The development of the modular Hard- and Software Architecture of the Autonomous Underwater Vehicle MONSUN

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Abstract

This paper presents the development of the new hard- and software architecture of the Autonomous Underwater Vehicle MONSUN, designed to perform underwater environmental monitoring and inspection tasks in a swarm. The design concept is based on modularity and robustness, augmented with a powerful embedded controller and a ROS-based software architecture, enabling a large number of different tasks.

1 Introduction

The environmental monitoring and inspection of waterbodies is becoming more and more indispensable because of rapidly changing environmental conditions and the intention to discover long-term environmentally relevant changes for the conservation of nature [1].
Autonomous Underwater Vehicles (AUV) can be one key factor to realize the above mentioned tasks and various types of AUVs have been developed, trying to perform underwater investigations like the CoCoRo project [3]. Such robots combine many benefits differing them from conventional methods, like manual explorations with divers or static underwater sensor nets. It is possible to investigate hard to reach areas, coupled with a significant lower amount of work and costs, and the possible applications are getting safer. The use of a robot swarm manifolds the possible applications. The swarm members are simple in construction, nevertheless allowing inspections in a wider area over a longer period. Apart from that, the control of a swarm is more complex than controlling just a single robot. As a consequence principles from nature like emergence, self-organisation and self-adaption are becoming increasingly popular.

Figure 1: The MONSUN Underwater Robot designed for applications like environmental monitoring tasks in a swarm. It has a small size with a length of 60 cm and a diameter of 10 cm, which makes it easy to handle by one person.

Hence, this paper presents the new MONSUN underwater vehicle (see ***Figure 1***), designed to handle the various mentioned tasks. The focus is set on a new modular design which enables an easier management of a robot swarm regarding hardware and software issues. The development was based on the criteria formed by Dorigo and Şahin [4]. The robot swarm should be scalable consisting of simple uniform robots operating locally together. The principles of emergence as also robustness based on modularity and adaptability are formulated as main goals of the development of swarm robots.
A great difference to surface vehicles is the possibility of localization and navigation. Already in 1998 the various opportunities for solving these problems where listed in [6], but solution approaches based on sonar data, inertial navigation systems (INS) and Doppler velocity sonar systems (DVS) are not feasible for small swarm robots, due to high costs and large scale factors. The Serafina Project [8] presented first approaches for communication and navigation via acoustic signals [7]. Thereby, relative localization results among single robots are used to estimate a global position information. This principle was extended and refined with the inclusion of more known GPS localization of swarm members at the water surface in [5].

This paper is structured as follows: Section 2 describes the new conceptual design of the autonomous underwater vehicle MONSUN based on predefined criteria for a flexible use in a robot swarm, whereas Section 3 illustrates the current hardware architecture subdivided into different units. In addition the first results regarding the new self developed underwater modem are shown. The development of the software architecture using the popular *ROS* Framework is mentioned in Section 4. At the end convincing results obtained by field experiments are presented in Section 5. Section 6 summarizes the paper and gives an outlook of future work.

2 Conceptual Design

The MONSUN Underwater Robot is currently released in the third generation. To reduce the effort for assembling,

