation at depths up to 5500m, field-tested to 1096m in Bermuda onboard a BRUV system, and used to visually guide benthic grabs to depths approaching 400m on the US continental shelf. DEEPi is fully user-configurable, and is supported by an extensive open-source development community. The work presented here offers a significant reduction in the size, form factor, and cost required to obtain HD imagery from the deep ocean. DEEPi can be used onboard ROV's, AUV's, BRUVs and other deep-sea platforms, and a wide range of applications are envisioned for the scientific, education, defense, and commercial sectors.

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Figure Legends:

Figure 1: A) DEEPi system components, including remote camera head (top) and epoxy-potted Raspberry Pi Zero W computer. B) BRUV system used to deploy the DEEPi system in Bermuda. Inset shows the layout of this configuration, which included two DEEPi camera heads connected with ribbon-cable pass-throughs potted in a custom 3D-printed bulkhead attached to a 1 atmosphere titanium housing. C) Custom imaging payload used to visually guide a Smith-MacIntyre benthic grab (not shown) in Baltimore Canyon, USA. The payload used a battery-powered wifi connection to stream live video from DEEPi control computers attached to the outside of a 1 atmosphere housing.

Figure 2: Left) DEEPi camera module 3D-printed shell models. Right) Assembly models of the camera module and Raspberry Pi Zero W control computer.

Figure 3: Cross-section of DEEPi camera module, showing the epoxy-filled volume in relation to the 3D-printed shell and glass viewport.

Figure 4: Image stills from HD video recorded at 700-1100m deep in Bermuda. Top: Dogfish shark (*Mustelus canis insularis)*, Middle: cutthroat eel (Synaphobranchidae family); Bottom: Sixgill shark (*Hexanchus griseus*).

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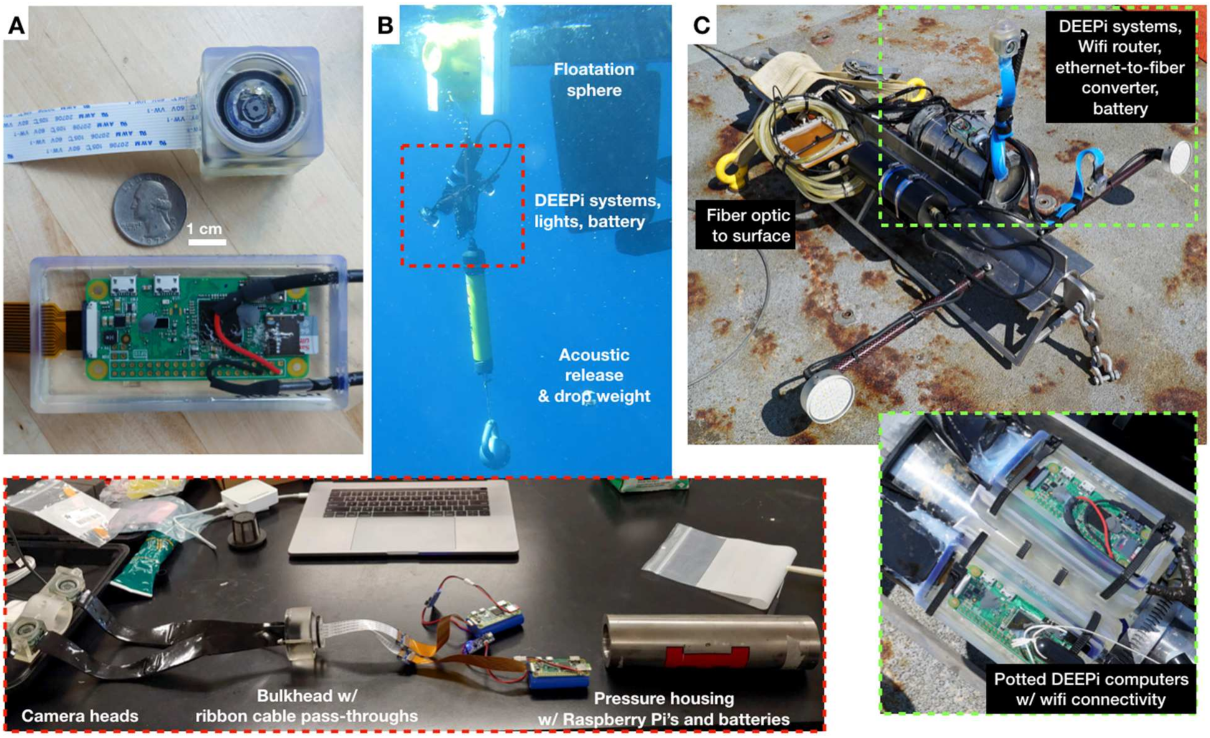
<u>Figures</u>



