

AUTONOMOUS UNDERWATER VEHICLE

5 The present invention relates to an autonomous underwater vehicle for performing subsea operations, methods of performing subsea operations using an autonomous underwater vehicle, methods of navigating autonomous underwater vehicles between sea level and a seabed, and methods of collecting subsea data using an autonomous underwater vehicle.

Autonomous underwater vehicles (AUVs) are used for various purposes, and can take many forms and sizes to fulfil their particular function.

10 Some AUVs are adapted for surveying purposes, e.g. mapping and monitoring of subsea structures. AUVs for this purpose typically have an elongate cylindrical shape with a propeller at the rear end to propel the AUV through the water. A number of control surfaces, such as fins or rudders, are provided along the surface of the AUV for steering. These AUVs usually require speed in the forward direction in order for their control surfaces to steer the AUV.

15 The propeller generates a roll torque that could undesirably cause the AUV to rotate about its roll axis. Conventional AUVs are generally bottom-heavy to maintain a roll angle of around zero degrees about their roll axis.

Other known AUVs include hovering-type AUVs which do not require constant forward motion, and can hold their position in water. Sizes of such AUVs vary from small and light, for example with weights of a few kilograms, to very large and heavy, for example on the order of 2,000kg. It can be impractical to use large AUV systems in some circumstances due to the difficulties of transporting and manipulating the vehicle.

25 Reliable and accurate control of AUVs is particularly important for AUVs adapted for surveying purposes, since the AUV should be suitably positioned during subsea operations to gather data associated with surveying the seabed.

It is therefore desired to provide an AUV which has improved manoeuvring and positioning capabilities.

30 Viewed from a first aspect of the present invention, there is provided an autonomous underwater vehicle, AUV, for performing subsea operations, comprising: a hull comprising a nose end and a tail end; a propulsion mechanism configured to propel the AUV; and an internal ballast located in the hull; wherein the propulsion mechanism comprises a pair of counter-rotating propellers, the rotational speed of each propeller being independently controllable; and wherein the AUV

35

comprises an internal ballast positioning mechanism configured to controllably move the internal ballast relative to the hull.

By using a pair of counter-rotating propellers, roll torques generated by each propeller may cancel out when the propellers are operated at the same rotational speed. Accordingly, the use of a pair of counter-rotating propellers can improve the roll control of the AUV by mitigating against the generation of undesirable roll torque during propulsion of the AUV. The use of a pair of counter-rotating propellers may also negate the need for additional control surfaces associated with mitigating undesirable roll torques induced by a propeller. Further, where it is desirable to adjust a rotational orientation of the AUV about its roll axis, the rotational speeds can be asymmetrically controlled since their respective speeds are independently controllable, providing further roll control for the AUV.

The internal ballast positioning mechanism may also provide further roll control for the AUV, such that the AUV can also be oriented in any desired orientation about its roll axis. The weight of the internal ballast will align the AUV with respect to the direction of gravity, and as such moving the internal ballast relative to the hull can result in the hull effectively moving about the roll axis.

Moreover, the combined and selective use of both the pair of counter-rotating propellers and the internal ballast positioning mechanism may provide improved roll control for the AUV across the breadth of its subsea operations. For example, the combined use of the independently controllable propellers and the internal ballast positioning mechanism can cause a swifter and more reactive roll control if required, providing the AUV with greater manoeuvrability. Further, in situations where one form of roll control is less suited for use the other may be able to compensate such that the AUV maintains full roll control capabilities at all times during subsea operations. For example, roll control through use of the pair of counter-rotating propellers may be more suited in situations where the AUV is ascending and/or descending, whilst roll control through use of the internal ballast positioning mechanism may be more suited in situations where the AUV is travelling in a generally horizontal, or not far-from horizontal, orientation.

Accordingly, the provision of the internal ballast positioning mechanism and the pair of counter-rotating propellers in combination may provide improved roll control for the AUV.

The AUV may comprise a steering mechanism configured to rotate the propulsion mechanism in at least one of a pitch and a yaw direction, relative to the hull.

5 Using the steering mechanism to provide pitch and yaw control to the propulsion mechanism may also provide greater and more responsive control for the AUV. For example, actuating the steering mechanism such that the propulsion mechanism is greatly offset to the longitudinal axis of the hull provides a tighter turning circle for the AUV in water, thereby improving its manoeuvrability.

10 Since the AUV does not require control surfaces to induce steering due to the presence of the steering mechanism, and further since no control surfaces are required to counteract roll torques introduced by the propellers, the AUV need not experience drag forces associated with the presence of said control surfaces. The AUV may therefore have an improved hydrodynamic profile, reducing drag it may experience and further improving the manoeuvrability of the AUV as a result.

15 Viewed from a second aspect of the present invention, there is provided an autonomous underwater vehicle, AUV, for performing subsea operations, comprising: a hull comprising a nose end and a tail end; a propulsion mechanism configured to propel the AUV, wherein the propulsion mechanism comprises a pair of counter-rotating propellers, the rotational speed of each propeller being
20 independently controllable; and a steering mechanism configured to rotate the propulsion mechanism in at least one of a pitch and a yaw direction, relative to the hull.

 By using a pair of counter-rotating propellers, roll torques generated by each propeller may cancel out when the propellers are operated at the same rotational
25 speed. Accordingly, the use of a pair of counter-rotating propellers can improve the roll control of the AUV by mitigating against the generation of undesirable roll torque during propulsion of the AUV. The use of a pair of counter-rotating propellers may also negate the need for additional control surfaces associated with mitigating undesirable roll torques induced by a propeller. Further, where it is desirable to
30 adjust a rotational orientation of the AUV about its roll axis, the rotational speeds can be asymmetrically controlled since their respective speeds are independently controllable, providing further roll control for the AUV.

 Using the steering mechanism to provide pitch and yaw control to the propulsion mechanism may also provide greater and more responsive control for
35 the AUV. For example, actuating the steering mechanism such that the propulsion

mechanism is greatly offset to the longitudinal axis of the hull provides a tighter turning circle for the AUV in water, thereby improving its manoeuvrability.

5 Since the AUV does not require control surfaces to induce steering due to the presence of the steering mechanism, and further since no control surfaces are required to counteract roll torques introduced by the propellers, the AUV need not experience drag forces associated with the presence of control surfaces. The AUV may therefore have an improved hydrodynamic profile, reducing drag it may experience and further improving the manoeuvrability of the AUV as a result.

10 The AUV may comprise: an internal ballast located in the hull; and an internal ballast positioning mechanism configured to controllably move the internal ballast relative to the hull.

15 The internal ballast positioning mechanism may also provide further roll control for the AUV, such that the AUV can also be oriented in any desired orientation about its roll axis. The weight of the internal ballast will align the AUV with respect to the direction of gravity, and as such moving the internal ballast relative to the hull can result in the hull effectively moving about the roll axis.

