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Manned submersible „JAGO“

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Abstract: The manned submersible „JAGO“ is a human occupied underwater vehicle (HOV) designed for personal exploration and research in all types of aquatic systems and habitats. The seafloor along the continental shelf and slopes within the ocean twilight zone is JAGO’s main target area. The DNV-GL classed 2-person submersible has a maximum operating depth of 400 m. The two occupants, the pilot and one observer, are seated at 1 Atmosphere in a steel pressure hull with two large acrylic windows. The submersible’s small size and lightweight construction (3 T) allows worldwide operations from on board a wide variety of vessels as well as transport in a single standard 20-foot container together with all support equipment. Typical applications include personal observation of the sea bed and water column, video and photo documentation, selective non-intrusive sampling, placement of sensors and experiments, underwater inspection, as well as location and recovery of objects.

1 Introduction

JAGO was built in 1989 by a small research team, consisting of four people and led by the German zoologist and author Hans Fricke. At that time, the team was based as an affiliated research group at the Max-Planck-Institute of Animal Behavior and Physiology in South Germany and specialized in deep-water marine ecology and exploration.

The team had gained substantial experiences in submersible operation since 1981 by using the manned submersible “GEO” for their research tasks. GEO had a depth rating of 200 m and was built in Switzerland on the basis of ideas of Hans Fricke. A research highlight achieved with GEO was the first in situ observation of the coelacanth *Latimeria chalumnae*, an ancient fish closely related to those fish-like vertebrates that made the first step on land and thus became the early ancestors of all land living four-legged animals.

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Based on this worldwide-respected discovery, the team decided to extend its diving facility with the construction of a deeper diving submersible. The construction was mainly financed by private funds and technically supervised by the German Lloyd, now DNV-GL. The name JAGO refers to *Jago omanensis*, a houndshark that was named after Iago, the villain in Shakespeare's Othello.

JAGO is Germany's only manned research submersible. Since 2006, the submersible is stationed at GEOMAR in Kiel, operated by the same team as at the start of operation in 1989. Though more than a quarter of a century old, JAGO remains a versatile research tool thanks to continued retrofitting and maintenance performed by a very experienced team. As of this publication, JAGO has made more than 1,300 dives, taking more than 600 scientists, engineers and observers to the seafloor. Dive sites are scattered all over the world, ranging from the polar region off Svalbard in the North Atlantic to the shelf of New Zealand in the southern Pacific. Dive targets comprise tropical to deep-water coral reefs, hydrothermal vents and cold seeps, underwater seamounts and volcanoes, and deep fjords and fresh water lakes.

2 Design principles

When planning a deeper diving replacement for the first submersible GEO, the aim was to construct a manned submersible that would be multipurpose, multifunctional, and easy to operate and maintain.

Most important, the submersible had to be robust, compact and lightweight to enable flexible operation from a wide variety of support vessels and easy transport in a standard 20' shipping container (internal dimension 5,89 m x 2,35 m x 2,39 m LWH, door opening 2,34 m x 2,27 m WH). The design should also allow transport on a custom road trailer, towed by a regular four-wheel drive vehicle, to enable shore-based operation at remote locations or usage in lakes.

Preliminary investigations had revealed, that at that time many manned submersibles have been large and heavy and required specially adapted support vessels that made operations expensive and less flexible. When launched and recovered with the crew aboard the submersible, the lifting facility on board a suitable support vessel must have a safety factor of 1.5, according to the DNV-GL rules for classification and construction of manned submersible. Many of the smaller research vessels or support ships for charter, however, have deck crane facilities with a Safe Working Load (SWL) of maximum 5 or 6 tons. This implies that the submersible's weight in air, including the crew, should not exceed 3-3.5 tons.

Operation from different support vessels also requires an unpretentious lifting design for easy integration into the vessel's launch and recovery system and in general robustness of the entire system. Fully acrylic pressure hulls for example are more sensitive to scratches than steel hulls and their wall thickness must be larger to withstand the outside water pressure. A thicker wall, however, increases the total weight of the vehicle. The team therefore decided steel would be the ideal construction material for the pressure hull.

