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(54) **AUTONOMOUS UNMANNED UNDERWATER VEHICLE WITH BUOYANCY ENGINE**

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(51) **Int. Cl.**
B63G 8/14 (2006.01)

(52) **U.S. Cl.** **114/330**; 114/337

(58) **Field of Classification Search** 440/1; 114/312, 114/330, 337, 244
See application file for complete search history.

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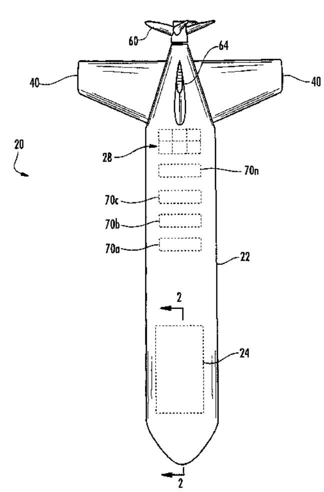
(57) **ABSTRACT**

An autonomous unmanned underwater vehicle ("AUV") includes a body, a controller, a buoyancy engine, a rotary propulsion system and pitch control surface(s). The buoyancy engine is for alternately ingesting and expelling ambient water to change the mass of the AUV and thereby cause the AUV to alternately descend and ascend in the water. The pitch control surface(s) are for causing the AUV to move forward while alternately descending and ascending in the water. The rotary propulsion system includes a motor for rotating a propeller in the water to provide thrust. The controller is operative for responsively, automatically switching between at least the glider and rotary propulsion modes. In the glider mode, the buoyancy engine and the pitch control surface(s) are cooperative for causing the AUV to move forward while alternately descending and ascending. In the rotary propulsion mode, the rotary propulsion system is operative for causing the AUV to move forward.

20 Claims, 10 Drawing Sheets



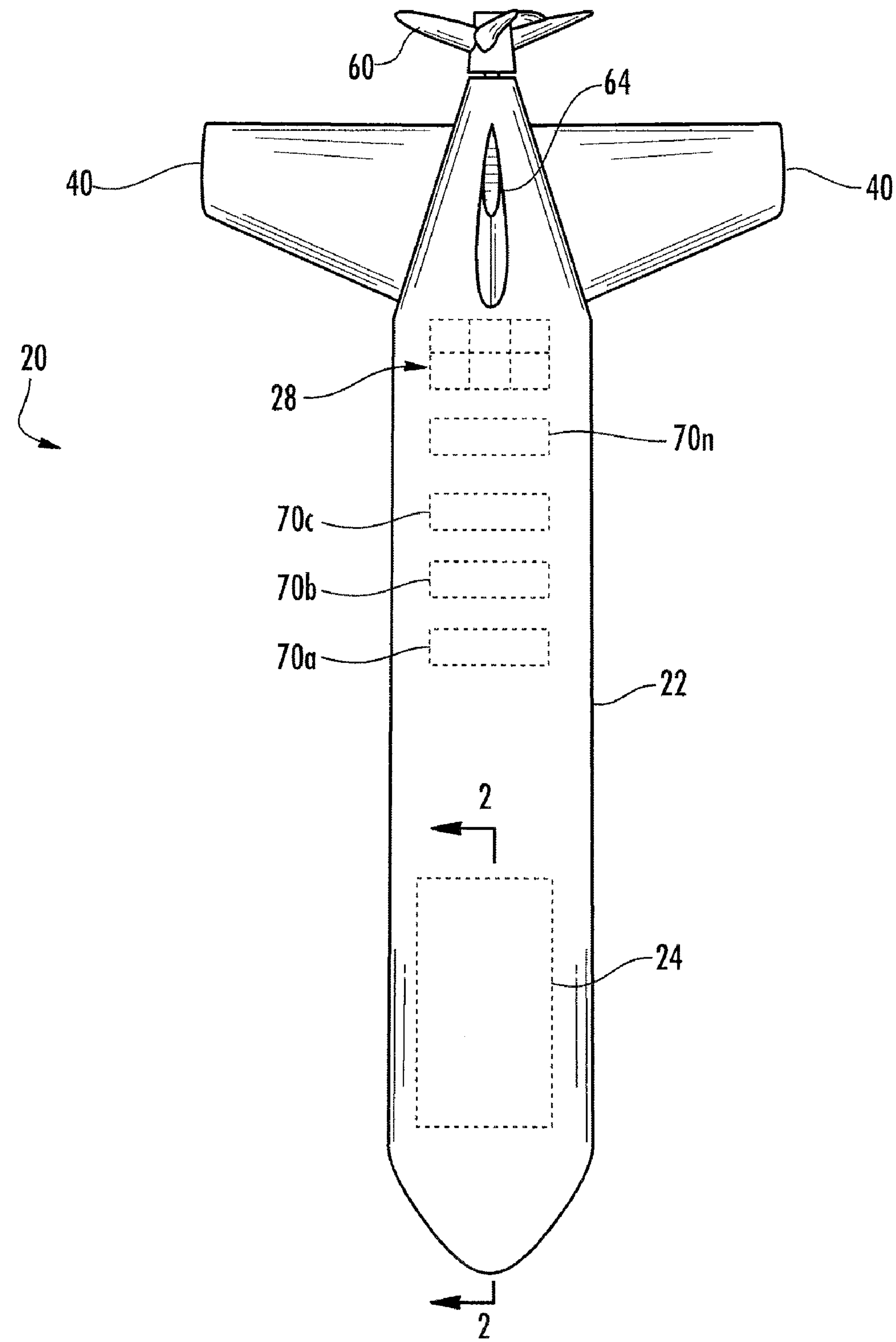


FIG. 1

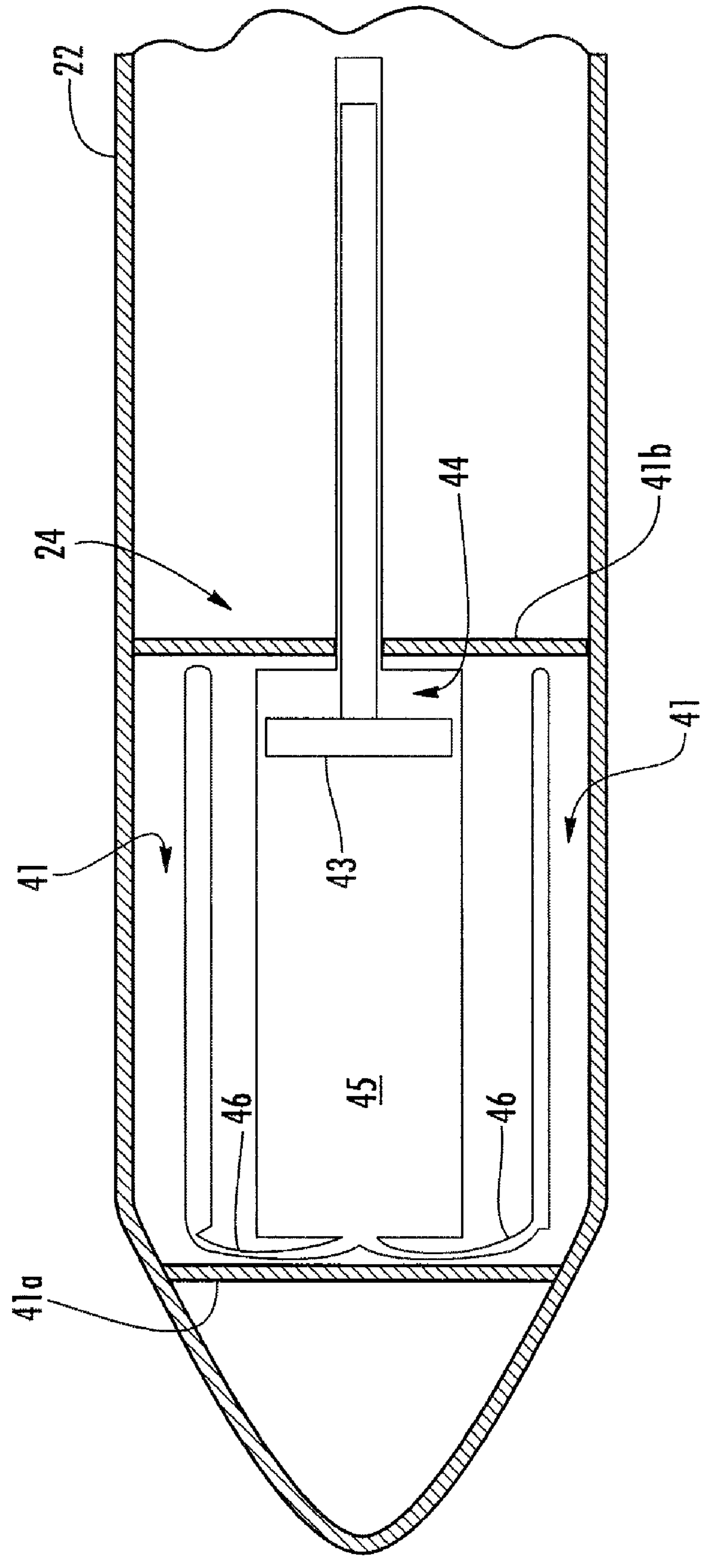


FIG. 2
(PRIOR ART)

