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(54) SYSTEMS AND METHODS FOR IMPROVED PRESSURE VESSELS

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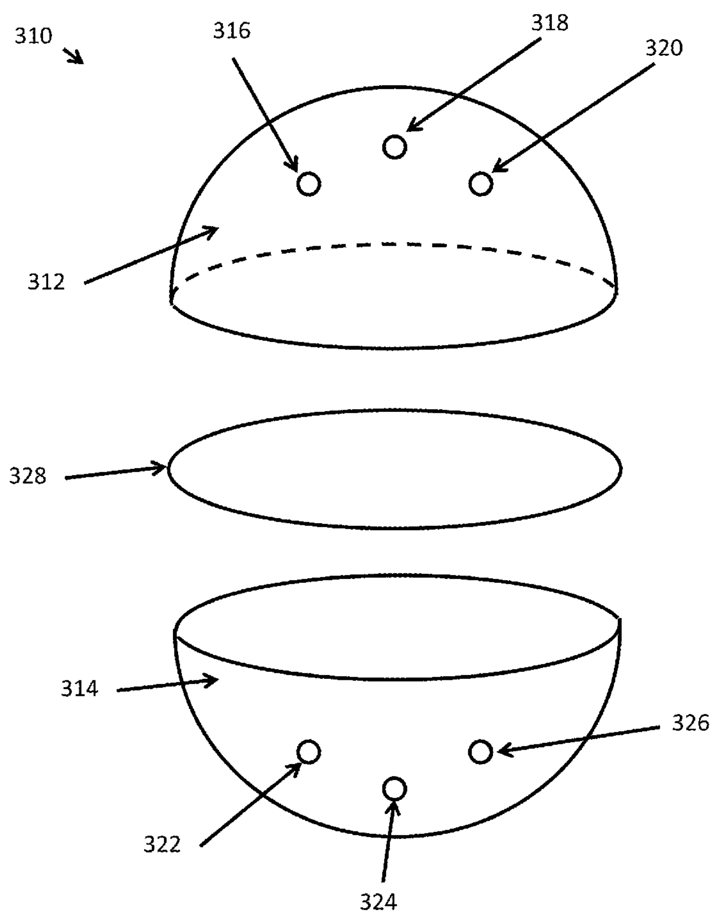
CPC .. ***B22D 31/00*** (2013.01); ***F17C 1/00*** (2013.01)
USPC .............................. **29/463**; 29/527.6; 29/56.5

(57) **ABSTRACT**

Systems and methods are described herein for manufacturing a pressure vessel component. The pressure vessel component may be made from a metal that is cast to produce a gross pressure vessel component. Casting the metal may comprise sintering the metal followed by a hot isostatic press (HIP) process. In other embodiments, casting the metal may comprise pouring molten metal into a mold. Portions of the gross pressure vessel component may have an increased thickness located at predetermined positions on the gross pressure vessel component. These portions may include bosses or other designed features intended for the finalized pressure vessel component. The gross pressure vessel may be indexed to select the portions, and these selected portions may then be machined to produce the final pressure vessel component.



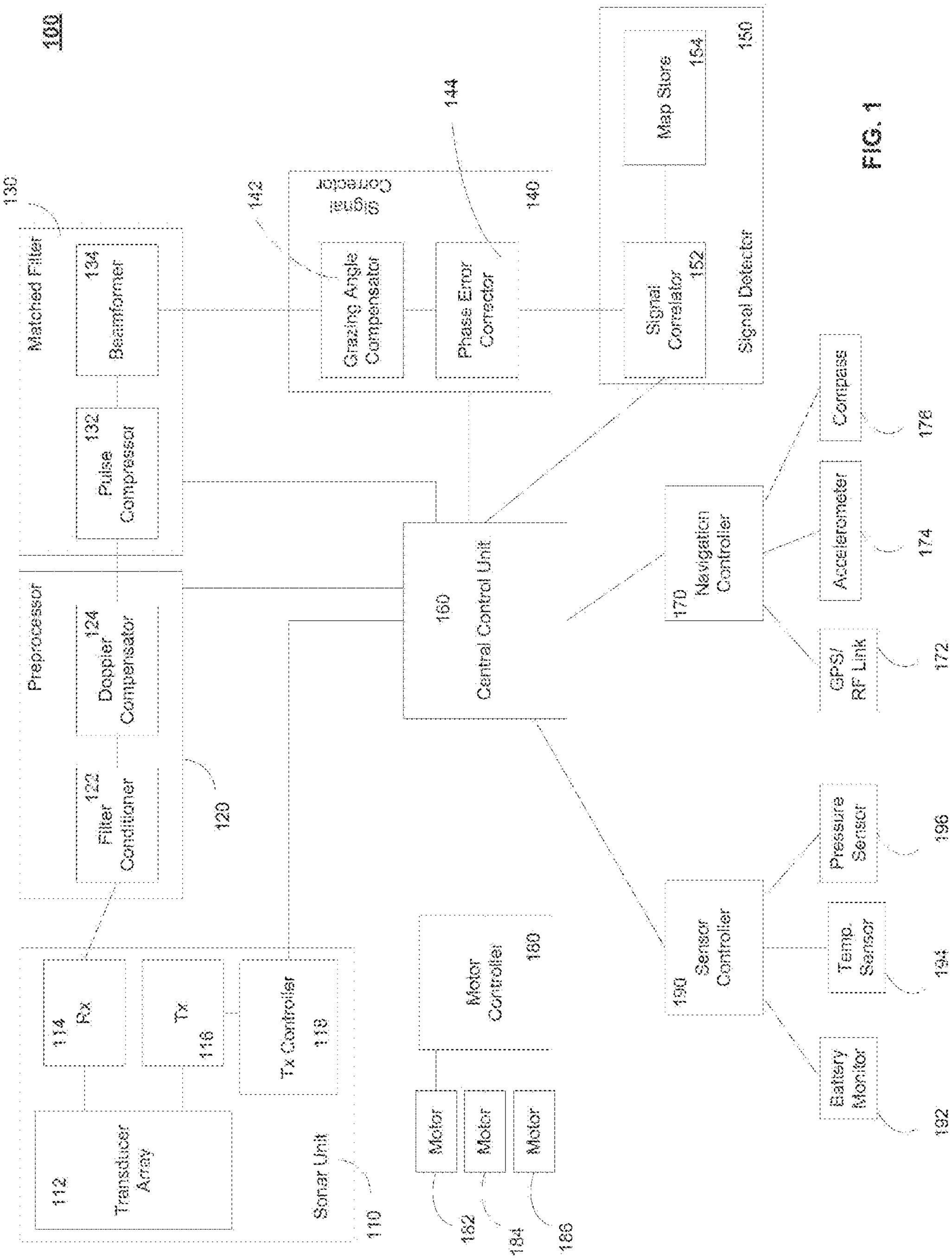

100
Matched Filter
130
Pulse Compressor
132
Beamformer
134
Preprocessor
120
Filter Conditioner
122
Doppler Compensator
124
Sonar Unit
110
Transducer Array
112
Rx
114
Tx
116
Tx Controller
118
Signal Corrector
140
Grazing Angle Compensator
142
Phase Error Corrector
144
Signal Detector
150
Signal Correlator
152
Map Store
154
Central Control Unit
160
Navigation Controller
170
GPS/ RF Link
172
Accelerometer
174
Compass
176
Motor Controller
180
Motor
182
Motor
184
Motor
186
Sensor Controller
190
Battery Monitor
192
Temp. Sensor
194
Pressure Sensor
196

