UNDERWATER VEHICLE BOUYANCY SYSTEM

Applicant: IROBOT CORPORATION, Bedford, MA (US)

Inventors: Edison Thurman Hudson, Chapel Hill, NC (US); Robert Eugene Hughes, Chapel Hill, NC (US); Frederick Roland Stahr, Seattle, WA (US); Jason Isaac Gobat, Burien, WA (US); Timothy James Osse, Sarzana (IT)

Assignee: iRobot Corporation, Bedford, MA (US)

Appl. No.: 13/890,939

Filed: May 9, 2013

Related U.S. Application Data

Continuation-in-part of application No. 13/038,373, filed on Mar. 1, 2011, which is a continuation-in-part of application No. 12/890,584, filed on Sep. 24, 2010, now abandoned.

Provisional application No. 61/309,420, filed on Mar. 1, 2010.

AT NEAR SURFACE NET BUOYANCY = 701 g

AT DEPTH NET BUOYANCY = -285 g

Publication Classification

Int. Cl. B63G 8/22 (2006.01)

U.S. Cl.

CPC B63G 8/22 (2013.01)

USPC 114/333

ABSTRACT

A multiple stage buoyancy changing system, or variable buoyancy device, for an underwater vehicle. The multiple stage buoyancy changing system comprises: a pressure hull containing a flexibly-sized internal fluid reservoir; a flexibly-sized external fluid reservoir attached to the pressure hull and connected to the internal reservoir; a system of devices and channels configured to move fluid between the internal fluid reservoir and the external fluid reservoir to change a displaced volume of the vehicle. Each stage of the variable buoyancy device can be optimized for maximum energy efficiency while changing the vehicle's displaced volume within an ambient pressure range. A control system for the variable buoyancy device engages different stages depending on ambient external pressure such that maximum energy efficiency is achieved over a large range of pressures/depths.
FIGURE 1: The path of an underwater vehicle, such as a glider (shown here as "AUV"), as it descends and rises through water of various depth (pressure) ranges. While in each depth (pressure) range, different parts of the multiple-stage variable buoyancy device are engaged to change the volume of the external reservoir (bladder) using as little energy as possible. Changing the volume makes the vehicle more or less dense (buoyant) than the water around it giving it vertical thrust and thus motion.

FIG. 1
FIGURE 2: Multiple-stage fluid pump and valve system for underwater vehicle of one to N (as many as necessary) stages to optimize energy efficiency of buoyancy changes at all ranges of pressure on the external reservoir or bladder.
FIGURE 3: The decision scheme used by the electronic control system for a multiple stage variable buoyancy device (VBD) where each stage is designed to pump at a particular output pressure for maximum energy efficiency.

FIG. 3
BEGIN DIVE SEQUENCE

1. PROCEED TO BOTTOM OF DESCENT SEGMENT
2. BREATHE OUT AND BLEED PRESSURE FROM EXTERNAL BLADDER TO REDUCE BUOYANCY AND DESCEND
3. IS THIS AN ASCENT SEGMENT?
   - NO: PERFORM NEXT SEGMENT OF DIVE PROFILE
   - YES: DISABUSE STAGE 2 ONCE BUOYANCY CHANGE FLOW RATE ACHIEVED TO SAVE ENERGY
4. IS DIVE DEPTH LESS THAN STAGE 2 (LOW PRESSURE) RANGE?
   - NO: PRESSURE (DEPTH) SENSOR
   - YES: IS PRESSURE IN STAGE 2 RANGE?
     - NO: PERFORM BUOYANCY CHANGE WITH STAGE 2 ONLY
     - YES: DISABLE STAGE 1 (HIGH PRESSURE) PUMP STAGE

FIG. 4
UNDERWATER VEHICLE BOUYANCY SYSTEM

RELATED APPLICATIONS


FIELD

[0002] The present teachings relate to a multiple stage buoyancy changing system for underwater vehicles.

BACKGROUND

[0003] Autonomous underwater vehicles that are propelled by changes in buoyancy have become commercial in recent years and demonstrated the ability to operate at sea for long periods. Such vehicles, known in the trade as underwater gliders, are in an early stage of deployment for oceanic research, coastline monitoring, and other applications. While such vehicles have shown viability for many desirable applications/missions, the existing designs are specialized to performing in limited ranges of depths that are optimized to the design of their “buoyancy engine” or buoyancy system. As a result, existing designs are typically optimized for shallow water (e.g., less than 200 meters), deep water (e.g., 200 meters to 1000 meters), or very deep water (e.g., 1000 to 6000 meters). This limits the operation of existing underwater gliders to a specific domain of underwater depth profiles that any specific vehicle can traverse.

[0004] Underwater gliders can work, for example, as described in U.S. Pat. No. 3,157,145 to Farris et al., the entire disclosure of which is incorporated herein by reference. A glider can comprise a main body, wings, and an adjustable portion such as an external bladder for changing the apparent displacement of the glider. The external bladder can initially be filled with a fluid such as oil to maximize the buoyancy of the glider when the glider is initially launched in the water. A valve can initially be set in a closed position to prohibit the fluid in the bladder from leaving the bladder. To begin the glider’s descent, the valve can be opened, allowing fluid to escape the bladder (for storage in, for example, an internal storage reservoir). As fluid leaves the bladder, the apparent displacement of the glider decreases while the glider’s mass stays the same, causing the glider to begin its descent into the water.

[0005] When the vehicle has reached the deepest point of its desired path, a pump system is used to move fluid from the internal reservoir back out to the external reservoir. As the glider descends, the wings of the glider cause it to move forward. Similarly, the wings cause the glider to move forward as it ascends through the water. To move forward, the glider must typically be ascending or descending in the water. The glider moves forward through its intended path by changing its buoyancy to move up and down through the water, propelling it forward. Because more vertical movement is possible in deeper waters, a greater horizontal distance can be traversed by a glider for a single descent and ascent in deeper waters. Thus, it may be possible to traverse 10 kilometers horizontally in a single dive in deeper water, whereas 10-20 dives can be required to traverse 10 kilometers in shallower water. If the same pump is used in both shallow and deep water, the 10-20 dives can use far more energy (e.g., pumping fluid into the bladder to cause the glider to ascend) than the single dive in deep water. Thus, smaller and more efficient devices such as pistons moving fluid in and out of the external bladder are typically used for gliders used in shallow water.

SUMMARY

[0006] The present teachings provide a multi-stage buoyancy changing system for an autonomous underwater vehicle comprising: an internal reservoir configured to hold a fluid; an external bladder connected to the internal reservoir via one or more channels and configured to exchange fluid with the internal reservoir via the one or more channels; a first device configured to move fluid through a channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of a first segment of the dive profile to increase an apparent displacement and a buoyancy of the autonomous underwater vehicle; and a second device configured to move fluid through a channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of a second segment of the dive profile to increase an apparent displacement and a buoyancy of the autonomous underwater vehicle. The first segment of the dive profile includes a different ambient pressure range than the second segment of the dive profile.

[0007] The present teachings also provide a method for employing a multi-stage buoyancy changing system for an autonomous underwater vehicle having an internal reservoir connected to an external bladder via one or more channels. The method comprises: in a first segment of a dive profile, increasing an apparent displacement and buoyancy of the autonomous underwater vehicle by moving water from the internal reservoir to the external bladder using a first device configured to move fluid through a channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of the first segment of the dive profile; and in a second segment of the dive profile, increasing an apparent displacement and buoyancy of the autonomous underwater vehicle by moving water from the internal reservoir to the external bladder using a second device configured to move fluid through a channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of the second segment of the dive profile. The first segment of the dive profile includes a different ambient pressure range than the second segment of the dive profile.

