

AUTONOMOUS ASCENT OF AN UNDERWATER VEHICLE

TECHNICAL FIELD

The presently disclosed subject matter relates to autonomous vehicles, and in particular to methods of controlling ascent of an autonomous underwater vehicles.

BACKGROUND

Problems of implementation in autonomous underwater vehicles have been recognized in the conventional art and various techniques have been developed to provide solutions.

10 GENERAL DESCRIPTION

According to one aspect of the presently disclosed subject matter there is provided a processing circuitry-based method of method of controlling ascent of an underwater vehicle (UV) from a safety depth to a water surface, the method comprising:

- 15 a) at the safety depth, controlling the UV to collect, from a passive sonar associated with the UV, first data indicative of first locations of surface targets within a first surface area of interest;
- b) controlling ascent of the UV to an intermediate depth in accordance with, at least, the first data;
- 20 c) at the intermediate depth, controlling the UV to collect second data indicative of second locations of surface targets within a second surface area of interest, wherein the second data comprises one or more of:
 - 25 a. data from a passive sonar associated with the UV,
 - b. data from one or more magnetic sensors associated with the UV,

- c. data from an active sonar associated with the UV, and
- d. data from a light detection and ranging (LIDAR) scanner associated with the UV;

- 5 d) controlling ascent of the UV to a periscope depth in accordance with, at least, the second data,

 wherein: the safety depth is not less than 15 meters beneath the surface,
 the intermediate depth is not less than 5 meters below the surface, and the
10 periscope depth is less than 8 meters below the surface.

 In addition to the above features, the method according to this aspect of the presently disclosed subject matter can comprise one or more of features (i) to (xiv) listed below, in any desired combination or permutation which is technically possible:

- 15 (i) the method additionally comprising:

- e) controlling ascent of the UV to the surface, in accordance with, at least, data from at least one mast-based sensor.

- 20 (ii) the at least one mast-based sensor includes at least one sensor from a group consisting of: an optical sensor, and a radar sensor.

- (iii) controlling ascent of the UV to the intermediate depth comprises:

 initiating ascent, responsive to determining, from the first data, a surfacing
25 zone from which detected surface targets are absent at a time of the collecting.

- (iv) the controlling ascent of the UV to the intermediate depth comprises:

 initiating ascent, responsive to determining, from the first data, a surfacing
30 zone from which detected surface targets are absent at a time subsequent to a time of the collecting.

- (v) the controlling ascent of the UV to an intermediate depth comprises:
- 5 delaying ascent, responsive to failure to detect, from the first data, a
 surfacing zone in which detected surface targets are absent at a time of the
 collecting.
- (vi) the controlling ascent of the UV to the periscope depth comprises:
- 10 initiating ascent, responsive to determining, from the second data, a
 surfacing zone from which detected surface targets are absent at a time of
 the collecting.
- (vii) the controlling ascent of the UV to the periscope depth comprises:
- initiating ascent, responsive to determining, from the second data, a
 surfacing zone from which detected surface targets are absent at a time
 subsequent to a time of the collecting.
- 15 (viii) the determining the surfacing zone is in accordance with: respective detected
 locations, respective detected directions, and respective detected velocities of
 the surface targets.
- (ix) the determining the surfacing zone is in further accordance with respective
- 20 target-specific minimum distances.
- (x) the controlling ascent of the UV to periscope depth comprises:
- 25 delaying ascent, responsive to failure to detect, from the second data, a
 surfacing zone in which detected surface targets are absent at a time of the
 collecting.

- (xi) the second data comprises data from a first magnetic sensor sensing in an upward direction and a second magnetic sensor sensing in a downward direction.
- 5 (xii) the second data comprises data from an active sonar that is a tiltable forward-looking sonar.
- (xiii) the tiltable forward-looking sonar can sense sound from at least 45 degrees above horizontal.
- 10 (xiv) the second data comprises:
 - a. data from a passive sonar associated with the UV,
 - 15 b. data from one or more magnetic sensors associated with the UV, and
 - c. data from an active sonar associated with the UV;

According to a further aspect of the presently disclosed subject matter there is provided a processing circuitry-based method of controlling ascent of an underwater vehicle (UV) from a safety depth to a water surface, the system comprising a processing circuitry configured to:

20

- a) at the safety depth, control the UV to collect, from a passive sonar associated with the UV, first data indicative of first locations of surface targets within a first surface area of interest;
- 25 b) control ascent of the UV to an intermediate depth in accordance with, at least, the first data;

- c) at the intermediate depth, control the UV to collect second data indicative of second locations of surface targets within a second surface area of interest, wherein the second data comprises one or more of:

- 5 a. data from a passive sonar associated with the UV,
 b. data from one or more magnetic sensors associated with the UV,
 c. data from an active sonar associated with the UV, and
 d. data from a light detection and ranging (LIDAR) scanner associated with the UV; and

10

- d) control ascent of the UV to a periscope depth in accordance with, at least, the second data,

15

wherein: the safety depth is not less than 15 meters beneath the surface, the intermediate depth is not less than 5 meters below the surface, and the periscope depth is less than 8 meters below the surface.

