



Autonomous underwater pumping system

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ABSTRACT

We present an inexpensive autonomous underwater pumping system that is lightweight, compact, independent, and versatile, making it easy to deploy in a multitude of settings. This system can be used to pump water into discrete and flow-through sensor systems. With the exception of the custom built pressure case housing, this system can be fabricated with off-the-shelf parts, making it easier to maintain. This system uses open source Arduino software code for easier customization and operations. The electronics and battery pack used to power this system can be adapted to fit into commercially available pressure case housings.

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1. Hardware in context

Scientists have pushed the development envelope of instrumentation and dedicated sensors to better understand the state of the oceans, aquatic systems, atmosphere, and climate [1,2]. While having improved sensors and instruments is important, so is the ability to deploy them in a range of environments. Today many platforms are used (i.e., ships, tripods, moorings, Autonomous Underwater Vehicles, Remotely Operated Vehicles, drifters, buoys) to place various sensors in areas of interest. Each platform has its own advantage in any given environmental setting [1].

The autonomous pumping system (AutoPump) we present here (Fig. 1) is designed to function in coastal marine settings such as coral reefs, kelp forests, seagrass beds, as well as in aquariums and aquaculture tanks. The AutoPump can be programmed to pump water at specified times for specified durations. This is especially useful for pumping water into discrete and flow-through sensor systems. In addition, the AutoPump can be used to pump water from different nearby locations through the same sensors to reduce cost and improve measurement precision by eliminating cross calibration issues.

We designed the AutoPump while building a more affordable and flexible version of the Benthic Ecosystem and Acidification Measurement System (BEAMS) used by Takeshita et al. [3]. The BEAMS system pumps water from two different depths through a Bresnahan et al. [4] SeapHOx to obtain pH, dissolved oxygen (DO), temperature, and salinity from both depths. A single SeapHOx is used to increase precision of the experimental observations as the analytical focus is on relative differences in pH and DO in samples obtained from two different depths rather than absolute values. These measurements are then used to calculate net community calcification and net primary production rates. Takeshita et al. [3] used a pump controller that was integrated into the circuitry of the SeapHOx and is not an independent pumping system. We built the AutoPump to reduce the cost and increase the flexibility of autonomous underwater pumping. Fig. 2 shows our pumping system connected to a Bresnahan et al. [4] designed SeapHOx during a BEAMS experiment with its integrated pump removed.

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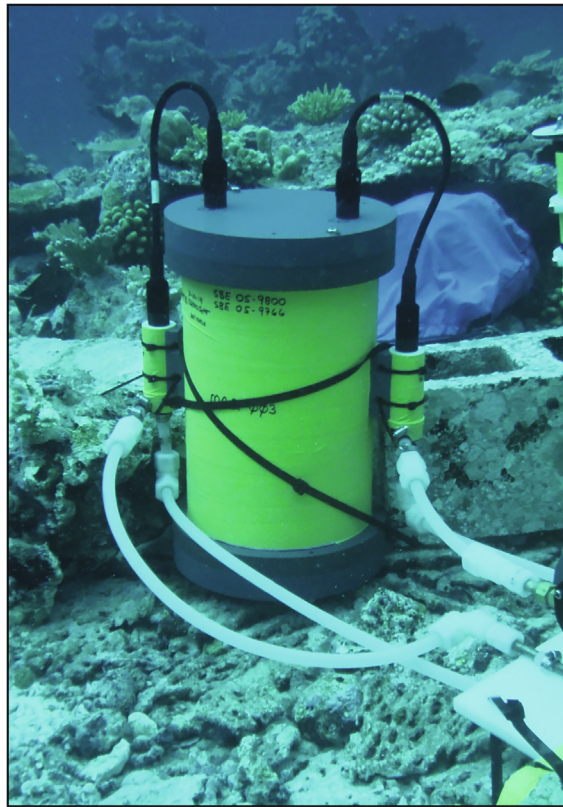


Fig. 1. AutoPump using two Sea Bird Electronics SBE5M pumps.

The goal in designing the AutoPump was to provide an independent instrument that is affordable, autonomous, expandable, and capable of feeding water to different flow-through sensors including the SeaFET (pH and temperature sensor) and SeapHOx, which includes an SBE37SMP-ODO measuring DO, temperature, salinity, and pressure, integrated with a SeaFET, both of which are commercially available from Sea Bird Electronics. The AutoPump is also designed to work with the C-sense pCO₂ sensor (Precision Measurement Engineering/Turner Designs), C3 and C6P Fluorometer sensor (Turner Designs), and

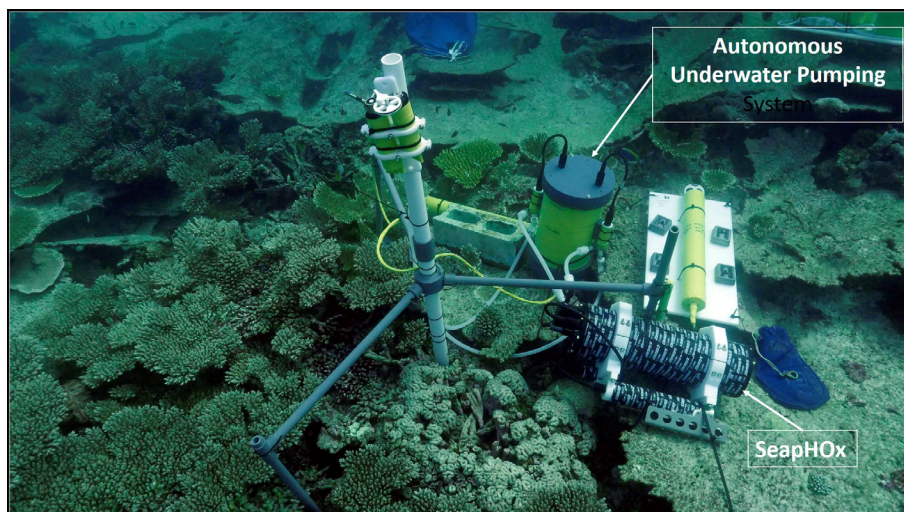


Fig. 2. AutoPump supporting a Bresnahan et al. [4] flow-through SeapHOx design for a BEAMS experiment in the British Indian Ocean Territory.

