

UNDERWATER VEHICLE

The present invention relates to an underwater vehicle for performing subsea operations and a method of performing subsea operations using an underwater vehicle, particularly wherein the underwater vehicle is an autonomous underwater vehicle (AUV).

Underwater vehicles are used for various purposes, and can take many forms and sizes to fulfil their particular function. Examples include autonomous underwater vehicles (AUVs) which can operate without continuous input from an operator, and remotely operated vehicles (ROVs) which are operated from a vessel or platform, with the ROV often linked to the host vessel or platform via a neutrally buoyant tether.

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, and therefore may be limited in their manoeuvrability.

Instead of using control surfaces, some AUVs can control the direction in which their propeller faces using active joints. Actively controlling the position of the propeller effectively steers the AUV, since the thrust produced by the propeller can be directed as required. Whilst being able to direct the resulting thrust without necessarily requiring speed in the forward direction may improve the manoeuvrability of the AUV, the use of such active joints may increase the cost of manufacturing and maintaining the AUV, as well as the number of complex components that can fail.

Other known AUVs include hovering-type AUVs which do not require constant forward motion, and can hold their position in water. Such AUVs may comprise multiple number of thrusters or propellers oriented in different directions, so as to stabilise and move the AUV 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. However, hovering-type AUVs are typically larger than other designs of AUV for a given sensor payload. It can be impractical to use

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large AUV systems in some circumstances due to the difficulties of transporting and manipulating the vehicle.

Reliable and accurate control of AUVs is particularly important for AUVs adapted for surveying purposes, since the AUV should be suitably positioned during
5 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 whilst being cost-efficient to manufacture and maintain.

Viewed from a first aspect of the present invention, there is provided an underwater vehicle for performing subsea operations. The underwater vehicle
10 comprises: a hull comprising a nose end and a tail end; a propulsion mechanism configured to propel the underwater vehicle; a passive joint module connecting the propulsion mechanism to the hull at one of the tail end or the nose end of the hull; and a controller in communication with the propulsion mechanism; wherein the propulsion mechanism comprises a pair of propulsion devices configured to propel
15 the underwater vehicle through water, the thrust of each propulsion device being independently controllable; and wherein the controller is configured to control an angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrust of each of the propulsion devices.

By using a passive joint module to join the propulsion mechanism to the hull,
20 and by controlling the angle at which the propulsion mechanism connects to the hull through independent control of the thrusts generated by each of the propulsion devices, steering of the underwater vehicle may be achieved in a simple yet effective manner. Since this form of steering does not rely on the use of control surfaces, which require the underwater vehicle to be moving in the forward direction
25 to provide a steering thrust, the manoeuvrability of the vehicle may be improved.

Further, passive joint modules may be cheaper, less complex, smaller and lighter than active joint modules. Accordingly, the use of a passive joint module indirectly and passively steered by the differential thrust of the propulsion devices of the propulsion mechanism to which it is connected may provide a steering
30 mechanism that has a number of benefits compared to an active joint module.

It will be understood that a passive joint module is a joint module that is only responsive to external forces changing its shape and/or angle of flexion. The passive joint module does not have the ability to dynamically control its own shape and/or angle, but is instead controlled under the influence of thrust from the
35 propulsion mechanism. A passive joint may still comprise a resistance to

movement and/or a bias, for example towards a neutral position. In this way, the passive joint module does not generate any appreciable active motive force itself to dynamically control an angle for the connection of the propulsion mechanism to the hull.

5 The passive joint module may thus provide a passive and pivotal, or rotatable, connection between the hull and the propulsion mechanism.

 The passive joint module may comprise a passive joint member rotatably connecting the propulsion mechanism to the hull, said mechanism provided within a casing extending between the hull and the propulsion mechanism, the casing
10 defining an exterior surface of the underwater vehicle.

 The passive joint member may comprise a joint comprising two or more parts capable of sliding or pivoting relative to one another, such as a ball joint or a hinge joint or a pivot joint. Additionally, or alternatively, passive joint member may comprise a flexible member, such as a spring member or a flexible member.

15 The casing may be an oil-filled casing. Filling the casing with oil may lubricate the passive joint member whilst also improving the pressure resistance of the casing for subsea operations. The casing may be a bellows member.

