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PlasPI marine cameras: Open-source, affordable camera systems for time series marine studies

Autun Purser [a,*], Ulrich Hoge [a], Johannes Lemburg [a], Yasemin Bodur [b,c], Elena Schiller [a], Janine Ludszuweit [a], Jens Greinert [a], Simon Dreutter [a], Boris Dorschel [a], Frank Wenzhöfer [a,b]

[a] *Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany*
[b] *Max Planck Institute for Marine Microbiology and Ecology, Bremen, Germany*
[c] *Department of Arctic Marine Biology, UiT – the Arctic University of Tromsø, Tromsø, Norway*
[d] *GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany*

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ABSTRACT

Imaging underwater can be particularly problematic and expensive given the harsh environmental conditions posed by salinity and for some deployments, pressure. To counter these difficulties, expensive waterproof pressure resistant housings are often used, commonly built from expensive materials such as titanium, if intended for long duration deployments. Further, environmental investigations often benefit from replicate data collection, which additionally increases study costs.

In this paper we present a new camera system, developed with off the shelf and 3D printed cost effective components for use in shallow waters of <150 m depth. Integrating Raspberry Pi Zero W microcomputers with open source design files and software, it is hoped these camera systems will be of interest to the global marine and freshwater research communities.

Specifications table

Hardware name	PlasPi marine camera system
Subject area	• Environmental, Planetary and Agricultural Sciences
Hardware type	• Imaging tools
Open Source License	CERN Open Hardware Licence v1.2
Cost of Hardware	PlasPi shallow marine camera: <200 Euro
Source File Repository	OSF https://osf.io/9t7h3/

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[*] Corresponding author.
E-mail address: autun.purser@awi.de (A. Purser).

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1. Hardware in context

Imaging systems for marine application have been under near continuous deployment since 1856, when William Thompson first attached a camera to a stick and took the first documented underwater image [1]. From the 1890s, and the work of Louis Boutan [2], the interest of the general public in underwater flora and fauna has continued to grow, with TV shows such as ‘Blue Planet II’ garnering huge audience numbers and driving policy changes in waste management [3].

Aside from a general interest in the marine environment by the public as a whole, there are numerous scientific questions on marine ecosystem functioning which may be investigated with imaging systems [4]. Prior to the development of marine cameras, direct sampling of the seafloor required dredging or box coring – destructive practices which only produce limited spatial information at the time of sampling [5]. In contrast, imaging systems, be these still or video camera type systems, can collect data from the seafloor and water column without damaging the environment within which it is sampling [6]. Additionally, the facility to leave cameras on the seafloor, or to tow them behind research vessels has allowed temporal and spatial data sets to be produced [7-9]. These temporal image data sets have been fundamental for the investigation of seasonality of food delivery to the deep sea seafloor over time, and for the mapping of marine habitats across scales of centimeters to kilometers.

Ongoing developments in Light Emitting Diode (LED) design, digital cameras, image storage techniques, deep sea pressure housings and power storage now allow for long-duration deployments on the seafloor of cameras for many months, even for several years, given an appropriate pressure housing. As part of marine cabled research infrastructure camera systems can even be operated directly by remote operators via standard internet browsers from anywhere in the globe. High resolution cameras also allow information on much smaller flora, fauna or features to be gleaned from image data than was possible even a few decades ago.

These new imaging systems are often very costly [10], limiting their use in temporal, remote or high risk deployments, such as within hydrothermal provinces or beneath ice in polar regions. For such research less expensive camera systems are required, where loss of devices can potentially be expected. For some investigations, such as those focusing on monitoring regions of seafloor, perhaps to assess changes over time both spatially and temporally, such as seafloor disturbance during a deep sea mining event, or following a pollution incident, then a number of cameras deployed in parallel would be advantageous. For this work, cheaper systems are to be preferred.

Off the shelf systems such as the ‘GoPro’ family of cameras have found thriving communities of shallow water researchers and those involved in fauna monitoring [11], particularly given the easy access to plastic waterproof housings produced for the recreational diving community [12]. For depths of deeper than ~50 m depth recreational diving is no longer possible with standard equipment, so the commercial development of cheap housings stops at this depth. To use ‘GoPro’ cameras at deeper depths, as with other standard camera systems, custom or limited commercial production housings are required [13]. Prices of these housings can be in the 1000 s of euros, depending on camera size, required batteries and construction materials suitable for the length of a particular deployment.

A further difficulty in using off the shelf camera systems, be they ‘GoPro’ cameras or from other companies is that the options available for the user are often limited, in terms of image capture duration, aperture, time series functionality etc. Some of these can be hacked by users, often invalidating warranties and resulting in imaging systems which collect data which is difficult for interested researchers to easily replicate. This renders these ‘ad-hoc’ systems not ideal for peer review science applications. In contrast, this paper presents an alternative solution, using a Raspberry Pi Zero W microcomputer placed within a plastic housing and integrated with a camera lens, flash unit and batteries to produce an easily tailorable, cheap (<200 euro) marine camera system capable of deployment to depths of 150 m. The Raspberry Pi has proved to be an attractive platform for environmental sensor developers in recent years [14–17]. To tap into the enthusiasm of the ‘maker’ community for Raspberry Pi development and coding, [18] the PlasPi camera has been developed to operate with the standard Raspbian operating system running open access Python 3 scripts.

