

DeepC

the German AUV Development Project

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1. Abstract

Underwater technology, especially at great depths, represents a very particular challenge which is now being tackled within the scope of the German co-operation project DeepC. The aim of this project which is being sponsored by the Federal Ministry for Education and Research is to develop a fully autonomous underwater vehicle (AUV) for great diving depths and long mission times .

The development of such AUV demands technologies that are either not available or as yet inadequately available. For instance, planning assistants and pre-launch checks have to assure that the expensive AUV will not be launched with planning or system errors. Computer structures both in the planning console and in the vehicle have to offer maximum flexibility, provide distributed intelligence and offer an object-oriented structure. Mission management systems perform vehicle guidance, assure intelligent behaviour in special situations, provide a degradation mode for emergencies and/or plan missions independently with due consideration to the targets set. Without external support, the navigation system must allow precise AUV navigation over longer periods of time. Mission-specific sensor systems support vehicle guidance, avoid collisions and perform the actual measuring tasks. The power supply has to deliver sufficient energy with maximum efficiency, while the system should be kept as small as possible. The pressure hull of the underwater vehicle consists of light, high-strength materials with minimum weight at maximum possible interior volume. Optimised shaping and drive systems allow operation with minimised energy consumption. Additionally, control and manoeuvring devices allow the desired - generally complex - movement properties. In the event of any defects, the system should be capable of diagnosing and eliminating these without external assistance.

Finally, a system simulator with virtual reality permits realistic system and mission simulation not only during the development phase but also in operation.

The paper describes the current development status, deals with the applications and gives an outlook into the future.

2. Introduction

AUVs, especially for inspection tasks, are drawing close to operational use. This is not only the result of technological advances but also due to the substantial financial advantage of AUV operations over missions with conventional vehicles.

At the end of 1999, a consortium for the development of an AUV with an extremely innovative character was founded with the involvement of the Federal Ministry for Education and Research: the *DeepC* AUV was to operate not only for very long periods at relatively high speeds and very great depths but was also to provide excellent manoeuvrability characteristics coupled with navigation accuracy. Another objective was to minimize the weight in air while at the same time allowing high payload weights. Finally, the overall system was to have a modular design to permit easy adaptation to various missions.

The implementation of these requirements was carried out by a consortium coordinated by STN ATLAS with the partners OSAE GmbH (Bremen), ATI Küste GmbH (Rostock),

ENITECH GmbH (Rostock), AIR GmbH (Rostock), Center for Solar Energy and Hydrogen Research (ZSW) (Ulm), Technical University of Ilmenau and University of Karlsruhe.

3. *DeepC* System

3.1 Requirements

The aim of the *DeepC* project is to develop and demonstrate (fall 2003/spring 2004) a fully autonomous underwater vehicle (AUV) with the related components on the water's surface for oceanographic and oceanologic applications. The main performance parameters of the *DeepC* system are in general

- Autonomous mission execution
- Low weight
- High manoeuvrability
- Hover capability
- Modular design
- Deployment from vessels of opportunities
- Intelligent behaviour
- In mission re-planning capability
- Precise navigation
- Advanced diagnosis and fault recovery system (CORBA/SOAP based)

and especially

- Mission depth 4000 m (Crush: 6000 m)
- Weight in air 2.4 t
- Cruise speed 4 kts
- Maximum speed 6 kts
- Mission time up to 60 hours
- Operating range up to 400 km
- Payloads 300 kg.

In addition, a comfortable Man-Machine Interface as well as a simulator with virtual reality is required for the mission planning and evaluation station.

3.2 Underwater Vehicle

3.2.1 Vehicle Design

Fig.1 shows the external configuration of the underwater vehicle.



Fig.1: *DeepC* vehicle configuration

The vehicle consists of three structures: two propulsion and one payload unit. The propulsion units are largely equipped with identical components so that a high functional safety is warranted by redundancy. Depending on the respective design, the components are either accommodated in the pressure hulls or in the flooded area. Both, the hulls and the pressure hulls are made from high-strength CFRP and therefore particularly light.