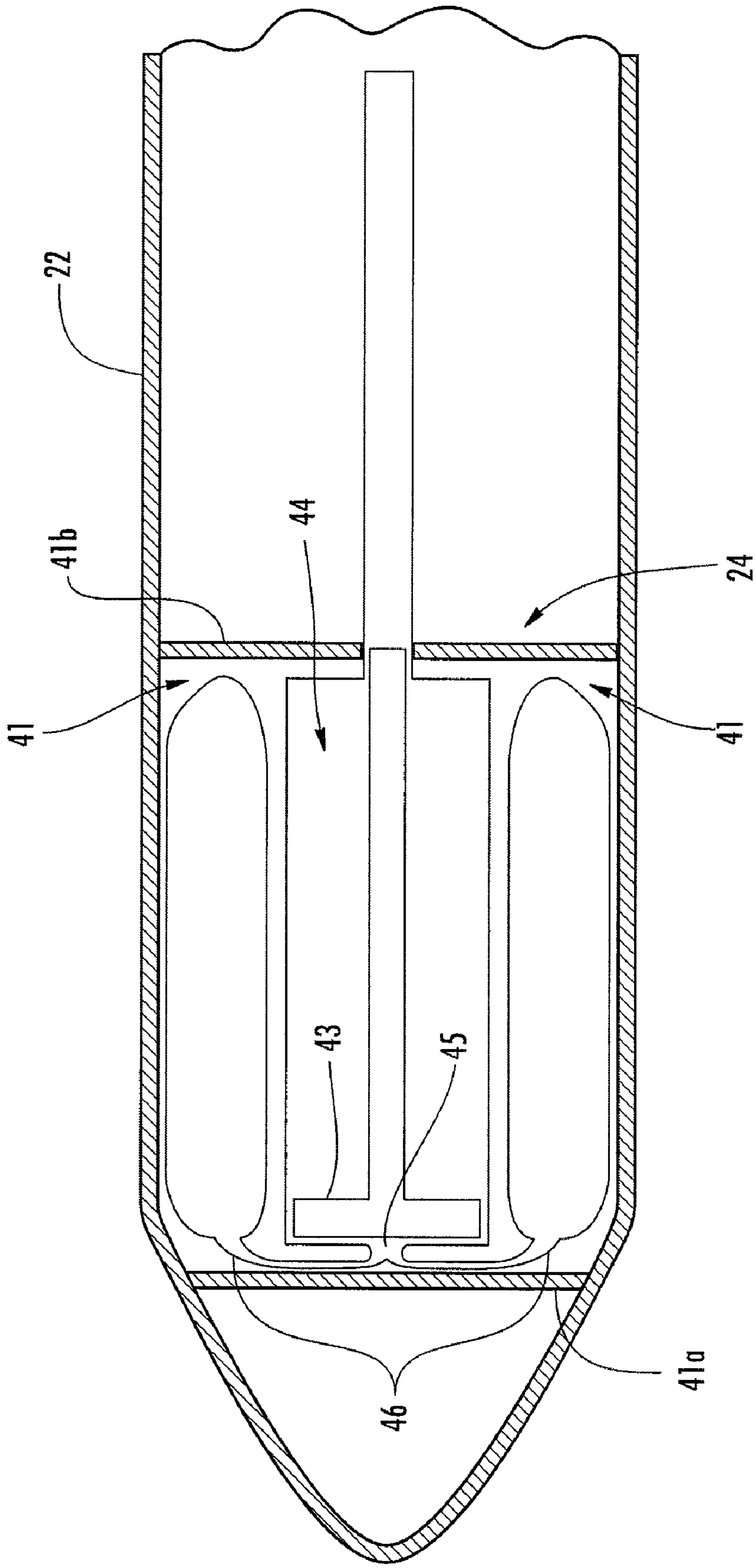


FIG. 3
(PRIOR ART)

