# Design of a μAUV



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# Design of a $\mu$AUV

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**Summary.** This paper introduces the mechanical and electronic design and the programming of a very small autonomous underwater vehicle (AUV). The $\mu$AUV was used as a demonstrator for artificial intelligence approaches in underwater robotic applications on the 2007 CeBIT fair. In addition we present our first experimental results which provide insights in the special conditions which apply on very small underwater robot systems.

## 1 Introduction

Miniaturized underwater vehicles have a broad field of application. Besides being used as demonstrators of large expensive vehicles, they also apply to pipe and cavern inspection, enviromental monitoring or future space applications. The latter, e.g. exploring water on distant planets, requires not just small and lightweight autonomous underwater vehicles (AUV). Future vehicles also have to be able to take samples and analyse them in situ.

In recent years quite a number of small AUVs were developed for various types of applications. But vehicles like Maya [2], Serafina [3], Kambara [4] or SubjuGator [5] all have sizes of 40cm and above and do not experience the special problems which arise when size and weight of a vehicle is much smaller. In such a case effects like water surface tension or the formation of gas bubbles on the surface of the vehicle have a surprising impact on the movement capabilities.

In this paper we will describe the design and development of such a small autonomous underwater vehicle. Regarding the small size of the vehicle we refer to it as $\mu$AUV. We start with the description of the mechanical design and the electronic components. The programming is described afterwards and the paper concludes with first experimental results describing the aforementioned problems imposed by the small size of the vehicle and with an outlook on our future research.

## 2 Design

The main body of the $\mu$AUV has a cylindrical shape with a diameter of 55mm and a length of 125mm. Two horizontal thrusters, two vertical thrusters and one thruster for the lateral movements (s. fig. 1) are attached to the upper part of the vehicle. This arrangemant makes it possible to hover in any direction. The batteries are mounted outside in two tubes attached to the lower part of the vehicle providing a very low center of gravity. Thus resulting in a stable standing position while the vehicle is aquatic.

For such a small scale system the stability of the system heavily depends on the production accuracy. Small changes in the volume and/or weight of the $\mu$AUV can result in an unstable behaviour as the vehicle is precisely balanced between all components. For example, the thrust of the two vertical thrusters is lower than 3 gram. The speed forward is 0,1 m per second. To maintain the maneuverability of the vehicle, it is important to calibrate the mass accurately to the tenth of a gram with a small amount of buoyancy left. This buoyancy is necessary to bring the AUV back to the safe surface, if the battery voltage is low or the electrical system is damaged. The $\mu$AUV has to be completely incompressible for the operation depth, because otherwise the change in volume would result in a negative buoyancy much greater than the maximum thrust provided by the thrusters. Therefore, at a certain depth, the vehicle wouldn't be able to withstand the rising relative weight and start sinking.

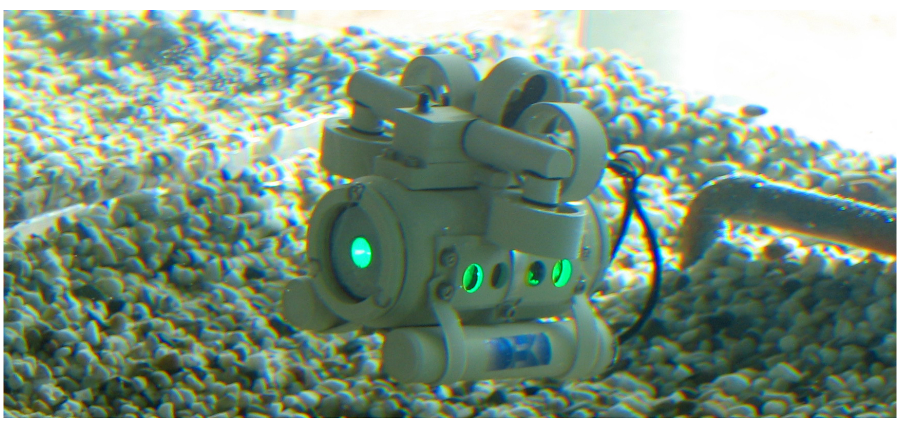

**Fig. 1.** The vehicle has a cylindrical body with a diameter of 55mm and a length of 125mm. It has five thruster to hover and externally mounted batteries providing a low center of gravity.

