Design of a Versatile AUV for High Precision Visual Mapping and Algorithm Evaluation

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***Abstract*— This paper presents the work on the design and construction of a new mapping AUV. The vehicle is specifically designed as a scientific AUV for visual mapping, incorporating high-end instrumentation and sensors to allow research in this area with the best technology can offer today. The complete process of development is described, starting with the design criteria and ending with the specifications of the system as it currently is undergoing final integration.**

I. Introduction

Visual mapping is becoming of increasing interest in the underwater society. A precise and fast means of creating visual maps has a number of important applications, e.g. visual inspection of underwater structures, resource exploration or underwater archeology [1], [2], [3], [4]. Besides the algorithms and software needed for such mapping tasks, there are a number of requirements for the vehicle actually performing such mappings. This paper will present the design of a vehicle specifically designed for the test and development of new, visual-inertial mapping technologies, focusing on key needs of this area. The basic idea of these visual-inertial mapping approach is described in [5].

II. Design Criteria

The design criteria for the new AUV can be roughly separated into mechanical criteria, describing the dimensions, actuation system and overall appearance, and into the sensor requirements, dictating the available sensory equipment of the vehicle. Both constraints will be described in the following two sections.

A. Mechanical Requirements

There are a number of design criteria which were considered high priority primary parameters. The vehicle should be small, not exceeding 60kg for ease of deployment and handling. Diving depth should be at least 150m, in order to retain the possibility of surveying near-shore continental shelfs. The speed over ground is required to be freely selectable (in reasonable ranges), in order to test algorithms at different speeds. In order to operate within narrow constraints of structures, high maneuverability and rate of turn are necessary. By attachment of a fibreoptic cable the experiments should be supervisable while keeping the diameter of the cable as low as possible to reduce the induced movement impendence. Parameters usually of high importance (long battery life, high speed, low hydrodynamic drag) only are of secondary interest, since they would interfere with the primary parameters in a negative way.

B. Sensor/Instrument Requirements

One basic problem in development of new navigation and mapping algorithms is measurement of their accurateness and robustness. In order to do so, ideally a ground-truth measurement should be available to which the new estimate can be compared. This usually is not the case in underwater environments, since highly precise and frequent absolute position measurements are hard to achieve. Our approach aims to use state-of-the-art sensors and technologies to get the best position measurement possible with 'traditional' methods, meaning a combination of external reference measurements (LBL, USBL), speed measurements (DVL) and inertial measurements (IMU, FOG). Since such systems have been widely used in the underwater community, their precision and performance is well known and documented. We will then use this measurement as gold-standard to compare newly developed, visual-inertial algorithms against. Of course, this directly means that a complete set of classical navigation instrumentation is required on the vehicle besides the camera system.

Since the camera system will be the main payload sensor on the system, a number of requirements exist for this sensor. The camera should be a color stereo camera with at least 20cm baseline between the lenses. One of the problems with stereo cameras is the rigidity of the rig against external deformation - in order to avoid such problems special care has to be taken to connect the cameras as rigidly as possible. The field of view (FOV) of the cameras should be as large as possible, in order to maximize image overlap both between stereo pairs and between consecutive images. The cameras should be ground tracking, their angle to ground be freely selectible between $0°$ and $45°$. The cameras should have high physical resolution in order to get high quality visual data as input for the algorithms. Digital cameras are preferable to their analogue counterparts to minimize image noise. The achievable frame rates should ideally be video frame rates (25 Hz), with a lower limit of 15 Hz. The usage of cameras equipped with highly sensitive CCDs has the advantage of reducing the illumination

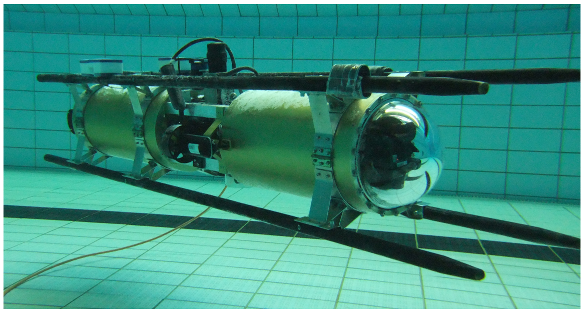

Fig. 1. The AUV AVALON.

requirements. Using lenses with a large aperture has the same positive effect, and should be used in combination with the former. Illumination should be as uniform as possible in the entire field of view. The last parameter for the camera system is the depth of field of the lenses, which should be as large as possible in order to avoid image blur.

