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Design and Testing of a Miniature Variable Buoyancy System for Underwater Vehicles

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ABSTRACT Buoyancy-driven underwater vehicles are key tools for obtaining data from the ocean. Underwater gliders and profiling floats, equipped with sensors, provide crucial information on ocean processes and climate changes. The Variable Buoyancy System (VBS) is a key element of these vehicles, and is in many cases the most complex and highest energy-consuming subsystem. Energy consumption directly determines a vehicle's endurance and mission duration. This paper presents the design and testing of a miniature hydraulic VBS suitable for integration into small underwater vehicles and platforms. Previous VBS are reviewed, existing principles such as hydraulics and pneumatics are described, and an overview of their strengths and weaknesses is provided. The paper explains the concept and the components of the micro-hydraulic VBS, and provides experimental results from its testing in a pressure vessel up to 1000 m equivalent depth. All the components of the system were designed to be of low weight and small size in order to be used in small underwater vehicles such as gliders and profiling floats. The efficiency of the system is characterized for different operating conditions, and provides the basis for vehicle energy system design and endurance characterizations.

INDEX TERMS Autonomous vehicles, electrohydraulics, electromechanical systems, hydraulic actuators, marine technology, micromechanical devices, micropumps, underwater technology, unmanned underwater vehicles.

I. INTRODUCTION

The Variable Buoyancy System (VBS) is one of the most crucial components onboard any underwater vehicle that relies on buoyancy to develop motion, such as profilers [1]. The failure of such systems can lead, for example, to the permanent loss of the vehicle. Variable buoyancy systems have, in the last 20 years, undergone improvements to increase efficiency and performance. These improvements have led to reduced operation costs, costs being a major disadvantage of using any underwater vehicle. They also have led to reduced energy consumption, which boosts vehicles' endurance and range, and increases payload capability.

A. PREVIOUS WORK

There is currently no standard VBS system. The number of systems used in different types of underwater vehicle are many, due to each system being designed and built for a specific vehicle and application. Each system is therefore completely different from other systems. There are currently, however, two primary methods for changing the buoyancy of a vehicle, by changing the vehicle's total mass, or by changing its volume. These two systems are used in vehicles available on the market, and still in the research and development phase. Systems that increase and decrease volume use components such as diaphragms, bladders, and bellows. These components can increase their volume, and so the total volume of the vehicle. Volume is increased through inside pressure being increased. The second approach changes the vehicle's total mass, to increase the force acting downwards and decrease vehicle's buoyancy. This is achieved by filling a ballast tank with seawater, the tank being partially or totally discharged when the vehicle is to ascend.

[2] compared variable buoyancy systems in different vehicles. Their conclusions were, however, based only on the total buoyancy change per unit mass of the system and total

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buoyancy change per unit volume of the system. The buoyancy systems on the Alvin HOV (Human Occupied Vehicle) developed by the Woods Hole Oceanographic Institution (WHOI), and on the Spray glider were compared in [2]. The Alvin used a water pumping-based variable buoyancy system of six titanium spheres, pre-pressurized with air at 13 MPa [2]. The Spray used a pump to transfer oil from inside the vehicle to an external bladder. The conclusion of the comparison was that Spray's system was the best of the two.

Two promising VBS methods were also suggested by [2]. The first was a system based on chemical energy, carbonate or bicarbonate reactions being used to generate gas for the buoyancy system. The second was the use of a tank of compressed gas, vehicle buoyancy being generated by releasing this gas, and across multiple cycles. This system has, however, some flaws, which will be described later.

[3]–[5] also compared the VBS of a number of gliders, including the Spray, Seaglider, Slocum Battery, and Slocum Thermal gliders. The Spray used an electric motor and a reciprocating pump to achieve a maximum volume change of 900 cc, the high-pressure pump transferring hydraulic oil between an inner and an outer bladder, so changing the total volume of the vehicle. The system had an efficiency of 20% at a depth of 100 m and 50% at 1000 m. The Seaglider used the same type of system, but with a maximum volume change of 840 cc, an efficiency of 8% at a depth of 100 m and 40% at 1000 m. The Slocum Battery, which is now known as the Slocum G3, used a single-stroke pump powered by an electric motor, to pump seawater into and out of the vehicle. This approach is, however, difficult at great depths. The vehicle had an efficiency of 50% [4]. Newer models of the Slocum, such as the Slocum G3, used hydraulics for normal operation and pneumatics for surfacing and communication.

The Seaglider's VBS, which is located in the aft of the glider, uses a small pump to transfer high-pressure oil to an outside bladder [6]. Potentiometers in the reservoir measure the exact displacement, and are used to calculate the amount of oil used. The system uses two pumps, a boost pump and an axial piston pump. The boost pump provides an adequate supply to the axial pump. Axial pumps are, however, known for their low suction capabilities. A solenoid controls the flow of the oil from the internal reservoir to the outer, and vice versa. A vacuum condition is maintained, the oil therefore bleeding naturally from the outside bladder to the inner diaphragm. [6] found the Seaglider VBS to more efficient at higher pressures, system power consumption at a depth of 1000 m being twice the consumption at 100 m. The efficiency of the VBS at a depth of 1000 m was around 40%, and around 10% at 100 m. The Spray glider used the same pump and oil system as the Seaglider [6], [7], and also was in the aft of the vehicle. The Spray used a latching hydraulic valve to control the flow of the oil from the outside bladder to the inside. Vehicle buoyancy could therefore only to be reduced when at the surface.

[8] used a swashplate type bi-directional axial piston pump in the Tsukuyomi glider buoyancy system. The pump was run by a brushless DC motor with a reduction gearbox of 26:1. The system was tested in a hyperbaric chamber up to 135 bar, the efficiency of the buoyancy engine being approximately 45% at 100 bars, but 25% at 20 bars. The system can be considered to be efficient compared with other systems. The buoyancy engine alone is, however, more than 30 cm in length, not including the tank, valves, and other system components. The system can also waste up to 40 W of energy in a damping resistor during oil suction.

The OceanScout glider uses a single-acting piston cylinder that acts as a ballast tank, actuated by a ball screw [9]. This is a different approach than that of current commercial gliders. The technique is, however, also used by the Kay Juul 2 glider [10]. The system is fast and can be precisely controlled. Both, however, only have a depth rating of 200 m. Other research gliders such as ROUGHIE used the same ballast system approach, but controlled the amount of water in the ballast tank using a micro-pump and a solenoid valve [11], [12]. The maximum depth for this system is, however, 100 m [11]. The technique was also used by Fòlaga, another research vehicle, the system using a ballast tank and the injection of water in to or out of the tank. The depth rating of 50 m is, however, also quite low compared to commercial gliders [13], [14].