20 Moreover, the combined and selective use of both the pair of counter-rotating propellers and the internal ballast positioning mechanism may provide improved roll control for the AUV across the breadth of its subsea operations. For example, the combined use of the independently controllable propellers and the internal ballast positioning mechanism can cause a swifter and more reactive roll control if required, providing the AUV with greater manoeuvrability. Further, in situations where one form of roll control is less suited for use the other may be able to compensate such that the AUV maintains full roll control capabilities at all times

25 during subsea operations. For example, roll control through use of the pair of counter-rotating propellers may be more suited in situations where the AUV is ascending and/or descending, whilst roll control through use of the internal ballast positioning mechanism may be more suited in situations where the AUV is travelling in a generally horizontal, or not far-from horizontal, orientation.

30 Accordingly, the provision of the internal ballast positioning mechanism and the pair of counter-rotating propellers in combination may provide improved roll control for the AUV.

The following features may be features of the AUV of the first aspect and/or the second aspect of the present invention.

A longitudinal axis of the hull generally extends between the nose end and the tail end, i.e. in a forward-aft direction of the AUV. Generally, in use, the nose end defines a forward-facing end of the AUV during forward propulsion of the AUV. The AUV may roll about the longitudinal axis. That is, the roll axis of the AUV may and the longitudinal axis of the AUV are generally identical.

The AUV may also comprise a port side and a starboard side. The hull may comprise a transverse axis extending between the port side and the starboard side, i.e. in a left-right direction of the AUV. The AUV may pitch about the transverse axis. That is, the pitch axis of the AUV and the transverse axis of the AUV are generally identical.

The AUV may also comprise a top side and a bottom side. The hull may comprise a vertical axis extending between the top side and the bottom side, i.e. in an up-down direction of the AUV. The AUV may yaw about the vertical axis. That is, the yaw axis of the AUV and the vertical axis are generally identical.

The propulsion mechanism may comprise two or more pairs of counter-rotating propellers, the rotational speed of each propeller being independently controllable.

The propulsion mechanism may be located at the tail end of the hull. The steering mechanism may connect the propulsion mechanism to the hull.

The internal ballast positioning mechanism may be configured to rotate the internal ballast relative to the hull, e.g. about the longitudinal axis or roll axis of the hull. The internal ballast positioning mechanism may comprise a motor configured to rotate the internal ballast relative to the hull.

The internal ballast and the internal ballast positioning mechanism may be located towards the tail end of the hull. The internal ballast and the internal ballast positioning mechanism may be located adjacent to the propulsion mechanism.

The steering mechanism may comprise an active joint configured to rotate the propulsion mechanism. The active joint may be any one of: a cardan joint; a motorised ball joint; a pneumatic actuator; an electric actuator; or a hydraulic actuator.

The steering mechanism may comprise a bellows extending between the hull and the propulsion mechanism, the bellows defining part of an exterior surface of the AUV.

The bellows may be an oil-filled bellows. Filling the bellows with oil may lubricate the active joint whilst also improving the pressure resistance of the bellows for subsea operations.

5 The AUV may comprise a pair of subsea surveying sensors located on opposing sides of the hull and configured to scan underwater surfaces or structures.

The pair of subsea surveying sensors may be diametrically opposed. Alternatively, the pair of subsea surveying sensors may be offset by less than 180 degrees. The pair of subsea surveying sensors may be arranged symmetrically
10 about the hull, i.e. such that each subsea surveying sensor of the pair is equally offset from a vertical axis of the AUV.

The pair of subsea surveying sensors may be a pair of sidescan sonar transducers located on opposing sides of the hull and each configured to emit a sonar beam. Each sidescan sonar transducer may extend in a forward-aft direction
15 of the AUV. The sonar beam may be a conical or fan-shaped beam.

The pair of subsea surveying sensors may be a pair of multibeam echosounders or a pair of cameras. The AUV may comprise multiple pairs of subsea surveying sensors.

The AUV may comprise a controller.

20 The controller may comprise a processor and a memory, and may be in wired or wireless communication with one or more components of the AUV. The memory may store computer-readable instructions which, when executed by the processor, causes the AUV to form one or more operations.

The controller may be in communication with the propulsion mechanism, the
25 controller being configured to control roll of the AUV using the pair of counter-rotating propellers.

The controller may be in communication with the internal ballast positioning mechanism, the controller being configured to control roll of the AUV using the internal ballast positioning mechanism.

30 The controller may be in communication with the steering mechanism, the controller being configured to control at least one of the pitch and the yaw of the AUV (e.g. relative to the hull) using the steering mechanism.

The controller may be in communication with the propulsion mechanism and the internal ballast positioning mechanism, the controller being configured to control

- 7 -

roll of the AUV using at least one of the pair of counter-rotating propellers and the internal ballast positioning mechanism.

5 The combined and selective control of both the pair of counter-rotating propellers and the internal ballast positioning mechanism may provide improved roll control for the AUV across the breadth of its subsea operations.

The controller may be configured to independently control the rotational speed of each propeller so as to control a roll of the AUV during substantially vertical ascent and/or descent of the AUV.

10 The controller may be configured to move the internal ballast relative to the hull using the internal ballast positioning mechanism so as to control the roll of the AUV when traversing along a seabed.

The controller may be in communication with the pair of subsea surveying sensors, the controller being configured to control the roll of the AUV, using at least one of the pair of counter-rotating propellers and the internal ballast positioning
15 mechanism, so as to scan an underwater surface or structure at least partially higher or lower than the AUV using the pair of subsea surveying sensors.

The direction in which the sensors scan underwater surfaces or structures is dependent on the orientation of the AUV, since the subsea surveying sensors are located on the sides of the hull (i.e. about the roll axis of the AUV). Accordingly, by
20 controlling the position of the AUV about its roll axis the scanning direction of the subsea surveying sensors can also be controlled, e.g. to aim at surfaces or structures higher or lower than the AUV (as well as level with the AUV). Controlling the scanning direction of the subsea surveying sensors may be of particular use when surveying inclined surfaces or structures of or on the seabed, since the
25 scanning direction can be aligned straight at said surfaces or structures

The controller may be in communication with the propulsion mechanism and the steering mechanism; the controller being configured to: control roll of the AUV by independently controlling the rotational speed of each propeller of the pair of counter-rotating propellers; and control at least one of the pitch and the yaw of the
30 AUV relative to the hull using the steering mechanism.

Using the steering mechanism to provide pitch and yaw control to the propulsion mechanism may also provide greater and more responsive control for the AUV.

The controller may be configured to control the steering mechanism and the propulsion mechanism such that the AUV is oriented in a substantially vertical orientation when descending to or ascending from a seabed.

5 When the AUV does not change in longitude and latitude when diving, it may be easier to determine the position of the AUV when performing subsea operations. For example, when ascending or descending from a seabed with the AUV in a substantially vertical orientation, the longitude and latitude of the AUV may not change, or may be negligible. Further, the use of the steering mechanism in combination with the use of the pair of counter-rotating propellers may enable the
10 AUV to move via a tighter turning circle, minimising any positional drift as it moves to ascend from, or descend to, the seabed in the substantially vertical orientation. This may improve the accuracy and reliability of the navigational capabilities of the AUV.