 Generally, in use the nose end defines a forward-facing end of the underwater vehicle during forward propulsion thereof. A longitudinal axis of the
20 underwater vehicle extends from the nose end to the tail end, i.e. in a forward-aft direction of the underwater vehicle.

 The propulsion mechanism can be connected to the hull at the nose end or the tail end, via the passive joint module.

 The underwater vehicle may comprise two propulsion mechanisms, each
25 connected to the hull at one of the tail end and the nose end via a respective passive joint module.

 The propulsion devices may be propellers, water jets, impellers, water screws, tunnel thrusters, or rotatable thrusters. The propulsion devices are preferably propellers or water jets, although any propulsion device capable of
30 generating a thrust for propelling the underwater vehicle through water may be employed.

 Where the propulsion devices comprise rotating elements, the rotating elements may be configured to counter-rotate. For example, the pair of propulsion devices may be a pair of counter-rotating propellers, the propellers being located on
35 axially opposite sides of the underwater vehicle.

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 operational (i.e. rotational) speed. Accordingly, the use of a pair of counter-rotating propellers can improve the roll control of the underwater vehicle by mitigating against the generation of undesirable roll torque during propulsion of the underwater vehicle. 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 underwater vehicle about its roll axis, the rotational speeds can be asymmetrically controlled since their respective speeds are independently controllable, providing further roll control for the underwater vehicle.

The controller can be configured to control the angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located either side of a steering axis of the passive joint module (i.e. an axis about which the passive joint module may pivot). Such control can induce a net torque on the passive joint module, causing the propulsion mechanism to rotate to the desired angle about the passive joint module.

In the case of a propeller or similar propulsion mechanism, the thrust generated by the propulsion device may be controlled by controlling a rotational speed of the propeller or other rotating element of the propulsion mechanism.

For example, the controller may be configured to control a pitch angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located either side of the pitch axis of the joint module.

Similarly, the controller may be configured to control a yaw angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located either side of the yaw axis of the joint module.

The propulsion mechanism may comprise a second pair of propulsion devices configured to propel the underwater vehicle through water, the thrusts of each of the second pair of propulsion devices being independently controllable; the passive joint module being configured to permit motion of the propulsion mechanism about a pitch axis and a yaw axis, relative to the hull, through independent control of the thrusts of each of the propulsion devices.

At least one propulsion device may be located on each vertical side of the underwater vehicle for pitch control, and at least one propulsion device may be located on each horizontal side of the underwater vehicle for yaw control.

5 For example, the first pair of propulsion devices may be located coaxially along a pitch axis of the passive joint module, and on opposite sides of a yaw axis of the passive joint module. The second pair of propulsion devices may be located coaxially along the yaw axis of the passive joint module, and on opposite sides of the pitch axis of the passive joint module. Accordingly, the first pair of propulsion devices may be used to control the yaw of the underwater vehicle and the second
10 pair of propulsion devices may be used to control the pitch of the underwater vehicle.

More preferably, at least two propulsion devices may be located on each vertical side of the underwater vehicle for pitch control, and at least two propulsion devices may be located on each horizontal side of the underwater vehicle for yaw
15 control.

In other words, at least two of the propulsion devices may be located on each side of the pitch axis of the passive joint module (i.e. above and below the pitch axis). Further, at least two of the propulsion devices may be located on each side of the yaw axis (i.e. on a port side and on a starboard side of the yaw axis).

20 Such an arrangement for the propulsion mechanism may provide more responsive steering about the passive joint module, since the motive force of two pairs of propulsion devices can be simultaneously used to generate a turning force and simultaneously propel the underwater vehicle at any time.

The passive joint module may comprise a sensor configured to measure an angle at which the passive joint module connects the propulsion mechanism to the hull. The controller may be configured to independently adjust the thrust of each of the propulsion devices based on the measured angle.

The sensor may comprise any one or a combination of a magnetic encoder, a flex sensor, a Hall sensor, a capacitive encoder or any other suitable sensor or
30 encoder for measuring the angle at which the passive joint module connects the propulsion mechanism to the hull.

The use of such a sensor may provide a further feedback input by which the steering angle of the underwater vehicle can be monitored and controlled. Such an arrangement may result in more accurate control and manoeuvring of the
35 underwater vehicle.