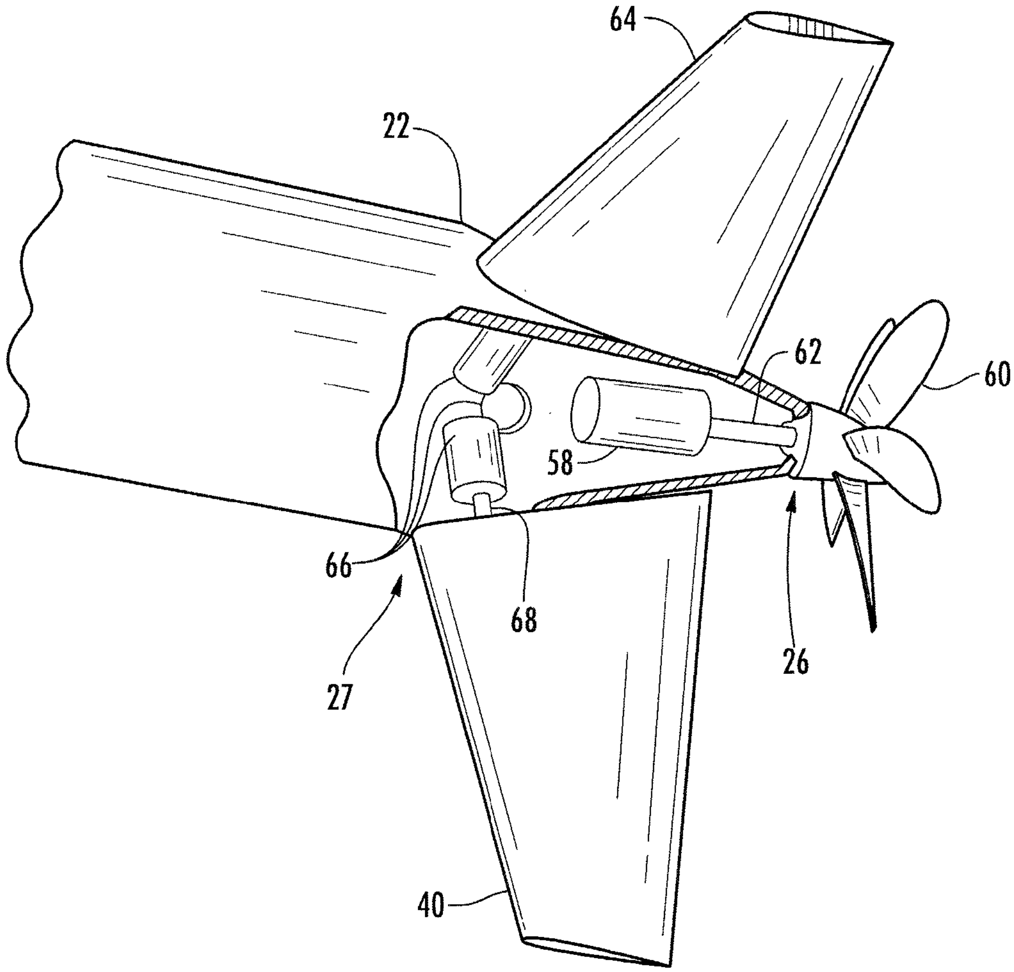


FIG. 4

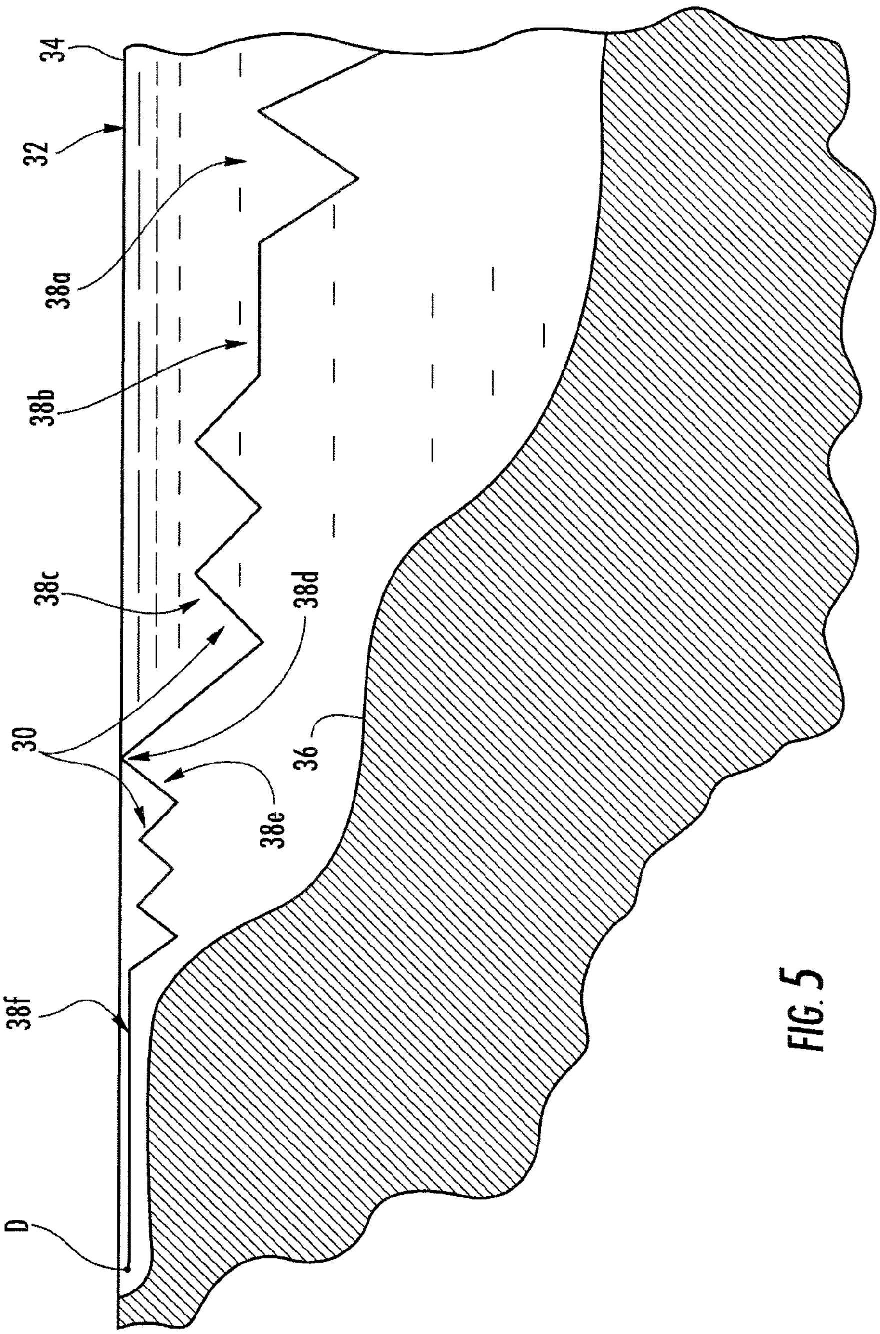


FIG. 5

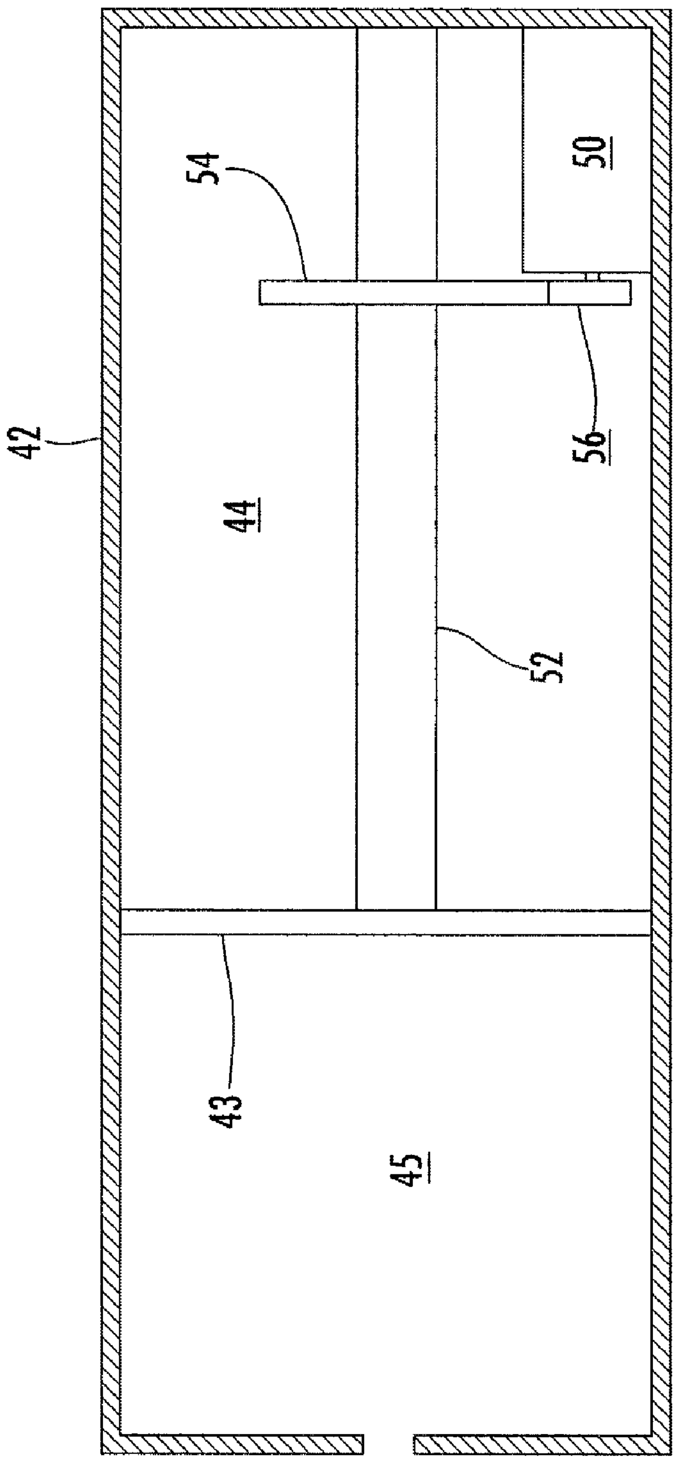
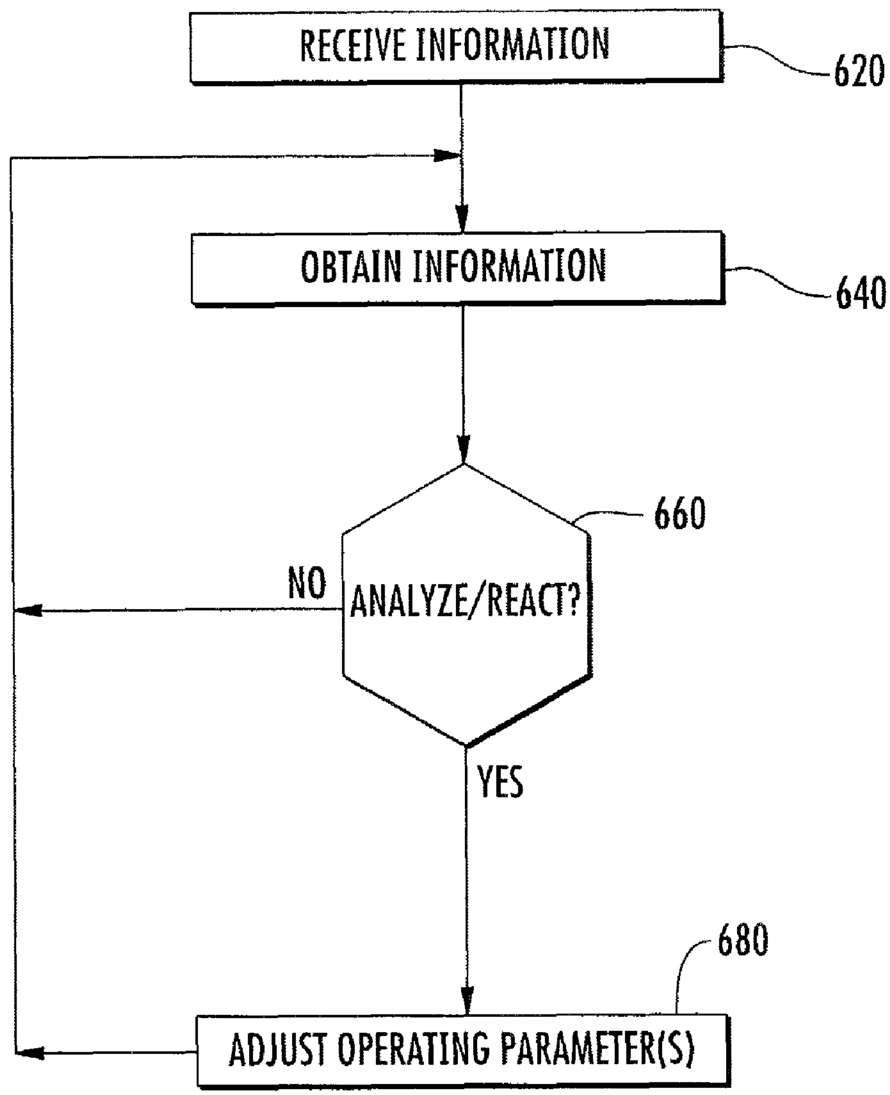


FIG. 6
(PRIOR ART)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620
OBTAIN INFORMATION
640
660
NO
ANALYZE/REACT?
YES
680
ADJUST OPERATING PARAMETER(S)

