Development of a passively pre-tensioned buoyancy engine for fail-safe underwater vehicle operation

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***Abstract*—This paper develops a systematic method to assess the suitability of buoyancy control systems to different mission profiles, risk acceptance thresholds and environmental sensitivities. We analyse various existing variable buoyancy engines (VBE) for different platforms and mission profiles. Our results identify a capability gap for low-energy seafloor survey platforms such as the Lagrangian imaging float that conduct most of their buoyancy control manoeuvres at depth and rely on end of missions recovery for data extraction. Based on these requirements, we introduce a novel VBE concept that uses the energy mechanically stored in a pre-tensioned spring to passively surface in the event of power loss and reduce power consumption when changing buoyancy at depth. The equations to size the pre-tensioning spring are developed and simulations are performed to demonstrate the reduced power consumption at depth. Unlike safety systems that use drop weights, the pre-tensioned VBE minimises environmental impact by achieving net positive buoyancy without leaving anything behind in the environment.**

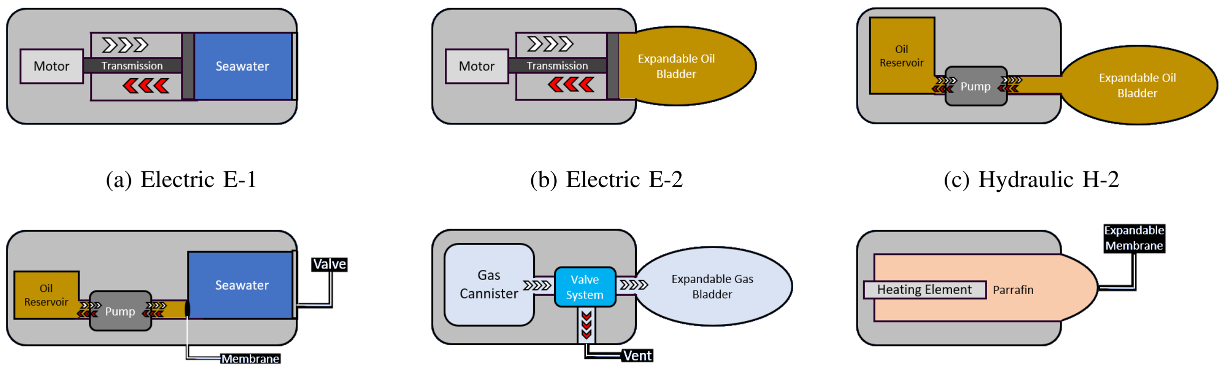
I. Introduction

The missions of submersibles are necessarily diverse, with different propulsion systems, depth profiles, durations, payloads and data transmission strategies. Regardless of the type of mission, most submersibles require some form of buoyancy control to change or maintain their depth when measuring vertical profiles or making seabed observations. Variable Buoyancy Engines (VBEs) work by displacing water from a floodable volume. The main advantages of VBEs are that they can be used to cycle across their buoyancy control range several hundreds of times, making them suitable for platforms that perform depth profiles (e.g. Argo-floats and gliders) [1], and also can do this without leaving material in the environment. VBEs however require energy to increase their buoyancy and so cannot guarantee a platform will return to the surface if power is lost. Drop-weights on the other hand, can be made inherently fail-safe by use electromagnets or galvanic corroding components to release weights and allow a platform to surface even in the event of power loss [2]. Precise buoyancy control can also be achieved during missions by using a micro-ballast dispenser, which uses a large number of small ball-bearings as drop-weights [3]. The disadvantages of these systems however, is that only a single depth profile can be performed and that the released weights can take several decades to corrode, leaving a lasting impact on the environment.

The most suitable choice of buoyancy control method depends not only on the expected mission profile of the platform, but also the consequence of a vehicle not surfacing at the end of its energy endurance and the sensitivity of the environment. The majority of Argo floats for example, sink to the bottom of the ocean at the end of their life since unlike drop-weights, the VBEs they use cannot guarantee positive buoyancy when their energy supply has been depleted. Although this might be acceptable for platforms where the majority of the data gathered can be transmitted via satellite without the need for physical platform recovery, for observation modalities that are too large to transmit over satellite communications, it is important that the platforms surface at the end of their missions so that they can be recovered to have their data extracted.

