C-Systems
– Concept for a Modular AUV Family –

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1. ABSTRACT

As opposed to ROVs (Remotely Operated Vehicles), self-propelled, unmanned autonomous underwater vehicles, so-called AUVs, are becoming increasingly important since, contrary to ROVs they can operate completely self-sufficiently, i.e. independent of the carrier platform and cable at practically any depth and for long periods of time, require only minor technical and logistic support and can be used in regions that are inaccessible to manned submersibles or ROVs (e.g. under ice regions). In other words, AUVs are distinguished by a wide range of applications, the extremely high quality of data collected, their very cost-effective operation and the large standoff capability to the carrier platform, the latter bringing about a distinct improvement in terms of carrier platform safety e.g. for military missions.

Due to these advantages over conventional systems, AUVs can be employed for a whole variety of applications, such as the following in the commercial sector:

- Sea Bed Mapping
- Pipeline and Route Survey
- Inspection/Control
- Site Clearance
- Debris Survey
- Science
- Search
- Environment
- Geology.

Possible military applications are e.g. mine countermeasure with the following missions:

Reconnaiss-ance	Fast and rough border estimation of mine areas for alternate routes
Exploratory	Discovering of mines in a given area
Clearance	Mine disposal (Simulation, Hunting)
Limited Clearance	Disposal of specific kind of mines (Simulation, Hunting)
Short - term Operations	Operation for a fast transit through a sea area with unknown kind and positions of mines (no Clearance Operation in advance).
Check Operations	Confirmation of a successful Clearance Operation.
Survey	Collection of environmental data for MCM operations.
Lead through	Guiding through a sea area with mines

Obviously, one single type of AUV will be unable to cover this entire spectrum if – over and beyond the aforementioned applications – one considers the different operating depths ranging from coastal regions (about 10m) to deep water (approx. 6000 m) and the variation of possible carrier platforms (helicopters, ships, submarines, shore stations).

On the other hand, the development and use of one specific type of AUV for one or a very limited

number of mission types would be very expensive, both in terms of costs involved and necessary logistics, and would hardly be acceptable on the market.
The solution to this problem is "modularity" of the AUV subsystems as well as a family concept for the vehicle design.
To implement this strategy, the companies STN ATLAS Elektronik (GE) and Maridan ApS (DK) have forged a development and marketing alliance aimed at a family concept for a wide array of AUV missions, based on the AUVs of both companies.
The AUV-family will offer commonality of a lot of parts to ensure that serviceability is maintained, while having a high degree of “customising” in key areas like payload sensor selection ensuring that they will fit customer needs.
The first AUV of the co-operation will not appear before 2005 – however, results of the technology fusion are already available in the suite of underwater vehicles developed and produced by STN ATLAS and in the AUV series developed and produced by Maridan.

This paper describes the basic vehicles *DeepC* und *MARIDAN 600* and gives details on the concept for future AUVs.

2. INTRODUCTION

Unmanned underwater vehicles are one of the main product areas of STN ATLAS Elektronik. The company has been developing and delivering such vehicles for military and civil applications for about thirty years. Fig 1 gives an overview of the history and latest products. Current products to be noted are the *SEAFOX* and *CScout*. More than 1800 underwater vehicles of the type *SEAFOX* – a fiber-optic cable guided mine disposal vehicle of the 40kg class – have been sold so far, so that this vehicle is the market leader. The *CScout* is a civil "further-development" of the *SEAFOX*. This unit which is equipped with a panoramic and side-looking sonar as well as a powerful TV camera has been available on the market since 2003.
Alongside these semi-autonomous vehicles (power on board, data exchange via fiber-optical cable, operator action only in case of need), STN ATLAS Elektronik has been concentrating its development activities in the field of autonomous underwater vehicles on a system called *DeepC* (Fig.1).

Fig.1: STN ATLAS Elektronik’s/ Maridan’s under-water vehicles

To improve the position on the market and develop AUVs of the latest generation, a cooperation has been agreed between STN ATLAS Elektronik and Maridan. This cooperation is based on the *Maridan 600* from Maridan and the *DeepC* from STN ATLAS Elektronik.

2.1 AUV *DeepC*

DeepC (www.deepc-auv.de) is a high efficient deep diving underwater vehicle system with long endurance and for a lot of applications. Many actions that would normally required high cost ROVs systems or which are not possible (e.g. under ice investigations) con now accomplished using *DeepC*, at less cost and manpower.
The main performance parameters of the *DeepC* system are in general

- Autonomous mission execution
- Low weight
- High manoeuvrability
- Hover capability
- Modular design
- Containerised Payload
- Deployment from vessels of opportunities
- Obstacle avoidance
- In mission re-planning capability
- Precise navigation
- Advanced diagnosis and fault recovery system.

In addition, a comfortable Man-Machine Interface as well as a simulator with virtual reality is available for the mission planning and evaluation station.
The technology highlights of the underwater vehicle are

- Vehicle body and pressure hulls: carbon composites
- Energy generation: PEM fuel cell
- Energy distribution: power bus
- Propulsion motors: pressure neutral

- Propulsion system: 80% efficiency
- Vehicle's guidance system software: CORBA based
- Vehicle control system: situation adaptive with obstacle avoidance and in mission re-planning capability
- Constant depths or terrain following survey mode
- Health monitoring: with self diagnosis capability and degradation mode
- Navigation system: high precise INS with DVL
- GPS Updating
- Acoustic and HF communication
- Simulator based vehicle's mission training
- Vehicle sensors: 3 TV cameras with spots, CTD
- Payload: high resolution, short range MBES
- Optional payload: Side Scan Sonar, Sub-bottom Profiler, customer specified sensors.

The underwater vehicle *DeepC* consists of two main structures: two propulsion bodies and one payload unit (Fig. 2). 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. Two main drive propellers made of CFRP too, together with four further thrusters provide maximum manoeuvrability of the vehicle. 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.