FIG. 7

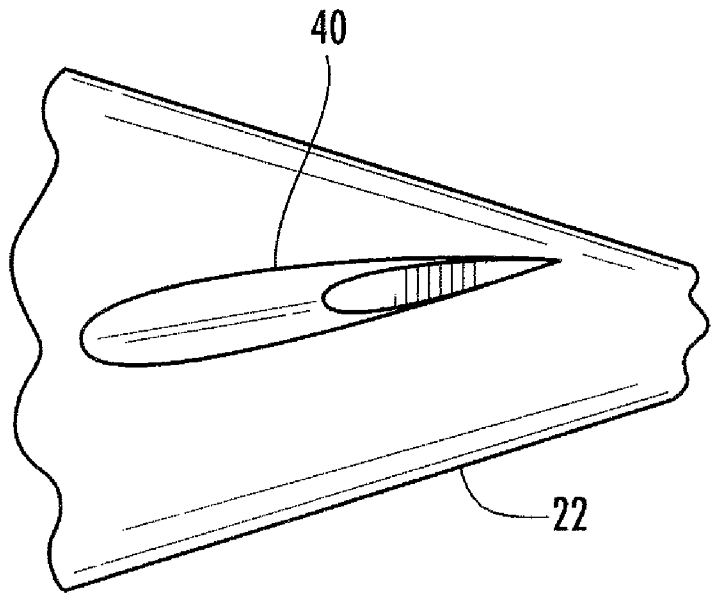

FIG. 8

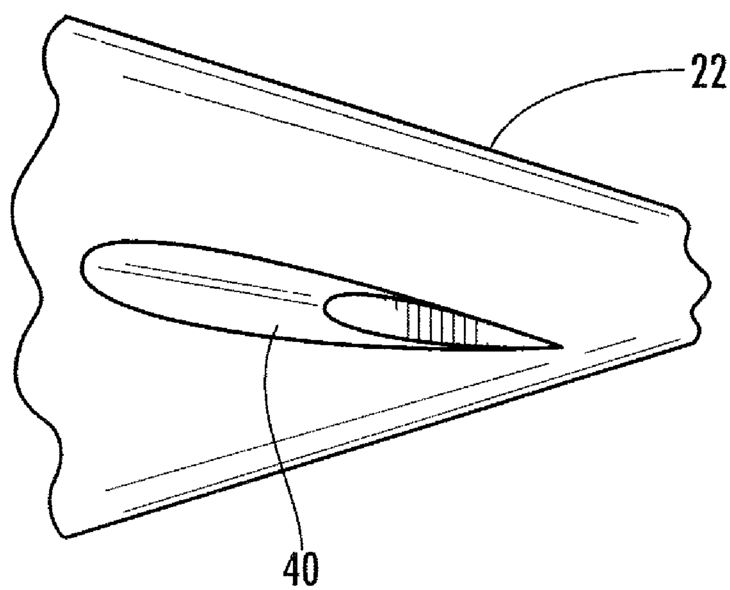

FIG. 9

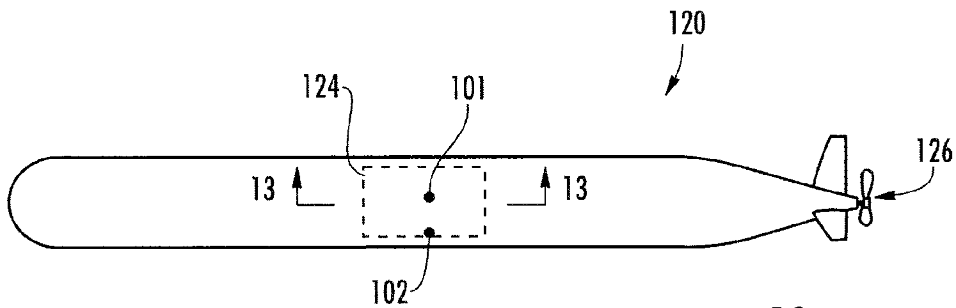

FIG. 10

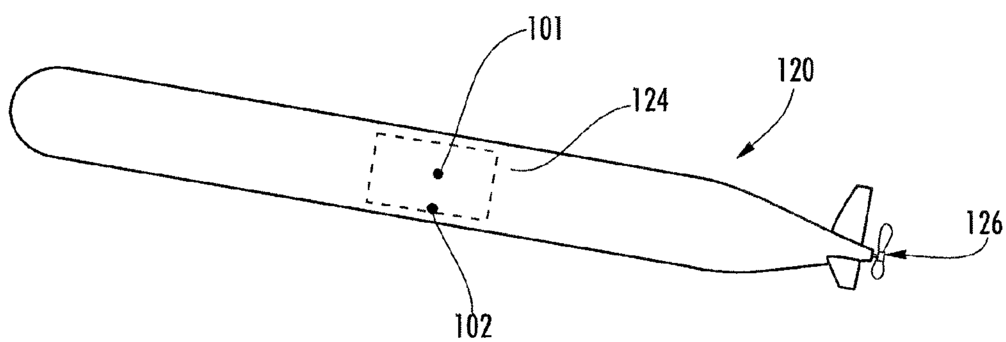

FIG. 11

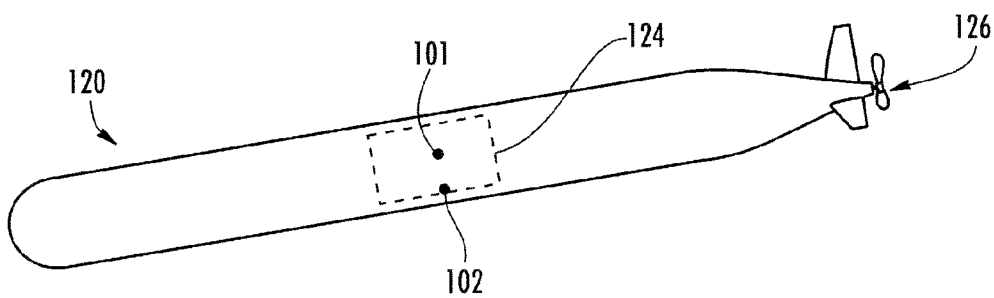

FIG. 12

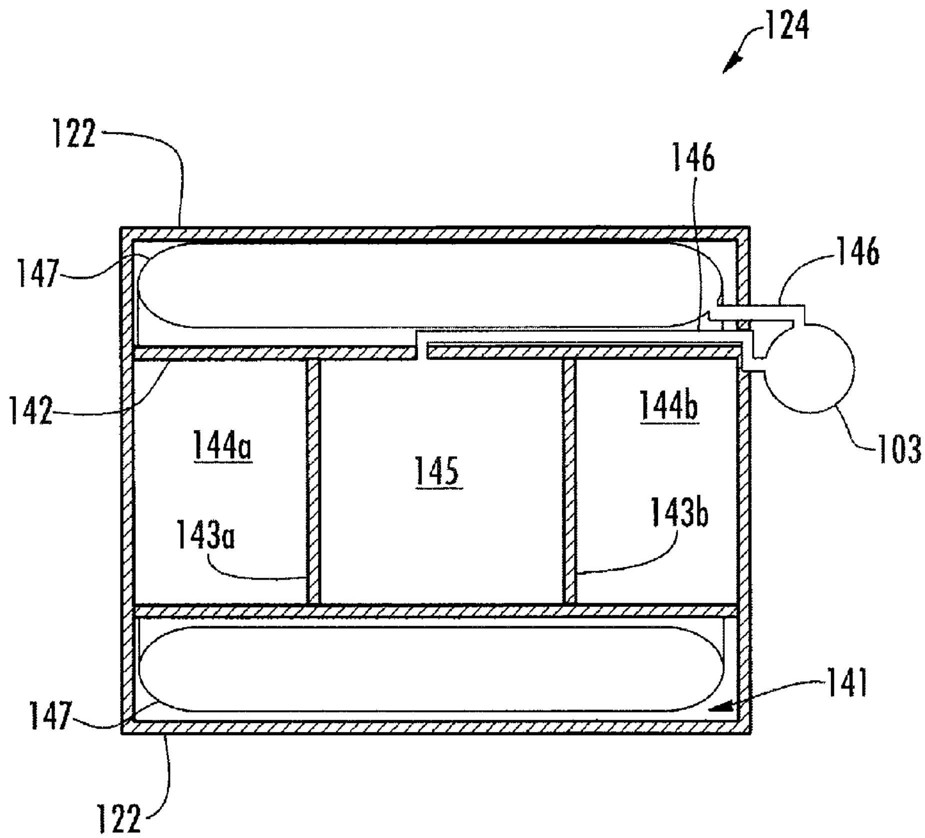

FIG. 13

AUTONOMOUS UNMANNED UNDERWATER VEHICLE WITH BUOYANCY ENGINE

TECHNICAL FIELD

The present disclosure relates to unmanned underwater vehicles and, more particularly, to an autonomous unmanned underwater vehicle that may be powered by a buoyancy engine.

BACKGROUND

An underwater glider is a type of autonomous unmanned underwater vehicle ("AUV") that is powered by a buoyancy engine. The buoyancy engine is carried by the glider and typically includes a motor that is operative for changing the effective volume of a chamber, so that the chamber alternately ingests and expels ambient water to change the mass of the glider, so that the glider alternately ascends and descends. Conventional gliders typically include hydrodynamic wings for causing the AUV to move forward while alternately descending and ascending in the water. A conventional underwater glider with a conventional buoyancy engine may be inadequate in some situations.

BRIEF SUMMARY

In accordance with one aspect of this disclosure, an autonomous unmanned underwater vehicle ("AUV") includes a controller, a buoyancy engine, a rotary propulsion system and at least one pitch control surface. The buoyancy engine is for alternately ingesting and expelling ambient water to change the mass of the AUV and thereby cause the AUV to alternately descend and ascend in the water. The pitch control surface is for causing the AUV to move forward while alternately descending and ascending in the water. The rotary propulsion system includes a motor for rotating a rotary agitator (e.g., a propeller or an impeller) in the water to provide thrust. The controller is operative for responsively, automatically switching between at least glider and rotary propulsion modes. In the glider mode, the buoyancy engine and the pitch control surface cooperate to cause the AUV to move forward while alternately descending and ascending. In the rotary propulsion mode, the rotary propulsion system causes the AUV to move forward. The automatic switching between the modes may enhance performance of the AUV.

Other aspects and advantages will become apparent from the following.

BRIEF DESCRIPTION OF THE DRAWINGS

Having described some aspects of this disclosure in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIG. **1** is a schematic top plan view of an autonomous unmanned underwater vehicle ("AUV") in accordance with a first embodiment of this disclosure.

FIGS. **2** and **3** are schematic cross-sectional views of a forward portion (e.g., buoyancy engine) of the AUV of FIG. **1**, with the cross-sections taken substantially along line **2-2** of FIG. **1**.

FIG. **4** is a schematic, perspective, partially cut-away view of a rear portion of the AUV of FIG. **1**, and it shows a rotary propulsion system and steering system of the AUV.

FIG. **5** is a schematic side view of a body of water and underlying ground, and it schematically illustrates an example of a path of travel of the AUV of FIG. **1** in the body of water, in accordance with the first embodiment.

FIG. **6** is a schematic, isolated, partially cutaway side view of a cylinder of the buoyancy engine and components within the cylinder, in accordance with the first embodiment.

FIG. **7** is a flow diagram that provides a high-level illustration of how a controller of the AUV of FIG. **1** may control the operation of the AUV, in accordance with one example of the first embodiment.

FIGS. **8** and **9** generally are end elevation views of a representative side fine of the AUV of FIG. **1**, with a portion of the underlying hull structure of the AUV also being shown, wherein these figures respectively show the side fin in inclined and declined configurations.

FIGS. **10-12** are schematic side elevation views of an AUV in accordance with a second embodiment of this disclosure, and these figures show that the location of the center of mass of the AUV remains the same (e.g., substantially the same) at different pitch angles.

FIG. **13** is a schematic cross-sectional view of a middle portion of (e.g., a buoyancy engine of) the AUV of FIGS. **10-12**, with the cross-section taken substantially along line **13-13** of FIG. **10**.

DETAILED DESCRIPTION

In the following, several exemplary embodiments of this disclosure are discussed in greater detail with reference to the drawings, in which like numerals refer to like parts throughout the several views. The exemplary embodiments are generally discussed in series, starting with a first embodiment, then a second embodiment, and then a third embodiment.

Initially, an autonomous unmanned underwater vehicle ("AUV") **20** of the first embodiment is described. A general discussion of the components of the AUV **20** is followed by a general discussion of how the AUV **20** may operate, and thereafter there is a more specific discussion of the components of the AUV **20**, followed by a more specific discussion of operation of the AUV **20**.

FIG. **1** is a schematic top plan view of the AUV **20**. In FIG. **1**, some of the AUV's internal components, which are typically hidden from view, are shown in dashed lines. As shown in FIG. **1**, the AUV has a body including a cylindrical hull **22** with a rounded front end and a tapered rear end. Any other suitably shaped body/hull may be used.

FIGS. **2** and **3** are schematic cross-sectional views of a forward portion of the AUV **20**, with the cross-sections taken substantially along line **2-2** of FIG. **1**. FIGS. **2** and **3** schematically show portions of one of the internal component of the AUV **20**, namely a portion of a buoyancy engine **24** (e.g., ballast system) that is for changing the net buoyancy of the AUV, and the changes in net buoyancy are used to propel the AUV. The buoyancy engine **24** of the first embodiment of this disclosure is conventional/is not novel per se. Generally described, the buoyancy engine **24** is in a configuration for causing the AUV **20** to descend in FIG. **2**, and a configuration for causing the AUV **20** to ascend in FIG. **3**. The buoyancy engine **24** provides negative net buoyancy for descending, and positive net buoyancy for ascending, as will be discussed in greater detail below with reference to FIG. **6**.

The buoyancy engine **24** that is schematically, partially shown in FIGS. **2** and **3** is of a type that is typically located in, or proximate to, the nose (e.g., front end) of the AUV **20**, and that causes a change in the center of gravity of the AUV while the buoyancy engine is operating. A variety of different buoyancy engines may be used at different locations within the AUV **20**. For example, FIG. **13** illustrates another buoyancy engine that is discussed in greater detail below, in accordance with the second embodiment of this disclosure. For example and as discussed in greater detail below, it is optional for the buoyancy engine of the AUV **20** to cause a change in the center of gravity of the AUV.

FIG. **4** is a schematic, perspective, partially cut-away view of a rear portion of the AUV **20**. FIG. **4** schematically shows additional internal components of the AUV **20**, namely internal components of a rotary propulsion system **26** and a steering system **27** that has fins **40**, **64** or other suitable control surfaces. In accordance with the first embodiment, the steering system **27** is operative (e.g., the side fins **40** of the steering system are operative), for example, for pitching the nose of the AUV **20** up and down in a manner that is cooperative with the changes in net buoyancy for propelling the AUV, as will be discussed in greater detail below.

Another of the internal components of the AUV **20** is a controller **28** (FIG. **1**) that is operative for, typically among other things, automatically switching between the different propulsion systems of the AUV **20** in response to detecting one or more predetermined conditions. More specifically and for example, the controller **28** may automatically switch between usage of the buoyancy engine **24** (e.g., a glider mode of travel in which the AUV may travel forward while alternately descending and ascending) and the rotary propulsion system **26** (e.g., a rotary propulsion mode of travel in which the AUV may travel forward, optionally without descending and/or ascending). Whereas the AUV **20** may, in some situations, operate in only one mode of travel (e.g., either the glider mode or the rotary propulsion mode) while traveling to a destination, the AUV **20** may, in some situations, function in multiple different modes while traveling toward a destination. That is and in accordance with the first embodiment, the controller **28** is operative for automatically switching between different modes of travel so that the AUV **20** may operate in one, two, or any number of different modes on a given mission.

An example of one theoretical/prophetic path **30** of travel of the AUV **20** (FIG. **1**) in a body of water **32** is schematically shown in FIG. **5**, although numerous other paths of travel of the AUV are within the scope of this disclosure. FIG. **5** is a schematic, vertical cross-sectional view illustrating that the body of water **32** is bounded between a top surface **34** and a bottom **36** of the body of water. The depth of the body of water **32** varies with the elevation of the bottom **36**, so that the body of water includes a shallow portion and a deep portion, and portions between the shallowest and deepest portions.