This aspect of the disclosed subject matter can further optionally comprise one or more of features (i) to (xiv) listed above with respect to the system, mutatis mutandis, in any desired combination or permutation which is technically possible.

20

According to another aspect of the presently disclosed subject matter there is provided a computer program product comprising a non-transitory computer readable storage medium retaining program instructions, which, when read by a processing circuitry, cause the processing circuitry to perform a method of controlling ascent of an underwater vehicle (UV) from a safety depth to a water surface, the method comprising:

25

- a) at the safety depth, controlling the UV to collect, from a passive sonar associated with the UV, first data indicative of first locations of surface targets within a first surface area of interest;

- b) controlling ascent of the UV to an intermediate depth in accordance with, at least, the first data;
- 5 c) at the intermediate depth, controlling the UV to collect second data indicative of second locations of surface targets within a second surface area of interest, wherein the second data comprises one or more of:
- 10 a. data from a passive sonar associated with the UV,
b. data from one or more magnetic sensors associated with the UV,
c. data from an active sonar associated with the UV, and
d. data from a light detection and ranging (LIDAR) scanner associated with the UV;
- 15 d) controlling ascent of the UV to a periscope depth in accordance with, at least, the second data,
- wherein: the safety depth is not less than 15 meters beneath the surface, the intermediate depth is not less than 5 meters below the surface, and the periscope depth is less than 8 meters below the surface.

20 This aspect of the disclosed subject matter can further optionally comprise one or more of features (i) to (xiv) listed above with respect to the system, mutatis mutandis, in any desired combination or permutation which is technically possible.

BRIEF DESCRIPTION OF THE DRAWINGS

25 In order to understand the invention and to see how it can be carried out in practice, embodiments will be described, by way of non-limiting examples, with reference to the accompanying drawings, in which:

Fig. 1A which illustrates an example scenario of autonomous ascent of an autonomous underwater vehicle, in accordance with some embodiments of the presently disclosed subject matter.

5 **Fig. 1B** illustrates an example surface zone of interest during autonomous ascent of an autonomous underwater vehicle, in accordance with some embodiments of the presently disclosed subject matter.

Fig. 1C illustrates an example surface zone of interest during autonomous ascent of an autonomous underwater vehicle, in accordance with some embodiments of the presently disclosed subject matter.

10 **Fig. 1D** illustrates an example surface zone of interest during autonomous ascent of an autonomous underwater vehicle, in accordance with some embodiments of the presently disclosed subject matter.

Fig. 1E illustrates an example surfacing zone that can be identified by an AUV from safety depth.

15 **Fig. 2**, illustrates a block diagram of an AUV with autonomous ascent capability, in accordance with some embodiments of the presently disclosed subject matter;

Fig. 3, illustrates a logical block diagram of an example autonomous ascent controller system, in accordance with some embodiments of the presently disclosed subject matter; and

20 **Fig. 4**, illustrates a flow diagram of an example method of ascent of an autonomous underwater vehicle, in accordance with some embodiments of the presently disclosed subject matter.

DETAILED DESCRIPTION

25 In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those skilled in the art that the presently disclosed subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, components

and circuits have not been described in detail so as not to obscure the presently disclosed subject matter.

Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as "processing", "computing", "comparing", "steering", "collecting", "determining", "calculating", "receiving", "providing", "obtaining", "scanning", "ascending" or the like, refer to the action(s) and/or process(es) of a computer that manipulate and/or transform data into other data, said data represented as physical, such as electronic, quantities and/or said data representing the physical objects. The term "computer" should be expansively construed to cover any kind of hardware-based electronic device with data processing capabilities including, by way of non-limiting example, the processor, mitigation unit, and inspection unit therein disclosed in the present application.

The terms "non-transitory memory" and "non-transitory storage medium" used herein should be expansively construed to cover any volatile or non-volatile computer memory suitable to the presently disclosed subject matter.