instruments that can sample water from a sipper tube such as the iSAMI, piSAMI, and SAMI pH sensors (Sunburst Sensors). Fig. 3 shows our pumping system supporting the Sea Bird SeapHOx instrument on a BEAMS experiment.

AutoPump uses a Polyvinylchloride (PVC) pressure housing, off-the-shelf hobby style electronics, and open source Arduino software code to reduce cost and provide ease of use and maintenance. We use two SBE5M mini submersible pumps (Sea Bird Electronics) because their performance specifications met our needs. The SBE5M pump provides consistent flows rates with supply voltages between 9 and 18VDC and will stop operating below 9VDC. Less expensive pumps do not provide this feature and flow rate decreases as the input voltage declines. This can be an issue with the response of various sensors. If constant flow rate is necessary, it is important to select the correct pump. Depending on needs, other 12VDC submersible pumps, such as a bulge pump, aquarium pump, or fountain pump could be used to deliver water, and with lower purchasing cost.

The AutoPump uses two submersible pumps. With this pressure case and mounting disc design, up to 10 pumps could be connected to the AutoPump with minor modifications to the pressure case end cap (more tapped holes for bulkhead connectors), electronics (more relays), and software. Since the Arduino Pro mini has extra General Purpose Input/Output (GPIO) pins, the same controller can be used along with the same real-time clock and micro SD card reader. There are 1, 4, and 8 channel relay boards, similar to the 2-channel relay board we used, that are commercially available and would fit on the same 7" diameter electronics mounting plate used in this design. Because we are using SBE5M pumps, we obtained our bulkhead connectors and cables from Sea Bird Electronics. There are other vendors who manufacture underwater connectors and cables (e.g., Teledyne Marine, Seacon, and Fischer Connectors, USA) that could be used to pair with other submersible pumps.

We opted to use a custom underwater pressure housing made from PVC because we desired a lightweight shallow water solution for working in water depths less than 100' (~30 m) that could be deployed via SCUBA. There are commercially available pressure housings (e.g., A.G.O Environmental Electronics, Prevco, Robotic Ocean, Blue Robotics) and "Do-it-yourself" designs on the Internet that can be used for this purpose and they can be fabricated from PVC, acrylic, aluminum, titanium, and other materials to suit various requirements. In our situation, it was less expensive to fabricate our pressure case housing using PVC. The advantage with our electronics design mounted on an acrylic disc is that it can be adapted to fit in almost any pressure case housing. Upgrading to a more robust pressure case fabricated from aluminum or other metal and using the SBE5P pumps (Sea Bird Electronics higher flow version of the SBE5M) would allow for the use of longer tubing or with more flow-through instruments or use the SBE5T for deeper deployments.

Electronics and SBE5M pumps are powered by 6 off-the-shelf 12VDC alkaline battery packs (D-cell shrink wrapped), each battery packs contain 8 batteries in series (total of 48 D-cells), and each individual battery pack is connected in parallel, providing ~90Ah of charge. The pumps will operate between 9VDC and 12VDC or ~25% of the total battery pack capacity or ~22.5Ah. Maximum power requirement for the electronics (including pump) is ~110 mA. The present 2 pump configuration is programmed so only one pump is running at any given time interval, providing approximately 25 days of continuous operation. Adding more pumps for sequential (serial) operation will not consume more battery power. Adding multiple and simultaneous pumping capabilities will increase power consumption proportionately.

The use of other battery chemistry types, such as lithium ion (Li-ion), nickel cadmium (NiCd), and nickel-metal hydride (NiMH), cell types (e.g. AAA, AA, C, D), and configurations are possible, as is the use of rechargeable battery packs, but modifications to the battery pack holder in the AutoPump would be required. There are obvious advantages in using batteries such as Li-ion, NiCd, and NiMH however, the disadvantages of cost and complications with shipping large quantities of them on aircraft, encouraged us to choose alkaline batteries. Since we have only tested the AutoPump using alkaline batteries, we will only discuss the alkaline battery 48 D-cell design.

The AutoPump is a compact system. The overall outside diameter of the pressure housing is 10" (25.4 cm) due to the diameter of the end cap and end cap ring, but the main housing body alone is approximately 8" (20.3 cm) with an overall height of 16" (40.6 cm). Total assembled weight is 25lbs (11.4 kg) in air and approximately ~2lbs (~1 kg) in seawater making it easy to work with as a SCUBA diver or snorkeler. Extra weight is required to keep it securely on the bottom and if deployed in a relatively high energy environment, additional restraint measures such as using cable ties to secure the pump to the substrate and/or the use and additional weighted objects are required as illustrated in both Figs. 2 and 3.

In summary, the AutoPump is an independent, affordable system that can be configured for use with many different sensors. The unit is compact and can be easily handled by a SCUBA diver and can be deployed in many different environments.

2. Hardware description

AutoPump is comprised of an underwater housing, two external pumps, Arduino Pro mini controller interfaced with a real-time clock, micro SD card reader, 2-channel relay board, and a battery pack. With the exception of the custom-built underwater pressure case housing and pump mounts, all of the remaining components are off-the-shelf and can be easily constructed with simple hand tools.