[0008] The present teachings further provide a multi-stage buoyancy changing system 400 for an autonomous underwater vehicle comprising: an internal reservoir configured to hold a fluid; an external bladder connected to the internal reservoir via one or more channels and configured to exchange fluid with the internal reservoir via the one or more channels; a pump motor in combination with a continuous variable transmission that can adapt to a torque-speed curve to obtain an optimal pressure/pumping rate needed for a current ambient pressure of the autonomous underwater vehicle, the pump motor and continuous variable transmission being configured to move fluid through a first channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of more than one segment of a dive profile to increase an apparent displacement and a buoyancy of the autonomous underwater vehicle; and a third channel configured to allow fluid to move from the external
reservoir to the internal reservoir, the third channel comprising a solenoid valve that can be selectively opened to allow water to pass from the external bladder to the internal reservoir.

Additional objects and advantages of the present teachings will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the present teachings. The objects and advantages of the teachings will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims.

The present teachings provide a multiple stage buoyancy changing system, or variable buoyancy device, for an autonomous underwater vehicle. The system or device comprises: a pressure hull; a flexible sized internal reservoir configured to hold a fluid; and a flexible sized external reservoir, or bladder, connected to the internal reservoir via one or more channels, each channel having multiple valves and pumps. The one or more channels are configured to exchange fluid between the reservoirs as variable buoyancy device stages which are specifically optimized for energy efficiency at a range of ambient external pressures for multiple segments of a dive profile.

The first segment of the dive profile can be handled by a first stage of the variable buoyancy device, the second segment of the dive profile can be handled by the second stage of the variable buoyancy device, et cetera, up to an Nth stage corresponding to a maximum depth or pressure to which the vehicle is designed to dive.

The present teachings also provide a method for controlling a multiple stage buoyancy changing system, or variable buoyancy device, for an autonomous underwater vehicle having an external pressure sensor and a volume measurement system for either, or both, of an internal reservoir and an external reservoir. The external pressure sensor and the volume measurement system are connected to an internal processor and electronics that control the valves and pumps of the variable buoyancy device. The present teachings include logic for selecting which stage of the variable buoyancy device is used at any given depth.

The present teachings further provide a multiple stage variable buoyancy device for an autonomous underwater vehicle that includes a pump and motor combination with a continuous variable transmission that can electronically adapt to a torque-speed curve to rapidly obtain an optimal pumping rate for changing buoyancy.

Additional objects and advantages of the present teachings will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the present teachings. The objects and advantages of the teachings will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the present teachings, as claimed.

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the present teachings and, together with the description, serve to explain the principles of the teachings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates an exemplary path of an autonomous underwater vehicle such as a glider descending and ascending through multiple depth ranges.

FIG. 2 schematically illustrates an exemplary embodiment of a multiple stage fluid pump and valve system for an underwater vehicle in accordance with the present teachings, the system being optimized for one to "N" stages to be energy efficient at all ranges of pressure (or depth) underwater.

FIG. 3 illustrates an exemplary embodiment of a decision scheme used by an electronic control system for a multiple stage variable buoyancy device (VBD), wherein each stage is designed to pump at a particular output pressure range for maximum energy efficiency throughout an underwater dive profile. The illustrated decision scheme uses information from an external pressure sensor and an internal volume sensor to know if a target volume has been achieved. Other system of the underwater vehicle can determine whether a change in vehicle volume is needed.

FIG. 4 is a flow chart outlining the basic steps of an exemplary algorithm for implementing a multi-stage system to achieve efficiency at various depth profiles.

FIG. 5 is a schematic diagram illustrating an exemplary embodiment of a hydraulic multi-stage buoyancy system in accordance with the present teachings.

FIG. 6 is a schematic diagram illustrating another exemplary embodiment of a multi-stage buoyancy system in accordance with the present teachings.

FIG. 7 is an exemplary embodiment of an energy storage system onboard an autonomous underwater vehicle for powering fluid displacement mechanisms.

FIG. 8 is an exemplary embodiment of an energy storage system onboard an autonomous underwater vehicle for powering fluid displacement mechanisms.

FIG. 9 is a cross section of an exemplary embodiment of an energy storage system onboard an autonomous underwater vehicle for powering fluid displacement mechanisms.

FIG. 10A is a top view of an exemplary embodiment of the autonomous underwater vehicle of the present invention.

FIG. 10B is a perspective side view of the autonomous underwater vehicle of FIG. 10A.

FIG. 11A illustrates an autonomous underwater vehicle descending into a deep depth range of a universal glider range.

FIG. 11B illustrates an exemplary dive profile having three distinct depth ranges for which multiple pump stages are utilized during ascent.

FIG. 12 is a chart illustrating pressure versus depth underwater.

FIG. 13 illustrates an exemplary underwater dive profile with time represented on the horizontal axis and depth represented on the vertical axis.

DESCRIPTION OF THE EMBODIMENTS

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which illustrative embodiments of the invention are shown. In the drawings, the relative sizes of regions or features may be exaggerated for clarity. This invention may, however, be embodied in many different forms and should not
be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

[0033] It will be understood that when an element is referred to as being “coupled” or “connected” to another element, it can be directly coupled or connected to the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly coupled” or “directly connected” to another element, there are no intervening elements present. Like numbers refer to like elements throughout.

[0034] In addition, spatially relative terms, such as “under”, “below”, “lower”, “over”, “upper” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as “under” or “beneath” other elements or features would then be oriented “over” the other elements or features. Thus, the exemplary term “under” can encompass both an orientation of up and under. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

[0035] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. As used herein, the expression “and/or” includes any and all combinations of one or more of the associated listed items.

[0036] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0037] It is noted that any one or more aspects or features described with respect to one embodiment may be incorporated in a different embodiment although not specifically described relative thereto. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination. Applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to be able to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner. These and other objects and/or aspects of the present invention are explained in detail in the specification set forth below.

[0038] Reference will now be made in detail to embodiments of the present teachings, examples of which are illustrated in the accompanying drawings.

[0039] In many implementations, an autonomous underwater vehicle (hereafter interchangeably called “AUV”) uses most (e.g., about 75%) of its energy to pump fluid (e.g., hydraulic fluid, water, seawater, or other non-compressible fluids or fluids having low compressibility) into an external bladder from an internal storage reservoir to increase the AUV’s apparent displacement and buoyancy to cause the AUV to ascend to move forward and/or to reach the surface of the water for data receipt and transmission. The amount of pressure required to pump fluid into the external bladder typically varies by depth. For example, in shallow water (e.g., less than about 200 meters) the required pressure can have a magnitude of hundreds of psi, whereas in deep water (e.g., about 200 meters to about 1000 meters) the required pressure can have a magnitude of thousands of psi.