Systems that use seawater face some key complications. The first is that great depths are challenging for such systems, [15] mentioning some of the problems. Some issues may result from the very low viscosity of water compared to hydraulic oils, the kinematic viscosity of mineral oil being around 45 times that of water. This can be a problem in the lubrication of moving frictional pairs, and can result in faster erosion and higher energy losses due to friction. Corrosion is another problem. Chemical or/and electrolytic corrosion is very likely to occur in the system, this requiring the use of advanced materials such as alloys, ceramics, or polymers [15].

Other vehicles combine the oil and seawater systems described above. The ANT Littoral Glider, which is now called the Exocetus Coastal Glider (ECG), used a combined system [16]. An ACME drive screw and an electrical motor was first suggested for the VBS of ANT. The efficiency of this system was, however, found to be very low. A hydraulic system that uses a micro-pump, solenoid valve, and accumulator to drive a piston that draws and pushes seawater into the vehicle, was therefore used instead [16]. The vacuum chamber pushes the oil back to an accumulator, the solenoid controlling this flow. This system, through coupling the pump directly to an electric motor, achieved an efficiency of approximately 70% [16]. The system was designed for coastal applications, the depth rating therefore being only 200 m.

A patent which included a very early conception of an underwater glider, that can operate fully mechanically without the need for batteries or any other electrical supply source, was published in 1964 by the United States Patent Office [17]. The patented design uses a reservoir of compressed air and a ballast system. Complicated mechanisms of springs and bellows of pre-determined stiffness allow the glider to detect when it reaches a specific depth, and re-surfacing to be begun. The glider's VBS uses a vent mechanism, gas relief valve, ballast tank, and a tank of compressed air. Gas relief is activated at a specific depth, air being released, which pushes the water out of the ballast tank through the vent mechanism (also actuated at that depth), the vehicle gaining positive buoyancy [17]. The vent mechanism opens on reaching near-surface depths, releases the gas in the ballast tank, and allows seawater to flow in. This decreases the buoyancy of the glider. Glider depth can be adjusted by changing the stiffness of the springs in the mechanisms. The system may seem primitive and complicated. It has, however, spurred a stream of other similar ideas which have improved the design over the years.

[18], [19] used a similar concept to [17]. They, however, used inflatable bladders instead of a ballast tank for system buoyancy, to avoid seawater corrosion. The pre-dive pressure of the air container can be calculated based on the predicted maximum depth, the number of cycles, volume of the bladder, and the volume of the pressurized container. [18] required a fast-acting VBS in their MOTH glider [20]. It should therefore be able to change approximately 10 L of volume in 2 minutes or less. Both [18], [19] list significant complications of the pneumatic system. The first is that the internal air tank has to be very highly pressurized, and can therefore only provide enough air for a limited number of cycles. [19] based calculations for their Virginia Tech Underwater Glider (VTUG) on a depth of 100 m and 13 dives [21]. This is very limited when compared with gliders that use a hydraulic system, such as the Seaglider. The Seaglider can complete a maximum of 650 dives. A second disadvantage of pneumatic systems is that less buoyancy is available the deeper the vehicle dives. The venting of compressed air also means that the weight of the vehicle changes for each dive, the resulting changes in the vehicle's centre of gravity also being very hard to compensate for, even after just a few dives [19]. The pressure difference across the bladder also needed to be continuously monitored. The compressibility of the gas used in the VBS meant that the bladder could fail if not sufficiently vented while the vehicle ascends [18].

The Slocum Thermal harvests thermal energy at different depths of the ocean, and utilizes this energy to alter the buoyancy state. The Slocum Thermal does not use any motors. It uses a heat engine to harvest energy from the ocean. 60-85% of the energy consumed by the glider is used by the VBS [4]. The range of a glider that uses this system can be 3-4 times larger than the range of a normal electrically powered glider. The Slocum Thermal therefore has the largest range, 40,000 km [5]. A temperature difference of at least 10 degrees is required for the VBS to operate. Only steering mechanisms, controls, and sensors use the batteries, which contributes to a considerable increase in vehicle endurance [22]. This method does, however, have one major drawback. Its efficiency is low, the thermal cycle used to generate vehicle buoyancy having an efficiency of around 3%. This is a result of low-temperature differences,

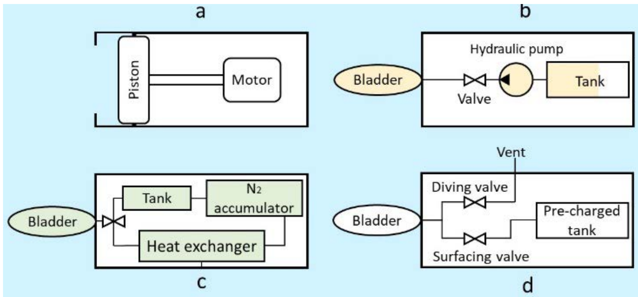

FIGURE 1. Different variable buoyancy systems and their concepts.

the temperature gradient across the depth of the ocean and to great depths being very small [23]. The low efficiency of the system is, however, not the only disadvantage. The mechanical and the dynamic complexity of the system, and the freezing of the working fluid at higher depths are also major system drawbacks [22]. The thermal system therefore seems promising. But it's use is restricted by the system not being suitable in all environments.

Hydraulic variable buoyancy systems are not only used in gliders, but also in profiling floats such as ALACE [24], SOLO-I [25], SOLO-II [1], Deep SOLO [1], NINJA [26] and Deep NINJA [27]. The ALACE buoyancy system uses a small reciprocating pump, oil system and an external bladder. The pressure housing is kept at negative pressure to draw oil from outside to inside the vehicle at the start of a dive [8]. The system, however, also experienced a problem with small bubbles moving to the pump inlet, which makes the oil compressible. The pump then loses its prime, due to the low compression ratio of the pump [7], [25]. A booster pump or a high compression ratio pump and a pop-off valve was suggested to redirect the bubbles to the exhaust valve [7]. SOLO-I used a single-cylinder pump to drive the oil to an external bladder, to avoid any problems associated with bubbles being trapped in the system [1], [2]. This system was, however, large and made the float heavier, but led to the design of SOLO-II, which used a reciprocating pump, and was 30% lighter than SOLO-I. The bubbles problem was avoided in SOLO-II by reconfiguring the entire hydraulic system, and by using a subsystem that detects bubbles using an optical sensor. A low-pressure pump was activated by the optical sensor [1]. The Deep NINJA profiler adapted this system, and replaced the single-stroke pump with a reciprocating pump, which allowed the float to reach 4000 m [27].

