MONSUN II: A small and inexpensive AUV for underwater swarms

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Abstract

This paper presents the design and hardware architecture of the small and inexpensive AUV MONSUN II for use in a swarm. Due to the high number of robots in a swarm, this approach can profit from the parallelization of tasks and its fault-tolerance based on redundancy. This allows the design of small and inexpensive AUVs for applications such as environmental monitoring. First experiments of a simple following behaviour were performed to show the suitability of the system design.

Keywords-autonomous underwater vehicle, swarm
Area: Mobile robots / underwater robotics

1 Introduction

The quality of waterbodies and the associated proof is part of a framework the European Union (EU) has established for the protection of inshore and coastal waters in 2000 [1]. The survey of the waterbodies can be done by boats, remotely operated vehicles (ROVs), static sensor networks or with the aid of divers. All these approaches have the disadvantage of either a high manpower requirement or stationary measurements only. Here autonomous underwater vehicles (AUVs) can save costs by reducing the workforce as well as dynamically survey environments due to their mobility. In [2] the small AUV *REMUS* is introduced that has been developed for e.g. coastal monitoring and environmental sampling. One design goal was to limit the vehicles size and weight to make it manageable for a single person. REMUS has length of 135 cm with a body diameter of 19 cm and weight of 31 kg. However, single AUVs are very expensive and require a long time to scan a large area. Small failures may even prevent the achievement of the whole task. To avoid these disadvantages a large coordinated swarm of inexpensive AUVs could be deployed. A swarm approach benefits both by parallelism of execution and the inherent redundancy given by the usage of multiple members and the concomitant fault-tolerance even in case of a damage of an AUV. The design of an AUV for swarms differs massively from a traditional AUV design. Doringo and Şahin present in [3] four criteria for measuring the grade when to regard a multi-robot system as a swarm:

1. The approach should consider the coordination of a large number of robots including the objective of scalability.
2. The swarm should be homogeneous, possible with the exception of a very few heterogeneous members, since high redundancy is required for the swarm.
3. The performance of the task should significantly be improved by the swarm solution compared to a single robot.
4. The robots should only have local and limited sensing and communication capabilities.

Furthermore ongoing technological achievements in MEMS and nanotechnology as well as other technological enhancements in swarm robotics advance the miniaturisation [6]. The main challenges of those swarms concern the control aspects. Due to the miniaturisation only a low complexity of the controller is required yet simple rules at the individual level can lead to an emergent complex global behaviour by numerous locally interacting members.
In conclusion, redundancy, emergence, robustness, locality, flexibility and decentralisation can be considered as the main characteristics of a robotic swarm.
There are only very few projects that address AUV swarms. The aim of the Serafina project [4] was to build a swarm of small AUVs that allows fault-tolerant and a scalable coverage. Localisation is realised both by active and passive localisation of single swarm members with respect to the neighbourhood and the whole group with respect to the environment. The communication among swarm members is done by dynamic communication and routing protocols that adept the actual knowledge of the 3D position of individual members. Unfortunately this project was discontinued since 2009. Another AUV swarm project is introduced in [5]. The focus of the CoCoRo project is not the development of hardware but of algorithms for generating cognition and self-awareness in a self-organised and decentralised way. The swarm members shall have a size of approx. 20 - 30 cm equipped with numerous on-board sensors for distance and pressure measurement and position estimation.
This paper presents the small and inexpensive AUV MONSUN II designed for operating in a swarm, and shows experimental results of simple following behaviour. The remainder of this paper is structured as follows. Section 2

provides an overview of the vehicle and the used hardware whereas section 3 describes the results of the experiments of a following behaviour of several AUVs. Section 5 presents the conclusion of the design and a short outlook of future work is given in section 6.

2 Vehicle Overview

MONSUN II is the second generation of our MONSUN project introduced in [7]. Different disadvantages of the design of MONSUN I like e.g. the propulsion that allows only dynamically diving or the sparse modularity and extensibility were improved. The objective of the new hardware design was to enhance the maneuverability and modularity of MONSUN. MONSUN has a length of 60 cm and a hull diamter of 10 cm. With its four vertically mounted motors MONSUN is able both to correct its posture even in breakdown of a thruster and to adopt any angle in yaw and pitch direction. In combination with the two horizontically mounted thrusters it has five degrees of freedom. As mentioned in section 1, robots designed for use in a swarm do not need sensors for wide ranges due to the high number of locally interacting members.