### 2.1 Mechanics

With respect to systems for edutainment or swarm robotics, the mechanics have to be functional and reproducible. The production and the material costs have to be small enough, so it is possible to make enough systems to provide several AUVs for different student groups. Furthermore the production has to be repeatable, as we make all components and assemblies in our own workshop on our turning and milling machines. We optimized the design to achieve a very short production time. Building a robot as an underwater vehicle requires a lot of special knowledge in materials and sealing. For the $\mu$AUV we use polypropylene with a density of 0.92 g/ cm$^3$. Thus the material itself has a positive buoyancy which is essential when building an underwater vehicle with such small dimensions. In addition, polypropylene has no hygroscopicity.

The small dimensions and the low production costs are of particular importance for projects dealing with swarm intelligence in underwater applications. By definition a robot swarm needs a high number of systems. The observability is significant for the evaluation of the experiments. Thus the environment has to have a relative small volume. But it is also necessary for the robots to have enough space for their experimental behaviour. The volume needed depends mainly on the robots dimensions. For the $\mu$AUV we built an aquarium (s. fig. 2) with the dimensions of $3\text{m} \times 1\text{m} \times 0.8\text{m}\,(L \times B \times H)$. The test environment for a whole swarm has to be much bigger depending on the number of the AUVs to be able to observe an intelligent swarm behavior. Using further minimized AUVs instead of a bigger enviroment is difficult, as normal production methods and the available sensors, engines and electronics are getting more and more restricted.

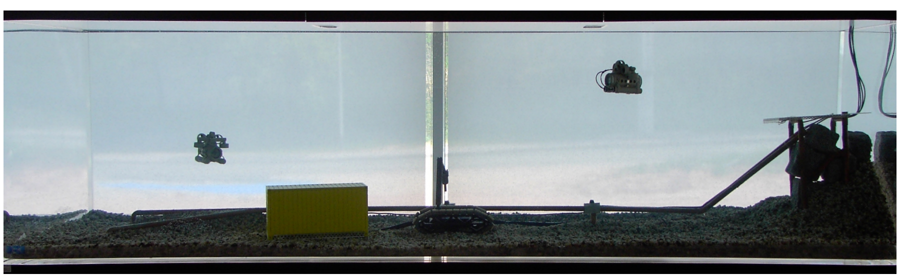

**Fig. 2.** Panoramic view of our aquarium with two of the $\mu$AUVs. The aquarium is $3\text{m} \times 1\text{m} \times 0.8\text{m}\,(L \times B \times H)$.

### 2.2 Electronics

Due to the size and weight constraints imposed by the dimensions of the vehicle the design of the $\mu$AUV electronics was a challenging task. The electronics of our $\mu$AUV consists of a main-board, eight sensor-boards and a pressure sensor directly integrated into the hull. The electricity supply is provided by four AA batteries with 2.7Ah providing electricity for up to 2.5h. The main-board is equipped with an Atmel ATMega128 microcontroller, two L298 dual full-bridge drivers and a ULN2803 darlington array. The eight sensor-boards are each equipped with a green SuperFlux LED by Lumileds Lighting and up to four RGB light sensors TCS230 by TAOS. The sensor-boards and the main-board are interconnected via an 8-wire bus. In addition a separate control wire for each TCS230 light sensor to the main-board exist (see Fig. 3). The pressure sensor is the MPX5100DP by Motorola and it is also directly connected to the main-board.

