The Deep Ocean Dropcam: A Highly Deployable Benthic Survey Tool

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***Abstract*—The deep ocean is a dark and unforgiving place. Buried under thousands of meters of water, the deepest part, the hadal zone, experiences extraordinary pressure. This deep seafloor habitat remains largely inaccessible to many current imaging tools. An inexpensive, reliable device is needed to explore these deep places and capture imagery of marine life in situ.**

The Deep Ocean Dropcam, developed by the National Geographic Society, is a low-cost research tool that can probe these depths and return valuable imagery to the surface. It combines a high-definition camera and onboard lights inside a glass pressure housing to capture high quality imagery of the deep seafloor environment. This device, deployed over 200 times in the past five years, has proven to be a robust platform for exploring the deep ocean.

Keywords—benthic, camera, free vehicle

I. Introduction

The deep ocean remains a largely unexplored region. There exists a great degree of biodiversity in this area, but it has yet to be fully described [1]. Deep ocean exploration can be a costly and time intensive operation. Exploring below diver-accessible depths often requires expensive ocean vehicles and large support vessels. However, a simple device known as a "free instrument vehicle" can explore the deep ocean by sinking to the seafloor and utilizing whatever instrumentation is onboard. These vehicles were first described and used in the 1930s [2], and were utilized in later decades for deep ocean research [3]. A "lander" system, a type of free vehicle, equipped with cameras, was recently used to explore the deepest hadal zone [4].

National Geographic's Deep Ocean Dropcam (DOD) system was designed to operate as a free vehicle, with the ability to descend to the depths of the ocean and visually record any life that exists in that environment. Intended to be a full-ocean capable device, the DOD is able to withstand immense external pressure. It has been designed to be highly portable, easily deployable, and inherently reliable.

II. System Design

The DOD was designed to be useful in any benthic environment. It descends to the seafloor using a temporary anchor and activates its onboard camera and lighting systems based on a preset program. After mission completion, the device releases the anchor, ascends to the surface, and broadcasts its position for retrieval.

A. Instrument Layout

The physical layout of the DOD is shown in Fig. 1. The system is comprised of three main elements: the glass pressure housing, lighting reflectors, and a pressure gauge inside an additional custom housing. The glass pressure housing is a 43 cm diameter, 2.1 cm thick borosilicate glass sphere (Vitrovex, Nautilus Marine, GmbH). The sphere is rated to 12,000 m. It is sealed at the interface between the upper and lower hemispheres and kept at an absolute pressure of 0.6 atm. The glass interface is covered with a butyl rubber tape, and vinyl tape is placed over the rubber. The bottom hemisphere is optically polished and contains a high definition (HD) camera and a stereo laser measurement system mounted to a custom servo-actuated tilt mechanism. The camera controller and batteries are also within the bottom hemisphere. The upper hemisphere contains the lighting system, the Argos satellite beacon and VHF beacon used for recovery, in addition to a single electrical bulkhead for data download and battery charging. A set of magnet switches are used to activate the camera controller and the recovery beacon. An external ring assembly surrounds the sphere and holds the lighting reflectors.

Mounted underneath the ring assembly is a 138 MPa pressure gauge (Ashcroft Inc.) mounted inside a custom aluminum (alloy 7075) housing. A single bolt on the bottom of the pressure gauge assembly serves as an attachment point for the release system and temporary anchor. The anchor typically weighs 200 N in water and is comprised of a piece of previously-used anchor chain or some type of scrap metal. In environments where it is not acceptable to leave behind a metal anchor, an equivalent weight of sand in biodegradable sandbags is used. The release system consists of a burn-wire and a galvanic time release (Neptune Marine Supply), also known as a GTR. The burn-wire is nylon-coated 1.65 mm diameter, 7x7 strand, 18-8 stainless steel wire. The wire coating is removed from a 6 mm section. The burn-wire and the bolt are electrically connected to the camera controller via the pressure housing bulkhead. When these components are energized, the wire disintegrates at this exposed metal point through electrolytic erosion and releases the anchor, allowing the DOD to ascend to the surface via its own buoyancy. Each

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burn-wire is single use only. The GTR acts as a back-up release in the case of burn-wire failure. It is a passive device that begins corroding once placed in salt water, and takes between 24 and 36 hours to completely disintegrate. The GTR is connected between the burn-wire and the anchor. A detailed view of the release system is shown in Fig. 1.