FIG. 1

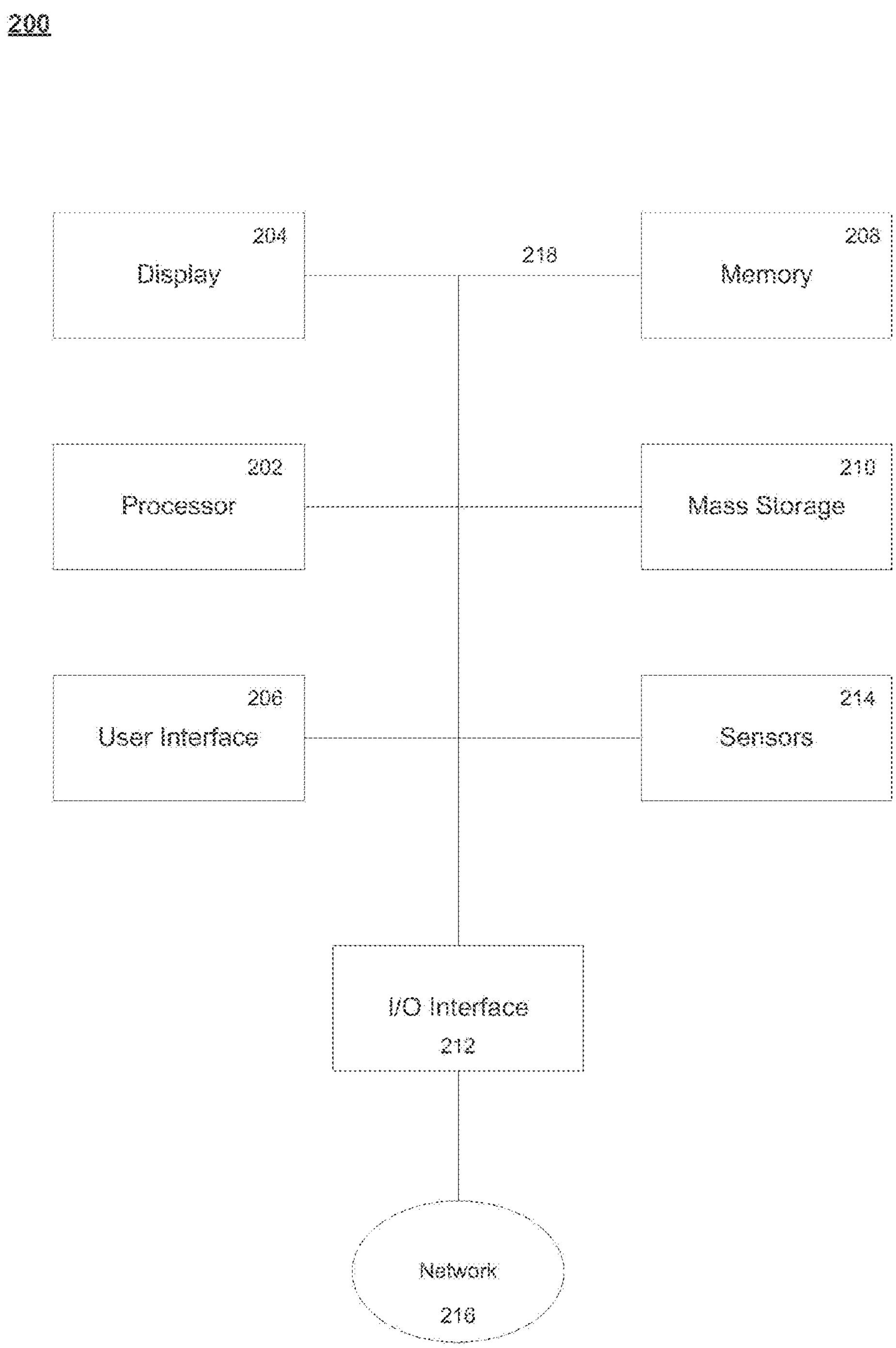

200
Display
204
218
Memory
208
Processor
202
Mass Storage
210
User Interface
206
Sensors
214
I/O Interface
212
Network
216

