

Two years of Experiments with the AUV Dagon - a Versatile Vehicle for High Precision Visual Mapping and Algorithm Evaluation

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Abstract—The AUV DAGON was designed as a vehicle for algorithm evaluation and visual mapping. Since its initial launching in early 2010 two years of experiments and experience with the vehicle have passed. This paper will give an overview of the work with the AUV DAGON and highlight the scientific experiments conducted with it, concluding with a “lessons learned” section with important modifications and ideas for future vehicles.

I. INTRODUCTION

It is a major decision for a research group to begin the lengthy endeavor of building an AUV. It is usually only considered, when it becomes apparent, that no other vehicle suiting the needs for the intended research is available on the market. This may have a number of reasons e.g. instrumentation, software-access to control/sensors, mass, size, endurance, depth-rating and export-restrictions. There might also be the issue of cost, but when the manpower necessary to completely build a new AUV from the scratch is factored-in this usually will become an argument *for* buying an existing vehicle.

In late 2009 the underwater robotics department of the DFKI RIC¹ came to the conclusion, that for its research into visual mapping and SLAM for underwater applications no suitable vehicle can be found on the market. The analysis coming to this conclusion included the option of buying and modifying an AUV/ROV, but due to the complexity of necessary modifications, the decision for building a vehicle from scratch was made. The cornerstone requirements for this vehicle were

- A complete set of “classical” navigation sensors, e.g. DVL, AHRS, FOG and USBL or LBL
- High-resolution stereo camera system observing the seafloor
- Mass < 70 kg
- Depth-rating > 150 m
- Hovering-capability
- Endurance of > 4 h
- Complete access to control/sensor software

¹German Research Center for Artificial Intelligence, Robotics Innovation Center

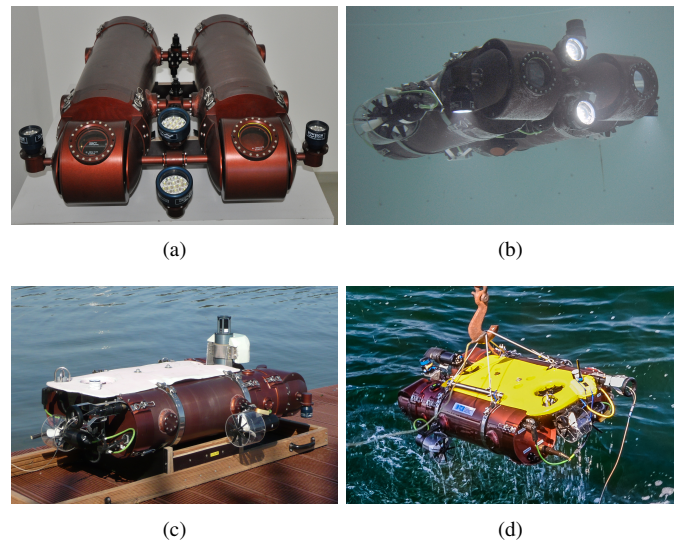


Fig. 1. The AUV DAGON evolving: (a) pressure hull testing; (b) basic indoor testing; (c) outdoor testing; (d) current state.

The necessity for both a complete set of classical navigation sensors as well as the stereo camera system is justified by the desire to provide a reference measurement for precise evaluation of the visual mapping algorithms based on the camera data. The design process which followed is described in detail in [1]. In the two years since, the vehicle (meanwhile named DAGON) was completely integrated, its control software implemented, algorithms developed and a number of trials in different environments mastered. Its evolution over the past two years is shown in figure 1. In this paper the authors want to share their experience including many problems, choices regretted or supported and hopefully contribute to future vehicle design processes.

DAGON is a hovering AUV comprising a catamaran-like pressure hull with two Full-HD cameras housed in tiltable sensor heads. It uses five thrusters (attached to the outer hull) controlled via a CAN bus, which are used up to an electrical

power of 150W each: Two surge, one sway and two heave thrusters (see figure 2).

II. ELECTRO-MECHANICAL COMPONENTS

In this section a number of special electro-mechanical components used in DAGON will be described. Although not necessarily unique, their usage had a special (positive or negative) impact on the usage of this particular AUV.