As schematically shown in FIG. **5**, the path **30** includes a destination D. In FIG. **5**, the destination D is shown in the shallow portion of the body of water **32**, although the destination may be in any other suitable location within the body of water. The destination D may be a location to which the AUV **20** autonomously travels (e.g., a location where a mission ends), or the destination D may be an intermediate location (e.g., the destination D may optionally also be a location from which the AUV **20** returns after travelling thereto). In one example of operating in the context of FIG. **5**, the AUV may travel from right to left along the path **30** to the destination D. The AUV **20** may be a disposable item that is launched in any suitable manner and thereafter never be recovered (e.g., the payload contained by the AUV may be detonated at the destination D), or the AUV may be an item that is retrieved in any suitable manner, and then reused one or numerous times.

As mentioned above, the controller **28** (FIG. **1**) is typically operative for automatically switching between different modes of travel of the AUV **20** in the body of water **32**. For example and not limitation, FIG. **5** schematically illustrates that the AUV **20** may operate in a glider mode, a rotary propulsion mode and a surface mode. In this regard, the path **30** shown in FIG. **5** includes sections **38***a*-**38***f* for schematically illustrating different modes of operation (e.g., modes of travel) of the AUV **20**.

Sections **38***a*, **38***c* and **38***e* of the path **30** schematically illustrate the AUV **20** operating in the glider mode. In the glider mode, the buoyancy engine **24** and the steering system **27**, namely the pitch control surfaces (e.g., see the side fins **40** in FIGS. **1** and **4**), cooperate to cause the AUV **20** to move forward in the body of water **32** while the AUV is alternately descending and ascending.

Sections **38***b* and **38***f* of the path **30** schematically illustrate the AUV **20** operating in the rotary propulsion mode. In the rotary propulsion mode, the rotary propulsion system **26** operates, typically in cooperation with the steering system **27**, for causing the AUV **20** to move forward, although the AUV may also move rearward in some embodiments.

Section **38***d* of the path **30** schematically illustrates the AUV **20** operating in a surface mode in which the AUV approaches and remains (e.g., remains stationary) at the surface of the body of water **32**. In accordance with the first embodiment, the rotary propulsion system **26** may be inoperative (i.e., turned off) while the AUV **20** operates in the buoyancy and surface modes, and the buoyancy engine **24** may be inoperative (i.e., turned off) while the AUV operates in the rotary propulsion mode.

The modes of operation of the AUV **20** and the switching between the modes are discussed in greater detail below. Notwithstanding the foregoing or the following, the AUV **20** may, in some situations, operate only in one mode of operation (e.g., mode of travel) while traveling to a destination (e.g., the destination D).

In accordance with one example, the buoyancy engine **24** (FIGS. **2**, **3** and **6**) in and of itself may be conventional, the rotary propulsion system **26** (FIG. **4**) in and of itself may be conventional, the steering system **27** (FIG. **4**) in and of itself may be conventional, and the hardware of the controller **28** (FIG. **1**) in and of itself may be conventional (e.g., the controller **28** may be a conventional computer). In contrast and for example, using the buoyancy engine **24** and the rotary propulsion system **26** in combination (e.g., automatically switching between using them), the controller's software or firmware modules (e.g., that are operative for signaling the switching), and other features of this disclosure may be inventive. The various features of this disclosure that are believed to be inventive may be in a variety of different combinations and subcombinations.

More specifically regarding the buoyancy engine **24** (FIGS. **2** and **3**), it is for using some of the ambient water **32** (FIG. **5**) as ballast, to change the mass of the AUV **20**. That is, the buoyancy engine **24** alternately ingests and expels water **32** to cause the AUV to alternately descend and ascend in the water. The water **32** is ingested into, and expelled from, a ballast chamber **41**. The ballast chamber **41** is typically contained within the hull **22** and is for being in fluid communication with the body of water **32** while the AUV **20** is in the body of water. In accordance with the first embodiment, the ballast chamber **41** has a fixed volume that extends around a cylinder **42** that is centrally located in the hull **22**. The ballast chamber **41** extends between the interior surface of the hull **22** and the outer surface of the cylinder **42**, and the ballast chamber **41** also extends between opposite ends **41***a*, **41***b* of the ballast chamber. The opposite ends **41***a*, **41***b* of the ballast chamber **41** may be in the form of water-tight bulkheads or any other suitable structures. While the AUV **20** is in the body of water **32**, the ballast chamber **41** is in fluid communication with the body of water **32** by way of one or more passageways (not shown) that extend between the exterior of the hull **22** and the interior of the ballast chamber **41**.

The inner chamber of the cylinder **42** contains a movable piston **43** that divides the inner chamber of the cylinder **42** into a gas chamber **44** (e.g., a fully closed chamber that contains air or any other suitable gas, or the like) and a liquid chamber **45** (e.g., a chamber that contains water, oil or any other suitable liquid that is not too compressible, or the like). The liquid chamber **45** is fully closed, except for being open to one or more passageways **46** (e.g., tube(s), pipe(s) or any other suitable means for fluid communication) that are open to the interior of one or more flexible bladders **47** within the ballast chamber **41**. Generally described and as will be discussed in greater detail, the piston **43** is moved to change the volume of the liquid chamber **45**, so that the size of the bladders **47** is responsively changed to cause the ballast chamber **41** to alternately ingest and expel ambient water **32** to change the mass of the AUV **20**.

Generally described, the volume of the liquid chamber **45** is changed in response to operation of a motor, so that the ballast chamber **41** alternately ingests and expels ambient water **32** to change the mass of the AUV **20**. That is, the ingestion and expulsion of water **32** is responsive to reciprocation of the piston **43**. Any suitable mechanism may be used for causing the reciprocation of the piston **43**, such as, but not limited to, a linear electric motor, a pneumatic system (e.g., including a pneumatic actuator) or a hydraulic system (e.g., including a hydraulic actuator (e.g., an electric motor-driven pump)).

In accordance with the first embodiment and as best understood with reference to FIG. **6**, the piston **43** is reciprocated by mechanical system to change the volume of the gas chamber **44** and liquid chamber **45**. In accordance with the first embodiment, the mechanical system for moving the piston includes a reversible, direct-current electric motor **50** and any suitable gear train for causing the piston **43** to reciprocate. For example, the gear train may include an externally threaded, rotatably mounted spindle/worm **52** that is rotatably connected (e.g., either directly or indirectly) to the piston **43** for reciprocating therewith, a worm gear **54** that extends around the worm **52** and has internal threads that are meshed with the worm, and a drive gear **56** that is mounted to the drive shaft of the motor **50** and meshed with external threads of the worm gear **54**.

The motor **50** is operated to cause the piston **43** to move forward so that water **32** is expelled from the ballast chamber **41** and the AUV **20** ascends. The AUV **20** may continue to ascend after the piston **43** is in its forward position. The motor **50** is operated to cause the piston **43** to move to its rearward position so that water **32** is ingested into the ballast chamber **41** and the AUV **20** descends. The AUV **20** may continue to descend after the pistons **43** is in its rearward position.

More specifically regarding the rotary propulsion system **26** (FIG. **4**) of the first embodiment, it includes a motor **58** for rotating a rotary agitator **60** (e.g., an impeller or a propeller) in the water **32** to provide thrust, and thereby cause the AUV **20** to move forward in the water. In accordance with the first embodiment, the motor **58** is a direct-current electric motor, which may include or otherwise be linked to gears (not shown) for stepping up or stepping down the motor's output, and the rotary agitator **60** is an external propeller. The propeller **60** is mounted on/for rotating with an output drive shaft **62** that is rotated by the motor **58**. In accordance with the first embodiment, the propeller **60** is a foldable propeller that automatically transitions between a folded-together, collapsed configuration and a radially outwardly extending operative configuration in response to the motor **50** being turned on, and vice versa. For example, each of U.S. Pat. Nos. 4,204,806 and 5,183,384 is incorporated herein by reference, in its entirety. Alternatively, the propeller **60** may be replaced with a non-folding propeller or an impeller which may be part of a pump jet or water jet that creates a jet of water for propulsion, and the propulsion system may include a movable nozzle for directing the jet of water for steering purposes.

The AUV **20** may include any suitable type of control surfaces, including one or more pitch control surfaces in the form of one or more conventional hydrodynamic wings (not shown) that are for causing the AUV to move forward while alternately descending and ascending in the water **32** due to operation of the buoyancy engine **24**. However and in accordance with the first embodiment, hydrodynamic wings are not included in the AUV **20**. Rather, the AUV includes the right and left side fins **40** that operate at least as pitch control surfaces. In addition, the AUV **20** typically includes at least one other control surface in the form of an upright fin **64** that operates at least as a yaw control surface. The fins **40**, **64** are movable control surfaces for steering or otherwise orienting the AUV in the body water **32**.

Referring to FIG. **4**, the movable fins **40**, **64** project laterally, outwardly from the hull **22**, and they are moved by respective internal components of the AUV **20** that are typically in the form of direct-current electric actuators **66**. The hull **22** is partially cut away in FIG. **4** to schematically show the drive shaft **68** by which one of the actuators **66** is connected to, and rotates, the respective side fin **40**. Regarding the representative drive shaft **68** shown in FIG. **4**, it extends through an opening in the hull **22** and can be rotated back and forth in response to operation of the respective actuator **66**. The respective fin **40** is fixedly mounted to the drive shaft **68** for rotating therewith. Each of the fins **40**, **64** is similarly driven, by way of a drive shaft or any other suitable mechanism, by the respective actuator **66**. The fins **40**, **64** may be replaced with different types of fin assemblies, such as, but not limited to, fin assemblies with rudders (e.g., trailing edge rudders or pedestal rudders).

More specifically regarding the controller **28** schematically shown in FIG. **1**, features of the controller may be embodied in any suitable manner, such as in software, firmware and/or hardware modules. For example, the controller **28** may be in the form of one or more computers (which may include appropriate input and output devices, a processor, memory, software modules, etc.) or any other suitable device(s) for controlling operations of the AUV **20** by virtue of receiving data from and providing data (e.g., instructions from the execution of software modules stored in memory) to respective components of the AUV. In this regard, the controller **28** may include or be associated with any suitable types of features or modules (e.g., software modules, such as an autopilot module for piloting the AUV **20**, a switching module for switching between the various modes of operation of the AUV, and communication module(s) for facilitating communications between the AUV and other device(s)) for aiding in operation of the AUV. The types of modules included may depend upon the mission(s) of the AUV **20**. For example, the controller **28** may include, or be operatively associated with, any modules that are conventionally included in AUVs, and the AUV **20** may include any types operational components (e.g., hardware in the form of sensing devices, transmitters, receives, etc.) that are conventionally included in AUVs. Some of the modules and/or features of the controller **28** are schematically illustrated in FIG. **1** by way of the controller being schematically shown as including compartments.