The AUV may be considered to be in a substantially vertical orientation
15 when the forward-aft direction of the AUV is substantially aligned with the direction of gravity. The substantially vertical orientation is therefore substantially perpendicular to sea level (i.e. the surface of the sea on a global scale).

The controller may be configured to: determine an initial position of the AUV at sea level using a first sensor; operate the AUV such that the AUV dives from the
20 initial surface position to the seabed with the AUV in a substantially vertical orientation; operate the AUV to arrive towards the seabed at an initial subsea position; and use the initial surface position as the initial subsea position.

The AUV can be operated to dive from the initial surface position, and to arrive at the initial subsea position, using the propulsion mechanism and the
25 steering mechanism.

The first sensor may be a GPS sensor.

The controller may be configured to: operate the propulsion mechanism and the steering mechanism such that the AUV traverses the seabed; monitor motion of the AUV using a second sensor; and calculate the position of the AUV based on the
30 initial subsea position and the motion of the AUV.

The motion may include, or be, a velocity of the AUV.

The second sensor may be an acoustic sensor configured to monitor the velocity of the AUV, such as a Doppler Velocity Logger (DVL).

The second sensor may be an inertial navigation system (INS) configured to
35 monitor the acceleration and/or the angular velocity of the AUV.

The controller may be configured to: operate the AUV to ascend from a final subsea position to sea level with the AUV in a substantially vertical orientation; operate the AUV to arrive at sea level at a final surface position; and determine the final surface position of the AUV at sea level using the first sensor.

5 The AUV can be operated to ascend from the final subsea position, and to arrive at the final surface position, using the propulsion mechanism and the steering mechanism.

The AUV may comprise a hover module configured to propel the AUV in a direction substantially perpendicular to a forward-aft direction of the hull.

10 The hover module may comprise a first propeller and a second propeller oriented substantially perpendicular to one another.

The propellers of the hover module may be arranged to translate the AUV in the left-right direction (i.e. in a direction parallel to the transverse axis) and in the up-down direction (i.e. in a direction parallel to the vertical axis). One of the first and second propellers may be oriented in a transverse plane, and the other oriented in the vertical plane.

15 The AUV may comprise a pair of hover modules configured to propel the AUV in a direction substantially perpendicular to the hull; wherein a first hover module of the pair of hover modules is located towards the nose end of the hull and a second hover module of the pair of hover modules is located towards the tail end of the hull.

A first hover module of the pair of hover modules may be located towards the nose end of the AUV, and a second hover module of the pair of hover modules may be located towards the tail end of the AUV.

25 First propellers of the first and second hover modules may be located in the same plane. Second propellers of the first and second hover modules may be located in the same plane. The control of the first and second propellers oriented in the same plane can be symmetric or asymmetric.

30 The controller may be in communication with the hover module or the pair of hover modules, the controller being configured to operate the hover module or pair of hover modules such that the AUV propelled in a direction substantially perpendicular to the forward-aft direction of the hull.

The AUV may comprise a navigation module. The navigation module may include one or more sensors for controlling and/or monitoring a position of the AUV.

35 The navigation module may include the pair of subsea surveying sensors, or

various subsea surveying sensors. The navigation module may also comprise the DVL and/or the INS.

5 The AUV may comprise a communications module. The communications module may comprise the GPS sensor. The GPS sensor may be configured to monitor a position of the AUV.

The AUV may comprise a battery module. The battery module may be configured to provide a source of electrical power for the AUV.

10 The AUV may comprise a data storage module. The data storage module may be located in a side of the AUV. Locating the data storage module in a side of the AUV may result in the data storage module being more easily interchanged, i.e. removed and replaced, in the field.

The AUV may comprise a nose module. The nose module may be arranged to house a payload.

15 The AUV may have a mass of 40 to 80 kg.
Providing a lightweight AUV may result in the AUV being more convenient to transport to its launching location. For example, the AUV may be suitable for two people to carry, avoiding the need for complicated and expensive crane systems for transporting and moving the vehicle.

20 The hull may comprise two or more modular sections which are configured to be connected and disconnected from one another.

The modular sections may include one or more of: a propulsion module comprising the propulsion mechanism; an internal ballast module comprising the internal ballast and the internal ballast positioning mechanism; and a steering module comprising the steering mechanism.

25 The modular sections may also include one or more of: the hover module; the pair of hover modules; the navigation module; the communications module; the battery module; the data storage module; and the nose module.

30 Each modular section may have a mass that is less than 80 kg. Each section may have a mass that is less than 70kg, or less than 60kg, or less than 50kg. Typically, each section will have a mass of greater than 10kg, or greater than 20kg, or greater than 30kg.

35 A hull of each of the sections may be made of a metal, such as aluminium, or titanium. In other embodiments, a hull of each of the sections may be made of a composite material, but such materials are likely to be pressure rated only for depths of up to about 100 meters. The AUV may be understood as being 'modular'

by virtue of the plurality of sections (i.e., modules) that are connectable together to form the AUV. The AUV may therefore be referred to as a modular AUV.

One or more or each section may be rigid, i.e. it cannot bend or flex in normal use. This provides strength and resilience to the sections individually and to the assembled AUV (in particular the rigid hull) once the sections are connected together.

The hull may be formed by all the sections which are rigidly connected together (as opposed to sections that are connected by flexible joints, as discussed further below.)

One or more of the elongate sections may have a length-to-width ratio of at least 5 to 1, or at least 6 to 1, or at least 7 to 1, or at least 8 to 1, or at least 9 to 1, or at least 10 to 1. Each section may have a substantially cylindrical shape. This provides a streamlined shape for efficient movement through water.

A length of the autonomous underwater vehicle may be less than 3 meters, or less than 2.5 meters.

A length of each of the sections may be less than 3 meters, or less than 2.5 meters, or less than 2.2 meters, or less than 2 meters, or less than 1.5 meters. A length of each of the sections of the AUV may be greater than 30 cm. An AUV may comprise of at least two, or at least three sections. In one example a section may be about 100 cm long, have a radius of about 10 cm, being neutrally buoyant in water, have a weight (in air) of approx. 31 kg.

Each section of the hull may be individually pressure-rated.

The term "pressure rated" means that a section can be submerged to a particular depth (or pressure) within water without water ingress occurring. The depth may range from tens of meters to thousands of meters. The pressure rating may be at least 10 meters, or at least 100 meters. A typical pressure rating, e.g. for a portable section of 50-80 kgs, may be at least 500 meters, or at least 1000 meters.

Viewed from a third aspect of the present invention, there is provided a method of performing subsea operations using an autonomous underwater vehicle, AUV, as described according to the first aspect, the method comprising: controlling a roll of the AUV by independently controlling the rotational speed of each propeller of the pair of counter-rotating propellers; and controlling the roll of the AUV using the internal ballast positioning mechanism.

5 The method of the third aspect may have one or more or all features corresponding to those of the AUV of the first aspect. Thus, the above-description of the AUV of the first aspect, including but not limited to all technical advantages and alternative embodiments, may be equally applicable to the method of the third aspect.

The method may comprise independently controlling the rotational speed of each propeller of the pair of counter-rotating propellers during substantially vertical ascent and/or descent of the AUV.