The operations in accordance with the teachings herein may be performed by a computer specially constructed for the desired purposes or by a general-purpose computer specially configured for the desired purpose by a computer program stored in a non-transitory computer-readable storage medium.

Embodiments of the presently disclosed subject matter are not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the presently disclosed subject matter as described herein.

In existing deployments of autonomous underwater vehicles (AUVs), external control (e.g. from a ship on the surface, typically with human involvement) is required to ensure collision-free AUV ascent to the surface.

Human-guided surface-vehicle-based AUV can be viewed as an intuitive task that is performed by experienced personnel and not easily automated.

Autonomous AUV ascent (e.g. without assistance from a surface entity) is a desired feature.

- 5 Challenges of autonomously controlled ascent of an underwater vehicle include:
- Wakes on the surface of the water, which may create noise and mask actual targets on the water surface and impede their detection
 - Large objects (ships) that mask smaller objects and impede their detection
 - 10 • False alarms due to the contour of the seabed, as well as other objects located on the seabed
 - Difficulty in continuous tracking of detected targets in an environment densely populated with ships due to high false alarm rate
 - 15 • Underwater sonars have various limitations:
 - Passive sonars can detect only targets which generate noise, so e.g. sailboats can't be detected passively
 - 20 ○ Active sonars can typically detect only vessels that are typically large
 - Forward-looking Sonars (FLS) are typically limited to very close ranges.

25 In some embodiments of the presently disclosed subject matter, an AUV includes an autonomous ascent system which utilizes phased ascent and detections, differentiates between real objects and noise and tracks objects, and performs final ascent in a manner that allows rapid descent upon optical and/or radar detection of objects at the surface.

30 In some embodiments of the presently disclosed subject matter, autonomous AUV ascent is stealthful i.e. utilizes mechanisms that avoid detection by other parties.

In the description hereinbelow, **Figs. 1A-1E** illustrate example stages of autonomous ascent. **Fig. 2** illustrates an example AUV with relevant detection systems, and **Figs. 4, 5A, and 5B** illustrate flow diagrams of example methods utilizing the detection systems and ascent phases.

5 Attention is directed to **Fig. 1A** which illustrates an example scenario of autonomous ascent of an autonomous underwater vehicle (AUV) **105**, in accordance with some embodiments of the presently disclosed subject matter.

 Safety depth **110** can be a depth at which AUV **105** generally travels and at which there are generally no obstacles. In some examples, safety depth **110** can be not less than
10 15 meters beneath surface **150** to effectively avoid collisions (e.g. 20 meters beneath surface **150**).

 Periscope depth **130** can be a depth at which AUV **105** can extend radar and/or optical scanning equipment above water. In some examples, periscope depth **110** can be less than 8 meters beneath surface **150** (e.g. 3 meters beneath surface **150**).

15 Various surface objects **115A 115B** (e. g. ships) can be stationed or moving on or near surface **150**. When autonomously ascending, AUV **105** can attempt to avoid these objects, thereby obviating the need for assisted ascent.

 AUV **105** can autonomously ascend in stages. In some embodiments, AUV **105** initially assesses whether ascent will be collision-safe, and then ascends from safety
20 depth **110** to first intermediate depth **120**. AUV **105** can then assess whether the remainder of the ascent will be collision-safe, and then ascend from first intermediate depth **120** to periscope depth **120**. AUV **105** can then perform a final assessment of whether ascending to surface **150** is collision-safe. If, at any stage, AUV **105** assesses a likelihood of collision, AUV **105** can either remain at its current depth or descend to a
25 different depth.

 In some other embodiments, AUV **105** ascends from first intermediate depth **120** to second intermediate depth **120**, performs an additional assessment of collision-safety, and then ascends to periscope depth **140**.

In some embodiments, the intermediate depth from which AUV **105** performs an assessment of collision-safety (i.e. before initiating ascent to periscope depth) can be not less than 5 meters (so as to effectively avoid collisions).

Attention is directed to **Figs. 1B-1D** which illustrate example surface zones of interest during autonomous ascent of an autonomous underwater vehicle (AUV) **105**, in accordance with some embodiments of the presently disclosed subject matter.

Fig. 1B illustrates a surface zone of interest **170B**. Safety depth scanning zone **160B** is associated with surface zone of interest **170B**. At safety depth, surface zone of potential collision **170B** is comparatively large, as AUV **105** needs to detect surface objects **105A 105B** in a comparatively large area, as these might move towards AUV **105** during its ascent. In some embodiments, AUV **105** can utilize a value larger than 1 kilometer (km) (e.g. 2 km) as a diameter of surface zone of interest **170B** when at safety depth.