2. Hardware description

Here a new camera system (the ‘PlasPi’ or ‘Plastic Pi’ camera), designed to capture underwater still images over extended time periods is presented. The system is built around a Raspberry Pi Zero W microcomputer board and runs open source python 3.0 scripts to operate. Built with standard off the shelf components and a limited number of small easily machined parts, within the capacity of small institutes to produce, the PlasPi is a shallow water (150 m depth rated) camera system with a plastic pressure housing (Fig. 1). The camera system has been well tested and can be mounted readily alongside other environmental sensing platforms, such as benthic Landers. By using an open source python script based programming approach, coupled with the Raspberry Pi Zero W microcomputer, the full array of previously developed maker community code is available for use in further developments of the camera system, as may be made by researchers keen to tailor the device for their own specific requirements. The version of the PlasPi camera presented here uses the cheap, low-end Raspberry Pi camera module v2, a commonly used 3280 × 2464 pixel camera of moderate quality, but known performance. This

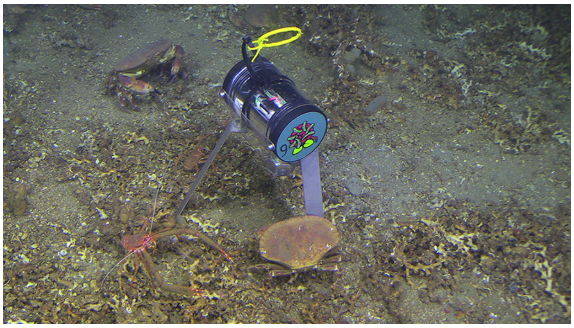

Fig. 1. PlasPi camera, deployed at the Tisler cold-water coral reef, Norway. ~100 m depth. Photo: GEOMAR JAGO team.

can be swapped out for more advanced modules by researchers requiring higher quality images, but for these build plans the v2 module will be discussed exclusively.

- 3 LEDs capable of illuminating several sq. m of seafloor sufficiently to allow ~5000 high resolution images to be collected per deployment
- Fully programmable exposure time and time series settings
- Cheap construction – plastic pressure housing rather than steel or titanium (traditional housings for commercial cameras)
- Standard camera lens components for straightforward replication/maintenance
- Low power consumption and WiFi (IEEE 802.11x) connectivity minimizes pressure housing opening requirements

3. Design files

Table 1 gives the full list of design files required to construct the PlasPi camera system. The descriptions of each uploaded file are divided below by specific camera type.

Table 1
Design Files and Software list.

Design file name	File type	Open source license	Location of the file
PlasPi_CAM_00-001.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_00-001.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_00-002.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_00-002.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_00-003.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_00-003.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_00-004.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_00-004.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_00-005.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_00-005.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-001.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-001.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-002.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-002.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-003.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-003.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-004.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-004.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-005.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-005.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-006.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-006.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_CAM_10-007.pdf	Pdf schematic	CERN OHL	https://osf.io/9t7h3/
PlasPi_Cam_10-007.SLDDRW	Solidworks file	CERN OHL	https://osf.io/9t7h3/
PlasPi_Combined_schematic.jpg	Schematic image	CERN OHL	https://osf.io/9t7h3/
PlasPi_circuit.dxf	Wiring file	CERN OHL	https://osf.io/9t7h3/
PlasPi_circuit.sch	Wiring file	CERN OHL	https://osf.io/9t7h3/
PlasPi_circuit.png	Wiring schematic	CERN OHL	https://osf.io/9t7h3/
Plaspi_run.py3	Python script	CERN OHL	https://osf.io/9t7h3/
Settings.txt	Python script	CERN OHL	https://osf.io/9t7h3/

3.1. PlasPi files

PlasPi_CAM_00-001.pdf,.SLDDRW – An overview schematic showing all the various components of the PlasPi camera integrated
PlasPi_CAM_00-002.pdf,.SLDDRW – technical drawing of the assembly of the front end cap
PlasPi_CAM_00-003.pdf,.SLDDRW – schematic showing the assembly of the interior components of the PlasPi camera
PlasPi_CAM_00-004.pdf,.SLDDRW – schematic showing tripod mounting attached to PlasPi camera
PlasPi_CAM_00-005.pdf,.SLDDRW – technical drawing of lens focus changer tool in action
PlasPi_CAM_10-001.pdf,.SLDDRW – technical drawing of plastic housing tube
PlasPi_CAM_10-002.pdf,.SLDDRW – technical drawing of front end cap
PlasPi_CAM_10-003.pdf,.SLDDRW – technical drawing of front plexiglass flash and camera ports
PlasPi_CAM_10-004.pdf,.SLDDRW – technical drawing of interior handling mount
PlasPi_CAM_10-005.pdf,.SLDDRW – technical drawing of LED/camera mounting piece
PlasPi_CAM_10-006.pdf,.SLDDRW – technical drawing of PlasPi camera mount attachment
PlasPi_CAM_10-007.pdf,.SLDDRW – technical drawing of steel leg, suitable for attachment to camera mount
PlasPi_Combined_schematic.jpg – Schematic showing full assembly of PlasPi camera and mount
PlasPi_circuit.dxf,.sch,.png – Wiring diagram for PlasPi camera
Plaspi_Run.py3 – A python 3 script to operate the PlasPi camera

4. Bill of materials

4.1. Bill of materials – PlasPi camera

Designator	Component	Number	Cost per unit –EURO	Total cost – EURO	Source of materials	Material type
	Raspberry Pi® Zero 512 MB ohne Betriebssystem	1	17.49	17.49	https://www.conrad.de/de/raspberry-pi-zero-512-mb-ohne-betriebssystem-1693283.html	Semiconductor
	Pololu Adjustable 4–12 V Step-Up/Step-Down Voltage Regulator S18V20ALV	2	14.76	29.52	https://www.exp-tech.de/sensoren/stromspannung/5684/pololu-adjustable-4-12v-step-up/step-down-voltage-regulator-s18v20alv	Semiconductor
	Osram Oslon SSL 120 Triple Star Weiss CRI 90+	1	7.49	7.49	https://www.led-tech.de/de/Osram-Oslon-SSL-120-Triple-Star-Weiss-CRI-90	Semiconductor
	LEDIL Satu Triple Star Linse 30°	1	3.49	3.49	https://www.led-tech.de/de/LEDIL-Satu-Triple-Star-Linse-30?ref=cl	Plastic
	Raspberry Pi Zero Kamera Kabel 150 mm	1	4.79	4.79	https://www.rasppishop.de/Raspberry-Pi-Zero-Kamera-Kabel-150mm	Semiconductor
	NoIR Kameramodul – Raspberry Pi Kamera V2	1	29.99	29.99	https://www.rasppishop.de/NoIR-Kameramodul-Raspberry-Pi-Kamera-V2	Semiconductor
	Samsung MicroSDHC 32 GB PRO Plus UHS Speed Class 3 Class 10 Memory Card	1	7.93	7.93	https://www.amazon.de/gp/product/B06XFSZGCC/ref=oh_aui_detailpage_o03_s01?ie=UTF8&psc=1	semiconductor
	TRU COMPONENTS BH-111-1D Batteriehalter 1x Mono (D) Lötanschluss	2	1.39	2.78	https://www.conrad.de/de/tru-components-bh-111-1d-batteriehalter-1x-mono-d-loetanschluss-1680439.html	semiconductor
	SAFT LSH 20 Lithium Battery 3.6 V Primary LSH20	2	23.90	47.80	https://www.amazon.de/SAFT-Lithium-Batterie-Primary-LSH20/dp/B00BBCYAIE/ref=sr_1_cc_1?s=aps&ie=UTF8&qid=1547128408&sr=1-1-catcorr&keywords=Lithium+Saft+LSH20	Battery