Table 1 summarizes the different buoyancy systems mentioned and the advantages and disadvantages of each. It also summarizes the vehicles and their systems, the type of vehicle, maximum volume change, and the depth rating of the VBS (not of the vehicle) based on the data in the cited literature. Fig. 1 presents a representation of the idea of each type of system explained.

B. SYSTEM REQUIREMENTS

Most current VBS systems are relatively heavy and large. The goal of this paper is to describe the development of a novel

TABLE 1. Summary of the described systems and vehicles.

System	Advantages	Disadvantages
Pneumatic	- Compact.	- Low depth rating.
	- Simple and light.	- Limited number of dives.
	- Fast.	- Not stable.
Hydraulic	- Compact.	- Poor suction capabilities.
	- High depth rating.	- Oil reaching vapor pressure likely.
Ballast	- Simple.	- Large size at great depth.
	- Easy to control.	- Corrosion.
		- Tribological problems.
Hybrid (Hydraulic/Ballast)	- Efficient.	- Complicated.
Thermal	- High endurance.	- Mechanical and dynamic complexity.
		- A minimum temperature gradient is required.
		- Allows only low speeds.

Name	Type of vehicle	System	Max Volume Change (L) (According to cited literature)	Depth (m)
Slocum	Glider	Hydraulic	1	1000
Seaglider	Glider	Hydraulic	1	1000
Spray	Glider	Hydraulic	0.9	1000
OceanScout	Glider	Ballast	0.82	200
Kau Juul 2	Glider	Ballast	1	200
ROUGHIE	Glider	Ballast	NA	100
Fòlaga	Hybrid (AUV/glider)	Ballast	0.485	50
ECG	Glider	Ballast	5	200
VTUG	Glider	Pneumatic	5	100
MOTH	Glider	Pneumatic	10	500
Alvin	HOV	Hybrid (Ballast/Pneumatic)	900	6500
Slocum Thermal	Glider	Thermal	0.4	1200
ALACE	Float	Hydraulic	0.75	1500
SOLO-I	Float	Hydraulic	1.2	2000
SOLO-II	Float	Hydraulic	//	2000
Deep SOLO	Float	Hydraulic	0.6	6000
NINJA	Float	Hydraulic	0.35	2000

miniature VBS that is suitable for small underwater vehicles. The following points were considered to be requirements for the variable buoyancy system developed.

1) VBS allocated a maximum weight of 2 kg, including motors, pump, valves, tank, and oil.
2) Able to operate in the range 0-1000 m
3) Provides precise feedback at all times on the buoyant force acting on the vehicle.
4) System efficiency should be as high as possible, to retain power for electronics, sensors, and communication.
5) A number of safety measures should be included to prevent the loss of the vehicle

The thermal and pneumatic systems were rejected due to their numerous complications, limitations, low efficiency and, for the pneumatic system, due to the low depth rating. Seawater systems were also rejected due to their tribological problems, and to such systems requiring a powerful electric motor and gearbox to operate at great depths. The motors will be large and will not fit inside the hull of a miniature vehicle. A hydraulic system with a bi-directional pump was therefore chosen, due to its low weight, and small size, and due to its high-pressure capabilities, which will allow the system to work at greater depths.

II. COMPONENTS OF THE PROPOSED SYSTEM

Electro-hydraulic buoyancy systems are more powerful and therefore smaller than other systems. Their components are common and off-the-shelf. The strict size and weight limitations means, however, that not all the hydraulic components can be used. The proposed system belongs to the electro-hydraulic volume-changing systems family. The pressure housing is kept at negative pressure, the pump running at low power and low rotational speed during the diving cycle of the vehicle, which saves energy and increases the efficiency of the system.

The proposed system has a total weight of 1.95-2.0 kg, the space occupied by the system inside the vehicle being 80 mm in diameter and 600 mm in length. The weight and the dimensions include all system components, cables, sensors, electronic circuit boards and fixings inside the vehicle (screws, shafts, etc.).

The system consists of a fixed displacement bi-directional internal gear, a micro hydraulic pump rigidly coupled with a sensorless brushless DC (BLDC) motor connected to a shaft encoder, a 4/3 directional control valve actuated by a servo motor, a flexible bladder, an internal tank coupled with a linear potentiometer to provide feedback on the volume of oil used, and compression fittings that connect the different elements of the system via copper tubing. The components of the system are illustrated in Fig. 2.

The hydraulic pump is actuated, in the surfacing cycle, by the BLDC motor transferring liquid from the internal reservoir, through the directional control valve, to the outside bladder. The valve is, however, actuated by the servo motor in the diving cycle, the control system determining whether the pressure difference resulting from the vacuum inside the vehicle is sufficient to draw oil back inside to the oil tank, or whether the pump needs to be actuated. This is based on feedback from the tank linear position system.

A. OIL RESERVOIR

A sliding mechanism is mounted on the oil reservoir, which moves on a linear potentiometer, and provides feedback on

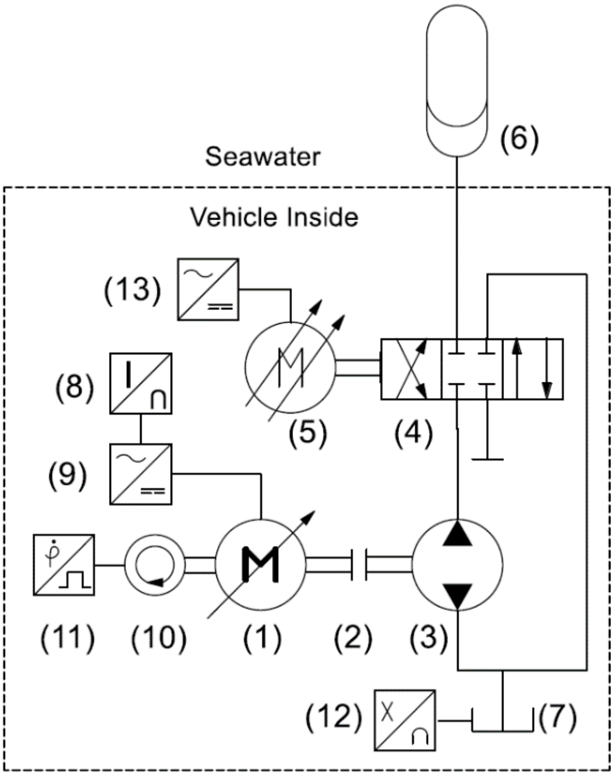

FIGURE 2. Representation diagram of the proposed system; 1-BLDC motor, 2-Rigid coupling, 3-Fixed displacement internal gear pump, 4-4/3 directional control valve, 5-Servo motor, 6-External bladder, 7-Internal reservoir, 8-Analog output current sensor, 9-BLDC electronic speed controller, 10-Shaft encoder, 11-Digital output angular velocity sensor, 12-Analog output linear position sensor, 13-Servo controller.