Fig. 1C illustrates a narrower surface zone of interest **170C**. First intermediate scanning zone **160C** is associated with surface zone of interest **170C**. surface zone of interest **170C** is smaller than at safety depth **110**, as the range in which surface objects **105A 105B** can interfere with ascent is reduced. In some embodiments, AUV **105** can utilize a value larger than .5 kilometer (km) (e.g. 1 km) as the diameter of the surface zone of interest when at first intermediate depth.

Fig. 1D illustrates an optional second intermediate surface zone of interest **170D**, and shows how its size is reduced further.

Fig. 1E illustrates a surfacing zone **180E** that can be identified by AUV **105** from safety depth **110**. Surfacing zone **180E** can be a zone that is free of detected targets, and thus an appropriate place for AUV **105** to emerge above surface **150**.

Attention is directed to **Fig. 2**, which illustrates a block diagram of an AUV with autonomous ascent capability, in accordance with some embodiments of the presently disclosed subject matter.

In some embodiments, AUV **105** is composed of a non-magnetic material e.g. aluminum or fiberglass, so as to reduce the magnetic signature and facilitate use of magnetic sensors (which would be disrupted if AUV **105** had substantially metallic composition). In some embodiments, AUV **105** is of comparatively small size (e.g. 1.5
5 meters in diameter), thereby enabling it to operate at a safety depth of e.g. 15-20m. Larger submarines can be required to operate at a lower safety depth (e.g. 40m).

Flank Array Sonar (FAS) **240** can be a passive or active/passive sonar that consists of 2 arrays – one on each side of AUV **105** . The arrays can be operably connected to transducer **260** for use in active mode.

10 When used in passive mode, FAS **240** can receive ambient sound in order to detect the presence of sound-generating objects such as an engine or a ship in motion. FAS **240** can have a range of detection that is – for example - as high as 1-2 kilometers (km) or more.

It is noted that - in some embodiments – an area of about 15 degrees behind AUV
15 **105** may be inaccessible to FAS **240**. Thus it can be necessary to turn the vehicle in order to scan this area.

In some embodiments, FAS **240** in passive mode is unable to provide information indicative of the specific direction of a detected object. Accordingly, AUV **105** can travel in a manner that enables FAS **240** to gather sonar data from multiple locations and
20 perform analysis of the data so as to locate and track targets. Travelling in this manner is herein termed a "scanning maneuver".

In some embodiments, FAS **240** in passive mode performs – for example - target motion analysis to determine distances and directions to detected objects.

In some embodiments, the detection envelope of FAS **240** is ring-shaped or tubed-
25 shaped and encircles AUV **105**. To avoid detection of objects below or lateral to AUV **105** , FAS **240** can utilize an appropriate threshold based on a noise level measured in the platform area.

In some embodiments, FAS **240** can operate in active mode. By way of non-limiting example, FAS **240** can perform active sonar detection by operating in tandem with transducer **260**. FAS **240** in active mode can operate at a lower frequency than Tiltable Forward Looking Sonar **230**, and can thereby have a longer range. In some
5 embodiments, FAS **240** in active mode can generate a directed pulse.

FAS **240** can be operably connected to an autonomous tracker (not shown). The autonomous tracker can include a tracking algorithm which identifies objects and tracks their motion. In some embodiments, FAS **240** includes an algorithm (e.g. an algorithm based on a Fourier Transform or on machine learning) that distinguishes targets such as
10 ships from other detected objects (e.g. wakes etc.).

In some embodiments, the autonomous tracker can determine maneuvers to be taken by AUV **105** in order to e.g. scan the rear blind area or determine locations of targets. In some embodiments, the autonomous tracker is collocated or integrated with FAS **240**. In some embodiments, the autonomous tracker is collocated or integrated with
15 autonomous ascent controller **250**.

Tiltable Forward Looking Sonar (FLS) **230** can be an active sonar located on the front of AUV **105** that detects objects in the path of AUV **105** as it moves underwater horizontally.

In many prior art systems, forward looking sonar is used to ensure that no
20 obstacles impede forward movement of the vehicle. In some embodiments of the presently disclosed subject matter, tiltable FLS **230** is additionally utilized to detect objects above AUV **105**, and thereby enable autonomous ascent. In many prior art systems, the forward looking sonar can have a detection range of e.g. tens of meters – which can be sufficient for avoiding collisions in forward movement.