The ATMega128 is an 8-bit microcontroller with 128KB flash memory and 4KB SRAM. The chip generates the PWM signals for motor control, measures the 12 light sensors and the pressure sensor and controls the movements of the vehicle via a behaviour based approach. To coordinate these different tasks on the microcontroller a very lightweight non-preemptive scheduler was implemented. The scheduler is described in more detail in section 2.3. The two L298 dual full-bridge drivers are used to drive the DC motors in the thrusters of the vehicle. Each of the L298 provides a total current up to 4A. The ULN2803 darlington array is used to drive the LEDs on the sensor-boards with a total current of 400mA.

### 2.3 Software

As described in the previous section the microcontroller has to process a variety of parallel tasks. Some processes, e.g. the PWM generation, require to be executed in a high frequency, where other processes, e.g. the behaviour control, can be executed in a relative low frequency. For this reason we developed a small lightweight non-preemptive scheduler. The different tasks are organized in modules. As the scheduling is non-preemptive the modules should not occupy the CPU for a long time. Thus the task of a single module is implemented as a series of small steps. After each step the control is given back to the scheduler. Contrary to common non-preemptive schedulers the modules not only yield the processor from time to time, but also tell the scheduler when (in relative microseconds) they wish their next step to be executed. This additional data induces a time-driven scheduling scheme. The only task of the scheduler is to keep the list of the modules' next steps in order with respect to the relative starting times of the steps. If there is a collision between two modules the scheduler uses a first-come-first-serve approach to decide which module's step is executed next. Due to this, the timing between two steps of a module can diverge from the desired timing. In the worst case, a collision between $n$ steps, the divergence for a single step can be the sum of the execution times of the previous $n-1$ steps. In general however, if the microcontroller is not overloaded with to many tasks, collisions are very few. Normally the modules want their steps to be executed at regular intervals and thus the execution se-

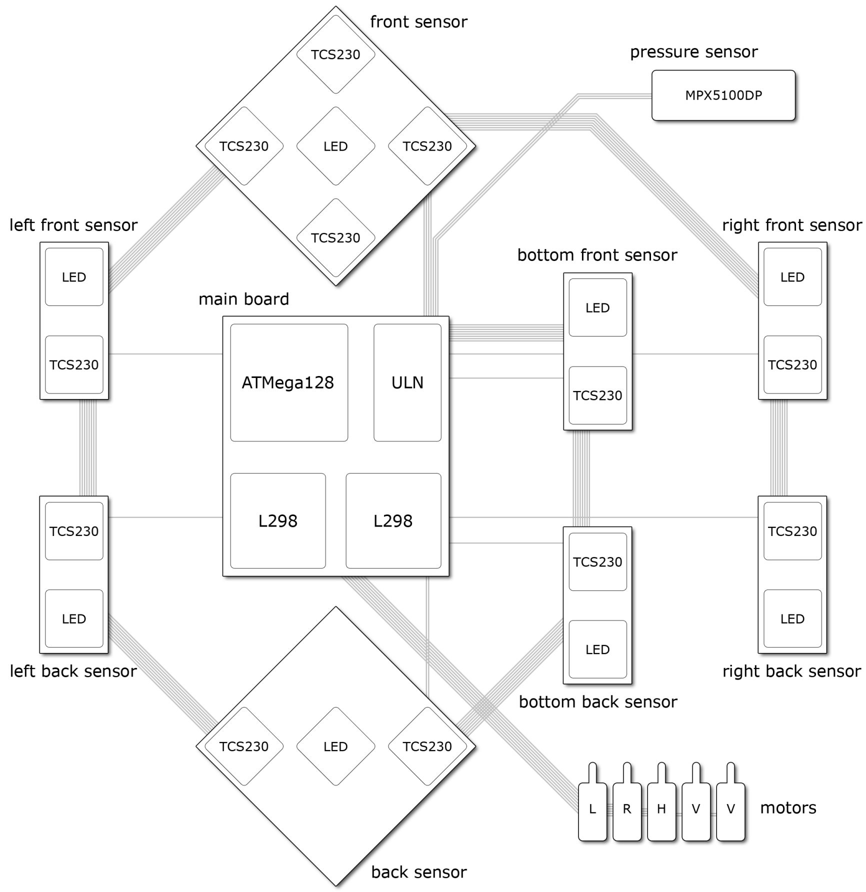


**Fig. 3.** Schematical overview of the main-board, the eight sensor-boards, the pressure sensor, the five motors and their interconnection.