- A. **Pressure case housing:** The pressure case housing is fabricated from Schedule 40 PVC although other materials can be used to make a case (e.g. acrylic, titanium, aluminum, stainless steel). The pressure case housing has five components: body, end cap ring, electronics end cap, battery pack end cap, and external pump mounts (Fig. 4).

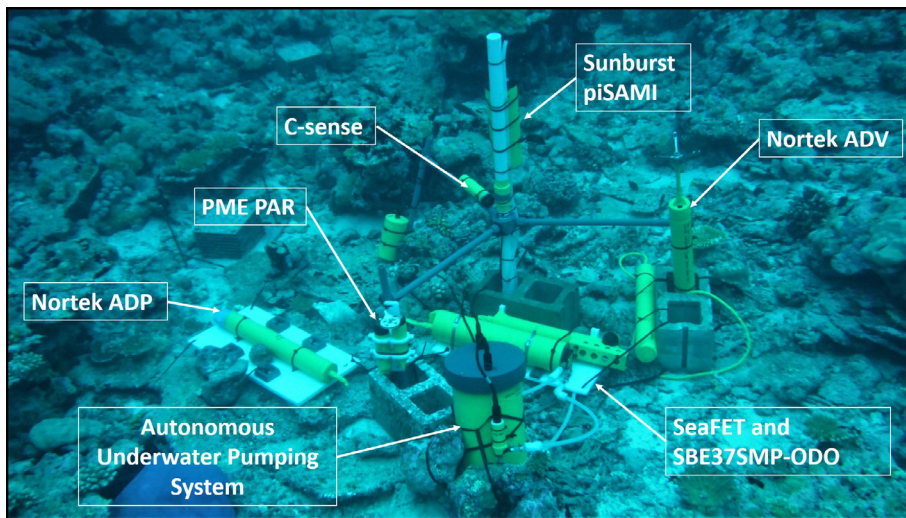


Fig. 3. AutoPump delivering seawater to a SeaFET, SBE37SMP-ODO (both Sea Bird Electronics) and a piSAMI (Sunburst Sensors) for a BEAMS experiment. The piSAMI has an input tube that is positioned inside the tube connected to the pump.

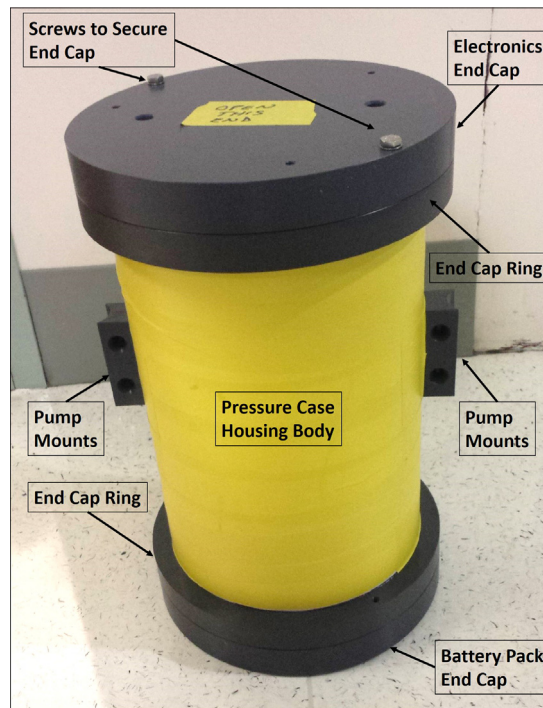


Fig. 4. PVC pressure case housing used for AutoPump. The housing is comprised of 7 pieces, body, end caps ($n = 2$), end cap rings ($n = 2$), and external pump mounts ($n = 2$).

1. **Body:** The body of the pressure housing is standard wall 8" PVC pipe. The pipe was cut to 14" length and milled to true up the ends and chamfered on the inside to make it easier for the o-ring to slide into the housing. The end caps are a piston design where the o-ring on the end cap seals against the inside wall of the body. There are multiple ways to make a piston designed end cap. We chose to use an End Cap Ring to secure and protect the seal.
2. **End Cap Ring:** Two end cap rings are needed with this design. The purposes of the end cap rings are to provide protection between the end caps and the body of the pressure case housing and to keep the end caps secured to the body. Once deployed in water, the pressure acting on the end caps as a function of depth is sufficient in keeping the case sealed. Therefore, the screws securing the end caps only need to be snug. The end cap rings were fabricated from 12" x 12" x

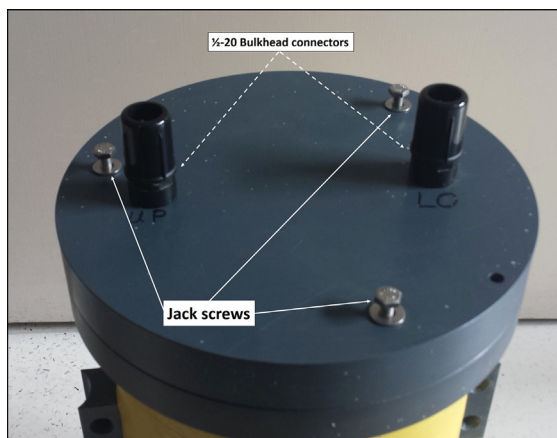


Fig. 5. Electronics end cap for AutoPump. The end cap is drilled and tapped for three 1/4-20 jack bolts and for two 1/2-20 Sea Bird Electronics bulkhead connectors.