FIG. 2

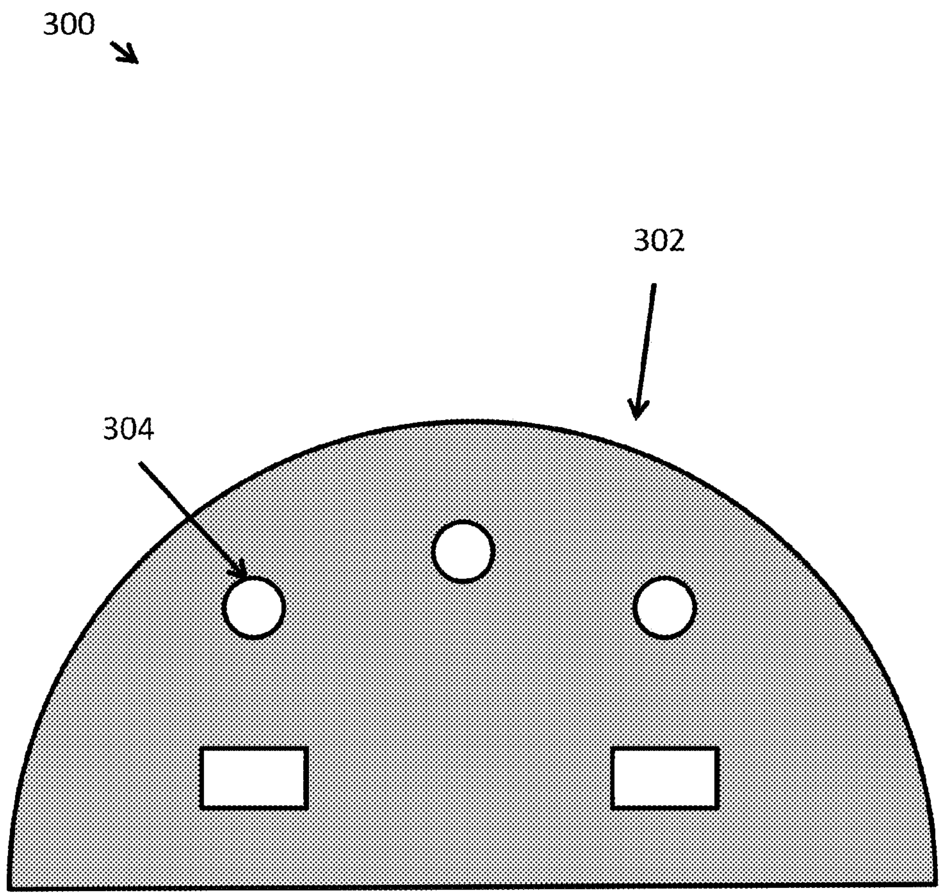



FIGURE 3A

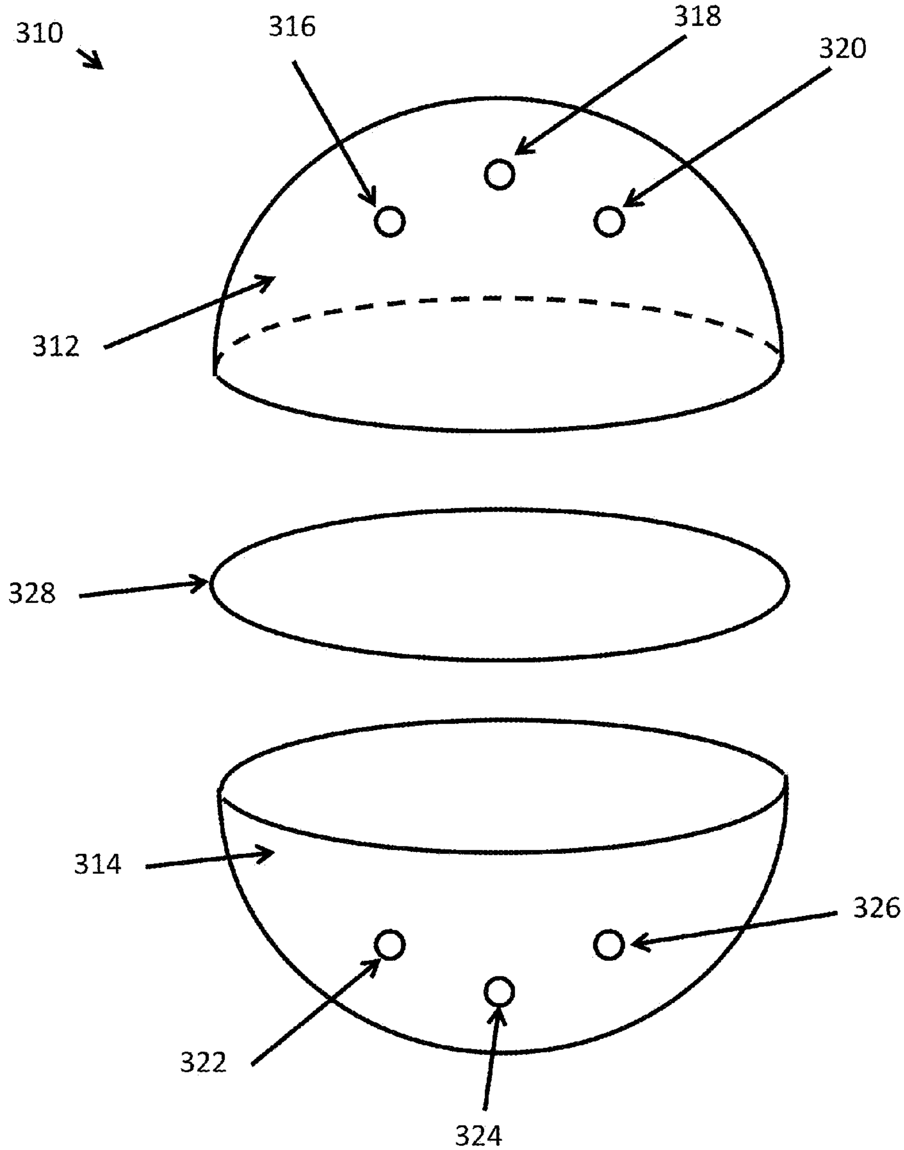



FIGURE 3B

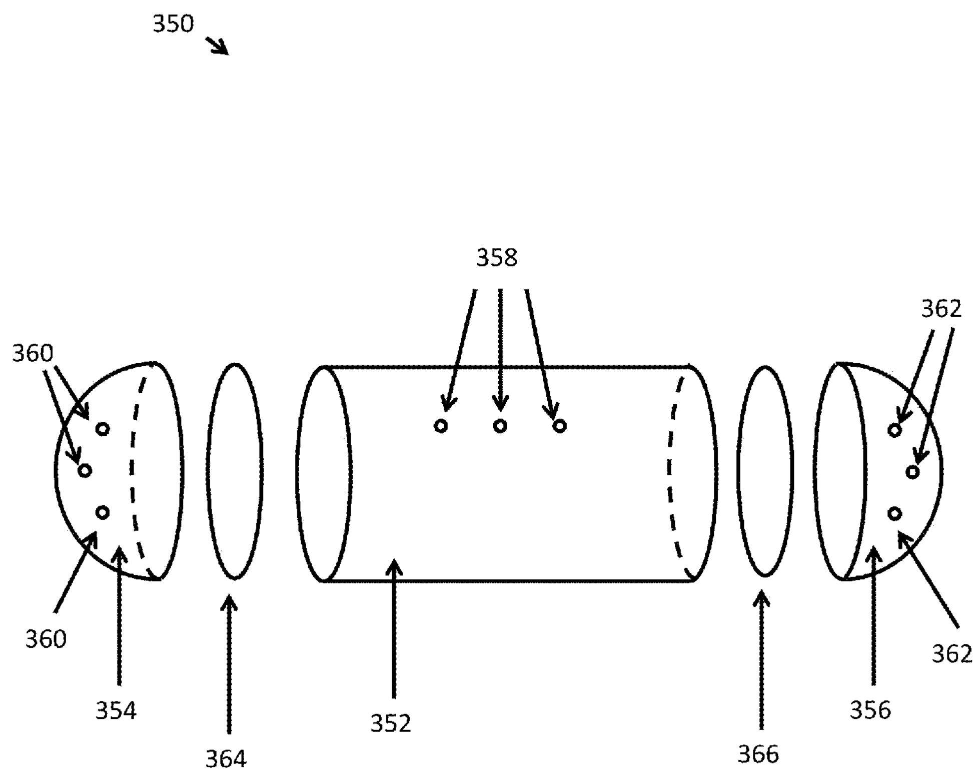



FIGURE 3C

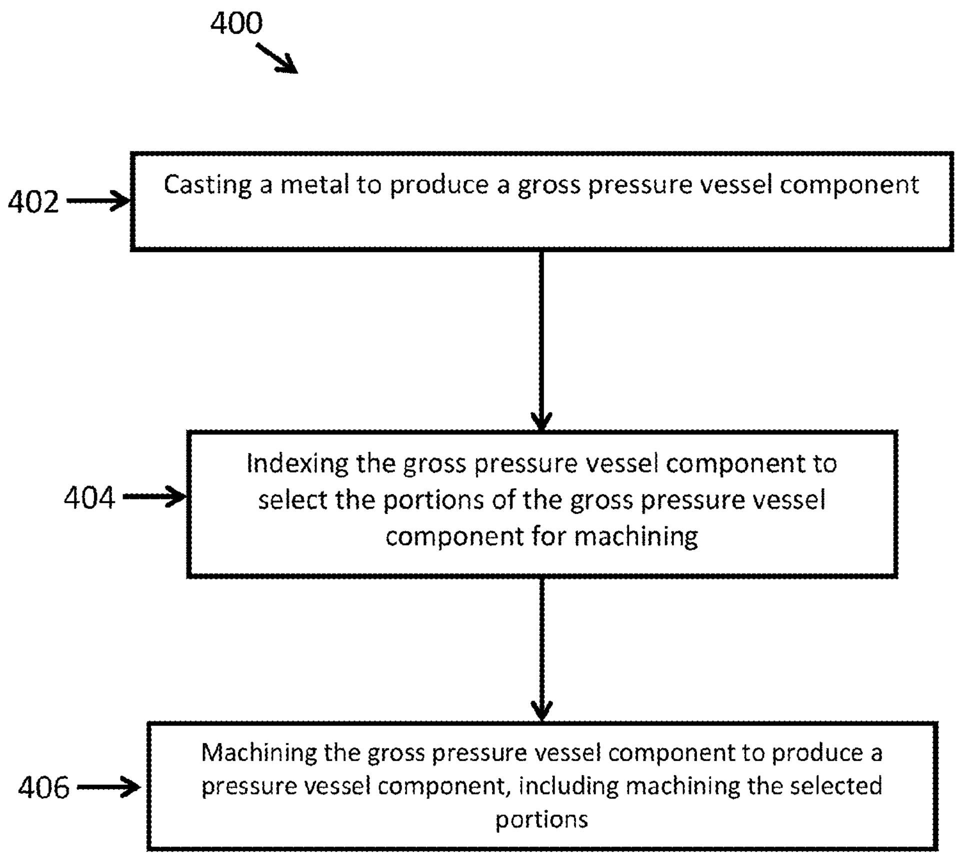

400
402
Casting a metal to produce a gross pressure vessel component
404
Indexing the gross pressure vessel component to select the portions of the gross pressure vessel component for machining
406
Machining the gross pressure vessel component to produce a pressure vessel component, including machining the selected portions

FIGURE 4

# SYSTEMS AND METHODS FOR IMPROVED PRESSURE VESSELS

## CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 61/792,708, filed Mar. 15, 2013, the contents of which is incorporated by reference herein in its entirety.

## BACKGROUND

[0002] The past several decades have seen a steady increase in the number of unmanned underwater robotic systems deployed for use in the ocean. These underwater systems often use pressure vessels that are configured to maintain an internal pressure and resist the high pressures at ocean depths. Typical methods for manufacturing pressure vessels often involve casting, forging, or machining titanium or a similar metal into the final shape of the pressure vessel. However, the pressure vessels may have bosses or other design protrusions that require custom casts or molds. Such custom designs may drive up the cost of manufacture, especially for larger pressure vessel designed for manned missions. As such, a need exists for a low cost method of manufacturing custom pressure vessel components.