Processing of high-resolution camera data requires a lot of processing power. Besides a control and guidance computer system a second system is required which solely handles the image processing tasks. Separation between the two systems is important, since overload caused by image processing tasks could adversely affect vehicle control, which is unacceptable. The aim is to get as much processing power into the system while maintaining power consumption low. Since it has been shown that stereo processing can be done on graphics cards (GPUs) very well ([6], [7]) an inclusion of such a device on the AUV would allow interesting possibilities. The cost in power consumption however still is relatively high for such devices.

III. Design Process

There are a number of different AUVs and AUV designs available in the research community and a growing retail sector for such vehicles. Yet the specific needs for a visual mapping vehicle are not met by the available AUVs. Still the design criteria were inspired by different other vehicle specifications, and the lessons learned with such vehicles.

A. AUV AVALON

The predecessor of the vehicle described in this work is an AUV called "'AVALON"' (Aquatic Vehicle for Autonomous Learning, Operation and Navigation), developed at the DFKI in the time between 2007 and 2010 (shown in figure 1). Envisioned as a low-cost (student) research vehicle, its design criteria differed in many points of the new vehicle. Nevertheless the experience gained in the design, operations and maintenance of AVALON greatly contributed to the new vehicle's design. Since AVALON has seen more than 100 hours of active operation in a number of environments (starting in swimming pools indoors, over lakes up to the open ocean) the flaws and problems of its design are well documented. Some of the graver flaws have already been addressed in AVALON: the ability to recharge the battery without opening the pressure hull, as well as mechanically fastening the hull to the end caps. The latter was deemed unnecessary (since water pressure would do the job), but of course changes in temperature or small mechanical influences would result in a slight opening of the cap, and thus water leaks. The ability to recharge without opening the pressure hull sounds like a matter of convenience, but in reality is very important: during prolonged operations at sea (e.g. in a small boat) opening the AUV in the field is extremely dangerous and hard. The second reason is that opening and closing wears the o-ring seals, and will lead to eventual failure of pressure resistance at these places. Other aspects of the system could not fully be remedied: the initial system weight of AVALON was 70 kg in air, which could be reduced to 60 kg. Since this still is a lot for two persons to carry over long distances, the aim is to reduce it as much as possible in the new vehicle.

As seen in figure 1 the AVALON AUV consists of two pressure hulls connected by superstructure, with two thrusters (one diving and one horizontal) in between. The two driving thrusters are mounted besides the vehicle in the center area. This concept allows the thrusters to apply their force near the center of gravity (COG), which results in less disturbances in attitude when diving/moving horizontally. Unfortunately, the thrusters could not be mounted perfectly at the COG, which resulted in the need to add two more thrusters at the rear of the vehicle for diving and horizontal movement. After this remedy the maneuverability of AVALON was excellent, the concept of six thrusters for actuation of five degrees of freedom (DOF) confirmed as benevolent. The other DOF, roll was kept stable by a low COG. This was achieved by a very simple means: the lower half of each pressure hull is filled with the batteries. Since the batteries weigh a lot more as the electronics mounted on top of them, the COG is kept low without the need for additional lead or a keel, and roll movement was limited to $\pm 5°$. A drawback of using two pressure hulls is the need to connect any electronics between the hulls with underwater connectors which tends to increase the amount of plugs and cabling significantly. For the new vehicle this was to be remedied.