2.1 Mechanical and Electrical System

MONSUN is fully actuated with six thrusters that allow forward and vertical moving as well as yaw, pitch and roll rotations (see **Figure 1**). One motor is mounted vertically in each of the four fins while two additional motors are mounted horizontally at the rear end of the front fins so that the vertical axis of rotation is in the centre of the robot and to allow the robot to turn on a spot.

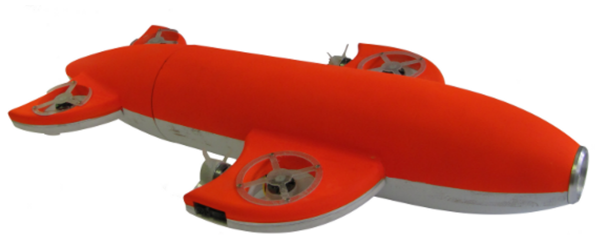

Figure 1: The small AUV MONSUN II with a length of 60 cm, diameter of the hull of 10 cm and a weight of 4.2 kg.

The hull of MONSUN is made of glass fibre reinforced plastic (GRP) and acts as a complete pressure housing for the electronic parts. It consists of two parts that are connected by a bayonet closure. The motors and lateral sensors are connected by waterproof waterproof connectors in the fins. The bottom half of the fins can be disassembled to remove or exchange a motor or a sensor. The hull and the bayonet closure are rated to a depth of 10 m.

The AUV can be switched on and off from outside by a magnetic switch. The motors are powered by a 11.1 V, 10 Ah lithium polymer accumulator allowing a mission time up to ten hours. The controller and sensors are powered separately by a 7.4 V, 3 Ah lithium polymer accumulator and 5 V and 3.3 V voltage transformers. The separate energy supply was chosen to reduce the influence of voltage peaks by the motors and to reduce the energy loss of the voltage converters that results in a higher temperature. The accumulators have to be charged outside the AUV. Hence they are located at the rear end of the front part and can be exchanged rapidly. The complexity when using lithium polymer accumulators is that batteries can be damaged if voltage drops below approx. 3.0 V per cell. To prevent this, each accumulator is equipped with a protection circuit that monitors the voltage of the cells. In case of a low voltage all motors can be stopped and MONSUN will surface due to its positive buoyancy.
To achieve a high modularity, compatibility and expandability of sensors and the CPU, a bus based architecture was chosen (see **Figure 2**). This board provides both several voltages for the power supply of boards and data buses like I2C or SPI with different voltage levels (3.3 V and 5 V). Each sensor or controller board can be plugged on an arbitrary socket. The only exceptions are the motor controller board, as the motors are connected to the controller by sockets at a specific position in the hull and the corresponding plugs on the motor controller board, and the camera module that has to be placed at the front of the AUV.

Motors and controller Because of the small size of the robot and to avoid shaft feedthrough we dispense of normal brushed motors in waterproof housings. Therefore brushless motors that were laminated to shelter the metal and magnets from rust and to avoid a short circuit among the phases were used. To fit in the small height of the fins the propellers are not fixed on the shaft but directly mounted on the rotor. This leads to a complete height of just 21 mm. Each motor is driven by a separate controller that is addressed by the I2C bus. The controllers are able to measure the power consumption of the motor and to set an upper limit for a short-period as well as a mean power consumption for the motor in case of e.g. low batteries or to prevent to whirl up the ground. The key features of MONSUN II are summarised in **Table 2.1**)

Table 1: Vehicle overview

Dimension	60x10x30 cm (lxhxw)
Weight	4.2 kg
max. depth	10 m
max. speed	2 m/s
Power	110W (motors) 22.2W (controller & sensor)

