MONSUN II - Towards Autonomous Underwater Swarms for Environmental Monitoring

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Abstract—**This paper presents the small and inexpensive autonomous underwater vehicle (AUV) MONSUN II that was designed to operate in a swarm. Particularly in the field of environmental monitoring a swarm based approach could increase the efficiency of the task by parallelization, the inherent redundancy and the fault-tolerance of a swarm. First preliminary results of the hardware and software are given to show the suitability of the system design. Basic approaches concerning the communication and localisation are presented to achieve an effective cooperative behaviour and to maximise the mission time for long time observations.**

I. INTRODUCTION

The survey of waterbodies to prove the quality of water and flora, the examination of pipelines or the surveillance of underwater wind farms are still challenging tasks. The most common techniques nowadays are the deployment of boats, static sensor networks, remotely operated vehicles (ROVs) and human divers. While sensor networks are rather appropriate for long time measurements of an environment, boats, ROVs and divers allow shorter term surveys at different places. Yet, the employment of these techniques require a high amount of manpower and are not suitable in some places due to the cable of the ROV or the dimensions of the boat in rough terrains. In addition, the operation in unknown environments can involve unforeseeable endangerments for a diver e.g. when investigating a shipwreck. Here autonomous underwater vehicles (AUVs) can save costs by reducing the workforce and can be employed even in hard-to-reach areas.

In [1] the AUV REMUS is introduced that has been developed for surveys in coastal environments for up to 12 hours. With a length of 135 cm and a weight of 31 kg it is manageable for a single person. However, single AUVs are very expensive and need a long period for the scanning of a large area. Even a small malfunction in the system can result in a failure of the whole mission and may result in the loss of the AUV in the worst case. The employment of several AUVs could decrease the attended time yet would result in very high costs. An alternative is the alignment with nature and hence the deployment of a swarm of multiple low-cost AUVs. The design of an AUV for swarm application differs massively from conventional AUV design. Due to the emergent behaviour of a swarm, a single swarm member does not need high-precision and long-range sensors and thereby can save costs. In [2] four necessary parameters are given to term a multi-robot system as a swarm. First the system should be scaleable and not restricted to a maximum number of members. Secondly, the system should (mainly) consist of homogeneous robots, possible with the exception of a very few heterogeneous ones, due to the high redundancy that is required for a swarm. Thirdly, the deployment of a swarm should significantly improve the performance of the task against a single robot. Fourthly, since global knowledge and communication is hard to scale with the number of robots, only local and limited sensing as well as communication can be applied. Environmental monitoring particularly benefits from the deployment of a swarm due to its parallelism of task execution and the inherent redundancy as a consequence of the multiple members. Even in case of a damage of a single or several members the swarm can proceed with its task.

Only very few projects address the field of underwater robot swarms. In [3], the CoCoRo swarm is introduced that has several heterogeneous members as floating base stations that act as global positioning and human interface to the swarm. The swarm itself is divided into two groups. The first group, the 'ground swarm' performs the task while the 'relay swarm' joins a chain between the ground swarm and the base station. Another project, called Serafina, is presented in [4]. The objective was to develop a fault-tolerant swarm of small AUVs with scalable amount, localisation of the members with respect to their neighbourhood as well as dynamic communication based on dynamic routing protocols. Unfortunately this project has ended in 2009.

This paper introduces the AUV MONSUN II [5] that was designed for the operation in a swarm and presents preliminary results of first tests and gives a prospect of capabilities to achieve a localisation in the swarm, effective cooperative behaviours and energy load balancing for long time operations. The Serafina project addresses only relative localisation in the swarm, we want to combine absolute and relative localisation for optimal covering of the surveyed area. In contrast to CoCoRo the swarm will consist of homogeneous robots that can change their role in the group. Thus one member can emerge and act as a base station while another floating robot takes its position in the underwater group. The remainder of this paper is structured as follows. Section 2 describes the hardware as well as the software architecture of the AUV MONSUN II. Preliminary results of first tests of the robot and a collective behaviour are given in section 3. Section 4 addresses the problems of communication and a feasible solution. Basic approaches for localisation and energy load balancing in the swarm are presented in section 5. A conclusion of the work and the conceptions in given in section 6.

II. MONSUN II

The overall goal of MONSUN II (see **Figure 1**) was to design a small and inexpensive AUV with high modularity and maneuverability. It has a length of 60 cm, a diameter of 10 cm and a weight of approx. 4 kg. Four vertically and two horizontally mounted motors allow the dynamic diving and rotations around the roll and pitch axis to compensate the pose in rough water as well as the yaw angle of the robot (5 DOF).