The weight of a submersible is directly proportional to its displacement volume. So in order to minimize the weight, one must minimize the interior volume of the pressure hull itself, in consideration of the number of occupants and the amount of equipment that needs to be installed inside the passenger cabin. The interior space of the pressure hull that is needed to hold 2 persons in comparison to e.g. 3 persons differs considerably. In order to meet the construction requirements – total weight of maximum 3 tons and dimensions that allow storage in a standard 20' shipping container – the number of occupants that can board the JAGO was therefore restricted to two.

An inclined position of the submersible forward or astern to facilitate diving or surfacing requires the implementation of trimming devices. Most civil manned submersibles, however, operate without trimming tanks. The submersible is kept in a horizontal position during vertical movements (de- and ascent), and during horizontal movements along the sea floor or at a certain depth within the water column. In order to achieve a stable horizontal position during all types of movements and manoeuvres, all constituent parts of the vehicle must be arranged in such a way that their different weights are well counterbalanced. The pressure hull, which is the largest and heaviest part of the vehicle, should be integrated in the entire system in such a way that the occupants inside the hull should be able to get as close as possible to the subjects they wish to study. This can only be achieved if the viewports incorporated into the pressure hull are facing forward and, at the best, are slightly tilted downward for an undisturbed view e.g. onto the sea floor. The pressure hull should therefore be placed as far as possible forward on the longitudinal axis of the vehicle. If the pressure hull has, for example, a spherical shape and is ideally placed at the very front of the submersible, it then needs to be counterbalanced by arranging most of the other components behind it. This arrangement also achieves suitable hydrodynamic performance of the vehicle. Even weight distribution, undisturbed close view of the seafloor and hydrodynamic performance are easier to reconcile if the shape of the pressure hull is elongated. An elongated pressure hull, however, is less pressure resistant than a sphere and thus needs to be stabilized by inside stiffener rings which, in turn, again add weight to the entire construction. The JAGO-Team decided in favour of an elongated pressure hull.

3 Technical Data and Capabilities

3.1 JAGO Specifications

- Owner and Operator: GEOMAR Helmholtz Centre for Ocean Research Kiel
- Crew: 1 pilot, 1 observer
- Maximum operating depth: 400 m
- Dimensions: Length 3.0 m, Width 2.0 m, Height 2.5 m
- Personnel cabin dimensions: Length 2.13 m, diameter 1.29 m
- Personnel cabin volume: 2.5 cubic meters
- Weight in air: 3,000 kg
- Maximum payload: 250 kg
- Pressure hull material: Steel
- Viewports: acrylic, 1 bow-window (ø700 mm), 1 top dome / hatch (ø450 mm)
- Power supply: lead-acid batteries, total capacity 13 KWh – 24 VDC
- Propulsion: electrically powered thrusters – 3 reversable thrusters at stern, 2 rotational thrusters on starboard and port side, 1 front and 1 aft thruster
- Cruising speed: 1 knot
- Emergency Life Support: 96 man hours
- Safety and Rescue Systems: Emergency drop weight, dead-man's switch, releasable emergency buoy, generation of >500 kg positive buoyancy
- Lighting: 9 multiple positional LED lamps, laser scaling
- Standard equipment: Underwater navigation and positioning system (USBL), voice communication through acoustic underwater telephone (UT), electronic compass, redundant depth sensors, vertical and horizontal sonar, hydraulic manipulator arm, GPS sensor for surface navigation, marine band (VHF) radio for surface communication
- Imaging: Full-HD video cameras for through viewport documentation, hand-held digital still camera, flashes, in-hull hard drive video recorders and monitors
- Scientific sampling equipment: CTD, temperature probes, sample boxes for biological samples or rock collection, water sampler (NISKIN), push corers for sediment samples, fluid and gas samplers, scoop nets and cups, acoustic marker beacons
- Launch & Recovery: man-rated single lifting point
- Transport: 1 x 20' ISO Container or on custom road trailer
- Classification: DNV-GL Hamburg