FIG. **1** is schematic, for example, because the AUV **20** includes numerous operational components **70***a*, **70***b*, **70***c* . . . **70***n* ("operational components **70***a-n*") that are schematically shown by dashed lines as being contained within one or more chambers that are hidden from view within the hull **22**. The operational components **70***a-n* are, for example, for providing functionality that helps to facilitate the operation of or usefulness of the AUV **20**. The operational components **70***a-n* may include an electrical power supply (e.g., a battery or batteries, which may be associated with one or more capacitors for providing relatively large pulses of current when desired); sonar; depth sensor; magnetometer; communication transceiver; autopilot system(s) or subsystem(s) (which may include a gyroscope) for controlling operations of the steering and propulsion systems of the AUV **20**; and/or any other devices that may be useful, such as for carrying out operations described in this disclosure. As will be discussed in greater detail below, one or more of the operational components **70***a-n* is for detecting predetermined condition(s) and the controller **28** is for providing signals that cause the AUV **20** to automatically switch between modes of operation (e.g., the buoyancy, rotary propulsion and surface modes of operation) in response to the detecting of the predetermined condition(s).

For example, the forward-most operational component **70***a* may be a battery or pack of batteries for providing power. In an alternative embodiment of this disclosure, the forward-most operational component **70***a* is a movable mass that is mounted so that it may be moved forward and rearward in the AUV, such as through the action of a motor and/or any suitable gearing (not shown), for pitching the nose of the AUV **20** up and down in a manner that is cooperative with the changes in buoyancy for propelling the AUV. In contrast and in accordance with the first embodiment, the forward-most operational component **70***a* (e.g., a battery or pack of batteries) is stationary (e.g., it is not mounted for being moved forward and rearward in the AUV and, thereby, is typically not used as a movable mass for pitching the nose of the AUV **20** up and down). That is, solely or substantially solely the side fins **40** are used for pitch control. Other means (e.g., conventional means) for controlling the pitch of the AUV **20** may alternatively be used.

Examples of methods of operating the AUV **20** are described in the following, in accordance with the first embodiment of this disclosure. The AUV **20** may be launched into the water **32** in any suitable manner. FIG. **7** is a flow diagram that provides a high level illustration of how the controller **28** (FIG. **1**) may control the operation of the AUV within the body of water **32**, in accordance with one example of the first embodiment. At block **620** of FIG. **7**, the controller **28** receives, such as by way of one or more of the operational components **70***a-n* (FIG. **1**), high-level information about the mission for the AUV **20** (e.g., information about the destination D (FIG. **5**), what is to be done at the destination, and any associated timeframe). This information may be received at any suitable time, such as before launching the AUV **20** or after the AUV has been launched (e.g., while the AUV is at the surface of the body of water and communicating by way of an antenna (not shown) that extends above the surface). For example, the high-level information about the mission for the AUV **20** may have originated from a human user, or the like, and these instructions may be received by the AUV by way of a computer interface, radio frequency signals, antennas and/or any other suitable methods of communicating with the controller **28**. The high-level information received by the controller **28** about the mission for the AUV **20** may include any suitable information about desired parameters and/or instructions that dictate how the controller is to control operation of the AUV. Notwithstanding the receipt of high-level instructions at block **620**, typically the controller **28** is allowed to operate at least partially, substantially and/or totally autonomously to carry out the instructions received at block **620**.

After receiving the high-level information about the mission at block **620**, the controller **28** may operate autonomously/automatically (e.g., without receiving additional instructions from any human) through blocks **640**-**680** of the exemplary method schematically illustrated by FIG. **7**. At block **640**, the controller **28** obtains information, such as from one or more of the operational components **70***a-n*. For example, one or more of the operational components **70***a-n* may be for detecting information relevant to predetermined condition(s), and the controller **28** obtains or otherwise receives that information at block **640**. For example, the information obtained at block **640** may be indicative of external environmental conditions around the AUV **20** and/or indicative of the AUV monitoring itself. For example, the information obtained by the controller **28** at block **640** may be indicative of how much energy is contained in the AUV's power supply.

At block **660** of FIG. **7**, the information obtained at block **640** is analyzed by the controller **28** to determine whether any reaction may be necessary or helpful, such as for carrying out the instructions received at block **620**. If it is determined by the controller **28** at block **660** that no reaction is necessary or desired, then control is transferred back to block **640**. If it is determined by the controller **28** at block **660** that a reaction is necessary or desired, then control is transferred to block **680** of FIG. **7**.

At bock **680**, the controller **28** provides signals for adjusting one or more of the operating parameters of the AUV **20**, and thereafter control is returned to block **640**. For example, block **680** schematically illustrates that the controller **28** is operative for providing controlling signals to the buoyancy engine **24**, rotary propulsion system **26** and steering system **27** that cause the AUV **20** to automatically switch between modes of operation (e.g., the buoyancy, rotary propulsion and surface modes of operation) and at least generally steer the AUV (e.g., toward the destination D) in response to the detecting of the predetermined condition(s). That is, blocks **640**-**680** schematically illustrate an example of a method by which one or more of the operational components **70***a-n* detects predetermined condition(s), and the controller **28** provides signals that cause the AUV **20** to automatically switch between modes of operation (e.g., the buoyancy, rotary propulsion and surface modes of operation) and steer the AUV in response to the detecting of the predetermined condition(s).

Blocks **640**-**660** of FIG. **7** schematically illustrates that, while the AUV **20** is in the water **32**, the controller **28** may continually or periodically acquire data from respective operational components **70***a-n* (FIG. **1**) and analyze the data in view of mission-related information obtained at block **620**, to determine the mode of operation in which the AUV should be operating and the direction in which the AUV should be steered. Block **680** schematically illustrates that, in response to decisions made by the controller at block **660**, the controller **28** provides signals for operating the AUV **20** (e.g., the controller provides signals to the buoyancy engine **24**, rotary propulsion system **26** and/or the **27** steering system for controlling the operating of these features). The operations associated with blocks **640**-**680** may occur substantially simultaneously and continuously until the mission of the AUV **20** is completed or otherwise terminated. A few examples of methods resulting from operations associated with the controller

28/blocks **640-680** are described in the following, in accordance with the first embodiment of this disclosure.

As best understood with reference to FIGS. **7** and **5**, an initial occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to operate in the glider mode along section **38***a* of the path **30**. Thereafter, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to operate in the rotary propulsion mode along section **38***b* of the path **30**. Thereafter, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to operate in the glider mode along section **38***c* of the path **30**. Thereafter, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to operate in the surface mode at section **38***d* of the path **30**. Thereafter, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to operate in the glider mode along section **38***e* of the path **30**. Thereafter, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to operate in the rotary propulsion mode along section **384** of the path **30**. Thereafter, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** to cease propelling itself when the AUV reaches the destination D. Thereafter or simultaneously, an occurrence of the operations associated with blocks **640-680** may cause the AUV **20** perform any suitable operation (e.g., any one or more operations that are conventionally performed by AUVs) while the AUV is at the destination D.

During the rotary propulsion mode, the motor **58** is operated to rotate the propeller **60** to provide thrust, and thereby cause the AUV **20** to move forward in the water **32**. During the glider mode, the buoyancy engine **24** operated so that the ballast chamber **41** alternately ingests and expels water **32** to change the mass of the AUV **20** and thereby cause the AUV to alternately descend and ascend in the water, and the side fins **40** are pivoted to change the pitch of the AUV, so that the AUV moves forward while alternately descending and ascending in the water.

Reiterating from above and in accordance with one example of processes that occur by way of blocks **640-680** of FIG. **7** while the AUV **20** is, operating, the controller **28** is operative in conjunction with one or more of the operational components **70***a-n* to detect a predetermined condition, and then provide a signal for causing switching between the buoyancy and rotary propulsion modes of operation in response to the detecting of the predetermined condition. In accordance with the present example, the switching comprises changing from one of the buoyancy and rotary propulsion modes of operation to the other of the buoyancy and rotary propulsion modes of operation.

In a more specific example of a method of operating that may result from passing through blocks **640-680** of FIG. **7**, the controller **28** provides signals for switching from the glider mode to the rotary propulsion mode in response to the controller **28** operating in conjunction with one or more of the operational components **70***a-n* to determine that the forward speed of the AUV **20** is below a predetermined value, the depth of the body of water **32** is below a predetermined value, and/or risk of a collision between the AUV and an object (e.g., a fishing trawler) exceeds a predetermined threshold. One of ordinary skill in the art will understand that it is conventional/not novel per se for a water vehicle to include operational components for determining the forward speed of the water vehicle, the depth of a body of water, and whether the risk of a collision between the water vehicle and another object exceeds a threshold. For example, conventional collision avoidance systems may work in conjunction with a water vehicle's radar or sonar system. More specifically, active systems using sonar are known for estimating the distance or range to an object or to a point on an object. Such systems may also be used to estimate velocity by differentiating the range, or by using the Doppler effect. The ratio of distance to velocity may then be used to estimate the time to contact. Examples of sonar-based collision avoidance systems are disclosed in U.S. Patent Application Publication Nos. 2009/0292468, 2009/0259401, 2009/0259400 and 2008/0024356, each of which is incorporated herein by reference, in its entirety.

In another specific example of a method of operating that may result from passing through blocks **640-680** of FIG. **7**, the controller **28** provides signals for switching from the rotary propulsion mode to the glider mode in response to the controller operating in conjunction with one or more of the operational components **70***a-n* to determine that any current that flows against the forward movement of the AUV **20** (e.g., a head-current that flows against the forward direction of travel of the AUV) is below a predetermined value, the time until arrival at the destination D is below a predetermined value, and/or the power (e.g., the remaining charge on the batteries **70***a*) available for operating the rotary propulsion system **26** is below a predetermined value.

In another example of a method of operating that may result from passing through blocks **640-680** of FIG. **7**, the controller **28** provides signals for switching from any one of the rotary propulsion mode and the glider mode to the surface mode. In this particular example, the switching may occur in response to the controller **28** operating in conjunction with one or more of the operational components **70***a-n* to determine that the power (e.g., the remaining charge on the batteries **70***a*) available is below a predetermined value or that at predetermined period of time has lapsed since the AUV **20** was last in the surface mode, such as for receiving instructions or other information at block **620** of FIG. **7**. For example, any time the AUV **20** is in the surface mode, an antenna (not shown) of the AUV may extend, or may be extended, above the surface of the body of water **32** for the purpose of communicating with other device(s) such as, but not limited to, navigations systems (e.g., space-based global navigation satellite systems such as the Global Positioning System (GPS)) other water vessels or land-based navigation or communication systems, or the like. It is conventional/not novel per se for an antenna (not shown) of an AUV to extend above the surface of a body of water while the AUV is proximate the surface of the body of water.