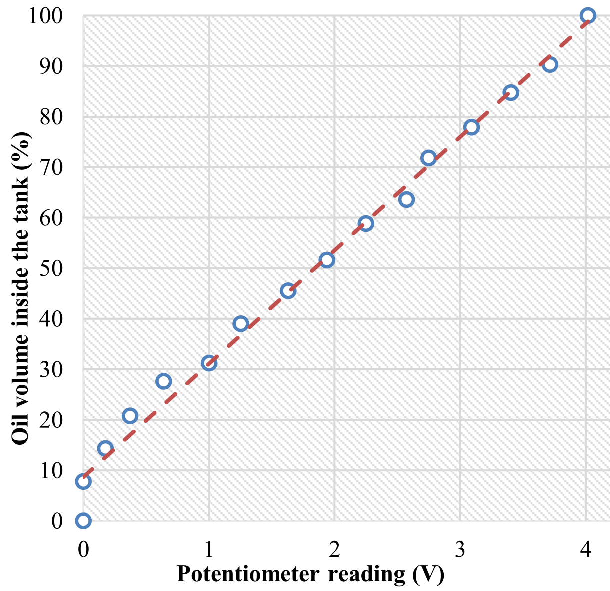

FIGURE 3. Calibration of tank feedback about percentage of oil in it.

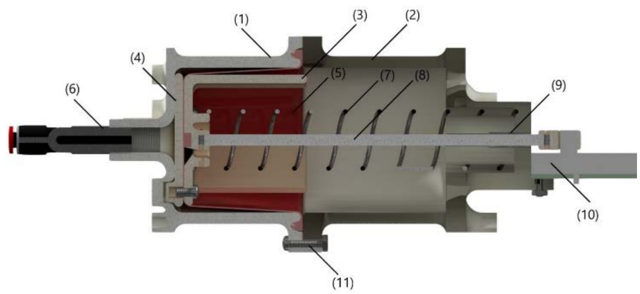

FIGURE 4. Cross-section of the assembly of the VBS tank; 1-Bonnet, 2-Cylinder, 3-Piston, 4-TopHat piston cap, 5-Rollin diaphragm, 6-Hose fitting, 7-Compression spring, 8-Shaft, 9-Linear bearing, 10-Linear potentiometer, 11-External fixing.

the amount of oil transferred. The use of a soft membrane potentiometer was first considered, due to the confined space. The membrane potentiometer consists of two conductive resistors (top and bottom circuits), a sealed enclosure, and a wiper. The potentiometer provides the required electrical output by pushing a wiper into the top circuit. The top and bottom circuits are separated by a spacer of distance 0.15 mm, interaction between the circuits being facilitated by the wiper pushing on the top circuit and connecting it to the bottom circuit, so creating a variable resisting output. The membrane potentiometer, after being tested several times in real conditions, was however shown to be less precise and accurate than the traditional linear potentiometer. Experiments performed on the system furthermore showed that the membrane potentiometer has a much shorter lifetime than the traditional sliding potentiometer. The decision was therefore made to switch to the traditional linear potentiometer. Fig. 3 shows calibration using the linear potentiometer. Approximately 8% of the tank volume is dead volume, which gives no feedback, and is a system constraint due to the shape of the tank.

A rolling diaphragm is contained within a rigid plastic housing inside the tank. On one side of the diaphragm is the oil, and on the other side is a compression spring that has a length and stiffness that is calculated to provide pressure on the oil at all times. This positive pressure ensures that the pump does not exert power when extracting oil from the tank, so moving the diaphragm and the potentiometer. This greatly reduces the possibility of cavitation in the pump. The diaphragm is made from an oil-compatible silicon material, reinforced with fabric polyester, to provide a thin, flexible and reliable diaphragm. Fig. 4 shows a cross-section of the tank assembly and its components.

B. VALVE AND TUBING

A 4/3-way rotary valve is used in the VBS, to control the direction of the oil, and to help pump starting. A rotational spool aligns the inlet and outlet ports in the casing of the valve, the structure and symbol of a typical valve being shown in Fig. 5. A rotational valve was selected because they are in general compact, simple, and require low working forces. The valve casing outer dimensions were 20 × 20 × 24 mm, and the spool diameter was ø15 mm. The valve is coupled to a 3 kg/cm servo motor. Two mechanical stops were added

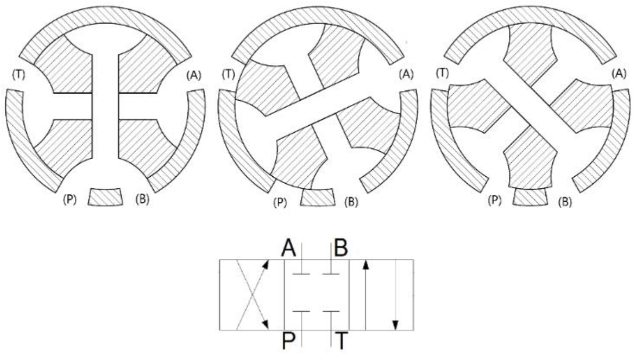

FIGURE 5. 4/3 Rotary Valve representation of three positions.

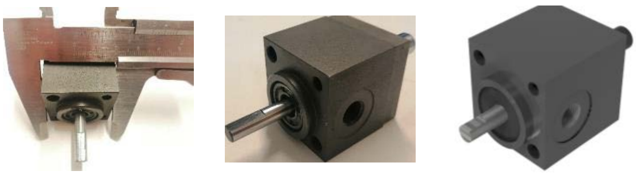

FIGURE 6. Internal gear pump used in the VBS and its 3D model.

at the exact positions of the two directions, as an additional safety feature.

The valve was connected to two different types of tubing. Highly durable and chemical resistant polyamide hoses were used on the low-pressure side of the valve, which was chosen for a number of reasons. They are flexible, light, and have a low bending radius, which helps achieve a more space efficient routing and a more compact system. The fittings for these are also light and small, their flexibility aiding vibration damping. The high-pressure side of the valve is, however, connected to copper tubing, which is often used in car brake systems and other hydraulic systems. It has a high-pressure rating that provides a 1.3 safety factor for the maximum pressure of the VBS. This tubing is more flexible, smaller, and much lighter than standard reinforced hydraulic hoses, and was fitted using compression fittings instead of standard hydraulic fittings. Standard hydraulic fittings are available in a greater range of specifications and are easily obtained off-the-shelf from many suppliers. Using compression fittings therefore represents a constraint of using this system. This trade-off, however, reduces weight and size.