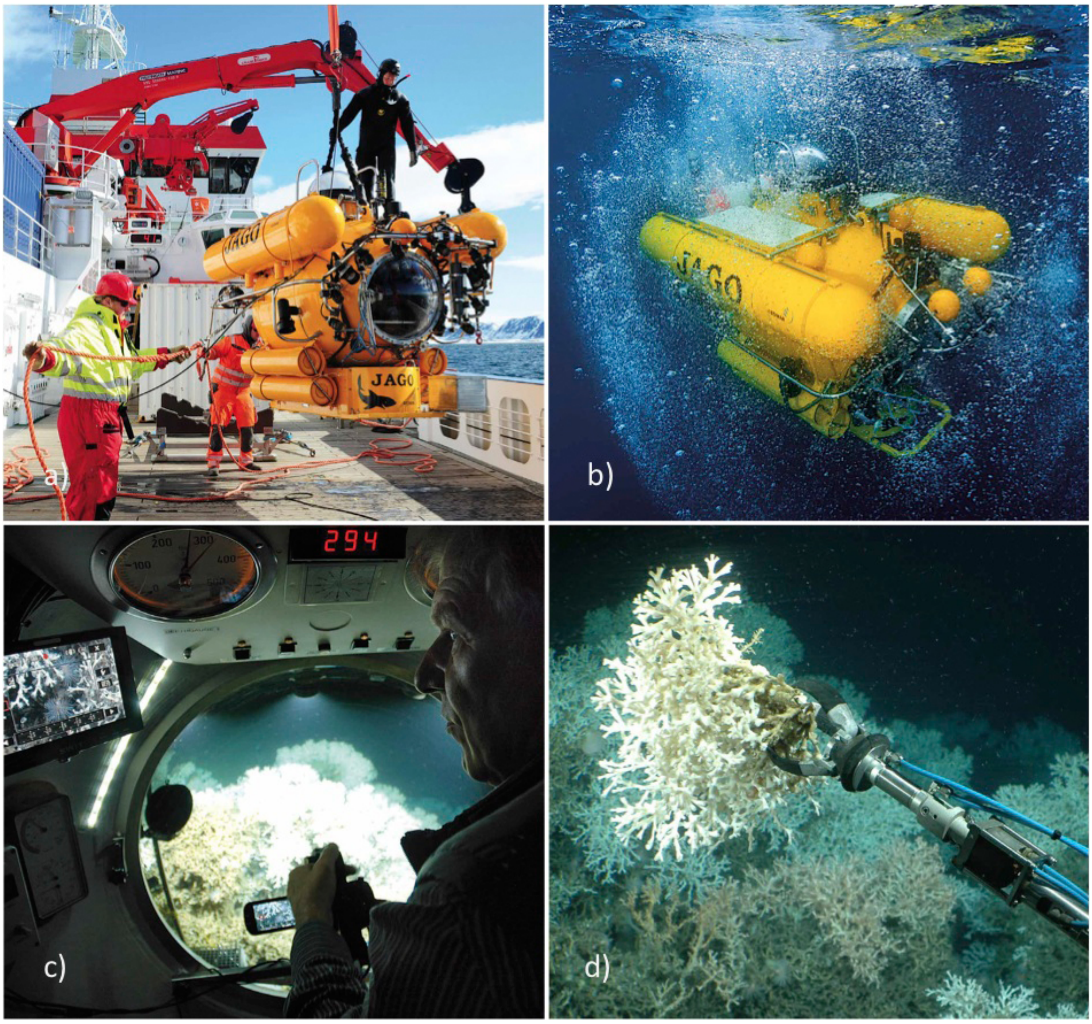

Figure 1: Manned Submersible "JAGO", a) recovered by the crew of the German research vessel "MARIA SYBILLE MERIAN" after a dive off Spitsbergen / Norway, b) approaching the surface after a dive off Namibia, c) pilot Jürgen Schauer adjusts HD video camera for filming cold water corals in a deep reef off Norway, d) non-intrusive sampling of cold water corals with JAGO's manipulator arm.