Visual surveys present a unique challenge due to the limited observational footprints (approximately 1,000 m^2/h per vehicle) that can be achieved when operating vehicles within a few metres of the seabed to overcome light attenuation. To increase the efficiency of visual mapping operations, several groups are now developing Lagrangian imaging floats, first described by Roman et al. in 2011[4]. These platforms have the potential for long mission endurances of several days to weeks since they do not use energy for lateral self propulsion, instead drifting passively on underwater currents using thrust only to maintain a fixed altitude while gathering seabed imagery. Long endurance however, can only be achieved if the floats can achieve neutral buoyancy to minimise the use of their vertical thrusters. These platforms can also potentially be deployed in larger numbers than conventional autonomous underwater vehicles (AUVs) owing to their simple operation and relatively low cost. However, the large size of the images gathered mean that these platforms need to be recovered to make use of their observations, and moreover, as the number of platforms in the ocean increases the sustainability of current practises for fail-safe surfacing needs review.

In this paper, we first investigate the different factors that influence the choice of buoyancy control system and develop an objective method to identify the most suitable type of buoyancy engine for the expected mission profile of a platform. Next, we develop the concept of a pre-tensioned VBE that targets the requirements of a Lagrangian imaging float by using energy mechanically stored in a spring to improve the energy efficiency for buoyancy manoeuvres at depth, and



(a) Electric E-1 (b) Electric E-2 (c) Hydraulic H-2

(d) Hydraulic H-3 (e) Pneumatic P-1 (f) Thermal T-1

Fig. 1: Classification of VBE types.

guarantees fail safe surfacing in the event of power loss.

II. Problem Formulation

VBEs can be classified based on the energy transformation they use to displace water from a floodable volume [5] as follows:

- E-type: Electrical energy is used to drive a piston that either draws in/out seawater (E1, Fig. 1a) or inflates/deflates an oil bladder (E2, Fig. 1b) [6].
- H-type: Hydraulic pumps are used to displace seawater (H1), oil (H2, Fig. 1c) or a combination of both (H3, Fig. 1d) [7].
- P-type: Pressurised gas is used to alter the displacement, where the gas can either be extracted from a container (P1, Fig. 1e) or generated in a chemical reaction (P2) [8].
- T-Type: Thermal actuation using the latent heat of fusion and thermal expansion of a phase changing material to control water displacement(T1, Fig. 1f) [9] .

Fig. 1 illustrates their operating principles. The energy consumption of different VBEs were modelled by Carneiro et al., 2020 [5] and Jensen et al., 2009 [10]. In particular, Jensen develops a quantitative metric to allow objective comparison of different engine types by normalising the mass and volume characteristics of VBEs relative to different target platform and mission depths. However, even platforms with the same size and depth rating can have different buoyancy control requirements, such as the importance of end of energy cycle surfacing, control resolution and expected number of depth cycles in a mission. In order to account for the different mission profiles, this paper develops a reward function that considers different mission profiles and risk acceptability to allow different types of VBE to be better matched to the specific requirements of different platforms and their expected mission profiles. The method we develop is an Multi-Objective-Optimisation, where we investigate what platform, mission and VBE parameters are needed to characterise the required performance, and develop a reward function derived that uses a soft switching sufficient condition function [11]. A key aspect of the method described here is that it allow the sensitivity of the metric to be visualised, which can help engineers identify design variable that will most improve VBE performance.

III. Characterisation and Reward

The requirements of a VBE depend on environment and platform specific variables, not all of which will be known with a high level of confidence during the design phase. The aim of a reward function is to allow for objective comparison of different potential VBE designs, while highlighting the variables that affect performance the most to focus further efforts to improve the design. The following sections introduce the buoyancy engine and platform parameters that need to be described, and defines a set of activation functions to calculate the reward.

A. VBE parameters

Different VBE architectures have different response times, efficiencies and rated depths that should be matching to specific platform and mission requirements. In this work, we define the following parameters to characterise VBE performance:

- Full volume time (s): Time taken for the VBE to fully expel or draw its volume.
- Volume increment: Smallest volume increment expressed as a percentage of the maximum VBE volume.
- Energy efficiency: Conversion of energy to volume displacement.
- Rated depth (m): Maximum operating depth
- Mass efficiency: Non-dimensionalised mass [10].

$$\beta_{me} = \frac{\text{Buoyancy change } (kg)}{\text{Mass of the VBE } (kg)} \tag{1}$$

- Volumetric efficiency: Non-dimensionalised volume [10].

$$\beta_{ve} = \frac{\text{Buoyancy change } (m^3)}{\text{Volume of the VBE at surface } (m^3)} \tag{2}$$

Table I gives examples of these parameters for different VBEs types, thruster (Th) based control of passively buoyant systems and drop-weight systems (DW) that have been sourced from [2], [7], [8], [9], [12].