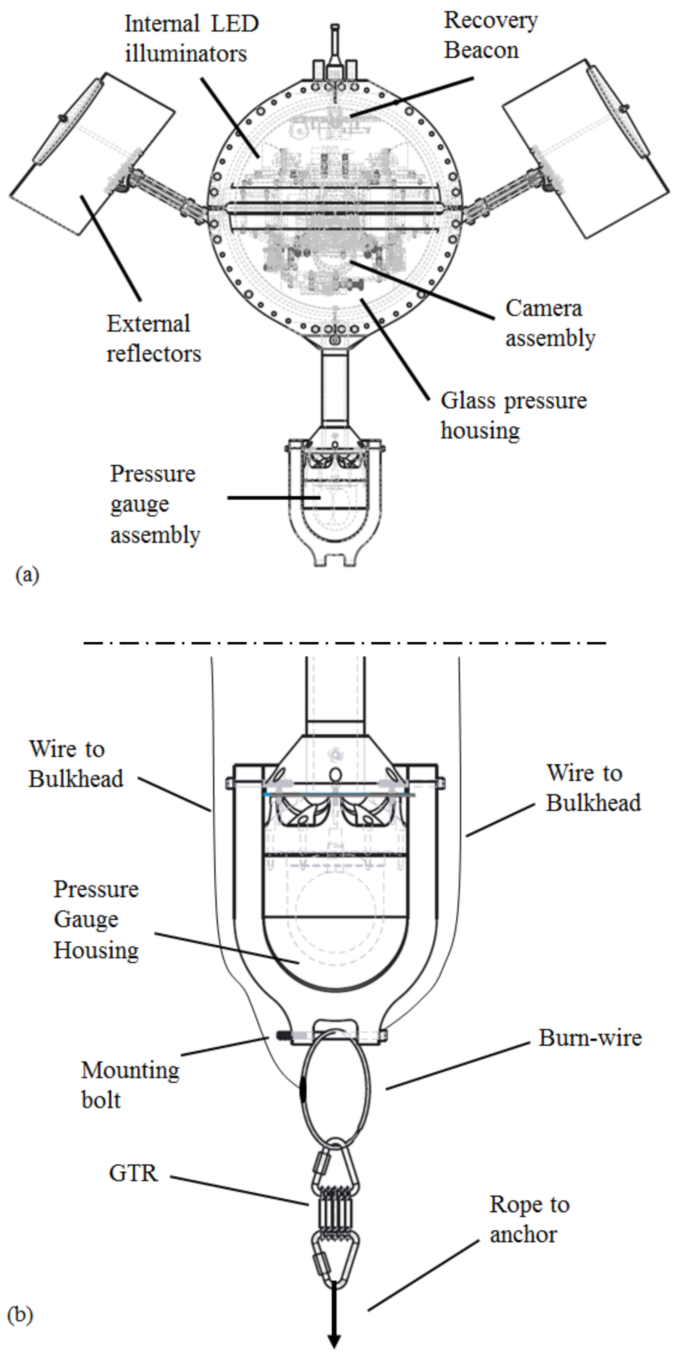

Fig. 1. (a) Shown is the Deep Ocean Dropcam mechanical layout. The glass pressure housing holds the camera and onboard lights. The external reflectors direct light from the illuminators onto the scene in front of the camera. (b) A detailed view of the DOD release system.

The system measures roughly 1.28 m across, stands 1.05 m tall, and has a mass of 46 kg. It is approximately 70 N positively buoyant in seawater. The pressure gauge assembly maintains the vehicle's center of gravity below the center of buoyancy, causing the system to remain in an upright position when released from the anchor. This allows the recovery beacon to remain fully out of the water for retrieval operations.