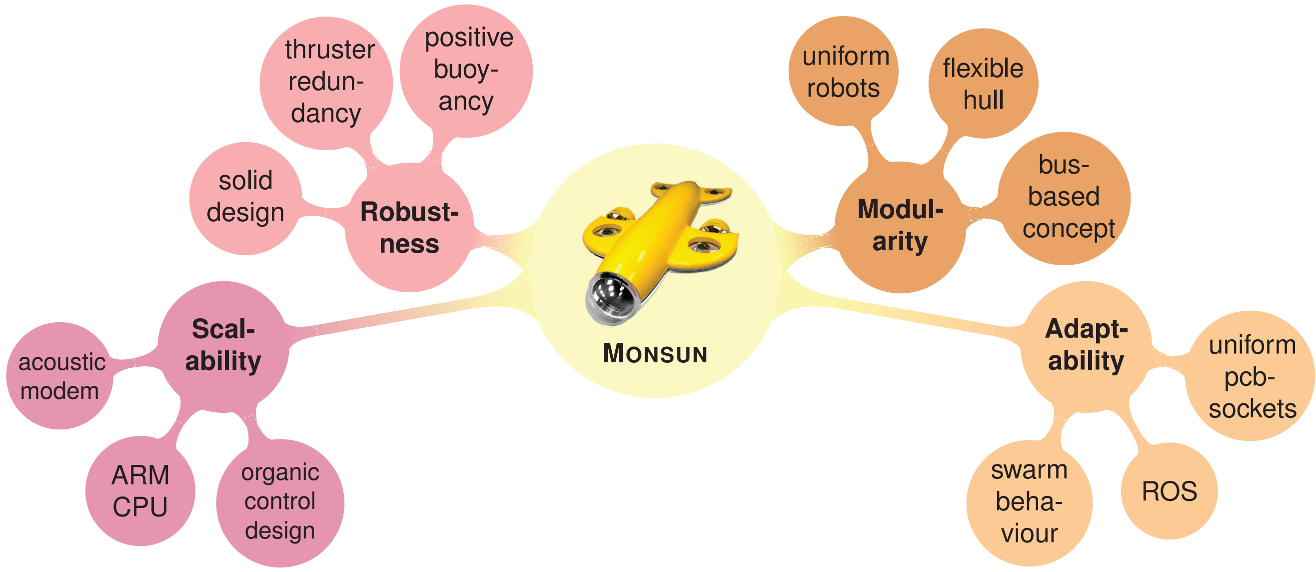

Figure 2: Conceptual design of the MONSUN autonomous underwater vehicle. It is characterized by a robust and modular design which makes it adaptive to many possible mission tasks. Due to the controllability in a swarm, the full design is scalable to a high number of swarm members achieved by high processing and communication capabilities.

deploying and maintaining, the new hard- and software concept of the robot is designed to achieve a robust and modular vehicle which makes it easy to handle and decreases the amount of work in failure cases, differing from the first design presented in [2]. With the help of e.g. additive manufacturing individual parts can be assembled rather quickly which allows a fast and fault-tolerant development of a large number of identical robots. Furthermore, the whole robot has a very manageable small size to enable a single person to get the robot ready for operation. With a weight of about 3 kg the vehicle has a length of only 60 cm by a diameter of 10 cm.
In the following the four main design concepts of MONSUN illustrated in Figure 2 are described.

2.1 Robustness

To enable the robot to survive in the misanthropic environment of the water, the main goal while developing the robot is to build a robust hull made of glass fibre reinforced plastic. The robot is composed of two parts sealed by a bayonet closure. Furthermore an acrylic glass dome is mounted at the front. The total weight of the robot is calculated to achieve a positive buoyancy. If the full system or the actuators fail, the robot will surface, to rescue the vehicle and possible collected data. The robot is actuated by six brushless motors, two orientated horizontally for driving in a plane and four orientated vertically for depth and posture control. Hence, a high redundancy is achieved to be forearmed concerning breakdowns of arbitrary thrusters.

2.2 Modularity

To achieve a high modularity, the robot's hull is build in a flexible way to allow mounting of specific sensor devices at predefined places at the robot e.g. at the robot fins. The MONSUN AUVs have a uniform shape to enable exchanging parts, like the back hull or the acrylic glass dome, among each other. Furthermore, the design of the electronics as a bus-based architecture is significant. The control boards, sensors and periphery are connected by uniform sockets and are not bound on specific places. This enables a customization to any mission task with a unique choice of sensors and control units. Moreover, this allows exchanging of the uniform pcb-boards among the robots.

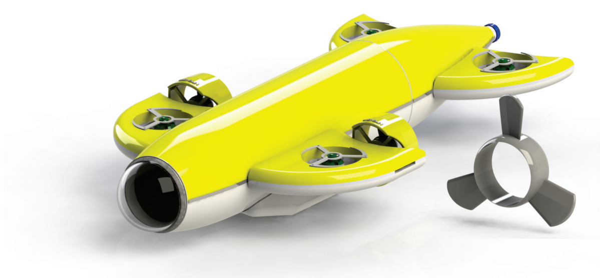

Figure 3: The CAD model of MONSUN including the new 3D printed propeller developed in *Solidworks*.