1" thick PVC flat stock and both are milled to make 10" OD $\times$ 8.655" ID $\times$ 1.0" thick disks with the faces and sides parallel and perpendicular. Both cap rings are identical in design. The two 0.2031" diameter holes in the end cap ring are tapped to for 1/4-20 threads. PVC cement is used to fix the end cap ring to the body.

3. **Electronics End Cap:** This end cap is machined from 12" $\times$ 12" $\times$ 3" thick PVC flat stock and milled to make 10" OD $\times$ 2.125" thick disks with the faces and sides parallel and perpendicular. The piston portion of the end cap is machined to 7.981" OD $\times$ 1.125" thick to fit into the ID of the pressure case housing body. An o-ring groove is cut into the side of the piston to accept a Viton o-ring.

Two 0.2656" diameter holes are drilled to match the tapped holes in the end cap ring. Three 0.2031" diameter holes are drilled and then tapped for 1/4-20 threads for "jack bolts" (Fig. 5). The "jack bolts" are used to separate the end cap from the body when opening the pressure case housing. The "jack bolts holes" line up with the center of the rim on the pressure case housing. Two additional 0.422" diameter holes are required for the 1/2-20 bulkhead fittings. These two holes will extend from the outer face of the end cap through to the face of the piston. On the face of the piston, four 0.159" diameter holes are drilled and then tapped for 10-32 threads to accept aluminum standoffs to support the electronics mounting plate.

4. **Battery Pack End Cap:** This end cap is very similar to the Electronics End Cap with one difference. Instead of two 0.422" diameter holes tapped for 1/2-20 threads, there is only one that will be used for a pressure release plug. On the piston face, four 0.2031" diameter holes drilled and tapped for 1/4-20 threads to accept stainless steel threaded rods to secure the battery pack.
5. **Pump Mounting Blocks:** The mounting blocks are optional, but they make for a cleaner and more robust way to secure the external pumps. On the prototype we used 2" wide PVC tape (e.g. McMaster PN: 6029 T96) with neoprene between the pump and the housing body to secure the pumps to the housing. The mounting blocks are 2" $\times$ 3" $\times$ 1" and are milled from 2" wide $\times$ 12" long $\times$ 1" thick PVC bar stock and cut to length (Fig. 6). PVC cement is used to secure the mounting blocks to the housing body. Two 0.25" diameter horizontal holes are into the side of the mounting block to secure the pumps to the blocks using cable ties. There are two arcs milled into the front to match the outside diameter of the SBE5M pump and to the back to match the arc of the pressure housing.

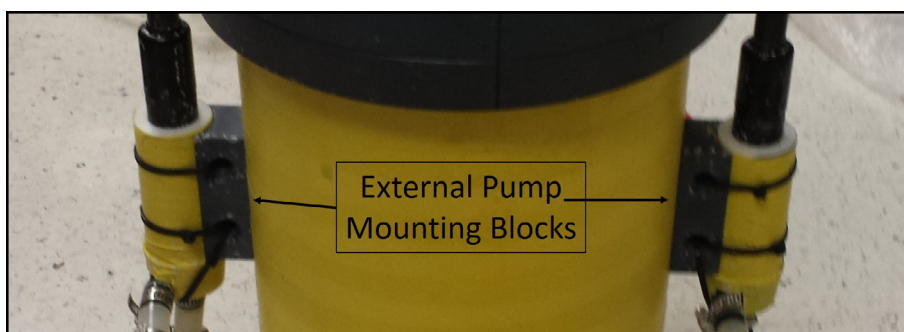


Fig. 6. External pump mounting blocks used to secure Sea Bird Electronics SBE5M pumps.

- B. Electronics Mounting Plate:** The electronic mounting plate is made from 7" OD $\times$ 1/8" thick clear laser cut acrylic discs. There are five components on the plate, an Arduino Pro mini controller, micro SD card reader, 2-channel relay board, a real-time clock, and a terminal block (Fig. 7). The prototype system used an Arduino Uno, but was larger than needed and has higher power demands. There are also other micro controllers that can be used, but the small footprint, power demand, and functionality of Arduino Pro mini controller is more than adequate for this application. The Arduino Pro mini also has plenty of GPIOs for connecting all of the components and enough extra GPIOs for upgrading to support more pumps.
- C. Battery Pack:** The battery pack consists of six individually shrink-wrapped 12VDC battery packs comprised of 8 alkaline D-cell batteries with approximately 15 Ah/pack (Fig. 8). The six individual battery packs are linked together in parallel to provide 12VDC and $\sim$ 90 Ah. An alternative to the premade shrink-wrapped battery packs, 8 D-cell battery holders linked together in parallel will work and can accept individual D-cell batteries. Other battery combinations and types can be used to power the internal electronics and pumps to meet the user's power requirements. Note that the Arduino Pro mini can only accept 5 V to 12 V input, but the SBE5M pumps can take up to 18VDC. The battery pack can be configured to deliver 5 to 12VDC to the internal electronics and up to 18VDC to the pumps by either providing a separate battery pack for each of these two circuits or by installing a step-down DC-DC converter.