10 The method may comprise moving the internal ballast relative to the hull using the internal ballast positioning mechanism so as to control the roll of the AUV when the AUV is traversing along a seabed.

The method may comprise controlling the roll of the AUV, using at least one of the pair of counter-rotating propellers and the internal ballast positioning mechanism, so as to scan an underwater surface or structure at least partially higher or lower than the AUV using the pair of subsea surveying sensors.

15 The method may comprise controlling at least one of the pitch and the yaw of the AUV relative to the hull using the steering mechanism.

The method may comprise controlling the steering mechanism and the propulsion mechanism such that the AUV is oriented in a substantially vertical orientation when descending to or ascending from a seabed.

20 The method may comprise propelling the AUV in a direction substantially perpendicular to a forward-aft direction of the hull using the hover module or the pair of hover modules.

25 Viewed from a fourth aspect of the present invention, there is provided a method of navigating an autonomous underwater vehicle, AUV, between sea level and a seabed, the method comprising: determining an initial surface position of the AUV at sea level using a first sensor; diving from the initial surface position towards the seabed with the AUV in a substantially vertical orientation; arriving at the seabed at an initial subsea position; and using the initial surface position as the initial subsea position.

30 The position of an AUV needs to be generally known to enable reliable and accurate navigation of AUVs. Conventionally, an initial position of an AUV when at sea level can be determined using GPS. However, GPS monitoring is not accurate subsea, and therefore the position of the AUV when subsea is monitored using alternative means. When subsea, the AUV can determine a change in its position

by monitoring its velocity, e.g. through use of a Doppler Velocity Logger (DVL). However, such sensors may only be reliably used when the AUV is within a certain range of the seabed. Therefore, further position monitoring means are required to monitor the position of the AUV as it transitions between sea level and the seabed.

5 An inertial navigation system (INS) is often provided to monitor the position of the AUV when moving between sea level and the seabed. The INS will calculate changes in the position of the AUV using data indicative of acceleration, by dead reckoning the current position of the AUV based on the position of the AUV measured at sea level. Conventionally, AUVs move between sea level and the
10 seabed along a sloped trajectory, and therefore it is necessary to monitor changes in the longitude and latitude of the AUV as it descends from, or ascends to, sea level. However, determining changes in the position of the AUV based on acceleration data can either be inaccurate due to cumulative errors associated with such calculations. Alternatively, highly accurate gyroscopic compasses or complex
15 software solutions used to mitigate such inaccuracies may be expensive to implement. Therefore, improvements when navigating AUVs between sea level and the seabed may be desired.

 When diving from an initial surface position of the AUV the seabed with the AUV in a substantially vertical orientation, the longitude and latitude of the AUV
20 may not change, or any such changes in the longitudinal or latitudinal position of the AUV may be negligible. As such, the initial position of the AUV at sea level may be reliably taken to be the same as the initial position of the AUV at the seabed.

 Therefore, by navigating an AUV between sea level and the seabed according to the third aspect, the AUV need not comprise a costly INS or use a
25 complex software solution to achieve reliable or accurate navigation. Instead, the initial surface position of the AUV can be reliably used as the initial subsea position of the AUV. Further, such a method may avoid introducing cumulative errors to the calculated position of the AUV otherwise associated with dead reckoning the position of the AUV when using an INS.

30 The AUV may be an AUV as described according to the second aspect. Accordingly, the AUV of the fourth aspect may have one or more features corresponding to those of the AUV of the second aspect. Thus, the above-description of the AUV of the second aspect, including but not limited to all technical advantages and alternative embodiments, may be equally applicable to the method
35 of the fourth aspect.

Conventionally, AUVs are unable to dive vertically, since they start to roll for high pitch angles, and because they generally have a large turning radius due to their use of control surfaces for steering.

5 By using an AUV according to the second aspect, the AUV may easily transition into a substantially vertical orientation to move between sea level and the seabed. Further, the use of the steering mechanism in combination with the use of the pair of counter-rotating propellers may enable the AUV to move via a tighter turning circle, further minimising any positional drift from its initial surface position at the sea level as it moves towards the seabed. This may improve the accuracy and
10 reliability of the navigational capabilities of the AUV.

The AUV may be considered to be in a substantially vertical orientation when the forward-aft direction of the AUV is substantially aligned with the direction of gravity. The substantially vertical orientation is therefore substantially perpendicular to sea level (i.e. the surface of the sea on a global scale).

15 The initial subsea position may be considered an initial seabed position. For example, the AUV may dive from sea level to be substantially above, or at, the seabed.

The AUV may dive towards the seabed until the AUV is within: at least 100 metres of the seabed; at least 90 metres of the seabed; at least 80 metres of the seabed; at least 70 metres of the seabed; at least 60 metres of the seabed; at least
20 50 metres of the seabed; at least 40 metres of the seabed; at least 30 metres of the seabed; at least 20 metres of the seabed; at least 10 metres of the seabed; or at least 5 metres of the seabed.

The AUV may be at least partially above seawater when at sea level. For
25 example, the first sensor may be above water when the AUV is at sea level.

The method may comprise: propelling the AUV backwards such that it is fully submerged underwater; and turning the AUV such that it is oriented in the substantially vertical orientation. These steps may be performed prior to the diving step, or as part of the diving step.

30 The first sensor may be a GPS sensor.

The method may comprise: traversing the seabed; monitoring motion of the AUV using a second sensor; and calculating the position of the AUV based on the initial subsea position and the motion of the AUV.

35 The step of traversing the seabed may comprise operating the AUV to follow a methodical subsea scanning path, such as a lawn mower pattern.

- 15 -

The motion may include, or be, a velocity of the AUV.

The second sensor may be an acoustic sensor configured to monitor the velocity of the AUV, e.g. using Doppler shift. The second sensor may be a Doppler Velocity Logger (DVL).

5 The motion may include, or be, at least one of an acceleration of the AUV and an angular velocity of the AUV.

The second sensor may be an inertial navigation system (INS) configured to monitor the acceleration and/or the angular velocity of the AUV.

10 The step of calculating the position of the AUV may be performed by the INS. The acoustic sensor, which may be a DVL, may be provided as part of the INS, or in addition to, the INS.

15 The method may comprise: ascending from a final subsea position to sea level with the AUV in a substantially vertical orientation; arriving at sea level at a final surface position; and determining the final surface position of the AUV at sea level using the first sensor.

20 Ascending to sea level with the AUV in a substantially vertical orientation may result in the longitude and latitude of the AUV not changing, similar to when descending in a substantially vertical orientation. Accordingly, changes in the longitudinal or latitudinal position of the AUV may be negligible, and as such the final position of the AUV at sea level may be reliably taken to be the same as the final position of the AUV at the seabed.

Taking the final position of the AUV at sea level to be the final position of the AUV at the seabed, when ascending between the two in a substantially vertical orientation, may serve the following exemplary purposes.

25 In a first example, the final position of the AUV at sea level can be used to confirm the final position of the AUV at the seabed. Recording this position may enable any positional drift in the calculated position of the AUV when subsea to be corrected, during post-analysis of any subsea data.