2.3 Scalability

To achieve a highly scalable robot swarm, the communication between the robots is designed to make a large number of swarm members without modifying any principles possible. Therefore, the home-developed acoustic

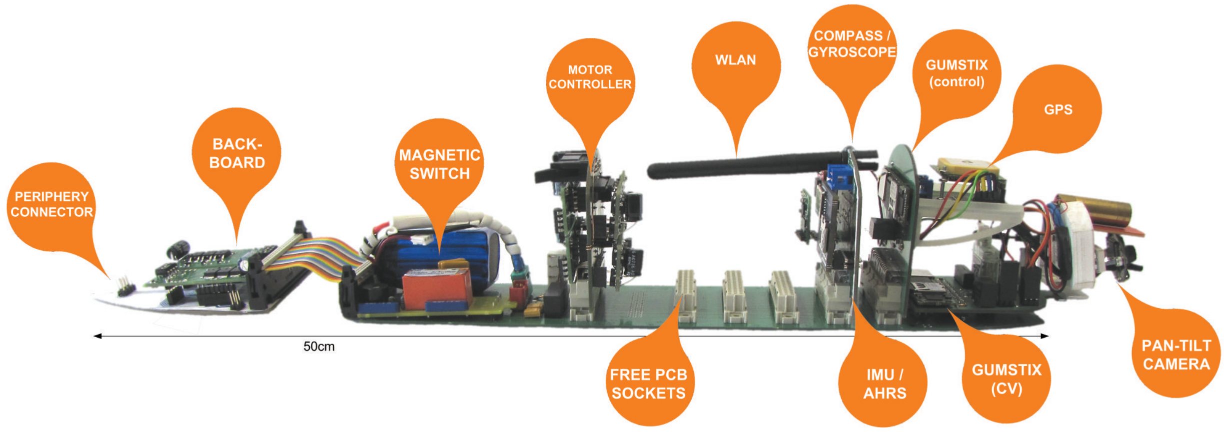

Figure 4: The MONSUN electronics designed as a bus-based architecture. Different pcb-boards equipped with controllers and sensors can be placed at various available sockets to achieve a high flexibility for different mission tasks. Due to the fact of uniform boards, they can be exchanged between different robots for a fast reaction to failure cases.

modem works with a package based communication, enabling a large number up to 63 swarm members.
The control of the robot is done with two 720 MHz Overo® Fire COM Gumstix modules. A Linux Ubuntu operating system is installed on a 8 GB micro SD-card that is placed on each module. Hence, the full system can be exchanged quickly among the robots by duplicating the SD-cards, making the software exchange progress between the swarm robots more easy.

2.4 Adaptability

The software of the robot is based on the Robot Operating System (*ROS*), enabling a high adaptability to new software methods and various mission tasks using open source community packages for e.g. swarm algorithms or prior self developed algorithms for other underwater robots. The re-usability and node-based software architecture speed up the software design and integrated network features are predestined for swarm behavior.

3 Hardware Architecture

Though autonomous underwater vehicles designed for swarm operations have to be simple in construction to guarantee an opportunity for a large number of swarm members, the current development stage of MONSUN is improved with a more powerful control unit. The used Overo® Fire COM Gumstix module enables higher control algorithms and the possibility to analyze various sensor data at the same time. The computational system is extended with a second Gumstix module used for computer vision algorithms to share the CPU-intensive computations on hardware level. On both gumstix devices a *Linux Ubuntu* operating system is applied to enable the use of the Robot Operating System. Furthermore, the modules are accessible via WLAN at the surface to allow a fast transmission of collected data over large ranges.

The used motor controllers from proprietary development allow current and velocity measurements for analyzing the robot regarding power consumption and health state and drive the brushless motors linked with 3D printed propellers illustrated in Figure 3.

The full system is completed with orientation and posture measurement sensors like various compasses, gyroscopes and an IMU/AHRS [9]. Together with an external pressure sensor, a set of PID controllers is able to control the robot's diving behavior.Figure 4 illustrates the current hardware and electronics of the MONSUN underwater vehicle with the minimum driving configuration.

3.1 Communication

One of the most challenging tasks in the field of underwater robotics is the underwater communication. Especially for tests and fine tuning of the controller, the internal realtime data of the robot are important. This contains not only the transmission of the actual state but also sensor information from e.g. the pressure sensor or the camera, to track the current behavior of the robot.
Common surface wireless communication techniques like WiFi or Bluetooth are not applicable for underwater communication due to the physical characteristics of the water: the higher the frequency the higher the damping and the lower the achievable range. Thus the communication range of WiFi and Bluetooth is up to a few centimeters. In case of a single robot and basic tests communication can be done by a simple cable connection. Therefore, MONSUN has a jack at its back end for a serial connection. However the behavior of the AUV changes by the weight and the tractive forces of the cable. For communication between the swarm members or a host station an acoustic modem can be used. Acoustic communication is the most common communication technique in the field of underwater robotics, inspired by the communication of whales and dolphins. The damping of acous-

tic waves is far lower than of electromagnetic waves and allows ranges of up to several kilometers. Commercial modems are often developed for long range communication and need a lot of energy and space. Furthermore, the field of application is mostly a point-to-point communication that affects the communication protocol, the medium access control and the addressing. Hence, such modems are unsuitable for integration in MONSUN.