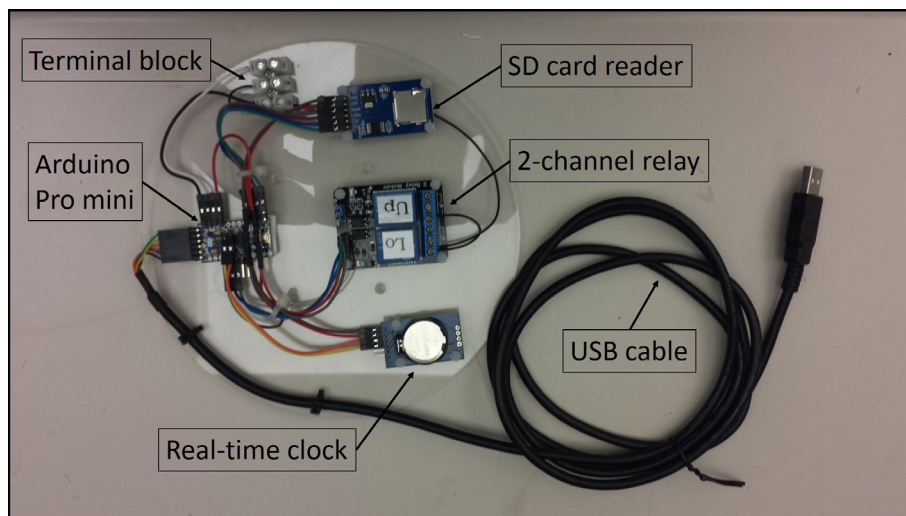


Fig. 7. Electronics mounting plate for AutoPump. An Arduino Pro mini, real-time clock, micro SD card reader, 2 channel relay board, terminal block, and a USB cable of communication with the Arduino Pro mini controller.

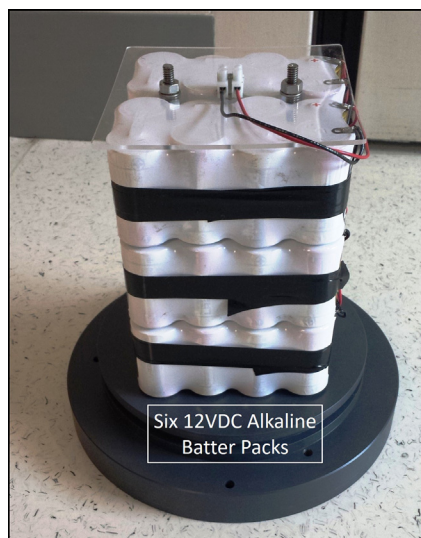


Fig. 8. Alkaline battery pack for AutoPump. Six 12VDC alkaline D-cell battery packs joined in parallel to provide 12VDC and 90 Ah of power the system.

- D. **External Pumps:** The SBE5M mini submersible pump (Sea Bird Electronics, Fig. 6) was selected due to its flow rate 25 ml sec⁻¹ delivered between 9 and 18VDC and has a power consumption of 95 mA. There are other less expensive submersible pumps on the market, but most pumps exhibit decreasing flow rates as battery power decreases. This can make for complicated flow calculations when supplying water to sensors.

3. Design and software files

Design and software files for the AutoPump are available for download from the Open Science Framework. The file **AutoPump Drawings and Schematics.pdf** (<https://doi.org/10.17605/OSF.IO/75MJ4>) contains a summary of all the drawings and schematics required to build the AutoPump. The AutoPump software was coded using the Arduino IDE platform that is available via download from <https://www.arduino.cc/en/Main/Software> and links to download the AutoPump code is provided in the table below.

Design file name	File type	Open source license	Location of the file
AutoPump Build of Materials	pdf	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4
AutoPump Build Instruction Manual	pdf	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4
AutoPump User Materials	pdf	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4
AutoPump Drawings and Schematics	pdf	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4
time_set_manually	ino	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4
current_time	ino	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4
AutoPump_Main_RTC	ino	GNU General Public License (GPL) 3.0	https://doi.org/10.17605/OSF.IO/75MJ4

A. **time_set_manually** – Used to set the real-time clock.

B. **current_time** – Used to display the time from the real-time clock on Arduino serial reader.

C. **AutoPump_main_RTC** – Used to run the autonomous pumping system after the real-time clock is set.

4. Bill of materials

A separate Build Instruction document for the AutoPump is available for download from the Open Science Framework in pdf format under file filename **AutoPump Instruction Manual.pdf** (<https://doi.org/10.17605/OSF.IO/75MJ4>). This manual includes the step-by-step assembly and wiring instructions for all components and the tools needed to assemble the system.

5. Build instructions

A separate Build Instruction document is provided under filename **AutoPump Build Instructions Manual.pdf** (<https://doi.org/10.17605/OSF.IO/75MJ4>). This manual includes the step-by-step assembly and wiring instructions for all components and the tools needed to assemble the system.

6. Operation instructions

The user manual for the AutoPump is available for download from the Open Science Framework in pdf format under file filename **AutoPump Users Manual.pdf** (<https://doi.org/10.17605/OSF.IO/75MJ4MJ4>). This manual provides the step-by-step operations of the entire system.

7. Validation and characterization

Three AutoPump systems were used in the field to supply water to underwater sensors on a coral reef in 2019. During this field season, the three pumping systems were deployed in different coral reef settings as outlined in Table 1. The amount of voltage drawn on each pump was very similar, ranging from 0.910 V to 1.039 V per week. Deployment 1 and 3 used the same pump cycle time of 15 min and flowed water through a Bresnahan et al., 2014 designed SeapHOx instrument. Deployment 2 used 20 min pump timing and flowed water through the Sea Bird Electronics SeapHOx. Upon recovery all pumps were still operational and the micro SD card data confirmed that all 3 pumps worked as expected.

To better illustrate the functionality of the pumping system we present a small portion of data collected from the Sea Bird Electronics SeapHOx instrument, in this case an SBE37SMP-ODO connected to a SeaFET, on Deployment 2. In this BEAMS

Table 1

Statistics for 3 autonomous pumping system deployments.