(*continued*)

Designator	Component	Number	Cost per unit –EURO	Total cost – EURO	Source of materials	Material type
	Plastic screws DIN 7991 M4x12	8				Plastic
	O-ring	2				Rubber
	O-ring	2				Rubber
	Stand attachment screws DIN 912M6x15	4				Steel
	Metal Leg	3				Steel
	Mounting frame	1				Plastic
	End Caps (Polyoxymethylene))	2				Plastic
	Cylinder	1				Acrylic
	Acrylic windows	2				Acrylic
	Interior plastic mount	1				Plastic

5. Build instructions

This section presents the detailed build instructions for the camera, as well as giving some instructions and outlines for optional extras, such as mounting systems or tripods to allow the cameras to be placed directly on the seafloor. A rudimentary knowledge of electronics is required for construction, though only standard, easily purchased off the shelf components are used, along with some simply milled and cut plastic components easily produced within the machine rooms or workshops of moderately sized research facilities.

5.1. Build instructions – PlasPi camera

Fig. 2 shows the schematic of the PlasPi camera. The camera consists of 5 individual component groups, which are shown integrated together to form the fully functional PlasPi camera in Fig. 2. The construction of each of these component groups is described in more detail separately below in Sections 5.2–5.6, then in Section 5.7 the assembly of these into the completed camera unit is given. In Section 5.8 the construction and mounting of optional tripod legs onto the PlasPi camera are given.

5.2. PlasPi housing cylinder

The main PlasPi housing component is a polycarbonate cylinder of the dimensions shown in the 'PlasPi_CAM_10-001' .pdf and .SLDDRW online files. This cylinder can be easily cut to length in a machine room, with the interior edges of each end of the tube filed or sanded slightly to allow easier access of the back end (Section 5.3) and front end (Section 5.4) caps.

5.3. PlasPi back end cap

The back end cap of the PlasPi housing is a piece of machined polyoxymethylene (POM), milled and lathed to the dimensions given on page two of the 'PlasPi_CAM_10-002' .pdf and .SLDDRW online files. Two threads are drilled in the side of the end cap to allow later connection to the mount frame (Section 5.6). Following production of this POM piece, the only additional pieces needed to compete the PlasPi back end cap are two rubber rings, which should be lightly greased with silicone then placed carefully into the two grooves on the inside of the end cap.

5.4. PlasPi front end cap

The main component of the front end cap is of comparable construction to the PlasPi back end cap (Section 5.3), milled and lathed to the dimensions given on page one of the 'PlasPi_CAM_10-002' .pdf and .SLDDRW online files. Two threads are drilled in the side of the end cap to allow later connection to the mount frame (Section 5.6). As can be seen from this file, two additional ports need to be cut out of the POM to allow the LED and camera to illuminate and image the water column, and therefor acrylic plastic port windows are also required to cover these ingresses.

The two acrylic port windows required are identical in dimensions and need to be cut to size, for mounting into the POM front end cap. The dimensions of these pieces are shown in 'PlasPi_CAM_10-003' .pdf and .SLDDRW online files. Care should be taken not to scratch the plastic during cutting.