During both the buoyancy and the rotary propulsion modes, the actuators **66** (FIG. **4**) may be operated to move the fins **40**, **64** in a manner that steers the AUV **20** through the water **32** toward the destination D or toward other locations, such as in response to signals that are provided by the controller **28** (e.g., the autopilot module of or associated with the controller) at block **680** of FIG. **7**. More specifically, during both the buoyancy and the rotary propulsion modes the top fin **64** may be pivoted in either direction relative to the hull **22** of the AUV **20** to steer the AUV right or left, respectively. Also during both the buoyancy and the rotary propulsion modes (e.g., throughout both the buoyancy and the rotary propulsion modes), the side fins **40** may be pivoted in either direction relative to the hull **22** of the AUV **20** to adjust the pitch of the AUV. More specifically and for example, the operating of the AUV **20** in the glider mode includes pivoting the side fins **40** (e.g., pitch control surfaces) of the AUV relative to the hull **22** of the AUV and, thereby, adjusting the pitch of the AUV while the AUV is moving forward in the body of water **32**. For example, the controller **28** may be operative by way of a method comprising blocks **640-680** of FIG. **7** for providing signals at block **680** that result in pivoting of the side fins **40** in either direction relative to the hull **22** to adjust the pitch of the AUV during any portion of (e.g., during the entirety of) both an ascending portion of the buoyancy mode and a descending portion of the buoyancy mode to control the trajectory of the AUV in a manner that optimizes its performance (e.g., in a manner that increases speed and/or reduces energy consumption).

In this regard, each of the side fins **40** may be pivoted between numerous positions including inclined and declined configurations that are respectively schematically shown in FIGS. **8** and **9** for a representative one of the side fins. In the inclined configuration, the top surface of each of the side fins **40** is more forward-facing than the bottom surface of the side fin. In the declined configuration the bottom surface of each of the side fins **40** is more forward-facing than the top surface of the side fin. The side fins **40** may be in the inclined configuration (e.g., see FIG. **8**) during both: the glider mode while the AUV **20** is descending and moving forward; and the rotary propulsion mode while the AUV is ascending and moving forward. The side fins **40** may be in the declined configuration (e.g., see FIG. **9**) during both the glider mode while the AUV **20** is ascending and moving forward; and the rotary propulsion mode while the AUV is descending and moving forward. That is and in accordance with a method of operating that may result from repeatedly passing through blocks **640-680** of FIG. **7**, the trim angle of the AUV **20** may be continually adjusted in real-time by adjusting the positions of the side fins **40** in response to detected operating conditions such as depth of the AUV, speed of the AUV, depth of the body of water **32** and/or salinity (density) of the water **32**. In this manner, the endurance of the AUV **20** may be optimized, since endurance is a function of the trim angle of the AUV and the life of the battery **70***a*. That is and in accordance with a method of operating that may result from repeatedly passing through blocks **640-680** of FIG. **7**, endurance may be increased by reducing power consumption. As another example, and in accordance with a method of operating that may result from repeatedly passing through blocks **640-680** of FIG. **7**, the trim angle of the AUV **20** may be continually adjusted in real-time by adjusting the positions of the side fins **40**, in order to optimize the speed of the AUV **20** in the glider mode and/or the rotary propulsion mode.

One of ordinary skill will understand that a change in salinity (i.e., a change in the amount of salt present in the water **32** and a change in the water's density) may occur during the course of a mission (e.g., when traveling from the ocean into a river). The amount of salinity impacts the buoyancy of the AUV **20** and its trim. In another example of a method of operating that may result from repeatedly passing through blocks **640-680** of FIG. **7**, the controller **28** may be operative for optimizing the buoyancy of the AUV **20** and its trim in response to water salinity in real-time.

The controller **28** typically includes or is otherwise associated with one or more computer-readable mediums (e.g., nonvolatile memory and/or volatile memory such as, but not limited to, flash memory, tapes and hard disks such as floppy disks and compact disks, or any other suitable storage devices) having computer-executable instructions (e.g., one or more software modules or the like), with computer(s) handling (e.g., processing) the data in the manner indicated by the computer-executable instructions. Accordingly, aspects of FIGS. **1**, **5** and **7** can be characterized as respectively being schematically illustrative of the computer-readable mediums, computer-executable instructions and other features of methods and systems of the exemplary embodiments of this disclosure.

The internal components of the AUV **20** may be mounted in any suitable manner. For example, they may be mounted to (e.g., within) the body (e.g., hull **22**) of the AUV **20**, such as by way of any suitable internal supports (e.g., bulkheads, mounting brackets, struts, or the like, that are not shown in the figures). One or more of the components that are typically internal to the AUV **20** may, alternatively, be external components, which may be mounted to the exterior of the hull **22** or in any other suitable manner.

Whereas the AUV **20** of has been described as including one of each of the buoyancy engine **24** and the rotary propulsion system **26**, the AUV may include two or more buoyancy engines, two or more rotary propulsion systems and/or two or more of any of the components of the buoyancy engine and/or the rotary propulsion system if desired (e.g., for purposes of redundancy). Similarly, whereas some specific types and arrangements of propulsion systems (e.g., the buoyancy engine **24** and the rotary propulsion system **26**) are described herein, any suitable arrangements and/or types of propulsion systems may be used in the AUV **20**.

The second embodiment of this disclosure is like the first embodiment, except for variations noted and variations that will be apparent to one of ordinary skill in the art; therefore, reference numerals for at least somewhat alike features are incremented by one hundred. FIGS. **10-12** are each schematic side elevation views of an AUV **120** that is described in the following, in accordance with the second embodiment. In FIGS. **10-12**, the AUV's internal buoyancy engine **124** (e.g., ballast system) is shown in dashed lines, and the center of buoyancy **101** and the center of mass **102** are also schematically shown. FIG. **13** is a schematic cross-sectional view of a middle portion of (e.g., the buoyancy engine **124** of) the AUV **120**, with the cross-section taken substantially along lines **13-13** of FIG. **10**.

As best understood with reference to FIG. **13**, the buoyancy engine's cylinder **142** has opposite ends that are fully closed, and there are two pistons **143***a*, **143***b* within the cylinder. A single liquid chamber **145** is between the pistons **143***a*, **143***b*, within the cylinder **142**. Within the cylinder **142**, gas chambers **144***a*, **144***b* are respectively between the opposite ends of the cylinder and the pistons **143***a*, **143***b*. Each of the gas chambers **144***a*, **144***b* is fully closed. Although the pressure within the gas chambers **144***a*, **144***b* changes in response to movement of the pistons **143***a*, **143***b*, the pistons move substantially symmetrically with respect to one another so that the pressure within the gas chamber **144***a* is substantially always substantially equal to the pressure within the gas chamber **144***b*.

A single bladder **147** encircles the cylinder **142** and is within the ballast chamber **141** defined between the exterior of the cylinder **142** and the interior of the hull **122**, although there could be more than one bladder and/or the bladder may be differently configured. Each of the liquid chamber **145** and the bladder **147** is closed, except for being open to one another by way of a passageway **146** (e.g., tube(s), pipe(s) or any other suitable means for fluid communication) having opposite ends that are respectively open to the bladder **147** and the liquid chamber **145**.

The pistons **143***a*, **143***b* may be synchronously reciprocated by any suitable devices such as, but not limited to, a hydraulic system for changing the volume of the liquid chamber **145**. The hydraulic system operates so that the pistons **143***a*, **143***b* move in response to changes in pressure between the liquid chamber **145** and the gas chambers **144***a*, **144***b*. More specifically, the hydraulic system is schematically shown in FIG. **13** as including a motor-driven pump **103** that is positioned between two parts of the passageway **146**. The motor of the motor-driven pump **103** may be a direct current, electric motor, and the motor may include or otherwise be linked to gears for stepping up or stepping down the motor's output.

The motor-driven pump **103** is operated in a first direction to pump liquid (e.g., oil) from the liquid chamber **145** to the bladder **147**, so that the pistons **143***a*, **143***b* move toward one another, and the bladder **147** expands to expel water **32** from the ballast chamber **141**, so that the AUV **120** may ascend. The motor-driven pump **103** is operated in an opposite, second direction (or otherwise valves (not shown) are operated to redirect the flow) to pump the liquid (e.g., oil) from the bladder **147** to the liquid chamber **145**, so that the pistons **143***a*, **143***b* move away from one another, and the bladder **147** contracts so that water **32** is drawn into the ballast chamber **141**, so that the AUV **120** may descend. One or more position sensors (not shown) may be respectively associated with the pistons **143***a*, **143***b*, for providing feedback that is used in controlling the motor-driven pump **103** (e.g., to turn the pump **103** off in response to the pistons having travelled to a predetermined position). The sensors may be respectively embedded in the pistons **143***a*, **143***b* for providing feedback for piston position within the cylinder **142**, for providing precision control over operation of the buoyancy engine **124**.

In accordance with the second embodiment, the pistons **143***a*, **143***b* are positioned and move concertedly so that the position of the center of mass **102** of the AUV **120** does not change (e.g., substantially does not change) with respect to the center of buoyancy **101** throughout all of the modes of operation of the second AUV. More specifically, the center of mass **102** and the center of buoyancy **101** of the AUV **120** may be at the same longitudinal position (e.g., substantially the same longitudinal position) along the length of the AUV **120** throughout all of the modes of operation of the AUV. For example, in FIG. **10** the AUV **120** has a pitch angle of about zero degrees, in FIG. **11** the AUV has a pitch angle of about positive ten degrees, and in FIG. **12** the AUV has a pitch angle of about negative ten degrees, and the location of the center of mass **102** remains substantially unchanged throughout FIGS. **10**-**12** (e.g., there is substantially no shift in the center of mass). The dual-piston buoyancy engine **124** may be characterized as being a self-contained, single unit, symmetrical-hydro-pneumatic buoyancy engine that provides the AUV **120** with a stable-fixed-point center of gravity (e.g., a stable center of gravity—zero shift in the center of gravity).

In accordance with the second embodiment, the AUV **120** has a stable center of gravity during changes in buoyancy and water salinity, due to the travel of the pistons **143***a*, **143***b* being symmetric as the volume of the liquid chamber **145** is either increased or decreased. The travel of the pistons **143***a*, **143***b* is symmetric because the air compression in the gas chambers **144***a*, **144***b* is uniform and equal. The oil in the hydraulic system (i.e., the oil in the liquid chamber **145**, bladder **147**, passageway **146** and pump **103**) may have a specific gravity of 0.92, which is very close to the specific gravity of saltwater, which is 1.025. When the oil is pumped from the bladder **147** to the liquid chamber **145** the reduced volume of the bladder is replaced by seawater in the ballast chamber **141**. As a result, the system is balanced as any ballast weight is changed symmetrically fore and aft from the center of the cylinder **142**.