B. Other AUVs/ROVs

Another vehicle which contributed to the vehicle design is the LBV150 from SeaBotix, which is owned by the DFKI as well. While being an ROV, one feature has proven invaluable with this vehicle: the ability to tilt the camera 180° up and down. While possibly not the most useful feature during AUV operations, it is extremely useful for human control. For AUV operations the ability to set the camera to a pre-selectable angle is of interest for many tasks as well.

The SeaBED vehicles by WHOI [8] are used for mapping and evaluation of mapping algorithms. Important work in the are of visually aided navigation was done by Ryan Eustice and tested with these vehicles [9], [10]. One of the properties directly visible with these AUVs is their double-hull. They look like catamarans driving capsized (see figure 2). This idea of reaching a higher degree of passive stability in the non-

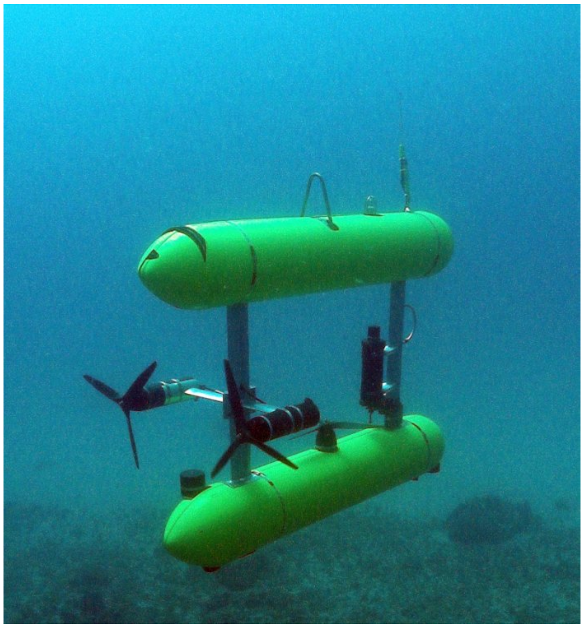

Fig. 2. A deployed WHOI SeaBED vehicle.

Fig. 3. Parallel setup without peripheral equipment.

actuated DOF by vertically separating the COG and the center of buoyancy is both intuitive as well as effective.

C. Vehicle Concept

The main purpose for the design of the AUV, is to build a multi functional vehicle in shape, mobility and integrated sensors. The design has also to combine the option of an streamlined shape with the option to install a stereo vision system that uses a defined distance between the cameras. The tube shape is a simple as well as effective design for AUVs. Unfortunately the integration of a stereo vision system into such a cigar-shaped vehicle is difficult: either the baseline of the stereo system is very small, or the tube diameter grows very large. This makes this design ineffective. A frame-based vehicle seems more appropriate for incorporation of a stereo camera. Open frame based AUVs often include separate water-proof containers which are connected with under-water connectors. Because of the effort and space of the containers this design is difficult to install in a small size system with a large number of equipment. Also a frame construction in the shape of a tube (often realized with additional covers for reduction of drag) increases the ratio of system volume to usable space, and thus weight, which is not desirable for this application.

It was decided that a hovering AUV with five active degrees of freedom is needed. The remaining DOF (roll) is to be passively stable. To reach this the basic design of the AVALON was taken, but not with the two hulls aligned to form a cigar-shaped structure, but besides each other in a more catamaran-type configuration. (see figure 3) This has a number of advantages: the stereo baseline can be greater than the hull diameter, because it is now only limited by distance of the hulls. The center of gravity is inside the vehicle, but since there is open water in between the hulls the diving thrusters can be mounted between the hulls, achieving high effectiveness. Additionally to the diving thrusters there is space between the hulls to accommodate additional sensors (e.g. the DVL). The whole vehicle is kept very compact, which reduces its tendency to pitch or roll. Especially the latter is of high importance, since it is the passive degree of freedom. The compactness also improves maneuverability, which will be helpful in confined spaces. A disadvantage is the higher water resistance and thus reduced endurance. Since these parameters were of secondary nature, this was deemed acceptable. The basic idea of the two hulls containing the batteries in the lower half, and the other electronics in the upper half was kept, in order to keep the COG low. The two hulls should be connected by dry tubes, reducing the amount of underwater connectors by wiring any connection between the two hulls through these dry tubes.