quence resembles to a periodic function. Thereby a delay caused by a collision can be seen as a phase shift of this periodic function and after some initial collisions the different modules run out-of-phase practically without further collsions. This module arrangement emerges without any computational costs just from the structure of this non-preemptive scheduler.

The behaviour of the $\mu$AUV is modelled as a set of concurrent time-driven state-machines which can interact through global variables. These state machines can easily be mapped onto the structure required by the scheduler as each state machine is implemented as a seperate module with the single steps of the module representing the states of the particular state machine. For example, there are global variables which contain the requested values for the different thrusters. Every module that wishes to change the values for the thrusters can write the appropriate values into these variables. The values are then read by the motor control module and translated into the corresponding PWM signals sent to the L298. The actions of different modules, e.g. the depth control changing the values for the vertical thrusters and the collision avoidance control chaning the values for the left and right thrusters, are therefore blended into a single request which can be served by the motor control. The whole behaviour system is inspired by the behaviour network architecture presented in [6], scaled down to the resources available on a small microcontroller system.

## 3 Experimental Results

The development of the $\mu$AUV has shown, that the requirements of a minimized system must be exactly specified before the beginning of construction, as it is inevitable that all components have to be taken into consideration with respect to the buoyancy. For underwater vehicles volume and weight of the vehicle are in a direct and sensitive relation to the balance of the AUV in water. For example changing the material of a few screws from metal to plastic can change the aquatic behaviour of the vehicle in such a way that normal operations are barely possible anymore.

Due to the size constraints of the $\mu$AUV we use very small dc-motors with no reduction gears for the thrusters. Every dc-motor drives a water screw with a diameter of 30mm. Because of the lack of reduction gears the water screw runs with high revolutions per minute. This induces cavitation at the tips of the propeller blades and reduces the thrust. For this reason the next version of the $\mu$AUV will have reduction gears on the dc-motors.

The experiments with the $\mu$AUV have also shown some interesting unexpected effects, which we did not observe on bigger scaled ROVs, e.g. small class league (s. [1]). One of this effects is the influence of interfacial tension of water on the vehicle. When a major part of the vehicle has contact to the water surface, the relative small vertical thrusters cannot produce enough thrust to push the vehicle underwater. To solve this problem we rearranged the thrusters so that the lateral thruster is the highest point of the $\mu$AUV resulting in only a small part of the vehicle being exposed to the facial tension. Thus the force needed for leaving the water surface is not to high.

Another unexpected effect which has a big influence on this small system is the formation of gas bubbles at the vehicles surface. Due to the relative low speed of the $\mu$AUV the flow rate at the material surface is slow as well. This allows for the outgassing of gas which was in solution with the water before. The gas bubbles build up at points with high surface roughness and create a positive buoyancy. Is the buoyancy of this extra gas bubbles to high with respect to the force of the thrusters, the $\mu$AUV is forced up to the surface (s. fig. 4). In our experiments we measured that it needs less than 2 cubic centimeter of randomly distributed bubbles to take the $\mu$AUV to the surface.

Once at the surface, the facial tension hold the robot additionally to the bubbles. Not until the gas bubbles are removed manually the $\mu$AUV can't dive and complete it's mission.