30 In a second example, ascending to the seabed in such a manner may enable the AUV to confirm its current position during a subsea operation, or mission, to maintain accurate positioning of the AUV, and hence reliable navigation of the AUV when subsea. That is, the AUV may pause its subsea operations to obtain a GPS fix of its position. Accordingly, the position of the AUV at the seabed and at sea level may be considered to be the 'final' position of a respective leg, or
35 portion, of the AUV's route. The final subsea and surface positions may therefore

each respectively be considered to be 'intermediate' seabed and surface positions of the AUV, should the AUV perform another diving operation subsequent to surfacing.

5 Viewed from a fifth aspect of the present invention, there is provided a method of collecting subsea data using an autonomous underwater vehicle, AUV, the method comprising: navigating an AUV between sea level and a seabed by: determining an initial surface position of the AUV at sea level using a first sensor; diving from the initial surface position to the seabed with the AUV in a substantially vertical orientation; arriving at the seabed at an initial subsea position; using the
10 initial surface position as the initial subsea position; ascending from a final subsea position to sea level with the AUV in a substantially vertical orientation; arriving at sea level at a final surface position; and determining the final surface position of the AUV at sea level using the first sensor; recording subsea data at a plurality of positions over the seabed; and correcting positional data associated with the
15 subsea data based on the final surface position.

Ascending to sea level with the AUV in a substantially vertical orientation may result in the longitude and latitude of the AUV not changing, similar to when descending in a substantially vertical orientation. Accordingly, changes in the longitudinal or latitudinal position of the AUV may be negligible, and as such the
20 final position of the AUV at sea level may be reliably taken to be the same as the final position of the AUV at the seabed.

By navigating the AUV in such a manner, the final position of the AUV at sea level can be reliably taken to be the final position of the AUV at the seabed. Accordingly, the final position of the AUV at sea level can be used to confirm the
25 final position of the AUV at the seabed, and positional drift in the calculated position of the AUV when subsea to be corrected during post-analysis of any subsea data to improve the accuracy of any positional data of the subsea data.

The method of the first aspect may navigate the AUV between sea level and the seabed according to the method of the fourth aspect. Accordingly, the method
30 of the fifth aspect may have one or more steps corresponding to those of the method of the fourth aspect, and the above-description of the method of the fourth aspect, including but not limited to all technical advantages and alternative embodiments, may be equally applicable to the method of the fifth aspect.

Certain preferred embodiments of the invention will now be described by
35 way of example only and with reference to the accompanying drawings in which:

Figure 1 shows an AUV from a side view;

Figure 2 shows the AUV of figure 1 in a perspective view;

Figures 3 and 4 show the AUV at different positions during subsea operations;

5 Figure 5 illustrates an AUV navigating during subsea operations;

Figure 6 shows an AUV from a side view;

Figure 7 shows the AUV of figure 6 in a perspective view; and

Figure 8 illustrates an AUV navigating between sea level and the seabed.

10 Figure 1 shows an autonomous underwater vehicle, AUV, 100 from a side view, and figure 2 shows the same AUV 100 from a perspective view.

The AUV 100 comprises a hull 101 formed of multiple sections and modules, extending from a nose end of the AUV 100 to a tail end of the AUV 100. Generally, in use, the nose end defines a forward-facing end of the AUV 100 during forward propulsion of the AUV 100. A longitudinal axis of the AUV 100 extends
15 from the nose end to the tail end, i.e. in a forward-aft direction of the AUV 100.

The hull 101 is a rigid hull 101 insofar as it maintains a stiff and inflexible housing for the various components located therein. However, the rigid hull 101 can be provided with one or more articulatable, flexible sections as desired for performing various subsea operations. The hull 101 is generally cylindrical.

20 The hull 101 comprises a nose 102, a navigation section 103, a battery module 104 and a propulsion section 105. The nose 102 is located at the nose end of the AUV 100 and can house a payload. The navigation section 103 includes various controllers and sensors for controlling the operations and navigation of the AUV 100. The battery module 104 is configured to provide a source of electrical
25 power for the AUV 100 which, in the present embodiment, is a 1.7 kWh battery. (batteries of differing capacity are contemplated in other embodiments). The propulsion module 105 is configured to generate a motive force to propel the AUV 100 subsea, and to control the positioning of the AUV 100.

The navigation section 103 comprises a sidescan sonar transducer 131 on
30 each side of the hull 101 of the AUV 100. The sidescan sonar transducers 131 are for scanning structures or landscapes during subsea operations. Each sidescan sonar transducer 131 extends in a forward-aft direction of the AUV 100 and is configured to emit a conical or fan-shaped beam in a direction perpendicular to the forward-aft direction of the AUV 100. The sidescan sonar transducers 131 are
35 diametrically opposed about the hull 101 in the present embodiment, although in

other embodiments they can be positioned at different circumferential positions as desired. Other subsea surveying sensors, such as multibeam echosounders (MBESs) and cameras, may also be fitted.

5 The navigation section 103 also comprises a communications module 132 comprising a WiFi transceiver for communications with any nearby vessels. A strobe light for signalling is also provided as part of the communications module 132.

10 Additionally, the navigation section 103 comprises equipment configured to determine a position of the AUV 100. For example, the navigation section 103 may comprise a GPS sensor for monitoring a position of the AUV 100, which may form part of the communications module 132. Additionally, or alternatively, the navigation section 103 comprises a Doppler Velocity Log, DVL, 133 for estimating a velocity of the AUV 100, and hence a position of the AUV 100 during subsea operations, relative to the seabed. The navigation section 103 may also comprise a series of transponders 134 forming a high precision acoustic positioning system for additionally monitoring the position of the AUV 100 during subsea operations. The DVL 133 and the transponders 134 are located on an underside of the hull 101. A positioning transponder similar to or the same as 134 may also be fitted at the top side of the AUV.

20 The navigation section 103 also comprises an interchangeable data storage module 135. The data storage module 135 is interchangeable in the field, and can therefore be changed rapidly when the AUV 100 is surfaced, which allows the AUV 100 to be rapidly redeployed, rather than recovering the AUV 100 and downloading data from the data storage module 135 by a wired connection or the like.

25 The AUV 100 comprises a controller comprising a processor and a memory. The controller is in communication, e.g. wired or wireless communication, with the payload located in or towards the nose 102, the various sensors and controllers of the navigation section 103, the battery of the battery section 104, and also the various components of the propulsion section 105. The controller is located in the navigation section 103 in the present embodiment, but can be provided in an alternative section or module as appropriate in other embodiments. The memory of the controller stores computer-readable instructions which, when executed by the processor of the controller, causes the AUV 100 to perform various operations.

30 The propulsion section 105 comprises an internal ballast module 151 and a propulsion mechanism 152. The propulsion mechanism 152 is located at the tail

end of the hull 101. In the present embodiment the internal ballast module 151 is located adjacent to the propeller mechanism 152 at the tail end of the hull 101. In other embodiments, however, the propulsion mechanism 152 and the internal ballast mechanism 151 can be located elsewhere along the hull 101, and elsewhere
5 relative to one another.