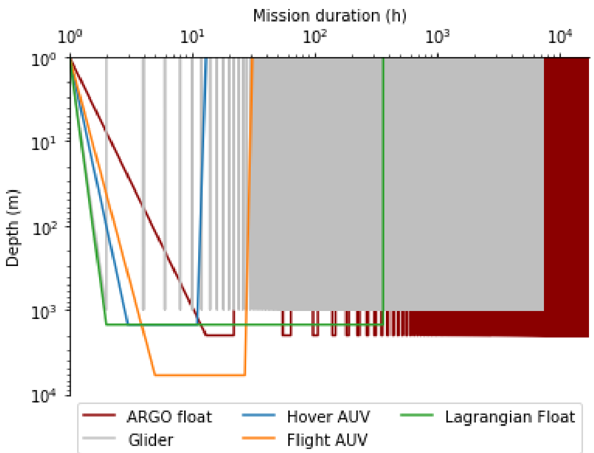


Fig. 2: Illustration of the different depth profiles of submersible platforms

B. Platform and mission parameters

The parameters used to characterise different platforms and their expected mission profiles are shown in table II together with examples values that have been sourced from the literature [13], [14], [15], [16]. These expand on previous studies by including the expected activity level, control resolution and number of cycles of a VBE, which vary significantly between platforms as illustrated in Fig. 2.

C. Evaluation metrics

In order to assess the suitability of different VBEs to the platform and mission requirements, we define the following reward function,

$$S = \frac{\Sigma_i^6 w_i f_i}{\Sigma_i^6 w_i}, \tag{3}$$

which gives a score between -1 (low) and 1 (high) for each VBE platform combination. w_i weights the outputs of soft switching sufficient condition activation functions of the following form

$$f_i(x_{V_i}, x_{PM_i}) = \frac{2}{\pi} \arctan\left(\frac{x_{V_i} - x_{PM_i}}{t_{f_i} \cdot x_{PM_i}}\right). \tag{4}$$

The non-dimensional variables x_{V_i} and x_{PM_i} describe the corresponding properties of the VBE performance, and the platform/mission requirements, respectively, where the subscript i indicates the reward components being evaluated. The variable t_{f_i} is a tolerance that determines the switching rate of the function, and can be used as a safety factor based on uncertainty in knowledge of the requirements of the platform/mission and the specification of the VBEs. The output of equation (4) is a value between -1 and 1, where a value of 1 indicates that the platform/mission requirement is completely met by the VBE, and -1 indicates that the requirement is not met. The equations and parameters used in this study are described in table III.

The speed metric evaluates whether a VBE can actuate fast enough to perform the required number of dived cycles in the mission time, or avoid obstacles for bottom following platforms, where x_{obs} is the distance to the closest object/obstacle on the seafloor, k_{FOS} is a factor of safety, v is the vertical speed of the platform, n_c is the number of cycles. The mission duration is t_m and the rated depth is z_P. The Minimum actuation speed for bottom following platforms is calculated based on avoiding an obstacle of height 2 m when travelling at a constant forward speed of 0.5 m/s. The control metric evaluates the precision needed, where m_P and m_V are the masses of the platform and the VBE respectively, η is the desired buoyancy and v_P is the platform volume. Power checks expected energy use by the VBE compared to the power available for the platform, and Depth checks that the depth rating of VBE and platform match. Mass and Volume evaluate the mass and volumetric efficiency of the VBE with respect to the platform [10].

Fig. 3 shows an example of a Volume and Power evaluation metrics for a hover AUV and a Lagrangian float respectively, with the scores achieved by different VBEs using the switching metrics. Fig. 3a showing that both E-1 and H-1 VBEs easily satisfy the design criteria, achieving a maximum score. It can also been seen that further optimisation of this parameter is not necessary as the score is insensitive to improvements in performance in the local region of the two design solutions. Fig. 3b shows that even though E-1 and E-2 have similar performance parameters, these are close to the platform requirements, straddling the most sensitive slope of the soft switching activation function. In this situation, small improvements or compromises in VB performance have a large influence of the component score.