B. Electrical System

The DOD contains two separate, isolated electrical systems: the recovery beacon and the camera controller, as shown in Fig. 2.

The recovery beacon consists of a 401 MHz Argos satellite transmitter and a 150 MHz VHF transmitter. Once the instrument has surfaced, the former is used for global tracking and the latter for short range tracking. This beacon is the same as the one described in [5]. The beacon is powered by three 3.6 V, 13 Ah LiSOCl2 primary batteries wired in parallel. The tested battery life with continuous operation is one year. The system is activated by a single magnet switch before deployment. The beacon will continue to transmit until the system is deactivated by placing a magnet near the magnet switch.

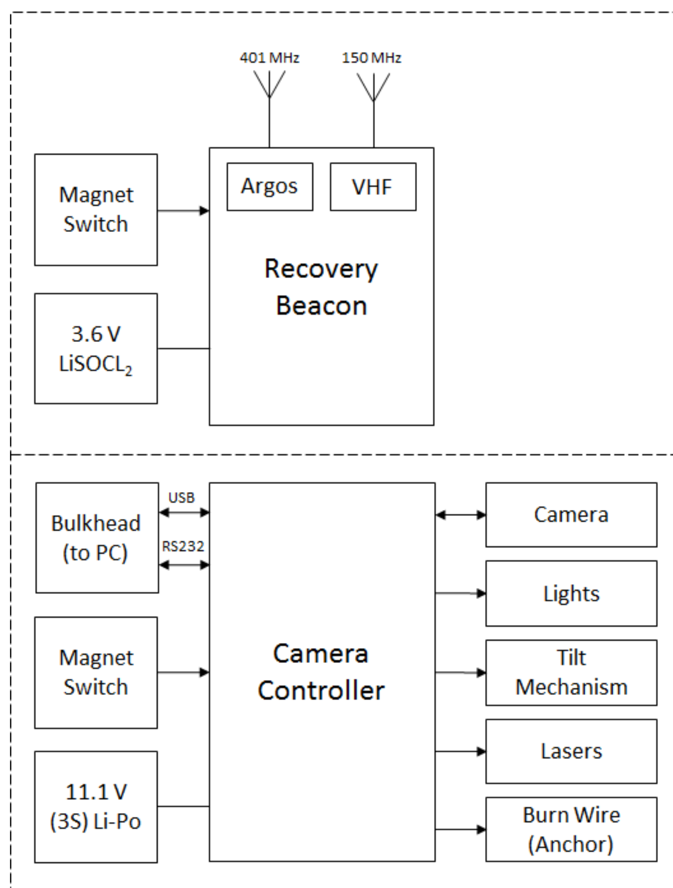

Fig. 2. A block diagram of the electrical system of the Deep Ocean Dropcam. The camera controller and the recovery beacon are completely isolated.

Fig. 3. View of the camera system mounted in the bottom hemisphere of the pressure housing (photo courtesy of Mark Thiessen and Rebecca Hale)

The camera controller and lighting systems are similar to ones described in [5]. The camera controller consists of a custom-designed PCB based on the Microchip Technology PIC24 series microcontroller. Current is delivered to the burn-wire through a power MOSFET switch located on the PCB. A single waterproof bulkhead (BH10MTi, SubConn) provides an electrical connection for charging and data retrieval. RS-232 serial and USB interfaces can be accessed through this bulkhead. The camera system is powered by a bank of 11.1 V, 13.2 Ah lithium polymer batteries for a total power capacity of 586 Wh. This battery capacity allows a total of four hours of recording time with the lighting system at full intensity and the remaining power applied to the burn-wire.

Two high-output solid-state LEDs (BXRA-C4500, Bridgelux) provide illumination. This light is directed through the pressure housing and cast onto the scene by the external reflectors. The reflectors are positioned to allow an even distribution of lighting across the scene in front of the camera. This indirect lighting scheme reduces backscatter due to particulates in the water.