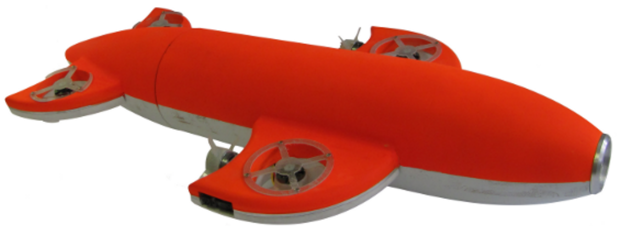

Fig. 1. The small AUV MONSUN II with a length of 60 cm, diameter of the hull of 10 cm and a weight of approx. 4 kg.

A. Hardware Architecture

The hull that acts as a pressure housing for up to 10 m is made of glass fibre reinforced plastic (GRP) and consists of two parts that are connected by a bayonet closure. Waterproof connectors for the motors and lateral sensors allow a quick exchange of the external components in case of a damage. The vertically mounted motors are located in each of the four fins and the horizontally mounted motors are located at the backside of the front fins in the center of the robot. The brushless motors are coated to prevent short circuit and shelter the metal and magnets from rust. The propellers are directly mounted on the rotor to achieve a height of just 21 mm. The electronic components can be switched on and off from outside the AUV by a magnetic switch inside the hull. A separate power supply for the motors and the controller and sensors allow mission times up to 10 hours with smooth diving. The batteries have to be charged outside the AUV and are located at the rear end of the front part to be exchanged quickly. In order to prevent damages to the batteries, each one is protected by a device to avert deep discharge. In this case the motors would stop and MONSUN would emerge due to its positive buoyancy.

In order to allow the exchange or to extend the internal electronic parts like sensors and controller, a bus based architecture of the hardware platform was chosen. This allows to plug sensor/controller boards to arbitrary sockets. The bus-board provides several voltages for the motors and the electronics as well as buses or serial interfaces. MONSUN is equipped with a camera in front of the AUV with a resolution range from 160x128 to 1280x1024 pixel. It has a 500 MHz Analog Devices Blackfin procecssor and is able to process images with 7.5 to 60 fps depending on the selected resolution. In addition to the integrated basic image processing algorithms like blob detection and frame difference the built in I^2C and SPI drivers of the camera module allow the complete control of the AUV. The external communication of the camera module to receive or send data, or to load a new firmware is done by a serial interface. If MONSUN is close to the surface this can be done by bluetooth, or in case of underwater operation by a serial cable, connected at the backside of the AUV.

To avoid lateral collisions with other swarm members or obstacles MONSUN includes two infrared distance sensors that are integrated in the front fins. Due to the absorption loss of infrared light in water and the refraction caused by the change of the medium the range is reduced to 30 cm that is still enough to avoid obstacles in time. The actual depth of MONSUN is measured by a precise temperature compensated pressure sensor that can achieve a resolution of 1.2 cm with a maximum sample rate of 15 Hz. The sensor is interconnected with a microcontroller that computes the actual depth based on the readout pressure and temperature and filters the data to reduce noise. Furthermore the controller ensures that the main controller is notified in case of a malfunction of the sensor. To control the orientation of MONSUN and to compensate an imbalance caused by drifts, the Attitude and Heading Reference System (AHRS) and Inertial Measurement Unit (IMU) x-IMU of the company x-io is integrated [6]. This module provides realtime measurements of the orientation with a maximum update rate of 512 Hz. To reduce load to the system, the output rate can be adapted to a rate between 1 and 512 Hz. For MONSUN an output rate of 16 Hz was chosen. Since the x-IMU outputs data by serial connection, an interconnected microcontroller receives the data, computes the e.g. euler angles and provides the resulting orientation in registers as an I^2C slave.

B. Software Architecture

Like the hardware of a swarm robot, the software can be kept very elementary. **Figure 2** shows the structure of the software architecture.

Tasks can be programmed as simple finite state machines that can change their state by the feedback of the underlying behaviours. These behaviours, like dive, wander or adapt depth to another MONSUN pass their parameters to the controller that requests the required data from the sensors and adjust the speed of the motors depending on the computation of the controller. The controller gives a feedback of the achievement of the target to the top behaviour. The tasks can either be started by a signal via the serial interface, at a predefined time after switching on the robot or by dunking the robot in the water. The tasks have to be written as program code and can not be modified during runtime. As mentioned before, the programming of the firmware can be done by a wireless or a cable connection via serial interface and takes only a few seconds.