The passive joint module may comprise a resilient member formed of an elastic material, the elastic material being arranged to bias the propulsion mechanism to be coaligned with the hull when there is no difference in the thrusts of the propulsion devices.

5 Providing a resilient member that biases the propulsion mechanism to be coaligned with the hull when there is no difference in the operational speed of the propulsion devices may provide more responsive control of the steering of the underwater vehicle. For example, when no steering about the passive joint module is required, the passive joint module may automatically be restored to provide a
10 coaligned, or zero-angle, connection between the propulsion mechanism and the hull. The use of the resilient member may also simplify the steering control of the underwater vehicle since the thrusts of the propulsion devices need not necessarily be controlled so as to indirectly restore the coalignment. The responsiveness of the passive joint module to changes in steering direction may thus be improved.

15 The propulsion mechanism will be understood to be coaligned with the hull when there is a zero pitch and/or yaw angle between the propulsion mechanism and the hull, i.e. the net direction of thrust produced by the propulsion devices is coaligned with the longitudinal axis of the hull.

 The resilient member may form, or be provided in addition to, a passive joint
20 member about which the propulsion mechanism rotates relative to the hull.

 The resilient member comprise a first element configured to bias the propulsion mechanism to be coaligned with the hull in a pitch direction, and a second element configured to bias the propulsion mechanism to be coaligned with the hull in a yaw direction.

25 The resilient member may form part of, be, or define the casing of the passive joint module.

 The underwater vehicle may comprise one or more sensors configured to track contouring of a seabed below the underwater vehicle. The controller can be configured to independently adjust the thrusts of the propulsion devices based on
30 the contouring of the seabed to remain substantially parallel to and/or equidistant from the seabed.

 The one or more sensors configured to track contouring of a seabed below the underwater vehicle may comprise altimeters, sonar transducers such as downscan and/or sidescan transducers, depth sensors, and cameras. Such

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sensors may be provided as part of a subsea surveying system and/or an imaging and illumination system.

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

10 The controller can be in communication with each propulsion device of the propulsion mechanism. Alternatively, the controller may communicate with each of the propulsion devices via a central control unit for the propulsion mechanism. The controller can also be in communication with the sensor configured to measure an angle at which the passive joint module connects the propulsion mechanism to the hull, and the one or more sensors configured to track contouring of a seabed below the underwater vehicle.

15 The underwater vehicle may weigh no more than 80kg, no more than 60kg, no more than 40kg, or no more than 20kg. The underwater vehicle may weigh about 15kg.

20 The underwater vehicle may be no more than 2.5 metres in length, or no more than 2 metres in length. The underwater vehicle may be around 1.5 metres in length.

25 Providing a lightweight and/or compact underwater vehicle may result in the underwater vehicle being more convenient to transport to its launching location. For example, the underwater vehicle may be suitable for one or two people to carry, avoiding the need for complicated and expensive crane systems for transporting, moving and launching the vehicle.

 The hull may be a single rigid hull defining at least 60% of the length of the underwater vehicle, more than 70% of the length of the underwater vehicle, or more than 80% of the length of the underwater vehicle.

30 The hull may be rigid insofar as it maintains a stiff and substantially inflexible (i.e. during operation and/or transport) housing for the various components located therein. All of the components of the underwater vehicle may be located within, on, or associated with, the rigid hull aside from the passive joint module and the propulsion mechanism. The hull may be a single hull insofar as the hull is a continuous structure, with no flexible links located between adjacent sections of the hull.

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The hull may comprise at least one handle for lifting the underwater vehicle by a person, e.g. when the underwater vehicle out of water. Optionally, the hull may comprise at least two handles. The at least one handle may extend from a side and/or a top of the hull.

5 The underwater vehicle comprises the hull, with the passive joint module connecting the propulsion mechanism to the hull at one of the tail end or the nose end of the hull. Thus, the propulsion mechanism can be considered to define the tail and/or the nose of the underwater vehicle, rather than any central portion or bulk of the underwater vehicle. Accordingly, the hull may define the majority of the
10 length of the underwater vehicle with the propulsion mechanism and passive joint module defining a minority of the length of the underwater vehicle. Such an arrangement may provide an aerodynamic, simple arrangement for an underwater vehicle with good manoeuvrability.