The system uses a Canon T3i camera with a Canon EF 20mm f/2.8 USM (Ultrasonic Motor) lens. The controller is designed to interface with either Canon DSLR cameras through a camera control IR LED or Sony cameras via a Sony LANC connection (used in previous generations of the DOD). The IR LED communication has been tested with a Canon T3i and Canon 5DmkIII. The LED issues “start recording” and “stop recording” commands to the camera. The focus is set using a custom 2 m long water-filled test tank. Footage is recorded at 1080p resolution and stored on the camera’s SD card. Canon camera settings can be changed prior to deployment through the bulkhead USB connection. Proprietary Canon EOS software allows camera settings, such as aperture and shutter speed, to be changed prior to deployment. The camera is powered through an 8.2 V switching mode power supply that is connected to the main battery.

The tilt mechanism and stereo laser system, seen in Fig. 3, are controlled by the camera controller as well. Linear servos allow the tilt mechanism to aim the camera from 25 to 60 degrees below the equatorial plane of the sphere. The mounting tray on the tilt mechanism has been designed to allow for a wide variety of cameras and lenses to be used within the sphere. The stereo laser system consists of two Class IIIa 650 nm lasers (VLM-650-1, Quarton Inc.) mounted to custom adjustable brackets. The lasers are spaced 127 mm apart and are adjusted to be in parallel in the same custom 2 m test tank used to set the camera focus.

C. Firmware

The firmware to control the DOD camera and release system was designed as a Queued Finite State Machine (QFSM) as described in [6]. This architecture scheme was chosen because it allows a high degree of scalability while retaining rigid, deterministic behavior. The state machine operates on a 1 Hz cycle; all queued states are executed in 1 s. Task states, which are executed based on system parameters, are queued by decision states. These parameters are entered by the user prior to deployment.

The state machine consists of parent states and numerous child states, as shown in Fig. 4. These states are queued and executed depending on the DOD's current state and the register values of user-programmable mission parameters. Mission parameters consist primarily of time duration and expiration values, as well as subsystem enable/disable bits. A PC is used to program these register values into the controller through the bulkhead RS-232 interface. These register values can be manually entered one-by-one for minor changes, or can be set all at once using a macro script template to expedite the programming of new mission profiles.

The QFSM was developed to run on the Microchip PIC24 series microcontroller in C using the XC16 Compiler (Microchip Technology).

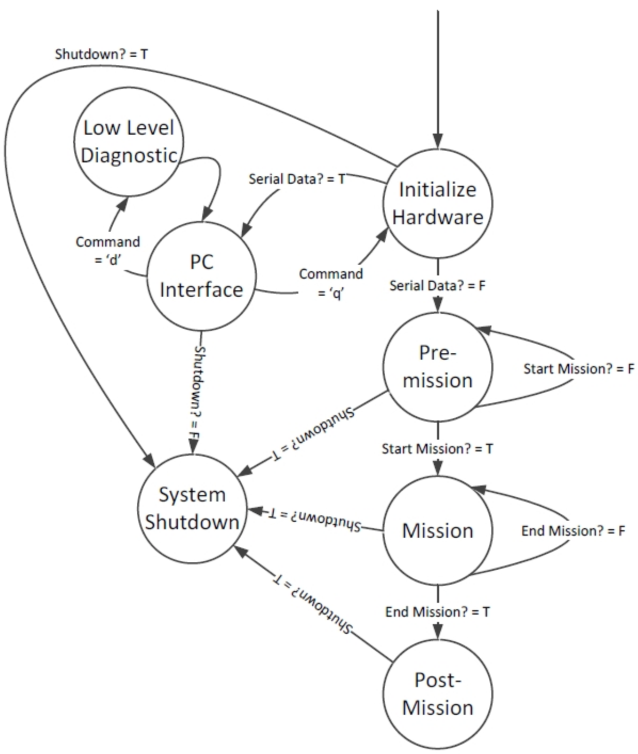

Fig. 4. DOD control firmware is implemented as a state machine. Task states are queued by decision states, based up user inputs.

III. Methods

Methodologies to streamline deployment and retrieval have been developed. Expeditions often have tight schedules, and it is critical to ensure that DOD deployments do not inhibit the expedition's timetable.