Fig.2: DeepC underwater vehicle

An user friendly operator console is available for

- Mission planning
- Pre launch checks
- Mission control (if applicable)
- Post mission evaluation
- Simulation.

Mission planning for instance, 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.3)

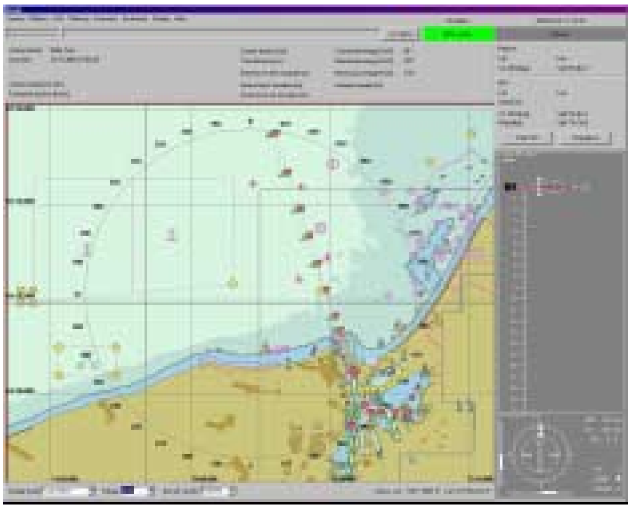

Fig.3: ECDIS for DeepC's mission planning & evaluation

The system specification is:

- **System Components**
  - Underwater Vehicle
  - Mission Planning/Evaluation Console
  - Portable Vehicle Control Unit
  - Board/Land Connection
  - Energy Refilling Station
- **Vehicle's Operational Data**
  - Mission depth 4000 m (Crush: 6000 m)
  - Cruise speed 4 kts (Maximum 6 kts)
  - Missiontime up to 60 hours
  - Operating range till 400 km
  - Payload up to 250 kg
- **Vehicle's Dimension**
  - Weight in air 2.4 to
  - Length 5.8 m
  - Width 2.3 m
  - Height 1.7 m
- **Propulsion**
  - 2 main propellers
  - 4 thrusters (3 vertical. 1 transversal)
- **Guidance and Control**
  - INS (gyro drift down to 0.002 deg/hr)
  - Doppler Velocity Log, 300 kHz
  - GPS updating

- ARCOS receiver
- Back up navigation Unit
- Acoustical communication
- Transponder for USBL
- 180° Sonar
- 3 TV Cameras with spots
- Obstacles avoidance and in mission re-planning

- **Energy:**
  - PEM Fuel Cell
  - Power: 3,8 kW
  - Hydrogen energy: (minimum) 140kWh
  - Power bus
  - Current: 24V, 264V DC
- **Payload Unit**
  - Power interface 50A/24V, up to 60h
  - Data interface Ethernet bus
  - Standard sensors MBES, Side Scan Sonar, Sub Bottom Profiler
  - Application designed payload up to 250kg,
- **Control Console**
  - Mission control by single operator
  - PC with flat panel display for planning, etc.
  - Portable control unit for short range vehicle control
  - WLAN vehicle connection
  - www access (off line, via modem)

2.2 Maridan 600 AUV

The primary aim of the Maridan AUV design has been to provide a payload sensor carrier, which will ensure precise positioning, stability and maneuverability for accurate scientific data collection. The on-board system provides all necessary position, attitude, status and time information to ensure effective and efficient performance throughout the mission. The on-board computer systems ensure that data collection, archiving and retrieval can be carried out in a highly effective manner. High positional accuracy and accurate stabilization of the vehicle attitude throughout the data collection allows the mapping of raw data to be implemented directly, without post-processing, to obtain the necessary correlation of the survey mosaic. Modularity has been accomplished by designing a modular hull with three compartments; a **front section** for the launch and recovery system, a **central section** for the batteries, computer systems and payload, and an **aft section** for the propulsion system. Furthermore, the electronics is housed in several small sealed compartments, thereby ensuring that the vehicle can survive a partial flooding. The electronic compartments are cylinders connected by "wet" cables into which both power and signals are combined to reduce the overall number of cables and hence reduce both the cost and the risk of leakage. The central section has recently undergone a design modification, which provides a large central bay for alternative sensor payloads and adds greatly to the flexibility and range of sensing which can be undertaken by the AUV. The mechanical, electrical and software architecture of the host system has been specifically designed to facilitate the easy exchange and addition of payload sensors and has a standard interface definition to facilitate the design of sensors for the vehicle.

The AUV is a multi-purpose platform designed for a range of underwater missions as follows:

- Site surveys (e.g. side scanning, multi-beam echosounding, bathymetry, sub-bottom profiling)
- Line surveys (e.g. pipeline, cable and obstacle inspections, engineering surveys (pre-route, as-laid, as-trenched, as-rockdumped)
- Video and photo documentation (e.g. archeological research)
- Oceanographic surveys (e.g. environmental monitoring, gradient following, gravity anomaly measurement).

Through the careful adoption of international and commercial standards the vehicle allows quick and easy exchange of sensor payloads to suit different missions. The hydrodynamic design of the low-drag, flatfish shape of MARIDAN 600 (see Fig. 4) has been a critical feature throughout its development and has been successfully accomplished as confirmed by extensive laboratory and sea trials. The design was selected to give the vehicle a large deck area for down-looking sensors and to give excellent stability in pitch and roll and heading for critical measurement applications. The vehicle is equipped with front ailerons and an overall control system that provides high responsiveness (i.e. fast lift) for obstacle avoidance and terrain following when flying close to the bottom. *MARIDAN 600* is equipped with a high-performance Doppler-inertial positioning system known as MARPOS. This system has been developed in close co-operation with Kearfott Guidance and Navigation Corporation (New Jersey, USA) and is providing outstanding performance in terms of positioning, navigation and attitude control (see § 3.2.3).

