Simulation based design and development of autonomous underwater vehicle IMGAM

An article by MAX ABILDGAARD

IMGAM (Intelligentes Monitoring von Gasaustritten im Meer, English: Intelligent monitoring of gas emanations in the ocean) is a project supported by the German Federal Ministry of Economics and Technology to build an autonomous system for gas flare detection, localisation and sampling in deep sea environment. In addition to today's standards for AUV operation, IMGAM employs so called sensor reactive behaviour to react to the unpredictable nature of underwater gas flares. Such behaviour has an inherent risk of »wrong« decisions, which could culminate in the loss of the vehicle. Care must therefore be taken to ensure a thorough understanding of how the vehicle reacts to external stimuli and to its own actions. For highly complex systems, such understanding can best be achieved by extensively measuring or estimating the performance of all known subsystems and by combining these into a simulation model, which can then be used for development and testing of control- and autonomy algorithms. Extensive tests made it possible to identify risks and necessary system improvements long before the first metal was cut.

AUV | gas sampling | sensor reactive autonomy | system identification SYSID | hybrid AUV/ROV

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Introduction

The scientific community has shown great interest in finding and locating gas flares, retrieving gas samples from deep sea sources and bringing them uncontaminated back on board ship for further analysis. This has traditionally been done using ROVs, but it is proposed that an autonomous underwater system with the capability to fulfil all three requirements: large scale survey, gas flare detection and gas sampling, can possibly increase the efficiency of such missions. IMGAM has the aim of performing this task. This requires a vehicle with a wide array of sensors, equipment and capabilities which are realised in IMGAM as illustrated in Fig. 1 and Fig. 2.

IMGAM has the following capabilities:

- Autonomy, capable of safe mission execution, controlling and autonomous re-planning throughout all mission phases.
- A combination of a high definition, high range downward looking sonar (DLS), capable of obtaining water column data – and a software capable of identifying, clustering and geo-referencing gas flares in the data. The sonar is mounted looking downward, 30° ahead from vertical, thereby allowing the sonar beams to »slice« through flares, which gives a better spatial/structural understanding of the flare.
- A short(er) range forward looking sonar (FLS) for short-range detection of flare position relative to the funnel inlet. The sonar is mounted looking 10° down from horizontal, allowing easier detection of the flares when approaching from higher altitudes for sampling.

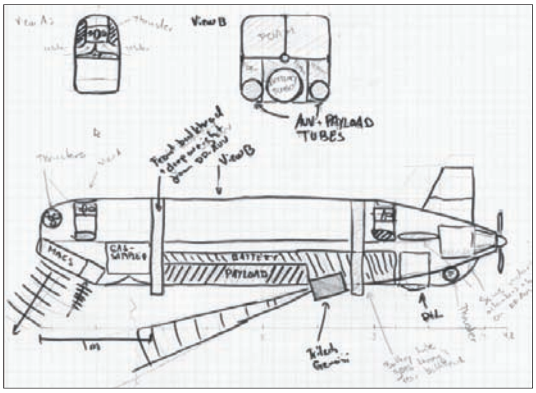

Fig. 1: The IMGAM vehicle in its various stages from concept to »real« hardware

- A gas sampling mechanism capable of taking samples and bringing these uncontaminated to the ship for further analysis.
- Cameras and lights for visual documentation.
- High bandwidth real-time communication by use of an optional fibre-optic link for hybrid ROV-mode operation.

Despite the multitude of payload systems, the vehicle has an overall length of just 4 m, a mass of approximately 1,300 kg. It dives to a depth of 2,000 m and features state-of-the-art navigation, communication and sonar equipment.

2 Autonomy concept

The vehicle is based around a conventional AUV system architecture with corresponding capabilities: Mission execution along preplanned waypoints with its payload running preset profiles. But given the unpredictable nature of gas flares, this alone will not suffice for successful sampling. Therefore, a »higher«, sensor reactive behaviour is necessary. This is centred on the idea of a standardised sequence, for which, initially, two fundamentally different concepts were considered:

- »Pre-survey and then sample«: First perform an overall search of complete survey area and choose the most »interesting« flare sites. Then auto-plan an optimal route to these sites and perform sampling sequentially as the auto-plan proceeds.
- »On-the-fly sampling«: AUV goes along a preplanned mission plan and interrupts this to sample flares immediately upon detection.