The two main drive propellers which are also made of CFRP have a diameter of 50 cm and rotate at a speed of 500 r.p.m. Four further thrusters provide maximum manoeuvrability of the vehicle, in which context it is worth noting that the thruster propellers are not attached to a shaft but are driven by an annular motor, and are therefore highly resistant to contamination. The material investigations regarding the hull/pressure hull of the vehicle were very thorough. The properties of the composite material were improved on the basis of comprehensive tests with various winding resins and by variation of the production parameters. Various winding tests with different resin systems yielded an optimum winding resin. Processes were developed and defined for extraction from the mould, saturation of the fibres, temperature treatment and the winding process to be employed for *DeepC*.

The practical verification of the structures of the pressure hull has been performed by destructive testing of models. Wound tensile specimens were manufactured for further material tests. Structural activities are rounded off by hydrodynamic calculations of the vehicle, e.g. calculation of drag, the torque with respect to the rotation axes and the mass moment of inertia. Used in combination with the information on the propulsion and control elements from the vehicle structure, these calculations provide information on curve manoeuvres in the horizontal plane, maximum static and dynamic pitch angles, maximum traversing and vertical speeds, braking properties (path and speed) as well as the maximum angle of roll.

3.2.2 Drive motors

The motors for the thrusters and the horizontal main drives are in the flooded areas of the vehicle and are cast as pressure-neutral structures. This helps to avoid critical openings for axles. At the same time, utmost care has been taken with the pressure-tightness of the motors. A whole variety of fundamental investigations has been performed in the *DeepC* project to clarify various questions concerning pressures up to 700 bar, e.g.

- determination of volume change of casting material,
- determination of mechanical properties of large rigid motor components, also with respect to sensitivity to stress-corrosion cracking and adhesion on metal,
- properties of the winding material,
- checking the insulation properties and water absorption properties,
- Properties of the cable and insulation material for electrical routing.

3.2.3 Energy Generation and Distribution

A highly efficient, high-energy power generation system is needed to provide long mission duration times at relatively high average speeds.

To meet this requirement, the *DeepC* underwater vehicle will be equipped with a polymer electrolyte membrane (PEM) fuel cell. For this purpose, not only the entire system (that is independent of the external air) requires a vehicle fitted configuration but the problems of reactant storage, the procurement thereof and storage on board the supply vessel as well as refueling need to be resolved.

A fuel cell system consists of the assemblies fuel cells, batteries, cooling system, power transformation and distribution assemblies.

The related power distribution inside the vehicle comprises these features:

- a non-contacting, redundant power bus system with current-limiting electronic coupling elements that are without fuses, with switch-off capability in the case of overload and switch-on capability
- damage switching functions
- on-condition monitoring including definition of expert knowledge
- total power management, power bus control and switching management.

The polymer electrolyte membrane (PEM-FC) stack allowing complete and position-independent permanent operation in so-called dead-ended operation is, however, the heart of the system.

The Fuel Cell system is based on two 60-cell fuel cell stacks (Fig.2) with re-circulation of the hydrogen and oxygen. This design permits the almost full conversion of the reactants so that the reaction gases do not require external moistening. The unit is integrated together with the cooling equipment and the power distribution electronics into the pressure hull of the vehicle (Fig.3).



Fig.2.: Fuel Cell System



Fig.3.: Power Distribution Electronics

3.2.4 Active Autonomy

This subsystem primarily involves the processes and sequences for the active autonomy of the vehicle, allowing situation-adapted mission and vehicle control on the basis of multi-sensor data fusion, image evaluation and higher-level decision techniques. The aim of the active and reactive process to achieve high levels of reliability and safety for longer underwater missions in different sea areas and in the presence of different ground topologies.

The active and reactive processes include:

- highly accurate long-term navigation underwater
- autonomous obstacle recognition
- autonomous operation monitoring system (system diagnostics)
- reactive mission management system
- case-sensitive track control
- situation-adaptive vehicle controller
- global and local communication and data management.

Navigation is based on the use of an inertial platform as the main sensor (Fig. 4), backed by a Doppler Log (DVL) and CTD information and Kalman filtering. A TCM II compass module as well as the vehicle model are available as back-up for position prediction. This already provides a fairly precise navigation accuracy which is, however, improved significantly by post-processing of the recorded navigation data. Fig. 5 shows a simulation calculation for this: at a vehicle distance of 200 m (!) over ground and a statistically distributed current of 4 knots (!), a course deflection in all three coordinates of max. 0.5 m per hour of operation is achieved. A position update by GPS is always possible when the vehicle surfaces.