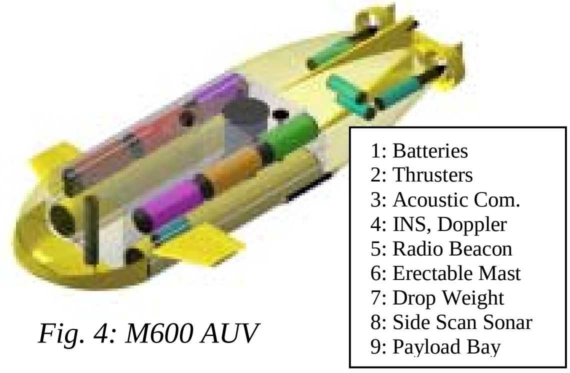

Fig. 4: M600 AUV

3. STRATEGY FOR A NEW AUV GENERATION

3.1 Overview

STN ATLAS Elektronik is basing related work on AUV technologies for e.g. *DeepC* and Maridan on e.g. the MARIDAN 600. *DeepC* represents the deep-diving system (crush: 6000m) and Maridan is the system best suited for shallower waters (600m).

With a unified development strategy, the two companies use synergistic effects to create a new, advanced family of AUVs for a wide range of applications.

The cornerstones in the development will be the two companies' command of very advanced technology solutions and experiences like for

- STN ATLAS Elektronik
  - Sonar & Sensor Systems
  - Mine hunting
  - Underwater vehicles (ROV, AUV)
  - System Integration and Tests
  - Systems for Submarines
  - Systems for Surface Ships
  - Logistics
  - Prime Contractor Projects

and for

- Maridan
  - AUV Development
  - Pre3cise AUV Navigation
  - AUV Sensor Integration
  - AUV Operation
  - Offshore Support
  - Safety & Security Operation.

3.2 Funktionen und Technologien of Modern AUVs

The application areas for AUVs vary greatly. Some examples for civil applications are given below:

- Underwater Research, e.g.
  - Geo-physical
  - Geological
  - Archaeological
  - Biological
  - Hydrographic
  - Environmental
- Underwater Survey. e.g.
  - Pipeline, Cable and Route Survey
  - Sea Bed Mapping
  - Search for lost Objects
  - Wreck Survey
- Inspections, e.g.
  - Cable, Pipelines
  - Rigs
  - Drilling Rig Foundations.

Possible military applications include mine countermeasure operations, the acquisition of environmental parameters, general search tasks, transport missions and the use as relay stations.

The diving depths vary between extremely shallow water down to approx. 1000m (military) or 6000m (civil) with mission times between several hours (approx. 10h) and several days (100h and more).

In spite of this considerable diversity, the technological core elements of the AUV systems largely consist of the components in the underwater vehicle and control console illustrated in Fig. 5.

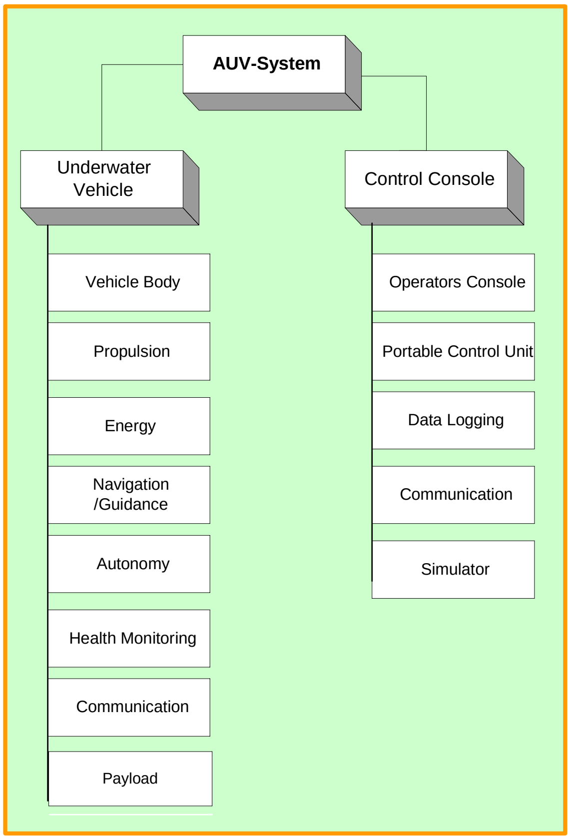

Fig.5: Major AUV components

The aim of STN ATLAS Elektronik/Maridan is to design the above-mentioned components as generically as possible in order to make them usable for all foreseeable military and civil AUV systems. In other words: irrespective of the external design of the underwater vehicle and its mission, the internal technology and the control console are largely common to the systems.
This paper concentrates on the future perspectives and synergies for the underwater system, the actual AUV.

3.2.1 Vehicle Body, Propulsion

The category "vehicle body" relates to the following features:

- Outer shape/Hydrodynamics
- Pressure hull
- Propulsion and motors
- Vehicle signature.

The **outer shape** of the underwater vehicle is determined by various factors. If, for example, it is to be launched from the torpedo tube of a submarine, it must have the shape of a torpedo. If, however, it will be launched from a surface vessel and is to work near the sea bottom in terrain following mode, a shorter, more compact and flatter outer shape will be advantageous. Basically, the outer shape is not the determining factor for implementing the philosophy "commonality of components for different systems", i.e. maximum possible synergy in the family of underwater vehicles.
An essential aspect to be allowed for when designing the systems is the modularity which will allow a simple re-configuration of the equipment and hence also the mission.

