11-2018

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***Abstract*—We report the design, sea trials, and scientific operation of a fast vertical profiling autonomous underwater vehicle, called *Clio*, designed to cost-effectively improve the understanding of marine microorganism ecosystem dynamics on a global scale by collecting high-volume filter samples autonomously, in contrast to conventional techniques that require a ship's wire.**

I. Introduction

We report the design and sea trials of a fast vertical profiling autonomous underwater vehicle, called *Clio* (Fig. 1), designed to cost-effectively improve the understanding of marine microorganism ecosystem dynamics on a global scale.

Life processes and ocean chemistry are linked: ocean chemistry places constraints on marine metabolic processes, and life processes alter the speciation, chemical associations, and water-column residence time of seawater constituents. Advances in sequencing technology and *in situ* preservation have made it possible to study the genomics (DNA), transcriptomics (RNA), proteomics (proteins and enzymes), metabolomics (lipids and other metabolites), and metallomics (metals), associated with marine microorganisms; however, these techniques require sample collection. To this end, *Clio* carries two to four Suspended-Particle Rosette (SUPR) multi-samplers [1] to depths of 6000 m. *Clio* has been designed specifically to complement conventional wire-based sampling techniques—to operate simultaneously and independently of conventional techniques to improve ship-time utilization. *Clio* transits vertically between the surface and 6000 m depth, stopping at multiple pre-programmed depths to filter up to 250 l/hr of seawater per sample (Fig. 2). Clio can optionally administer an *in situ* preservative (RNA Later) after completing each sample.

As an Autonomous Underwater Vehicle (AUV) devoted entirely to vertical motion, *Clio* occupies an uncharacteristic design space. *Clio* must efficiently hold station at multiple depths between the surface and 6000 m, but must also move rapidly between sampling depths to keep dives short. It must be chemically clean and avoid disturbing the water column while sampling. *Clio* must be operationally friendly, requiring few personnel to operate, and have minimal impact on shipboard operations. We selected a positively-buoyant thruster-driven design without ascent/descent weights or a variable ballast system. Thrusting constantly to overcome static positive buoyancy incurs and energetic penalty, however, we argue that for *Clio*, the benefit in terms of reduced vehicle and operations complexity outweighs the cost of an incremental increase in battery capacity. In what follows we describe *Clio*'s design in more detail, the trades that drove our design decisions, and devote particular attention to the hydrodynamic stability of *Clio*'s hull-form, and predicting and managing vehicle compressibility and its effects on buoyancy.

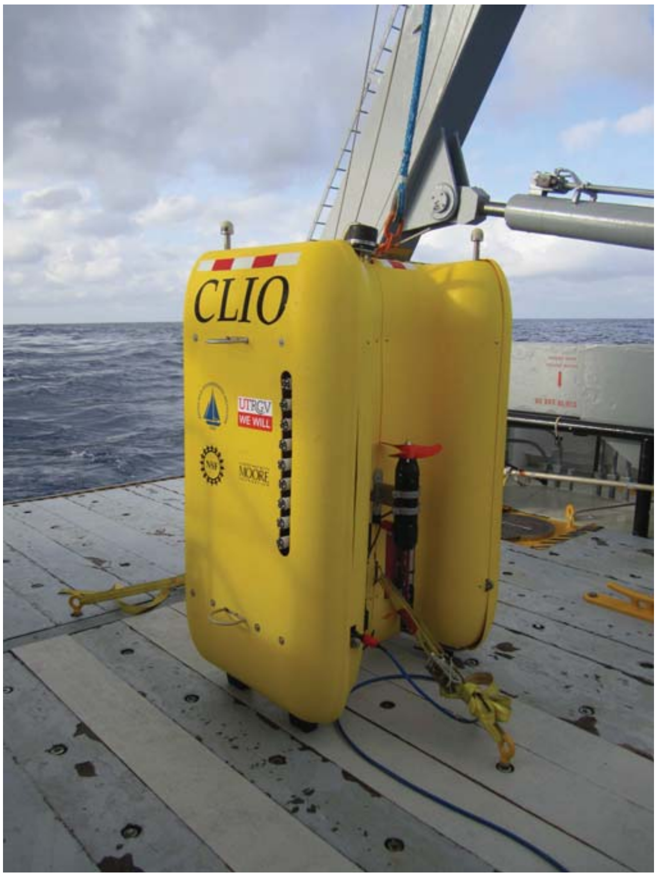

Fig. 1. *Clio* aboard the *R/V Atlantic Explorer* in April 2018. The intake ports for one of two SUPRs are visible on the right-hand side of the panel bearing the vehicle's name. One of two thrusters is visible between the hulls.

II. Background and Related Work

Current practice in water column sampling primarily relies on discrete sampling devices attached to a cable or wire and lowered by winch from a ship. Water samples are collected by Niskin and GO-Flo bottles on water carousels and suspended particulates are collected by wire-deployed large volume *in*