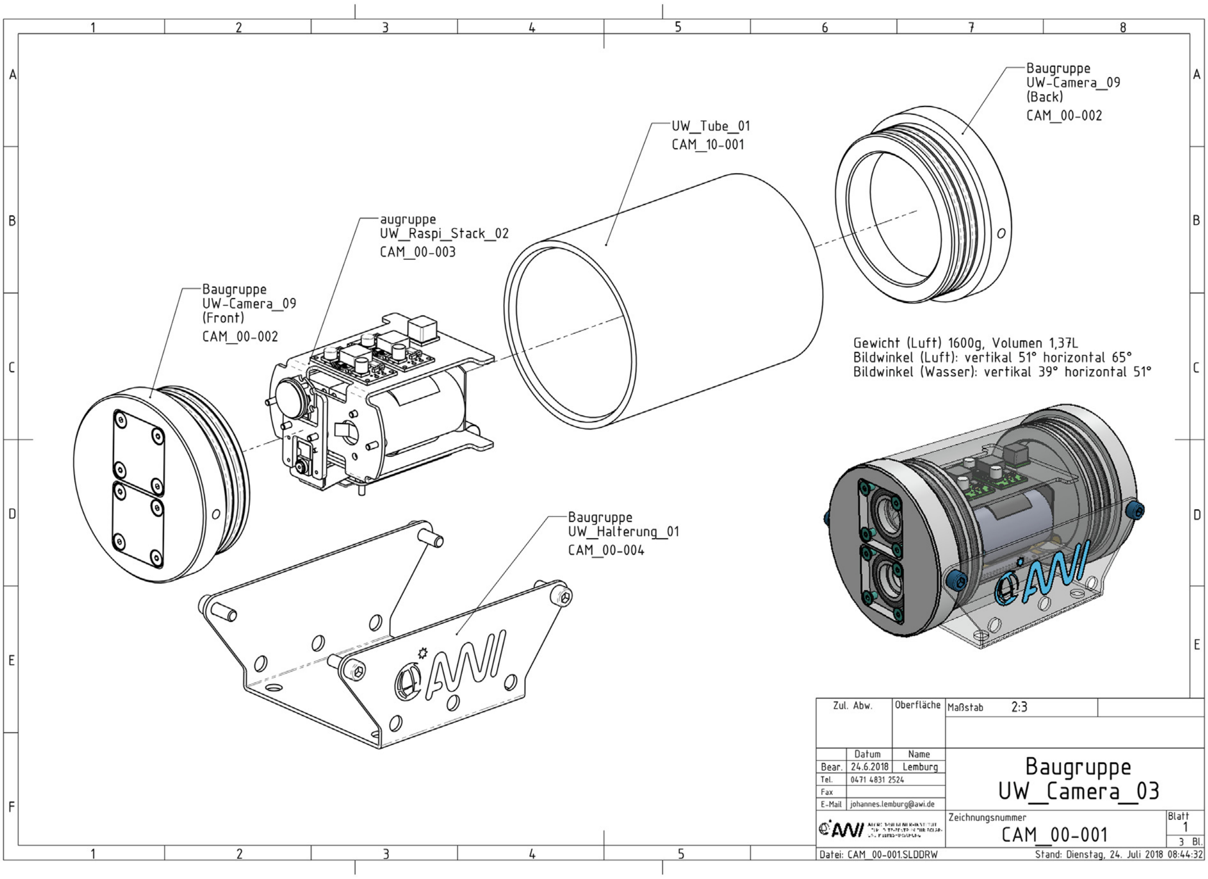

Fig. 2. Schematic drawing of the PlasPi camera.

Following the production of the POM end cap piece, the front end cap can be assembled as shown in ‘PlasPi_CAM_10-002’ .pdf and .SLDDRW online files.

Two rubber rings should be greased with silicone then placed in the two grooves on the inside of the end cap. Two small rubber rings should also be greased and placed in the grooves on the front of the end cap, in each of the two ingresses. Following this the acrylic windows can be screwed into place, as shown in the ‘PlasPi_CAM_00-002’ .pdf and .SLDDRW online files. Care should be taken not to overscrew these threads and then damage the plastic. Ideally, the greased rubber rings mounted behind each window should be visibly pressed against the plastic (the grease applied to the rings forms an easily observed seal here).

5.5. PlasPi electronics

The electronics and power supply for the PlasPi camera system is all mounted as a central component which will later be attached directly to the front end cap (see Section 5.7). The first piece of this central component required is a piece of cut and folded polycarbonate, manufactured to the dimensions given in the ‘PlasPi_Cam_10-004’ .pdf and .SLDDRW files. An additional small piece of cut polycarbonate is also required to ensure the correct mounting of the camera module and the LED unit. The dimensions of this second polycarbonate piece are given in the ‘PlasPi_Cam_10-004’ .pdf and .SLDDRW files.

After the two polycarbonate pieces have been manufactured, the electronic components can be glued to the ‘PlasPi_Cam_10-004’ folded polycarbonate mount piece, as shown in the ‘PlasPi_Cam_00-003’ .pdf and .SLDDRW files. These components consist of the LED unit, the camera module (mounted first onto the small polycarbonate piece manufactured from ‘PlasPi_Cam_10-004’), the battery housing, the Raspberry PI microcomputer, the camera cable and the power convertors and regulator. The 32mb flash card should ideally be mounted into the Raspberry Pi at this stage too.

Following the physical mounting of the various electronic components to the folded polycarbonate piece, the PlasPi wiring can be completed, as shown in the wiring diagram given as Fig. 3. The connection of various wires to the General Purpose Input Output (GPIO) ports of the Raspberry Pi can be seen in Fig. 4. Schematic files ‘PlasPi_CAM_00-003’ .pdf and .SLDDRW illustrate how the power regulators/Raspberry Pi are physically connected to the battery boxes, integrating the components from the ‘PlasPi_CAM_10-004’ and ‘PlasPi_Cam_10-005’ .pdf and .SLDDRW files described above with the electronics.