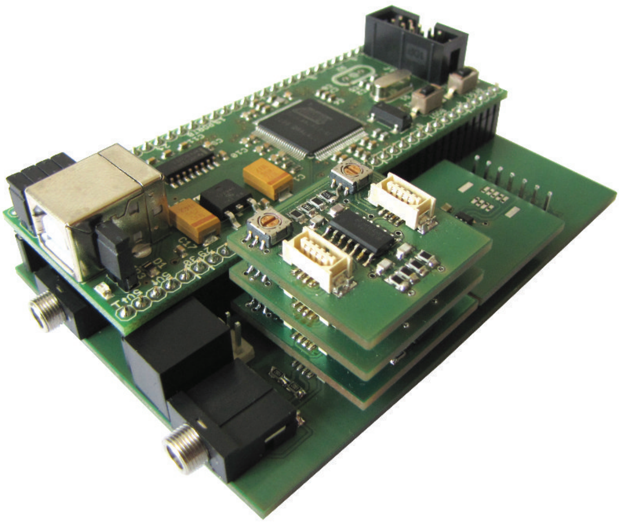

Figure 5: The acoustic modem for MONSUN assembled on an evaluation board. Modular PCB boards containing filter and amplification parts can be connected in a predefined way to perform first analogue preprocessing of the acoustic signals.

For this reason a modem especially for the operation in swarms of small AUVs for a range of up to 50 m was home developed. Here the focus was on a small design, low power consumption and adjustable range. To reduce the protocol overhead, a lightweight header structure was implemented that allows the addressing of up to 63 members as well as broadcast.

Figure 5 shows the modem with an actual size of 95x60x25 mm. The modular design of the hardware allows to reconfigure the amplification and the frequency range in case of changing regulations of allowed frequency domains. The maximum power consumption is only 570 mW in receive and 770 mW in send mode.

Although acoustic communication has some advantages compared to electromagnetic communication, especially in shallow water influences caused by the low velocity of the sound-waves can have significant influences on the quality of the communication. This is because of the multipath-propagation caused by reflection between the bottom and the surface, and as a result inter-symbol-interferences (ISI) in the range of commonly 10 ms in medium-range shallow water channels.

The used frequency range for acoustic communication is from 10 to 100 kHz since the ambient noise decreases with increasing frequency, but over 100 kHz the ambient thermal noise increases. In this case a frequency range from 15 to 30 Khz and a non-coherent FSK to simplify the architecture of the receiver was chosen. To reduce the influence of inter-symbol-interferences a FHSS with a hopping sequence of five is implemented. With a symbol duration time of 2.5 ms a channel clearance time of 10 ms is achieved.

This configuration allows a bit-rate of 400 bit/s. To increase this bit-rate the data is transmitted parallel on five channels with 3 kHz bandwidth each. This results in a bit-rate of 2.000 bit/s. Furthermore, broadband emissions have less effect to the communication.

For ensure the data against single and burst errors a forward error correction in combination with interleaving is used. Additionally the header and the payload are protected separately by CRC.

Furthermore, the modem allows to estimate the distance to the transmitter by the receiver. This is done by measuring the signal strength during packet transmission. Based on this measurement value and the information about the amplification of the sending/receiving signal the distance can be read out of an internal look-up table.

4 Software Architecture

The software architecture of MONSUN is hierarchically structured focusing on adaptability and modularity. Nevertheless, it can use the real-time toolbox which can publish *ROS* messages from single real time threads. The communication between different software nodes is realized by using *ROS* handled TCP/IP packages while the Gumstix modules communicate with other hardware periphery by using interfaces like I^2C. The software can be partitioned into three levels, namely the *Task Level*, the *Behavior Level* and the *Sense/Act Level*, see Figure 6.