## SUMMARY

[0003] Systems and methods are described herein for manufacturing a pressure vessel component. According to one aspect, a method of manufacturing a pressure vessel component may comprise casting a metal to produce a gross pressure vessel component. The gross pressure vessel component may be shaped as a hemisphere, a cylinder, a cube, a rectangular prism, or any other suitable shape. Portions of the gross pressure vessel component may have an increased thickness located at predetermined positions on the gross pressure vessel component. These portions may include bosses or other designed features intended for the finalized pressure vessel component. In some embodiments, the portions may occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane. The predetermined locations for the bosses may be based on a plurality of possible arrangements of components with a pressure vessel. In some embodiments, the gross pressure vessel may be indexed to select the portions of the gross pressure vessel component for machining. The selected portions may comprise only a subset of the portions of the gross pressure vessel component having an increased thickness. This subset may be determined based on one of a plurality of possible component arrangements within the pressure vessel. These selected portions may then be machined to produce the pressure vessel component. In some embodiments, cable pass-throughs (e.g., holes) may be machined at the portions having the increased thickness. In some embodiments, the selected portions are machined after casting and indexing the gross pressure vessel component.

[0004] In some embodiments, the pressure vessel component may be made from titanium. In alternate embodiments, any other suitable materials may be used to produce the pressure vessel component, including, but not limited to, steel, aluminum, or tungsten carbide. Casting the metal may comprise sintering the metal followed by a hot isostatic press (HIP) process. In alternate embodiments, casting the metal may comprise pouring the molten metal into a mold. In some embodiments, the pressure vessel component may be heat treated, either before, during, or after machining.

[0005] The pressure vessel component may be designed to mate with a second pressure vessel component. As an illustrative example, the pressure vessel component may comprise a hemisphere designed to mate with another hemisphere to form a full sphere. The pressure vessel component may use a hinge to open, close, and align with the second pressure vessel component. In some embodiments, the hinge may be a clam-like hinge. In some embodiments, at least a partial vacuum may be formed in the cavity formed by the mated pressure vessel component and the second pressure vessel component.

[0006] According to another aspect, a system for manufacturing a pressure vessel component may comprise a mold for casting a metal to produce a gross pressure vessel component. Portions of the gross pressure vessel component having an increased thickness may be located at predetermined positions on the gross pressure vessel component. The system may further comprise machining equipment configured to index the gross pressure vessel component to select the portions of the gross pressure vessel component for machining. The machining equipment may be used to machine the selected portions to produce a pressure vessel.

[0007] Other objects, features, and advantages of the present invention will become apparent upon examining the following detailed description, taken in conjunction with the attached drawings.

## BRIEF DESCRIPTION OF THE FIGURES

[0008] The systems and methods described herein are set forth in the appended claims. However, for purpose of explanation, several illustrative embodiments are set forth in the following figures.

[0009] FIG. **1** is a block diagram depicting an exemplary remote vehicle, according to an illustrative embodiment of the present disclosure.

[0010] FIG. **2** is block diagram of an exemplary computer system for implementing at least a portion of the systems and methods described in the present disclosure.

[0011] FIG. **3**A depicts an illustrative pressure vessel component.

[0012] FIG. **3**B depicts an illustrative pressure vessel according to one embodiment.

[0013] FIG. **3**C depicts an illustrative pressure vessel according to an alternate embodiment.

[0014] FIG. **4** depicts a process of manufacturing a pressure vessel component according to an illustrative embodiment.

## DETAILED DESCRIPTION

[0015] To provide an overall understanding of the invention, certain illustrative embodiments will now be described. However, it will be understood by one or ordinary skill in the art that the systems and methods described herein can be adapted and modified for other suitable applications and that such other additions and modifications will not depart from the scope hereof.

[0016] Systems and methods are described herein of manufacturing a pressure vessel component. The pressure vessel components may be any suitable shape, including spherical, hemispherical, cylindrical, or rectangular. The pressure vessel components may be cast from titanium designed for use in the ocean. In one embodiment, the pressure vessel may be a spherical titanium pressure vessel with two hemispheres; one hemisphere may be used for supporting the internal electronics chassis assembly, while the other hemisphere may be adorned with external bosses for cable pass-through to enable access to the internal electronics. The two hemispheres may be sealed at the equatorial plane of the sphere with an o-ring seal that enables safe operation of the internal electronics at great depths. In some embodiments, a spherical form factor pressure vessel may be designed to an appropriate wall-thickness with a factor of safety to safely operate at a pre-determined service depth (or pressure). To prevent slippage between the hemispheres, the internal cavity may be evacuated to a fraction of standard atmospheric pressure (i.e., <14.7 psi). The spheres may be separated by removing the vacuum and subsequently separating the hemispheres. Jack screws can be used to separate the hemispheres, or the pressure inside the pressure vessel can be increased to force the two sides apart. Internally, the pressure vessel may or may not contain internal structure or electronics, depending on the application.

**[0017]** A first pressure vessel component may be shaped as a hemisphere and may have no external features or pass-throughs. Thus, the first pressure vessel component may only require machining on the interface surface. A flange may be machined to a 32 RMS finish to act as a sealing surface against the o-rings.

**[0018]** A second pressure vessel component may also be shaped as a hemisphere, but may have both external features and a flange with o-ring glands to enable watertight sealing during normal operation. The o-ring gland may be machined into the equatorial flange at a larger diameter than the nominal sphere outer diameter. This leaves the spherical structural geometry intact to support compressive loading.

**[0019]** Bosses may protrude from the exterior surface of the second pressure vessel component. The bosses may comprise portions of increased material thickness located at predetermined angles of elevation and azimuth relative to the sphere equatorial plane. These boss locations may be chosen to minimize stress and to maximize the packing efficiency of connected cables and devices. However, not all bosses may require post-casting machining. The remaining bosses may remain as cast and left for modification at a later time. When the bosses are machined, the pass-throughs may be machined using watertight connectors that fasten to the outer face of the sphere with threaded hardware (e.g., hex head screws). The locations of the connector bolt-holes may be chosen to minimize stress.

**[0020]** In some embodiments, a pressure vessel may have a cylindrical form factor. The pressure vessel may consist of a main body comprised of one or more cylindrical sections with end caps. The end caps may be hemispheres or square-shaped. All components may be designed to the appropriate wall-thickness with a factor of safety to safely operate at a pre-determined service depth (or pressure). The cylinder and sphere diameters may be concentric and the same length and align for assembly.

**[0021]** During normal operation, the cylinder may be arranged such that their sealing surfaces are joined to create a watertight seal that carries the load to support compressive and bending moments. Hemispheres may be situated at either end of the cylinder body and may be sealed by use of an o-ring seal at a flange located at the equatorial plane of the hemispheres. The internal cavity may be evacuated to a fraction of standard atmospheric pressure (i.e., <14.7 psi). To facilitate internal access, the hemispheres may be separated from the cylinders by removing the vacuum and subsequently removing the band clamps. Internally, the pressure vessel may or may not contain internal structure or electronics, depending on the application.

**[0022]** For a manned submersible, the pressure vessel may be cast with holes or bosses for windows.

**[0023]** In some embodiments, the manufacturing process may consist of casting titanium to produce the gross pressure vessel component shapes, including any boss features. As discussed above, the boss features may be cast into their final shape, or the boss features may require additional machining to achieve a final shape. The manufacturing process may comprise several steps: casting a metal (such as titanium), indexing the cast part for machining, and machining specific regions of the cast part. Heat treating is optional and may be unnecessary for thinner walled pressure vessels. The casting process chosen may depend upon the wall thickness and size of the part being cast. In some embodiments, the casting process may comprise sintering a metal followed by a hot isostatic press (HIP) process. In alternate embodiments, the casting process may comprise pouring molten metal into a mold, such as a lost-wax or a graphite mould.