Fig. 4 shows an example of the evaluation metrics computed for different platforms and VBEs. The most suitable VBE for each platform by taking the weighted sum of each component using equation (3). The scores for the VBEs and platforms in tables II,I are given in table IV.

IV. Pre-tensioned VBE

The analysis shows that even though VBEs have good properties for Imaging floats, their use requires some augmentation with to surface when their energy supply is depleted. Also, unlike Argo-floats and gliders that perform buoyancy control manoeuvres regularly at both the surface and at depth, imaging floats perform most of their control manoeuvres at depth, making simple VBE solutions like the E-1 inefficient in terms of energy. To address these points, we propose a modified VBE concept that uses mechanical energy stored in a pre-tensioned spring that can achieve passive to-surface response in the event of power loss, without leaving material in the environment, and also reduces the power required to perform buoyancy control manoeuvres at depth.

In conventional VBEs, the increase in external pressure with depth pushes the piston head or expandable membrane

Metric	Variable	E1	E2	H1	H2	H3	P1	P2	T1	Th	DW
Full volume time (s)	t_{FV}	20	80	20	30	25	2	2000	2400	3	1
Volume increment	ΔV	2%	6%	1%	0.8%	1%	20%	2%	5%	1%	100%
Energy efficiency	β_E	0.23	0.3	0.32	0.3	0.2	0.3	0.6	1	0.12	0.95
Rated depth (m)	z_V	100	2100	1500	2100	440	200	200	2000	10000	10000
Mass efficiency	β_M	0.5	0.4	0.5	0.4	0.35	0.8	0.85	0.5	3	4
Volumetric efficiency	β_V	0.5	0.3	0.5	0.45	0.35	0.8	0.85	0.1	5	3.8

TABLE I: Buoyancy engine metrics for electric-based (E-type), hydraulic-based (H-type), pressure-based (P-type) and temperature-based (T-type) buoyancy engines, as well as thrusters (Th) and drop-weight (DW) solutions.

Parameter	Hover AUV	Flight AUV	Glider	ARGO float	Img. float 200m	Img. float 1500m
Platform mass (kg), m_P	278	862	60	25	50	60
Platform volume (l), v_P	278	862	60	25	50	60
Max. VBE mass (kg), m_V	10	10	5	5	5	6
Max. VBE volume (l), v_V	10	10	5	5	5	6
Mission duration (h), t_m	8	22	7200	34560	360	360
Rated depth (m), z_P	1500	6000	1000	2000	200	1500
Number of cycles, n_c	1	1	650	150	1	1
Energy (kWh), E	0.907	11	4.7	0.35	1.92	1.92
Active time, t_a	8%	5%	3%	7.5%	3%	3%
Min. Relative Buoyancy, η	1%	1%	1%	1%	1%	1%
Essential end of mission recovery	yes	yes	yes	no	yes	yes

TABLE II: Platform requirements for evaluation. *Img.* stands for Imaging.

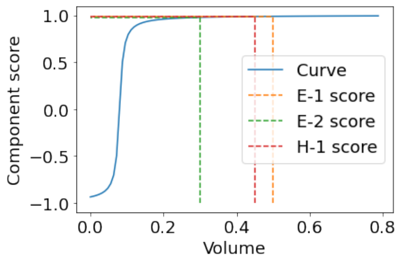
i	x_{V_i}	x_{PM_i}	t_{f_i}	w_i
Control	ΔV	$\eta(m_P + m_V)/(\rho \cdot v_P)$	0.1	2
Speed	t_{FV}	$x_{obs} \cdot k_{FOS}/v$ if $n_c = 1$; $\frac{t_m - 2z_{RD} \cdot}{2n_c n_c/v}$ otherwise	0.1	2
Volume	β_V	$\eta(m_P + m_V)/m_V$	0.1	1
Mass	β_M	$\eta(v_P + v_V)/v_V$	0.1	1
Depth	z_V	z_P	0.05	1
Power	β_E	$2.72 \cdot 10^{-3} \cdot \eta \cdot m_P \cdot z_{RD} \cdot 2 \cdot n_c/(E \cdot t_a)$	0.1	4

TABLE III: Evaluation metrics.