 The underwater vehicle may be a torpedo-shaped vessel having a
15 substantially cylindrical hull, with the propulsion mechanism and the passive joint module defining a tail end of the torpedo-shaped vessel.

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

 As well as including a propulsion module comprising the propulsion
20 mechanism and the passive joint module, the modular sections may also include one or more of: a hover module; a pair of hover modules; a navigation module; a communications module; a battery module; a data storage module; and a nose module.

 The hover module may be configured to propel the underwater vehicle in a
25 direction substantially perpendicular to a forward-aft direction of the hull. 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 underwater vehicle 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
30 parallel to the vertical axis). One of the first and second propellers may be oriented to generate thrust in a horizontal, transverse direction, and the other oriented in the vertical direction.

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

The navigation module may include one or more sensors configured to track contouring of a seabed below the underwater vehicle. These one or more sensors may be comprised in the one or more sensors for controlling and/or monitoring a position of the underwater vehicle.

5 The communications module may comprise a GPS sensor. The GPS sensor may be configured to monitor a position of the underwater vehicle, for example while the underwater vehicle is at the surface. The communications module may also comprise at least one acoustic transponder. The acoustic transponder may be for sending and/or receiving communications, and/or for
10 monitoring the position of the underwater vehicle from a topside system, typically installed on a surface vessel.

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

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

The nose module may be arranged to house a payload.

20 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 underwater vehicle may be understood as being 'modular' by virtue of the plurality of sections (i.e., modules) that are connectable together to form the underwater vehicle. The underwater vehicle may
25 therefore be referred to as a modular underwater vehicle.

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 underwater vehicle (in particular the rigid hull) once the sections are connected together.

30 The hull of the modular underwater vehicle is formed by all the sections which are rigidly connected together (as opposed to sections that are connected by flexible joints).

35 One or more of the 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. Such sections can be regarded as being 'elongate' modular sections.

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

5 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.

10 The underwater vehicle may be an autonomous underwater vehicle, AUV. Alternatively, the underwater vehicle may be a remotely operated vehicle, ROV, which may be remotely operated via a wireless data link.

The underwater vehicle is preferably not a manned underwater vehicle.

15 Viewed from a second aspect of the present invention, there is provided a method of performing subsea operations using an underwater vehicle as described according to the first aspect. The method comprises: controlling an angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices.

20 By controlling the angle at which the propulsion mechanism connects to the hull through independent control of the thrusts of the propulsion devices, steering of the underwater vehicle may be achieved using a passive joint module joining the propulsion mechanism of the underwater vehicle to its hull. Since this form of steering does not rely on the use of control surfaces, which require the underwater vehicle to be moving in the forward direction to provide a steering thrust, the manoeuvrability of the vehicle may be improved.

25 Further, passive joint modules may be cheaper, less complex, smaller and lighter than active joint modules. Accordingly, the use of a passive joint module indirectly and passively steered by the differential thrust of the propulsion devices of the propulsion mechanism to which it is connected may provide a steering mechanism that has a number of benefits compared to an active joint module.

30 As stated above, the method of the second aspect relates to performing subsea operations using the underwater vehicle of the first aspect. Accordingly, the above-description of the underwater vehicle of the first aspect may be equally applicable to the method of the second aspect. Further, the method of the second aspect may have one or more steps corresponding to, or relating to the use of, one

or more or all features, including but not limited to all technical advantages and alternative embodiments, of the underwater vehicle of the first aspect.

5 The method may comprise controlling the angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located either side of a steering axis of the passive joint module (i.e. an axis about which the passive joint module may pivot).

10 The method may comprise controlling a pitch angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located on each side of a pitch axis of the passive joint module.

The method may comprise controlling a yaw angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located on each side of a yaw axis of the passive joint module.

15 The method may comprise measuring the angle at which the passive joint module connects the propulsion mechanism to the hull; and independently controlling the thrusts of the propulsion devices based on the measured angle.

20 The method may comprise tracking a contouring of a seabed below the underwater vehicle; and independently controlling the thrusts of the propulsion devices based on the contouring of the seabed such that the underwater vehicle remains substantially parallel to and/or equidistant to the seabed.