25 In order to additionally detect potentially colliding surface targets from e.g. intermediate depth, tiltable FLS **230** can be equipped with a mechanical or electronic method that enables it to direct sonar pulses in an upward direction. Tiltable FLS **230** can have a range of – for example - 200 meters. Accordingly tiltable FLS **230** can have an

appropriately strong transmitter. In some embodiments, tiltable FLS **230** can sense sound from at least 45 degrees above horizontal.

Magnetic sensor **220A** can be attached to an upper surface of AUV **105** and be configured to sense upward. Magnetic sensor **220B** can be attached to a lower surface of AUV **105** and be configured to sense downward. Magnetic sensors **220A 220B** can be –
5 for example – magnetometers which measure magnetic signals according to the proximity of metallic objects. Each magnetic sensors **220A 220B** can have a detection range of, for example, 50 to 500 meters.

In some embodiments, magnetic sensors **220A 220B** are part of optional
10 gradiometer **270**, which can reduce the noise level of the magnetic sensor signal. Magnetic sensors **220A 220B** can measure a magnetic field (e.g. field strength/ field direction). Gradiometer **270** can evaluate the difference between two measurements to determine whether a detected object is above or below AUV **105**.

AUV **210** can be equipped with a light detection and ranging (LIDAR) sensor (not
15 shown). The LIDAR sensor can be a green laser LIDAR, which enables detection of small or thin underwater objects (such as fishing nets or plastic rope). The LIDAR sensor can have a range of e.g. 100 meters.

Autonomous ascent controller **250** can be equipped with an object detection/
classification algorithm utilizing the FLS active sonar data pertaining to zone above it. In
20 some embodiments, this algorithm can also do target tracking. By way of non-limiting example, a three-layer method can be used

- a) Autonomous ascent controller **250** can employ a constant false alarm rate detector to take into account a cluttered environment
- 25 b) Autonomous ascent controller **250** can then apply a deep learning network is to exclude detections from clutter.
- c) Autonomous ascent controller **250** can then apply a geometrical-blob-based classifier.

Autonomous ascent controller **250** can utilize the FAS passive sonar data to detect and track targets in the zone above.

Attention is now directed to **Fig. 3**, which illustrates a logical block diagram of an example autonomous ascent controller system, in accordance with some embodiments of
5 the presently disclosed subject matter.

Autonomous ascent controller **250** can include a processing circuitry **310**. Processing circuitry **310** can include a processor **320** and a memory **330**.

Processor **320** can be a suitable hardware-based electronic device with data processing capabilities, such as, for example, a general purpose processor, digital signal
10 processor (DSP), a specialized Application Specific Integrated Circuit (ASIC), one or more cores in a multicore processor etc. Processor **320** can also consist, for example, of multiple processors, multiple ASICs, virtual processors, combinations thereof etc.

Memory **330** can be, for example, a suitable kind of volatile and/or non-volatile storage, and can include, for example, a single physical memory component or a plurality
15 of physical memory components. Memory **330** can also include virtual memory. Memory **330** can be configured to, for example, store various data used in computation.

Processing circuitry **310** can be configured to execute several functional modules in accordance with computer-readable instructions implemented on a non-transitory computer-readable storage medium. Such functional modules are referred to hereinafter
20 as comprised in the processing circuitry. These modules can include, for example, flank array sonar control unit **340**, forward-looking sonar control unit **350**, and magnetic sensor monitoring unit **360**, and ascent control unit **370**.

Attention is now directed to **Fig. 4**, which illustrates a flow diagram of an example method of ascent of an autonomous underwater vehicle, in accordance with
25 some embodiments of the presently disclosed subject matter.

One challenge of autonomous UV ascent is preventing collisions with targets at or near the water surface.

Accordingly, at safety depth, autonomous ascent controller **250** can seek to identify targets in a wide surface zone of interest (for example: diameter of 2 km), in order to have awareness of targets that may be moving towards a potential surfacing zone. Similarly, autonomous ascent controller **250** can seek to identify targets that are
5 currently located in a potential surfacing zone, including targets that may soon move out of the potential surfacing zone.

To identify surface targets over a large area, processing circuitry **310** (e.g. ascent control unit **370**) can utilize wide-area passive sonar to receive sound from noise-generating targets (such as an engine or a moving ship).