[0040] This difference in pressures required to pump fluid into the autonomous underwater vehicle’s external bladder has created a design dilemma, because existing pumps that are powerful enough to create enough pressure to pump fluid into the external bladder in deeper water with high ambient pressure are typically inefficient for use in shallower waters with low ambient pressures and in certain dive profiles where the pump must cause the autonomous underwater vehicle to ascend more frequently to cover a given horizontal distance. The pressure that must be generated by existing deep water glider pumps makes those pumps less energy efficient. Low pressure pumps are more energy efficient but typically do not provide sufficient pumping force in deeper waters. This design dilemma causes existing autonomous underwater vehicles to be optimized for a limited range of depths.

[0041] As stated above, this pump design dilemma is imposed by the existence of increasing hydrostatic pressure with increasing depth, which is illustrated in FIG. 12. For example, as shown in FIG. 11A, a system required to compensate for the hydrostatic pressures that are encountered in water that is typically considered shallow 200, for example from the surface to a depth of 100 meters, must overcome ambient pressures ranging from 1 atmosphere (14.7 psi) to about 14 atmospheres (200 psi). By comparison, the pressure change that must be overcome by a deep diving vehicle (i.e. an AUV 100 deployed in a deep AUV range 250) can range from a surface pressure of about 1 atmosphere (14.7 psi) to nearly about 102 atmospheres (1500 psi). FIG. 12 is a chart illustrating pressure versus depth underwater; where the vertical axis represents hydrostatic pressure in pounds per square inch (psi) and the horizontal axis represents depth in meters. A single pumping system that can overcome 1500 psi in the deep AUV range 250 will not be as energy efficient for pumping lower psi that occurs in shallower depths 200. In contrast, a buoyancy system designed to handle a smaller range of pressure compensation will use significantly less energy to do so. Thus, as stated above, existing autonomous underwater vehicles are offered to be efficient in, generally, one or four ranges: 0 to 30 meters; 10 to 100 meters; 40 to 200 meters; and 200 to 1000 meters.

[0042] A pump capable of producing enough pressure to move fluid into an autonomous underwater vehicle’s external bladder in deep water 250 is far less efficient than a pump that is capable of producing enough pressure to move fluid into the external bladder in shallow water 200. A deep water pump can use, for example, nine times more energy than a shallow water pump. An example of a commercial pump used in deep diving gliders is the Hydro LeDuc model PB32.5 which can pump against 100 atmospheres and requires 14 ft lbs (20 nm) of
energy to drive. By comparison a hydraulic pump, such as the MicroPump GB models, requires about 1.25 lb energy to pump against the pressure at 100 meters, about 11 atmospheres. When the Hydro LeDuc is used to pump against the lower pressure (e.g., 11 atmospheres), it uses nearly the same amount of energy as it does when pumping against 100 atmospheres.

[0043] Turning to FIG. 10A, the present teachings provide a universal or increased depth range autonomous underwater vehicle 100 comprising a multi-stage buoyancy system 400 and a control system 105 that can plan the travel of an autonomous underwater vehicle using a depth profile plan (See FIG. 10A) and depth sensors 110 (e.g., one or more pressure sensors and/or one or more acoustic altimeters). In one embodiment, the AUV 100 may determine a range and heading by, for example, an acoustic modem 107 USB, message to determine which portions of the multi-stage buoyancy system to use to achieve the profile plan while utilizing the least amount of onboard stored energy. By sensing the depth and/or the position of the underwater vehicle 100 in its dive profile (e.g., via sensors including depth/pressure sensors 110 and/or acoustic altimeters 112), a control system 105 and buoyancy system 400 in accordance with the present teachings allow a single autonomous underwater vehicle to produce efficient motion covering a broad range of depth, including shallow coastal waters 200 to deep ocean domains 250.

[0044] As depicted in FIGS. 2 and 6, the present teachings provide a multiple stage buoyancy changing system 400, or variable buoyancy device, that can make an autonomous underwater vehicle 100 energy efficient over a large range of depths 200, 250. Multiple stages including a channel, a pump, a motor, and a valve can be optimized to each cover a portion of an external pressure range that the vehicle will encounter in a typical dive cycle. By sensing the depth or ambient pressure surrounding the underwater vehicle in a given dive profile, and engaging the correct stage for pumping fluid for that ambient pressure, a system in accordance with the present teachings allows a single autonomous underwater vehicle 100 to produce energy efficient vertical motion covering a broad range of depths, including shallow coastal waters 200 to deep ocean domains 250.

[0045] FIGS. 2 and 6 schematically illustrates an exemplary embodiment of a multiple stage buoyancy system 400 in accordance with the present teachings. The embodiment of FIG. 5, for example, illustrates a multiple stage buoyancy system 400 having a first channel 420 including a bypass channel 422, a second channel 415, and a third channel 425. By utilizing multiple channels within the device, including bypass channels 422, a multiple stage buoyancy system 400 of the present teachings achieves high efficiency in buoyancy changes without allowing one stage to compromise or restrict the performance of any other stage. Check valves 450 can be provided to prevent fluid from returning to previous pump stages. In the embodiment of FIG. 2, a filter is shown, which can protect the system 400 from contaminants in the fluid that would decrease the flow or clog the valves, but is not essential to operation.

[0046] An autonomous underwater vehicle 100 having a multi-stage buoyancy system 400 in accordance with the present teachings, an exemplary embodiment of which is illustrated schematically in FIG. 11A, can traverse a dive profile ranging from shallow coastal water 200 to deep water 250 with a single vehicle 100, without a significant compromise of energy consumption or reliability that might occur in a design optimized for a narrow range of depths.

[0047] The present teachings contemplate an underwater vehicle including as many stages as are deemed necessary and expedient to produce the best trade-off between energy use for pumping and (a) the mass of parts needed for each stage, (b) the volume occupied by each stage within the pressure hull, and (c) the complexity of controls and plumbing.

[0048] FIGS. 1 and 11B illustrate an exemplary dive profile having one or more distinct depth (or pressure) ranges (hereafter interchangably called depth “stages”) for which different variable buoyancy device pump stages are utilized. As indicated in the flow chart of FIG. 3, the choice 500 of which pump stage 505, 510, 515 to utilize can be made, for example, by the vehicle’s on-board processor 105 with input from various sensors 110, 112 and command files. In accordance with certain embodiments, the autonomous underwater vehicle 100 can absorb a dive when a problem (e.g., a system error) is detected. When a dive is aborted, the autonomous underwater vehicle 100 can, for example, pump as much fluid into the external reservoir 405 as possible to reach the surface 205 for retrieval, preferably using the most efficient stages of the variable buoyancy system.

[0049] The fluid displacement systems (e.g., the pump 460a, 460b, 460c, motor, and valve systems) of the present teachings need not be of the same type. Different dive stages 260a, 260b, 260c can comprise different components. Exemplary fluid displacement systems that can be used in accordance with the present teachings include, for example, a piston-driven pump, a siphonic pump, a submersible, and/or other suitable devices that can move fluid.

[0050] A multiple stage buoyancy system 400 in accordance with the present teachings can be implemented using a variety of approaches that embody the principle of depth/pressure dependent selection of the most efficient pump stage 505, 510, 515 corresponding to the dive stages 260a, 260b, 260c. An example of an implementation and decision process 500 is illustrated in FIG. 3. By using a pressure sensor 112 that detects the surrounding water pressure at a given depth 260a, 260b, 260c, and a volume sensor 114 that detects the vehicle’s 100 displacement volume, the control system 105 and/or electrical logic of the vehicle 100 can enable a pumping stage 505, 510, 515 that is most energy efficient for the detected environmental pressure if a change in external volume is needed. In principle, a system of many (“N”) stages can be employed, wherein two is the simplest case and may be adequate for many different vehicles. The present teachings illustrate in FIG. 2, however, that more than two stages can be utilized to achieve high efficiency across the entire depth of the ocean.