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

25 Figure 1A shows an underwater vehicle in a perspective view;

Figure 1B shows the underwater vehicle of Figure 1A in a different perspective view;

Figure 2 shows a schematic diagram of a control system of an underwater vehicle;

30 Figures 3 illustrates a propulsion mechanism of an underwater vehicle being used to induce a yaw motion;

Figure 4 illustrates a propulsion mechanism of an underwater vehicle being used to induce a pitch motion;

Figure 5A shows a schematic diagram of a first propulsion mechanism of an underwater vehicle;

Figure 5B shows a schematic diagram of a second propulsion mechanism of an underwater vehicle; and

Figure 6 shows an underwater vehicle traversing along a seabed.

Figure 1A shows an underwater vehicle 100 from a perspective view, and
5 figure 1B shows the same underwater vehicle 100 from a different perspective view. In the present embodiment, the underwater vehicle 100 is an autonomous underwater vehicle, AUV, 100.

The AUV 100 comprises a hull 101 defining a nose end 102 and a tail end 103 of the AUV 100. Generally, in use the nose end 102 defines a forward-facing
10 end of the AUV 100 during forward propulsion of the AUV 100. A longitudinal axis of the AUV 100 extends from the nose end 102 to the tail end 103, i.e. in a forward-aft direction of the AUV 100.

The hull 101 is a rigid hull insofar as it maintains a stiff and inflexible housing for the various components located therein during normal use, e.g. during
15 operation and/or transport. The hull 101 is generally cylindrical, and comprises handles 111a, 111b to assist with lifting the AUV 100. The handles 111a, 111b protrude upward from the hull 101 to ease manoeuvrability of the AUV 100 in and out of water. A first handle 111a is located toward the nose end 102 of the AUV 100, whilst a second handle 111b is located toward the tail end 103 of the AUV 100.

The hull 101 comprises a communications module 130 which, in the present
20 embodiment, is in the form of an antenna protruding from an upper surface of the hull 101. The communications module 101 facilitates WiFi, GPS and satellite communications for the AUV 100. WiFi and satellite communications are used for communicating with any nearby vessels, whilst GPS communications are used to
25 monitor the location of the AUV 100 in order to guide navigation of the AUV 100 during operation and to log coordinates associated with sensor readings captured by the AUV 100.

The hull 101 also comprises a number of sensors to assist with navigation, which in the present embodiment are altimeters used for seabed tracking and
30 collision detection. A first altimeter 131a is located at the nose end 103, and faces in a forward direction. A second altimeter 131b is located toward the nose end 103 and is located on an underside of the hull 101, such that it faces the seabed in general use. A third altimeter 131c is located toward the tail end 103, and similarly to the second altimeter 131b, is located on an underside of the hull 101.

The hull 101 further comprises an imaging and illumination system 132a, 132b, which can be used for surveying subsea structures.

5 The AUV 100 also comprises a propulsion mechanism 105 located at the tail end 103 of the AUV 100. The propulsion mechanism 105 generates a motive force to propel the AUV 100 when subsea. The propulsion mechanism 105 is connected to the hull 101 at the tail end 103 of the AUV 100 via a passive joint module 104.

10 In certain embodiments the propulsion mechanism 105 can instead be connected to the hull 101 at the nose end 102 of the AUV 100 via the passive joint module 104. In other embodiments the AUV can comprise two propulsion mechanisms 105 joined at the nose end and the tail end of the AUV respectively, via respective passive joint modules 104.

15 The propulsion mechanism 105 shown comprises four propulsion devices 150a-d in a square arrangement, with each propulsion device 150a-d fixedly attached to a central hub of the propulsion mechanism 105. The operational speed of each the propulsion devices 150a-d is independently controllable, such that each propulsion device 150a-d can produce a different thrust if desired. The propulsion devices 150a-d are arranged such that two propulsion devices 150a,b are located above a pitch axis of the passive joint module 104 and two propulsion devices 20 150c,d are located below the pitch axis. Two propulsion devices 150a,c are similarly located on a starboard side of a yaw axis of the passive joint module 104, whilst two propulsion devices are located on a port side of the yaw axis.