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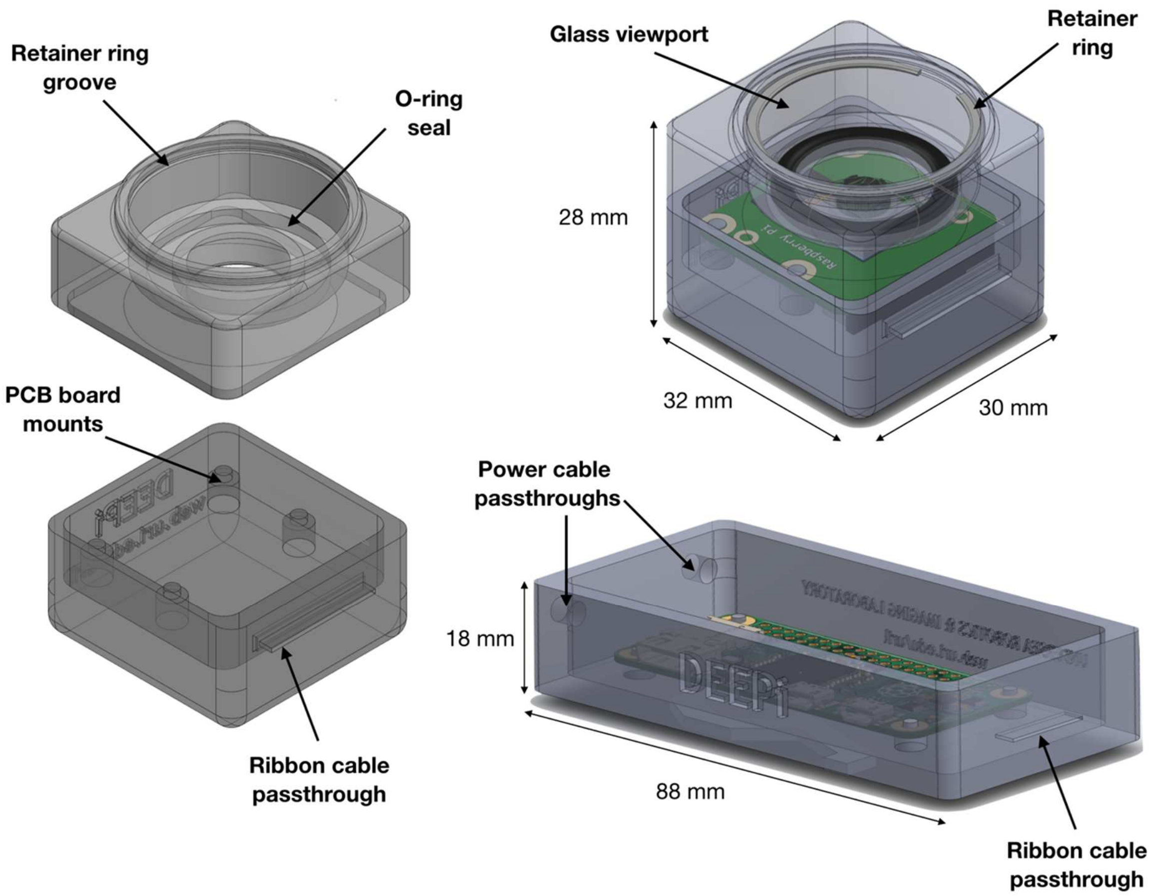

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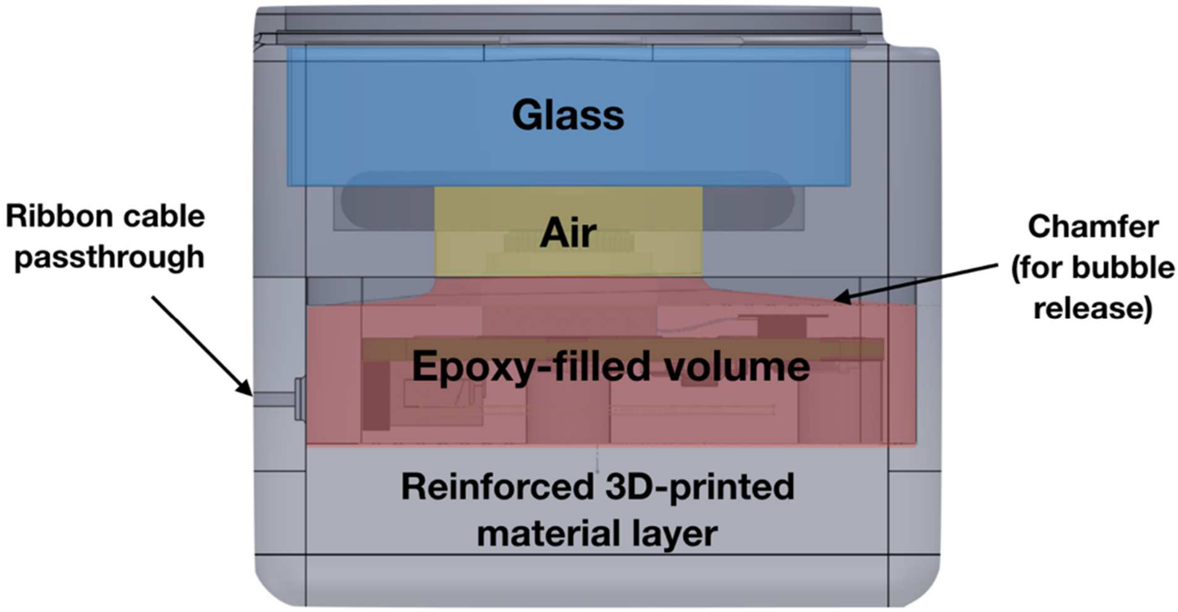

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