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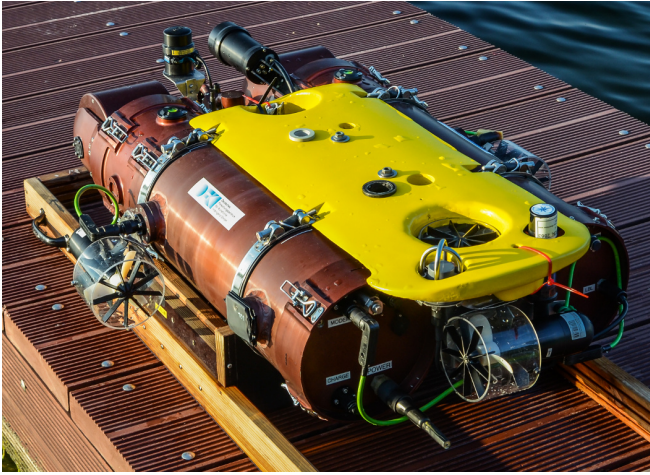


Fig. 2. The hovering AUV Dagon with its five thrusters.

The vehicle is controlled and data is processed by two embedded PCs with dual-core mobile processors. One of them is equipped with a graphics card for GPGPU computations and a RAID-0 disk array for storing camera images coming in at high data rates (up to 120 MB per second).

The available data link options are:

- 54 MBps WiFi link
- 1 GBps copper cable
- 1 GBps fiberoptic link
- 15 Bps acoustic modem

A. Battery

The battery used for DAGON is a lithium-ion battery system. It consists of two individual serialized blocks with 14.7 V and 50 A h, resulting in a total capacity of about 1.5 kW and an endurance of about 8 to 10 hours. The battery management system supervising charge and discharge of the battery is capable of showing the current rest capacity and can be used to determine how much time can be spent before re-charging. A quick-charge is possible in two hours, although this is only possible when the vehicle is not being operated at the same time due to temperature limitations. The battery system has proven very reliable, especially as compared to the battery system used on DAGON's predecessor AVALON, which had to be replaced twice already due to damaged cells.

B. Fiber-Optic-Cable

DAGON has a Seacon fiber-optic cable port. This allows the connection of a single strand amide-reinforced fiber cable, which can be used to monitor the AUV during missions. While this violates the idea of an autonomous underwater vehicle, effectively demoting DAGON to a ROV with its own power supply, this option is invaluable. Since it is impossible to transfer broad-band data through the water-column, without a hard link the AUV and its behavior can only be observed in retrospect, by analyzing the recorded data. Debugging like this can be very tedious, especially during the early development stages, where many of the basic behaviors still have to be tested and tuned. A traditional copper data cable suffers from low transmission ranges or low data rates, and heavily impacts vehicle control, since it either is heavy in water, or made neutrally buoyant with floaters, increasing its diameter and thus drag. With a diameter of only 1.6 mm, neutral buoyancy in fresh water and a tensile strength of 1200 N, the fiber we used is very slender. Still it can support data rates of full-duplex Gigabit Ethernet over a distance of 20 km using CWDM technology².

Our 500 m of fiber have been used excessively during field trials. Our typical mode of use was the following: Even though a data line was available all processes and computations were run on the vehicle PCs. The only processes allowed on surface PCs were for monitoring purposes (e.g. camera image viewer, behavior inspector). this ensures a clean transition to fully autonomous modes without cable. During the final tests it often occurred that DAGON was executing a mission while the operations team was simply observing to make sure everything was working well. The ability to quickly modify software or adapt it to a change in the environment has been invaluable.

The downside of the use of a fiber cable is its fragility and its cost. In contrast to copper cable great care has to be taken to not over-bend it. The cable used was exhibiting a tendency of forming loops, which according to the manufacturer originated in the manufacturing process and could not be remedied. If a loop was put under strain, it could tighten to a degree where the data transmission was interrupted. Luckily the cable was not harmed in any of these occurrences, but this experience will influence the choice of future cables. A second issue is the cost. The components necessary for operation (bulkhead connector, cable connector, cable, reel with rotary joint, converters) do not come cheaply, and were complicated to procure in Europe (e.g. the cable had to be sent to the connector manufacturer in the US for cable molding).

C. Tilting Camera Head

At the front of DAGON is its tilting camera head. It consists of two individual elements for each of the two cameras, allowing them to be electronically rotated either independently or synchronously within 270°. Originally conceived in order

²In CWDM the RX and TX data channels operate on different frequencies of light in a single fiber

to allow reconfiguration during a mission (e.g. from ground-following to wall-following), it has been seldom used due to calibration problems. Since the two cameras require a stereo calibration for the visual mapping algorithm, moving them independently will render the calibration useless. In order to avoid this positioning sensors were included which were supposed to have an accuracy high enough to allow adjustment of the calibration data after moving the camera heads. Unfortunately the accuracy of the sensors is not enough for this to work properly. In order to avoid constant re-calibration, the camera heads now are usually fixed, and only moved in-between missions when necessary.