Figure 2 shows a schematic diagram of a control system of the AUV 100. The AUV 100 comprises a controller 110 which is in communication with the 25 propulsion mechanism 105, as well as the other components and systems of the AUV 100. The controller 110 is configured to control an angle at which the passive joint module connects the propulsion mechanism 105 to the hull 101, through independent control of the propulsion devices 150a-d.

30 In prior art systems, rudders have been employed as control surfaces to steer the direction of forward motion of the AUV 100. However, such control surfaces require the AUV 100 to be moving forward to generate a steering thrust. Active joints have also been envisaged for steering the propulsion mechanisms of the AUV, and thus the resulting thrust, and can direct the thrust from a standstill.

The passive joint module 104 obviates the need for additional control surfaces, whilst also providing responsive steering using a simple steering mechanism, as will be explained with reference to Figures 2 and 3.

Figure 3 shows the propulsion devices 150a-d being controlled to steer the AUV 100 in a yaw direction. The propulsion devices 150a, 150c located on the starboard side of the yaw axis of the passive joint module 104 are operated at a greater operational speed than the propulsion devices 150b, 150d located on the port side of the yaw axis of the passive joint module 104, such that a differential thrust is produced about the yaw axis. The differential thrust is greater on the starboard side (c.f. the arrows representing the thrust of each respective propulsion device 150a-d), such that the propulsion mechanism 105 is steered away from the starboard side about the passive joint module 104. In turn, the resulting thrust produced by the propulsion mechanism 105 causes the AUV 100 to turn toward the port side in the yaw direction, i.e. to turn in a yaw-left direction. It will be readily appreciated that opposite control of the propulsion devices 150a-d can steer the AUV 100 in a yaw-right direction.

Figure 4 shows the propulsion devices 150a-d being controlled to steer the AUV 100 in a pitch direction. The propulsion devices 150c, 150d located below the pitch axis of the passive joint module 104 are operated at a greater operational speed than the propulsion devices 150a, 150b located above the pitch axis of the passive joint module 104, such that a differential thrust is produced about the pitch axis. The differential thrust is greater below the pitch axis (c.f. the arrows representing the thrust of each respective propulsion device 150a-d), such that the propulsion mechanism 105 pitches downward. In turn, the resulting thrust produced by the propulsion mechanism causes the AUV 100 to pitch downward, i.e. to turn in a pitch-down direction. It will be appreciated that opposite control of the propulsion devices 150a-d can steer the AUV 100 in a pitch-up direction.

Thus, the AUV 100 is steered by independently controlling the operational speeds of the propulsion devices 150a-d located on axially opposing sides of the passive joint module 104, such that a differential thrust affects the angle at which the propulsion mechanism 105 joins to the hull 101 via the passive joint module 104.

In the present embodiment, two propulsion devices 150a, 150b are located above the pitch axis P-P' of the passive joint module 104, whilst the other two propulsion devices 150c, 150d are located below the pitch axis P-P' of the passive

joint module 104 and opposite the upper propulsion devices 150a, 150b. Two propulsion devices 150a, 150c are also located on a starboard side of the yaw axis Y-Y' of the passive joint module 104, whilst the other two propulsion devices 150b, 150d are located on the port side of the yaw axis Y-Y' of the passive joint module 104 and opposite the starboard side propulsion devices 150a, 150b. This arrangement is illustrated schematically in Figure 5A. Such an arrangement can provide more responsive steering since selective control of each of the propulsion devices 150a-d can generate a turning force in either or both of the pitch direction or the yaw direction at any time.

An alternative arrangement for a propulsion mechanism 105' is illustrated schematically in Figure 5B. In this arrangement, the propulsion devices 150a-d are again arranged in a square arrangement. However, in this arrangement, a first pair of propulsion devices 150a', 150b' are located coaxially along a pitch axis P-P' of the passive joint module 104, and on opposite sides of a yaw axis Y-Y' of the passive joint module 104. A second pair of propulsion devices 150c', 150d' are located coaxially along the yaw axis Y-Y' of the passive joint module 104, and on opposite sides of the pitch axis P-P' of the passive joint module 104. Using this arrangement, steering in the yaw direction is controlled by controlling only the first pair of propulsion devices 150a', 150b'; and steering in the pitch direction is controlled by controlling only the second pair of propulsion devices 150c', 150d'.