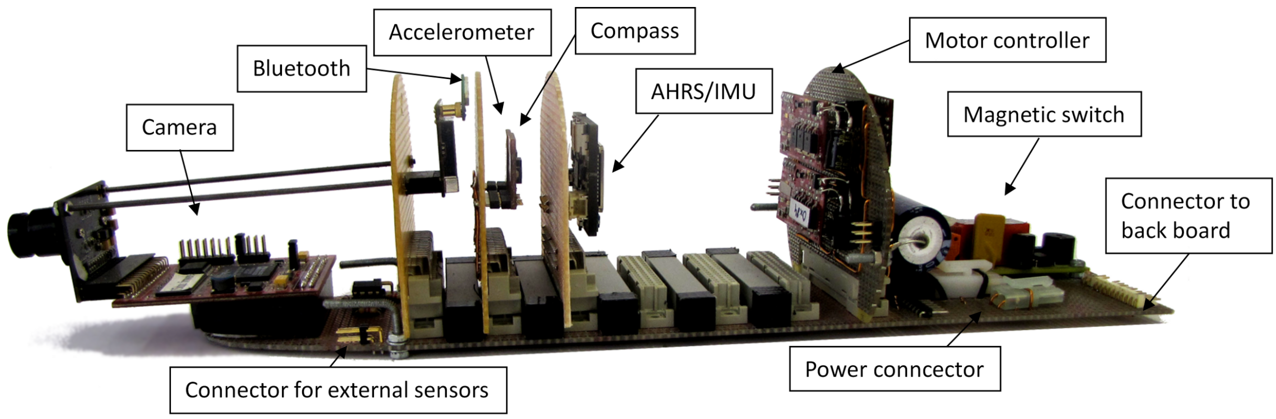

Figure 2: MONSUN bus board with racked sensor boards. This design was chosen because of the modularity, compatibility and expandability of the components. With the exception of the motor controller board the sensor boards can be plugged into an arbitrary socket.

2.2 CPU and Sensors

Camera and CPU The selection of an appropriate processing unit is a challenging task not only because of the evaluation of the required computing power but of the small form factor given by the modular design of MONSUN, the power consumption and the heat generation. Thus processors that need an active cooling can not be used due to the high generation of heat. Common used PC modules such as a PC/104 [8] with e.g. a 800 MHz Vortex86DX and a power consumption of 2.5 W or the BeagleBoard with an ARM Cortex-A8 CPU clocked at 600 MHz and a power consumption of 2 W offer enough computing power but can not be integrated because of their oversized dimensions. To reduce the complexity of the system it would also be preferable to have a direct connection to the camera module. An example of a small form factor module that could both control the AUV and process images from the connected CMOS camera sensor module is the CMUCAM3 with a maximum resolution of 352x288 pixel. For a blob tracking with the CMUCAM3 on full scale resolution only 4 fps are to be expected. A reduction to 176 x 90 pixels can reduce the processing time to output images with 26 fps. Due to the low computation power of the processor and the low resolution of the camera the CMUCAM3 is not appropriate for this application. For MONSUN we decided to use the Surveyor SRV-1 Blackfin camera [10] that is equipped with an 500 MHz Analog Devices Blackfin Processor and a 1.3 megapixel sensor that allows a resolution range from 160x128 to 1280x1024 pixel with 7.5 to 60 fps depending on the selected resolution. The firmware of the SRV-1 already includes basic image processing algorithms like histogram, frame difference and blob detection as well as a direct control of I2C and SPI devices. The software can be transmitted to the SRV-1 by the XMODEM protocol for reliable file transfer via a serial interface.

Communication An external communication with the camera can be established by the serial interface. Therefore, either a serial cable, connected at the backside of MONSUN or the implemented class 1 bluetooth module in case of diving at the surface can be used. The speed of the serial interface is set to 256 kbps to allow both a fast programming and transmission of the images from the camera module as well as sensor information.

AHRS/IMU To control the orientation, pitch and roll of MONSUN, it is equipped with the x-IMU Attitude and Heading Refence System (AHRS) and Inertial Measurement Unit (IMU) of the company x-io [11]. The module comes with a temperature compensated triple axis gyroscope, a triple axis accelerometer and a triple axis magnometer. While the algorithms of the x-IMU provide realtime measurement of orientation relative to earth with an update rate of 512 Hz, the module outputs its sensor and algorithms data automatically and continuously at a selectable bandwidth between 1 and 512 Hz. Since we currently apply only the posture of the robot we have chosen an output rate of 16 Hz. To reduce the communication load of the serial interface and to prevent collisions between IMU data and control signals to the camera we interconnected a microcontroller between the IMU and the camera. This microcontroller receives the output data from the x-IMU, computes the e.g. euler angles of the AUV and provides the data in registers as an I2C-Slave.

Pressure and Temperature For the accurate determination of the diving depth a precision temperature compensated pressure sensor is integrated. It has a resolution of 1.2 mbar and can be sampled at a maximum of 28 Hz (without temperature compensation). As with the AHRS/IMU an interconnected microcontroller is responsible to get the latest pressure and temperature value from the sensor and to compute the actual depth. In order to prevent the reading of obsolete data in case of a malfunction, an additional register indicates a new pressure value and if this value has been sent once already.