D. Electronic Fuse

During the first year DAGON had to be frequently opened because of blown fuses. For security reasons all components are individually equipped with a one-way fuse. Especially the fuses of the thruster control boards tended to blow on a regular basis (due to over-current or jamming). Since opening of the vehicle is problematic, especially during field-tests, a solution for this was necessary. Our electronics department created an electronic fuse board. It has five individual power ports, each allowing up to 36 V with 10 A. A micro-controller monitors the output ports and deactivates them using a solid-state-relay if over-current is detected. The permitted current can be selected via a serial link. While this electronic fuse does not offer the same security as a mechanical fuse, it has proven a very good middle way, and performed without any problems.

E. Thrusters

The five thrusters used for DAGON have been developed specifically for this AUV. They consist of a brushless DC-motor, equipped with hall-sensors in a custom housing. The motor control electronics are built into the pressure housing as well, reducing the external cabling significantly: only 5 leads are required, two for DC power and three for CAN communications. The FPGA-based motor control electronics (called BLDC V1.3, developed at the DFKI-RIC) used the hall sensor information to accurately commute the brush-less motor. This allows extremely accurate control of the RPM even at low speeds (starting at 10 RPM), as opposed to sensorless approaches, where RPM control is only possible at higher speeds. As a result the AUV is able to very accurately apply thrust – important for a hovering vehicle.

The downside of having such sophisticated thrusters was the high number of problems they were experiencing during the last two years. Since they were not thoroughly tested before integrated into the vehicle (due to time constraints), many initial quirks were still present. This resulted in a number of experiments being aborted due to thruster malfunction. During the outdoor tests in mid-2012, not a single thruster failed. This is regarded as a tentative signal, that we now have found and fixed most of the problems. Still a more thorough testing before integrating them into an operational vehicle would be recommended for the future.

III. CONTROL SOFTWARE

The control software on DAGON uses the ROCK-Toolkit [2] as framework. Since DAGON as the first AUV using this framework, two other AUVs have already migrated to this framework (DFKI's AVALON and the H-ROV from Marum). The impact of the choice of control framework and its experiences will be detailed in this section. Furthermore, an overview of the layout of the control software will be given in order to underline the versatility of the ROCK-Toolkit.

A. Pose Estimation

The orientation estimator (OE) combines the measurements of the AHRS (attitude-heading-reference-system) and the FOG (fiber-optic gyroscope) into a three-dimensional orientation measurement. This is necessary, since the gyroscopes used by the AHRS in DAGON are simple MEMS-based gyros, which are prone to drift and need a drift-free reference in order to function properly. For the pitch and roll axes, the gravity vector can be used as reference, for the yaw direction the magnetic field is used. The problem is, that due to the usage of metallic materials and strong motors, the magnetic field inside of DAGON is severely distorted, and cannot be used as reference. A simple deviation compensation was also not possible since some of the distortions are dynamic and dependent on thruster currents and external fields, making a compensation not impossible but very complex. Instead we decided to include a single-axis FOG into the vehicle. While still experiencing drift, it is low enough (3° per hour) to not affect the experiments with DAGON adversely.

An issue in development of new localization algorithms is the necessity to characterize the accuracy of the new algorithm by comparison with a reference measurement. The complete set of classical navigation sensors on DAGON makes it possible to compute two individual and independent localization solutions and compare them. Since the algorithm used for the sonar-based (LBL-DVL-OE) solution is a well-known standard algorithm, it is used as reference pose estimator (RPE). It is basically an Extended Kalman filter (EKF) fusing all the sensor information into a measurement of pose (position and orientation) at an update rate of 12 Hz. The same EKF implementation is used as algorithm pose estimator (APE) with different parameters and the visual processing pipeline as input instead of the sonar sensors (LBL and DVL).

B. Basic Controllers

DAGON has a number of simple controllers, which are essential for most work with the vehicle. Most basic is the thruster controller. It allows the selection of a RPM for each thruster, which is then maintained by the electronic control board inside the thruster. The input for this thruster controller can come from a number of sources, depending on the mission profile. The most basic control path is the completely manual control, where a joystick controls all thruster movements. The joystick axes are linked with the thrusters by a simple thruster control matrix.