Instead of mounting the cameras behind acrylic domes (as was done in the AVALON) it was decided to put the cameras onto a tilt unit, which can be tilted 180 degrees around the pitch axis. This has two advantages: the view port of the cameras can be flat (which facilitates camera calibration) and made of standard glass (which improves the pressure rating), and the camera viewing angle can be selected very easily. The price for this setup is a more complex head design. Similarly to the main hulls the electronics of the head is connected dryly to the main hull, making the vehicle one big pressure hull. In order to protect the system from water in case of a leak, the two heads and the two hulls are sealed with low-pressure sealants from each other.

IV. System Description

The basic specifications of the AUV are given in the following list:

- **Navigation**
  - LBL/USLB tracking system transponders integrated
  - DVL
  - IMU
  - FOG
  - Pressure sensor
  - HD Stereo Camera
- **Communication**
- Fibreoptic cable link
- Telemetry modem

- **Dimensions**
- 700x600x300mm outer dimensions
- 50kg weight in air
- **Instruments**
- 2 Embedded PC systems (Intel Core2Duo 2.8 GHz)
- 1.6 kWh Lithium-Ion Battery @ 29.6 V
- approx. 5000 Lumens worth of light
- 6 brushless thrusters, 3.5 kg bollard thrust@150W

Further details on the sensor systems can be seen in table I.

All of the required sensors could be integrated into the system. Most sensor systems are typical underwater equipment, and not very exceptional. As stated above, the stereo camera system is considered the main sensor system. The selected cameras, two Prosilica GE1900C Gigabit-Ethernet cameras are extremely sophisticated sensor systems. Equipped with a Kodak KAI-2093 1”CCD sensor with Full-HD resolution (1920x1080 pixels) and a quantum efficiency of more than 30%, they offer crisp, low noise color images. The camera can record as many as 30 frames per second at full resolution, which is even beyond video framerates. Together with an Lensagon 8 mm 1” lens with an f-number of 1.4, the camera becomes a great instrument to visualize underwater scenery. The lens offers a diagonal FOV of 101° in air, which will translate into roughly 67° in water (the system uses a straight viewport). The selected baseline of the stereo camera system is 30 cm, which results in a stereo overlap of 92% at three meters viewing distance from the seafloor. At this distance the cameras have a single image swath of 4 m, which translates to a resolution of 2 mm per pixel - an excellent value for mapping applications. Together with the powerful LED-based illumination system this camera system can be considered one of the most sophisticated setups in AUVs today.

The AUV is equipped with two absolute position measurement systems: a reverse-LBL and an USBL. The reverse-LBL allows the system to measure its own position relative to a grid of four pre-installed transponders in an area of about 500m x 500m. This position measurement is used together with the DVL and the IMU for ground-truth measurements as described above. Because of weight restrictions the LBL transponder was integrated into the main pressure hull of the AUV as opposed to its external fixture. Only the transducer and the pressure sensor are mounted in the water directly. The USBL solution is not meant for usage for vehicle navigation, but in order to track the vehicle during autonomous surveys from a boat. The USBL transponder from Tritech is so small as not to impede the vehicle.

The AUV design consists of two main tubes with equal supports for the rear and front cap. This construction enables a various number of combinations using different caps. The tube itself is a welding construction with bonded rings on the ends for the cap locking device. The material in use is depended on corrosion (ALMg4,5Mn) and availability (AlMg3). The coating is a red colored hard-coating which gives a much better control to the fit tolerances to other techniques like anodization. Of course it has to be kept in mind that the hard coating is not a decorative but a technical coating, which is clearly visible in the imperfections of color at the long tubes. Attached to the front of the two main hulls is the stereo head. The main setup for the stereo based system is shown in figure 5. For an easy access and for maintenance reasons the caps are fixed with quick-release clamps.