Deployment #	Site	Depth (m)	Deployment Time (d)	Start Voltage	End Voltage	Voltage loss/ Week	Cycle Time (min)
1	inner reef	6	16.37	12.96	10.82	0.915	15
2	outer reef	8	15.37	12.95	10.96	0.910	20
3	outer reef	10	21.35	12.92	9.79	1.026	15

experiment the pumps circulated water from two different tube heights (58 cm and 116 cm) above the coral reef bottom with the objective of observing differences in pH and DO from the two different tubes within the boundary layer (Fig. 9). The pump cycle time is 20 min where the SeapHOx samples temperature, salinity, depth, DO, and pH every 15 s and the PiSAMI records only temperature and pH every 3 min. A subset of these results is shown in Fig. 10.

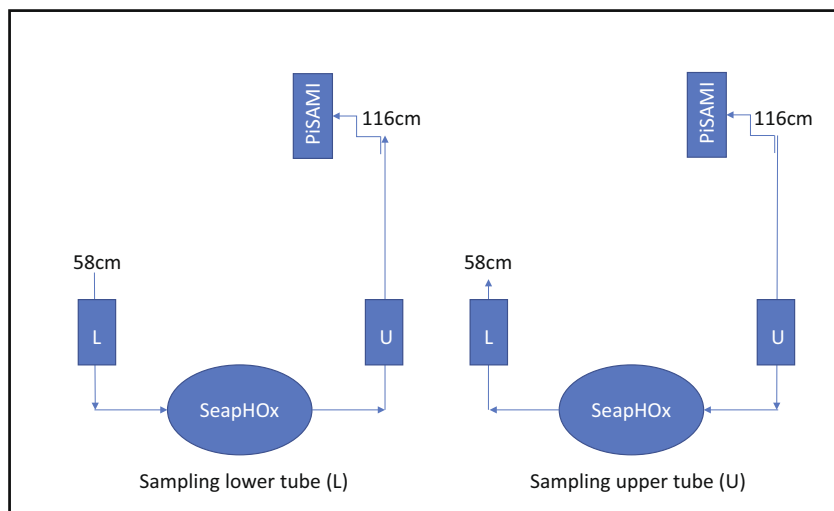


Fig. 9. AutoPump BEAMS schematic. The arrows indicate flow direction. The SeapHOx is a flow-through sensor and the PiSAMI is a discrete sipping sensor that samples water flowing from both directions in the upper tube. The SeapHOx is sampling ever 15 s and the PiSAMI every 3 min over a 20-minute cycle time.

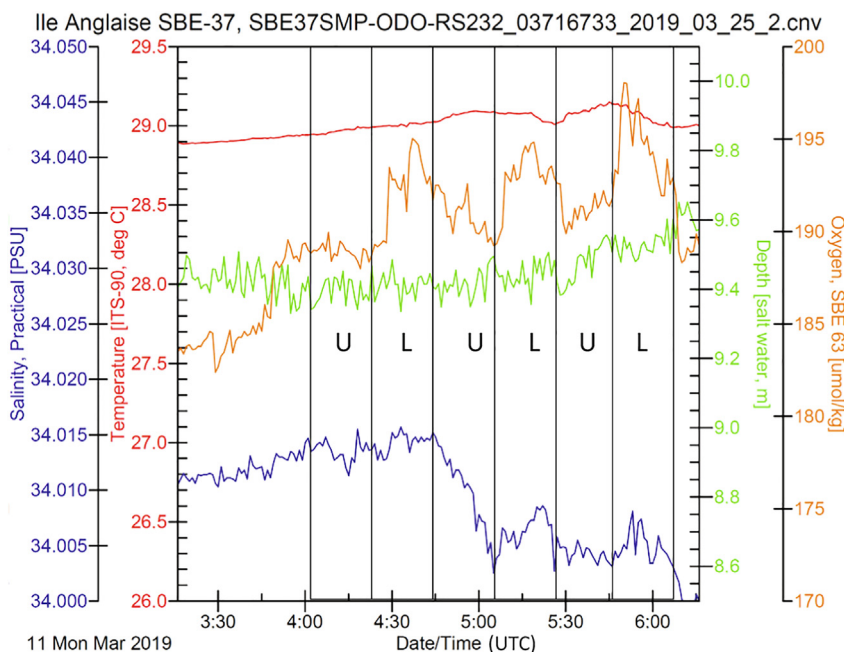


Fig. 10. Daylight results from the SBE37SMP-ODO, salinity (blue), temperature (red), DO (orange), and pressure (green). Data subset was collected between 0300 and 0630 UTC on March 11, 2019 (+6 hrs local time).

Prior to the first U (upper pump) in Fig. 10, the sensors were equilibrating until approximately 0430 (0230 to 0630 UTC) on March 11, 2019 (+6 hrs local time). After this equilibration time, distinct cycles in DO are shown for both the upper (U) and lower (L) pump heights. This data makes sense since the lower tube is closer to the corals and during daylight hours should be pumping water with higher DO than 116 cm above the surface of the corals, indicating net benthic primary productivity. Conversely, Fig. 11 represents nighttime results collected from 1700 to 2030 UTC on March 11, 2019 (+6 hrs local time). Here the opposite with respect to DO is observed, where the water being pumped from the upper tube is higher than the lower tube, which is indicative of net benthic respiration. The overall level of DO is lower at night vs daylight hours.