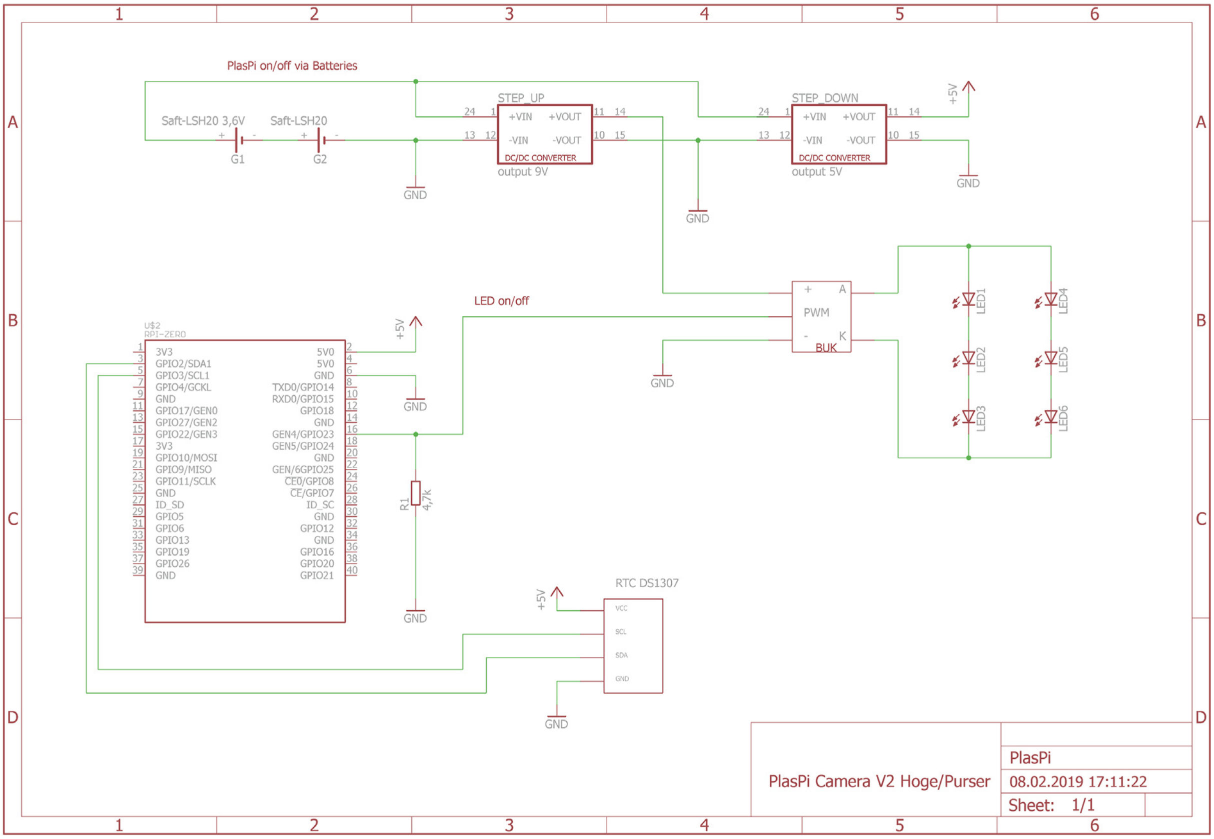

Fig. 3. Wiring diagram of the PlasPi camera.

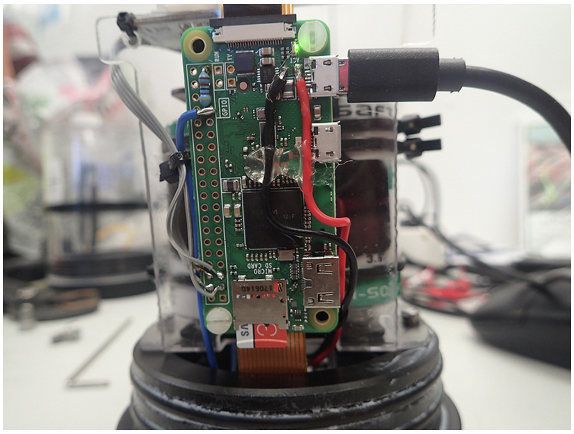

Fig. 4. Photograph of the PlasPi electronics integrated into the front end cap.

5.6. PlasPi mount frame

Although when underwater the PlasPi is designed for environmental pressure to press and maintain the end caps in place, with the rubber rings preventing leakage, an additional mount frame insures this.

The PlasPi mount frame is constructed from the same polycarbonate as was used for the electronics mount component (Section 5.5). This should be cut and folded to the dimensions given in the 'PlasPi_CAM_10-006' .pdf and .SLDDRW online files. This schematic also shows the positions of a number of holes which need to be drilled through the plastic, to allow bolts

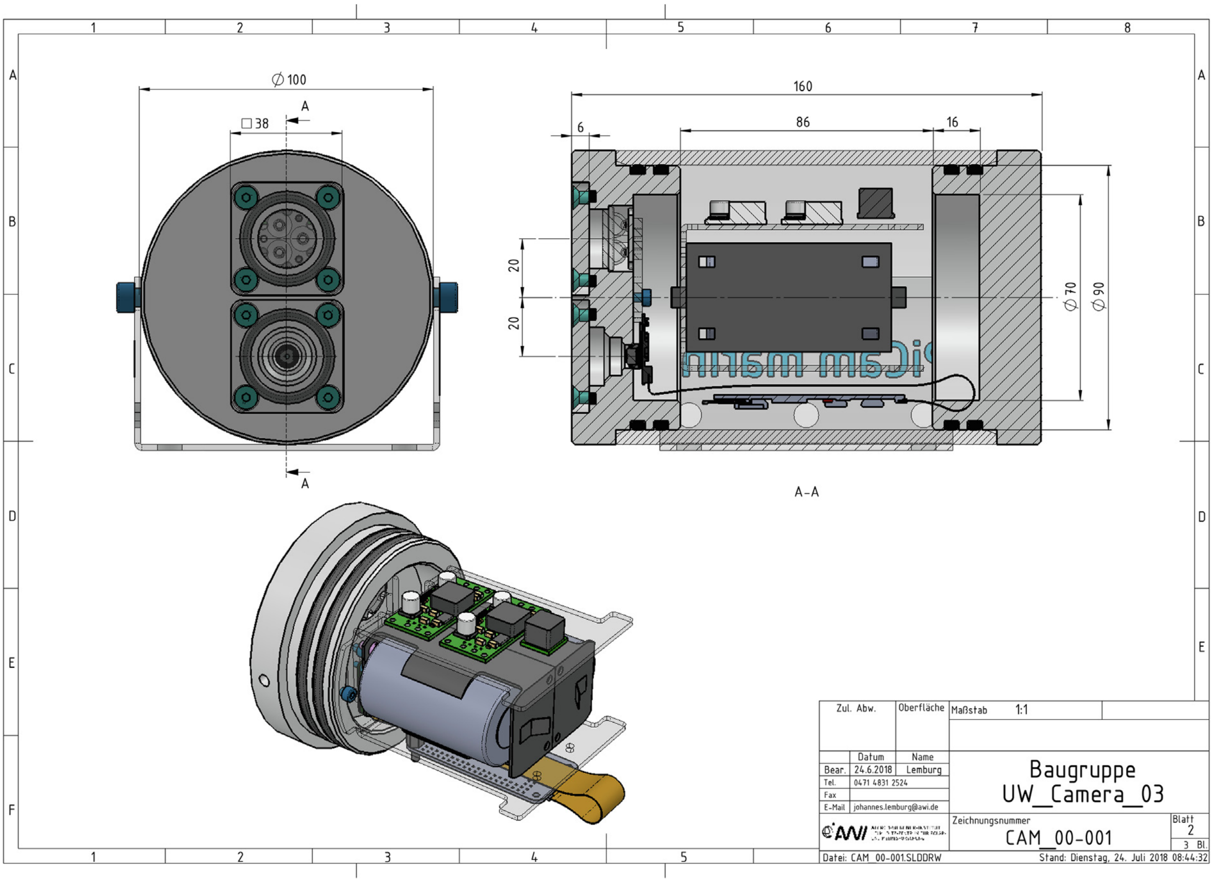

Fig. 5. Schematic of attachment of PlasPi electronics to the front end cap.

to be placed during assembly, or through which to mount tripod legs or other connection mechanisms, depending on the intended deployment use.