**[0024]** In some embodiments, the pressure vessel may be sealed by partially evacuating the internal cavity through a dual seal vent plug valve of the sphere so that the hemisphere flanges engage under the force generated by the relative pressure difference between inside and outside the sphere. A "band" clamp may be affixed to the flanges of the hemispheres to provide additional clamping force, for example, during shallow water operation. The clamp may contain an equally-spaced hole pattern for bolting with threaded hardware. The spherical pressure vessel band clamp may contain eye bolts that can be shackled to straps for lifting and handling of the sphere pre and post mission. When the pressure vessel is opened, the hemispheres may need to rest securely in a holder. In one embodiment, a plastic plate cut with a hole larger than the hemisphere and a finger access pattern that matches the band clamp bolt pattern may be used. Alternatively, a band clamp can be applied to both hemispheres and connected via a hinge. In some embodiments, the spherical pressure vessel band clamp may double as a mounting bracket.

**[0025]** In some embodiments, a cylindrically-shaped pressure vessel may be sealed by bolting the cylindrical section flanges together to create a structurally watertight seal. The internal cavity may be partially evacuated through a dual seal vent plug valve, allowing the hemisphere end cap flanges to engage under the force generated by the relative pressure difference between inside and outside the housing.

**[0026]** In some embodiments, additional features may be cast into the pressure vessel component to simplify internal mounting of components. The internal mounts may feature slotted holes to prevent the application of stress as the pressure vessel shrinks under pressure. Likewise, flexible standoffs may be applied to the inside of the pressure vessel component when mounting objects such as electronics to prevent the transfer of stress as the pressure vessel component shrinks under pressure. This protects the electronics from damage and protects the pressure vessel component from asymmetric loading.

**[0027]** Titanium is a poor heat conductor and therefore expunging internal heat (i.e., generated from electronics) typically requires the use of a radiator. In some embodiments, radiators may include a beryllium copper radiator for liquid cooling. The coolant may be a non-conducting and a non-flammable coolant, such as Fluorinert, or Opticool, rather than normal engine coolant (which conducts) or distilled water (which is non-conducting, but in the event of a leak is difficult to guarantee purity).

**[0028]** FIG. **1** is a block diagram depicting an illustrative remote vehicle, according to an illustrative embodiment of the present disclosure. The system **100** includes a sonar unit **110** for sending and receiving sonar signals, a preprocessor **120** for conditioning a received (or reflected) signal, and a matched filter **130** for performing pulse compression and beamforming. The system **100** is configured to allow for navigating using high-frequency (greater than about 100 kHz) sonar signals. To allow for such HF navigation, the system **100** includes a signal corrector **140** for compensating for grazing angle error and for correcting phase error. The system **100** also includes a signal detector **150** for coherently correlating a received image with a map. In some embodiments, the system **100** includes an on-board navigation controller **170**, motor controller **180** and sensor controller **190**. The navigation controller **170** may be configured to receive navigational parameters from a GPS/RF link **172** (when available), an accelerometer **174**, a gyroscope, and a compass **176**. The motor controller **180** may be configured to control a plurality of motors **182**, **184** and **186** for steering the vehicle. The sensor controller **190** may receive measurements from the battery monitor **172**, a temperature sensor **194** and a pressure sensor **196**. The system **100** further includes a central control unit (CCU) **160** that may serve as a hub for determining navigational parameters based on sonar measurements and other navigational and sensor parameters, and for controlling the movement of the vehicle.

**[0029]** In the context of a surface or underwater vehicle, the CCU **160** may determine navigational parameters such as position (latitude and longitude), velocity (in any direction), bearing, heading, acceleration and altitude. The CCU **160** may use these navigational parameters for controlling motion along the alongtrack direction (fore and aft), acrosstrack direction (port and starboard), and vertical direction (up and down). The CCU **160** may use these navigational parameters for controlling motion to yaw, pitch, roll or otherwise rotate the vehicle. During underwater operation, a vehicle such as an AUV may receive high-frequency real aperture sonar images or signals at sonar unit **110**, which may then be processed, filtered, corrected, and correlated against a synthetic aperture sonar (SAS) map of the terrain. Using the correlation, the CCU may then determine the AUV's position, with high-precision and other navigational parameters to assist with navigating the terrain. The precision may be determined by the signal and spatial bandwidth of the SAS map and/or the acquired sonar image. In certain embodiments, assuming there is at least a near perfect overlap of the sonar image with a prior SAS map with square pixels, and assuming that the reacquisition was performed with a single channel having a similar element size and bandwidth, and assuming little or no losses to grazing angle compensation, the envelope would be about one-half the element size. Consequently, in certain embodiments, the peak of the envelope may be identified with high-precision, including down to the order of about $1/100^{th}$ of the wavelength. For example, the resolution may be less than 2.5 cm, or less than 1 cm or less than and about 0.1 mm in the range direction.

**[0030]** As noted above, the system **100** includes a sonar unit **110** for transmitting and receiving acoustic signals. The sonar unit includes a transducer array **112** having a one or more transmitting elements or projectors and a plurality of receiving elements arranged in a row. In certain embodiments the transducer array **112** includes separate projectors and receivers. The transducer array **112** may be configured to operate in SAS mode (either stripmap or spotlight mode) or in a real aperture mode. In certain embodiments, the transducer array **112** is configured to operate as a multibeam echo sounder, sidescan sonar or sectorscan sonar. The transmitting elements and receiving elements may be sized and shaped as desired and may be arranged in any configuration, and with any spacing as desired without departing from the scope of the present disclosure. The number, size, arrangement and operation of the transducer array **112** may be selected and controlled to insonify terrain and generate high-resolution images of a terrain or object. One example of an array **112** includes a 16 channel array with 5 cm elements mounted in a 12¾ inch vehicle.

**[0031]** The sonar unit **110** further includes a receiver **114** for receiving and processing electrical signals received from the transducer, and a transmitter **116** for sending electrical signals to the transducer. The sonar unit **110** further includes a transmitter controller **118** for controlling the operation of the transmitter including the start and stop, and the frequency of a ping.

**[0032]** The signals received by the receiver **114** are sent to a preprocessor for conditioning and compensation. Specifically, the preprocessor **120** includes a filter conditioner **122** for eliminating outlier values and for estimating and compensating for hydrophone variations. The preprocessor further includes a Doppler compensator **124** for estimating and compensating for the motion of the vehicle. The preprocessed signals are sent to a matched filter **130**.

**[0033]** The matched filter **130** includes a pulse compressor **132** for performing matched filtering in range, and a beamformer **134** for performing matched filtering in azimuth and thereby perform direction estimation.

**[0034]** The signal corrector **140** includes a grazing angle compensator **142** for adjusting sonar images to compensate for differences in grazing angle. Typically, if a sonar images a collection of point scatterers the image varies with observation angle. For example, a SAS system operating at a fixed altitude and heading observing a sea floor path will produce different images at different ranges. Similarly, SAS images made at a fixed horizontal range would change if altitude were varied. In such cases, changes in the image would be due to changes in the grazing angle. The grazing angle compensator **142** is configured to generate grazing angle invariant images. One such grazing angle compensator is described in U.S. patent application Ser. No. 12/802,454 titled "Apparatus and Method for Grazing Angle Independent Signal Detection," the contents of which are incorporated herein by reference in their entirety.

**[0035]** The signal corrector **140** includes a phase error corrector **144** for correcting range varying phase errors. Generally, the phase error corrector **144** breaks the image up into smaller pieces, each piece having a substantially constant phase error. Then, the phase error may be estimated and corrected for each of the smaller pieces.