A. Deployment

The DOD is most often used for short benthic surveys, usually with a bottom time of six hours or less. The mission parameters are programmed prior to deployment. These parameters are typically set so that the camera and lights cycle on for 15 minutes each hour, leaving 45 minutes for wildlife to accumulate in the frame, undisturbed by lighting. The camera is allowed to fully power on before the lighting system is activated, which allows the camera to capture any wildlife in frame that may flee because of the sudden illumination.

The system is baited to attract marine life into the frame while the camera is at depth. A mesh bag is filled with a measure of locally obtained bait and attached just below the portion of the pressure housing where the camera is located. The bag remains just out of the frame during filming, ensuring the entire scene is unobstructed.

Just prior to deployment the magnets are removed, activating the beacon and the camera system. Both systems are then checked to ensure proper functionality.

The system requires no special equipment to be placed in the water and is often lowered by hand into the ocean by a two-person team. This has been an effective method that has been used extensively in deployments from small rigid inflatable boats. As seen in Fig. 5, the top of the instrument offers a sling attachment point for use with cranes on larger boats where there is no direct access to the water line.

Fig. 5. National Geographic engineers prepare to deploy a Deep Ocean Dropcam into the Puerto Rico Trench. (photo courtesy of Shelbi Randenberg)

B. Recovery Procedures

Once the mission timer has expired, the DOD will release its anchor and ascend to the surface. With a 200 N anchor, the instrument has been estimated to descend at 1.3 m/s. With the anchor released, the system ascends at approximately 0.5 m/s.

Fig. 6. Shown is a map of all locations the DOD system has been deployed. Refer to Table 1 for location names and number of deployments.

With these values, the operator can estimate a probable time the DOD will surface, often within minutes of the actual event. Once on the surface, a general location of the instrument can be determined by utilizing a radio receiver tuned to the specific frequency of the instrument's VHF beacon, coupled with a directional Yagi antenna. The VHF signal has been detected with a Yagi antenna up to 10 km away.

If it becomes impossible to retrieve the DOD when it first surfaces (e.g. due to extreme weather), the operator can use location fixes provided by the Argos satellite network to track the device. Fair seas and ideal Argos constellation passing conditions can provide a location fix within 250 m. The accuracy of this location fix can vary greatly depending on a variety of conditions, such as sea state, broadcast signal strength, etc. The coordinates of the location fix can be forwarded to an operator's satellite phone to allow for retrieval.

In addition to the beacons, a high-visibility orange flag allows the device to be spotted easily when an operator is within several hundred meters during daylight hours. The DOD will also flash its illuminators once every 10 seconds as soon as the mission timer has elapsed, making the system highly visible on the surface at night.

IV. Results

A. Deployments Worldwide

The DOD system has been deployed in 17 locations worldwide from various ships of opportunity, with a total of 216 deployments completed to date (refer to Fig. 6 and Table 1 for a complete list of deployment locations). Though there have been successful deployments to ocean trenches, the majority of the deployments have been in less than 3,000 m of water. The DOD is often deployed and recovered once per day; up to four instruments are brought on expeditions to allow four simultaneous deployments. The limiting factor for deployment rate is battery charging time. Charging can take up to eight hours, depending on the battery state of charge and the method used for charging.

The system has been used extensively in seamount surveys. At least 171 species of fish and 111 species of invertebrates have been identified from the resulting footage, described in [7]-[11]. At least eight species previously unknown to science have been identified with the system [7], [8], and several species have been observed in areas where they were unknown to exist [7], [9]. Sample images of organisms observed with the DOD can be seen in Fig. 7.

The system has been deployed nine times to the hadal zone and imaged the seafloor at depths up to 10,641 m. It has been utilized in some of the ocean's deepest points such as the Puerto Rico Trench, Tonga Trench and Marianas Trench. The footage from the Marianas Trench expedition, completed in 2011, documented the deepest known xenophyophores, a type of deep sea, single-cell organism [12].