It will be appreciated that the angle at which the propulsion mechanism 105 connects to the hull 101 via the passive joint module 104 can be influenced by the differential thrust of a single pair of propulsion devices 150. For example, in certain embodiments steering may be controlled about only the pitch or the yaw axis, with other steering mechanisms used to control the yaw or pitch of the AUV 100.

In the present embodiment the passive joint module 104 is a flexural coupling that has two degrees of freedom, thus enabling yawing and pitching of the propulsion mechanism relative to the hull. The passive joint module 104 also comprises an elastic material that acts to restore the propulsion mechanism 105 into coalignment with the hull 101 (i.e. substantially zero yaw or pitch angle between the propulsion mechanism 105 and the hull 110) when there is no difference in the operational speed of the propulsion devices 150a-d.

With reference to figure 2, the passive joint module 104 also comprises a sensor 104a which, in the present embodiment, is a magnetic encoder. The sensor 104a is configured to measure an angle at which the passive joint module 104

connects the propulsion mechanism 105 to the hull 101. The controller 110 is in communication with the sensor 104a, and is configured to independently adjust the thrusts of each of the propulsion devices 150a-d based on the angle measured by the sensor 104a. The sensor 104a accordingly provides a further feedback input by which the steering angle of the AUV 100 can be monitored and controlled.

Figure 6 illustrates an AUV 100 navigating during subsea operations, and how it controlled through indirect control of the passive joint module 104. The AUV 100 is shown traversing the seabed S, which comprises a flat portion S' and a hill portion S''. The AUV 100 traverses from left to right in figure 6, such that the AUV 100 progresses from position A, then to position B, and then to position C. The position of the AUV 100 is controlled by steering the AUV 100 via independently controlling the propulsion devices 150a-d of the propulsion mechanism 105, such that the angle at which the passive joint module 104 connects the propulsion mechanism 105 to the hull 101 is indirectly controlled.

The AUV 100 follows a path generally parallel to the contours of the seabed S. At position A, the AUV 100 travels generally parallel to the flat portion S' of the seabed S, with zero pitch control induced through the passive joint module 104.

As the AUV 100 traverses the seabed S, the controller 110 receives data or signals indicative of the contouring of the seabed S measured by the altimeters 131 and the imaging and illumination system 132. The controller 110 will independently adjust the thrusts of each propulsion device 150a-d such that the AUV 100 then maintains a substantially parallel trajectory and equidistant position relative to the seabed S.

As the AUV 100 approaches the hill portion S' of the seabed S at position B, the controller 110 controls the propulsion devices 150a-d such that those below the pitch axis P-P' produce a greater thrust than those above the pitch axis P-P' of the passive joint module 104. The result is that the propulsion mechanism 105 connects to the hull 101 at an angle so as to induce a pitch up motion of the nose end 102 of the hull 101 through indirect steering of the propulsion mechanism 105 via the passive joint module 104. The AUV 100 thus pitches up and follows the uphill contouring of the hill portion S''.

At position C, the AUV 100 breaches the summit of the hill portion S'' and is therefore controlled so as to induce a pitch down motion. The controller 110 now controls the propulsion devices 150a-d such that those above the pitch axis P-P' produce a greater thrust than those below the pitch axis P-P' of the passive joint

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module. The result is that the propulsion mechanism 105 connects to the hull 101 at an angle so as to induce a pitch down motion of the nose end 102 of the hull 101 through indirect steering of the propulsion mechanism 105 via the passive joint module 104. The AUV 100 thus pitches down, and follows the downhill contouring
5 of the hill portion S''.