For additional controllers a simple PID-controller was implemented and parameterized for the specific task. It is used for the following controllers:

- *depth/altitude controller*
Using input from the pressure sensor (depth control) or the DVL (altitude control) the vehicle's position in the heave direction is maintained at the selected position.
- *pitch controller*
Using the two diving thrusters differentially, the pitch can be actively controlled in the range of $\pm 45^\circ$, using the AHRS as sensor.
- *heading controller*
The vehicle yaw is controlled using the orientation-estimator as input and applying thrust on the rear thruster to turn the vehicle

C. Station-keeping

Station keeping is a very useful behavior, especially during field-testing when an external current was present. The underlying controller tries to maintain zero velocity on the x/y axes as well as the current heading. The DVL is used as input. While this does not necessarily result in absolute position keeping, it performs rather well. One of the problems observed during the sea-trials in the Baltic Sea was that since DAGON has only one thruster for lateral movement, it is sometimes not strong enough for station keeping when a cross-current is present. This could be easily remedied by monitoring the direction of the current, and rotating the vehicle so it can use its surge thrusters to counter the current. This is still under development.

D. Trajectory-follower

In order to survey or map pre-defined areas, a typical AUV application is the automatic and precise execution of trajectories. A trajectory is defined by a set of vertices creating the support polygon, which are interpolated by a C2-steady curve [3]. The AUV controller then tries to follow that curve as precise as possible. For this to work properly, the curve interpolation parameters have to be selected according to the AUV's capabilities with regard to turning radius and degrees of freedom. This is relatively easy for a hovering AUV like DAGON, since due to the fact that it can freely select its speed and point-turn, its minimum turning radius is zero. However since this would potentially produce unwanted behavior, the minimum curve radius at different traveling speeds was experimentally determined, and can now be used for parameterization of trajectory interpolation.

The vertices for the support polygon can either be in $\mathbb{R}^2$ or $\mathbb{R}^3$. $\mathbb{R}^2$ vertices are used when the depth of the vehicle is to be determined by a different controller, e.g. terrain following or constant depth. $\mathbb{R}^3$ vertices can be used to navigate in known environments.

The implementation of the trajectory follower uses the input of a pose estimator (either RPE or APE, see section III-A) to determine the vehicle's current position on the trajectory, and the vehicle motion commands and model (MCM) together

with input from the DVL to determine the vehicle's current speed and motion flexibility.

E. Vehicle Motion Commands and Model

The dynamic modeling of DAGON is done in 3 DOF (surge, sway and yaw). The nomenclature used for describing the DAGON movement directions is according to the SNAME notation [4]. The model is useful for analyzing and understanding the vehicle. The unknown physical parameter is identified using on-board sensors. The identification method used here was inspired by Indiveri [5] and Ridao, et.al., [6]. Since DAGON is a slow moving underwater vehicle, Coriolis parameters and coupling between any two degrees of freedoms are removed. The simplified equation of motion is of the form

$$M\dot{v} + D(v)v + g\eta = \tau + disturbance \quad (1)$$

where the matrices M , and $D(v)$ denote inertia, and damping parameters, $g(\eta)$ is the vector of generalized gravitational and buoyancy forces. τ is the input forces and moments caused by the thrusters. The on-board sensors used for the identification purpose are DVL and FOG, the former is used to measuring linear velocity and the latter is used for angular velocity. The acceleration is obtained by differentiating the velocity signal using the Savitzky-Golay filter [7]. We used Levenberg-Marquardt nonlinear least square algorithm for identifying the unknown system parameters. The modeled velocity in surge, sway and yaw are shown in figure 3, 4 and 5.

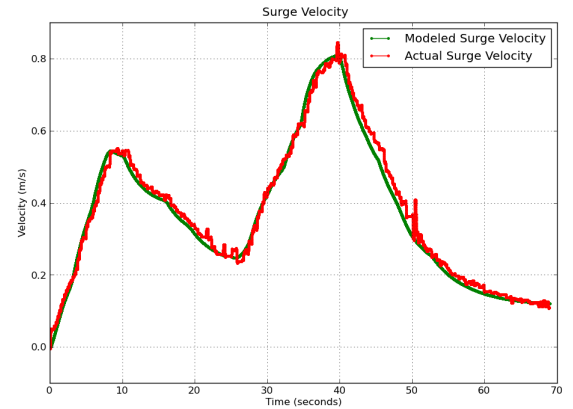


Fig. 3. Modelled surge velocity.

IV. OPERATIONAL EXPERIENCE

DAGON has been used in a number of environments, ranging from the test basin at our lab, in lakes, the open sea and under ice. These diverse environments each pose different operational circumstances and limitations, which had to be learned by the operations team. Experiences with different launch/recovery strategies, balancing/buoyancy tuning, external supervision and in-field maintenance will be given in this section.