To give some examples:
In its present form, the underwater vehicle *DeepC* has an external payload container provided with standard interfaces and capable of carrying any payloads up to 250kg, so that the system offers absolute mission flexibility. For power generation, the *DeepC* has a PEM fuel cell with reactant storage in conventional pressure gas bottles If, however, e.g. H_2 is obtained from water-reactive hybrids (e.g. LiH), the energy stored on board increases by at least 50% so that the mission time increases accordingly. If the vehicle is to be operated in shallow waters only, the wall thickness of the pressure hulls decreases significantly. If, e. g. the diving depth is limited to 500m, an additional 150l volume is available in the two upper *Deep* C hulls which can be filled with payload. In such an instance, the special payload container would not be used and the three-hull *DeepC* would be reduced to a two-hull structure. (Fig. 6).
The question of the material for the outer shape and the **pressure hulls** is also fundamental to the "generic" approach. It is sensible to select the same material for all possible diving depths and simply to vary the wall thickness of the pressure hulls. If a depth of between 0m and 6000m is relevant, the materials titanium and CFRP (carbon fiber reinforced plastics) can be considered.

Fig.6: Twin-Hull-DeepC

Allowing for the factors

- availability
- processing
- strength
- weight and
- cost.

CFRP offers advantages, especially if the so-called wet-winding process is applied as production technology for great depths. In this case, only simple reproductions of the pressure hulls (with different wall thicknesses) have to be manufactured. Fig. 7 shows the manufacture of

Fig.7: Pressure hull manufacturing

The segment **propulsion and motors** relates to the main drive units and the thrusters with their motors. For reasons of noise, slow-rotating, narrow-blade propellers are advantageous for main drive unit. If they are laminated from carbon fibers, the “technology” is closely related to that for the pressure hulls. Additionally, such propellers have an up to 10% better efficiency than conventional propellers in the partial load range. Smaller propeller blades e.g. for the thrusters are also made from carbon fiber material, however, from short fibers in a casting process in this case. If the thrusters are driven by pressure-neutral ring motors (Fig.8), this rules out problems of propeller blockage from algae, seaweed etc.

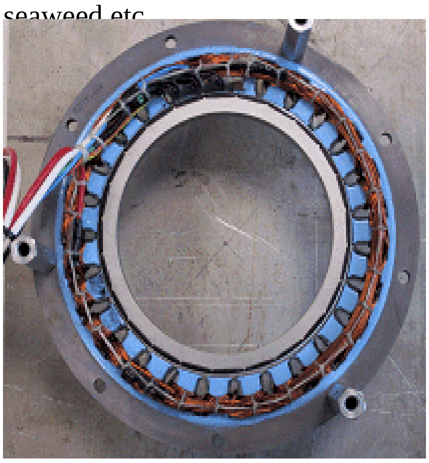

Fig.8: DeepC ring motor for the thrusters

The motors are a key element of the propulsion system. Three-phase current motors are preferred for reasons of output alone, although the pressure-neutrality of such motors is of overriding importance, i.e. they are cast, have their own water circulation and can be operated at any diving depth. Added to this modularity, another essential advantage is that no openings are needed through the pressure hull for the propeller drive since the complete system is in water (Fig. 9).

The **vehicle signature** is far more important for military missions than for civil applications. Nonetheless, for reasons of mission flexibility and also due to possible sonar interference from the propulsion system, importance always has to be attached to the low signatures.

Optimized shaping of the underwater vehicle already reduces noise and energy levels for hydrodynamic reasons. The avoidance of protruding parts and unfavorable length/thickness ratios helps to improve the efficiency. Simple methods like, e.g. designing

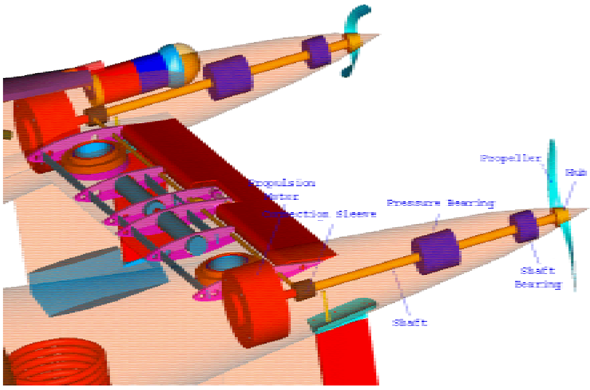

Fig9: Main Propulsion Concept

the shape according to proven profile geometries have already turned out to be very successful on numerous occasions. An unfavorable shape of the vehicle's geometry can lead to early delamination of the vehicle body and cause under-pressure and overpressure fields. This causes unnecessary turbulence and vortices which use up energy and produce noise.

An optimum design is always achieved by hydrodynamic calculation processes using appropriate CFD computation programs followed by flow tests.

Additionally, the use of "advanced" materials like composites or titanium reduces the energy required and the total weight. Fig. 10 gives an example of an optimized *DeepC* underwater vehicle based on CFD calculations.

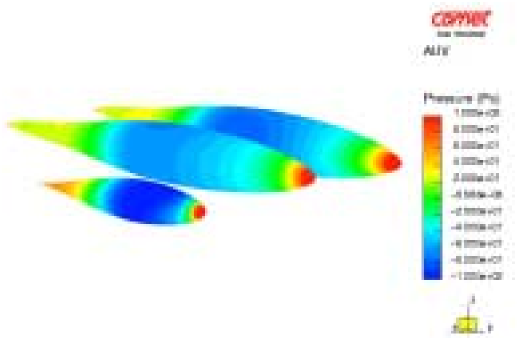

Fig.10: CFD-Calculation of the DeepC AUV

3.2.2 Energy

The requirements with regard to power generation are focused largely on the signature, the energy/weight ratio, the efficiency and the performance characteristics allowing for mission criteria and cost.

If a lower signature is a must, batteries or fuel cells can be used for power generation. The most promising types of battery are the reusable Li-ion batteries or aluminum-oxygen semi-fuel cells. These batteries are very powerful and robust and are similar to Li batteries in terms of energy density.

Hydrogen/oxygen fuel cells have an efficiency greater than 50% and a higher energy density than batteries Such systems consist of the actual power generation and the components for storage of the reactants. This means that a fuel cell with a certain rating has to have a certain minimum size for storage of the reactants. As an element that depends on the mission time, a point to consider is the kind of storage of these reactants. In other words: batteries are the best option for short mission times up to approx. 10 hours whereas fuel cells are preferred for longer missions.