The mission monitoring feature that is responsible for the mission sequence is at the heart of the system. It is used to analyse running missions and gives recommendations for any re-planning to mission control.

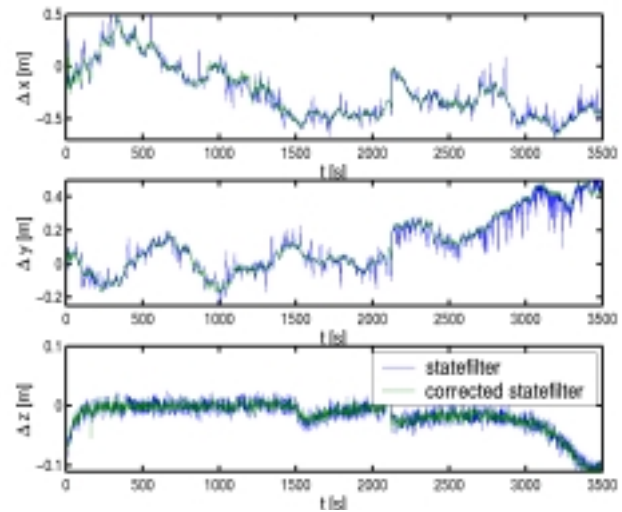
Mission re-planning is requested by mission control, as a result of which the current mission plan is requested by the mission plan handler and modified to suit the respective situation.

The fundamental feature of the intelligent DeepC behaviour is the ability to successfully handle a collision situation autonomously. In the simplest case, this would mean

circumnavigating a stationary object. Generally, however, the AUV should be able to avoid several objects that may be moving.



Fig.4: Navigation System iNAV-RQH-N with gyro drift down to 0.002 deg/hr (iMAR, Germany)



The objective of the manoeuvre to be initiated is to avoid any collision and to return to the required path on the shortest or safest route.

In view of the dynamic properties of the AUV (and possibly also of the objects to be avoided), the environmental influences (currents, depth), the limited range of the reconnaissance sensors (e.g. the forward looking sonar in this case) as well as the range-dependent detection quality and resolution of the sensors in medium water, the problem to be resolved is generally extremely complex and non-linear.

In addition, the procedure employed has to be tolerant of expected errors and stochastic changes of object measurement data like bearing, velocity vector, dimensions etc., these being essential influence factors for the avoidance decision and strategy.

Therefore the Mission Management system is mainly divided in

- Upper level decisions, mission control
- normal mission procedure with
 - vehicle guidance according to mission plan
 - autopilot and equipment control
- event driven mission procedure (in mission re-planning) with
 - mission monitoring or payload request mission re-planning
 - evasive manoeuvre: obstacle avoidance, inspection manoeuvre.

For performance of the *In-Mission Re-planning* function, one or several re-planning actions is/are assigned to numerous conceivable situations; these are stored in a library.

- Low navigation accuracy

In the event of an excessively high CEP (circular error probability) from the navigation, a GPS update can be planned into the current manoeuvre or subsequently. To this end, an allowable CEP for each manoeuvre is defined in mission planning and transferred to the mission plan

- Planning of manoeuvres at request by the payload.

During performance of a manoeuvre with payload activity, it is possible to include manoeuvres at the request of the payload. All manoeuvres from the manoeuvre catalogue of the AUV are available for this purpose

- Adaptation of manoeuvres to changed environmental conditions

Prior to performance of a manoeuvre it is possible to adapt the manoeuvre to the prevailing conditions (e.g. current).

- Adding a rendezvous point
If a parameterisable distance from the rendezvous point is exceeded, a transit manoeuvre has to be planned. This can be repeated several times until the carrier platform arrives.
- Insufficient power reserves
A three-stage re-planning process is envisaged should the power of the AUV be insufficient for the rest of the mission.
- Failure of the acoustic modem
Should the acoustic modem fail, the AUV will remain at the rendezvous point on the water's surface
- Failure of the sensors / actors / payload
In the event of a failure of components required for certain manoeuvres (defined in the mission plan), they are cancelled in the mission plan and replaced by transit sections to the next manoeuvre that can be performed
- Exceeding the maximum mission duration.
A surfacing manoeuvre is initiated if the mission duration defined in the mission plan is exceeded. The AUV establishes contact with the carrier platform.