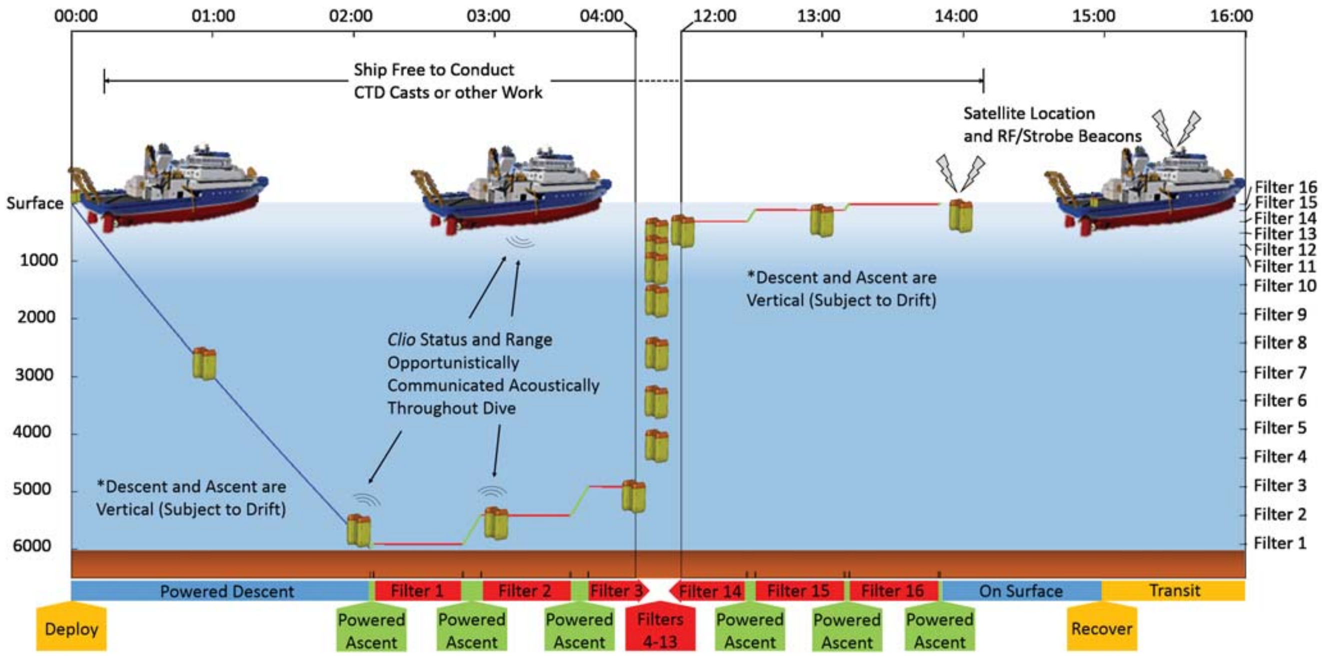

Fig. 2. *Clio* concept of operations for a 16-sample profile shown schematically as depth vs. time (the vehicle does not actively control its horizontal position). The vehicle begins its dive after being deployed using a support ships crane, A-frame or J-frame. Upon reaching the near sea floor, *Clio* begins its ascent, thrusting upwards between sample depths, and engaging a closed-loop controller to hold depth for the duration of each filtering operation. The vehicle completes its dive in 14 hours. Operators can optionally track the vehicle during its dive using an acoustic ranging system (WHOI Micro Modem [2]) and receive regular vehicle status information with integrated acoustic telemetry. The vehicle alerts operators to its arrival back on the surface using four independently-powered beacons: a pair of redundant GPS/Iridium units to provide over-the-horizon location, and radio-frequency and strobe beacons for line-of-sight location. Our recovery procedure is modeled after other mid-size AUV systems.

situ stand-alone pumps. A number of Autonomous Underwater Vehicles (AUVs) have been equipped with sampling payloads, including with the MBARI Gulper [3] and with the Suspended-Particle Rosette (SUPR) sampler [4]. The SUPR sampler family of instruments was originally developed for deep-sea hydrothermal plume studies from Remotely Operated Vehicles (ROVs) [1], [5]; and is the basis of the *Clio* sampling system. However, most AUVs and ROVs are designed for seafloor work or lateral surveys and are not well suited to sampling the ocean water column from surface to seafloor, i.e. for profiling. Profiling floats and gliders designed specifically to profile are not large enough and lack sufficient battery capacity to carry significant sampling payloads. *Clio* was designed specifically for this vertical ocean profile sampling task.

Clio is capable of deploying as many as four independent SUPR samplers, each capable of sequentially collecting from 10 to 19 samples per deployment depending on sample type. Each *Clio* SUPR system consists of a large multi-port valve, a Mclane Laboratories pump, a digital flowmeter, associated control and drive electronics, and custom filter and sample holders. In concept a wide variety of filtering media and sample holders can be used in the system, but currently the primary filter media type used has a diameter of 142 mm, typically with a 0.2 micron poresize membrane. The primary sample container that holds this filter also retains aliquot samples of whole water and filtrate.

The *Clio* SUPR multi-samplers collect individual samples comparable to those collected with single-point wire-deployed pumping systems, e.g., McLane Research Laboratories, WTS pumping systems. Multiple of these samplers are typically deployed on a hydrographic wire at specified intervals as they are lowered over the side. The pumps are pre-programmed to begin and end pumping on a schedule designed to accommodate lowering of the wire so as to deliver a simultaneous profile at discrete depths, with a resolution limited by the number of samplers available. Once deployed, the *Clio* system operates independently, freeing the ship to carry out simultaneous tasks (not possible when performing analogous sample collection with a wire-deployed system). The *Clio* system can, furthermore, collect samples at precise depths, whereas ship heave from wave action and other ship motion cause wire-deployed systems to smear samples over depth intervals typically several meters to tens of meters thick depending on weather and sea state. *Clio* can potentially also deliver near-surface samples free from ship-derived contamination (this capability has not yet been quantitatively confirmed). Future adaptive sampling, e.g., tracking and sampling a feature within a water-column layer with *in situ* instruments, is rarely practical with a wire-based technique but is very feasible with an AUV such as *Clio*.