»Pre-survey-and-then-sample« concept

Whereas the first concept can likely results in a more »optimal« coverage rate and sampling of only the most »interesting« flares, it has several inherent drawbacks:

- A substantial amount of time can pass between initial detection and actual sampling. Since gas flares cannot be expected to be consistent in gas flow rate or position, the »Pre-survey-and-then-sample« type of mission would face a high risk of having the vehicle return to sites, where gas flares had changed position or simply attenuated.
- Optimisation of the route for taking the samples resembles the »travelling Salesman problem«, taking into account additional aspects like the remaining battery charge, currents and other parameters. Although interesting in terms of engineering, it adds little value to the user or customer.
- The idea of coming back involves using time and battery energy to essentially visit the same locations twice.

»On-the-fly«-concept

The »On-the-fly« concept was considered superior. A next step was the definition of how to structure this in detail, i.e., the manoeuvring of the AUV prior to and after the sampling sequence. The manoeuvring concept chosen was termed the standard sampling sequence is illustrated in Fig. 3. It consists of various phases:

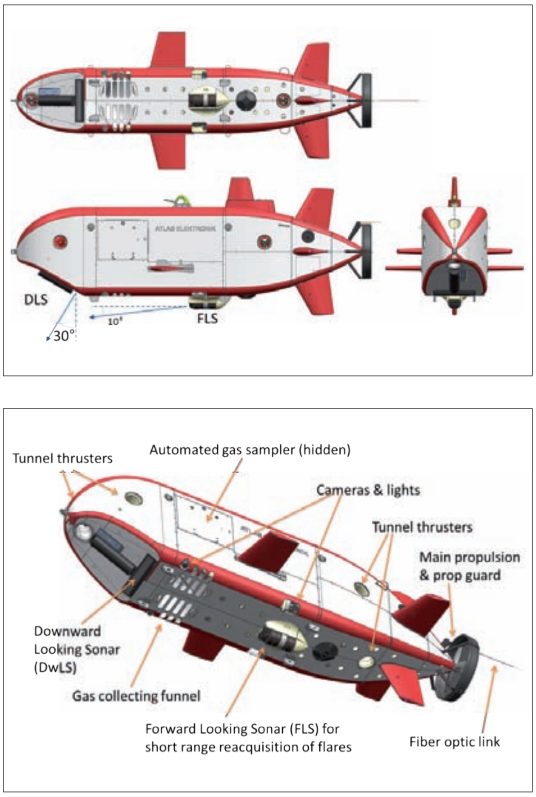

Fig. 2: IMGAM vehicle and mission specific systems

1) Initial survey with »standard AUV capabilities« based on pre-determined mission waypoints. While going along these waypoints, the vehicle searches for flares, using DLS. This is typically conducted at 20 m to 200 m height above sea floor. The flare's position is geo-referenced and stored.
2) After detection of a flare, the vehicle must move towards a position from which it can safely move towards the stored flare position while maintaining controllability, safety margins, but also path geometry, from where the flare can be expected to be visible to the sonars. This has been solved by letting the vehicle turn towards a point downstream (down current) of the stored flare location. The distance to this point is calculated based on the initial height above sea floor such that the vehicle can reach it while maintaining a descent angle of 10° to 15°. The choice of this angle is governed by contradictory motives:
   a) High steepness: Keeps vehicle away from (potential) obstacles and minimises the distance from survey to downstream waypoint. But it has the FLS looking steeper down, thereby giving it a more limiting the forward view range.
   b) Low steepness: Requires less violent manoeuvring and allows FLS a more horizontal look (less chance of misinterpreting sea floor as flare).