For most of the situations mentioned, re-planning consists in adaptation, insertion and replacement of manoeuvres in the mission plan; optimisation processes are triggered in the case of power problems.

The expert system CLIPS is used as the basic system for re-planning. CLIPS (C Language Integrated Production System) is a programming language for expert systems developed at the Johnson Space Center of NASA in 1984. It is distinguished by the support of procedural, rule-based and object-oriented language structures. The main aim was to develop a portable (platform-independent), inexpensive system that is readily integrated in the existing software. CLIPS has been the subject of ongoing extension and improvement since 1984. CLIPS can be integrated in other C-programs and vice-versa via the Application Programming Interface API.

Regarding *obstacle avoidance and inspection manoeuvres*, it is possible not only to detect the obstacles and objects but also to inspect them thoroughly, i.e. to perform identification manoeuvres for closer inspections in cases of doubt. An identification can consist in a visual or cartographic inspection of the object and/or the determination of the object's physical/chemical characteristics. To perform an identification, the vehicle must adopt a defined position with reference to the object and must hold this position. Larger objects are circumnavigated by the vehicle at a defined distance from a defined position.

A two-level structure was favoured for the avoidance strategies. The lower level consists of a reactive control, performing an evasive manoeuvre in the case of unforeseeable, sudden obstacles. The higher level consists of path planning, allowing the predictive avoidance in a known environment. In this case, a path is determined that will lead the vehicle back to the desired path past the obstacle.

3.2.5 Payload

Due to its separate design, the *DeepC* payload module is capable of meeting practically any payload requirements. The main payload in the *DeepC* project is a multi-beam echo sounder system since this unit covers the broadest operating spectrum. The multi-beam echo sounder system with its very high resolution and adequate pressure strength will be employed for deep sea operations.

The system consists of a transmitter and an annular receiver with a high geometric solution and a large field-of-view. The complete unit is accommodated in the payload section of

DeepC. A quick-release fastener (clamping ring) is used for mechanical integration of the receiver.

This allows quick and simple installation/removal and underlines the flexibility of the payload module. All components are recessed or filler material is used for optimum streamlining with reference to the pressure hull.

3.3 Mission Planning and Evaluation

3.3.1 General

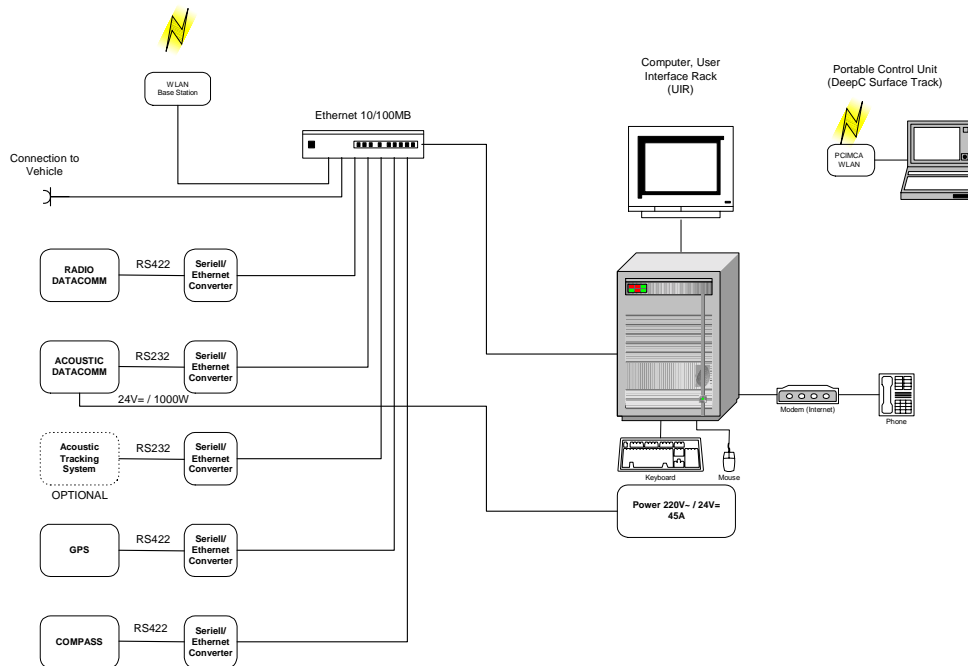


Fig.6: General Structure of Mission Planning and Evaluation Unit

The basic set-up of the mission planning and evaluation system is shown in Fig. 6. The heart of the system is a computer via which mission planning and, to the extent possible, a certain degree of mission control can be carried out with the aid of digital sea charts. A DeepC simulation system is also integrated in this computer system.