**[0036]** The system **100** further includes a signal detector **150** having a signal correlator **152** and a storage **154**. The signal detector **150** may be configured to detect potential targets, estimate the position and velocity of a detected object and perform target or pattern recognition. In one embodiment, the storage **154** may include a map store, which may contain one or more previously obtained SAS images real aperture images or any other suitable sonar image. The signal correlator **152** may be configured to compare the received and processed image obtained from the signal corrector **140** with one or more prior images from the map store **154**.

**[0037]** The system **100** may include other components, not illustrated, without departing from the scope of the present disclosure. For example, the system **100** may include a data logging and storage engine. In certain embodiments the data logging and storage engine may be used to store scientific data which may then be used in post-processing for assisting with navigation. The system **100** may include a security engine for controlling access to and for authorizing the use of one or more features of system **100**. The security engine may be configured with suitable encryption protocols and/or security keys and/or dongles for controlling access. For example, the security engine may be used to protect one or more maps stored in the map store **154**. Access to one or more maps in the map store **154** may be limited to certain individuals or entities having appropriate licenses, authorizations or clearances. Security engine may selectively allow these individuals or entities access to one or more maps once it has confirmed that these individuals or entities are authorized. The security engine may be configured to control access to other components of system **100** including, but not limited to, navigation controller **170**, motor controller **180**, sensor controller **190**, transmitter controller **118**, and CCU **160**.

**[0038]** Generally, with the exception of the transducer **112**, the various components of system **100** may be implemented in a computer system, such as computer system **200** of FIG. **2**. More particularly, FIG. **2** is a functional block diagram of a general purpose computer accessing a network according to an illustrative embodiment of the present disclosure. The holographic navigation systems and methods described in this application may be implemented using the system **200** of FIG. **2**.

**[0039]** The exemplary system **200** includes a processor **202**, a memory **208**, and an interconnect bus **218**. The processor **202** may include a single microprocessor or a plurality of microprocessors for configuring computer system **200** as a multi-processor system. The memory **208** illustratively includes a main memory and a read-only memory. The system **200** also includes the mass storage device **210** having, for example, various disk drives, tape drives, etc. The main memory **208** also includes dynamic random access memory (DRAM) and high-speed cache memory. In operation and use, the main memory **208** stores at least portions of instructions for execution by the processor **202** when processing data (e.g., model of the terrain) stored in main memory **208**.

**[0040]** In some embodiments, the system **200** may also include one or more input/output interfaces for communications, shown by way of example, as interface **212** for data communications via the network **216**. The data interface **212** may be a modem, an Ethernet card or any other suitable data communications device. The data interface **212** may provide a relatively high-speed link to a network **216**, such as an intranet, internet, or the Internet, either directly or through another external interface. The communication link to the network **216** may be, for example, any suitable link such as an optical, wired, or wireless (e.g., via satellite or 802.11 Wi-Fi or cellular network) link. In some embodiments, communications may occur over an acoustic modem. For instance, for AUVs, communications may occur over such a modem. Alternatively, the system **200** may include a mainframe or other type of host computer system capable of web-based communications via the network **216**.

**[0041]** In some embodiments, the system **200** also includes suitable input/output ports or may use the Interconnect Bus **218** for interconnection with a local display **204** and user interface **206** (e.g., keyboard, mouse, touchscreen) or the like serving as a local user interface for programming and/or data entry, retrieval, or manipulation purposes. Alternatively, server operations personnel may interact with the system **200** for controlling and/or programming the system from remote terminal devices (not shown in the Figure) via the network **216**.

**[0042]** In some embodiments, a system requires a processor, such as a navigational controller **170**, coupled to one or more coherent sensors (e.g., a sonar, radar, optical antenna, etc.) **214**. Data corresponding to a model of the terrain and/or data corresponding to a holographic map associated with the model may be stored in the memory **208** or mass storage **210**, and may be retrieved by the processor **202**. Processor **202** may execute instructions stored in these memory devices to perform any of the methods described in this application, e.g., grazing angle compensation, or high frequency holographic navigation.

**[0043]** The system may include a display **204** for displaying information, a memory **208** (e.g., ROM, RAM, flash, etc.) for storing at least a portion of the aforementioned data, and a mass storage device **210** (e.g., solid-state drive) for storing at least a portion of the aforementioned data. Any set of the aforementioned components may be coupled to a network **216** via an input/output (I/O) interface **212**. Each of the aforementioned components may communicate via interconnect bus **218**.

**[0044]** In some embodiments, the system requires a processor coupled to one or more coherent sensors (e.g., a sonar, radar, optical antenna, etc.) **214**. The sensor array **214** may include, among other components, a transmitter, receive array, a receive element, and/or a virtual array with an associated phase center/virtual element.

**[0045]** Data corresponding to a model of the terrain, data corresponding to a holographic map associated with the model, and a process for grazing angle compensation may be performed by a processor **202**. The system may include a display **204** for displaying information, a memory **208** (e.g., ROM, RAM, flash, etc.) for storing at least a portion of the aforementioned data, and a mass storage device **210** (e.g., solid-state drive) for storing at least a portion of the aforementioned data. Any set of the aforementioned components may be coupled to a network **216** via an input/output (I/O) interface **212**. Each of the aforementioned components may communicate via interconnect bus **218**.

**[0046]** In operation, a processor **202** receives a position estimate for the sensor(s) **214**, a waveform or image from the sensor(s) **214**, and data corresponding to a model of the terrain, e.g., the sea floor. In some embodiments, such a position estimate may not be received and the process performed by processor **202** continues without this information. Optionally, the processor **202** may receive navigational information and/or altitude information, and a processor **202** may perform a coherent image rotation algorithm. The output from the system processor **202** includes the position to which the vehicle needs to move to.

**[0047]** The components contained in the system **200** are those typically found in general purpose computer systems used as servers, workstations, personal computers, network terminals, portable devices, and the like. In fact, these components are intended to represent a broad category of such computer components that are well known in the art.

**[0048]** It will be apparent to those of ordinary skill in the art that methods involved in the systems and methods of the invention may be embodied in a computer program product that includes a non-transitory computer usable and/or readable medium. For example, such a computer usable medium may consist of a read only memory device, such as a CD ROM disk, conventional ROM devices, or a random access memory, a hard drive device or a computer diskette, a flash memory, a DVD, or any like digital memory medium, having a computer readable program code stored thereon.

**[0049]** Optionally, the system may include an inertial navigation system, a Doppler sensor, an altimeter, a gimbling system to fixate the sensor on a populated portion of a holographic map, a global positioning system (GPS), a long baseline (LBL) navigation system, an ultrashort baseline (USBL) navigation, or any other suitable navigation system.

**[0050]** FIG. **3**A depicts an illustrative pressure vessel component. Pressure vessel component **300** may comprise gross pressure vessel component **302** and one or more bosses **304**.

**[0051]** Although gross pressure vessel component **302** is depicted as a hemisphere, the gross pressure vessel component **302** may be shaped as any suitable shape, including a sphere, a cylinder, an ellipsoid, a cube, or a rectangular prison. Gross pressure vessel component **302** may be made from titanium or any other suitable material. In some embodiments, the gross pressure vessel component **302** may be cast by sintering the metal followed by a HIP process. In alternate embodiments, the gross pressure vessel component **302** may be cast by pouring molten metal into a mold. The gross pressure vessel component **302** may be optionally heat treated.

**[0052]** Bosses **304** may be portions of the gross pressure vessel component **302** having an increased thickness. Bosses **304** may be located at predetermined positions on the gross pressure vessel component **302**. Although the bosses **304** are depicted in FIG. **3**A as holes, bosses **304** may comprise any designed features intended for the finalized pressure vessel component. In some embodiments, the bosses **304** may occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane. In some embodiments, the bosses **304** may comprise cable pass-throughs (e.g., holes).

**[0053]** FIG. **3**B depicts an illustrative pressure vessel according to one embodiment. Pressure vessel **310** includes top hemisphere **312**, bottom hemisphere **314**, bosses **316**, **318**, **320**, **322**, **324**, and **326**, and o-ring **328**.