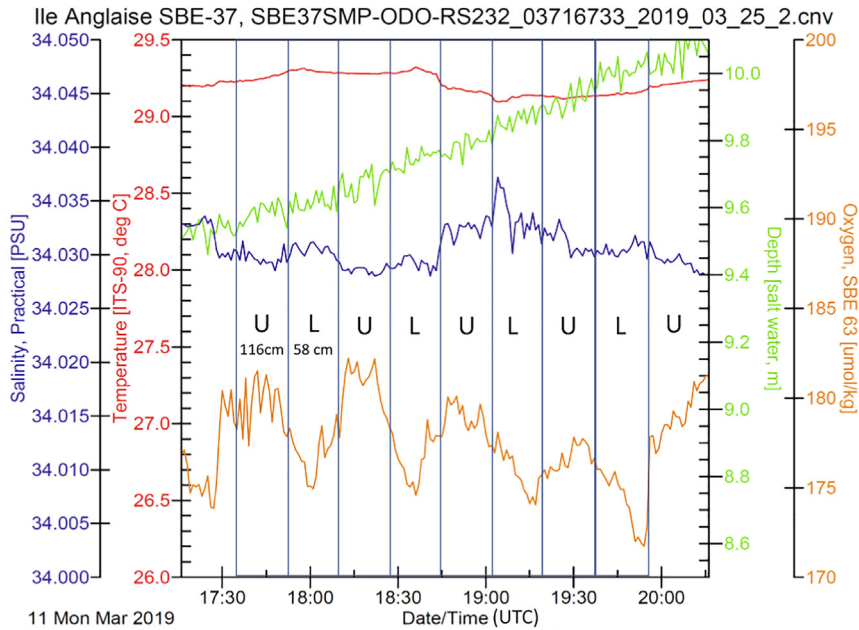


Fig. 11. Night-time results from the SBE37SMP-ODO, salinity (blue), temperature (red), DO (orange), and pressure (green). Data subset was collected between 1700 and 2030 UTC on March 11, 2019 (+6 hrs local time).

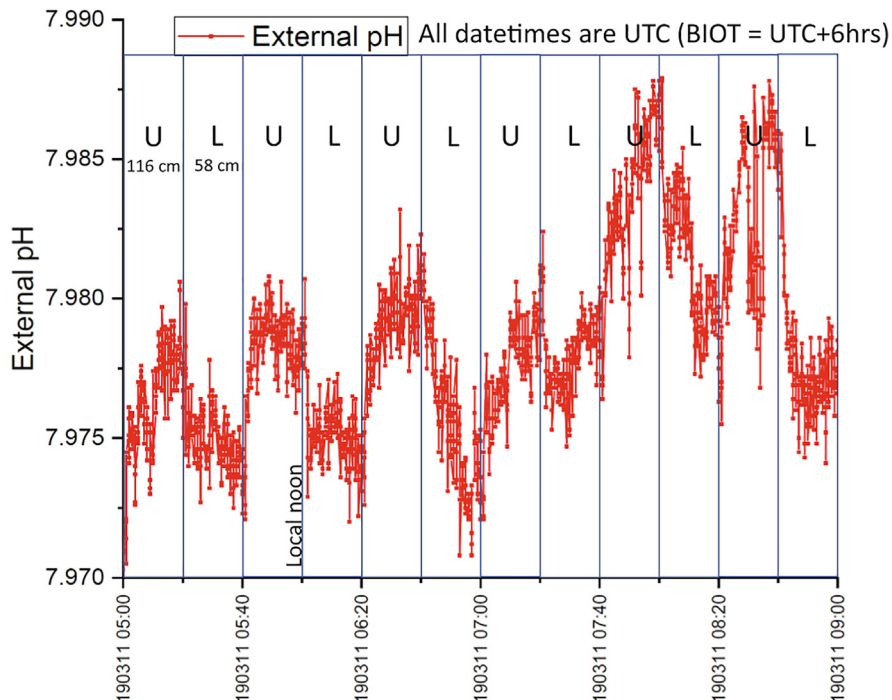


Fig. 12. pH results from the Sea Bird SeapHOx during daylight hours from 0500 to 0900 UTC on March 11, 2019 (+6 hrs local time). The upper tube (U) was placed 116 cm above the reef bottom and lower tube (L) at 58 cm.

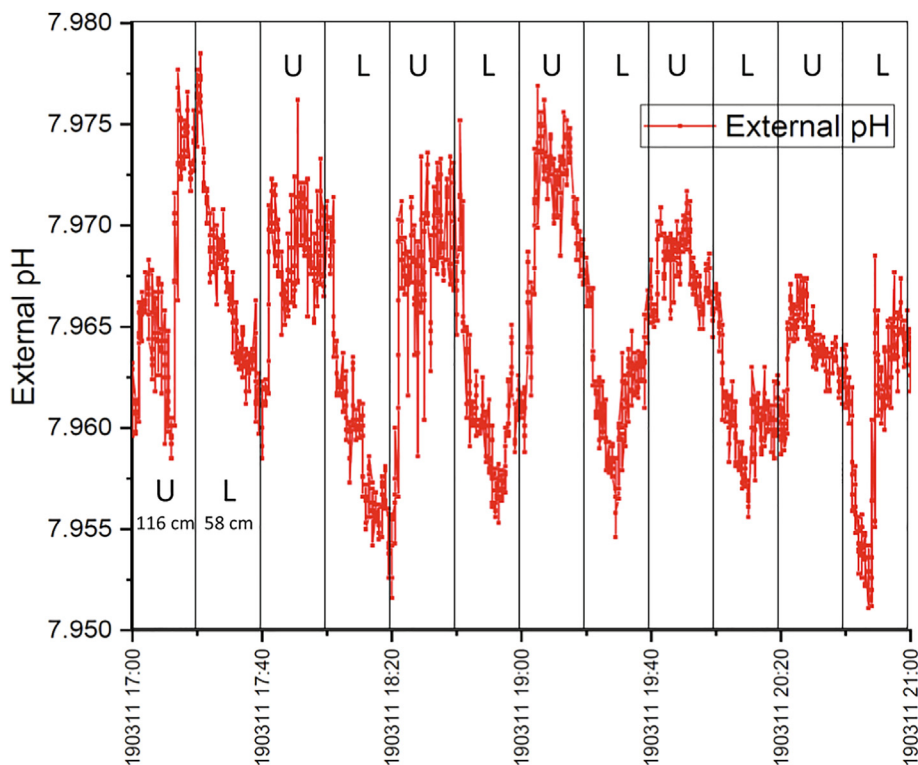


Fig. 13. pH results from the Sea Bird SeapHOx during daylight hours from 1700 to 2100 UTC on March 11, 2019 (+6 h local time). The upper tube (U) was placed 116 cm above the reef bottom and lower tube (L) at 58 cm.