The internal ballast module 151 comprises an internal ballast. The internal ballast is configured to self-right the AUV 100, or bias the hull 101 of the AUV 100 to be in a particular rotational orientation, such that the roll of the AUV 100, i.e. the rotational orientation of the AUV 100 about a roll axis coincident with the
10 longitudinal axis of the AUV 100, can be controlled. The weight of the internal ballast will align the AUV 100 with respect to the direction of gravity, thereby orienting the AUV 100 about the roll axis accordingly. In use, the internal ballast can therefore be used to orient the AUV 100 in any desired orientation about the roll axis.

The internal ballast module 151 further comprises an internal ballast
15 positioning mechanism configured to position the internal ballast relative to the hull 101 of the AUV 100. The internal ballast will always cause the AUV 100 to attempt to orient itself in a particularly orientation under the influence of gravity. Accordingly, controlling a position the internal ballast relative to the hull 101 can
20 influence the rotational position of the hull 101. The internal ballast module 151 thus provides roll control to the AUV 100, since it is configured to position the AUV 100 in one of a plurality of rotational orientations about its roll axis.

In the present embodiment the internal ballast positioning mechanism is configured to rotate the internal ballast about a central axis of the hull 101 of the
25 AUV 100, and can therefore be considered to be an internal ballast rotation mechanism. The internal ballast rotation mechanism is a motor configured to rotate the internal ballast about the central axis of the hull 101.

The propulsion mechanism 152 is configured to propel the AUV 100 during subsea operations. The propulsion mechanism 152 comprises a pair of counter-
30 rotating propellers 153 and a plurality of fins 154. The counter-rotating propellers 153 each generate a motive force for propelling the AUV 100 through water, and the fins 154 improve the efficiency of the propellers 153 by stabilising the motion of the AUV 100. The rotational speed of each propeller in the pair of counter-rotating propellers 153 is independently controllable. This can provide roll control to the
35 AUV 100 as follows.

In prior art systems where a single propeller blade was used, the rotational motion of the propeller would cause the AUV to roll undesirably. This would be counteracted by various control surfaces, together with the use of a fixed ballast at the bottom of the AUV, to maintain a normal orientation of the AUV. In the present embodiment, the use of a pair of counter-rotating propellers 153 results in the torques induced by each propeller cancelling out. Therefore, where the pair of counter-rotating propellers 153 are operated at the same rotational speed, no roll torque is undesirably induced. The use of a pair of counter-rotating propellers 153 can therefore improve the roll control of the AUV 100 by mitigating against the generation of undesirable roll torque during propulsion of the AUV 100.

Further, where it is desirable to induce a roll torque, e.g. to adjust a rotational orientation of the AUV 100 about its roll axis, the rotational speeds of the propellers 153 can be asymmetrically controlled. When the rotational speeds are imbalanced, the roll torque components induced by each propeller do not cancel out and accordingly the desired roll torque can be induced.

Whilst the internal ballast module 151 and the propulsion module 152 each provide independent roll control to the AUV 100, the combined and selective use of both modules 151, 152 provides improved roll control for the AUV 100 across the breadth of its subsea operations.

For example, the combined use of the independently controllable propellers and the internal ballast positioning mechanism can cause a swifter and more reactive roll control if required, providing the AUV 100 with greater manoeuvrability. Further, in situations where one form of roll control is less suited for use the other may be able to compensate such that the AUV 100 maintains full roll control capabilities at all times during subsea operations.

Figures 3 and 4 illustrate the rotational orientation of the AUV 100 being controlled about its roll axis during subsea operations. The roll of the AUV 100 is controlled using the internal ballast positioning mechanism and the pair of counter-rotating propellers 153. In the example illustrated, the AUV 100 is performing sidescan operations and therefore emits sonar beams from each of its sidescan sonar transducers 131, located on opposing sides of the AUV 100. The direction of the emitted beams is dependent on the orientation of the AUV 100. Accordingly, by controlling the position of the AUV 100 about its roll axis the direction of the beams emitted by the sidescan sonar transducers 131 can also be controlled, e.g. to aim at surfaces or structures higher or lower than the AUV 100 (as well as level with the

AUV 100). Controlling the direction of the beams emitted by the sidescan sonar transducers 131 has particular utility when surveying inclined surfaces or structures of or on the seabed, since the beams can be directed straight at said surfaces or structures.

5 The AUV 100 also comprises a steering mechanism 155. The propulsion mechanism 152 is mounted to the hull 101 via the steering mechanism 155. The steering mechanism 155 is configured to provide directional control to the propulsion mechanism 152 relative to the hull 101, and hence to the pair of counter-rotating propellers 153. Accordingly, the steering mechanism 155 can provide pitch
10 and yaw control for the AUV 100 by directing the motive force generated by the propulsion mechanism 152 relative to hull 101.

 The steering mechanism 155 comprises a motorised joint, such as a motorised cardan joint, that is configured to provide pitch and yaw control to the propulsion mechanism 152 relative to the axis of the hull 101 of the AUV 100. The
15 motorised joint is protected by an oil-filled bellows defining a part of the exterior surface of the AUV 100. In other embodiments, the motorised joint can instead be a motorised ball joint, or can be replaced with any other suitable active joint such as a pneumatic, electric or hydraulic actuator.

 Compared to prior art AUVs that use control surfaces to provide steering,
20 using the steering mechanism 155 to provide pitch and yaw control directly to the propulsion mechanism 152 can provide greater and more responsive control for the AUV 100. For example, actuating the steering mechanism 155 such that the propulsion mechanism 152 is greatly offset to the longitudinal axis of the hull 101 provides a tighter turning circle for the AUV 100 in water, thereby improving its
25 manoeuvrability. Also, since the AUV 100 does not require any control surfaces to induce steering due to the presence of the steering mechanism 155, the hull 101 of the AUV 100 does not experience drag forces associated with the presence of control surfaces, thus improving its hydrodynamic profile and reducing drag.

 Further, the use of control surfaces as in the prior art requires the AUV to
30 have forward motion to induce a directional thrust. For the AUV 100 of the present embodiment, however, the AUV 100 can make a directional turn from a standstill since the steering mechanism 155 directly controls the direction of the propulsion mechanism 152 and hence the motive force it generates.

 Figure 5 illustrates a process of controlling the position of the AUV 100
35 through direct control of the propulsion mechanism 152 using the steering

mechanism 155. The AUV 100 is shown traversing the seabed 1, which comprises a flat portion 1A and a contoured hill portion 1B. The AUV 100 traverses from left to right in figure 5, such that the AUV 100 progresses from position A through to position E. The position of the AUV 100 about its roll axis is controlled throughout the process, such that undesirable roll of the AUV 100 does not inadvertently disturb the directional control provided by the steering mechanism 155.

The AUV 100 follows a path generally parallel to the contours of the seabed 1. At position A, the AUV 100 travels generally parallel to the flat portion 1A of the seabed 1, with zero pitch control induced by the steering mechanism 155.