**[0054]** Top hemisphere **312** may be a pressure vessel component similar to component **302** discussed in relation to FIG. **3**A. Although top hemisphere **312** is depicted in FIG. **3**B as having bosses **316**, **318**, and **320**, these bosses are shown merely for illustrative purposes. Top hemisphere **312** may have any number of bosses located at any suitable location, and in some embodiments, top hemisphere **312** may not have any bosses at all and comprise a smooth hemisphere with no features. In some embodiments, the top hemisphere **312** may be adorned with external bosses **316**, **318**, and **320** for cable pass-through to enable access to internal electronics. These boss locations may be chosen to minimize stress and to maximize the packing efficiency of connected cables and devices. Top hemisphere **312** may include a flange (not shown) to act as a sealing surface against an o-ring. In some embodiments, the flange on the top hemisphere **312** is machined to a 32 RMS finish.

**[0055]** Bottom hemisphere **314** may be a pressure vessel component similar to component **302** discussed in relation to FIG. **3**A. Although bottom hemisphere **314** is depicted in FIG. **3**B as having bosses **322**, **324**, and **326**, these bosses are shown merely for illustrative purposes. Bottom hemisphere **314** may have any number of bosses located at any suitable location, and in some embodiments, bottom hemisphere **314** may not have any bosses at all and comprise a smooth hemisphere with no features. In some embodiments, the bottom hemisphere **314** may be used for supported an internal electronics chassis assembly. Bottom hemisphere **314** may include a flange (not shown) machined to a 32 RMS finish to act as a sealing surface against an o-ring.

**[0056]** Bosses **316**, **318**, **320**, **322**, **324**, and **326** may be portions of top hemisphere **312** or bottom hemisphere **314** having an increased thickness. Bosses **316**, **318**, **320**, **322**, **324**, and **326** may be located at predetermined positions on the top hemisphere **312** or the bottom hemisphere **314**. Although the bosses **316**, **318**, **320**, **322**, **324**, and **326** are depicted in FIG. **3**B as holes, bosses **316**, **318**, **320**, **322**, **324**, and **326** may comprise any designed features intended for the finalized pressure vessel component. In some embodiments, the bosses **316**, **318**, **320**, **322**, **324**, and **326** may occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane. In some embodiments, the bosses **316**, **318**, **320**, **322**, **324**, and **326** may comprise cable pass-throughs (e.g., holes).

**[0057]** In some embodiments, the top hemisphere **312** and bottom hemisphere **314** may be sealed at the equatorial plane of the sphere with an o-ring seal **328** that enables safe operation of the internal electronics at great depths. The o-ring seal **328** may be any suitable o-ring for sealing the pressure vessel from water ingress. In some embodiments, the top hemisphere **312** and bottom hemisphere **314** may be joined by one or more hinges, such as a clam-like hinge. In some embodiments, the top hemisphere **312** and the bottom hemisphere **314** may be designed to an appropriate wall-thickness with a factor of safety to safely operate at a pre-determined service depth (or pressure). To prevent slippage between the hemispheres **312** and **314**, the internal cavity may be evacuated to a fraction of standard atmospheric pressure (i.e., $<14.7$ psi). The hemispheres **312** and **314** may be separated by removing the vacuum and subsequently separating the hemispheres **312** and **314**. Internally, the pressure vessel may or may not contain internal structure or electronics, depending on the application.

**[0058]** FIG. **3**C depicts an illustrative pressure vessel according to an alternate embodiment. Pressure vessel **350** includes cylinder **352**, top hemisphere **354**, bottom hemisphere **356**, bosses **358**, **360**, and **362**, and o-rings **364** and **366**.

**[0059]** Cylinder **352** may be a pressure vessel component similar to component **302** discussed in relation to FIG. **3**A. Although cylinder **352** is depicted in FIG. **3**C as having bosses **358**, these bosses are shown merely for illustrative purposes. Cylinder **352** may have any number of bosses located at any suitable location, and in some embodiments, Cylinder **352** may not have any bosses at all and comprise a smooth hemisphere with no features. Cylinder **352** may include a flange (not shown) machined to a 32 RMS finish to act as a sealing surface against an o-ring. Pressure vessel **350** uses top hemisphere **354** and bottom hemisphere **356** as endcaps. Although the endcaps are depicted as hemispheres **354** and **356** in FIG. **3**C, the endcaps could be any suitable shape, such as circular disks or square-shaped. The cylinder **352** and hemispheres **354** and **356** may have concentric diameters and/or the same length to align for assembly.

**[0060]** Top hemisphere **354** may be a pressure vessel component similar to component **302** discussed in relation to FIG. **3**A. Although top hemisphere **354** is depicted in FIG. **3**C as having bosses **360**, these bosses are shown merely for illustrative purposes. Top hemisphere **354** may have any number of bosses located at any suitable location, and in some embodiments, top hemisphere **354** may not have any bosses at all and comprise a smooth hemisphere with no features. In some embodiments, the top hemisphere **354** may be adorned with external bosses **360** for cable pass-through to enable access to internal electronics. These boss locations may be chosen to minimize stress and to maximize the packing efficiency of connected cables and devices. Top hemisphere **354** may include a flange (not shown) machined to a 32 RMS finish to act as a sealing surface against an o-ring.

**[0061]** Bottom hemisphere **362** may be a pressure vessel component similar to component **302** discussed in relation to FIG. **3**A. Although bottom hemisphere **362** is depicted in FIG. **3**C as having bosses **362**, these bosses are shown merely for illustrative purposes. Bottom hemisphere **362** may have any number of bosses located at any suitable location, and in some embodiments, bottom hemisphere **362** may not have any bosses at all and comprise a smooth hemisphere with no features. In some embodiments, the bottom hemisphere **362** may be used for supported an internal electronics chassis assembly. Bottom hemisphere **362** may include a flange (not shown) machined to a 32 RMS finish to act as a sealing surface against an o-ring.

**[0062]** Bosses **358**, **360**, and **362** may be portions of top hemisphere **354** or bottom hemisphere **356** having an increased thickness. Bosses **358**, **360**, and **362** may be located at predetermined positions on the top hemisphere **354** or the bottom hemisphere **356**. Although the bosses **358**, **360**, and **362** are depicted in FIG. **3**C as holes, bosses **358**, **360**, and **362** may comprise any designed features intended for the finalized pressure vessel component. In some embodiments, the bosses **358**, **360**, and **362** may occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane. In some embodiments, the bosses **358**, **360**, and **362** may comprise cable pass-throughs (e.g., holes).

**[0063]** In some embodiments, the cylinder **352**, top hemisphere **354**, and bottom hemisphere **362** may be sealed with o-rings seal **364** and **366** to enable safe operation of the internal electronics at great depths. The o-ring seals **364** and **366** may be any suitable o-ring for sealing the pressure vessel from water ingress. In some embodiments, the cylinder **352** and the hemispheres **354** and **356** may be joined by one or more hinges, such as a clam-like hinge. In some embodiments, the cylinder **352**, top hemisphere **354**, and the bottom hemisphere **356** may be designed to an appropriate wall-thickness with a factor of safety to safely operate at a predetermined service depth (or pressure). To prevent slippage between the cylinder **352** and hemispheres **354** and **356**, the internal cavity may be evacuated to a fraction of standard atmospheric pressure (i.e., <14.7 psi). The cylinder **352** and hemispheres **354** and **356** may be separated by removing the vacuum and subsequently separating the cylinder **352** and hemispheres **354** and **356**. Internally, the pressure vessel may or may not contain internal structure or electronics, depending on the application.

**[0064]** FIG. **4** depicts a process of manufacturing a pressure vessel component according to an illustrative embodiment. Process **400** may include casting a metal to produce a gross pressure vessel component where casting includes forming portions of the gross pressure vessel component having an increased thickness and being located at predetermined positions on the gross pressure vessel component (Step **402**). The positions are "predetermined" because the locations are determined before casting or forming the gross pressure vessel. Then, indexing the gross pressure vessel component to select the portions of the gross pressure vessel component for machining (Step **404**). Finally, machining the gross pressure vessel component to produce a pressure vessel component, including machining the selected portions (Step **406**).