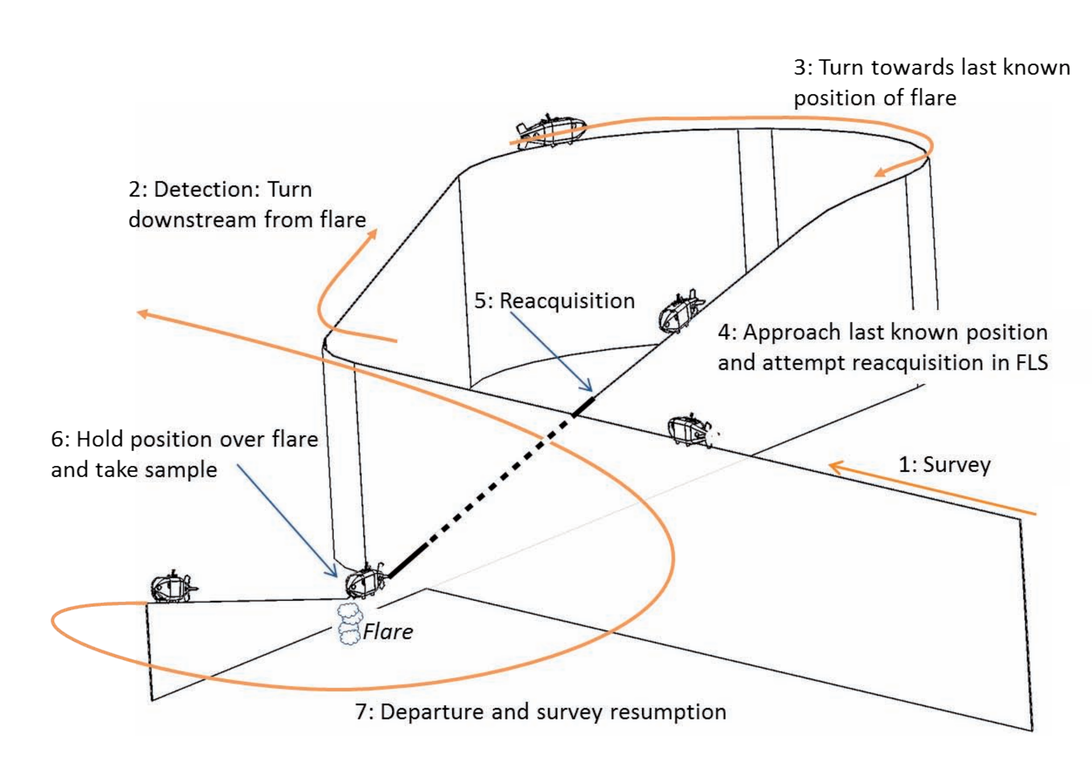

Fig. 3: IMGAM standard sampling sequence

3) After reaching downstream waypoint, turn around, towards the stored flare position. This now has the vehicle in a position, where it »comfortably« flies against the current, thereby allowing making best use of its control surfaces for manoeuvring.
4) Continue approach towards stored flare position in a steady descent and attempt reacquisition of flare using FLS.
5) After reacquisition: Change control mode to ROV-control mode (described below), where the vehicle simply moves in whatever axis necessary to reach the flare.
6) Hold position and safety altitude over gas flare for gas sampling. If water current is pronounced, point nose against current in order to maximise use of control surfaces instead of hovering thrusters.
7) Departure and survey resumption. Climb steeply away from sea floor, back to initial survey altitude, where mission plan is resumed.

3 Safety concept

The mission concept and sampling procedure described above involves many steps, where the vehicle performs autonomous decision making. It is furthermore nearly impossible to foresee all possible combination of environment parameters and resulting decisions and it is therefore difficult to ensure safe decisions under all conditions. The vehicle therefore utilises an additional protection mechanism in the form of »carefree-depth-controllers«: The control algorithms (described below) are designed such that in situations, where safe height above sea floor or maximum diving depth settings conflict with calculated diving depth, the safe height above sea floor and maximum diving depth always dominate.