For a modular AUV, this means the option of installing batteries as well as fuel cells.

3.2.3 Navigation/Guidance

The **navigation** system of an AUV will mainly consist of an INS with DVL. Additionally, there should be a back-up system (dead reckoning) and it should be possible to do GPS updates as well as AUV tracking via an USBL system.

GPS position updates are not realistic for missions at great diving depths and for covert operations due to the need for the vehicle to surface. A high-precision INS navigation function is absolutely essential in such cases.

The use of such an inertial measurement system in an underwater vehicles has three goals:

1. Determination and stabilisation of roll, pitch and heading to improve the operational behaviour of the vehicle
2. Position determination of the vehicle
3. Navigation, guidance and stabilisation/control of the *DeepC* .

The following demands made on the navigation unit are typical for an advanced AUV:

- Highest accuracy in heading, roll, pitch and position for stabilisation of sensors and future tools.
- Short alignment time, even under difficult dynamical conditions, i.e. autonomous north seeking.
- Open interfaces for external aiding devices such as Doppler velocity log (DVL), acoustic positioning system (APS), GPS, pressure sensor, etc., and output of an integrated navigation solution as well as the possibility of connecting the actuators (rudders, thrusters) of the AUV to control the vehicle globally or locally, if desired.
- Flexible design of the navigation system with the option to realise it in a customer-specific design (e.g. integration of DVL and INS in one single housing).
- Availability of a range of navigation systems from medium performance (dynamical stabilisation only) up to ultra-high performance (autonomous long-term operation tasks of AUVs like *DeepC*).
- Open user interface to allow the user to control all features of the navigation system. Hardware interfaces supported by the navigation system will be CAN, Ethernet, RS232, RS422, etc.

The Maridan MARPOS system can be taken as a possible example of a navigation system for all missions and vehicles.

The kernel of MARPOS is an inertial system known as the KN5053 (from the Kearfott SEANAV family of inertial systems). The KN5053 is a “full inertial” platform incorporating Kearfott’s advanced monolithic 3-axis ring-laser-gyro with a triad of high performance single-axis pendulous accelerometers to provide inertially derived position, velocity, attitude and attitude rate in all six axes of linear and rotational freedom. The KN5053 utilises additional inputs from differential GPS and DVL, using a sophisticated Kalman filter, to compute optimal high accuracy data throughout the operation of the vehicle. Once initialised at the seabed, the MARPOS provides high accuracy position and attitude data and, although a robust self-contained system in its own right, can if necessary be used in conjunction with Long Baseline (LBL) and Ultra-Short Baseline (USBL) acoustic positioning systems. The generic performance of the KN5053 can be summarised as follows:

Position accuracy:	0.03% of distance traveled (RMS)
Heading accuracy:	0.03 degree (RMS)
Roll, Pitch accuracy:	0.03 degree (RMS)

In addition to reporting precise position and attitude data MARPOS provides high integrity motion data to the Autopilot ensuring a precise path following system for the AUV. In addition to the inertial system the following sensors are included in MARPOS:

- A Doppler Velocity Log for measuring vehicle speed over the seabed (bottom track mode) or vehicle speed in water (water track mode). The DVL also provides altitude and depth.
- A Differential GPS receiver for calibration and updating of the positioning system when the vehicle surfaces. The DGPS receiver is mounted on a telescopic mast that can be erected at the surface allowing the AUV to maintain satellite contact during the time required to receive the update. When diving the DGPS receiver is lowered into the hull.
- A CTD (Conductivity, Temperature, Depth) sensor for measuring parameters to compute the sound velocity.
- A Pressure Sensor (redundant depth sensor) with an accuracy 0.2% of full scale.

The positioning accuracy of MARPOS is of course dependent on the accuracy of the initial position fix provided to the system. The initial position fix must be provided after diving to the seabed to commence the mission proper. It can be provided autonomously by MARPOS or by an external acoustic positioning system update depending on the depth and the accrued inertial drift error during the dive. The 1200 kHz DVL has been selected to operate in the bottom track mode when the vehicle flies at low altitude of around 30 m. In-transit to the bottom MARPOS utilizes the "free-inertial" performance of the KN5053 with DVL aiding in the water-track mode where appropriate. When the vehicle arrives within the specified altitude from the bottom the DVL enters the bottom-track mode and the vehicle performs its survey initialization. The initial position error provided by MARPOS autonomously as a result of the free inertial dive can be estimated as 1 m per minute until the DVL has bottom contact. The position error relative to the initial position fix depends on the survey pattern as well as geographic latitude, updating intervals and the time available for apriori calibration of the system at the surface prior to the dive. For a "Lawnmower" survey pattern sensor drift is bounded by performing the turns. For a linear survey pattern, with a minimum of dynamic input to the INS, the accuracy is heavily dependent on the DVL aiding provided to the INS. Following initial position input and gyrocompass alignment prior to or at the point of launch from the mothership, the vehicle performs a prescribed apriori calibration procedure at the surface to measure and effectively eliminate the residual boresight misalignments between the INS and DVL reference frames.

After switch-on the KN5053 INS enters an automatic gyro compass alignment establishing its precise orientation with respect to the local gravity vector and the earth's north-south polar axis. Stationary alignment (on land) would typically require between 15 and 30 minutes depending on the geographic latitude. Dynamic alignment on the deck of a ship or on the AUV at the surface may typically require up to 60 minutes. Following the gyrocompass alignment the system enters a calibration procedure of approximately one hour at the surface to optimize the system performance for the dive to the seabed. This alignment procedure is not required for repeated dives at the same site.

The above initialisation procedure utilises differential GPS position and velocity data in combination with the inertial and doppler velocity information of the MARPOS and, once completed, allows the vehicle to dive and initiate its operational mission without the need to re-surface for further calibrations or position updates.