**[0065]** At step **402**, a metal may be cast to produce a gross pressure vessel component. The metal may be any suitable metal for pressure vessels, including, but not limited to, titanium, steel, aluminum, or tungsten carbide. In some embodiments, the gross pressure vessel component may be cast by sintering the metal followed by a HIP process. In alternate embodiments, the gross pressure vessel component may be cast by pouring molten metal into a mold. In some embodiments, the pressure vessel component may be optionally heat treated, either before or after machining.

**[0066]** At step **404**, the gross pressure vessel may be indexed to select the portions of the gross pressure vessel component for machining. The portions may include bosses having an increased thickness located at predetermined positions on the gross pressure vessel component. In some embodiments, the bosses may occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane. In some embodiments, the bosses may comprise cable pass-throughs (e.g., holes).

**[0067]** At step **406**, the gross pressure vessel component may be machined to produce a pressure vessel component, including machining the selected portions. As discussed above, some of the selected portions may not require additional machining. However, some of the selected portions may require machining to remove extraneous material to produce a finalized boss shape.

**[0068]** In certain implementations, a pressure vessel component such as, for example, pressure vessel component **302**, top hemisphere **312**, bottom hemisphere **314**, or cylinder **352**, is machined after the vessel component **302** has been cast with various bosses **304**, **316**, **318**, **320**, **322**, **324**, or **326**. One advantage to forming bosses **304** at the time of casting a pressure vessel component **302** is that a standard set of bosses may be formed efficiently, but then the manufacturer can determine which ones of the cast bosses **304** are to be machined into portals or holes depending on the configuration and/or arrangement of the components within the pressure vessel component **302**. This can be particularly advantageous when the pressure vessel includes a metal such as titanium. Furthermore, a common mold may be used for all pressure vessels, and bosses, holes, supports, flanges, and other features may be machined after casting/forging in order to produce a custom pressure vessel. Hence, a plurality of bosses **304** are formed to enable hole machining for multiple possible configurations, but then only a subset or portion of the plurality of bosses **304** is subsequently machined into holes or portals based on a selected configuration or arrangement of components. In contrast, existing manufacturing processes of pressure vessels typically includes casting a pressure vessel, then determining the required locations of bosses/holes based on the designed component configuration, and then forming the bosses and holes at the determined locations after a pressure vessel component has been cast. Such a process, while limiting the number of bosses on a pressure vessel, is substantially more time-consuming, costly, and inefficient as compared with the advantageous process as described above where a set of bosses **304** are formed during the casting process and, after casting, a subset of the bosses **304** are machined depending on the particular configuration or arrangement of components within the pressure vessel **302**, **312**, **314**, **352**, **354**, **356**.

**[0069]** It will be apparent to those skilled in the art that such embodiments are provided by way of example only. It should be understood that numerous variations, alternatives, changes, and substitutions may be employed by those skilled in the art in practicing the invention. Accordingly, it will be understood that the invention is not to be limited to the embodiments disclosed herein, but is to be understood from the following claims, which are to be interpreted as broadly as allowed under the law.

What is claimed is:

**1**. A method of manufacturing a pressure vessel component, comprising:

casting a metal to produce a gross pressure vessel component, wherein casting includes forming portions of the gross pressure vessel component having an increased thickness and being located at predetermined positions on the gross pressure vessel component;

indexing the gross pressure vessel component to select the portions of the gross pressure vessel component for machining; and

machining the gross pressure vessel component to produce a pressure vessel component, including machining the selected portions.

**2**. The method of claim **1**, wherein the pressure vessel component is one of: a hemisphere, a cylinder, an ellipsoid, a cube, a rectangular prism, or a square endcap for a cylindrical pressure vessel.

**3**. The method of claim **1**, wherein the metal is titanium.

**4**. The method of claim **1**, wherein casting the metal to produce a gross pressure vessel component comprises sintering the metal followed by a hot isostatic press (HIP) process.

**5**. The method of claim **1**, wherein casting the metal to produce a gross pressure vessel component comprises pouring molten metal into a mold.

**6**. The method of claim **1** further comprising heat treating the pressure vessel component.

**7**. The method of claim **1**, wherein the pressure vessel component is designed to mate with a second pressure vessel component.

**8**. The method of claim **7**, wherein a hinge is used to open, close, and align the pressure vessel component with the second pressure vessel component.

**9**. The method of claim **7**, further comprising:

mating the pressure vessel component with the second pressure vessel component; and

forming at least a partial vacuum in a cavity formed by the pressure vessel component and the second pressure vessel component.

**10**. The method of claim **1**, wherein the portions having the increased thickness occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane.

**11**. The method of claim **1**, wherein machining the gross pressure vessel component comprises machining cable pass-throughs at the portions having the increased thickness.

**12**. The method of claim **1**, wherein the predetermined locations of the portions of the gross pressure vessel component having an increased thickness are based on a plurality of possible arrangements of components within the gross pressure vessel.

**13**. The method of claim **12**, wherein the selected portions of the gross pressure is a subset of the portions of the gross pressure vessel component having an increased thickness.

**14**. The method of claim **13**, wherein the subset is determined based on one of the plurality of possible arrangements of the components within the gross pressure vessel.

**15**. The method of claim **14**, comprising machining the selected portions after casting and indexing the gross pressure vessel.

**16**. A system for manufacturing a pressure vessel component, comprising:

a mold for casting a metal to produce a gross pressure vessel component, wherein casting includes forming portions of the gross pressure vessel component having an increased thickness and being located at predetermined positions on the gross pressure vessel component; and

machining equipment configured to:

index the gross pressure vessel component to select the portions of the gross pressure vessel component for machining; and

machine the gross pressure vessel component to produce a pressure vessel component, including machining the selected portions.

**17**. The system of claim **16**, wherein the pressure vessel component is one of: a hemisphere, a cylinder, a cube, or a rectangular prism.

**18**. The system of claim **16**, wherein the metal is titanium.

**19**. The system of claim **16**, wherein casting the metal to produce a gross pressure vessel component comprises sintering the metal followed by a hot isostatic press (HIP) process.

**20**. The system of claim **16**, wherein casting the metal to produce a gross pressure vessel component comprises pouring molten metal into the mold.

**21**. The system of claim **16**, wherein the machining equipment is further configured to heat treat the pressure vessel component.

**22**. The system of claim **16**, wherein the pressure vessel component is designed to mate with a second pressure vessel component.

**23**. The system of claim **22**, wherein a hinge is used to open, close, and align the pressure vessel component with the second pressure vessel component.

**24**. The system of claim **22**, wherein the pressure vessel component and the second pressure vessel component are configured to form at least a partial vacuum in a cavity formed by the pressure vessel component and the second pressure vessel component.

**25**. The system of claim **16**, wherein the portions having the increased thickness occur at predetermined angles of elevation and azimuth relative to a sphere equatorial plane.

**26**. The system of claim **16**, wherein the machining equipment is configured to machine the gross pressure vessel component by machining cable pass-throughs at the portions having the increased thickness.

**27**. The system of claim **16**, wherein the predetermined locations of the portions of the gross pressure vessel component having an increased thickness are based on a plurality of possible arrangements of components within the gross pressure vessel.

**28**. The system of claim **27**, the selected portions of the gross pressure is a subset of the portions of the gross pressure vessel component having an increased thickness.

**29**. The system of claim **28**, wherein the subset is determined based on one of the plurality of possible arrangements of the components within the gross pressure vessel.

**30**. The system of claim **29**, comprising machining the selected portions after casting and indexing the gross pressure vessel.

**31**. The system of claim **16**, wherein the pressure vessel component includes a radiator for heat exchange.

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