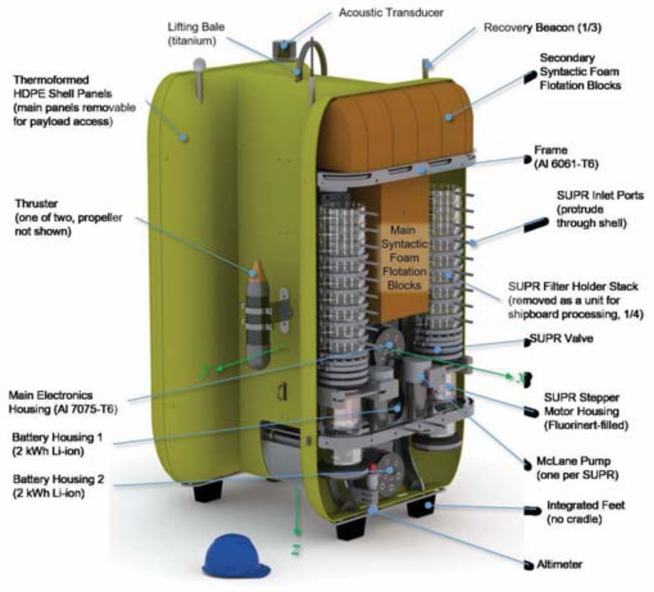

Fig. 3. A rendering of *Clio* showing its essential components. One of two large skin panels used to access the SUPRs is shown removed. Four fasteners allow rapid removal and installation of these panels so that the SUPR filter stacks spend minimal time on deck. The vehicle's body-frame axis convention is shown in green.

TABLE I
Clio SPECIFICATIONS

Air weight	<700 kg
Size	H 2.1 m × W 1.2 m × D 1.3 m
Maximum depth	6000 m
Vertical transit speed	0.75 m/s
Battery	4 kWh
Attitude	Microstrain GX4-25
Depth	Paroscientific Nano-resolution Digiquartz
Altimeter	Valeport
SUPR	Up to 4 units; each unit 9 or more sample sets
Profiling instruments	SBE49 FastCAT CTD, WetLabs fluorometer (Chl/NTU), Aanderra optode, CStar transmissometer; additional ports available

III. Design Overview

Clio is actuated in only a single degree of freedom, so while relatively simple, operation throughout the water-column imposes a number of design challenges not usually encountered on a typical AUV. Basic specifications appear in Table I.

Clio must avoid contaminating its samples and altering the active biochemical pathways, for example, by introducing iron. Eight years of development effort devoted to the SUPR multi-sampler have led to a good understanding of acceptable materials for contact with sample water. *Clio* itself is constructed almost entirely of non-ferrous materials, principally plastics and aluminum. Titanium fasteners replace conventional steel ones in high-strength joints. The high cost these fasteners drove us toward a frame design requiring few fasteners.

Clio must quickly and efficiently execute its profiles. *Clio* is designed to complete a nominal 16-station profile and return to deck within 14 hrs, a time-line designed to be compatible with the standardized wire-based sampling protocols developed for the multi-national decadal GEOTRACES program.[1] The SUPRs aboard *Clio* employ the same pumps (McLane Laboratories) used for conventional wire-based filtering. For typical filter pore sizes these pumps require between 30 minutes and 1 hour of continuous pumping to collect a complete sample. To complete a 6000 m dive, *Clio* must therefore spend the vast majority of its dive-time actively sampling, and move rapidly between sample depths. *Clio* must precisely maintain its depth while sampling. The precision requirement (5 m) demands closed-loop depth control, though not necessarily a particular means of propulsion. Thrusters render the control problem trivial—*Clio* maintains depth to within 5 cm while sampling. Using thrusters, as opposed to a variable ballast system, means *Clio* must expend energy continuously to hold depth. However, pumping is energetically intensive, and therefore thrusting to hold depth incurs only an incremental additional cost. While this increases the required battery capacity, it also requires no fundamental change to vehicle infrastructure already necessary. But the most compelling reasons for preferring active thrust over expendable or variable ballast systems have to do with the logistical and maintenance implications.

Typical AUV systems designed for sea floor work use expendable ascent/descent weight systems to execute rapid descents, become approximately neutral at depth, and then positively buoyant for ascent or in case of emergency. *Clio* must operate throughout the water column, whereas a two-weight descent/ascent system is effective for attaining neutral buoyancy only at a single depth. An ascent/descent weight system would enable *Clio* to transit the water column in one direction "for free," and/or to provide positive buoyancy in an emergency. However, we found no inexpensive, non-ferrous materials suitable for routine use as expendable ballasts. Concrete, stone, etc., have specific gravities < 3 whereas the most common expendable ballast material, steel, has a specific gravity of about 8. Steel can be coated, e.g. with polyurethane, but at extra cost. Dissolved lead (from leaded gasoline) is a valuable tracer in the ocean, rendering lead weights both expensive and a contaminant risk. More importantly, our experience with other deep-diving AUV systems (ABE [6], Sentry, Nereus [7]) indicates that servicing drop-weight systems, necessarily required after every dive, poses a significant maintenance burden and incurs significant costs associated with shipping and storing large quantities of ballast material.