The differential correction signal is sent by Ethernet to the AUV from the surface computer. The signal is processed to RTCM104 input of the DGPS receiver. MARPOS is designed to accept input aiding from conventional LBL and USBL systems, floating LBL (GIB buoys) or Syntehic LBL.

Fig. 11 shows the MARPOS elements.

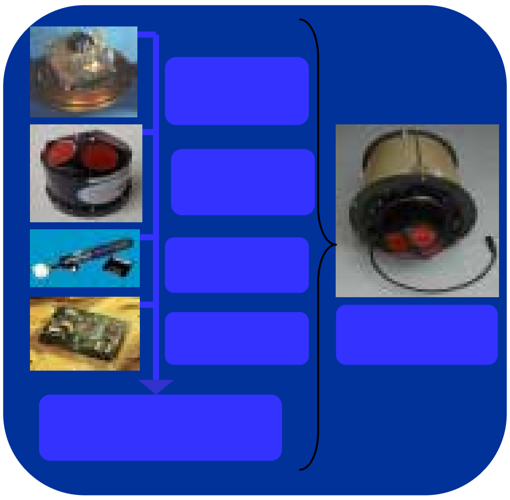

Fig. 11: MARPOS navigation unit

Thereafter MARPOS can be used as a stand-alone system or with external input under the following conditions without the need to re-surface for position updating:

- **Site survey in shallow water** (up to 300m). By flying in a "lawnmower" pattern MARPOS can provide very high accuracy, thus eliminating the need for external LBL or USBL tracking.
- **Site survey in deep water** (300+ m). The relative positions can be provided by MARPOS to the same accuracy as for shallow water. To bind the relative positions in a global frame the initial position after diving may be provided from an external source (LBL or USBL) or by reference to a recognisable location with known position.
- **Line survey (pipeline and cable inspection)**. The vehicle can follow a pipeline or cable autonomously using an electro-magnetic tracking system in combination with apriori information on the as-laid position of the pipeline or cable. In this way MARPOS can be updated periodically when passing joints with a characteristic magnetic signature.

Fig. 12 gives an example of the accuracy of the MARPOS system.

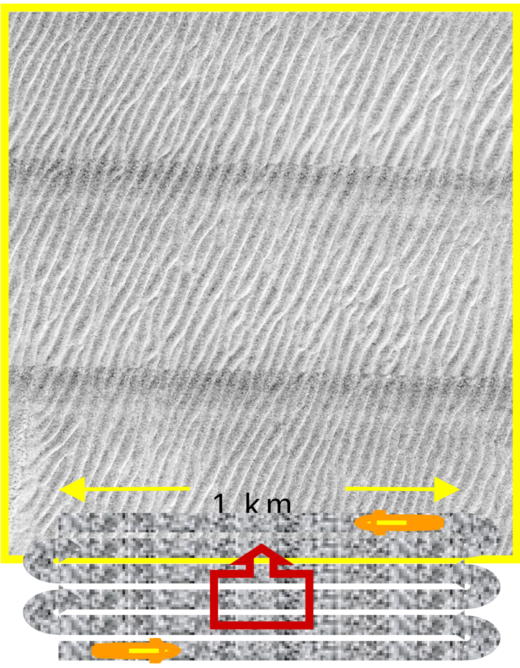

Fig. 12: MARPOS performance

The figure shows a view taken with a side scan sonar during meandering operation. The excellent fit accuracy of the ground structures regarding forward and rearward movement is remarkable from a navigation standpoint. It is evident that the structures almost perfectly cover the meander limits (dark lines).

The mission **guidance** system is the highest level decision and control function for performance of AUV missions. Activities are based on the mission plan, the current AUV mission scenario, the current system status and possibly any interventions by the operator via external communication.

The mission guidance system is capable of independently changing mission planning and generating new mission plans in the event of any unexpected events:

- Terminating mission and surfacing if defined abort criteria have been fulfilled
  (Situation: continuation of mission not possible).
- Reduction of full mission
  (Situation: continuation of mission only to limited extent, mission elements have specified priority).
- Replanning at request of payload
  (Situation: e.g. no track. Payload demands alternative manoeuvres that are predefined for certain mission sections.

3.2.4 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
- reactive mission management system
- case-sensitive track control
- situation-adaptive vehicle controller.

The mission management feature that is responsible for the mission sequence is at the heart of the system. It is used to analyze 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 AUV behavior 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.

The objective of the maneuver 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.
Future high performance AUVs and the STN ATLAS *DeepC* can manage situations like:

1. stationary and moving objects
2. one or several objects
3. allowance for own dynamics and current status variables of the vehicle as well as possible environmental influences
4. possible failure of the sensors and drive units
5. power and time-optimized avoidance maneuvers.

In such an *obstacle avoidance* case, it is possible not only to detect (and avoid) the obstacles and objects but also to inspect them thoroughly, i.e. to perform identification manoeuvres for closer inspections in cases of doubt (e.g. identification of mines in case of a MCM mission). 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 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 is 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 Health Monitoring System (HMS)

To ensure successful mission performance, it is essential that all subsystems should function perfectly. This requirement is absolutely vital, especially for AUVs with long mission times like the *DeepC*. This is why future AUVs has to be provided with a intelligent monitoring, fault diagnosis and degradation system.
A Health Monitoring structure as shown in Fig. 13 and as favored for future AUVs is completely generic and therefore suitable for all types of AUVs.
This process is employed to monitor the AUV subsystems and to diagnose malfunctions by means of intelligent modules based on fuzzy logic, neural networks and a Bayesian Belief Network. Using a situation analysis and the mission objective, a proposal for degraded mission continuation or mission abort is generated, adopted (or rejected) by the Decision Module and carried out by the Piloting Module. The decisions and results are filed in a database which additionally has expert knowledge so that – in specific cases – other alternatives to the automated decision are available.