C. HYDRAULIC PUMP

The system uses a bi-directional pump with a fixed displacement discharge. Two different types of pumps were inspected, a swashplate and an internal gear pump. The swashplate was, however, chosen based on a number of factors, which will be explained later. The pump weighs 300 g, has a volume displacement of 0.3 ccm/RPM, and a max RPM of 5000. Fig. 6 shows the pump used in the system.

The pump is coupled to a 1.5 kW brushless motor. The motor is 350 KV, with a maximum torque of 1.54 N.m. 350 rev/volt is quite a low KV factor in brushless motors. A low-KV motor was, however, selected due to most of the power required being torque rather than speed. Selecting an appropriate motor eliminates the need for a reducing gearbox, which reduces the size and weight of the VBS, and also the efficiency of the system. The BLDC motor that was used weighs 280 g.

[8] used an EC 40 Maxon motor, which has a no-load speed of 9840 RPM. A Takako TFH-080 pump was also used, which had a maximum rotational speed of 3000 RPM [28]. A two-stage planetary reduction gearbox (26:1) was therefore required. The motor/gearbox combination weighed 940 g and had an efficiency of 71% [29]. The 'ESCON 70/10' motor driver from Maxon, which weighs 259 g [29], was also used. A standard off-the-shelf Electronic Speed Controller (ESC) could have been used in this system.

The motor was coupled to the pump on one side and to a shaft encoder on the other. The encoder, in combination with the brushless motor, was used to provide accurate feedback on the rotational speed of the pump, to the control system, to determine whether there is any fault in the system and to drive the VBS at the rotational speed that provides the highest efficiency. This is further explained in the following section.

D. BLADDER

The bladder is made from Nitrile-Butadiene Rubber (NBR) and is connected to the VBS through the far front cap of the hull. The bladder has a wall thickness of 2 mm. It was fail tested and punctured at 200% of the volume recommended by the supplier. Fig. 7 shows the bladder used in the system. A bladder, in a real-life scenario, usually experiences a small amount of pressure difference across its rubber walls, for two reasons. The first is that the hydraulic oil inside the bladder has the same pressure during VBS idling as the depth, and a slightly higher pressure during bladder filling and buoyancy increase. The second reason is that depth slowly decreases during surfacing cycles, the pressure difference across the bladder therefore increasing. The bladder therefore expands slightly to relieve this pressure difference, the pressure of the oil in the VBS therefore decreasing.

The bladder was removed from a hydraulic accumulator and adapted to the system. This was chosen instead of manufacturing a bladder using moulding, as it is an off-the-shelf reliable product and as a moulded bladder would be much more expensive. The bladder and the internal reservoir were both cross-designed based on their volume, to prevent either being damaged in the event of the failure of the feedback system. The maximum volume of oil used in the system was set to 90% of the volume of the bladder.

III. VBS PERFORMANCE

A. TEST SETUP

System performance was tested and measured under a number of conditions. The test setup is shown in Fig. 8. The bladder was kept in a high-pressure vessel filled with water,

FIGURE 7. Oil bladder directly after testing in the pressure vessel.

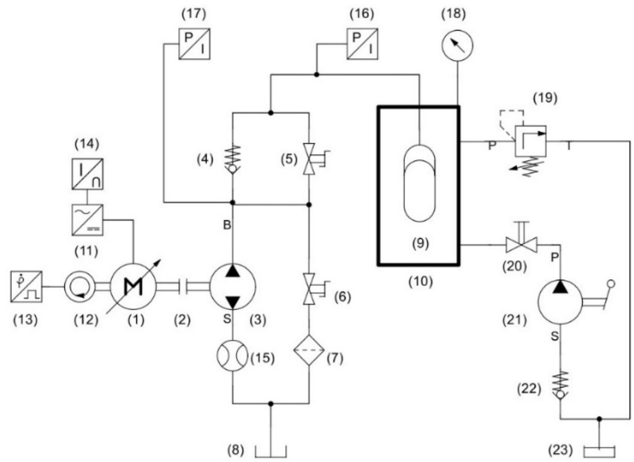

FIGURE 8. Test bench of the VBS; 1-BLDC motor, 2-Rigid coupling, 3-Hydraulic pump, 4-Non-return valve, 5&6-Manually operated ball valve, 7-Filter, 8-Oil Reservoir, 9-Bladder, 10-Hydrostatic pressure vessel, 11-Electronic speed controller, 12-Shaft encoder, 13-Digital output angular velocity sensor, 14-Analog output current sensor, 15-Volume flow meter, 16&17-Analogue output pressure sensor, 18-Digital pressure gauge, 19-Pressure relief valve, 20- Manually operated shut off valve, 21-Water hand pump with fixed displacement, 22-Non-return valve, 23-Water tank.

to simulate external pressure, and was connected to the rest of the VBS by the copper tubing and compression fittings.

Two scenarios were tested for the inflation of the bladder. The first scenario was filling under increasing external pressure load. The pressure tank was kept at atmospheric pressure and the pump was started, pressure in the entire system therefore increasing exponentially. No data was collected from this, as it was just a means of determining the maximum pressure that the pump/motor combination can reach. The system reached 120 bar and the experiment was stopped at this level, as it is the maximum pressure recommended by the pump manufacturer The second scenario, which was applied to the bulk of the tests, is the inflation of the bladder under constant external pressure. The pressure relief valve was set to the desired testing pressure, and the hand pump was used to increase the pressure inside the pressure vessel to this pressure. The pump was only started when this high-pressure was reached. The pressure inside the tank remained constant, the water displaced by the bladder being inflated, and directed through the relief valve. Such tests allow the simulation of the VBS at different depths and the calculation of its efficiency at these depths.

B. TEST RIG SENSORS

Several sensors were installed on the setup to measure different parameters during the test. The sensors, which are shown in Fig. 8, primarily calculate the efficiency of the system. The electronic pressure gauge on the hydrostatic pressure vessel provides, however, visual feedback on the pressure inside the vessel, as shown in Fig. 9.

The testing procedures were divided into two main categories. The first was a set of preliminary tests carried out to select the components and to, for example, differentiate between two pumps or between different brushless motors. The second category was a set of tests performed to test the final design of the VBS, to validate the efficiency of the whole system and to judge its performance. This final set of

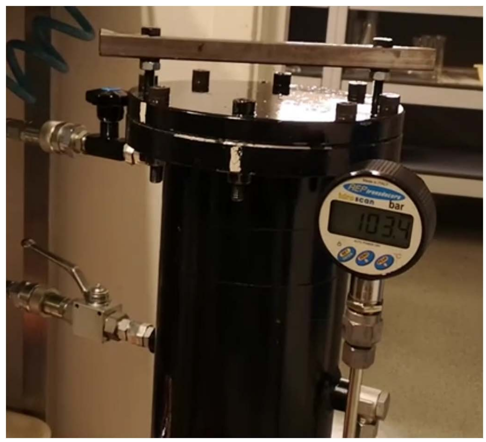

FIGURE 9. Pressure testing rig with digital pressure gauge, that is used to perform VBS tests.

tests, which was performed on the whole system, were more accurate than the preliminary tests.