III. PRELIMINARY RESULTS

First experiments were performed to evaluate the diving capability of the robot. Starting at the surface, the target

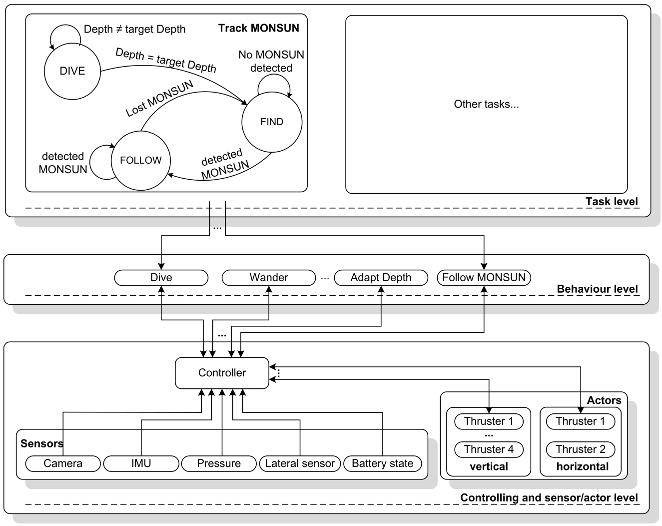

Fig. 2. The software architecture of MONSUN. Tasks are organised as state machines that call implemented behaviours. The behaviours control the depth, speed and orientation based on the corresponding sensor information.

depth was changed every 10 seconds (see **Figure 3**). The maximum motor speed was capped at 20% of the maximum speed to reduce high currents during the submerging. Due to its positive boyance that guarantees an emerging in case of a failure, several overshots can be noticed when the target depth is reached and the motors are stopped. Furthermore, brushless motors are mainly designed for high rotation speeds and require a certain rate to overcome the magnetic field. Once this speed is passed the motor starts.

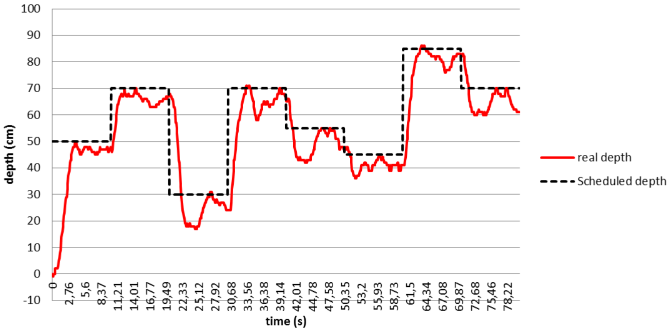

Fig. 3. The adapting (solid line) of several given depths (dotted line) changing every ten seconds.

Further tests with two MONSUNs have been completed. The objective of these tests was a simple camera based follow behaviour of two MONSUNs as shown in **Figure 2**. As MONSUN may detect its own reflection at the surface the a blob detection to find another MONSUN starts when reaching a predefined depth. While no other robot is in the field of vision, it wanders around avoiding walls and obstacles. If a second AUV enters the visual range, the AUV tries to follow the leading MONSUN by computing the target orientation and depth. While the distance is determined by the height of the blob, the orientation can be computed by the ratio of height and width of the blob that provides information about the heading of the leading robot. The results showed that the detection of other robots worked well and, starting in line, a simple follow behaviour is realised. Starting in random positions leads sometimes to a clustering since the algorithm can not distinguish between another robots front and back. Therefor further distinguishing marks have to be applied.

IV. COMMUNICATION

The current state of MONSUN allows only a loose linkage between the robots. This means that they can acknowledge each other but act independently. But for effective cooperative behaviours robots have to communicate with other robots. A distinction is made between *implicit* and *explicit* communication [7]. The implicit communication means a modifying of the environment that can be determined by other robots (like pheromones in the nature). In the area of environmental monitoring this of course can not be applied. In contrast explicit communication means the direct passing of a message from one robot to one or multiple robots. Due to the special characteristics of the medium water, underwater communication is a challenging task. The absorption of high-frequency electromagnetic waves prevents the application of wifi or bluetooth. Therefore acoustic communication is the most common communication technique in the field of underwater robots. Commercial modems are often designed for long range communication and thus need a lot of energy and space. Such modems are unsuitable for integration in MONSUN because of their size and weight and also the wide communication range. In [8] we presented a small acoustic modem that is appropriate for underwater swarm. This modem can adapt its output power to decrease or to extend the range for up to 50 m. This allows a sparse as well as a close distribution of the robots. The communication bandwidth is small due to the low frequency range. Nevertheless the bandwidth is sufficient for short status messages. Our next step will be to implement this modem in MONSUN to enable a cooperation of the AUVs.