JAGO is an extremely compact and light-weight manned submersible for its depth class. It is 3 m long, 2 m wide and 2.5 m high. The weight in air is 3 tons.

JAGO's steel pressure hull consists of a cylindrical and longitudinally oriented midsection and two half spheres, one attached to the front and the other to the stern end of the cylinder. A second, smaller cylinder is vertically attached to the top-side of the midsection. It carries a 45 mm-wide acrylic dome that serves as the entry hatch and provides the pilot with a 360-degree field of vision around the top and above the submersible. A second acrylic spherical shell window is integrated into the bow of the submersible. The window is down tilted by 8 degrees and has a diameter of 700 mm and an opening angle of 120 degrees. It provides for both, the observer and the pilot, a spacious view onto the scenery in front of the submersible and at the sea floor (Figure 1, Figure 2).

The hull rests on a free-flooded substructure in the form of an open-top steel compartment. It houses at the centre-of-mass the ballast tank, the battery system, the hydraulic system for the manipulator arm and a system for pressure compensating the air volume inside the batteries. An emergency drop weight in the form of a 50 kg steel plate is attached to the underside of the substructure.

Tow 360-litre diving tanks are attached to JAGO's sides at the upper half of the pressure hull. They provide buoyancy and stability when the submersible is floating at the water surface. At the surface, the diving tanks are filled with air. The freeboard (the distance between water line and the upper edge of the top-hatch flange) measures 60 cm in still water. For initialising the diving procedure, the diving tanks are flooded, and the water level rises to mid-level of the cylinder that carries the top entry hatch. Submerging and the actual descent are then initialized by streaming a defined amount of water into the variable ballast tank, which decreases buoyancy. Descent and ascent speed is under normal conditions about 10 m/min. The variable ballast is also used to compensate differences in payload that occur by picking up samples or deploying instruments at the sea floor. Weight differences between the observers participating in a dive or by loading additional equipment into the personnel cabin are compensated by adding or removing small led weights that are stored inside the cabin.

Two compressed gas cylinders are attached to each side of the substructure and the lower sides of the pressure hull (40 litre each at 200 bar). Three cylinders are filled with pressure air and one with compressed oxygen. The compressed air is used to blow the diving tanks and the variable ballast tank clear of water and thus to control buoyancy. It is also used to pressure compensate the batteries. The 40-litre oxygen cylinder is dedicated for the emergency to supply 96 hours of life support for the two occupants. The medical oxygen, which is consumed by the occupants during a regular dive, is injected through a flowmeter into the personnel cabin from another 10-litre pressure cylinder. This cylinder is stored inside the cabin below the floor cover. The carbon dioxide, exhaled by the occupants, is removed from the atmosphere inside the cabin by a CO_2 absorption unit. It comprises a filter filled with calcium-hydroxide-based scrubber and ventilators that suck the breathing air through the filter. Additional fans help to circulate the air inside the cabin. Spare filters for exchanging saturated filters and to ensure 96 hours life support in case of emergency are stored inside the cabin. The O_2 and CO_2 partial pressure within the cabin is continuously monitored by a multi gas detector. The cabin pressure is always approximately one atmosphere.

The power for all electrical systems is provided by lead-acid batteries with a total capacity of 13 kWh at 24 Volt DC. The batteries are not stored in a heavy pressure housing or an oil-filled pressurized enclosure. Instead, the air volume inside the batteries is kept constant and adjusted to the water pressure at any given depth by adding or releasing pressure air through the compensation system. This battery arrangement is very reliable, maintenance-free, and provides a dive time of up to 10 hours under normal circumstances.