CLAIMS

1. An underwater vehicle for performing subsea operations, comprising:
a hull comprising a nose end and a tail end;
5 a propulsion mechanism configured to propel the underwater vehicle;
a passive joint module connecting the propulsion mechanism to the hull at
one of the tail end or the nose end of the hull; and
a controller in communication with the propulsion mechanism;
wherein the propulsion mechanism comprises a pair of propulsion devices
10 configured to generate thrust to propel the underwater vehicle through water, the
thrust of each propulsion device being independently controllable; and
wherein the controller is configured to control an angle at which the passive
joint module connects the propulsion mechanism to the hull through independent
control of the thrust of each of the propulsion devices.
15
2. An underwater vehicle as claimed in claim 1, wherein the pair of propulsion
devices is a pair of counter-rotating propellers, the propellers being located on
axially opposite sides of the underwater vehicle, and wherein the thrust of each
propeller is controlled by controlling a rotational speed of that propeller.
20
3. An underwater vehicle as claimed in claim 1 or 2, wherein the propulsion
mechanism comprises a second pair of propulsion devices configured to generate
thrust to propel the underwater vehicle through water, the thrust of each of the
second pair of propulsion devices being independently controllable; and
25 wherein the passive joint module is configured to permit motion of the
propulsion mechanism about a pitch axis and a yaw axis, relative to the hull,
through independent control of the thrust of each of the propulsion devices.
4. An underwater vehicle as claimed in claim 3, wherein the controller is
30 configured to control a pitch angle at which the passive joint module connects the
propulsion mechanism to the hull through independent control of the thrust of the
propulsion devices located either side of the pitch axis of the passive joint module.
5. An underwater vehicle as claimed in claim 3 or 4, wherein the controller is
35 configured to control a yaw angle at which the passive joint module connects the

propulsion mechanism to the hull through independent control of the thrust of the propulsion devices located either side of the yaw axis of the passive joint module.

- 5 6. An underwater vehicle as claimed in claim 3, 4 or 5, wherein at least one propulsion device is located on each vertical of the underwater vehicle for pitch control, and wherein at least one propulsion device is located on each horizontal side of the underwater vehicle for yaw control.
- 10 7. An underwater vehicle as claimed in claim 6, wherein at least two propulsion devices are located on each vertical side of the underwater vehicle for pitch control, and wherein at least two propulsion devices are located on each horizontal side of the underwater vehicle for yaw control.
- 15 8. An underwater vehicle as claimed in any preceding claim, wherein the passive joint module comprises a sensor configured to measure an angle at which the passive joint module connects the propulsion mechanism to the hull;
 wherein the controller is configured to independently adjust the thrust of each of the propulsion devices based on the measured angle.
- 20 9. An underwater vehicle as claimed in any preceding claim, wherein the passive joint module comprises a resilient member formed of an elastic material and being arranged to bias the propulsion mechanism to be coaligned with the hull when there is no difference in the thrust of the propulsion devices.
- 25 10. An underwater vehicle as claimed in any preceding claim, comprising:
 one or more sensors configured to track contouring of a seabed below the underwater vehicle;
 wherein the controller is configured to independently adjust the thrust of the propulsion devices based on the contouring of the seabed to remain substantially
30 parallel to and/or equidistant from the seabed.
11. An underwater vehicle as claimed in any preceding claim, wherein the underwater vehicle weighs no more than 40kg.

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12. An underwater vehicle as claimed in any preceding claim, wherein the underwater vehicle is no more than 2.5 metres in length.
13. An underwater vehicle as claimed in any preceding claim, wherein the hull is
5 a single rigid hull defining at least 60% of the length of the underwater vehicle.
14. An underwater vehicle as claimed in any preceding claim, wherein the underwater vehicle is an autonomous underwater vehicle, AUV.
- 10 15. A method of performing subsea operations using an underwater vehicle as claimed in any preceding claim, the method comprising:
controlling an angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrust of the propulsion devices.
- 15 16. A method as claimed in claim 15, comprising:
controlling a pitch angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located on each side of a pitch axis of the passive joint module.
- 20 17. A method as claimed in claim 15 or 16, comprising:
controlling a yaw angle at which the passive joint module connects the propulsion mechanism to the hull through independent control of the thrusts of the propulsion devices located on each side of a yaw axis of the passive joint module.
- 25 18. A method as claimed in claim 15, 16 or 17, comprising:
measuring the angle at which the passive joint module connects the propulsion mechanism to the hull; and
independently controlling of the thrusts of the propulsion devices based on
30 the measured angle.
19. A method as claimed in any of claims 15 to 18, comprising:
tracking a contouring of a seabed below the underwater vehicle; and

independently controlling the thrusts of the propulsion devices based on the contouring of the seabed such that the underwater vehicle remains substantially parallel to and/or equidistant to the seabed.