Additionally, surface and underwater communication equipment as well as a navigation system (GPS receiver and compass of the carrier) and (optionally) an underwater tracking facility are included here.

Fiber-optical cables are available for test purposes and also for transmission of data from the carrier platform to the underwater vehicle. Moreover, remote planning and evaluation operations, fault diagnoses and maintenance as well as software updates are to be performed via an Internet link. A portable control unit is available, especially for launching and recovery manoeuvres.

3.3.2 Mission Planning



Mission planning is carried out in form of a computer-based waypoint planning process with the corresponding specified manoeuvre and waypoint inputs using digital sea charts. Fig. 7 shows such a chart with details for an individual manoeuvre.

Fig.7: Mission Planning

3.3.3 DeepC Simulator

AUVs operate in complex, unstructured working environments. Numerous disturbance variables influence the dynamic properties of the underwater vehicles (current, variation of buoyancy, unforeseen obstacles). Due to the extreme demands on autonomy, the *DeepC* technologies for vehicle control therefore have to be verified directly on the basis of complex simulation models and the results have to be visualized. Real-time simulation models (vehicle, environment), tools for planning and control (*AUV Simulator*) as well as a *Virtual Reality* are therefore an integral part of the *DeepC System Simulator*. Fig. 8 shows the block diagram of the *DeepC Simulator*.

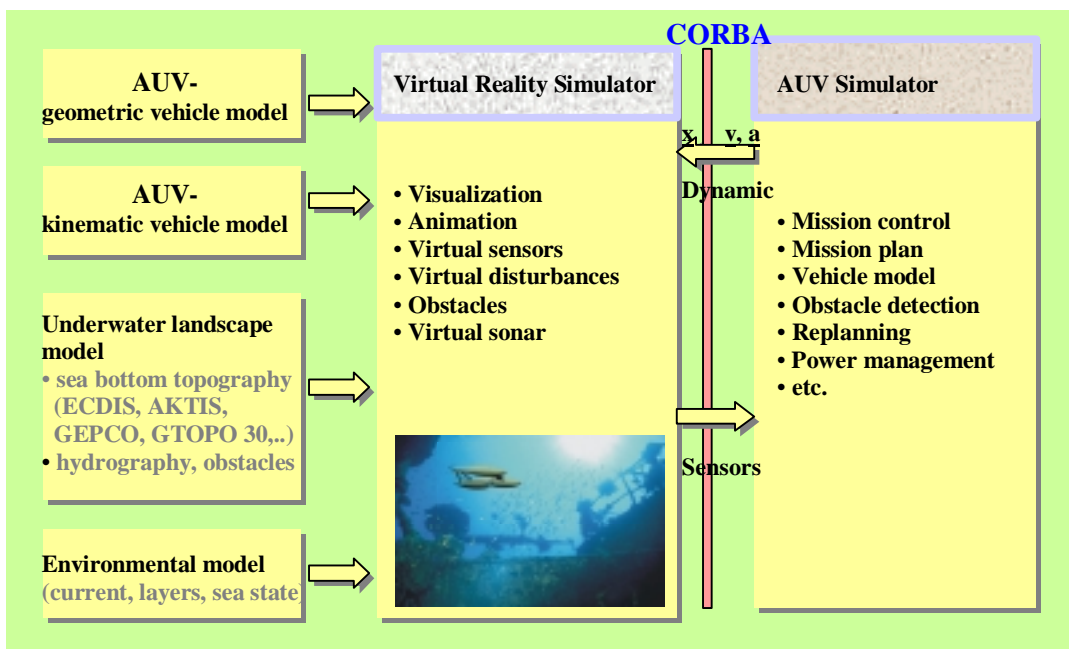


Fig.8: DeepC System Simulator

The *AUV-Simulation* part has the following sub-functions:

- Mission planning/mission monitoring, controlled from various panels.
- AUV vehicle data. Here, the required vehicle data like position (long., lat.), speed, position, depth are to be made available for *Virtual Reality* and the actual positions adopted for presentation on the Mission Control Panel of the mission monitoring system.
- Availability of avoidance strategies in the case of a threat of collision.
- Check of the actual energy situation on board the AUV to assure the mission.