Samples were taken from the sensors at a rate of 15 samples/sec and saved in a file. One sensor, the flowmeter, had to be recalibrated. The flowmeter was used in all the tests, and was originally planned to be used in order to provide feedback on the amount of oil used. There were, however, many problems with using flowmeters. The first was that all the flow sensors found on the market were either low accuracy, do not work well with oil, or are very heavy and expensive in this application. One flowmeter, a hall effect turbine flow sensor was, however, suitable for the application and was installed on the suction side of the pump. The rotating turbine, which was mounted on a PTFE-made bearing, very often trapped impurities from the hydraulic oil, which affected its rotational speed, so giving false readings. A filter was therefore installed on the suction side of the pump. The results were, however,

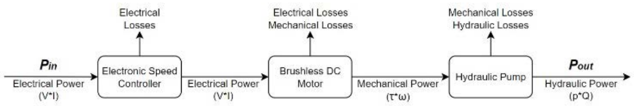

FIGURE 10. Block diagram of the main components of the proposed VBS.

not promising due to the pump having to suck oil through a sensor and a 10 μm cartridge filter. Both the filter and the flowmeter had to be installed on the suction side of the pump due to their low-pressure ratings, which affected the performance of the pump. The sensor had to be recalibrated and even finally replaced with a new sensor before correct readings were obtained. This was not, however, a sustainable solution. A final drawback of the flow sensor was that suitable sensors were unidirectional, no feedback on the volume of the oil pumped in the opposite direction therefore being available. A trial was carried out in which two sensors of opposing directions were used in series, one for each direction. This was not successful, again due to this increasing losses on the suction side, and reducing the efficiency of the pump. The flow sensor concept was eventually rejected and replaced by the movable tank described earlier.

The other sensors showed stabile and accurate readings, all sensor readings being validated using an external gauge, device, or instrument. The pressure sensors were validated using the digital pressure gauge on the pressure vessel, the current sensor was validated using the current readings from the power supply, the shaft encoder readings were validated by a tachometer, and the flowmeter was calibrated and validated using a millilitre beaker, Fig. 3.

C. EFFICIENCY CRITERIA

The VBS converts electric power to hydraulic power, voltage and current being input to one end of the system, a flow of pressurized oil being the output. Fig. 10 shows the main elements of the VBS and their losses. Some minor losses were ignored, such as copper losses in electric connections and friction losses in the tubes, fittings, and valves. These losses are low compared with other major losses in the system, for example copper losses, iron losses, friction in the motor, internal leakage and mechanical friction in the pump.

The efficiency of the entire VBS system is therefore the output hydraulic power divided by the input electric power. As shown in equation 1, where I and V are current and voltage, τ and ω are torque and rotational speed, and Q and p are the volumetric flow rate and pressure of the hydraulic oil used in the VBS.

$$\eta_{VBS} = \frac{P_{out}}{P_{in}} = \eta_{ESC} \times \eta_{BLDC} \times \eta_{Pump} = \frac{V_{ESC} \times I_{ESC}}{V_{supply} \times I_{supply}} \times \frac{\tau_{BLDC} \times \omega_{BLDC}}{V_{ESC} \times I_{ESC}} \times \frac{p_{pump} \times Q_{pump}}{\tau_{BLDC} \times \omega_{BLDC}} = \frac{p_{pump} \times Q_{pump}}{V_{supply} \times I_{supply}} \tag{1}$$

TABLE 2. Specifications of the two pumps tested.

Type		Unit	Axial Piston Pump	Internal Gear Pump
Maximum pressure		bar	140	120
Rotational speed	maximum	rev/min	2000	5000
	minimum	rev/min	500	1000
Displacement		cm^3/ rev	0.40	0.30
Weight		g	270	300
Size (not including the shaft)		mm	30x30x63.4	35x35x46.5

Rotational speed was measured to relate efficiency to pump RPM. Torque, on the other side, was not measured due to the difficulty and complication of adding a rotary torque transducer between the prime mover (brushless motor) and the load (hydraulic pump). Torque measurement is only required when calculating the specific efficiency of the motor and the pump, which was not required in this study.

D. PUMP AND MOTOR SELECTION

Two types of micro pumps were tested, to find the pump with the highest efficiency and the smoothest operation. The two pumps are compared in Table 2 below.

Torque was not measured. The performance of the two pumps were analysed and compared by installing one pump in the system and performing experiments at two rotational speeds, 1000 and 2000 RPM, at different pressures, and then installing the other pump in the system and performing the same experiments again. This allows the efficiency of the entire system for both pumps to be compared, the two pumps tested using the same procedures and under the same conditions. A minimum amount of 100 mL was pumped in each experiment, the efficiency of the system being calculated 15 times per second, and the average of these readings being calculated.

The results of the two pumps were similar. However, the internal gear pump was favoured for three reasons. The first is that it showed a slightly higher efficiency than the axial piston pump, as shown in the graph in Fig. 11, especially at low depths. Secondly, the internal gear pump showed smoother starting, especially at higher pressures, than the axial piston pump. The axial piston pump is also more expensive, almost triple the price of the gear pump. It also requires a secondary part to be CNC manufactured, to be used properly and to connect it to the hydraulic fitting used in the system.

Two motors were selected based on the preliminary calculations and the power needs. Both are sensorless BLDC motors. The two have very similar weights, size, and power ratings. One is, however, rated to operate with 4S batteries and the other with 6S batteries. Table 3 shows the specifications of each motor.