Nevertheless there are obvious benefits to minimizing the energy required to hold depth. The energy required depends strongly on *Clio*'s static ballast condition. We ballast *Clio* to be positively buoyant at the surface. This ensures that it will passively rise to the surface in the event of most system failures. Like nearly all AUVs, *Clio* is less compressible than seawater and therefore gains buoyancy as it descends. Where

[1] www.geotraces.org

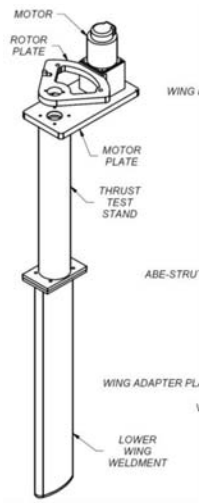

Fig. 4. The apparatus used to directly study the stability of *Clio*'s hull form and to measure selected hydrodynamic coefficients. The device consists of a motor connected via zero-backlash cabling to the rotor plate and a shaft passing through the strut that connects to a 1/4 scale model of the vehicle. The motor is controlled in closed-loop to allow for modification of the effective scale CB/CG separation, to set the static side-slip angle, and to measure the hydrodynamic moment about the vertical axis. A mount (not shown) with integrated load cell measures drag.

Fig. 5. The 1/4-scale *Clio* model mounted on the apparatus of Fig. 4, shown at a side-slip angle of 15°. The model can be mounted with either the roll-axis actuated (as shown) or the pitch axis. (The axes refer to the full-scale vehicle.)

possible we chose materials having lower bulk moduli to minimize this effect. A isopycnal hull like that on the Seaglider [8], designed to match average seawater compressibility, is a more sophisticated solution to the same problem, but less suited to a flooded-hull vehicle like *Clio* where pressure housings comprise only a small portion of the vehicle's total displacement. "Compressees" in the form of spring-backed compensators, e.g. [9], or bulk materials with low bulk moduli [10] strive to achieve a net vehicle compressibility similar to seawater, and may be added to *Clio* in the future.

We chose *Clio*'s unique hull shape for several reasons: to accommodate the form factor of the SUPRs, to keep the samplers vertical throughout a dive, to avoid the need for a cradle on deck, to enable rapid access to the samplers and to prevent contamination by removing them to a clean room between dives, to ensure the vehicle fits into typical CTD-rosette hangars and standard ISO shipping containers, and to achieve reasonably low drag. Being symmetric about the horizontal plane causes a destabilizing moment that scales quadratically with speed. A deliberately large separation between center-of-mass and center-of-buoyancy stabilize the vehicle, up to a certain threshold speed.

IV. Hydrodynamics

Clio must travel efficiently during both ascent and descent. To achieve specifications it must transit 6000 m at a speed above 0.75 m/s. *Clio* uses thrusters rather than expendable ballast, and therefore hull drag detracts directly from battery energy. To keep drag low in both directions we chose a hull form symmetric about the horizontal plane. Potential theory predicts that such a hull form is unstable—it will tend to rotate such that its long axis is perpendicular to the direction of motion. It would be possible to stabilize the vehicle during descent by adding fins to the upper end of the vehicle, but these would act to destabilize the vehicle during ascent, absent some means of transferring them to the bottom of the vehicle or vice versa. To avoid this complexity, we rely on the hydrostatic restoring moment that results from the vertical separation between the vehicle's center of buoyancy (CB) and center of mass (CG) to counteract the destabilizing hydrodynamic moment. The hydrostatic stabilizing moment is invariant with speed, whereas the destabilizing hydrodynamic moment scales quadratically with speed. *Clio* is therefore stable only up to a certain threshold speed, and that threshold speed must exceed the specification. It is straightforward to predict a vehicle's CB and CG using computer aided design tools (CAD), whereas predicting a vehicle's hydrodynamic coefficients using computational fluid dynamics (CFD) remains challenging. The lack of empirical studies for a hull form of *Clio*'s unusual shape led us to measure the key hydrodynamic coefficients experimentally with a scale model.

To measure these parameters and to confirm stability directly we designed the apparatus shown in Fig. 4 along with a 1/4-scale model of *Clio* (Fig. 5) and then performed a series of runs in the University of Rhode Island tow tank. The model was driven horizontally down the length of the flume at speeds up to 3 m/s (0.75 m/s full-scale speed) while measuring drag and moment about the axis parallel to the strut. We varied angle of attack, α, up to 15°. Drag was measured in order to predict propulsion system energy consumption. The moment was measured to determine the threshold speed as a function of CB/CG separation. (On *Clio* there is no incentive to make the CB/CG separation anything other than as large as possible, but it cannot be arbitrarily large.) The moment was measured about the vehicle's geometric center (the CG was unknown at