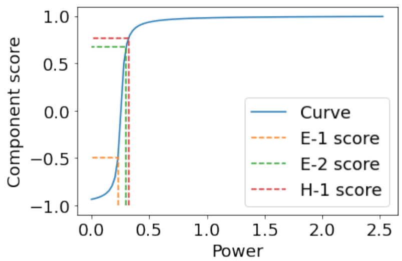
VBE	Hover AUV	Flight AUV	Glider SASP	ARGO float	Img. float 200m	Img. float 1500m
E-1	0.109*	N.A.	0.079*	N.A.	0.813*	0.191*
E-2	0.096*	N.A.	0.088*	N.A.	0.285*	0.319*
H-1	0.526*	N.A.	0.245*	0.089	**0.935***	**0.664***
H-2	0.226*	N.A.	**0.284***	**0.218**	0.696*	0.474*
H-3	N.A.	N.A.	0.054*	0.081	0.860*	N.A.
P-1	N.A.	N.A.	N.A.	N.A.	0.534*	0.633*
P-2	0.418*	0.216*	0.084*	0.085	0.532*	0.421*
T-1	0.549*	0.079*	0.189*	N.A.	0.281*	0.410*
Th	0.263	0.258	0.269	0.260	0.271	0.264
DW	**0.613**	**0.596**	N.A.	N.A.	0.624	0.618
PVBE	**0.766**	0.573	0.083	0.082	0.871	**0.750**

TABLE IV: Reward function scores for VBEs and platforms. Bold indicates, where * shows augmentation is needed to meet end of life recovery. Scores below zero are discarded as not available options (N.A.).

in a VBE to the minimum displacement condition. Current practice uses structural strength or use electrical power to push against this force and maintain buoyancy. As such, VBEs require the greatest power when operating at depth as they need to overcome this force. The concept illustrated in Fig. 5 introduces a compressive spring behind the piston, sized to the

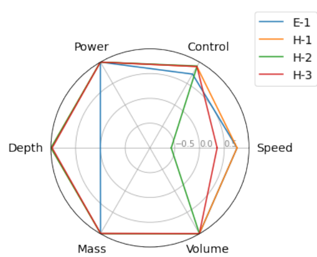


(a) Volumetric efficiency metric for a hover AUV.

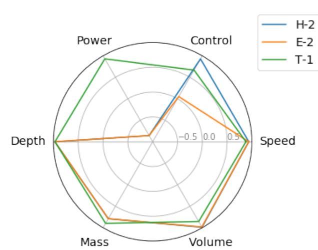


(b) Power efficiency metric for a 1500m lagrangian float.

Fig. 3: Switching function under evaluation of VBE platforms.



(a) Lagrangian float 200m



(b) Glider

Fig. 4: A radar plot showing the evaluation performance of different VBEs for the specified platforms.

expected maximum operational depth and pre-loaded before deployment. This reverses the trend between power consumption and depth, so that the peak force requirement and energy consumption of any actuation system can be significantly reduced when operating at depth. By counteracting the ocean pressure the system becomes more efficient as more time is spent at depth, as the energy required to change buoyancy decreases with depth. Conversely, the system is less efficient at the surface, which is not a problem for Lagrangian float mission profiles that typically have a single dive profile with the majority of the buoyancy control manoeuvres are carried out at depth. Since the spring will always try to force the VBE to its maximum displacement condition over the expected operational depth range. In the event of a loss of power, the spring will fully expand and expel water to allow the platform to safely float to the surface

To demonstrate this concept, we develop a modified E-1 type VBE, using a geared stepper motor with a wire transmission system linked to the piston head through the centre of the compression spring. The actuator used for active buoyancy control buoyancy only needs to pull the reciprocating element in because the spring will always try to force the VBE to its maximum displacement condition over the expected operational depth range.

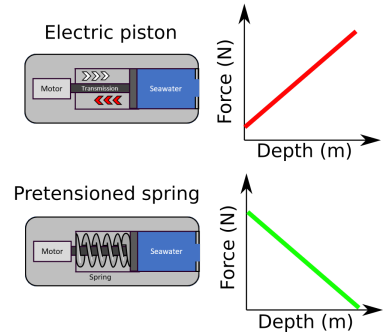


Fig. 5: Proposed failsafe pretensioned spring buoyancy engine based on E-1. The relationship between force required and depth is reversed.