[0051] As depicted in FIG. 5 as an optional element (dashed lines), another embodiment of the present teachings contemplates utilizing a pump 260 and motor 261m in combination with a continuous variable transmission 261r that can adapt to a torque and speed curve, resulting in different pumping rates at different depths to efficiently change the buoyancy of an autonomous underwater vehicle 100. Continuously variable transmissions can provide an effective continuum of torque-speed ratios over a predetermined range, with slower speeds corresponding to higher torque output and higher speeds corresponding to lower torque output.

[0052] The illustrated exemplary embodiment of FIG. 2 places the stages (or channels) 415, 420, of the multiple stage buoyancy system in parallel with each other to eliminate a
potential negative impact of serial placement. Serial placement can impede optimal performance by restricting the downstream pump’s access to the internal reservoir.

[0054] During an underwater vehicle’s 100 descent, fluid can move from the external reservoir (or bladder) 405 to the internal reservoir 410 when a high-pressure return valve 452 between the external reservoir and the internal reservoir is opened. In one embodiment the external bladder 405 and/or the internal reservoir are expandable. Ambient pressure can be used to push fluid from the external reservoir 405 to the internal reservoir 410 by pressing on the external reservoir 405. In addition, the autonomous underwater vehicle 100 can have a reduced internal pressure (e.g., a vacuum) that encourages fluid flow from the external reservoir 405 to the internal reservoir 410. Certain embodiments of the present teachings also contemplate using one or more pumps to drive fluid from the external reservoir to the internal reservoir if more speed is required in that process.

[0055] In accordance with certain embodiments of the present teachings, a connection can exist from the output of one pump stage to the intake of another pump stage. This series-like plumbing can function as a safety path for any pump stage that needs priming.

[0056] An autonomous underwater vehicle 100 employing control and buoyancy systems 400 in accordance with the present teachings can travel long distances (e.g., thousands of kilometers) over durations of many months using buoyancy changes that combine algorithms and multiple stage buoyancy control to conserve onboard stored energy by utilizing an optimized fluid displacement strategy, selecting the most energy efficient fluid displacement mechanism(s) to traverse all desired diving profiles.

[0057] FIGS. 1, 11B and 13 illustrate an exemplary dive profile of an embodiment of the AUV 100 having three distinct depth ranges (or stages) for which three pump stages are utilized during ascent, Pressure Range 1 260a, Pressure Range 2 260b and Pressure Range n 260n. Many depth (pressure) ranges may exist between Pressure Range 1 260a and Pressure Range n 260n. As shown, the dive profile includes a single deep dive having five segments: first SURFACE 265, DIVE 270, APOGEE 275, CLIMB 280, and second SURFACE 285. In a first SURFACE 265 segment, the autonomous underwater vehicle 100, a position of which is indicated by various dots 290a–290n, starts a surface phase 265 and transmits information including, for example, vehicle health, atmospheric, all systems self-test and indicate that they are working normally, available onboard energy, a dive log, data from onboard instruments 113 (e.g., chemical compounds in water, optical backscatter, sound detection, salinity, predominant currents, images, other physical properties of the ocean, etc.), and receives information including a dive plan having waypoints (e.g., latitude, longitude, depth, descent rate, and ascent rate), instrument sampling rates, and other parameters associated with controlling instruments (turning them off or when to turn them off). After a dive plan is received, the vehicle 100 can calculate a correct rate and angle of descent based at least in part on the new dive plan. An initial GPS location is taken (GPS1) with an onboard GPS sensor 114 when the vehicle 100 surfaces or is initially placed in the water and then, after data transmission and receipt of a new dive plan (which presently typically takes about 10-15 minutes (using, e.g., about 10 Watts of energy), another GPS location is taken (GPS2) because the vehicle 100 may have moved during data transmission and receipt. Movement of the vehicle 100 from GPS1 to GPS2 can provide information regarding predominant currents affecting the vehicle 100. A dive log can comprise data indicating how each dive profile step went. The dive log can also record errors and error mitigation attempts, and can collect instrument data.

[0058] During a second dive plan segment, labeled DIVE 270, the autonomous underwater vehicle’s 100 nose 155, or front, is pointed downward and the vehicle 100 begins its dive phase by beginning a descent into a first depth range 260a (typically without using a pump but rather by letting fluid bleed out of the external bladder 405 to an internal reservoir 410). After descending through the first depth range 260a, the autonomous vehicle enters a second depth range 260b of the DIVE segment 270 that can be identified, for example, by external pressure sensor 112 readings indicating a depth of the vehicle 100 based on the ambient pressure. In accordance with certain embodiments, during descent, the underwater vehicle can change its angle of descent by changing its pitch angle as needed to follow the requested dive profile 255.

[0060] After descending through the second depth range 260b, the autonomous vehicle 100 enters a third depth range 260c of the DIVE segment 270 that can be identified, for example, by external pressure sensor 112 readings indicating a depth of the vehicle 100 based on the ambient pressure. In certain embodiments of the present teachings in which a bathymetric map has been stored, the autonomous underwater vehicle 100 can make sure it has reached a maximum depth set forth in the dive profile 255 and/or avoid collision with the bottom 210 (e.g., using acoustic pings to find the bottom) before beginning an APOGEE dive plan segment 275. As the underwater vehicle 100 reaches the bottom of its dive, for example in the third depth range 260c, it enters an APOGEE dive plan segment 275. The APOGEE dive plan segment 275 can include a transition from descent to ascent, wherein the autonomous underwater vehicle 100 levels out (becomes horizontal) and changes its inclination (by, e.g., turning its nose 115 upward for an ascent by shifting a mass 117 within the vehicle 100) before changing buoyancy by pumping fluid from the internal reservoir 410 to the external bladder 405 to begin its ascent and begin a CLIMB segment 280 of the dive plan 255.

[0061] The CLIMB segment 280 of the illustrated dive plan 255 begins in the third depth range 260c, where a Pump Stage (channel) 3 315 is utilized to pump fluid into the external bladder 405 of the autonomous underwater vehicle 100, which requires a pumping force sufficient to overcome the ambient external pressure at the underwater vehicle’s depth 260c. Pump Stage 3 315 can comprise one or more pumps 460a, 460b, optimized for the third depth range (i.e., deep water 250). As the external bladder 405 fills with fluid, the surface area and thus the buoyancy of the underwater vehicle 100 increase, causing the underwater vehicle to ascend. In accordance with certain embodiments, only a nominal amount of fluid is move to the external bladder 405—just enough to get a desired rate of rise. As the autonomous underwater vehicle 100 begins to ascend, it may need to change the amount of fluid in the external bladder 405.
because, for example, the density (e.g., the salinity) of the water may not be what was originally predicted. Thus, more fluid can be pumped into the external bladder 405 or some fluid can be allowed to bleed from the external bladder 405 to alter the rate of ascent. Adding and removing water from the external bladder 405 can be performed, for example, in a PID loop type of arrangement. In certain embodiments, the system 400 may not allow fluid to be bled from the external bladder 405 to slow the underwater vehicle’s 100 ascent, because the vehicle 100 typically eventually hits an area of water in its ascent that slows the vehicle down and makes up for a too-rapid rise. Ocean water density tends to be more uniform near the ocean’s bottom 210. Toward the ocean’s surface 205, the density is more likely to vary, for example due to varying temperature or salinity. Salinity may vary due to, for example, fresh water sources such as rivers, streams, runoff, and rain water.