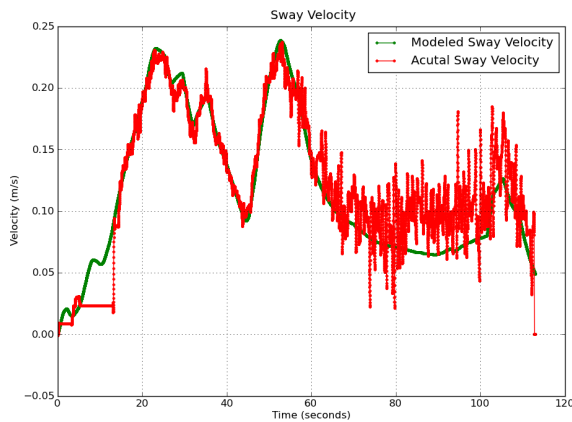


Fig. 4. Modelled sway velocity.

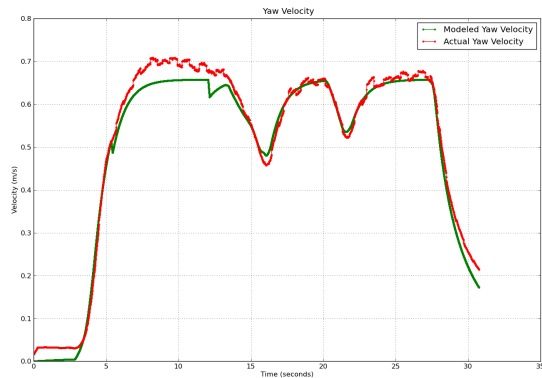


Fig. 5. Modelled yaw velocity.

A. Testing Environments

By mid 2012 the AUV DAGON has accumulated over 400 active hours in the water. Most of that time was spent in the underwater testbed at the DFKI-RIC, followed by a lake near the University of Bremen. Additionally two open water field-tests were conducted in the Baltic Sea, one in Kiel and the second near Rostock. Each of these diverse testing environments has its unique advantages and limitations:

- *Underwater testbed*

The DFKI-RIC's underwater testbed offers two test basins: a 40 m³ glass wall tank and a 20 m³ black basin (see figure 6). The glass tank is a 5 m × 4 m × 2.5 m glass/steel basin, which due to its three large glass sides is ideal for basic testing and low-level controller tuning, since the vehicle can be observed. Its moderate size allowed even some scientific experiments under very controlled conditions. The black tank is smaller (3.4 m × 2.8 m × 2.5 m), and has only two small windows. Its purpose is to allow visibility control by preventing any external light from entering, and the ability to select the turbidity of the water. This was very useful

to determine if the illumination of the vehicle was potent enough, and to find the limit of turbidity the visual mapping algorithm can still cope with.

- *Lake*

The second environment was a lake near the University of Bremen, which is more suitable for larger scale tests and more realistic environmental conditions. It is a former gravel pit, which makes its shores very steep. Unfortunately this also means that its ground is rather muddy, reducing visibility to one meter and below most of the year. Nevertheless the lake was a great test environment for gaining operational handling experience in an outdoor environment, as well as for large-scale experiments such as the trajectory follower.

- *Under Ice*

In Winter 2011/2012 a unique opportunity arose as our test lake froze completely shut due to the low temperatures. The Bremen fire-department was kind enough to cut a hole into the 0.2 m thick ice, which we could use to lower the AUV and explore the lake under ice. A special challenge for the vehicle was the task to return to this hole after the mission – otherwise it would have been stuck. This was an exciting field-test, and provided some exciting imagery from under the ice (see figure 7).

- *Harbor Kiel*

As preparation for the tests in the Baltic Sea, which were planned for mid-2012, a series of tests were conducted in November 2011 in a harbor near Kiel. Originally it was planned to only use the harbor as access to the Baltic Sea, but due to bad weather and strong wind we were forced to stay inside the harbor. Still a lot of preparation could be done, as the visibility was better than in the lake, and we had to cope with waves, obstacles and bad weather.

- *Artificial reef near Rostock*

The final tests were conducted mid-2012 in the Baltic Sea. The artificial reef off the coast of Nienhagen³ near Rostock was the test environment. The artificial reef is a test site for biological long-term observation, where 1400 artificial concrete elements were placed in a 50 000 m² area. For this campaign we chartered the RV *Gadus* from the University of Rostock as base vessel, and additionally brought our own small RV, the 6 m RIB “Polarsternchen” (see figure 8).

This test site was the first time DAGON was used in the open sea. During a mixture of weather (from sunny to strong rain, calm to 5 Bft), current and waves, the vehicle performed very well. Water conditions and visibility were optimal, a huge amount of data was recorded and has yet to be analyzed. On our last test day of this two-week campaign, DAGON performed two fully-autonomous missions, without any cable attached.