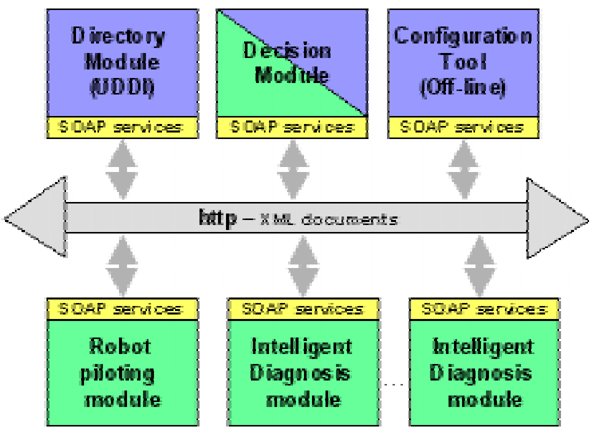

Fig.13: Generic health monitoring structure

The health monitoring software is organised around the **Directory Module**, the central point for communication between the modules. Communication itself is based on XML and some innovative recent technologies, as SOAP (Simple Object Access Protocol) and UDDI, upon HTTP communication protocol. Among others these techniques have the following qualities:

- Fully generic
- Interoperable & Distributed
- Synchronous and asynchronous messages.

The **Configuration Tool** (off line) is one of the main features which allows flexibility in the definition of the data to be exchanged between modules, The configuration tool is used first to support the development of the communication interfaces and then, during the initialisation phase, to dynamically adapt the autonomous system to its current configuration and mission. The tool features graphical user interfaces, showing for example the different modules plugged on the architecture, the data they will exchange and some parameters. The foreseen technology to be used for this innovative development is Java SVG.

The Piloting Module is AUV specific. The module has access to all sensor / actuator data and is able to send commands to the vehicle control unit. Thus it is a central data handling unit of the vehicle and serves as an interface to the HMS components. As HMS is based on SOAP it builds the bridge between the vehicle and the HMS architecture.

Intelligent Diagnosis Modules have specific knowledge of the AUV. They can compute indications about vehicle's status and environment to detect abnormal situations, using different Artificial Intelligent techniques adapted to the problems to be solved. Three different types of AI modules will be used:

- Neuro-symbolic System
  Symbolic rules are used to represent an expert knowledge, which is then converted into an artificial neural network. This is capable to be trained on a set of examples, allowing the module to diagnose even unknown situation. The quality of the diagnosis (time response and correctness) will directly depend on the quality of the expertise present in the system and the training possibilities.
- Bayesian Belief Networks (BBN)
  This module allows introducing a notion of a relative risk (utility) in comparing one solution to another. This is a very important point for AUV applications. Continuing a mission in a degraded mode presents a certain risk of loosing the vehicle. BBN enables a decision about taking this risk under certain conditions. The constraints are not the same if the mission is to save a life or to survey a cable.
- Fuzzy Logic (FL)
  To describe a decision or control process FL uses linguistic rules which are stored in a rule base. These rules are quite close to the language used by domain experts. That "proximity" between the language used by the experts and that representing the fuzzy rules simplifies the process of knowledge extraction, and makes the decision process understandable by the experts. In addition, the underlying reasoning methods are particularly well adapted to decision or control problems working with uncertain or noisy data.

The Decision Module is in charge to manage the complete diagnosis process and to interpret the proposed recovery action provided by the intelligent modules. The module makes decisions in order to provide the Piloting Module with high level orders (recovery process). It also allows interaction with human operators (if any) with regard to diagnosis and recovery (remote decision).

3.2.6 Communication

A modern AUV like e.g. the *DeepC* has communication possibilities both above and below water.

When the AUV has surfaced, the AUV position can e.g. be transmitted via ARGOS and additionally a short connection e.g. for hand-guided recovery maneuvers is possible via wireless LAN (WLAN). Due to the wash-over effect, antennas should be installed as high as possible on the vehicle, preferably on a mast. Fig. 14 shows a *DeepC* mast configuration at the rear part of the AUV.

Underwater data transmission, especially in the horizontal channel is highly complex. Such an acoustic data link should meet the following requirements:

- range 2000m
- hydroacoustic link 36kb/s

and

- range 4000m
- hydroacoustic link 20kb/s

with a bit error rate in each case of 10^{-7}.

These data rates must be possible both in deep and shallow (10m!) waters, i.e. multiple path propagations should not impair the quality of transmission. A Doppler shift (difference between transmitter and receiver velocities) up to min. 15 kts should not present a problem.
Fig. 15/16 show an image transmitted with 36kb/s over a distance of 750 m (with and without error correction) in a horizontal channel in shallow waters (15m depth).

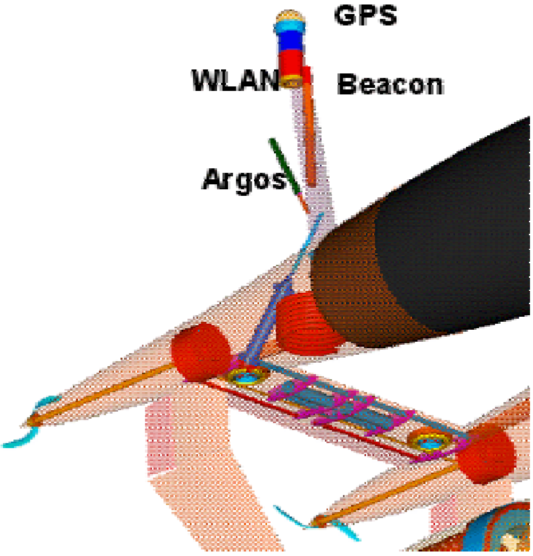

Fig. 14: DeepC mast configuration

3.2.7 Payload

The configuration of the compartment for the payload shows the flexibility and extensive usability for very different missions.
Fundamentally, a modern AUV must be able to carry numerous different sensors. Standard sensors for civil missions can be multi-beam echo sounders, in addition to which not only TV systems, side scan sonars and sub-bottom profilers are needed but also specific sensors for the various missions. Military missions require not only side scan sonars but often also sediment sonars or so-called synthetic aperture sonars or magnetic sensors.
A high payload capability, sufficient electrical power and standard interfaces are key requirements.
The *DeepC* AUV is equipped with a special container which is easy to remove and can be equipped by the user (see Fig. 17). Standard interfaces allow the easy integration of a new