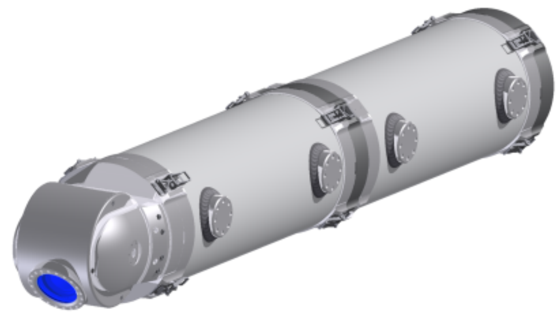

Fig. 4. Aligned setup without peripheral equipment.

Fig. 5. Rotatable cameras with aligned LED light.

For the primary stereo vision setup the front cap is equipped with a 180 degree turnable tilt unit. The two main tubes are connected with side connectors parallel to make the two front cameras aligned on a turnable horizontal axis. To realize a fixed position of the two cameras in the offset angle they are connected with a horizontal tube construction. This tube is also used to fix two of the four LED lamps, so that the lamps are always aligned with the cameras. On the left and right side there are two additional LED headlamps in a fixed down position. The details are shown in figure 5.

Each of the head tilt units is independently driven by a gear motor with a gear ratio of 1/1014. Combined with a gear ratio of 1/5 installed on the head main axis the available torque is limited by the gear shaft up to 10Nm. The motor requires 25s for a complete 180 degrees tilt. The head mechanic is shown in figure 6.

The head axis is sealed with three Turcon Roto-Glyde rings from TSS Trelleborg sealing solutions company. These sealings are rated for 30Mpa. This kind of sealing is more effective than a common sealing o-ring, with the disadvantage of higher friction. Considering the low speed and available torque fortunately this does not limit the function of the tilt unit. The motor incremental encoder is use for speed control

TABLE I

List of Sensors/Instruments of the AUV.

Instrument	**Measured Property**	**Update Rate**	**Precision**	**Range**
XSens MTi AHRS	Attitude	120 Hz	1° (Hdg) 0.5° (Roll/Pitch)	360°
KVH DSP-3000 single axis FOG	Yaw rate	100 Hz	1-6 $^\circ$/h	$\pm 375\,^\circ$/s
Desert-Star SSP-1 Pressure Sensor	Depth	0.25-16 Hz	0.1% RMS	0-344 m
Desert-Star SAM-1 Acoustic Modem	Telemetry	23 bits/sec	-	250-1000 m
Desert-Star VLT-3 LBL Transponder	XYZ position	0.2-2 Hz	$\pm$0.15 m	2000 m
Teledyne RDI Explorer DVL EXP600	speed over ground	12 Hz	$\pm$0.007-0.03 m/s	0.3-80 m
Micron DST Scanning Sonar	Distance	0.5 Hz[a]	-	2-75 m
Micron NAV USBL Transponder	Range/Bearing[b]	0.1-2 Hz	$\pm$0.2 m range, $\pm 3^\circ$ bearing	150-500 m
4 Bowtech LED800/1600 Underwater	Illumination	22 kHz PWM	255 steps dimmable	-
2 Prosilica GE1900C GigE-Cameras	Image	0-30 FPS	Full-HD (1920x1080)	-

[a]For 360° scan
[b]Relative to receiver

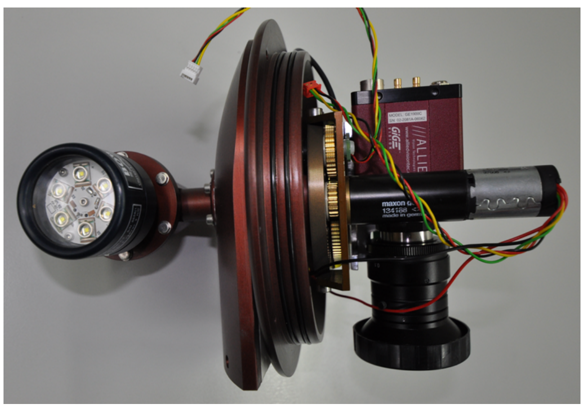

Fig. 6. Head mechanics with camera and power electronic holder.