As the AUV 100 approaches the hill portion 1B of the seabed 1 at position B, the steering mechanism 155 is actuated to induce a pitch up motion of the AUV 100. The AUV 100 turns in response, such that the AUV 100 proceeds along a path parallel to the contour of the hill portion 1B at position C. The steering mechanism 155 can be controlled again to induce no change in the pitch of the AUV 100.

At position D, the hill portion 1B flattens out. The steering mechanism 155 is controlled to induce a pitch down motion of the AUV 100. The AUV 100 turns accordingly.

At position E, the hill portion 1B descends and the AUV 100 is steered to be parallel to the angle of descent. The steering mechanism 155 is controlled to induce no change in the pitch of the AUV 100.

The steering mechanism 155 is therefore controllable such that the AUV 100 follows the contours of the seabed 1 in a substantially parallel manner. That is, the tighter turning circle provided by the steering mechanism 155 in the pitch and yaw directions provides the AUV 100 with the required manoeuvrability to stay close to the surface of the seabed 1 during subsea operations. The speed of the pair of counter-rotating propellers 153 can also be varied such that the AUV 100 can follow different turning circles and radius, where necessary.

The various modules and sections of the hull 101 can be reordered and include further sections according to the desired operations of the AUV 100.

For example, turning to figures 6 and 7 the AUV 100 is shown comprising a pair of additional hover modules 106, 107. The hover modules 106, 107 are configured to propel the AUV 100 in a direction substantially perpendicular to a forward-aft direction of the hull 101 (i.e. in a direction extending between the nose end and the tail end of the hull 101). The hover modules 106, 107 each comprise

two respective propellers 106A,B, 107A, B oriented in perpendicular planes. A first hover module 106 is located towards the nose end of the hull 101, whilst a second hover module 107 is located towards a tail end of the hull 101.

5 The hover modules 106, 107 can be used to translate the AUV 100 across a two-dimensional plane. For example, control of the propellers 106A, 107A oriented in the same plane can induce a left-right translation of the AUV 100; whilst control of the propellers 106B, 107B oriented in the same plane can induce an up-down translation of the AUV 100. The control of the propellers oriented in the same plane 106A, 107A, 106B, 107B can be symmetric or asymmetric, depending on the
10 desired control of the position of the AUV 100.

The hover modules 106, 107 can also be used to maintain a position of the AUV 100 subsea. For example, the propellers 106A,B, 107A,B can also be controlled to counteract underwater currents or to provide lift to the AUV 100 to hold its position subsea. The use of the hover modules 106, 107 in combination with the
15 propulsion section 105 provides the AUV 100 with increased control over its positioning.

In certain embodiments, the propellers 106A,B, 107A, B of each hover module 106, 107 oriented in parallel planes are counter-rotating so as to not induce any undesirable torque components.

20 Figure 8 illustrates a process of navigating the AUV 100 between sea level 3 and the seabed 1, when performing subsea operations. The AUV 100 moves from left to right and into the page in figure 8, such that the AUV 100 progresses from position F through to position K.

The AUV 100 starts at sea level 3, as shown at position F. The AUV 100
25 has either surfaced from a previous dive, or has been deployed on the surface at sea level 3. The position of the AUV 100 is monitored using its GPS, located in the communications module 132. The GPS is capable of reliably monitoring the position of the AUV 100 when at sea level 3, but not during subsea operations. The AUV 100 is stationary at position F.

30 The AUV 100 moves between sea level 3 and the seabed 1 via a diving operation. As shown at position G, the AUV 100 is substantially vertical during a diving operation, and therefore can be regarded as experiencing only a change in depth, rather than a change in its longitude or latitude.

The AUV 100 moves to the vertical orientation by action of the steering
35 mechanism 155, which orients the propulsion mechanism 152 so as to turn the hull

101. Since the steering mechanism 155 directly controls the direction of the propulsion mechanism 152, a turning force can be generated even when the AUV 100 is as standstill. That is, the use of the steering mechanism 155 controlling the direction of the pair of counter-rotating propellers 153 can enable the AUV 100 to
5 easily turn for a vertical diving operation.

When beginning the diving operation, the steering mechanism 155 can be used to pitch the propulsion mechanism 152 towards the seabed 1, and the propulsion mechanism 152 can be operated to propel the AUV 100 backwards such that it is fully submerged just below sea level 3. The propulsion mechanism 152 is
10 generally more efficient when fully submerged.

Once the AUV 100 is oriented for travelling vertically downward towards the seabed 1, the steering mechanism 155 returns the propulsion mechanism 152 to be in line with the hull 101 of the AUV 100. The AUV 100 dives to depths of up to 500 metres during the diving operation.

15 During the diving operation, the roll of the AUV 100 is controlled by the pair of counter-rotating propellers 153. When no roll is desired, the pair of counter-rotating propellers 153 operate at the same rotational speed. When roll is desired, e.g. to alter the direction of the AUV 100 as it reaches the seabed 1, the propellers 153 can operate with different rotational speeds, thereby causing the AUV 100 to
20 rotate about its roll axis as desired.

As the AUV 100 approaches the seabed 1, the steering mechanism 155 again directs the propulsion mechanism 152 such that the AUV 100 moves to an orientation substantially parallel to the seabed 1, as illustrated at position H. The AUV 100 reaches the seabed 1 at a roughly identical longitude and latitude to when
25 the AUV 100 began its descent from the surface (displacement of the AUV 100 due to ocean currents acting on the vehicle during diving operations can be disregarded).

GPS positioning does not work underwater, and the navigation sensors used by the AUV 100 to determine the position of the AUV 100 when subsea, such
30 as the DVL 133, do not work reliably until the AUV 100 is in close proximity to the seabed 1, e.g. within 50-70 m of the seabed 1. However, since the vertical diving operation results in the AUV 100 being located at a substantially similar longitude and latitude, i.e. since only the depth of the AUV 100 generally changes during the diving operation, the position of the AUV 100 determined by the GPS sensor at sea

level 3 can be taken to be the approximate position of the AUV 100 above the seabed 1.

Once the AUV 100 reaches the seabed 1, the DVL 133 can be used to monitor a velocity of the AUV 100. The position of the AUV 100 can be estimated using the velocity of the AUV 100, an onboard orientation sensor which measures the roll, pitch and heading of the AUV, and the starting position of the AUV 100 (i.e. the position determined by the GPS sensor before the AUV 100 descended to the seabed 1). In some embodiments, the AUV may also include an inertial navigation system (INS) to track the position of the AUV while manoeuvring subsea. The GPS location recorded at position F is set as the starting position of the INS once the AUV reaches the seabed.

With the subsea position of the AUV 100 determined, the AUV 100 can perform a subsea operation, such as a survey, following a known or predetermined path. As shown at position I, the AUV 100 performs a survey comprising performing a sidescan operation with the sidescan sonar transducers 131. As shown in figure 8, the survey can involve the AUV 100 following a methodical scanning path, such as a lawn mower pattern as shown in figure 8, to cover an area of the seabed 1 in detail.