JAGO’s propulsion system comprises seven electrically powered thusters that provide precise manoeuvring in all three axes (X,Y,Z). Three thrusters, mounted horizontally at the stern, provide forward and reverse thrust. Two thrusters at the sides of the pressure hull are mounted on a shaft that is rotatable from inside the personnel cabin. By turning they can provide thrust to all directions except laterally. They are mainly used for fine-tuning the distance of the submersible to the sea floor when manoeuvring close above the bottom in rugged terrain. Two thrusters are mounted horizontally but perpendicular to the longitudinal axis of the vehicle, one at the stern and one above the front window. They provide lateral thrust for sideward motion, e.g. motions parallel to a vertical structure. The thruster system allows the submersible to travel at a speed of 1.5 knots. Survey speed during dives close to the sea bed is usually kept to half a knot to enable detailed observation and video documentation. The control board for the thrusters is simple to operate and attached to a long flexible cable that allows the pilot to steer the submersible from any position inside the cabin while the submersible is submerged or floating at the surface.

The exterior of the submersible or parts of it are not covered with a shell that is usually made of composite material like carbon or fiberglass-reinforced plastic (FRP). Shells and covers usually have the function to smooth the surface to improve the hydrodynamic performance of the vehicle and to protect sensitive parts against damages and entanglement with ropes, lines and nets. The main free-flooded exterior components of JAGO are therefore designed and arranged in such a way that they can buffer and resist forces that may occur if the vehicle accidentally hits solid objects like ship structures or rocky surfaces under water. Railings and rope deflectors help to protect against entanglement. Syntactic foam, which is often used to gain additional positive buoyancy underwater but which also adds weight to a vehicle in air, is only used in the form of two small blocks specially shaped to fit under the grating at both sides of the entry hatch on the topside of the pressure hull.

The safety and rescue systems on board the submersible comprise several components and procedures that can be activated and applied independently from each other. In the highly unlikely event of a power failure, the submersible, which is neutrally buoyant under water, will ascend to the surface by dropping weight. The drop weight below JAGO's substructure can be either released manually or is automatically released if the submersible descends deeper than 440 meter or if an acoustic alarm signal, that occurs every 10 minutes, is not turned off by the occupants within 30 seconds. This so called 'Deadman' system is installed for the event that both occupants become incapacitated for any reason. The submersible is also equipped with a red emergency buoy that can be manually released from inside the cabin. When released and raised to the surface the buoy marks the position of the submersible on the surface. The buoy's Dyneema rope, attached with one end to the submersible and with the other to the buoy, measures in length 1.25 times the operating depth of JAGO. The rope is strong enough to be used to lift the submersible to the surface. By blowing pressure air into both of the upper diving tanks, more than 500 kg of positive buoyancy/uplift force can be generated. The life support system of JAGO for cases of emergency comprises additional 96 hours reserves of medical oxygen, CO_2 scrubber, pressure air, battery power, as well as protection against cold, food and water.

Voice communication between the JAGO crew and the support vessel during diving is provided by a single sideband acoustic underwater telephone with a range of up to 5 km. Handheld VHF radios are used for communication when JAGO is on the surface, mainly shortly before submerging and after surfacing.

Underwater navigation sensors comprise an electronic compass to provide vehicle heading as well as mechanical and electronic depth gauges to measure the external ambient hydrostatic pressure (depth). Both data, heading and depth, are shown on digital displays inside the cabin. A down- and forward-looking sonar provides information on the distance of the submersible to the sea floor and to obstacles ahead. It is also used for target or object detection. An USBL navigation and positioning system installed on the support vessel continuously calculates JAGO's GPS position under water. The system enables the support vessel to track the submersible while cruising along the sea floor and to determine where the submersible is going to surface at the end of the dive. Position data are computer-logged on board the vessel and displayed on geo-referenced bathymetric maps to enable precise navigation to specified targets.