[0062] The underwater vehicle ascends through the third depth range 260a to the second depth range 260b. In the second depth range 260b, the depth and thus the ambient pressure decrease, and a Pump Stage 2 510 can be used to pump fluid into the external bladder 405 if needed to maintain a desired rate of ascent. Pump Stage 2 510 can comprise one or more pumps 460a, 460b, 460c optimized for the second depth range 260b. In accordance with certain embodiments, during ascent, the underwater vehicle 100 can change its angle of ascent by changing its pitch angle as needed to follow the requested dive profile. The underwater vehicle 100 ascends through the second depth range 260b to the first depth range 260a. In the first depth range 260a, the depth and thus the ambient pressure decrease, and a Pump Stage 1 505 can be used to pump fluid into the external bladder 405 if needed to maintain a desired rate of ascent. Pump stage 1 505 can comprise one or more pumps 460a, 460b, 460c, 260a optimized for the first depth range 260a (i.e., shallower water 200). Within the first depth range 260a, for example at about 10 meters or less, a second SURFACE segment 285 can begin as illustrated. At surfacing 285, more fluid can be pumped into the external bladder 405 and the vehicle’s mass 117 may be shifted to get the vehicle’s tail (or rear) 120 up to an antenna 135 located at the tail 120 to rise for communication.

[0063] During the second SURFACE segment 285, the autonomous underwater vehicle 100 can transmit information including, for example, vehicle health (e.g., all systems self-test and indicate that they are working normally), available onboard energy, a dive log, data from onboard instruments (e.g., chemical compounds in water, optical backscatter, sound detection, salinity, predominant currents, images, other physical properties of the ocean, etc.), and can receive information including a dive plan having waypoints (e.g., latitude, longitude, depth, descent rate, and ascent rate), instrument sampling rates, and other parameters associated with controlling instruments (turning them off or when to turn them on). After a dive plan 255 is received, the vehicle 100 can calculate a correct rate and angle of descent based at least in part on the new dive plan 255. An initial GPS location is taken (GPS1) with an on board GPS 114 when the vehicle 100 surfaces and then, after data transmission and receipt of a new dive plan 255 (which presently typically takes about 10-15 minutes (using, e.g., about 10 Watts of energy), another GPS location is taken (GPS2) because the vehicle 100 may have moved during data transmission and receipt. Movement of the vehicle from GPS1 to GPS2 can provide information regarding predominant currents affecting the vehicle. A transmitted dive log can comprise data indicating how each dive profile step went. The dive log can also record errors and error mitigation attempts, and collect instrument data. Certain embodiments of the underwater vehicle 100 can remain surfaced without using any energy. The underwater vehicle 100 can also be retrieved after a single dive.

[0064] In accordance with certain embodiments, the autonomous underwater vehicle 100 can abort a dive 255 when a problem (e.g., a system error) is detected. When a dive 255 is aborted, the autonomous underwater vehicle 100 can pump as much fluid into the external bladder 405 as possible to reach the surface for retrieval.

[0065] When the dive plan 255 requires the vehicle 100 to re-dive without surfacing, the vehicle 100 typically levels out and shifts a mass 117 within the vehicle to point its nose 200 downward before the vehicle 100 allows bleeding from the external bladder 405 to begin to dive again.

[0066] To provide an autonomous underwater vehicle 100 that can efficiently traverse a dive profile 255 ranging from shallow coastal water 200 to deep water 250, the present teachings contemplate a multi-stage buoyancy system comprising, for example, a system employing multiple fluid displacement mechanisms (e.g., a multi-pump system or a system employing a combination of pumps and other fluid displacement systems) to provide efficient movement of fluid at a variety of depths. The fluid displacement systems need not be the same type of fluid displacement system and can comprise, for example, a piston-driven pump, a syringe pump, a Stirling engine, and/or other suitable devices that can move fluid.

[0067] Various embodiments of the present teachings provide a system for changing the apparent displacement or incorporated mass of an autonomous underwater vehicle by displacing fluid within an underwater vehicle comprising two or more stages or subsystems of displacement mechanisms as set forth hereinabove, and a control system that determines an appropriate stage to utilize in the environment that is ambient to the underwater vehicle at any given segment of the underwater vehicle’s dive profile.

[0068] As stated above, an autonomous underwater vehicle must descend and ascend in the water to move forward and traverse its intended path. FIG. 13 illustrates an exemplary underwater dive profile with time represented on the horizontal axis and depth being represented on the vertical axis. FIG. 3 shows that the ascent phase of the underwater vehicle’s dive profile is where the multi-stage control of the present teachings is effective in allowing the underwater vehicle to employ more than one fluid displacement mechanism to move fluid to the external bladder with maximum efficiency while providing the pressure needed to fill the bladder based on the ambient pressure at the underwater vehicle’s depth.

[0069] At the end of the ascent phase, the autonomous underwater vehicle can reach a surface level (or at least come close enough to the surface) where it can send data (e.g., via satellite transmission) regarding its preceding path and/or begin a new decent and ascent cycle. Upon surfacing, the underwater vehicle can reconcile its location by receiving its current GPS location and inputting that location into its dive profile.

[0070] A multi-stage buoyancy system in accordance with the present teachings can be implemented in a number of ways using a variety of approaches that embody the principle of depth-driven and pressure-driven selection of the most efficient stage. For example, by using a pressure sensor that
detects the surrounding water pressure at a given depth, the control system or electrical logic of the vehicle can enable the pumping stage that is most efficient for the detected environmental pressure. In principle, a system of many stages can be employed, wherein two is the simplest case for use as an exemplary embodiment herein and may be adequate for many coastal to deep water oceanic missions for autonomous underwater vehicles. The present teachings contemplate, however, more than two stages being used to achieve high efficiency across the entire depth of the ocean from a few meters to 6000 meters or more.

[0071] The design principle driving selection of different pumps and pump drive motors for differing depth ranges can be such that the pumping energy for predefined depth ranges and associated pressure is minimized on the basis of balancing the rate of pumping against the torque and hence energy consumption required to resist and overcome the range of pressures within a depth range and move enough fluid to achieve a required buoyancy offset. For example, a depth range of from 0 to 100 meters typically has a corresponding pressure range of from about 1 atmosphere to about 11 atmospheres, and this would dictate that a pump and drive motor capable of most efficiently overcoming the 11 atmospheres maximum value would be selected for this depth range. For a range of 100 meters to 500 meters, having a pressure range of from 12 atmospheres to 50 atmospheres, a stronger pump/motor drive combination is needed, preferably having the best energy efficiency for that range. This design criteria can continue until a maximum depth demanded by the vehicle is serviced by a pump and motor drive stage that meets the maximum pressure demand, while using the minimum energy to achieve buoyancy change by volume of expelled fluid to overcome pressure at any given depth.