10 Accordingly, when an AUV **105** is at safety depth, processing circuitry **310** (e.g. ascent control unit **370**) can control (**410**) the AUV **105** to collect passive sonar data that is informative of the presence of targets within an initial surface zone of interest. The collected passive sonar can also be more generally be informative of any sound-generating targets at any depth of safety depth scanning zone **160B**.

15 By way of non-limiting example, processing circuitry **310** (e.g. ascent control unit **370**) can perform a scanning maneuver such as steering AUV **105** in a u-shaped or other pattern so as to:

a) receive data from blind spots (such as the rear area in some types of AUV **105** as described above with reference to **Fig. 2**)

20

b) receive data from a series of positions so as to be able to locate and track the surface targets (as described above with reference to **Fig. 2**). Tracking the surface targets enables processing circuitry **310** (e.g. ascent control unit **370**) to determine a surfacing zone based on future locations of the targets.

25 In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) confirms the presence of identified targets by using passive sonar in active mode (for example: by utilizing transducer **260**).

Processing circuitry **310** (e.g. ascent control unit **370**) can next control (**430**) AUV **105** ascent to intermediate depth **120** in accordance with the collected passive sonar data.

In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) analyzes the collected passive sonar data to determine whether there is a surfacing zone that is clear of detected targets at the time of the collecting the data, and controls AUV **105** accordingly to initiate ascent.

5 In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) determines whether there is a surfacing zone that is clear of detected targets at the time subsequent to the time of the collecting the data (e.g. at an estimated time of AUV **105** arriving at the surfacing zone). Processing circuitry **310** (e.g. ascent control unit **370**) can perform this determination in accordance with respective detected locations, respective
10 detected directions, and respective detected velocities of the surface targets. Processing circuitry **310** (e.g. ascent control unit **370**) can control AUV **105** accordingly to initiate ascent.

In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) controls AUV **105** to steer it toward the determined surfacing zone.

15 In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) utilizes the collected passive sonar data in another suitable manner – for example: by steering AUV **105** away from noise sources.

It is noted that processing circuitry **310** (e.g. ascent control unit **370**) can – for example - perform additional scanning maneuvers and collect additional passive sonar
20 data, or perform additional descents and re-ascents before arrival at intermediate depth **120**.

In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) can, responsive to failure to detect a current surfacing zone clear of detected targets, postpone ascent. In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) can,
25 responsive to failure to detect a future surfacing zone clear of detected targets, postpone ascent.

It is noted that processing circuitry **310** (e.g. ascent control unit **370**) can use other information in conjunction with the collected passive sonar data to control AV ascent.

At intermediate depth, processing circuitry **310** (e.g. ascent control unit **370**) can – in preparation for ascent to periscope depth attempt to detect targets in the region directly above AUV **105**. Moreover, the surface zone of interest **170C** is smaller (e.g. 500-800m). Accordingly autonomous ascent controller **250** can seek to identify targets in the narrower surface zone of interest using passive sonar, active sonar, and magnetic detection. In some embodiments, autonomous ascent controller **250** utilizes at least one of a group consisting of: passive sonar, active sonar, magnetic detection, and LIDAR.

Thus, at intermediate depth, processing circuitry **310** (e.g. ascent control unit **370**) can control the AUV **105** to collect **(440)** second data that is informative of the presence of targets within a surface zone of interest. The second data can include one or more of:

- a. passive sonar data (e.g. as described above for safety depth)
- b. magnetic sensor data (e.g. from gradiometer **270**), and
- c. active sonar data (e.g. from tiltable forward-looking sensor **230**)
- d. LIDAR (e.g. green laser LIDAR (not shown)).

By way of non-limiting example, processing circuitry **310** (e.g. ascent control unit **370**) can perform a scanning maneuver such as steering AUV **105** in a u-shaped or other pattern so as to:

- a) receive data from blind spots (such as the rear area in some types of AUV **105** as described above with reference to **Fig. 2**)
- b) receive data from a series of positions so as to be able to locate and track the surface targets (as described above with reference to **Fig. 2**). Tracking the surface targets enables processing circuitry **310** (e.g. ascent control unit **370**) to determine a surfacing zone based on future locations of the targets.

Processing circuitry **310** (e.g. ascent control unit **370**) can next control **(460)** AUV **105** ascent to periscope depth **140** based on the second data.

In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) analyzes the second data to determine whether there is (or whether there will be) a surfacing zone clear of targets, and controls AUV **105** accordingly.