Lateral avoidance sensor To avoid collisions with lateral obstacles like walls or other swarm members infrared distance sensors are integrated in the front fins. The range of the measurable distance decreases due to the decay of the infrared light in water from around 80 cm to only 30 cm that is still enough to detect obstacles in time. The analog output of the sensor is converted by an analog-to-digital converter that was integrated on the reverse side of the IR sensor to keep the noise from the motors as low as possible.

3 Software Architecture

The software architecture of MONSUN was designed to be modular and hierarchically organised (see **Figure 3**).

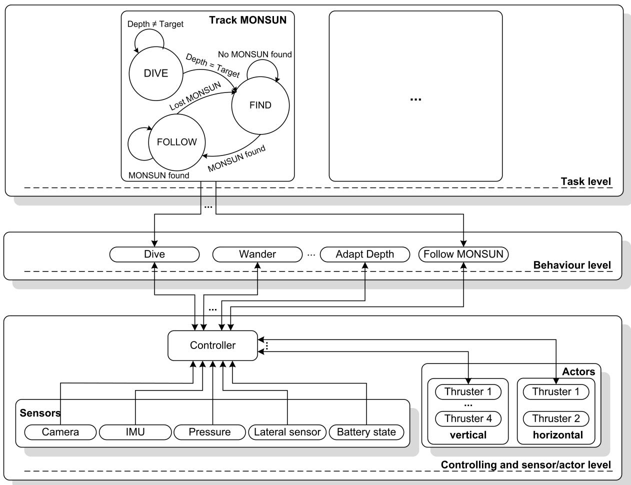

Figure 3: The software architecture of MONSUN. Tasks are organised as state machines that use provided behaviours. The behaviours control the depth, speed and orientation based on the corresponding sensor information.

It can be divided into three level: the *controlling and sensor/actor level*, the *behaviour level* and the *task level*. At the controlling and sensor/actor level the controller requests the required data from one or multiple sensors and adjusts the speed of the horizontal and vertical motors. The parameters (e.g. the target depth or the orientation) are passed by the current running behaviour. The controller gives a feedback to the behaviour to indicate the current state like if the target depth has been reached or a sensor readout failed. The tasks are organised as simple finite state machine (FSM). Depending on the feedback of the current behaviour the FSM can change to the next scheduled state or to a special state to handle faults. Currently, tasks have to be written in the program code that requires a compiling of the firmware on the host PC and a transmitting to the memory of the camera afterwards to adapt parameter or states of the tasks. The flashing is done either by a serial cable or bluetooth and takes only a few seconds. Tasks can be started in variant predetermined ways: by a start signal via serial interface, when switching on the robot, after a defined period or when the robot is dunked in the water.

4 Experiments and results

First experiments to evaluate the performance of the vehicle has been conducted. The responding characteristics of the vertically mounted thrusters is shown in **Figure 4**.

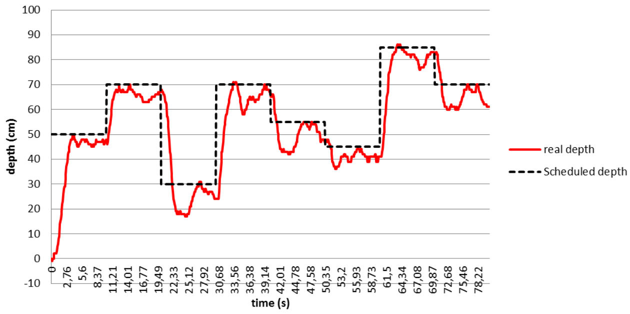

Figure 4: The Adapting (solid line) of several given depths (dotted line) changing every ten seconds.

Starting at the surface a sequence of depths were given. The target depth changed every 10 seconds and the maximum speed of the motors was limited to 20% since a smooth start of the motors is not yet implemented. It can be seen that the motors have a good response. MONSUN needs about three seconds to reach the first depth of 50 cm. The slight overshoot in one directions is attributable to the fact that MONSUN has a positive buoyancy and is starting to emerge when motors are stopped. Since brushless motors are designed for high rotary speeds the torsional moment is to low to overcome magnetic field. Thus a minimum speed was defined to guarantee to start of the motor. The experimental results of a simple following behaviour with its corresponding controller are presented below (see **Figure 5**).
The camera is performing a blob detection of orange colored blobs of MONSUN. Once a second MONSUN is detected in the field of vision, blob coordinates are computed. Given the bottom edge of the bounding box, that is the horizontal centre of MONSUN, the difference between this line and the half of the height of the image is computed to appropriate the new target depth corresponding to the actual depth. To follow the ahead MONSUN, the displacement in horizontal direction is computed by the difference of half of the image width and the horizontal centre of the