[0072] Using the above design approach for very large depth ranges can, in certain instances, produce a sub-optimal match of pumping stage to the encountered pressure at some depths, or can produce a design with an excessive number of stages and thus excessive complexity and a significant number of parts lending toward failure modes. Thus, another embodiment of the present teachings contemplates utilizing a pump motor in combination with a continuous variable transmission (CVT) that can adapt to a torque-speed curve resulting in an optimal pressure/pumping rate needed at any given depth of the autonomous underwater vehicle. CVTs can provide an effective continuum of torque-speed ratios over a predetermined range, with slower speeds corresponding with higher torque output. A continuous variable transmission would effectively allow a pump to work across an entire pressure range efficiently by virtue of operating at a faster rate (using a low gear ratio for shallower water, lower ambient pressure, lower torque requirements) or slower rate (using a high gear ratio for deeper water, higher ambient pressure, higher torque requirements) of fluid displacement as needed to minimize the torque and hence the energy required to change buoyancy as needed to allow the underwater vehicle to follow its dive profile.

[0073] A CVT-based implementation of the present teachings is practical for increased dive durations associated with increased dive depths. For example, dives to 50 meters will typically take from 15 to 20 minutes, whereas dives to 1000 meters can take up to 5 hours, affording a far longer time frame for the pumping system to move the fluid to achieve ascent velocity when ascending from a 1000 meter depth. In other words, a CVT-based embodiment would pump slowly, using less energy when at greater depths by employing a high gear ratio in the CVT, resulting in low pumping speed but high enough torque to overcome external pressure. Given the longer duration of deeper dives, this can produce an acceptable and optimized result with a single pump design. Where pressures are low in shallow dives, the amount of torque required by the pump to overcome the external water pressure is much lower, but rapid pumping to achieve rapid ascent is typically desirable, so the CVT would then be set to a low gear ratio between the drive motor and the output pump, achieving a higher pumping rate with the lower torque demand. The best effective gear ratio of the CVT for a given ambient pressure can be automatically selected by reading the pressure sensor, then applying an algorithm or other analog control scaling to cause the control arm or other mechanisms that determines the CVT’s effective gear ratio to react proportionally or in steps to pressure changes, in a relationship that decreases the effective gear ratio as depth (and hence pressure) increases.

[0074] An exemplary embodiment of the present teachings that employs a CVT can utilize a NuVinci™ Model N360 continuously variable planetary drive train transmission or another continuously variable or step gearbox mechanism that can vary the pump-to-drive motor effective gear ratio based on a proportional algorithm that is keyed to pressure. As will be understood by those skilled in the art, low gear ratios can be used at shallower depths with lower external pressures, and high gear ratios can be used in deeper waters to produce the extra torque needed to push fluid into the external bladder and against the higher external pressure exerted on the external bladder.

[0075] A flow chart outlining the basic steps of an exemplary algorithm for implementing a multi-stage buoyancy system to achieve efficiency at various depth ranges is illustrated in FIG. 4. The flow chart of FIG. 4 illustrates the basic concept of a two-stage system, one stage being for shallow dive segments of the autonomous underwater vehicle’s dive profile and the other stage being for deep dive segments of the underwater vehicle’s dive profile. The present teachings contemplate using either the profile sequence or the actual pressure to determine which of the fluid displacement mechanisms (e.g., which pump) is used for a given segment of a dive. In certain embodiments, two or more fluid displacement mechanisms (e.g., two pumps or two stages) can be used for a single segment. In certain embodiments, only the ascent phase of a dive, as illustrated in FIG. 3, uses the underwater vehicle’s fluid displacement mechanisms to change the underwater vehicle’s buoyancy.

[0076] As shown in FIG. 4, after a dive sequence begins, the autonomous underwater vehicle performs a next segment of the dive profile, which can be the initial dive profile segment. Each time a new segment of the dive profile begins (e.g., based on a reading of the depth, compass, attitude, or other sensors, singularly or in combination), the algorithm determines whether the profile is an ascent segment (in which one or more fluid displacement mechanisms may need to be employed to displace fluid into an external bladder). If the next segment of the dive profile is not an ascent segment, pressure can be bled from the external bladder to reduce buoyancy, as needed, and the underwater vehicle can begin a descent through the water until a next segment of the dive profile is reached. If the next segment of the dive profile is an ascent segment, the algorithm determines whether the depth of the next segment and the current ambient conditions are less than “Stage 2,” which means that the depth of the next
segment and the current ambient conditions are less than a predetermined depth that is optimal for the pump/motor combination currently being utilized, and thus the ambient pressure is below a predetermined value. To determine the ambient pressure, the algorithm can utilize input from a pressure/depth sensor employed on the underwater vehicle. If the depth of the next segment and the current ambient conditions are less than Stage 2, a high pressure fluid displacement mechanism (referred to herein as a “Stage 1 pump”) can be disabled to improve efficiency of the overall system. Thereafter, the system can perform a buoyancy change with just the Stage 2 fluid displacement mechanism and then move on to perform a next segment of the dive profile.

[0077] If either the depth of the next segment or the current ambient conditions are greater than or equal to “Stage 2,” which means that the depth of the next segment or the current ambient conditions are greater than or equal to a predetermined depth that is optimal for the next range of pressure and thus the ambient pressure is above a predetermined value, the high pressure fluid displacement mechanism (the Stage 1 pump) can be enabled to provide the pressure needed to move fluid to the external bladder against higher ambient pressures. When the Stage 1 pump is enabled, it can be used alone (by disabling the stage 2 pump as shown), or in conjunction with the Stage 2 pump. The algorithm then performs a next segment of the dive profile. In certain embodiments, two fluid displacement mechanisms can be employed to create a three-stage buoyancy system when each fluid displacement mechanism can be used alone or the two mechanisms can be used together.

[0078] In certain embodiments, the control system for the autonomous underwater vehicle uses stored dive profile information, such as the profile illustrated in FIG. 11B or a profile including more than one dive segment such as the segments in FIG. 13, to determine at what time (or distance) an appropriate stage should be used—based on a profile desired depth. Since this method depends on an accurate assessment of the vertical distance traversed by the subaqueous vehicle 100, which can be significantly affected by currents and density structure of the dive environment; certain embodiments of the present teachings can employ a secondary method for selecting the buoyancy stage, such as by reading an external pressure sensor 112 or another method to determine actual depth (e.g., by an acoustic altimeter or by a range and heading determined by an acoustic modem USBL message). The depth and/or depth analog such as pressure can then be used to select the appropriate stage 505, 510, 515 to be used for the desired buoyancy changes in that segment of the dive profile 255. The terms stages, pumps, and fluid displacement mechanisms are used interchangeably herein.

[0079] FIG. 5 is a schematic diagram illustrating an exemplary embodiment of a hydraulic multi-stage buoyancy system in accordance with the present teachings. The exemplary embodiment of FIG. 5 includes, among other elements: a first stage (Stage 1) pump for high pressure depths; a second stage (Stage 2) pump for lower pressure depths; an internal reservoir for fluid (e.g., hydraulic fluid) used to change buoyancy; and a buoyancy chamber or external bladder mounted on an external surface of the underwater vehicle that changes in size and displacement when hydraulic fluid is pumped into it or expressed from it by ambient pressure as the underwater vehicle enters deeper water. The external bladder is preferably at least somewhat elastic.