Once the AUV 100 (i) finishes its subsea operations, (ii) needs to surface for maintenance, or (iii) confirm its current position using GPS during subsea operations before diving again, the AUV 100 performs an ascending operation. In essentially reverse operation to the diving operation, the steering mechanism 155 controls the propulsion mechanism 152 so as to turn the AUV 100 into a vertical orientation. With the AUV 100 facing sea level 3, the AUV 100 ascends towards sea level following a substantially vertical path, as shown at position J.

The AUV 100 reaches sea level 3, as indicated by position K, at a substantially similar longitude and latitude to when the AUV 100 began its ascending operation. With the AUV 100 back at sea level 3, the GPS sensor can be used to confirm the position of the AUV 100. Since this positional value should correspond to that of the AUV 100 as it began its ascension from the seabed 1, this position value can be used to correct the positional data of the AUV 100 estimated during its subsea operations.

CLAIMS

1. An autonomous underwater vehicle, AUV, for performing subsea operations, comprising:
5 a hull comprising a nose end and a tail end;
a propulsion mechanism configured to propel the AUV; and
an internal ballast located in the hull;
wherein the propulsion mechanism comprises a pair of counter-rotating propellers, the rotational speed of each propeller being independently controllable;
10 and
wherein the AUV comprises an internal ballast positioning mechanism configured to controllably move the internal ballast relative to the hull.
2. An AUV as claimed in claim 1, comprising:
15 a steering mechanism configured to rotate the propulsion mechanism in at least one of a pitch and a yaw direction, relative to the hull.
3. An AUV as claimed in claim 2, wherein the steering mechanism comprises an active joint configured to rotate the propulsion mechanism.
20
4. An AUV as claimed in claim 2 or 3, wherein the steering mechanism comprises a bellows extending between the hull and the propulsion mechanism, the bellows defining part of an exterior surface of the AUV.
- 25 5. An AUV as claimed in any preceding claim, comprising:
a controller in communication with the propulsion mechanism and the internal ballast positioning mechanism,
wherein the controller is configured to control roll of the AUV using at least one of the pair of counter-rotating propellers and the internal ballast positioning
30 mechanism.
6. An AUV as claimed in claim 5, wherein the controller is configured to:
independently control the rotational speed of each propeller so as to control a roll of the AUV during substantially vertical ascent and/or descent of the AUV; and

- 27 -

move the internal ballast relative to the hull using the internal ballast positioning mechanism so as to control the roll of the AUV when traversing along a seabed.

- 5 7. An AUV as claimed in claim 5 or 6, comprising:
 a pair of subsea surveying sensors located on opposing sides of the hull
 and configured to scan underwater surfaces or structures;
 wherein the controller is in communication with the pair of subsea surveying
10 sensors and is configured to control the roll of the AUV, using at least one of the
 pair of counter-rotating propellers and the internal ballast positioning mechanism,
 so as to scan an underwater surface or structure at least partially higher or lower
 than the AUV using the pair of subsea surveying sensors.
- 15 8. An autonomous underwater vehicle, AUV, for performing subsea operations,
 comprising:
 a hull comprising a nose end and a tail end;
 a propulsion mechanism configured to propel the AUV, wherein the
 propulsion mechanism comprises a pair of counter-rotating propellers, the rotational
20 speed of each propeller being independently controllable; and
 a steering mechanism configured to rotate the propulsion mechanism in at
 least one of a pitch and a yaw direction, relative to the hull.
- 25 9. An AUV as claimed in claim 8, wherein the steering mechanism comprises
 an active joint configured to rotate the propulsion mechanism.
- 30 10. An AUV as claimed in claim 8 or 9, wherein the steering mechanism
 comprises a bellows extending between the hull and the propulsion mechanism, the
 bellows defining part of an exterior surface of the AUV.
- 35 11. An AUV as claimed in claim 8, 9 or 10, comprising:
 an internal ballast located in the hull; and
 an internal ballast positioning mechanism configured to controllably move
 the internal ballast relative to the hull.

12. An AUV as claimed in any of claims 8 to 11, comprising:
a controller in communication with the propulsion mechanism and the steering mechanism, wherein the controller is configured to:
control roll of the AUV by independently controlling the rotational speed of
5 each propeller of the pair of counter-rotating propellers; and
control at least one of the pitch and the yaw of the AUV relative to the hull using the steering mechanism.
13. An AUV as claimed in claim 12, wherein the controller is configured to:
10 control the steering mechanism and the propulsion mechanism such that the AUV is oriented in a substantially vertical orientation when descending to or ascending from a seabed.
14. An AUV as claimed in any preceding claim, comprising:
15 a hover module configured to propel the AUV in a direction substantially perpendicular to a forward-aft direction of the hull;
wherein the hover module comprises a first propeller and a second propeller oriented substantially perpendicular to one another.
- 20 15. An AUV as claimed in claim 14, comprising:
a pair of hover modules configured to propel the AUV in a direction substantially perpendicular to the hull;
wherein a first hover module of the pair of hover modules is located towards the nose end of the hull and a second hover module of the pair of hover modules is
25 located towards the tail end of the hull.
16. An AUV as claimed in any preceding claim, wherein the AUV has a mass of 40 to 80 kg.
- 30 17. An AUV as claimed in any preceding claim, wherein the hull comprises two or more modular sections which are configured to be connected and disconnected from one another.
18. An AUV as claimed in claim 17, wherein each section is individually
35 pressure-rated.

19. A method of performing subsea operations using an autonomous underwater vehicle, AUV, as claimed in any of claims 1 to 7 or 14 to 18 when dependent on any of claims 1 to 7, the method comprising:
- 5 controlling a roll of the AUV by independently controlling the rotational speed of each propeller of the pair of counter-rotating propellers; and
 controlling the roll of the AUV using the internal ballast positioning mechanism.
- 10 20. A method of navigating an autonomous underwater vehicle, AUV, between sea level and a seabed, the method comprising:
 determining an initial surface position of the AUV at sea level using a first sensor;
 diving from the initial surface position towards the seabed with the AUV in a
15 substantially vertical orientation;
 arriving towards the seabed at an initial subsea position; and
 using the initial surface position as the initial subsea position.
- 20 21. A method as claimed in claim 20, wherein the first sensor is a GPS sensor.
22. A method as claimed in claim 20 or 21, comprising:
 traversing the seabed;
 monitoring motion of the AUV using a second sensor; and
 calculating the position of the AUV based on the initial subsea position and
25 the motion of the AUV.
23. A method as claimed in claim 22, wherein the second sensor is an acoustic sensor configured to monitor the velocity of the AUV.
- 30 24. A method as claimed in any of claims 20 to 23, comprising:
 ascending from a final subsea position to sea level with the AUV in a substantially vertical orientation;
 arriving at sea level at a final surface position; and
 determining the final surface position of the AUV at sea level using the first
35 sensor.

- 30 -

25. A method of collecting subsea data using an autonomous underwater vehicle, AUV, the method comprising:
- 5 navigating an AUV between sea level and a seabed according to a method as claimed in claim 24;
- recording subsea data at a plurality of positions over the seabed; and
- correcting positional data associated with the subsea data based on the final surface position.