5.7. PlasPi assembly

Following construction of the five PlasPi sections outlined in Sections 5.2–5.6, they can be mounted together as shown in Fig. 2. Prior to closing the end caps, ensure that the 32 gb flash card and batteries are correctly mounted. Fig. 5 shows the correct connection position of the electronics with the front end cap. Two Lithium D Li-SO (Lithium/Sulphur Dioxide) 3.6v batteries supply power to the system for long-term or cold water deployments, but for shorter deployments, or when costly lithium single use batteries are unavailable due to logistical or financial reasons, then any pair of D sized 1.2 V batteries may also be used, though the number of images which can be collected during a deployment will be less than achievable with Li-SO batteries. It is good practice to include a silica gel bag to reduce and condensation effects within the camera during deployment at this stage.

Ensure that the rubber rings on both end caps are lightly greased with silicone. As soon as the batteries are put into place the Raspberry Pi should automatically boot and be accessible via wifi (see Section 6).

5.8. PlasPi optional tripod construction and assembly

The PlasPi camera is suitable for many marine imaging tasks, and how the system should be mounted will vary accordingly. Perhaps the commonest envisioned deployment is as a standalone camera unit positioned to record images of the seafloor over time. For this, a stable tripod design is most appropriate (Fig. 6).

Given that the PlasPi camera approaches neutral buoyancy in water due to the air trapped within the main cylinder and the plastic construction materials, using a tripod with metal legs will add stability to deployments, as shown in Fig. 1. A schematic mounting of metal tripod legs to the PlasPi is given in ‘PlasPi_CAM_00-004’ .pdf and .SLDDRW online files, with the stainless steel construction schematics for each leg given in the ‘PlasPi_CAM_10-007’ .pdf and .SLDDRW online files.

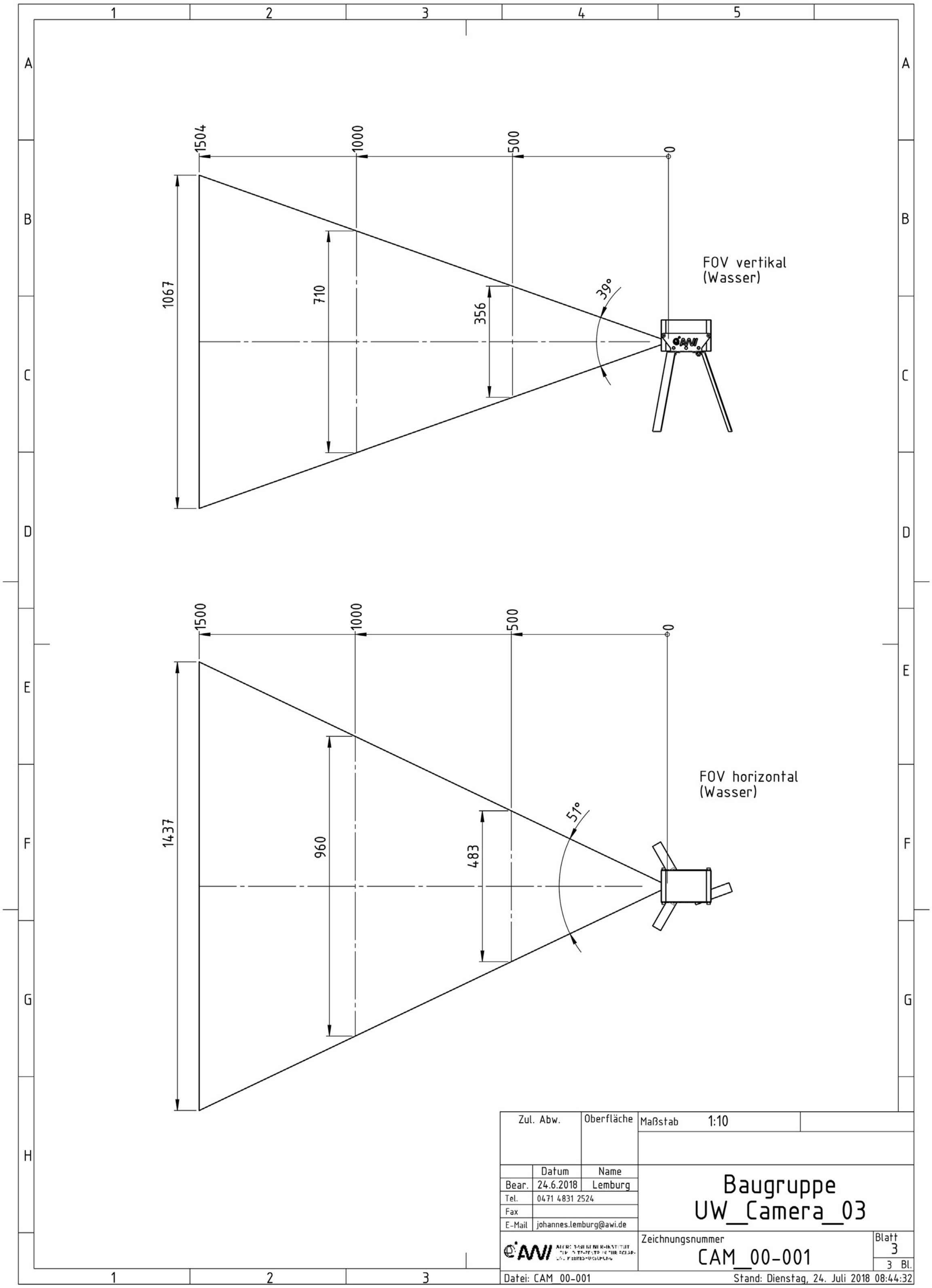

Fig. 6. Field of view of the PlasPi camera, when used on the seafloor for time series monitoring.

6. Operation instructions

6.1. Hazards associated with PlasPi and GlasPi use

6.1.1. LED illumination

Although only operating for a few seconds at a time, the LED illumination provided by the cameras can be very bright. Because of this, care should be taken to ensure that the front end of the camera system is always facing away from the operator during testing/deployment.