4.1 Task Level

The tasks are defined at the highest level and have access to information provided by the *Behavior Level* and the robots system e.g. the current time. Complete missions are defined as Finite State Machines *(FSMs)*. The definition of *FSMs* is done with SMACH, a *ROS* independent Python library designed to build hierarchical state machines. SMACH provides straightforward syntax and visualization of the state machine's transitions and data flow. *FSMs* can be hierarchically organized in containers in order to maintain even complex sequences of tasks. This allows for a rapid iteration and introspection of the mission plan. The designed mission may contain tasks like submerging to a target depth, followed by the search for an object and the inspection of it as well as surfacing at the end of the mission, to retrieve the AUV. Depending on the received feedback during the mission it is possible to switch to another state, for example if the AUV took too long to find an object, and thereby activate a different behavior. To guarantee the safety of the vehicle each state has at least one failure state to handle task specific problems or to initiate surfacing, in case of mayor problems.

4.2 Behavior Level

Behaviors can be defined as *FSMs* with SMACH, too. Contrary to the *Task Level*, they are able to directly access sensor information and to control the actors of the AUV. These behaviors can be rather simple like diving or cruising, up to more complex jobs such as finding a certain object in the area of deployment. The navigation for example receives upon execution a new desired position of the AUV's GPS. In a first step an estimation of the current position is obtained from the localization followed by an iterative process of computing a new heading and setting the thruster's speed until the AUV reaches the desired position or it is decided that the behavior failed.

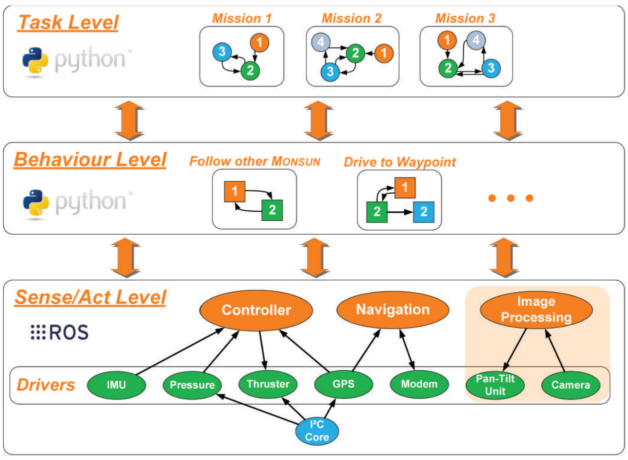

Figure 6: Software architecture of the MONSUN underwater robot subdivided into three levels.

4.3 Sense/Act Level

The *Sense/Act Level* is subdivided into four groups: the image processing, the navigation, the controller and the drivers for the hardware periphery. The drivers interact with the sensors and actors via I^2C. For some of the hardware, which do not provide native I^2C support, an Atmega168 on the particular circuit board is used to provide an interface. In the case of the IMU and the GPS module an Atmega168 performs all needed computations, aggregates the usable sensory data and makes it time-invariant available. The corresponding *ROS* drivers only need to request the data and publish them for other nodes. However, with many nodes attempting to access the I^2C bus at any given time and since exclusive access to the bus is essential for two communicating devices, some sort of regulation is needed. The so called I^2C Core administrates the use of the bus. Nodes can send requests to the I^2C Core, which are queued up in order of arrival. The Core then grants a single node the right to use the bus by principle of mutual exclusion. After a node finished its work, the bus is freed up and following the queue the next node is granted access. The image processing is exclusively performed on the second gumstix module due to the high computational costs of applications like object recognition. The gained data are sent to the other gumstix via UART where it can be processed by behaviors. Localization is performed by combining information of the acoustic modem and other sensory inputs like the IMU and GPS data. The controller directly controls the thrusters. It receives a command containing a heading, the desired speed and the depth of the AUV. Depending on these input values the speed of the thrusters must be set. In order to do this, the controller subscribes the data from the IMU and the pressure sensor. These sensor inputs are used by four PID controllers for depth and pitch, roll and yaw angles. The pitch, roll and depth controllers are only influencing the four vertical thrusters, while the yaw controller and the desired speed determine the values of the horizontal thrusters. This way the controller regulates the pose and the depth of the AUV.