A. *Spring sizing*

The pre-tensioning spring should be designed so that:

- The spring is at less than half compression when the piston head is at maximum displacement.
- The elastic constant of the spring is such that the force from the spring in this position is equal to that of the maximum expected pressure head at maximum depth.
- The remaining available compression length of the spring is sufficient for the required volume change to be achieved.

The force needed to move the piston at depth is defined by equation (5).

$$F = F_{pre} + k \cdot x - P \cdot A \tag{5}$$

where F_{pre} is the preloading spring force, k is the spring constant, x the piston position, P is the pressure at depth and A the piston area. The spring constant can be computed with equation (6).

$$k = f(z, A, l, k_{pre}) = k_{pre} \frac{\rho \cdot g \cdot z \cdot A}{l} \tag{6}$$

where z is the rated depth, ρ is the seawater density at depth, A is the piston area and l its length. k_{pre} is the preloading coefficient and g the gravity acceleration.

B. *Simulated performance*

A simulation for a 200m version of the PVBE in figure 6 shows how the force pattern is inverted and the total energy (area under the curve) is smaller using this system. The traditional VBE power (in dashed lines) increases with depth, whereas the PVBE becomes more efficient. Table V summarises the results, and table IV shows the evaluation metric for this engine, scoring 1^{st} for hover AUV and 1.500 m float, and second for the 200 m float and flight AUV, where the mass and volumetric efficiency are sligtly worse for the PVBE and the chosen set of reward function weights.

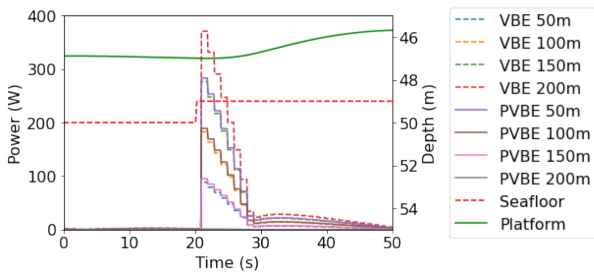


Fig. 6: Piston power needed to overcome a 1 m step at different depths for E-1 VBE and proposed PVBE, both designed to 200 m. In solid green, the platforms trajectory avoids a step on the seafloor, in red, the simulation of 50 m of depth. Other depths responses are comparable.

Depth (m)	E-1 Energy (J)	PVBE Energy (J)
50	508.69	1634.05
100	1051.61	1092.06
150	1594.97	550.14
200	2139.03	8.05

TABLE V: Simulated energy for a 1 m step change in altitude for an E-1 VBE and the proposed PVBE.

V. Discussion

This paper has developed a systematic approach to assess the suitability of different VBEs for specific platforms and expected mission profiles. This builds on previous work by introducing parameters to describe mission profiles and risk acceptability, and describes how soft-switching condition functions can be used to form evaluation metrics and visualise the sensitivity to changes in VBE performance or platform/mission requirements.

The analysis highlighted the limitations of current VBE solutions for low-energy, seafloor survey systems such as the Lagrangian float. Based on the platform requirements, we developed a novel VBE concept that achieves a fail-safe passive to surface behaviour and reduces the energy consumption of buoyancy control manoeuvres at depth by incorporating a pre-tensioning compressive spring. The design method to size the pre-tensioning system is described and theoretical calculations are performed to demonstrate the energy and peak-force advantage compared to conventional VBE systes.

VI. Future work

We are currently developing a prototype, shallow water pre-tensioned VBE system in figure 7. Our plans are to perform tank trials of this system to investigate the reliability of the passive to-surface function and energy performance of the system at different hydrostatic pressures.

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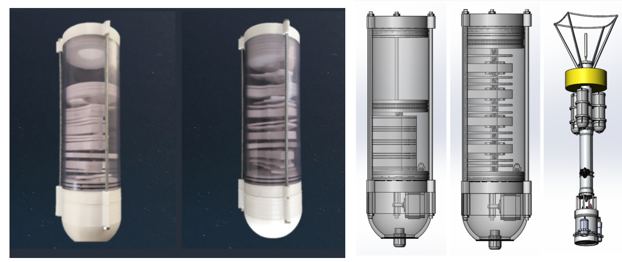

Fig. 7: PVBE prototype and proposed integration on Driftcam.

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