³<http://www.riff-nienhagen.de>



Fig. 6. A view of the DFKI-RIC's underwater testbed with the glass basin in the foreground and the black basin at the back.

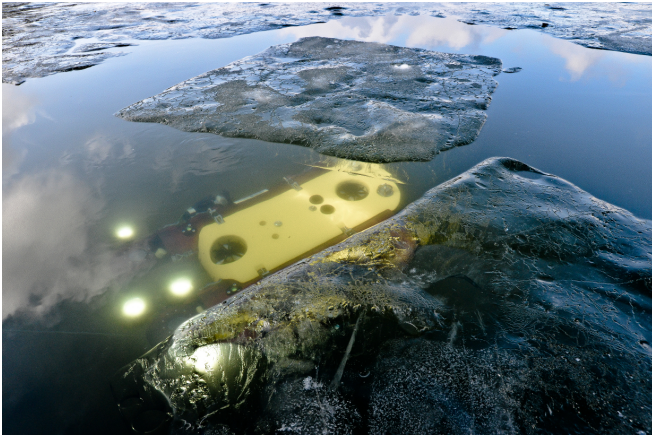


Fig. 7. DAGON emerging from a trial under ice at a lake near the University of Bremen in winter 2011/12.



Fig. 8. The testing environment at the artificial reef Nienhagen ($54^{\circ}10.5'N$ $11^{\circ}56,6'E$). To the left the observation tower can be seen, to the right the research vessel *Gadus*, which was used as base.

B. Field Testing

Due to the relatively small size of DAGON, launch and recovery proved to be both easy and challenging. We use a system of four fixtures (two each hull) where we attached a harness for usage by a crane. This proved to be a safe system for putting the AUV into our tank or launching it from the crane built into DFKI's own RIB. For the launch from the research vessel *Gadus* during the trials in the Baltic, we exchanged the nylon rope harness with one made of steel. Due to the high stiffness of this harness catching the AUV with a hook on *Gadus*' crane proved to be very feasible up to the sea states where DAGON can be operated in. For launch in shallow water environments like the gravel pit in Bremen, we directly use the maintenance sledge and two people with rubber trousers.

The main operation mode of DAGON is in an hybrid mode, where the fibre is attached to view the actual state and sensor output of the control software, even when we run an autonomous mission. The ROCK framework allows for a seamless transition between direct controlled and autonomous operation. The system is started in the same way, whether we are tethered or operate the AUV via a WiFi link when on the surface before a full autonomous run. Via the underwater modem link we can give basic commands to the vehicle and receive status information. A TriTech MicroNav USBL system can be attached to DAGON giving a rough estimation about direction and distance during full autonomous operation. During the various field tests we discovered, that we can safely operate DAGON in most conditions. The only problem we encountered is the unreliability of the WiFi link due to reflections on a more bumpy water surface. We currently plan to adopt the dual-mode radio link we use on our older AUV AVALON to get rid of these problems.

The problem with a control software research vehicle is, that the internal electronics are changing a lot. Even during tests in the field there are sometimes changes, which is the source for numerous bugs (e.g. wiring problems). The layout of DAGON was done in such a way, that most internal parts are accessible for in-field maintenance. Both pressure hulls can be opened without special tools, the transport ledge is constructed in such a way, that the hulls open easily. The system is sealed by applying negative pressure. All tools and spare parts fit within several normal sized boxes, and DAGON can be transported with all necessary equipment within a van.

V. SCIENTIFIC EXPERIMENTS

The AUV was build in context of a research project (called CUSLAM), where an algorithm for visual mapping and localization is developed and tested on the AUV. For this work a number of experiments were performed using DAGON, and this section will give further detail on how this specific AUV design was crucial in acquiring the necessary data for the algorithm development.

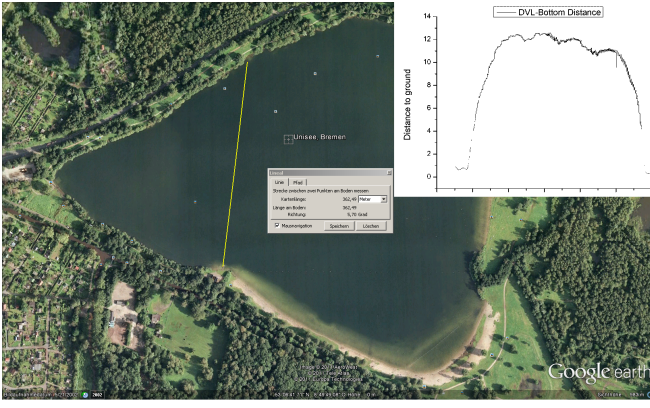


Fig. 9. Depth profiling mission at a lake near the University of Bremen in mid-2011.