Also, by changing the net buoyancy of the AUV **120** with the buoyancy engine **124** and adjusting the side fins **140** accordingly, the AUV may rise and dive symmetrically (i.e., while remaining horizontal) at a zero horizontal speed, without operating the rotary propulsion system. This seeks to avoid (e.g., preclude) surface capture. Surface capture is a condition in which an underwater glider develops enough speed for its rear fins to pitch the nose down, and the positive buoyancy lifts the vehicle's aft end with the fins and propeller above the surface of the water so that propeller propulsion and fin control are lost. Stated differently, surface capture is the loss of propulsion and fin control due to vehicle buoyancy lifting the aft section of the vehicle into the air when the vehicle attempts to dive off (i.e., below) the water surface.

The third embodiment of this disclosure is like the second embodiment, except for variations noted and variations that will be apparent to one of ordinary skill in the art. The rotary propulsion system **126** is omitted from the AUV of the third embodiment.

It will be understood by those skilled in the art that while the present disclosure has been discussed above with reference to exemplary embodiments, various additions, modifications and changes can be made thereto without departing from the spirit and scope of the invention as set forth in the claims.

What is claimed is:

1. An autonomous unmanned underwater vehicle ("AUV") for traveling in a body of water, the AUV comprising:
- a body comprising a hull;
- a buoyancy engine carried by the body, wherein the AUV has mass, and the buoyancy engine is for alternately ingesting and expelling the water to change the mass of the AUV and thereby cause the AUV to alternately descend and ascend in the water, and wherein the buoyancy engine comprises a reciprocating piston;
- at least one pitch control surface carried by the body for causing the AUV to move forward while alternately descending and ascending in the water;
- a rotary propulsion system carried by the body and including an electric motor for rotating a rotary agitator in the water to provide thrust, and thereby cause the AUV to move in the water, wherein the rotary agitator includes at least one of a propeller and an impeller; and
- a controller operative for responsively, automatically switching between at least
  - a glider mode in which the buoyancy engine and the at least one pitch control surface are cooperative for causing the AUV to move forward while alternately descending and ascending, and
  - a rotary propulsion mode in which the rotary propulsion system is operative for causing the AUV to move forward.

2. The AUV of claim **1**, wherein:
- the rotary propulsion system is not operative during the glider mode; and
- the buoyancy engine is not operative during the rotary propulsion mode.

3. The AUV of claim **1**, comprising an actuator, wherein:
- the at least one pitch control surface comprises a fin that projects laterally, outwardly from the hull,
  - is pivotable relative to the body of the AUV for adjusting pitch of the AUV, and
  - has opposite top and bottom surfaces;
- the actuator is operatively connected to the fin for pivoting the fin and thereby adjusting pitch of the AUV; and
- the controller is operative for controlling the actuator to pivot the fin between a plurality of positions including
  - an inclined configuration in which the top surface of the fin is more forward-facing than the bottom surface of the fin, and
  - a declined configuration in which the bottom surface of the fin is more forward-facing than the top surface of the fin.

4. The AUV of claim 3, wherein the controller is operative so that:

the fin is in the inclined configuration during both

the glider mode while the AUV is descending and moving forward, and

the rotary propulsion mode while the AUV is ascending and moving forward; and

the fin is in the declined configuration during both

the glider mode while the AUV is ascending and moving forward, and

the rotary propulsion mode while the AUV is descending and moving forward.

5. The AUV of claim 1, wherein:

the AUV has a center of buoyancy when submerged in water;

the hull defines a centroid that is the center of buoyancy of the AUV when the AUV is submerged in the water;

the AUV has a mass and a center of mass; and

the buoyancy engine is operative to move the center of mass of the AUV relative to the center of buoyancy of the AUV.

6. The AUV of claim 5, wherein the buoyancy engine is operative to move the center of mass of the AUV:

forward of the center of buoyancy of the AUV during the descending of the AUV; and

rearward of the center of buoyancy of the AUV during the ascending of the AUV.

7. The AUV of claim 1, wherein the rotary agitator includes the propeller, and the propeller extends from a rear end of the hull.

8. A method of operating an autonomous unmanned underwater vehicle ("AUV") in a body of water, comprising:

operating the AUV in a glider mode, comprising operating a buoyancy engine of the AUV to cause the AUV to move forward in the body of water while alternately descending and ascending in the body of water;

operating the AUV in rotary propulsion mode, comprising operating a rotary propulsion system of the AUV to cause the AUV to move forward in the body of water;

detecting a predetermined condition, wherein the predetermined condition comprises at least one condition selected from the group consisting of

forward speed of the AUV being below a predetermined value,

depth of the body of water being below a predetermined value, and

risk of a collision between the AUV and an object exceeding a threshold; and

switching from the glider mode to the rotary propulsion mode in response to the detecting of the predetermined condition, wherein the switching comprises changing from the glider mode to the rotary propulsion mode.

9. The method of claim 8, wherein the operating the AUV in the glider mode further comprising pivoting a pitch control surface of the AUV relative to a hull of the AUV during the glider mode and, thereby, adjusting pitch of the AUV while the AUV is moving forward in the body of water.

10. The method of claim 8, wherein the predetermined condition is a first predetermined condition, and the method comprises:

detecting a second predetermined condition; and

switching from the rotary propulsion mode to the glider mode in response to the detecting of the second predetermined condition.

11. The method of claim 10, wherein the second predetermined condition comprises at least one condition selected from the group consisting of:

any current that flows against the forward movement of the AUV being below a predetermined value;

a time until arrival at a destination being below a predetermined value; and

power available for operating the rotary propulsion system being below a predetermined value.

12. The method of claim 8, wherein:

the operating of the buoyancy engine comprises alternately ingesting water from the body of water into the AUV and expelling water from the AUV to the body of water to change mass of the AUV and, thereby, cause the AUV to alternately descend and ascend in the body of water; and

the operating of the rotary propulsion system comprises rotating a rotary agitator in the water to provide thrust and, thereby, cause the AUV to move forward in the body of water.

13. The method of claim 8, further comprising operating the AUV in a surface mode, comprising expelling water from the AUV to the body of water to decrease mass of the AUV and, thereby, cause the AUV ascend to a surface of the body of water.

14. An autonomous unmanned underwater vehicle ("AUV") for traveling in a body of water, the AUV comprising:

a body comprising a hull;

a buoyancy engine carried by the body, wherein the AUV has mass, and the buoyancy engine is for alternately ingesting and expelling the water to change the mass of the AUV and thereby cause the AUV to alternately descend and ascend in the water;

at least one pitch control surface carried by the body for causing the AUV to move forward while alternately descending and ascending in the water, wherein the at least one pitch control surface comprises a fin that

projects laterally, outwardly from the hull,

is pivotable relative to the body of the AUV for adjusting pitch of the AUV, and

has opposite top and bottom surfaces;

an actuator operatively connected to the fin for pivoting the fin and thereby adjusting pitch of the AUV;

a rotary propulsion system carried by the body and including a motor for rotating a rotary agitator in the water to provide thrust, and thereby cause the AUV to move in the water, wherein the rotary agitator includes at least one of a propeller and an impeller; and

a controller operative for responsively, automatically switching between at least

a glider mode in which the buoyancy engine and the at least one pitch control surface are cooperative for causing the AUV to move forward while alternately descending and ascending, and

a rotary propulsion mode in which the rotary propulsion system is operative for causing the AUV to move forward,

wherein the controller is operative for controlling the actuator to pivot the fin between a plurality of positions including

an inclined configuration in which the top surface of the fin is more forward-facing than the bottom surface of the fin, and

a declined configuration in which the bottom surface of the fin is more forward-facing than the top surface of the fin.

15. The AUV of claim 14, wherein the controller is operative so that:
the fin is in the inclined configuration during both
the glider mode while the AUV is descending and moving forward, and
the rotary propulsion mode while the AUV is ascending and moving forward; and
the fin is in the declined configuration during both
the glider mode while the AUV is ascending and moving forward, and
the rotary propulsion mode while the AUV is descending and moving forward.

16. An autonomous unmanned underwater vehicle ("AUV") for traveling in a body of water, the AUV comprising:
a body comprising a hull, wherein the AUV has a center of buoyancy when submerged in water, and the hull defines a centroid that is the center of buoyancy of the AUV when the AUV is submerged in the water;
a buoyancy engine carried by the body, wherein
the AUV has mass, and the buoyancy engine is for alternately ingesting and expelling the water to change the mass of the AUV and thereby cause the AUV to alternately descend and ascend in the water, and
the AUV has a center of mass and the buoyancy engine is operative to move the center of mass of the AUV relative to the center of buoyancy of the AUV;
at least one pitch control surface carried by the body for causing the AUV to move forward while alternately descending and ascending in the water;
a rotary propulsion system carried by the body and including a motor for rotating a rotary agitator in the water to provide thrust, and thereby cause the AUV to move in the water, wherein the rotary agitator includes at least one of a propeller and an impeller; and
a controller operative for responsively, automatically switching between at least
a glider mode in which the buoyancy engine and the at least one pitch control surface are cooperative for causing the AUV to move forward while alternately descending and ascending, and
a rotary propulsion mode in which the rotary propulsion system is operative for causing the AUV to move forward.

17. The AUV of claim 16, wherein the buoyancy engine is operative to move the center of mass of the AUV:
forward of the center of buoyancy of the AUV during the descending of the AUV; and
rearward of the center of buoyancy of the AUV during the ascending of the AUV.

18. A method of operating an autonomous unmanned underwater vehicle ("AUV") in a body of water, comprising:
operating the AUV in a glider mode, comprising operating a buoyancy engine of the AUV to cause the AUV to move forward in the body of water while alternately descending and ascending in the body of water;
operating the AUV in rotary propulsion mode, comprising operating a rotary propulsion system of the AUV to cause the AUV to move forward in the body of water;
detecting a predetermined condition, wherein the predetermined condition comprises at least one condition selected from the group consisting of
any current that flows against the forward movement of the AUV being below a predetermined value,
a time until arrival at a destination being below a predetermined value, and
power available for operating the rotary propulsion system being below a predetermined value; and
switching from the rotary propulsion mode to the glider mode in response to the detecting of the predetermined condition, wherein the switching comprises changing from the rotary propulsion mode to the glider mode.

19. The method of claim 18, wherein the operating the AUV in the glider mode further comprising pivoting a pitch control surface of the AUV relative to a hull of the AUV during the glider mode and, thereby, adjusting pitch of the AUV while the AUV is moving forward in the body of water.

20. The method of claim 18, wherein:
the operating of the buoyancy engine comprises alternately ingesting water from the body of water into the AUV and expelling water from the AUV to the body of water to change mass of the AUV and, thereby, cause the AUV to alternately descend and ascend in the body of water; and
the operating of the rotary propulsion system comprises rotating a rotary agitator in the water to provide thrust and, thereby, cause the AUV to move forward in the body of water.

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