6.1.2. Operation under high pressures

Prior to deployment in the field the PlasPi camera should ideally be tested in a pressure tank to ensure suitable pressure resistance. Using the design plans, materials and build instructions presented within this paper regular deployments of the camera have been made up to depths of 200 m (50 m deeper than the intended maximum deployment depth). When these systems are to be deployed by expensive underwater platforms such as Remote Operated Vehicles (ROVs) it is advisable that each individual PlasPi camera is checked individually with a pressure test. Failure of such systems at depth can cause a shockwave which may damage the deploying platform. If cameras are to be deployed by manned submarine such pressure tests should be considered mandatory.

6.2. Camera focus optimization

The camera module used in the PlasPi camera has a manually set focal distance. The depth of field of each particular camera module purchased should be checked prior to deployment, ideally with an underwater test made in a swimming pool or test facility. Good practice is to conduct these tests under dark conditions if the intended deployment depth is to be of more than 10 m. A target board or item of interest should be placed in the test area, at a distance comparable to the deployment distance which is intended in the field. Changing the focus of the camera module can be tricky, particularly after construction of the full PlasPi camera. To assist in this, if repeated changes in focal distance are envisioned, a focusing aid has been designed and can be 3D printed or milled. The dimensions of this piece, as well as a guide to its use are given in the 'PlasPi_CAM_00-005' .pdf and .SLDDRW online files

6.3. Communicating and setting up the PlasPi camera

Operating the PlasPi camera is a straightforward process, requiring the running of short python scripts. The Raspberry Pi at the heart of the PlasPi will boot whenever batteries are inserted, with the green 'power' indicator illuminated indicating that this is so. The current Raspbian operating system should be installed on the 32gb flash cards mounted into the camera, and the appropriate python software files loaded onto these these cards, either by direct connection of the Raspberry Pi when the pressure housing open, or via a file transfer program over wifi. The software provided is extremely straightforward, and anyone with access to the internet or rudimentary python skills will be able to inspect and modify the code as required to achieve their particular research need.

The most efficient way to operate the cameras is to connect to them from a control laptop via a wi-fi application such as 'puTTy' or 'Real VNC' after housings are sealed. The Raspberry Pi operating system should be set up as standard, ensuring that the internal clock is correctly set prior to deployment.

6.4. Running the PlasPi camera software and collecting data

The 'Plaspi_run.py3' script file, when run, will commence taking one photograph with the PlasPi camera every 60 s. To take an image, the LED flash will be triggered and the camera take an image, which will be timestamped with the time of collection and the name of the particular PlasPi camera taking the photo (this name being the name of the Raspberry Pi camera, which can be manually configured as per standard Raspberry Pi Rasabian setup). The camera will continue to take images until the program is interrupted via wifi (IEEE 802.11x) network command issued via puTTy or VNC, until the memory card is full or until the camera system battery is exhausted.

The collected images can be retrieved from the camera at any time via an FTP program, such as 'FileZilla'. Each image will be of <8 mb size, providing that the unmodified software is being run. The 'Plaspi_run.py3' script is self-evident, and should a different interval between images be required by a research project, the script can easily be modified by the researcher(s).

6.5. Seafloor deployments

The main scientific use of this camera system is envisioned to be as seafloor monitoring devices for measuring biological community change over time. Any other environmental changes which can be detected from images can also be monitored with these cameras, such as sediment transport in the water column or the onset of a phytoplankton transport event at the seafloor following a surface bloom. With this in mind, an appropriate tripod leg design has been provided in the design files.

Depending on the focus settings set manually for a particular camera, the PlasPi should be placed either by ROV, diver or submarine at an appropriate distance from the target, bearing in mind the viewing angle of the camera (Fig. 6). In Fig. 1 the PlasPi has been placed to photograph coral, as discussed in Section 7.4.

6.6. Marine instrument monitoring deployments

The PlasPi camera is also useful for the monitoring of remote equipment operating on the seafloor or within the water column. In Fig. 10a a PlasPi camera can be seen attached to the foot of an experimental lander, in this case mounted at the correct focal distance from an array of glass penetrating optodes, designed to slowly lower into the sediment after Lander deployment. Time series images (such as that in Fig. 10b) were collected by the PlasPi camera to monitor the descent and sediment penetration of these optodes, to verify the depth within the sediment (or height in the water column) of each measurement.

6.7. Cabled deployments

In addition to mounting PlasPi cameras on tripods or marine equipment, they may also be attached to ropes or cables lowered below a vessel. Fig. 9 shows an image taken with a PlasPi attached to a Conductivity, Temperature, Depth (CTD) probe, from 200 m depth, whilst being towed by the research ship RV Poseidon during cruise POV526 at a speed of 0.7 kt.

7. Validation and characterization

7.1. Validation and characterization – pressure tanks

Having a waterproof housing of sufficient strength to resist the water pressures associated with the depths of deployment is of crucial importance for marine sensors. This is particularly true for devices which may be deployed either by manned submersibles or expensive Remote Operated Vehicle (ROV), a deployment option intended for the PlasPI cameras. A failure at depth can cause implosion, the loss of the sensor itself and damage to secondary devices such as the deploying vehicle from the resultant pressure wave. It is common practice therefore to place new systems in pressure test tanks prior to use. For the PlasPi camera, testing was conducted at 20 bar, to ensure safe operations at the recommended maximum deployment depth of 150 m.

7.2. Validation and characterization – optics underwater

Light behaves quite differently in water than in air, and any interface between material, such as glass or plastic camera ports and the ocean, further complicates the predicted light pathways. Given the cheap, off the shelf camera components used in this camera system, theoretical light pathways for both designs were estimated from the component specifications using light path software, then physical testing was carried out underwater using a calibration board (Fig. 7) positioned at a particular distance from the camera system. By analyzing the images collected by the cameras under these conditions, the theoretical light pathways could be verified. These test showed that with the components used herein, a distance to item of interest was optimally 1 m for the camera, and therefore the focal length of the cameras manually set with this in mind prior to deployment. Fig. 8 shows an image of a coral reef thicket 1.5 m from the PlasPi camera shown in Fig. 1, taken at 90 m

Fig. 7. Calibration board mounted in a test basin, 1.5 m in front of a PlasPi camera.