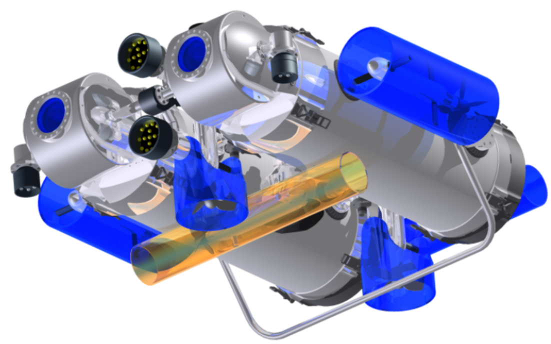

Fig. 7. CAD drawing of the final vehicle configuration.

of the tilt motors, a reflective encoder or an hall effect absolute encoder detects each of the heads positions. The absolute encoder is a IC-Haus sensor, and has a resolution of 0.1 degrees. The reflective encoder with a resolution of 0.3 degrees is an additional sensor for redundancy. This hight degree of precision is necessary to achieve high repeatability in camera head alignment. Since the two tilt units are independently driven, but mechanically connected by an aluminum bar, caution has to be taken during operation as to avoid damage to electronics or hardware. The motor and LED control are realized with in-house designed power electronics controlled via CAN communication.

V. Conclusion

The vehicle currently is under final electric assembly. The pressure hull was previously assembled and its water tightness proven in long-time submersion tests. After its final integration the first tests will focus on vehicle control and guidance, as well as sensor testing. As soon as the vehicle is deemed fully operational, the scientific measurements will commence. Target environments for this AUV are lakes and near-shore oceans. The vehicle described in this paper is the result of four years of experience with AUV systems and a year of design and construction efforts. Most of the design criteria could be completely fulfilled, some even surpassed. The resulting vehicle is very well instrumented for a vehicle of its size, and in this respect can very well compete against commercial systems like the IVER2 from OceanServer, the Gavia AUV, the Remus 100 from Hydroid or the Bluefin-9 from Bluefin Robotics. Of course a stereo camera system of this high quality cannot be found on any of these vehicles.

A. Future Work

A number of experiments are planned for the new AUV. As stated in the introduction, the main application for the vehicle is testing of new vision-based navigation algorithms while recording a ground-truth measurement with the rest of the sensors. Because no real vehicle data was available at this time,

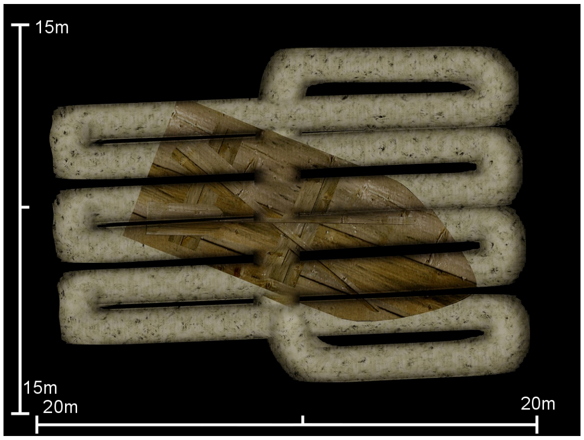

Fig. 8. Mosaic from 900 single images using synthetic data.

synthetic data was created using a 3D-Authoring program (3DSMax). Using this data the first versions of the algorithms were tested (for details see [5]). Using the trajectories given by the visual odometry approach a mosaic of the complete scene could be reconstructed, which is shown in figure 8. This mosaic consists of 900 single images which were re-projected in to 3D-space only using the trajectory information from the visual odometry, no stitching techniques were used. The next step will be to replicate such results using real data from the AUV.

Because of the tilting functionality of the camera head different camera angles can be investigated in order to find the most suitable configuration for visual mapping approaches. As an extreme case the camera head can be tilted completely up, facing the surface. This way under-ice / under ship surveys can be made without any lengthy reconfiguration of the vehicle.

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