[0080] FIG. 5 illustrates an exemplary embodiment of paths fluid can take between the internal reservoir 410 and the external bladder 405. In the illustrated embodiment, three paths 415, 420, 425 exist between the accumulator/reservoir 410 and the external buoyancy chamber or bladder 405, two of which contain a fluid displacement mechanism. One path 420 runs fluid through a low pressure “Second Stage” (Stage 2) pump 460b and through a check valve 450 such as the illustrated bypass (check) valve that prevents movement to fluid in an unwanted direction. Another path 415 runs fluid through a bypass (check) valve 450 and through a high pressure “First Stage” (Stage 1) pump 460a. The parallel channels having bypass check valves 450 can combine to eliminate unproductive loads on a stage that is currently operating, by providing a direct path to the internal reservoir 410, without the fluid needing to be pushed or pulled through any non-operating elements (e.g., non-operating stages). The third path 425 allows fluid to return from the external bladder 405 to the internal reservoir 410 through a valve 452 such as, for example, a solenoid valve (e.g., a Skinner valve).

[0081] To cause the autonomous underwater vehicle 100 to descend, the Skinner valve 452 can be opened between the external bladder 405 and the internal reservoir 410, allowing fluid to be driven by ambient pressure from the external bladder 405 to the internal reservoir 410. In the illustrated embodiment of FIG. 5, a return valve such as electronically actuated solenoid valve (e.g., a Skinner valve) 452 is located between the external bladder 405 and the internal reservoir 410, although those skilled in the art will appreciate that other suitable types of valves can alternatively or additionally be used. The valve 452 between the external chamber 405 and the internal reservoir 410 should remain selectively closed while the external buoyancy chamber 405 is being filled to cause the underwater vehicle 100 to ascend.

[0082] In the illustrated embodiment, a check valve 450 is provided between the line returning fluid from the external bladder 405 to the internal reservoir 410 and the Stage 1 pump 460a. This check valve can prevent fluid returning to the internal reservoir 405 from being diverted to the Stage 1 pump 460a.

[0083] While atmospheric pressure can be sufficient to drive fluid from the external bladder 405 to the internal reservoir 410, certain embodiments of the present teachings also contemplate using one or more of the pumps 460a, 460b, 460c to drive fluid from the external bladder 405 to the internal reservoir 410, for example if fluid is not moving therebetween or if fluid is not moving fast enough therebetween to achieve a desired rate of descent.

[0084] The illustrated exemplary embodiments of the present teachings eliminate the impact of serial placement of stages 415, 420, 425, by placing the stages in parallel. Serial placement of the stages can impede an optimal performance of stages downstream or upstream in the system 400. If, for example, a smaller pump was positioned between a larger pump and the reservoir 410, the smaller pump could restrict the larger pump’s access to the reservoir, making it less efficient and/or slower for the larger pump to move fluid from the reservoir 410 to the external bladder 405. Pumps arranged in series between the reservoir 410 and the bladder 405, rather than in parallel as illustrated in FIG. 5, would tend to add frictional and orifice (size) restrictions that can impede fluid flow.

[0085] Certain embodiments of the present teachings can combine two or more stages 415, 420, 425, to achieve either
greater total pressure output to overcome pressures at deeper depths 250 or to increase the rate of change of buoyancy by pumping more fluid into the bladder 405 to increase a rate of ascent. Certain embodiments of a control system 400 for an embodiment utilizing two stages to increase a rate of change of buoyancy can, for example, sense the rate at which buoyancy of the underwater vehicle 100 is being changed, which in some embodiments can be determined by the displacement of an internal plate inside the fluid reservoir 410, and in other embodiments by, for example, measuring a reservoir pressure. When the rate of buoyancy change reaches or exceeds a level required to achieve the underwater vehicle ascent or descent rate desired in the dive profile, one of the stages can be halted to save energy. The stage to be halted can depend, for example, on the underwater vehicle’s 100 depth. For example, if the underwater vehicle 100 is in deeper water 250 requiring use of a stage 1 pump 460a, the stage 2 pump 460b would be halted. Otherwise, if the underwater vehicle 100 is in shallower water 200 requiring use of a stage 2 pump 460b, the stage 1 pump would be halted. If less than all of the stages 415, 420, 425, of the system 400 are being utilized and the rate of buoyancy change falls below a desired level, one or more additional stages can be switched on to provide additional buoyancy fluid flow.

In certain embodiments of the present teachings, a flow-through connection can exist through an intake reservoir 463 of the main pump 462a. Pressure from the boost pump 462b can flow to the external bladder 405 until a predetermined ambient pressure of, for example, 200 psi exists. When the predetermined ambient pressure is reached, fluid from the boost pump 462b can be sent (circumvently but effectly) through the main pump’s 462a intake reservoir 463 via a flow-through connection 464 and back to the internal reservoir 410. The flow-through connection 464 thus can function as a safety path.

A 425 path exists for fluid to flow from the external bladder 405 to the internal bladder 410 to cause the underwater vehicle 100 to have a decreased apparent displacement and a decreased buoyancy, and therefore to descend, the path including a return valve 452 such as an electronically actuated solenoid valve (e.g., a Skinner valve) 452 as shown in the embodiment of FIG. 5.

The autonomous underwater vehicle 100 can comprise a variable buoyancy displacement chamber or variable volume enclosure that can be offset from the center of gravity CG of the underwater vehicle 100, providing a means to change the displacement volume or the mass of the underwater vehicle 100 relative to its center of gravity CG, for example to tip the nose 115 of the underwater vehicle up or down. For example, such a mass distribution mechanism 117 can comprises a vehicle battery or another defined mass 117 within the underwater vehicle that can be adjusted within the underwater vehicle to tip the nose 115 of the underwater vehicle 100 up or down, or to roll the underwater vehicle 100 to its left or right. Movement of the mass distribution mechanism 117 can be controlled by the control system 105, allowing the control system 105 to steer the underwater vehicle 100 as needed to cause the underwater vehicle 100 to descend to desired depths 200, 250, 260a, 260b, 260n, ascend to the water surface 205, roll/steer left or right, or keep station as might be determined by the buoyancy of the underwater vehicle 100 relative to the surrounding ambient water and the center of buoyancy CB of the underwater vehicle 100.

The present teachings provide a multi-stage buoyancy engine or system 400 in which two or more stages 415, 420, 425, can be combined to increase the rate of buoyancy change as determined by the control system 105 to maintain a desired rate of horizontal and/or vertical velocity for the vehicle 100 in accordance with a predetermined dive profile plan. A bypass system such as the bypass valves 450 disclosed above for the multiple stages 415, 420, 425, of the buoyancy engine or system 400 enables use of one or more stages to obtain optimal energy consumption at a given depth, with no significant impedence or degradation of efficiency imposed by any other stage of the system 400.

Various embodiments of the present teachings provide an arrangement of multiple stages 415, 420, 425, such that they can be combined to provide a higher rate of buoyancy change or higher torque, whereby a bypass system allows the stages to be provided in parallel. Various embodiments can also comprise a mechanism to change the center of gravity of the autonomous underwater vehicle to cause the underwater vehicle to roll (rotation about the longitudinal axis of the vehicle) and pitch (rotation about the lateral axis of the vehicle), such that the attitude of the vehicle can be changed to provide a desired glide angle relative to forward
motion. The external bladder 405 can be used to cause the underwater vehicle 100 to roll and pitch, and can change the center of gravity of the autonomous underwater vehicle 100.

[0094] As depicted in FIGS. 7-9, one or more known energy storage systems 600a, 600b onboard the autonomous underwater vehicle 100 can power the fluid displacement mechanisms 460a, 460b, 460c, the sensors 110, 112, 114, and the control system 105. In certain embodiments, the energy storage systems 600a, 600b can comprise one or more rechargeable (e.g., lithium) batteries.