Another safety feature stems from the realisation that the level of programmability and continued tuning necessary for iterative development and evolution are best situated in a »sandbox« environment, whose operation of the vehicle is safeguarded by a second layer of safety. This is achieved by splitting the vehicle's control concept into two segments:

Payload segment

Gas flare detection, trajectory planning and manoeuvring around flares are situated in an experimental segment on its own computer hardware. Code can be developed using Matlab-Simulink in models, which can potentially be shared with the inclined user, for easy contribution of own ideas and modules. These models can be tested against a high fidelity vehicle simulation and eventually be exported to executable code for running on the vehicle.

AUV core system segment

From a system safety point of view, a user programmable payload segment as described above must be considered potentially unsafe – and it must therefore be monitored and possibly overruled by a more »static« and proven »housekeeping« system. In IMGAM all tasks known from regular AUV systems: mission execution, communication, monitoring and emergency systems, logging, navigation, health and usage monitoring, controllers, hardware interfacing, battery management, and so on are clustered in the AUV core system. The AUV core system is supplied by the ATLAS subsidi-

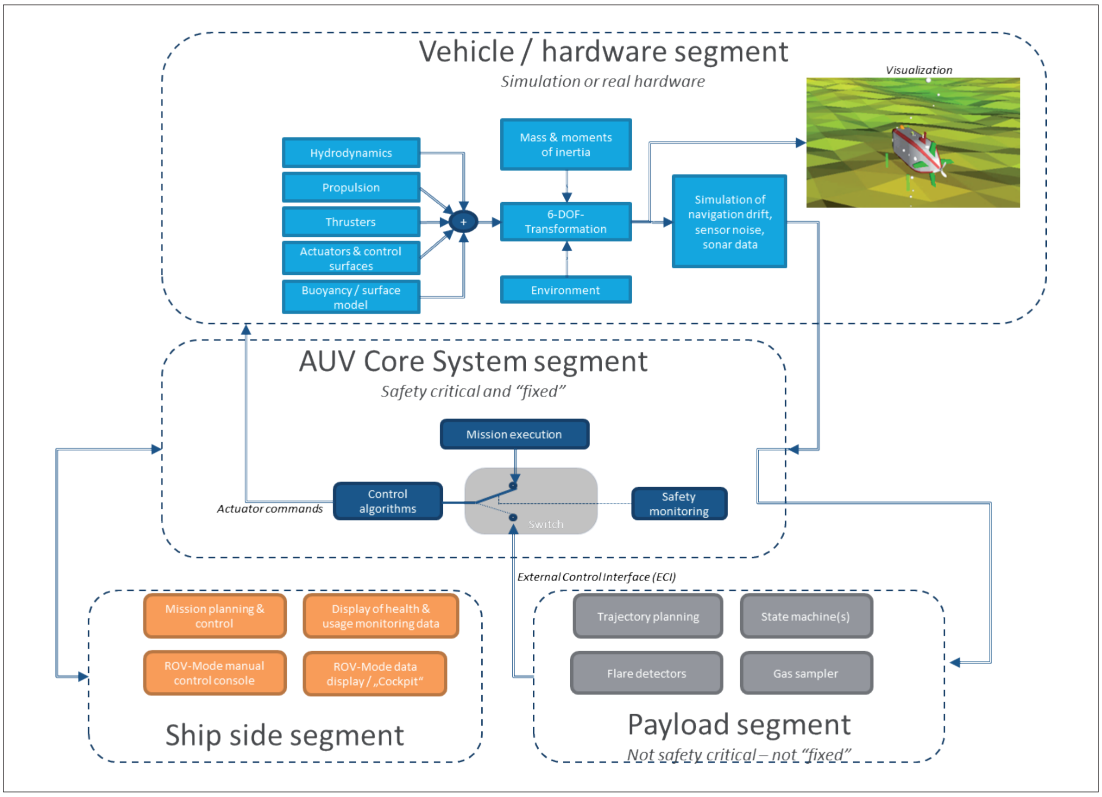

Fig. 4: Safety concept used in IMGAM

ary ATLAS Maridan ApS, whose AUV system architecture has an exceptionally good track record and features a monitored »back seat driver functionality« (the External Control Interface mentioned in Fig. 4) through which the payload can be allowed to gain control of the AUV. This division into an »open« segment and a dominant »safe« segment has the system safety advantage that testing and validation need only be performed once for safe segment, whose safety critical functionality essentially doesn't change throughout the life cycle of the vehicle. It also has the potential that the »open« segment can be made available to interested and inclined user, who can use the vehicle as a test bed to develop and test their own mission sequences without having to care about the complex systems of AUV itself.

Overall system and simulation segmentation

The two segments listed above, the »open« payload segment with its autonomous vehicle control and the supervising/monitoring »safe« AUV core system are built as modular blocks with open interfaces, allowing use of hardware-in-the-loop and software-in-the-loop methods throughout the development phase. A method has, for instance, been successfully used where the decision making process was run on a development notebook on the accompanying ship and interfaced to software and hardware on the AUV.

Fig. 4 shows how the vehicle's control system sub-divides into several modular blocks:

- The »vehicle/hardware segment« is understood as either being the »real« vehicle with its hardware – or an in-depth simulation of the vehicle. Interfaces of both are kept identical to ensure that simulation neighbouring blocks can be tested under realistic conditions.
- The AUV core system is the »heart« of the vehicle's safety critical and is considered »semi-fixed«. It contains all systems and software necessary for running the vehicle's »housekeeping«. A central element is a »switch« which opens to allow the payload segment to take control of the vehicle (via the External Control Interface). This external control is only tolerated as long as system parameters such as safety zones, minimum altitudes, safe battery levels, etc. are safe. The moment any of these are considered unsafe, the switch takes back control from the payload and appropriate steps are initiated. Depending on severity of the safety breach, the core system can choose among safety measures ranging from dropweight-release and safety surfacing to simple re-establishing of safe height above ground and mission continuation.
- The payload segment contains the »complex« algorithms needed during sampling. This also includes the software algorithms responsible for detection of gas flares in the water column. These algorithms are supplied by project partner MARUM.
- The ship side segment includes an operator's station for mission planning and control – but also more IMGAM-specific units such as a control station for use during ROV-mode operation.

4 Control system and development tools

Good vehicle controller performance can either be achieved by luck or by good understanding of the vehicle's dynamics. In IMGAM, this understanding has been combined into the form of a nonlinear simulation model, against which control algorithms have been developed. This allowed controller development to take place in parallel with construction work, thereby saving time.

Model formulation and system identification

The simulation model is realised as a rigid body, six-degrees-of-freedom model whose properties are based on mechanical data as generated by the CAD-design system, forces and moments as predicted by computational fluid dynamics (CFD), measurements of thruster forces and power draw as function of supply voltage and control signal, measurements of main propulsion thruster torque, RPM, efficiency and so forth. Although these methods are used with care and consideration, assembling all the resulting sub-models into a combined model implies the intrinsic risk that inaccuracies of individual sub-models can accumulate and distort the overall model's predictions – which in turn distorts the performance of the control algorithms when applied to the real system. It is therefore advisable to obtain vehicle performance data and use system identification methods to improve model fidelity. In IMGAM, this is done using a system identification toolbox FitLab2, which help obtain reliable estimates of model parameters.