TABLE 1. DEPLOYMENTS OF THE DOD SYSTEM

Map No. [a]	Date	Location	Number of Deployments	Depth Range (m)
1	Apr. 2010	Puerto Rico	2	7526-7618
2	May 2010	Porcupine Abyssal Plain	2	Approx. 4000
3	Nov. 2010	Puerto Rico	3	8483-8490
4	Feb. 2011	Sala y Gomez	22	552-1849
5	Jul. 2011	Marianas Trench	3	3682-10641
6	Mar. 2012	Pitcairn Is.	22	142-1585
7	Sep. 2012	Tonga Trench	2	7300-9200
8	Feb. 2013	Desventuradas Is.	36	90-2363
9	Aug. 2013	Franz Josef Land	24	32-392
10	Apr. 2014	Mozambique	10	46-222
11	May 2014	Palmyra	11	189-1555
12	Jul. 2014	Puerto Rico	1	2329
13	Sep. 2014	Palau	28	178-2400
14	Oct. 2014	Rapa Iti	15	30-1057
15	Jan. 2015	Chagos Archipelago	21	304-3359
16	Jan. 2015	Solomon Islands	7	28-1761
17	Mar. 2015	Seychelles	7	173-2095

a. Refer to Fig. 6.

B. Uses

Although used primarily for benthic exploration, the system has also been utilized in other ways. It has been attached to other research instruments such as water samplers, and lander-type free vehicles. In May 2010, the DOD was attached to a deep ocean coring sampler and also to a benthic instrument platform known as the BOBO lander. The DOD provided footage of the benthic environment while these devices conducted experiments on the seafloor. The DOD has also been attached to water samplers in deployments to the Tonga Trench and the Puerto Rico Trench [13].

In a separate case, the system was utilized as a time-lapse device to monitor the underwater decomposition of a dolphin carcass near the San Diego Bay. The system was mounted to a large aluminum frame, which was lowered into the ocean and secured to the seafloor near the dolphin carcass by a diving team. The DOD was programmed to film for 10 seconds every 30 minutes for two weeks. After the two week period, the frame and DOD were recovered and the footage retrieved by the same divers.