A. Depth Profiling

One of the first external missions with the fully integrated vehicle was a depth profiling of our test lake. Since at this time the trajectory-follower (see section III-D) was not yet fully implemented, the AUV was simply given a static course and a predefined speed. The depth controller was commanded to keep a depth of 1 m below the surface in order to remove bias by surface effects. The distance between the AUV and the lake floor d_v was measured using the DVL sensor. Its four beams each yield a measurement of their individual distance to the lake floor d_{di} . Since the emitters are arranged in 45° angle from the horizontal plane, a simple trigonometric transformation was used to obtain the four DVL to floor readings $d_{fi} = d_{di} * \cos(\pi/4)$. These values were averaged to form the current AUV to lake floor distance $d_v = \sum_{i=0}^4 (d_{fi})/4$. At the same time the depth sensor was sampled, recording the distance between the AUV and the surface d_s . The depth of the lake could then be computed as $d_{lake} = d_s + d_v$. Since the DVL samples at 12 Hz, the depth profile has a quite high resolution, as depicted in figure 9.

B. Trajectory Following

The trajectory-follower described in section III-D was usually tested in the lake environment, since its behavior was difficult to test in the confines of the glass basin. A number of different trajectories were tested, including simple lawn-mower type survey patterns and more complex patterns with multiple intersections along the curve. The latter are of relevance for the visual mapping algorithms described in section V-C. During experiments, the trajectory-follower usually allowed a constantly low deviation between the desired trajectory and the recorded measurements from the pose estimator. During field trials DAGON's ability to compensate side forces induced by currents were extremely helpful in order to avoid skewing of the trajectory. A typical example of trajectory-follower performance can be seen in figure 10.

C. Visual Mapping

Visual mapping was the key scientific purpose for which DAGON was built. The basic idea of this algorithms is to

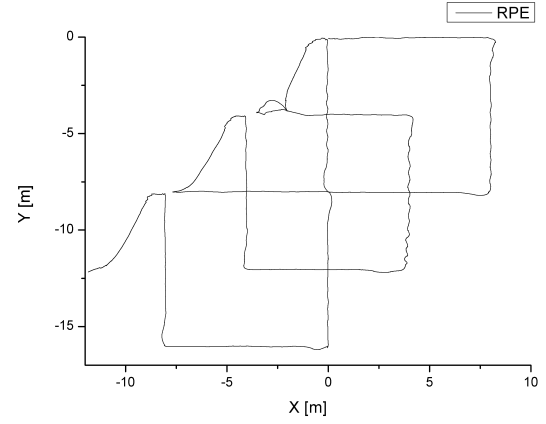


Fig. 10. Trajectory as performed in the Baltic Sea. The intersections are necessary for loop-closing during visual mapping.

observe the sea-floor with the stereo camera system mounted on the vehicle's center. In each image salient features are calculated using robust feature extraction algorithms. These can be matched among the stereo camera images in order to calculate three-dimensional landmarks for each frame. These landmarks can be tracked for several frames, and the vehicle motion calculated by the resulting geometric relations. Additionally since the features have been calculated by a robust feature extractor (algorithms tested included SIFT, SURF etc.), the landmarks can be re-matched even if re-observed after some time, which allows loop-closing and thus SLAM. The basic idea is depicted in figure 11, the complete mapping algorithm is explained in further detail in [8].

A major problem of visual mapping algorithms is computational complexity. While simple feature detectors for visual-odometry-only applications can be computed with high frequency on state-of-the-art computer hardware (dual-core CPU with 2.8 GHz), the robust detectors required for SLAM applications require calculation times in the order of seconds even for moderate-resolution images (0.5 MP, HD/2). An easy remedy for this is to reduce the sampling interval accordingly, and move very slowly, maybe even stop from time to time in order to calculate more complex sections such as loop-closings. This remedy does not work for application of SLAM algorithms on underwater robots, since due to the environment low speeds may be impossible, and stopping is usually impossible, since the vehicle is floating in the water column.