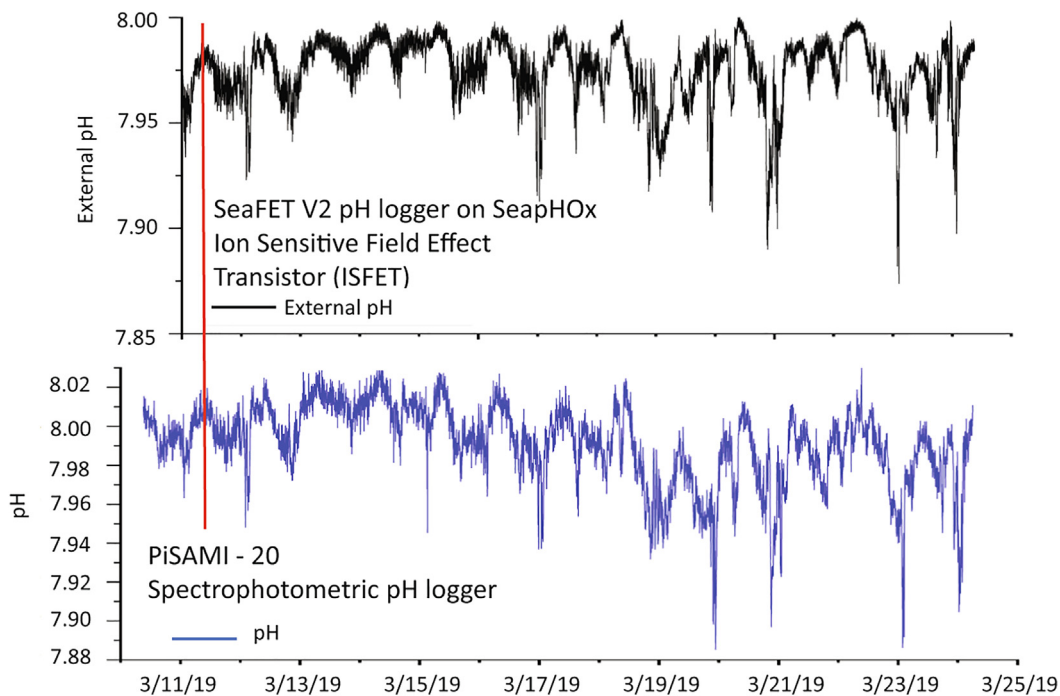


Fig. 14. pH data from both the SeapHOx (top, black line) and PiSAMI (bottom, blue line) from a 14 day experiment for Deployment 2. The red vertical line marks the beginning of the data comparison.

The pH data also indicates that the AutoPump is working properly. Fig. 12 represents pH data collected from the SeapHOx every 15 s for a 4-hour time interval from 0500 to 0900 on March 11, 2019 (+6 hrs local time). During daylight hours pH is lower on the lower tube (L) than water pumped from the upper tube (U) within the benthic boundary layer. This is often indicative of net benthic calcification on the reef since calcification reduces pH of the surrounding fluid. As shown in Fig. 13, the opposite relationship was observed in pH when pumping water between the upper and lower tubes during the night hours 1700 to 2100 on March 11, 2019 (+6 hrs local time). This is usually associated with net community dissolution at night.

A second pH logger (Sunburst Sensors PiSAMI) was installed on Deployment 2, but not on Deployment 1 and 3, to compare the results obtained from two pH sensors using different technology and to serve as an analytical comparison. The SeapHOx uses an Ion Sensitive Field Effect Transistor (ISFET) and the PiSAMI uses a color indicator method and a spectrophotometer. The ISFET sensor on the SeapHOx is setup as a flow-through system where the two pumps circulate water from the upper and lower tubes and the PiSAMI is a discrete sipping system (Fig. 9). The results presented in Fig. 14 shows a comparison between the SeapHOx and PiSAMI pH sensor data for the duration (14 days) of Deployment 2. The offset between the two sensors is less important for the purpose of this comparison, what is remarkable is that the trends from both pH sensors are very similar and support that the AutoPump is providing enough flow for both types of sensors.

Final Assessment: The AutoPump is a compact, lightweight, user-friendly pumping system that can be deployed for over 3 weeks on one alkaline battery pack. We demonstrate that the pumping system can accurately turn pumps on and off at specified intervals over a multi-week deployment in field conditions. This system can be used to pump water to a variety of different discrete and flow-through sensors. In addition, the AutoPump can pump water from multiple locations into a single sensor, reducing costs and increasing precision of the measurement since different sensor measurements can drift apart from each other. With the exception of the pressure case housing, all of the components are inexpensive and readily available as off-the-shelf parts. While we opted for a custom pressure case housing, there are several vendors who sell off-the-shelf or custom housings. The results presented here show that the system can provide research quality data obtained from flow-through or a discrete sensor.

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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Human and animal rights

This section does not apply.

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