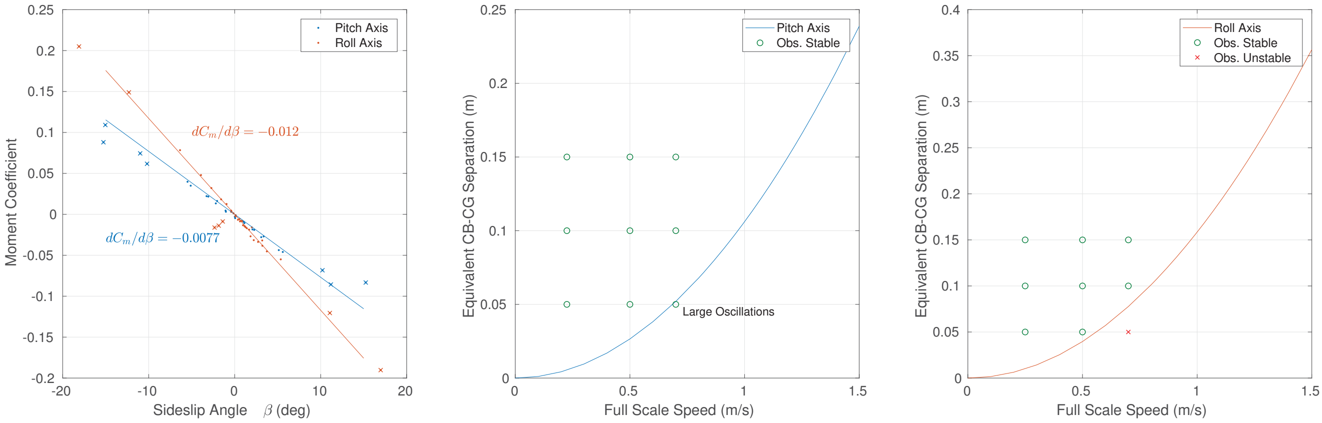

Fig. 6. Left: Moment coefficient as a function of angle of attack about pitch (y) and roll (x) axes. Both axes exhibit a destabilizing moment. The roll axis is the less stable of the two. Middle and right: Predicted and observed stable and unstable operating points from towing tests about the pitch (middle) and roll (right) axes. The moment coefficient data predicts speeds and CB-CG separations to the right of the solid lines will result in instability. Oscillations three times larger than for any other run were observed for the point labeled "Large Oscillations" suggesting near-instability.

this point in the design process). *Clio* has a flooded hull. With the entrained water included, the vehicle's effective CG and CB are both close to the geometric center. The magnitude of the hydrostatic restoring moment is unaffected whether entrained water is included or not. Therefore, stability about the geometric center closely approximates stability about the CG (i.e., self-propelled stability).

Drag data indicate a coefficient of drag referenced to frontal area $C_{d_o} \approx 0.3$ that is approximately constant for small side-slip angle $|\beta| < 3°$ and the range Reynolds Numbers tested $2e5 < Re_L < 6e5$ (referenced to body length). Fig. 6 shows the moment coefficient about the pitch and roll axes referenced to body length cubed. This is the key stability parameter. The plot indicates a destabilizing moment derivative $dC_m/d\beta < 0$ about both axes that varies approximately linearly with small $|\beta| < 15°$.

A stable ascent or descent requires a net negative moment about the CG in response to an angular displacement from the vertical. For a small angular displacement in roll $\delta\phi$, the total moment $P(\delta\phi)$ about the vehicle's roll axis is

$$P(\delta\phi) = C_m(\delta\phi)L^3 q + mgz_{GB}\delta\phi \; , \tag{1}$$

where L denotes the body length in the vertical axis, q denotes the dynamic pressure associated with a constant vertical speed, m denotes vehicle mass, g gravity, and z_{GB} the vertical CB/CG separation. A corresponding equation applies to pitch. Taking derivative with respect to $\delta\phi$ yields the stability criterion

$$mgz_{GB} > -\frac{\delta C_m}{\delta\phi} qL^3 \; . \tag{2}$$

The quantity on the left is constant. The quantity on the right scales quadratically with increasing speed; therefore while increasing z_{GB} always improves stability, the vehicle will always be unstable at sufficiently high speed. The apparatus allowed us to both predict this speed from the measurements of C_m as well as to observe the onset of instability directly. The proportional gain in the motor holding the model into the flow replicates the action of z_{GB} through an appropriate constant of proportionality. Fig. 6 compares the predicted range of speeds and z_{GB} at which instability was observed versus predicted, for both the roll and pitch axes. Eq. 2 yields the solid line in the plots. *Clio*'s final design predicted a full scale CB/CG separation of 0.15 m, suggesting a threshold speed of 0.75 m/s to 1.0 m/s.

Our predictions were confirmed on the full-scale vehicle. Fig. 7 shows a series of ascents and descents performed at various constant thrusts. Above about 0.8 m/s the vehicle begins to experience wild oscillations in pitch and roll and a corresponding oscillation in depth rate. Below this threshold speed, oscillations are present but an order of magnitude smaller, and the depth rate is approximately constant.

V. Compressibility

Clio uses thrusters to transit the water column and to hold depth. Any residual buoyancy incurs an energy penalty. A residual positive buoyancy is necessary to assure vehicle safety in case of propulsion system failure. These requirements pose competing objectives. We manage the trade-off in the conventional way, by maintaining a detailed weight and ballast sheet, updating it as instruments are removed or installed, and cross-checking/re-calibrating it against thrust data from dives.

Seawater is compressible and the ocean is stratified. These two effects mean that *in situ* density increases with depth and therefore a vehicle's buoyancy typically changes with depth. In the upper water column, above the thermocline, temperature drives density variation; below the thermocline bulk compression becomes dominant. Typical AUVs are 2-5 times less compressible than seawater [10] and gain buoyancy with depth. For a vehicle of *Clio*'s size this range of compressibilities corresponds to a range of 10 kg to 15 kg in added buoyancy at 6000 m, a significant parasitic propulsion

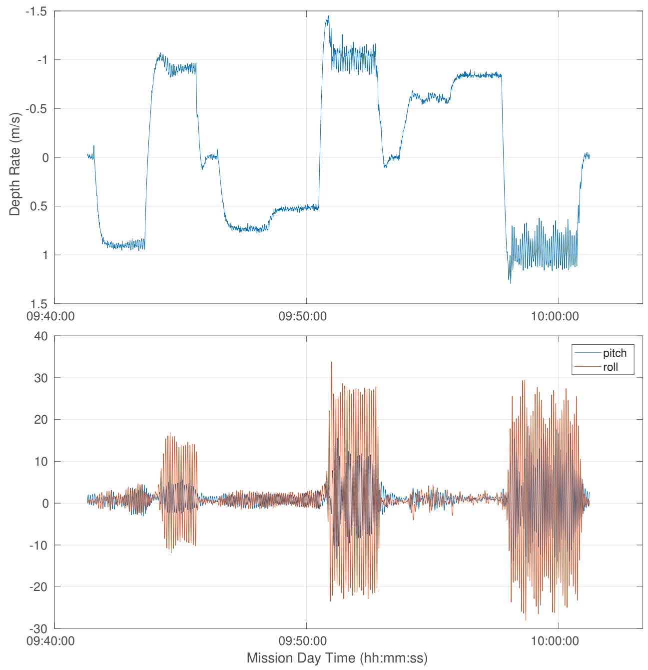

Fig. 7. Depth rate and attitude from a series of ascents and descents performed at different constant thrusts. The data indicate instability in the form of large oscillations in pitch and roll sets in above speeds of approximately 0.8 m/s, in keeping with predictions.