The sealing of such a small system is more challenging than it seems at the first glance. For a good weight- and volume ratio plastics was chosen. Thereby the produced material surfaces have not a precise surface finish. As the pressure in shallow water is to low for a pressure based sealing, screws build up a preliminary tension. The surface finish of the seal face have capillary. This leads to infiltration of water. Since a differential pressure sensor is used, a small amount of water is enough to balance the pressure between inside and outside the vehicle. Thereby the vehicle dives deeper, because the robot assumes the vehicle is at a lower depth than it actually is. In a small testbed with shallow water fluctuation in barometric pressure also causes the $\mu$AUV steering to the wrong depth. The barometric pressure has to be measured continuously to solve this problem. As this is rather complicated being underwater we solved this problem by periodic surfacing and recalibrating the pressure sensor.

At the moment by virtue of the relative small thrust available the $\mu$AUV is extreme susceptible to any form of current. Only in still water it is advisable to use the $\mu$AUV. With further miniaturisation there are more effects to study. The water temperature and the salinity influence the water density. Underwater vehicles without a ballast tank have problems to compensate this density change. The propulsion must be studied. Propellers with blades of a diameter less than 20mm seem ineffective. Maybe there are other concepts for minimized AUV's, e.g. jet or fin based propulsion.

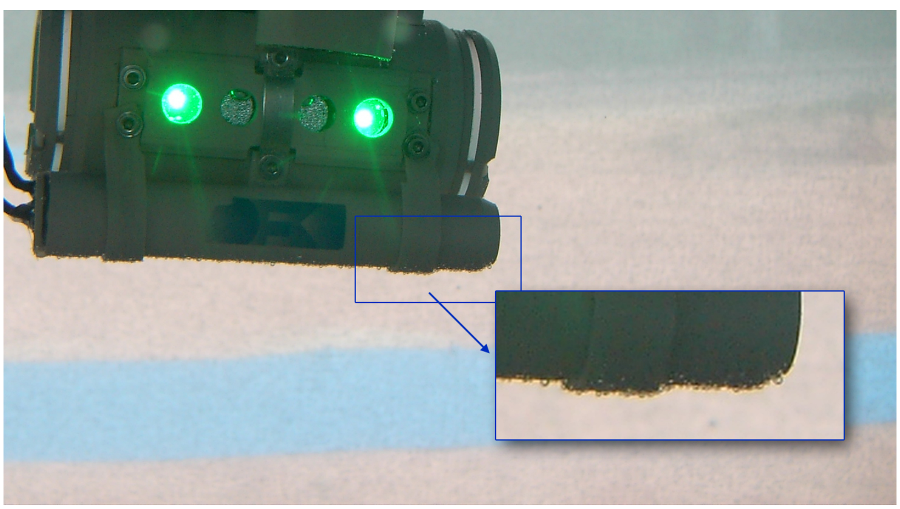

**Fig. 4.** Outgassing at points with high surface roughness of gas which was in solution before building up a buoyancy.

## 4 Conclusions and Outlook

The $\mu$AUV project has successfully proven the ability to build a small-scale full autonomous underwater robot, which sustained hours of operation during this years CeBIT fair.

Further miniaturization of the $\mu$AUV will enhance the effects of surface tension and the outgassing of bubbles. It has to be assured, that the system won't touch the surface or when touching the surface, that the area in contact with the surface is as small as possible. Another possibility to reduce the effects of surface tension would be the to use hydrophobic materials. In some restricted cases, e.g. the demonstration scenario we used the $\mu$AUVs in, it would also be possible to use detergences to lower the surface tension. Regarding the formation of gas bubbles, the surface of a smaller vehicle has to have a very precise finish to prohibit the outgassing. As a first technical soltution we currently try to use a small vibration motor which is attached to the $\mu$AUVs rigid body. The vibration of this motor should remove the bubbles in an early stage of formation.

In parallel to further investigation of much smaller underwater systems which will provide insight on how far miniaturisation is sensible with the current state of the art system components we will build a slightly bigger AUV, equipped with a camera and a more powerful proccessor to use computer vision approaches for navigation and obstacle avoidance and docking. Further projects will deal with the implementation of different approaches of underwater swarm robotics in a man handable environment.

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