Fig. 15: Acoustical data transmission, with error correction

Fig. 16: Acoustical data transmission, without error correction

payload configuration in the overall system of the *DeepC*:

- Data Ethernet
- Power 24V/50A
- Volume 250l

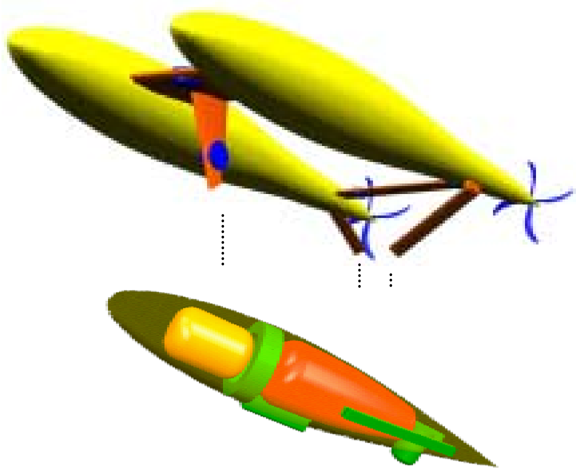

Fig. 17: DeepC payload configuration

The basic sensor installed is a multi-beam echo sounder with the typical image quality shown in Fig. 18. The side scan sonar and sub-bottom profiler are installed as dummies.
Since vehicle development was also based on the assumption that TV sensors would always be used, these are not integrated in the payload container but are part of the standard equipment located in the upper section of the vehicle. *DeepC* has three TV cameras (with lighting): one each at the propulsion units and one in the horizontal connecting section.

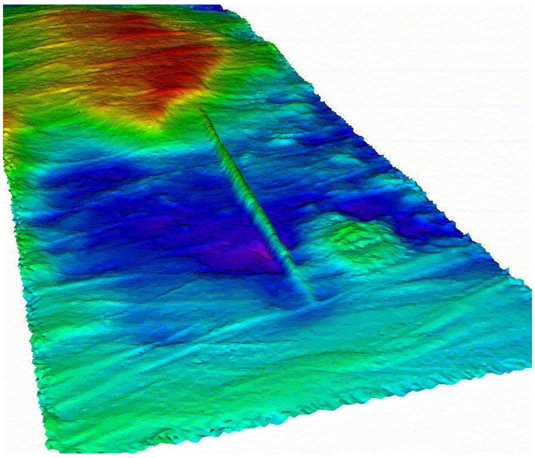

Fig.18: Multi-Beam-Echo-Sounder picture

4. CONCLUSION

Modern AUVs of the type *DeepC* or its successors are distinguished by their high modularity. This means that such systems are either capable of performing a whole variety of operations without modifications or, as a minimum, the subsystems installed in different platforms can be used for general purposes. Such a concept allows not only substantial development savings – and therefore helps to cut the cost of the series units – but also means that capital spending is optimized due to the technological synergies across the difference mission applications.

The following table which lists the basic requirements for a military AUV and compares these with the systems of the *DeepC* highlights the extensive synergies possible between military and civil variants.

Parameter	**Mil. Req.**	**DeepC**
Acoust. Communic.	✓	✓
DVL	✓	✓
Echosounder	✓	✓
Mine/Obst. Avoidance	✓	✓
Side Scan Sonar	✓	✓
TV Camera	✓	✓
Transponder	✓	✓
INS/DVL	✓	✓
GPS Update	✓	✓
Nav. Back Up	✓	✓
Terrain Following	✓	✓
Pressure Sensor	✓	✓
Mission Management	✓	✓
Intelligent Behavior	✓	✓
Health Monitoring	✓	✓
Object Recognition	✓	✓
Speed	-0.5-10knt	-0.5-6knt
Diving Depth	1000m	4000m
Range	tbd	ca. 400km
Endurance	tbd	ca. 60h
Stealth	✓	(✓)
Active Trimming	-	✓

The modularity of the vehicle can be achieved in various ways:

- *DeepC* satisfies this requirement by providing an own payload container and adapting the pressure hulls to the diving depth with the resulting additional installation space.
- The military AUV of the third generation (*ADELIE*) that is currently in the concept phase at STN ATLAS Elektronik and Maridan is based on the M600. Selective improvements of subsystems by employing *DeepC* components and dividing internal areas into vehicle functionalities (rear vehicle area) and energy & payload will produce a vehicle of high modularity and power (Fig. 19).

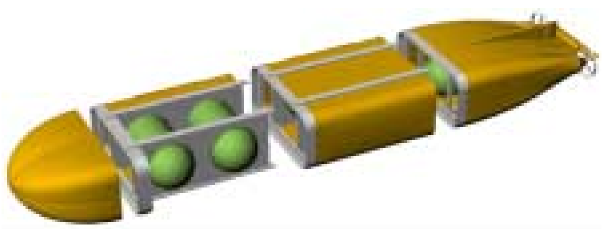

Fig. 19: Third generation AUV: ADELIE

The vehicle is designed for naval applications, the operational depth rating for the vehicle is till 600m water depth and the design has been selected with

special regards to achieve a low magnetic and acoustics signature.
STN ATLAS Elektronik and Maridan have therefore already established the prerequisites for the third generation of AUVs: systems with maximum synergy and modularity, incorporating autonomous, intelligent behavior and offering extreme flexibility for a whole range of different applications.

References:

- **Development of an Advanced Diagnosis and Recovery System for AUVs;**
  J. Kalwa, UDT Europe 2003, Malmö

- ***DeepC*, the AUV for Ultra-Deep Water;**
  Willi Hornfeld; UI 2003, New Orleans