load. Where feasible *Clio*'s design uses materials with low bulk moduli so as to keep the net bulk modulus of the vehicle low. The large potential impact of compressibility on battery sizing and vehicle endurance required a tight coupling between mechanical design and simulation. A bespoke extension to our CAD software generated a comprehensive list of parts, along with their volumes, coefficients of thermal expansion, and bulk moduli (or effective bulk modulus in the case of housings) that a numerical simulation consumed and then used to simulate a nominal mission. The simulation used a globally representative profile of seawater temperature and *in situ* density [11]. In this way we could rapidly adjust battery capacity, flotation and other vehicle design elements.

Field trials in July 2017 afforded an opportunity to experimentally determine *Clio*'s effective bulk modulus and coefficient of thermal expansion. We used the ship's Conductivity Temperature and Depth (CTD) to measure a background profile of temperature and (derived) *in situ* density and then compared the thrust required to hold station at a series of depths down to 2000 m. *Clio*'s thrusters were independently calibrated during earlier dock trials so that the mapping between commanded current and output bollard thrust was known. The vehicle's volume as a function of depth $V(z)$ can be determined from applied vertical thrust $Z(z)$ according to

$$V(z) = \frac{Z(z) + mg}{g\rho(z)} \ , \tag{3}$$

where $\rho(z)$ denotes *in situ* density and m denotes vehicle

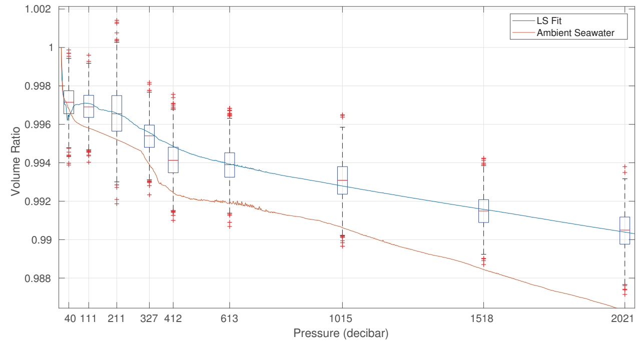

Fig. 8. Experimentally observed change in vehicle displacement from the combined effects of thermal contraction and volumetric compression. The ambient seawater line shows the change in displacement for a unit mass of seawater at that depth relative to the same mass of water at atmospheric temperature and pressure. The data indicate *Clio* is about half as compressible as seawater but also that thermal expansion is more important in the upper water column. The box plot indicates the spread of the thrust data used to compute the buoyancy at each station. The solid blue line is a least squares fit to this data.

mass. Fig. 8 shows the ratio of vehicle volume at depth versus volume at the surface. The vehicle's volume decreases rapidly in the upper water column due to thermal contraction and then near-linearly due to compression below about 500 m. A first-order model for vehicle volume as a function of ambient temperature $T(z)$ and pressure $P(z)$ is

$$V(z) = V_o \left(1 + \alpha(T(z) - T_o) - \frac{1}{\kappa}(P(z))\right) \ , \tag{4}$$

where T_o and V_o denote the temperature and vehicle volume at the surface, α denotes the vehicle's net coefficient of thermal expansion, and κ its net bulk modulus. A least squares fit to the data yielded values of $\alpha = 9.4e-5$ K^{-1} and $\kappa = 4.8e9$ Pa. Typical values for seawater are $\alpha_{sw} = 1.5e-4$ K^{-1} and $\kappa_{sw} = 2.2e9$ Pa. *Clio* is therefore 2.2 times less compressible than seawater, at the low end of the typical range, but still significant with respect to the energy penalty incurred on deep dives. Simulations late in the design phase predicted a lower bulk modulus of $2.5e9$ Pa, much closer to seawater. The cause of this discrepancy remains unclear. A dive to *Clio*'s full rated depth, planned for 2019, will improve the estimate for κ, which is presently sensitive to α and the rapid change in temperature in the upper water column.

VI. Field Results

Clio has dived 14 times over 4 cruises as of October 2018, including field trials in July 2017. An additional 2 cruises are scheduled through June 2019. With the exception of field trials, all cruises to date have focused on seasonal variability in the microbiome at the BATS (Bermuda Atlantic Time Series) station (31°40'N 64°10'W).