JAGO's hydraulic system supplies hydraulic power for a manipulator arm mounted on the starboard front side below the large bow window. The manipulator is operated semi-manually, combined with four degrees of hydraulically controlled movement: arm extension and retraction, elbow pitch and stretch, wrist rotate, and claw open and close. The main axis of the upper part of the arm penetrates the pressure hull with an O-ring sealed ball joint. The ball joint enables the pilot to move the manipulator arm manually in any desired direction. The ability to direct the arm manually and not hydraulically or electrically enables a very fast execution of any kind of task, like collecting items from the sea floor, handling sampling tools and devices, triggering instruments or deploying experiments. The manipulator has a maximum extension of 1 m and a lift capacity of 5 kg. The three-finger claw is sensitive enough to perform very delicate tasks like picking up extremely fragile items (branched corals, shells etc., Figure 1d) and at the same time robust enough to grab and hold solid materials, tools and instruments.

The submersible is fitted with 9 LED lamps for illuminating the environment. Their position on the mounting bar above and around the front window can be individually adjusted to the specific tasks and environmental conditions. Two paired lasers provide a scale bar on the sea floor for length measurements of organisms and objects. In-hull HD video cameras and recorders as well as externally mounted HD mini-video cameras are available for documentation and close-up observation. An HD flat screen monitor is connected to the in-hull video camera for viewing and controlling the recorded image (Figure 1c). Hand-held digital still cameras for photographing through the front window are also part of the imaging capabilities of JAGO. Autonomous video- or still cameras that can be placed on the sea floor are available for time-lapse documentation. Video images can be converted to different formats and overlaid with timestamp for geo-referencing and video annotation.

Permanently installed sensors for scientific data collection comprise a profiling CTD that measures conductivity/salinity, temperature, and depth (pressure) and two temperature probes that measure ambient water temperature and the temperature when inserted into soft sediment or fluids. Other sensors like e.g. oxygen or pH/ORP sensors can be easily integrated.

JAGO can be fitted with an array of other specialized equipment, depending on the requirements of the scientists. Sampling tools and instruments are typically mounted on a platform that is attached to the ram bar in front of JAGO's substructure and on a vertical equipment rack that is mounted between the platform and the lamp bar above the front window.

Sampling baskets and tubes are available in different sizes and configurations, with and without lids. They provide many mounting options and can be easily rearranged to meet the specific objectives of each dive. Rock samples for instance are usually stored in a large open-top basket, while obtaining living organisms often requires temporary storage in ambient sea water and thus in sampling boxes that have a sealing lid.

A 2.5 litre Niskin water sampling bottle is permanently installed on a rack on the port side of the front window. It is used for taking water samples in the water column, close to the bottom, or in hydrothermal vent plumes. The number of Niskin bottles taken on a dive can be expanded if needed. The Niskin bottles are triggered with JAGO's manipulator arm.

Water and fluids discharged from hydrothermal vents or freshwater outlets can be collected with a gas-tight flow-through system mounted to the vertical rack. The sample cylinders, the in- and outlet valves, the sampling hose and the nozzle that is guided into the vents by the manipulator arm are all made of inert and high-temperature resistant material.

Gas that is released from the seafloor can be collected with two types of bubble samplers, one has a pressure-tight stainless steel sampling cylinder, the other a glass cylinder.

Push corers of different diameters are used for sampling sediment without destroying the original layering structure. The sediment core is caught in a transparent acrylic tube which is stored in a rack for transport to the surface and deck handling.

A number of smaller sampling devices and tools like scoop nets, scoop cups, chisels and cutters are also available.

Instruments or experiment platforms that should be deployed at the sea floor for a certain period and recovered at the end of a cruise can be equipped with optical or acoustic markers in form of a small transmitter that can be relocated under water from on board the submersible.

Figure 2: Manned submersible “JAGO”, a) view from outside through the front window into the personnel cabin, b) at the sea surface after deployment from on board the German research vessel “POSEIDON” in the Trondheim Fjord /Norway.

4 Deployment, recovery and operations

When designing JAGO, a priority was the safe and highly flexible operation from on board a broad variety of working platforms comprising research vessel, commercial support ships, barges or marinas during shore-based campaigns.