The following **models** are linked to the *DeepC System Simulator*:

- geometrical model of the own AUV or other underwater vehicles (e.g. CAD model)
- kinematics model of the AUV or other objects (the dynamic behaviour of the underwater vehicle is simulated here)
- modelling of the underwater landscape with computation of ground structure as well as flora and fauna.
- modelling of the underwater environment like currents, layers, etc..

The **Virtual Reality** part, the core element for presenting the simulation result, has the following functions:

- visualization/animation of all activities around the AUV in a virtual world in real-time and with a high degree of realism,
- visualization of the sonar system for operator-guided AUV operation,
- aids for generating strategies of computerized learning and training neural networks. Based on the operator-guided AUV operations in the virtual world, human behavioural patterns in specific situations (e.g. avoidance behaviour or reconnaissance strategies of complex objects) are transferred to the vehicle,
- aids for visualization and validation of the simulated vehicle operations within the scope of system developments of AUV mission guidance systems, for control of vehicle dynamics, route planning and power management.

Essential tasks of the visualization component are the display of a scene (virtual world), the acquisition of user inputs and the transmission of these to the element *AUV Simulation Model* via the CORBA interface architecture. A scene consists of a 3D landscape (terrain model, textured underwater topography) and all static and dynamic 3D objects (AUV, obstacles, foreign objects, fauna, flora) contained therein, the definable cameras (dynamic observer standpoints) and multimedia boxes (text, sound, pictures, film).

4 Applications

The Autonomous Underwater Vehicle (AUV) DeepC will recently emerge as an offshoot of the ROV market place, looking to the Oil and Energy underwater inspection market e.g. survey, inspection, monitoring, production support and exploitation in general (including gas hydrates and minerals) For the underwater telecommunication sector, work will range from the examination of the sea bed through to the inspection of cables that have already been laid. Oceanographic research will e.g. encompass hydrographic survey of the sea bed, collecting specific data and investigations in connection with coastal zone management. Moreover, general search and exploration tasks will have to be performed.

As this vehicle develop and take advantage of new and emerging technology, increased flexibility of mission programs will mean the vehicle is capable of carrying out many more tasks than originally envisioned. Continuous improvements in the design and capacity of the

power supply systems will result in greater endurance and increased mission flexibility with more complex tasks being able to be carried out.

The oil and Gas market place for instance has many applications for such technology, commercial considerations require that annual inspection programs are carried out on the fixed structures the flow lines connecting these structures to the remote well heads and to the shore based facilities and on the well heads themselves.

Typically such inspections would look for physical damage, intrusion of foreign objects and other such anomalies that may have a negative impact on the structural integrity of the object being surveyed.

DeepC will provide a valuable service in this area, typically at the moment this work is done utilizing ROV technology, this requires a high level of support in the form of a mother ship and all the associated personnel and support equipment needed to place a vehicle in the Ocean and conduct a survey.

The suitably equipped DeepC could become part of the platform equipment, programmed to carry out predetermined tasks it could be deployed from a garage lowered into the water from the platform and when well below the surface surge zone it would leave its garage and carry out the predetermined mission.

There are a lot of tasks that a suitably equipped and programmed DeepC will carry out.

5 Conclusion

The development of the DeepC AUV system has set new standards in the technology for underwater vehicles, e.g. the use of carbon composites for a high-strength yet light-weight pressure hull – a solution that is unique for such applications – the use of a compact PEM fuel cell system with hydrogen and oxygen as an efficient power generation system, the application of a new type of electrical drive motors with adapted propulsion systems which can be used as pressure-neutral structures, the innovative power distribution and safety process on power-bus basis, the vehicle guidance system using CORBA (Common Object Request Broker Architecture) and distributed redundant processor nodes (distributed intelligence), the autonomous situation-adaptive vehicle guidance and control, the vehicle-integrated autonomous operational monitoring/status control with derived fault strategy as well as the extremely precise underwater long-term navigation on the basis of stochastically drifting measurement values.

The development status achieved so far has confirmed the feasibility of these goals, and offers a favourable market perspective for the AUV System *DeepC*, ultimately also due to the technological attractiveness of the system and the good price/performance ratio.