5 In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) determines whether there is a surfacing zone that is clear of detected targets at the time subsequent to the time of the collecting the data (e.g. at an estimated time of AUV **105** arriving at the surfacing zone). Processing circuitry **310** (e.g. ascent control unit **370**) can perform this determination in accordance with respective detected locations, respective detected directions, and respective detected velocities of the surface targets. Processing
10 circuitry **310** (e.g. ascent control unit **370**) can control AUV **105** accordingly to initiate ascent to periscope depth.

In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) utilizes the second data in another suitable manner – for example: by postponing ascent until all sensors indicate absence of targets in the surface zone of interest.

15 In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) makes a determination to ascend to periscope depth only if there are no targets within a "one minute zone" of the point of ascent i.e. if processing circuitry **310** (e.g. ascent control unit **370**) determines that a target could reach the ascent point within one minute (given its detected current location, direction, and velocity), processing circuitry **310** (e.g.
20 ascent control unit **370**) will not control AUV **105** to ascend. In some other embodiments, processing circuitry **310** (e.g. ascent control unit **370**) uses a time other than one minute to make the determination of ascent.

The term "target-specific minimum distance" as used herein refers to a distance from a target at which the AUV **105** target must be located to ensure that the target
25 cannot collide with AUV **105** within a given period of time (e.g. one minute – in the case of the "one minute zone") – given the target's location, direction and velocity. The period of time utilized can be statically or dynamically selected so as to provide AUV **105** with enough time to descend if AUV **105** detects proximate targets at the surface using optical sensors and/or radar sensors.

It is noted that processing circuitry **310** (e.g. ascent control unit **370**) can – for example - perform additional scanning maneuvers and collect additional data, or perform additional descents and re-ascents before arrival at periscope depth **120**.

5 In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) can, responsive to failure to detect a current surfacing zone clear of detected targets, postpone ascent or initiate descent. In some embodiments, processing circuitry **310** (e.g. ascent control unit **370**) can, responsive to failure to detect a future surfacing zone clear of detected targets, postpone ascent or initiate descent.

10 From periscope depth, processing circuitry **310** (e.g. ascent control unit **370**) can detect (**470**) targets at surface e.g. using an optical sensor and/or radar sensor attached to a mast. If a proximate target is detected, processing circuitry **310** (e.g. ascent control unit **370**) can control AUV **105** to descend.

15 Finally, processing circuitry **310** (e.g. ascent control unit **370**) can, in the absence of detecting targets with the optical sensor and/or radar sensor, control (**480**) AUV **105** to complete ascent to surface.

20 It is to be understood that the invention is not limited in its application to the details set forth in the description contained herein or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Hence, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for designing other structures, methods, and systems for carrying out the several purposes of the presently disclosed subject matter.

25 It will also be understood that the system according to the invention may be, at least partly, implemented on a suitably programmed computer. Likewise, the invention contemplates a computer program being readable by a computer for executing the method of the invention. The invention further contemplates a non-transitory computer-readable memory tangibly embodying a program of instructions executable by the computer for executing the method of the invention.

Those skilled in the art will readily appreciate that various modifications and changes can be applied to the embodiments of the invention as hereinbefore described without departing from its scope, defined in and by the appended claims.

CLAIMS

1. A method of controlling ascent of an underwater vehicle (UV) from a safety depth to a water surface, the method being performed by a processing circuitry, the processing circuitry comprising a processor and memory, and the method comprising:
- 5
- a) at the safety depth, controlling the UV to collect, from a passive sonar associated with the UV, first data indicative of first locations of surface targets within a first surface area of interest;
- 10
- b) controlling ascent of the UV to an intermediate depth in accordance with, at least, the first data;
- c) at the intermediate depth, controlling the UV to collect second data indicative of second locations of surface targets within a second surface area of interest, wherein the second data comprises one or more of:
- 15
- a. data from a passive sonar associated with the UV,
- b. data from one or more magnetic sensors associated with the UV,
- 20
- c. data from an active sonar associated with the UV, and
- d. data from a light detection and ranging (LIDAR) scanner associated with the UV; and
- d) controlling ascent of the UV to a periscope depth in accordance with, at least, the second data,
- 25
- wherein: the safety depth is not less than 15 meters beneath the surface, the intermediate depth is not less than 5 meters below the surface, and the periscope depth is less than 8 meters below the surface.
- 30
2. The method of claim 1, the method additionally comprising:

e) controlling ascent of the UV to the surface, in accordance with, at least, data from at least one mast-based sensor.