JAGO has a single lifting point that makes it easy to adjust the launch and recovery procedure to the lift types and configurations on board the different vessels. Suitable lifting devices are A-frames, articulated cranes (knuckle-boom and/or telescopic) and non-articulated cranes (derricks). They have to be rated to lift minimum 5 tons at an outreach of minimum 3 meters off the ship’s stern or side. The procedure of the launch-and-recovery operation has to be adjusted also to the position of the lifting device on the vessel, which can be at the stern or at the side of the ship.

JAGO’s lifting strop is connected to and disconnected from the crane hook by a swimmer who is standing on top of the submersible during off- and on-boarding (Figure 1a, Figure 2b). During the dive, the strop remains attached to the submersible. The swimmer also connects or disconnects several lines, comprising two side lines (tag or stabilizing lines), a towing line and occasionally a centre line if the submersible is launched and recovered over the ship's stern. The side lines help to prevent horizontal rotation of the submersible and reduce swinging side to side while the heavy vehicle is hanging on the lifting cable. The towing line is connected to JAGO's stern and to an accompanying boat. The boat is used to clear off the submersible from the ship's side or stern and to tow the submersible to the dive site after deployment and back under the crane position after surfacing. The tow boat also transfers the swimmer back to the ship at the beginning of the dive or to the submersible at its end.

In general, JAGO can be deployed and recovered at weather conditions with a swell of up to 1.5 m and wind speeds of up to 5 Beaufort. However, many combinations of wind and sea conditions define the acceptable window for launch and recovery. The mentioned thresholds of velocity or height of wind or sea conditions are therefore only assessment values. During normal cruise operations and favourable weather and sea conditions up to two dives are performed per day, usually during daylight hours. Night time operations are possible but need to be carefully planned and discussed with the ship's command and the scientific cruise leader to ensure appropriate staffing.

During cruises, maintenance requirements are usually low. Prior to each dive, the installation and loading of equipment is adjusted to the specific objectives of the dive. Pre-dive checks are performed by the pilot shortly before launching and before starting the descent. After the dive, the submersible is rinsed with fresh water, the batteries are recharged, which usually takes 2-3 hours between the dives, the pressure air tanks are topped up to 200 bar, the CO_2 filters are replaced and the cabin interior is aerated and dried.

Operating and maintaining JAGO requires a minimal crew of three people: two pilots / technicians and a topside coordinator / controller who monitors and records each dive. The coordinator /controller is the link person between the submersible team, the ship's navigators, the ship's deck crew, and the scientific party.

Mobilisation and demobilisation on board the support vessel usually takes one to two days. During transits and between dives, the submersible remains lashed down on deck during the entire cruise. The transport container then serves as storage space for sampling equipment, tools and spare parts. At the end of operations, the vehicle is stocked back into the container. The entire system, the submersible and the support equipment, fits into a single standard sea freight 20-foot container, which makes worldwide transportation easy and cost-efficient.

The submersible is certified by DNV-GL and annually inspected by DNV-GL engineers since its start of operation. JAGO has a perfect safety record and has never been involved in any accidents, severe hazards or system breakdowns during more than 27 years of operation. At the end of the year 2016, the submersible has accomplished a total of 1334 dives with 4145 hours under water on 72 expeditions. JAGO has been deployed from 20 different research vessels and support ships, the largest was the South African icebreaker R/V AGULHAS (134 m), the smallest the Spanish coastal research vessel B/O GARCíA DEL CID (37 m). The JAGO pilots have taken more than 600 different dive participants to the sea floor, most of them scientists, students and engineers, but also journalists, film-makers, politicians, celebrities and citizen representatives. By immersing themselves into the underwater environment, all of them gained not only a new or deeper insight into their research field but also an intensity of experience that is difficult to achieve with unmanned exploration tools.

5 Selection of publications based on JAGO dives

Since its first deployment in 1989, JAGO has been involved in many research projects of different disciplines. Numerous bachelor, master and doctoral theses, as well as more than 200 publications are based on data and samples collected by the submersible. The following list is a selection of some of those publications.

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