Filter samples are *Clio*'s primary data product, the scientific interpretation of which requires knowing the depth of each sample and the quantity of water pumped through

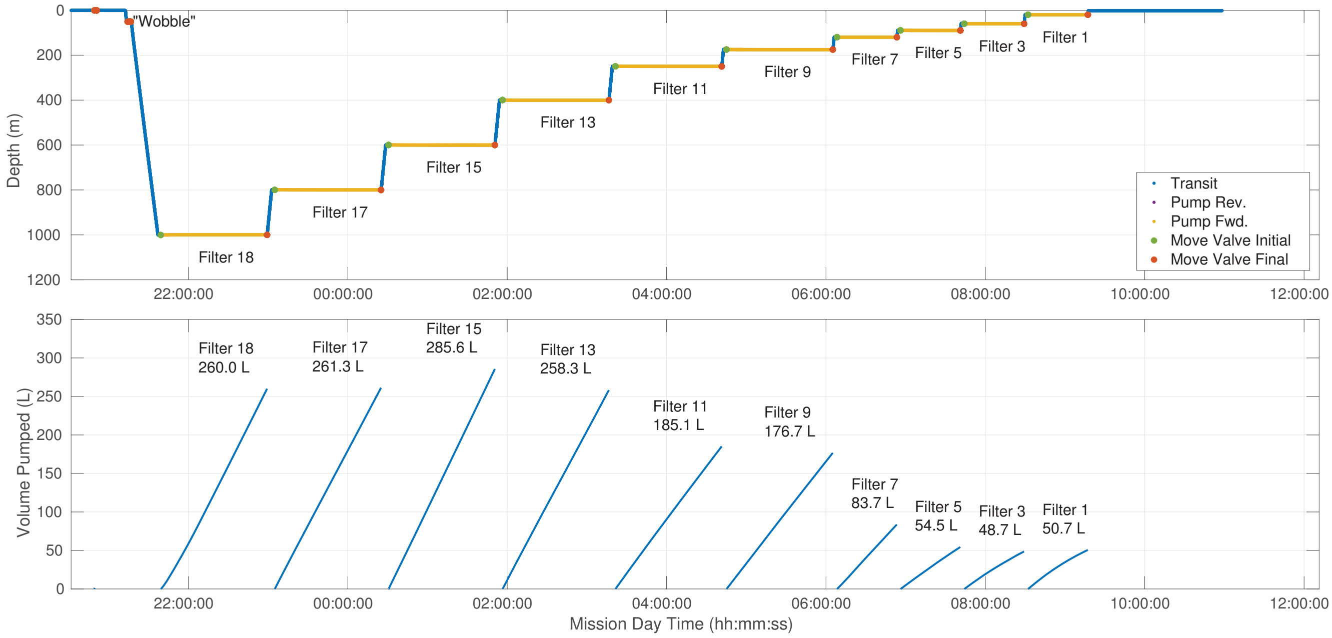

Fig. 9. Depth and pumped volume on clio011 versus time, showing also the associated activity of one SUPR unit.

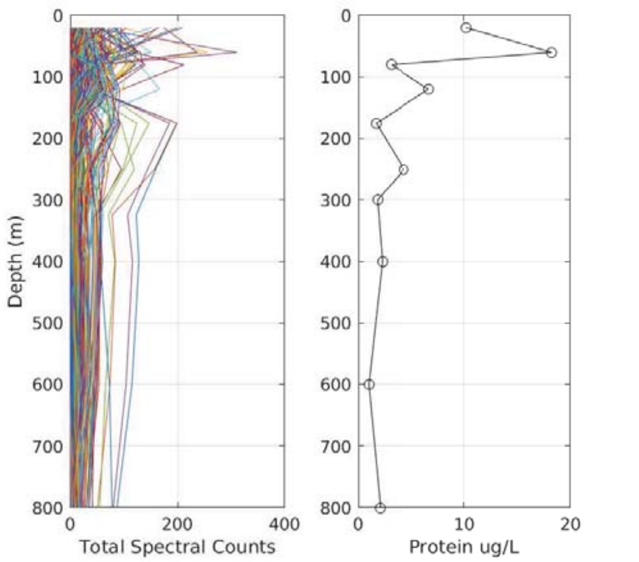

Fig. 10. Global metaproteome of the upper 800 meters as collected on the clio007 at the BATS station. Left: vertical profiles of several thousand individual proteins isolated, extracted, and analyzed from samples taken from the Clio AUV. Right: Total protein abundance extracted from microbial filters showing enhanced biomass in the euphotic zone.

the filter (measured using a Seametrics S-series impeller-type flow meter). *Clio* also measures profiles of temperature, conductivity, chlorophyll fluorescence, and dissolved oxygen, and can accommodate additional profiling sensors. These data provide context for the filter samples. Fig. 9 shows a typical dive, clio011, consisting of a short descent and purge of the SUPR valves ("wobble"), then a descent to 1000 m followed by sampling at progressively shallower depths. The concentrations of thousands of proteins can be measured from each filter (Fig. 10).

The primary objective of the BATS cruises is scientific verification of the data products against conventionally obtained samples. From an engineering and operations perspective we are striving to streamline dive planning, launch, recovery and turn-around, with the objective of transitioning *Clio* to routine operation by a single at-sea technician (exclusive of filter processing). To date we have operated the vehicle successfully with two engineers. Installation and removal of the SUPR filter stacks can be accomplished less than 30 minutes before and after diving, but the practicality of doing so depends strongly on weather and other considerations. Other inter-dive vehicle activities consist of charging and data processing. The primary impediment to a further reduction in staffing is the maturity of the software interface.

VII. Conclusion

Clio is a 6000 m rated vertical profiling AUV primarily designed to carry Suspended-Particle Rosette (SUPR) filter samplers. Logistical concenrs and a desire for operational simplicity led to a positively-buoyant thruster-driven design and an up/down symmetric hull with moderate drag. We discussed the implications of these decisions, their role in the design cycle including scale model testing and simulation, and verification of our predictions in the field. *Clio* is now operating in service of scientific oceanography.