blob. To keep a defined spacing between the two AUVs, the relation of the height and the width of the blob gives some indications about the posture. If the posture of the following MONSUN is orthogonal to the posture of the MONSUN ahead, the ratio $(x_2 - x_1)/(y_2 - y_1)$ will reach its maximum. In case that the second MONSUN is accurately behind the first one the ratio will reach its minimum. Combined with dimensions of the blob that provide the information about the distance and the bearing information from the IMU, these data are given to the controller to set the new values for the motor control.

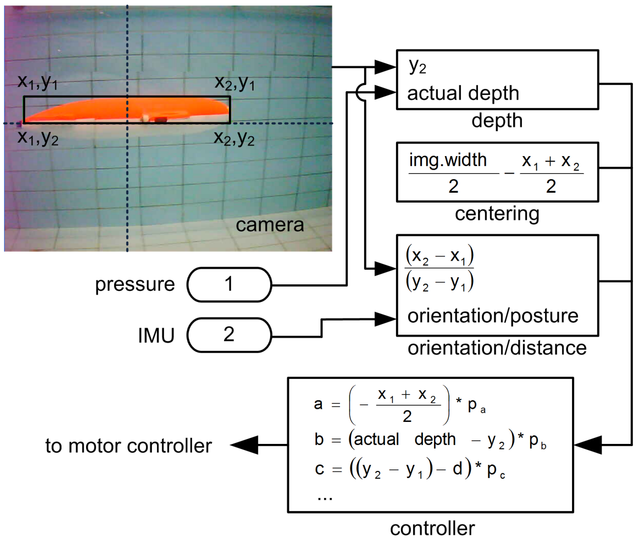

Figure 5: The controller for a simple follow behaviour. The blob information of a leading MONSUN and the information of the pressure sensor and IMU are used to adopt its depth, posture and speed in order to achieve a line formation.

The tests were run in a pool with a size of 3.6 x 5.5 m and a depth of 1.5 m with two MONSUNs. The AUVs were randomly positioned and launched by bluetooth communication. Starting at the surface the robot detected its own reflection at the water surface and tried to center this reflectance in horizontal position by submerging. To avoid this reaction, the following behaviour was first activated after getting to an initial depth of 50 cm. Running at 25 % of the maximum speed, MONSUN needs less than 2 s to reach that depth.
The AUVs were programmed to wander around until they detect a MONSUN ahead and consequently start the following behaviour. Running at a camera resolution of 160x120 pixel the detection of the leading MONSUN was stable up to three meters. With an update rate of around 25 Hz the image processing is fast enough for an accurate adjusting of the depth and orientation. Since the algorithm can not distinguish between the rear and the front of the AUV, the following behaviour results in a clustering when starting face to face. This behaviour also eventuated when the ahead diving AUV reverses due to an edge of the pool. Once the AUV started the following behaviour already in a line or an appropriate position, good results were achieved.

5 Conclusion

In this paper we presented the AUV MONSUN II that has been designed for application in a robotic swarm. Following the definition and the requirements of swarm robots, MONSUN is equipped with sensors that allow mainly limited range sensing like the camera or the lateral avoidance sensor. This results in an inexpensive vehicle since costly sensors as e.g. a doppler velocity log are not required. The small size makes it even applicable in environments that are difficult to access. Preliminary experiments have shown that MONSUN is capable of manoeuvring and diving even in case of malfunction of a vertical thruster. The built-in camera allows the detection of other swarm members and thus a simple following behaviour of several robots by following the robot ahead.

6 Future Work

The design and the construction of MONSUN II is only the first step towards an applicable swarm robot. Next we have to include our underwater acoustic modem presented in [12] to establish a direct communication between members. This allows collaboration of the robots and formations without the need of having a neighbour in the field of view. Furthermore communication and distance estimation by measuring the signal propagation delay of a message can be used to detect e.g. a disfunction in the IMU. A calorimetric 2D flow sensor mounted on the bottom of MONSUN will provide the relative speed in case of moving but can also be used to measure the flow speed in case of standing still. To detect obstacles in front of the AUV a green line laser will be integrated upon the camera. Implementing the laser light section MONSUN is able to detect barriers in front of the AUV and to avoid these.
Quantitative analysis will be presented in the final version of this paper to validate the presented approaches.

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