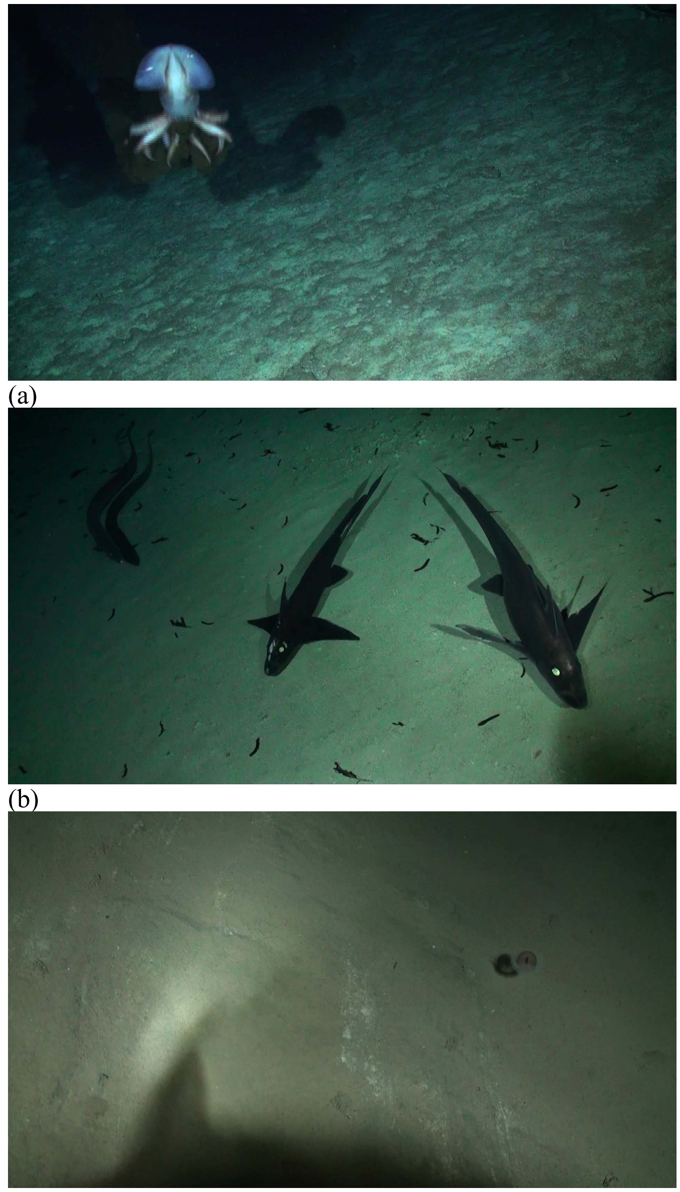

Fig. 7. (a) A squid releases ink as it comes into frame just offshore Pitcairn Island at a depth of 282 m. (b) Two chimaeras come into frame in the deep ocean near the Seychelles at a depth of 1,873 m. (c) A jellyfish crosses in front of the camera at a depth of 9,970 m in the Marianas Trench.

C. System Failures

The Deep Ocean Dropcam has not been recovered in two instances during its deployment history. Both deployments resulted in a complete loss of the instrument; a probable explanation is that defects in the glass caused a catastrophic implosion. Both instances occurred during deployments to ocean trenches deeper than 6,000 m.

Another instance occurred near the Porcupine Abyssal Plain that resulted in near catastrophic failure. It was surmised that while the DOD was attached to the previously mentioned BOBO lander one of the lander's onboard glass buoyancy spheres imploded at a depth of approximately 4,000 m. The lander was lost, but the DOD was recovered on the surface near the site of the deployment. The DOD pressure housing was heavily spalled inside and the circuit boards were broken, indicative of a catastrophic underwater event. Damage to the sphere is shown in Fig. 8. The damage rendered the entire device useless for future deployments, however, the spherical housing remained intact during its ascent to the surface.

Fig. 8. Damaged DOD used with the BOBO lander. The bottom hemisphere is full of glass dust from internal spalling due to a catastrophic event.

The DOD has relied on the GTR as a secondary release seven times during its deployment history. The most common cause has been damage to the electrical connection to the burn-wire. This damage can be due to unpredictable events (e.g. sharks biting the burn-wire release cable) or improper handling during deployment and recovery. In these instances, it is important to note that despite the primary release failure, the secondary release (GTR) was able to return the instrument to the surface.

V. Discussion

The Deep Ocean Dropcam is a useful tool for benthic surveys. The system is easily deployable from a variety of craft and can be deployed continuously, factoring in time for data retrieval and battery charging. The system can be deployed daily for weeks without the need for maintenance and requires only a single operator. The DOD allows scientists access to a deep ocean system without sacrificing expedition time or berth space. Compared to an equivalent ROV or manned submersible system, the DOD provides an extremely cost effective way to reach the deep ocean. Despite its lack of mobility while on the seafloor, the DOD is capable of returning valuable images of benthic biodiversity through baiting the system, encouraging local demersal life to approach the camera.

The ability to survive full ocean depths is critical, as it allows scientists to access any depth; the system can be deployed to depths of 50 m one day and 10 km the next without changing any physical hardware.

Data retrieval and battery charging are simple due to the single bulkhead. This single bulkhead allows the pressure housing to remain sealed, reducing time needed between deployments and preventing any human errors or damage that may occur in the reassembly of the pressure housing.

All these factors, as well as the robust retrieval system (i.e. recovery beacon, flag, etc.), make the DOD an inherently simple and dependable device.

VI. Summary and Future Work

A benthic survey camera system has been developed and proven to be highly reliable and easily deployable. The system combines an HD camera system and lights to capture imagery of benthic life. The system has been deployed over 200 times in five years with a successful recovery rate of 100 percent for deployments shallower than 5,000 m.

Several improvements are in development for the system. Currently, a very low-light camera is being integrated. This will reduce the amount of illumination required, decreasing battery load and thus allowing for increased mission time. A "fish detector" circuit is also being developed to activate the camera system only when larger targets come into frame.

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