[0095] As set forth above, various embodiments of the present teachings comprise a control system 400 for an autonomous underwater vehicle 100, the control system 105 comprising a control computer, sensors to determine depth, heading angles, and rate of descent, and a buoyancy system 400 for changing the apparent displacement or mass of the underwater vehicle using fluid displacement mechanisms 460a, 460b, 460c to move fluid between an internal reservoir 405 and an external bladder 410.

[0096] Certain embodiments of the present teachings provide an algorithm for determining the appropriate fluid displacement mechanism to use to achieve a desired change in buoyancy to maintain ascent or descent at a specified velocity through a specific range of depths. The fluid displacement mechanisms can comprise a hydraulic system configured with multiple pumping stages or alternate gearing ratios that can efficiently transfer work from one stage to another without significant impairment of a selected stage, and can work in concert or separately to produce changes in buoyancy with respect to the ambient pressure in effect at the time of execution of buoyancy change.

[0097] The present teachings provide a configuration of controls, sensors, and fluid displacement mechanisms that can include motors, pistons, or similar mechanisms that enable a change of buoyancy of the autonomous underwater vehicle in accordance with its environment, to minimize its expenditure of stored energy. An advanced method uses a continuously variable transmission to effectively obtain the benefits of a large number of physically separate stages by employing a single stage having continuously changeable torque, flow rate, and pressure outputs.

[0098] The present teachings also comprise a control algorithm for execution by the controller 105 that can store a desired path 255 of the autonomous underwater vehicle 100 including a depth profile and bathymetric information about the intended path of travel 255 of the vehicle 100, such that appropriate buoyancy control actions can be programmed to use the most efficient employment of fluid displacement mechanisms to minimize utilization of onboard stored energy.

[0099] An autonomous underwater vehicle 100 employing control and buoyancy systems in accordance with the present teachings can travel across long distances (e.g., thousands of kilometers) over durations of many months using buoyancy changes that combine algorithms, controls, and multi-stage buoyancy control 400 to conserve onboard stored energy by utilizing an optimized fluid displacement strategy, selecting the most efficient fluid displacement mechanism(s) to traverse both shallow water 200 and deep water diving profiles 250.

[0100] Other embodiments of the present teachings will be apparent to those skilled in the art from consideration of the specification and practice of the teachings disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the present teachings being indicated by the following claims.

That which is claimed is:

1. A multi-stage buoyancy changing system for an autonomous underwater vehicle, the system comprising:
   - an internal reservoir configured to hold a fluid;
   - an external bladder connected to the internal reservoir via one or more channels and configured to exchange fluid with the internal reservoir via the one or more channels;
   - a first device configured to move fluid through a first channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of a first segment of a dive profile to increase an apparent displacement and a buoyancy of the autonomous underwater vehicle;
   - a second device configured to move fluid through a second channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of a second segment of the dive profile to increase an apparent displacement and a buoyancy of the autonomous underwater vehicle, wherein the first channel and the second channel are arranged in parallel rather than in series;
   - a third channel configured to allow fluid to move from the external bladder to the internal reservoir, the third channel including a solenoid valve that can be selectively opened to allow water to pass from the external bladder to the internal reservoir, wherein the first segment of the dive profile includes a different ambient pressure range than the second segment of the dive profile, and wherein a check valve is located in each of the first channel and the second channel and is configured to prevent fluid from moving from the external reservoir to the internal reservoir through either of the first channel and the second channel.

2. The system of claim 1, further comprising a mass distribution mechanism configured to shift a center of gravity of the autonomous underwater vehicle to allow a portion of the autonomous underwater vehicle to surface when a buoyancy of the underwater vehicle is positive.

3. The system of claim 2, wherein the autonomous underwater vehicle remains surfaced by maintaining positive buoyancy and a shifted center of mass, so that a tail end of the autonomous underwater vehicle is held above a surface of the water while information is transmitted and received.

4. The system of claim 2, wherein the autonomous underwater vehicle is configured to shift its center of mass to travel horizontally in a neutrally buoyant state.

5. The system of claim 1, wherein the autonomous underwater vehicle comprises an expandable internal reservoir that is capable of withstanding ambient pressures of surrounding water up to a predetermined depth.

6. The system of claim 5, wherein the autonomous underwater vehicle displaces a volume of water and is configured to expand or contract the internal reservoir to increase or decrease, respectively, the displaced volume of water to control a buoyancy and a center of gravity of the autonomous underwater vehicle.

7. The system of claim 1, wherein the autonomous underwater vehicle comprises a nose and a tail, the tail comprising a portion configured to rise above a surface of the water that includes one or more of an antenna for radio communication and a GPS locator configured to communicate data that the
autonomous underwater vehicle has collected while submerged and obtain a geographical location of the autonomous underwater vehicle.

8. The system of claim 1, further comprising one or more sensors that collect data while the underwater vehicle is submerged.

9. The system of claim 1, wherein the autonomous underwater vehicle has a front and a rear, and is configured to shift its center of buoyancy and center of mass toward the front or the rear while decreasing and increasing its buoyancy, respectfully.

10. A method for employing a multi-stage buoyancy changing system for an autonomous underwater vehicle having an internal reservoir connected to an external bladder via one or more channels, the method comprising:

   in a first segment of a dive profile, increasing an apparent displacement and buoyancy of the autonomous underwater vehicle by moving water from the internal reservoir to the external bladder using a first device configured to move fluid through a channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of the first segment of the dive profile; and

   in a second segment of the dive profile, increasing an apparent displacement and buoyancy of the autonomous underwater vehicle by moving water from the internal reservoir to the external bladder using a second device configured to move fluid through a channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of the second segment of the dive profile,

wherein the first segment of the dive profile includes a different ambient pressure range than the second segment of the dive profile,

wherein the first device moves fluid from the internal reservoir to the external bladder through a first channel and the second device moves fluid from the internal reservoir to the external bladder through a second channel that is different than the first channel and is arranged in parallel with the first channel, and

wherein a check valve is located in each of the first channel and the second channel and is configured to ensure that fluid does not move from the external reservoir to the internal reservoir through the first channel and the second channel.

11. The method of claim 10, further comprising shifting a center of mass of the autonomous underwater vehicle so that a nose portion of the underwater vehicle is raised before increasing the apparent displacement and a buoyancy of the autonomous underwater vehicle.

12. A multi-stage buoyancy changing system for an autonomous underwater vehicle, the system comprising:

   an internal reservoir configured to hold a fluid; an external bladder connected to the internal reservoir via one or more channels and configured to exchange fluid with the internal reservoir via the one or more channels;

   a pump motor in combination with a continuous variable transmission that can adapt to a torque-speed curve to obtain an optimal pressure/pumping rate needed for a current ambient pressure of the autonomous underwater vehicle, the pump motor and continuous variable transmission being configured to move fluid through a first channel from the internal reservoir to the external bladder at an optimized efficiency for an ambient pressure of more than one segment of a dive profile to increase an apparent displacement and a buoyancy of the autonomous underwater vehicle; and

   a third channel configured to allow fluid to move from the external reservoir to the internal reservoir, the third channel comprising a solenoid valve that can be selectively opened to allow water to pass from the external bladder to the internal reservoir.