V. LOCALIATION

In addition to the communication between the robots, localisation and positioning are the key functions of effective cooperation. Only knowing that there are local neighbours but not having information about their position leads to a non optimal distribution. The robots do not have to know their absolute position but the relative position by meaning of the distance to their neighbours. As mentioned in the communication section, electromagnetic waves are very intensively absorbed. Insofar localisation by GPS under the surface is not possible. The usage of scanning sonars and doppler velocity logs (DVL) could help to get the actual position of the AUV but would massively increase costs. To address the problem of the localisation our idea is to let some AUVs equipped with a GPS-receiver remain at the surface (see **Figure 4**). This allows a communication with the swarm on the one hand, and an absolute position of the surfaced AUVs on the other hand. The underwater swarm members must only be able to measure the distance between each other. This can be done by the received signal strength indication (RSSI) of the acoustic communication signal. Knowing the output power of the sender and the attenuation of the water for the used frequencies, an approximation of the distance from the sender to the receiver could be calculated. Since underwater communication is almost omnidirectional, a message from one sender to a receiver also reaches the members in the local neighbourhood. Communicating the own depth and the distance to the other neighbours may improve the distance measurement of the group. This could lead to an adaptation of the swarm formation in case of a variation of the local environment. In case of a constriction of the waters, the robots have to move closer together to pass this area. The outer robots would recognize the bank and therefor start the evasion movement. The neighbours measure the lower distance to this robot and try to retrieve the equidistant clearance to its lateral neighbours. This reconfiguration of the gaps between the neighbours could also be used to performe a closer monitoring of a place of special interest caused by e.g. salient measurements.

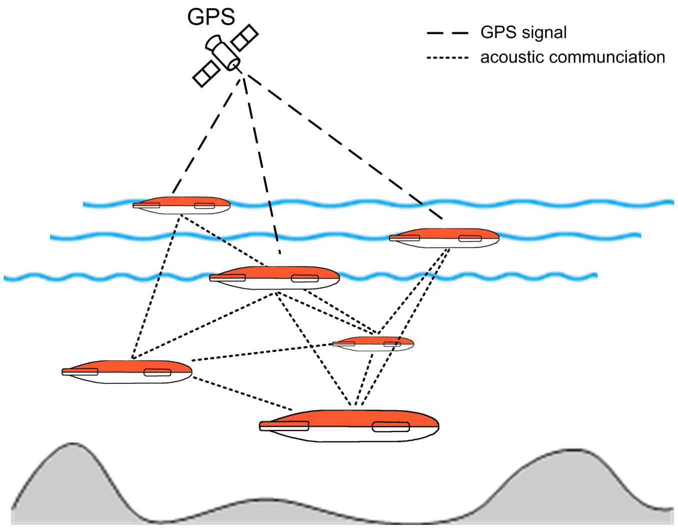

Fig. 4. Approach of an underwater localisation: floating AUVs at the surface receive a GPS signal and get their absolute position. Submerged AUVs can calculate their position by the distance to the emerged AUV and their local neighbours given by the signal strength of the communciation.

Using a homogeneous swarm for both the GPS-stations at the surface and the swarm members under the surface enables a load energy balancing of the whole system. The surfacing AUVs only need the horizontally mounted motors for the propulsion. In addition, several system functions, like the image processing unit, can be disabled. If the power of an AUV gets low in case of a malfunction with e.g. the vertically thrusters, the AUV can emerge and one of the floating AUVs could take its position in the underwater group. This could increase the operating time of the whole swarm and allows the emerged AUVs to transfer their measurement results to an external receiver e.g. on a ship.

VI. CONCLUSION

In this paper we presented the AUV MONSUN II and illustrated the benefits of the deployment of swarms in underwater environmental monitoring. As a consequence of the definition of the requirements of swarm robots in section I high cost and long range sensor are not necessary due to the inherent redundancy of the swarm. This enables an affordable design without costly sensors as e.g. DVL. The small size of MONSUN makes it deployable even in narrow and hard-to-reach areas. Preliminary results have shown the capability of the design and integration. Basic approaches were introduced for communication and localisation and it was shown that energy load balancing could increase the operating time of the swarm to achieve long time observations.

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