- 5 3. The method of claim 2 wherein the at least one mast-based sensor includes at least one sensor from a group consisting of: an optical sensor, and a radar sensor.
4. The method of claim 1, wherein the controlling ascent of the UV to the intermediate depth comprises:
- 10 initiating ascent, responsive to determining, from the first data, a surfacing zone from which detected surface targets are absent at a time of the collecting.
5. The method of claim 1, wherein the controlling ascent of the UV to the intermediate depth comprises:
- 15 initiating ascent, responsive to determining, from the first data, a surfacing zone from which detected surface targets are absent at a time subsequent to a time of the collecting.
6. The method of claim 1, wherein the controlling ascent of the UV to an intermediate depth comprises:
- 20 delaying ascent, responsive to failure to detect, from the first data, a surfacing zone in which detected surface targets are absent at a time of the collecting.
7. The method of claim 1, wherein the controlling ascent of the UV to the periscope depth comprises:
- 25 initiating ascent, responsive to determining, from the second data, a surfacing zone from which detected surface targets are absent at a time of the collecting.
8. The method of claim 1, wherein the controlling ascent of the UV to the periscope depth comprises:
- 30

initiating ascent, responsive to determining, from the second data, a surfacing zone from which detected surface targets are absent at a time subsequent to a time of the collecting.

- 5 9. The method of claim 8, wherein the determining the surfacing zone is in accordance with: respective detected locations, respective detected directions, and respective detected velocities of the surface targets.
- 10 10. The method of claim 9, wherein the determining the surfacing zone is in further accordance with respective target-specific minimum distances.
11. The method of claim 1, wherein the controlling ascent of the UV to periscope depth comprises:
- 15 delaying ascent, responsive to failure to detect, from the second data, a surfacing zone in which detected surface targets are absent at a time of the collecting.
12. The method of claim 1, wherein the second data comprises data from a first magnetic sensor sensing in a upward direction and a second magnetic sensor sensing in a
20 downward direction.
13. The method of claim 1, wherein the second data comprises data from an active sonar that is a tiltable forward-looking sonar.
- 25 14. The method of claim 11, wherein the tiltable forward-looking sonar can sense sound from at least 45 degrees above horizontal.
15. The method of claim 1, wherein the second data comprises:
- 30 a. data from a passive sonar associated with the UV,

- b. data from one or more magnetic sensors associated with the UV, and
- c. data from an active sonar associated with the UV;

5

16. A system of controlling ascent of an underwater vehicle (UV) from a safety depth to a water surface,

the comprising a processing circuitry, the processing circuitry comprising a
processor and memory, and being configured to:

10

- a) at the safety depth, control the UV to collect, from a passive sonar associated with the UV, first data indicative of first locations of surface targets within a first surface area of interest;

15

- b) control ascent of the UV to an intermediate depth in accordance with, at least, the first data;

20

- c) at the intermediate depth, control the UV to collect second data indicative of second locations of surface targets within a second surface area of interest, wherein the second data comprises one or more of:

25

- a. data from a passive sonar associated with the UV,
- b. data from one or more magnetic sensors associated with the UV,
- c. data from an active sonar associated with the UV, and
- d. data from a light detection and ranging (LIDAR) scanner associated with the UV;

30

- d) control ascent of the UV to a periscope depth in accordance with, at least, the second data,

wherein: the safety depth is not less than 15 meters beneath the surface, the intermediate depth is not less than 5 meters below the surface, and the periscope depth is less than 8 meters below the surface.

- 5 17. A computer program product comprising a non-transitory computer readable
storage medium retaining program instructions, which, when read by a
processing circuitry, cause the processing circuitry to perform a computerized
method of controlling ascent of an underwater vehicle (UV) from a safety
depth to a water surface, the method comprising:
- 10 a) at the safety depth, controlling the UV to collect, from a passive sonar
associated with the UV, first data indicative of first locations of
surface targets within a first surface area of interest;
- 15 b) controlling ascent of the UV to an intermediate depth in accordance
with, at least, the first data;
- c) at the intermediate depth, controlling the UV to collect second data
indicative of second locations of surface targets within a second
20 surface area of interest, wherein the second data comprises one or
more of:
- a. data from a passive sonar associated with the UV,
- 25 b. data from one or more magnetic sensors associated with the
UV,
- c. data from an active sonar associated with the UV, and
- 30 d. data from a light detection and ranging (LIDAR) scanner
associated with the UV;

- d) controlling ascent of the UV to a periscope depth in accordance with, at least, the second data,

5 wherein: the safety depth is not less than 15 meters beneath the surface, the intermediate depth is not less than 5 meters below the surface, and the periscope depth is less than 8 meters below the surface.