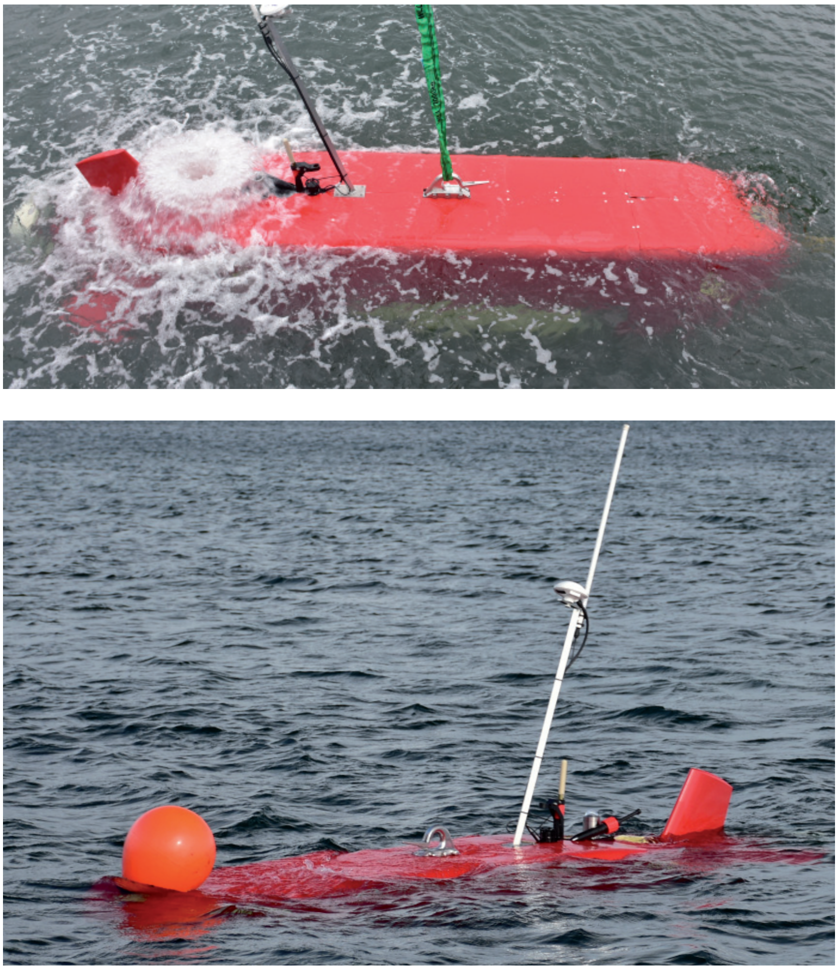

Fig. 5: Performance test of hovering thrusters in vehicle (top), controller test at sea

Control modes

Complex mission profiles require complex control algorithms and can easily end up being too many and too feature-rich. In order to counter this scenario, IMGAM has been designed with just three control algorithm »building blocks«, which have been designed in a way that they cover all expected mission phases. These controllers are:

- Waypoint-to-waypoint/depth/speed control: This controller guides the vehicle on a straight line between waypoints. This is the control mode used during »normal« surveying/mission plan execution but, for instance, also during phases 2, 3 and 4 in the standard sampling sequence.
- Heading/depth/speed control: This controller is both used as an underlying layer by the waypoint controller but also during manual control of the vehicle when operating outside the hovering regime.
- Hybrid ROV-control: This controller controls the vehicle in forward, lateral and vertical speed and yaw using all thrusters, rudders and the main propulsion thruster. It is typically used during pilot-in-the-loop control when inspecting flares – but also by vehicle control itself during phase 5 and 6 in the standard sampling sequence.

5 Current state of development and next steps

At the time of writing, the vehicle is undergoing initial shake-down-tests and controller testing (Fig. 5). Here, the simulation based controllers have shown stable performance. The ROV-mode control system has shown to be a great help when operating in and out of harbour and alongside ship.

Next follows a phase where the autonomous sampling is tested in confined waters with depths within the range of conventional divers. This will allow live footage of the vehicle and also the use of artificial flares, which can be set up in various configurations to test the system's ability to discriminate between individual flares. Finally, the vehicle shall go on missions in open sea at depths up to 2000 m to collect real samples for the scientific community.

6 Conclusion

This paper describes the concept development of an autonomous underwater vehicle for detection and retrieval of gas from subsea flare sites. The paper focuses on the conceptual breakdown of the system's autonomy into regimes and sequences that can be analysed and permuted individually and still be tested as a whole against a simulation. The paper also describes the vehicle's autonomy structure, which consists of an open part and a »fixed« core system, which safeguards safe operation throughout the mission. ⚓