5 Results

The first test results for the third-generation MONSUN were recorded during test runs in a 20 m^2 pool. In the test scenario the robot performed a self-controlled depth and posture control with the help of four PID controllers for the robot's depth together with its roll, pitch and yaw angles. Figure 7 illustrates the results as a plot of the target depth against the actual depth of the robot over a period of 15 min. The depth values are indicated in centimeters whereby a value of 0 cm represents the depth while the robot floats on the water surface.

At the beginning the target depth values are incremented in steps of 5 cm followed by steps of 10 cm down to a total depth of 55 cm, to evaluate the behavior of the controllers. MONSUN dives with a root mean squared error of 1.4 cm of the actual depth corresponding the target depth. Compared to the robots height of 10 cm and the target depth it is a very good result and shows that the parameters of the PID controller were determined very well.

After about 10 min the robot was manually forced into deep to see the capability of the system to adapt to various conditions. MONSUN tried to hold a depth of 20 cm and was forced down to nearly 50 cm. After releasing the robot the target depth was reached after a few seconds without large overshoots. The same result was accomplished at about 12 min. In this case the robot was lifted from the water and a target depth of 30 cm was reached with one overshoot after 10 sec.

Independent from that, first tests with the modem in a pool, that can be seen as worst-case scenario since many reflections an echoes affect the communication, were performed. The distance of the sender and receiver varied between 0.5 and 9 m. During these tests a bit error rate

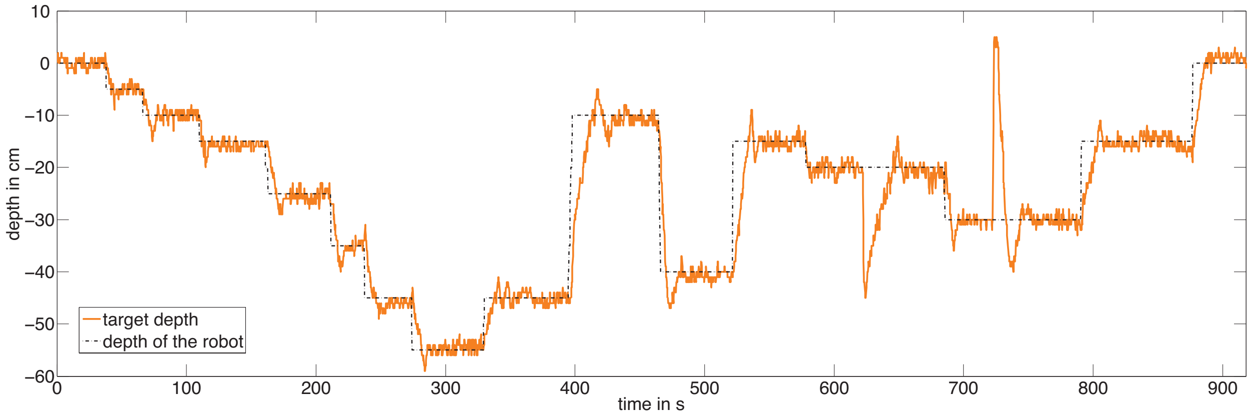

Figure 7: Evaluation results of the performed depth control. The black dashed line represents the target depth and the orange line stands for the actual depth measured by the pressure sensor of MONSUN. The values given in centimeter are plotted over the time given in seconds. The plot shows, that the robot is able to dive to defined depths with a root mean squared error of 1.4 cm. At the end MONSUN was forced manually to a larger depth and kept out of the water to see the adaptation to this situations. In both cases the robot returned to the target depth in only a few seconds.

of $1.05 \cdot 10^{-5}$ to $3.96 \cdot 10^{-4}$ was achieved. It could be observed that the error rate does not depend on the distance between sender and receiver but on the characteristics of the environment. Furthermore, first experiments with distance measurements where completed. The typical accuracy of the measurement over an averaging of 10 packets is $\pm 50\,cm$.

6 Conclusion

This paper has described the hard- and software design of the MONSUN AUV to achieve a highly modular vehicle capable to perform a large number of various tasks. The new hardware with its new central processing unit is capable to perform intensive algorithms e.g. for swarm behaviors and navigation. The presented underwater acoustic modem can be used to get real-time data from the system and for the communication between the swarm members. The software development is accelerated by using the open source Robot Operating System which enables the re-usability of software components implemented for other in-house underwater robots. Finally, the performance of the robot was evaluated under real conditions. The experiments prove the high agility with contemporary controllability of the MONSUN autonomous underwater robot.

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