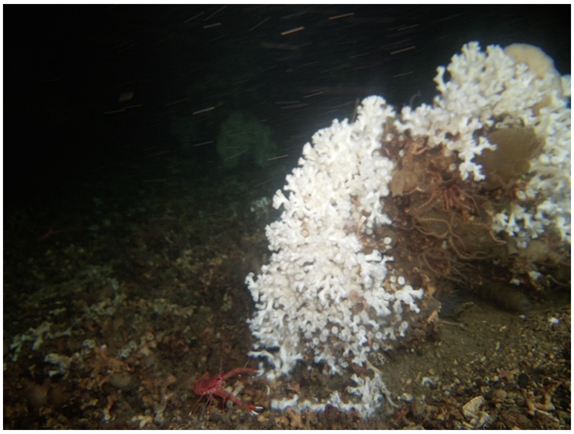

Fig. 8. Image of cold water coral reef taken at ~90 m depth by the PlasPi camera shown in Fig. 1.

Fig. 9. PlasPi camera image of damaged coral reef seafloor, taken at the Tisler Reef, Norway. The weight and rope mark a distance of ~2 m. The camera was being towed at 0.7 kt by RV Poseidon when the image was taken.

depth at the Tisler Reef, Norway. The camera taking the image monitored coral polyp and crab behavior over a 4 day period, collecting an image every 5 min.

7.3. Validation and characterization – test basin time series tests

To verify the Python 3 scripts written for the camera operated correctly over time, and to determine the number of images which could be collected with each camera, underwater, under a particular seafloor temperature with a set of fresh batteries, cameras were placed in the Jacobs University Bremen 50 m^3 test pool overnight. For all deployments made with standalone systems it is important to determine this number so the most appropriate temporal spacing between images can be programmed into the system to facilitate maximum science output from each deployment.

7.4. Field validation

PlasPi cameras were fully tested during the RV POSEIDON research cruise POS526 to the Tisler Reef [19]– a cold-water coral reef in the Norwegian Skagerrak in the summer of 2018. During this cruise, 20,000 images of the seafloor were taken in total by 10 PlasPi cameras, deployed at depths of ~100–150 m. Cameras were placed on cabled oceanographic water sampling platforms and placed on the seafloor directly by submarine to record the response of the seafloor community to tidal variation. For the cabled deployments the PlasPI cameras were tested under 0.7 kts ship speed, with images being collected every 5 s from two meters above the seafloor (Example image Fig. 9). For the timeseries seafloor deployments, cameras were positioned on three sides of a coral atoll, with images collected every minute for up to 4 days (cameras equipped with tripods, as shown in Fig. 1). These cameras were placed ~1.5 m from the coral, with individual 1 cm diameter polyps clearly visible in the collected data (Example image Fig. 8). PlasPi cameras have also been used to image underwater equipment

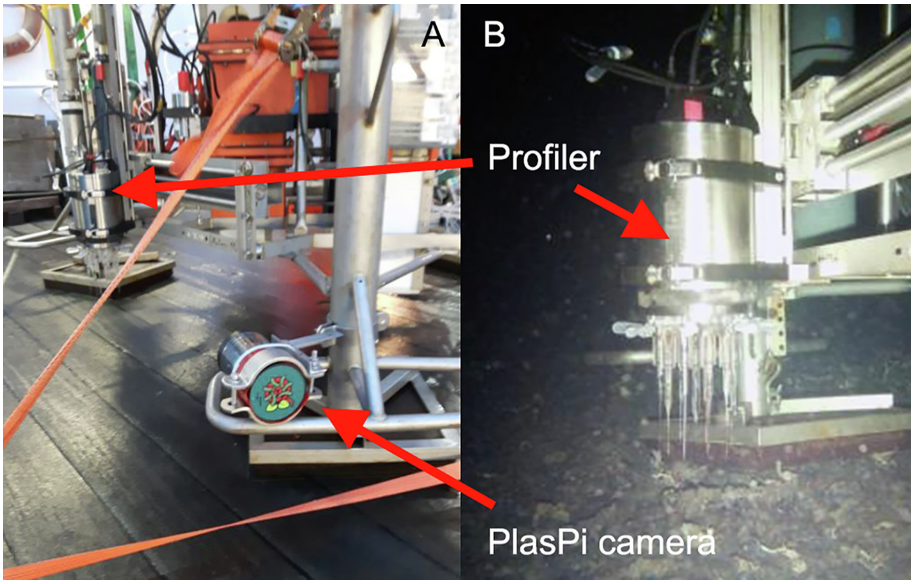

Fig. 10. PlasPi camera used to monitor operation of glass profiling system on the seafloor. A) PlasPi camera mounted on the leg of a lander focused on the tips of a glass profiling unit. B) photograph taken by PlasPi camera of optodes approaching the seafloor.

in action. Some sensor systems used to measure biogeochemical fluxes in marine sediments are delicate in nature, particularly glass optodes used to measure oxygen concentrations with depth. In Fig. 10a a PlasPi camera can be seen mounted on the leg of a benthic Lander, onto which an oxygen optode sensor was also mounted. Throughout the deployment the PlasPi camera took a photograph of the positions of these optodes as they slowly penetrated the seafloor sediments over time (Fig. 10b). Such 'housekeeping' camera uses do not require expensive camera systems to be useful; the aim of deployment purely being to determine whether or not the optode system is working correctly. The image data quality collected by the PlasPi system presented herein is certainly sufficient for such use.

7.5. Ongoing developments/software updates/new designs

The PlasPi camera presented here represents the initial, tested and cheap camera sensor platform designed and used by the Deep Sea Ecology and Technology Group of the Alfred Wegener Institute of Polar and Marine Science, Bremerhaven, Germany. The group is at time of writing actively developing new platforms taking the open source approach forward, to allow deployments of camera systems at greater depths and for longer periods, whilst keeping costs to a fraction of those commonly found with off the shelf solutions. Glass housings are currently under extensive testing, with many deployments made with 500 euro systems at depths of up to 5000 m. Although at time of writing these glass systems are still problematic, suffering from temperature related failures over extended length deployments. The design files for these prototypes are also available for download from the source file repository (https://osf.io/9t7h3/) by interested researchers or technicians for active independent development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ohx.2020.e00102.

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