Several rotational speeds were tested at different pressures, simulating different depths. Each point was tested twice

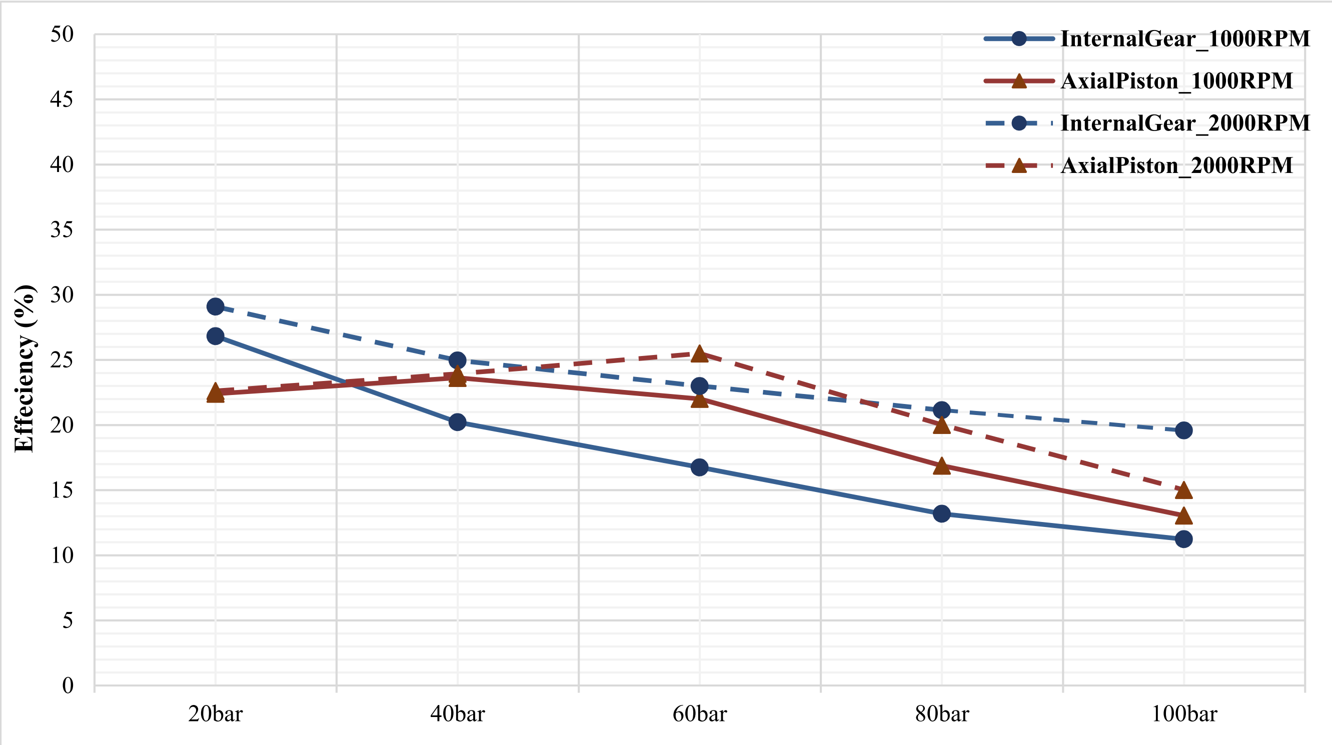

FIGURE 11. Results of the comparison tests between the two types of pumps.

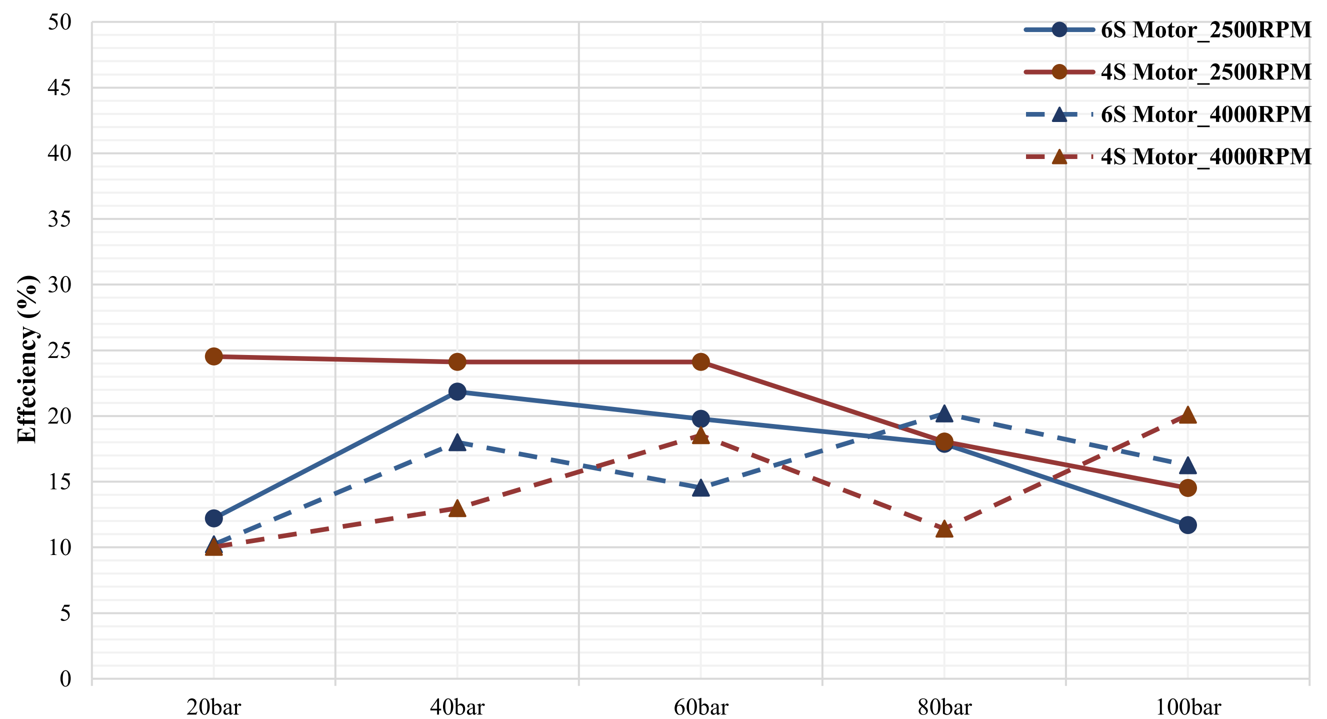

FIGURE 12. Results of the comparison tests between the two BLDC motors.

under the same conditions and an average of the two efficiencies was taken. The maximum pressure tested was 800 m, as opposed to 1000 m in the previous tests. This change was made to include a safety factor for the vehicle VBS. A total of 40 tests were therefore carried out. Fig. 14 and 15 show an example of the data taken from one test, testing at 20 bar at 1000 RPM. The efficiency of the system is shown in Fig. 16.

TABLE 3. Specifications of the two BLDC tested.