In order to remedy the problem of computational complexity, DAGON is equipped with a dedicated embedded-PC only for computer-vision processing, which includes a GPU. This is helpful since the feature detector used for the mapping algorithm (SURF [9]) can be parallelized and reduced to operations for which the GPU is specialized. This results in a ten-fold reduction of calculation time for feature detection/extraction, allowing update rates of 5 Hz for the mapping algorithm on the hardware used in DAGON (Intel i7 2x2.8 GHz CPU, NVIDIA Quadro2000 GPU). Since the computational load is shifted to

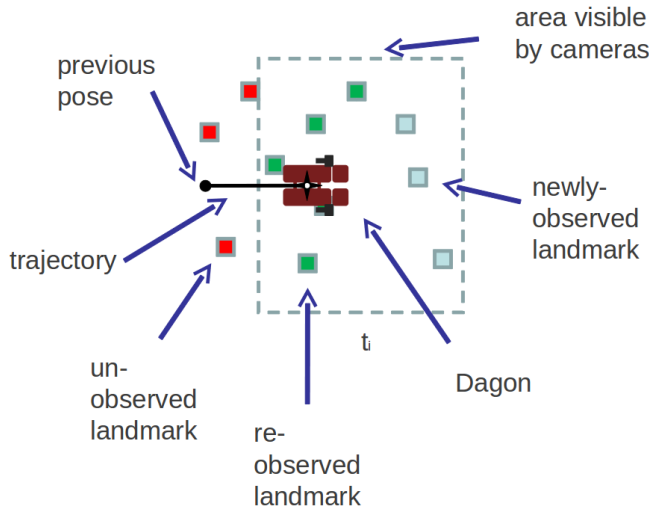


Fig. 11. Basic idea of visual odometry localization.

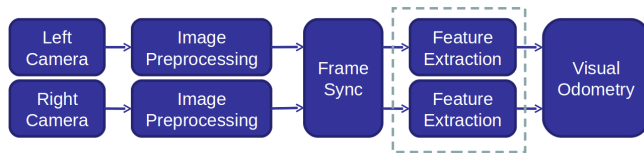


Fig. 12. The real-time capable visual odometry pipeline.

the GPU, the CPU is relieved and can handle the other tasks of visual processing required for mapping. The processing pipeline used in DAGON is shown in figure 12.

First results of the visual mapping algorithm are shown in figure 13. Both the output of the RPE and APE are plotted while a number manual square was driven in the glass basin (only one square is depicted for better clarity). While there is some deviation along the trajectory, the start-end-points differ only slightly even after ten squares. The results were a deviation of 0.74 m after a traveled distance of 72 m, resulting in a deviation of 1.02 %.

VI. CONCLUSION

During the past three years the AUV DAGON has been developed, integrated, tested and used. Even though a lot of work could still be done to improve the vehicle, it can now be regarded as ready for further experimental use. It has proven its utility and versatility in a number of different environments and situations, hopefully remaining in service for a long time.

A. Future Work

There is a large number of ideas for further work. The following items are of high interest and will be hopefully implemented in the near future.

DAGON currently has a semi-open-frame hull. In order to improve its performance with regard to endurance and robustness to currents a streamlined outer hull made from glass fiber reinforced plastic is being planned. It is supposed to

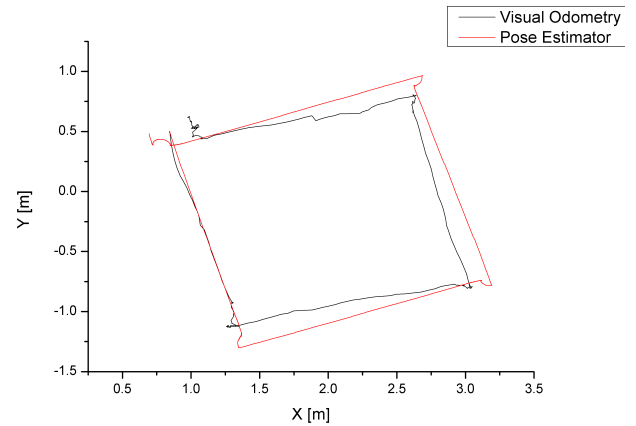


Fig. 13. Result of visual odometry and reference pose estimator plotted for comparison.

be easily detachable for maintenance and additionally provide some mechanical protection for the pressure hull and sensors.

The computation of SURF features on the GPU has the disadvantage of being relatively inefficient with regards to power consumption. Although a low-power GPU is used, it still consumes up to 49 W. While this is not a major concern, there is the idea of using an FPGA instead - which promises a better efficiency as demonstrated by Svab et.al. [10].

The visual data acquired by the vehicle can currently only be visualized with a simple video viewer. Since all data is available for the generation of a three dimensional mosaic, an approach as described in [11] is planned to post-process the data into a more user-friendly representation.

ACKNOWLEDGMENT

The authors would like to thank all colleagues at the DFKI Bremen for their support and feedback. The work presented here is part of the CUSLAM project (grant No. 03SX290) and the CSurvey project (grant No. 03SX262B), both funded by the German Ministry of Economics (BMWi).

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