Clio meets or exceeds the design specifications established at the beginning of the project; however, opportunity exists for improving performance and for further development, especially novel sampling strategies. Reducing the energy penalty associated with increased buoyancy at depth, by the addition of passive "compressees" [9], [10], would extend endurance and reduce water-column disturbance caused by active thrusting while sampling without the complexity of an active variable ballast system. Differential thrust could be used to damp roll oscillations in closed loop and thereby to increase *Clio*'s threshold speed an operating envelope.

Clio is capable of acquiring samples difficult or impossible to acquire using conventional wire-based techniques. It is a nearly Lagrangian sampler, can hold depth an order of magnitude more precisely than wire-based samplesm and sample surface waters away from the contaminating influence of a vessel. It carries an altimeter and putatively can sample near the seafloor at fixed altitude rather than fixed depth. *Clio* is designed with sample cleanliness in mind, but we must characterize both contamination direct from the vehicle and indirect from exposure to contaminants during shipping and storage or time on deck between dives. Quantifying and ameliorating these potential sources of contamination will ultimately determine what kind of measurements can be extracted from *Clio* samples. Perhaps the greatest potential for innovation lies in adaptive sampling, e.g., to target discrete samples in phytoplankton thin layers by searching for peaks in continuous chlorophyll fluorimetry. Algorithms designed for this purpose developed for other AUVs [12] are readily adaptable to *Clio*.

Clio promises to lower the operational and financial barriers to realizing global-scale "-omics" survey of the world's oceans by operating simultaneously and independently of wire-based oceanographic sampling. Such knowledge, collected on a global scale, and combined with the data from GEOTRACES, and WOCE before it, will engender deeper understanding of the linkages between life, chemistry, and physical processes in the ocean.

ACKNOWLEDGMENT

The *Clio* development project was made possible by a grant from the National Science Foundation (OCE-1333212). Initial development support for the SUPR multi-sampler was provided by The Woods Hole Oceanographic Institution's Deep Ocean Exploration Institute. We wish to acknowledge the captains and crews of the R/V Armstrong and R/V Atlantic Explorer for their expert handling of *Clio* at sea.

REFERENCES

[1] J. A. Breier, C. G. Rauch, K. McCartney, B. M. Toner, S. C. Fakra, S. N. White, and C. R. German, "A suspended-particle rosette multi-sampler for discrete biogeochemical sampling in low-particle-density waters," *Deep Sea Research Part I: Oceanographic Research Papers*, vol. 56, no. 9, pp. 1579–1589, 2009.

[2] E. Gallimore, J. Partan, I. Vaughn, S. Singh, J. Shusta, and L. Freitag, "The whoi micromodem-2: A scalable system for acoustic communications and networking," Sept 2010, pp. 1–7.

[3] L. E. Bird, A. Sherman, and J. Ryan, "Development of an active, large volume, discrete seawater sampler for autonomous underwater vehicles," in *OCEANS 2007*. IEEE, 2007, pp. 1–5.

[4] D. Valentine, G. Fisher, O. Pizarro, C. Kaiser, D. Yoerger, J. Breier, and J. Tarn, "Autonomous marine robotic technology reveals an expansive benthic bacterial community relevant to regional nitrogen biogeochemistry," *Environmental Science & Technology*, vol. 50, no. 20, pp. 11 057–11 065, 2016.

[5] J. A. Breier, C. S. Sheik, D. Gomez-Ibanez, R. T. Sayre-McCord, R. Sanger, C. Rauch, C. M. Coleman, S. A. Bennett, B. R. Cron, M. Li, C. R. German, B. M. Toner, and G. J. Dick, "A large volume particulate and water multi-sampler with in situ preservation for microbial and biogeochemical studies," *Deep Sea Research I: Oceanographic Research Papers*, vol. 56, pp. 1579–1589, 2014.

[6] D. R. Yoerger, M. Jakuba, A. M. Bradley, and B. Bingham, "Techniques for deep sea near bottom survey using an autonomous underwater vehicle," *International Journal of Robotics Research*, vol. 26, no. 1, pp. 41–54, Jan. 2007.

[7] A. Bowen, D. Yoerger, C. Taylor, R. McCabe, J. Howland, D. Gomez-Ibanez, J. Kinsey, M. Heintz, G. McDonald, D. Peters, C. Young, J. Buescher, B. Fletcher, L. Whitcomb, S. Martin, S. Webster, and M. Jakuba, "The Nereus hybrid underwater robotic vehicle," *International Journal of the Society for Underwater Technology*, vol. 28, no. 3, pp. 79–89, 2009.

[8] C. C. Eriksen, J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, J. W. Ballard, and A. M. Chiodi, "Seaglider: A long-range autonomous underwater vehicle for oceanographic research," *IEEE Journal of Oceanic Engineering*, vol. 26, no. 4, pp. 424–436, oct 2001.

[9] D. C. Webb, "Variable buoyancy profiling device," Oct. 26 2004, uS Patent 6,807,856.

[10] C. Eriksen, "Systems and methods for compensating for compressibility and thermal expansion coefficient mismatch in buoyancy controlled underwater vehicles," May 20 2014, US Patent 8,726,827. [Online]. Available: https://www.google.com/patents/US8726827

[11] S. Levitus, "Climatological atlas of the world ocean," NOAA/ERL GFDL Professional Paper 13, Princeton, N.J., Tech. Rep., 1982.

[12] Y. Zhang, R. S. McEwen, J. P. Ryan, and J. G. Bellingham, "Design and tests of an adaptive triggering method for capturing peak samples in a thin phytoplankton layer by an autonomous underwater vehicle," *Oceanic Engineering, IEEE Journal of*, vol. 35, no. 4, pp. 785–796, Oct. 2010.