Property	Unit	Motor A	Motor B
Power	Watt	1200	1500
Nominal Voltage	V	14.8 (4S)	22.2 (6S)
Maximum current	A	55	29
kV	-	400	350
Motor size (φxL)	Mm	42 x 55	49.5 x 45.2
Type	-	Outrunner	Outrunner
Weight	g	261	280

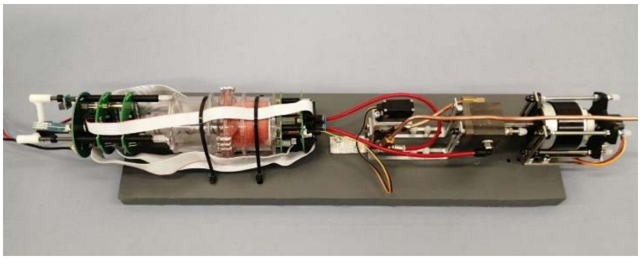

FIGURE 13. An assembly of the VBS, assembled and mounted for testing.

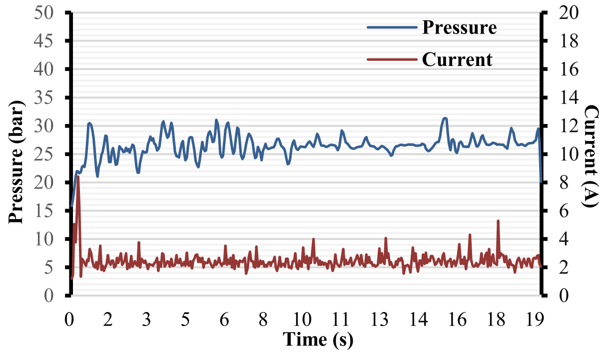

FIGURE 14. Example of the collected data about current and pressure.

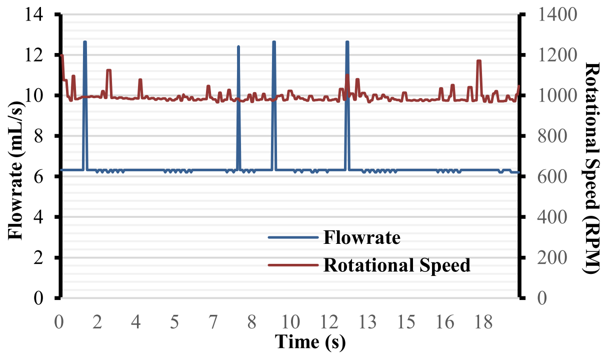

FIGURE 15. Recorded data example about flowrate and RPM.

The experiments showed the highest efficiency at 40 bar depth, and the lowest efficiency at 80 bar. t is not clear why the system exhibited lower efficiency at 20 bar, but one possible explanation is that this is due to the relatively high motor rotational speed during the experiments. And that higher efficiency could have been measured by reducing rotational speed under 1000 RPM while operating the VBS at 20 bar.

IV. CONCLUSION

This work introduced the design and testing of a new variable buoyancy system. The system includes a bi-directional internal gear pump, a brushless DC motor, and a tank which provides feedback on oil usage volume and flow rate. Two hydraulic pumps and BLDC motors were tested, the most

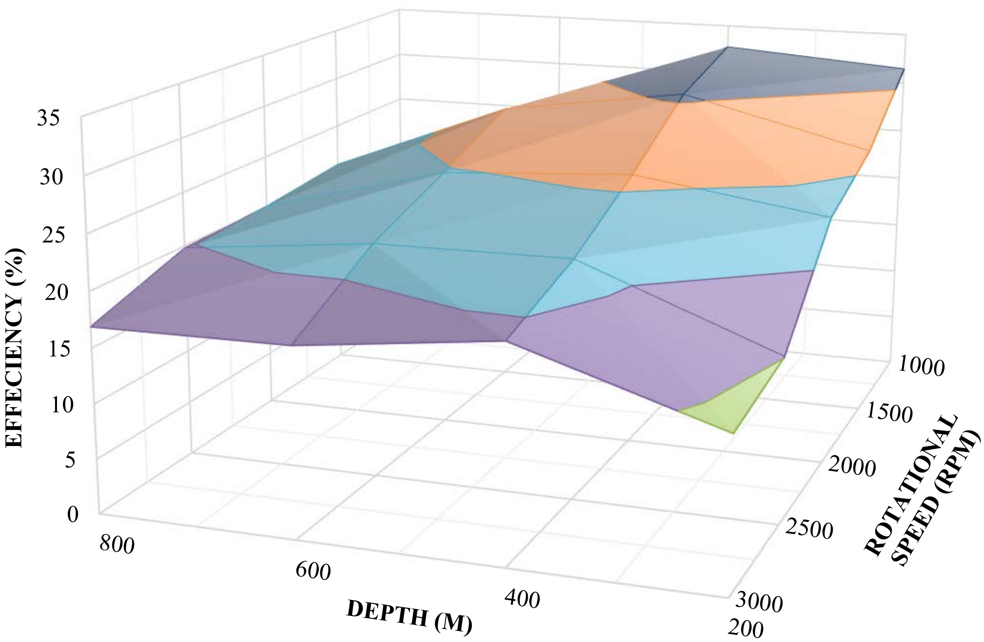

FIGURE 16. Performance of the system under different depths at several rotational speeds.

suitable being selected based on efficiency, size, and cost. The system utilizes a 4/3 valve, used only for directional control.

The entire system was tested up to 80 bar in a pressure testing vessel. The system showed the highest range for the vehicle and highest efficiency when operating at ∼400 m. It also showed the maximum number of cycles when working at a depth of 200 m.

Although, the efficiency of the system is lower than some of the existing solutions, such as [8], this compromise, however, allows a light affordable system to be produced, that can be used in small-sized vehicles.

The work presented shows the system to be operational, and reliable enough to be integrated into a vehicle. The total weight of the VBS is 2 kg, including all major components such as the pump, motor, and valve, and minor components such as hoses, fixings etc. The VBS introduced here is not only small, but also more affordable than available solutions. The system did show two limitations. One is that approximately 8% of the inside tank has no feedback on oil volume, although this can still be used without feedback. The second limitation is that the pump showed poor suction properties. This was, however, mitigated by adding a spring inside the tank to keep the oil pressurized between the tank and the pump, and by keeping the inside of the vehicle's hull at vacuum. The pump must be run when the vehicle is at the surface, to draw the oil inside. The pressure difference is not enough to naturally draw the oil inside when the vehicle is at the surface, despite the vacuum inside.

A number of improvements should be made to the system in future work. The first is that the servo motor that actuates the spool of the directional control valve, could be replaced by a fast-acting motor. This modification would allow the soft starting of the pump and the motor. This modification would also increase the pressure rating from 800-900 dbar to 1200 dbar, because of the smoother starting of the motor at high pressures. This operation was tested successfully, but no data was recorded from the test. A second improvement that should be made is to develop a better design of the tank that reduces the dead volume with no feedback. If this is shown not to be viable, then the control system can be used to detect whether oil is flowing, from the feedback of the current sensor and the shaft encoder mounted on the motor, or not.

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