Towards Fault-Tolerant and Energy-Efficient Swarms of Underwater Robots

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***Abstract*—The increasing urgency to study the worlds native waterbodies regarding environmental monitoring leads to a worldwide growing interest in the development of autonomous underwater vehicles (AUVs). The robots are equipped with several sensors, e.g. cameras, environmental tracking systems and acoustic modules which provide an inexpensive alternative towards man-made investigations. To increase mission time and decrease sensitivity against faults, a swarm of such underwater robots can afford many benefits.**

Hence this paper presents the development of the miniature AUV *MONSUN II*, which acts in a networked swarm to reach an energy-efficient behaviour with simultaneous consideration of fault-tolerance. Therefore the robots use their communication network to propagate internal states and build underwater formations regarding current mission tasks.

I. Introduction

Environmental monitoring and underwater inspection tasks are today mainly performed by boats, divers or Remotely Operated Vehicles *(ROVs)*. These solutions are capable of operating in different places but are expensive and require an expert workforce. Additionally ROVs have limitations because of the needed cable or the movement of the supporting boats. Because of these circumstances autonomous underwater vehicles *(AUVs)* are useful alternatives, that efficiently and autonomously explore hard to reach areas at the coast or inshore waterbodies.

Some tasks require investigations of large areas like explorations of oil spills. A swarm of AUVs could try to locate the source of the oil spill and send the data to the cleaning team much faster then a unique robot, because simple behaviours are combined together to accomplish complex tasks more easily [1], [2]. Furthermore any problem in the behaviour of a unique robot could make it out of service. In comparison to that, a swarm can still perform its mission because it is robust against failures of single robots. On the other hand, an important factor taken into account when engaged in a mission, is the energy consumption which increases with higher complexity of the behaviours and processing of data. The swarm based approach has many advantages. Inspired by nature the principles of self-organized cooperation allow collective decision-making to improve performance optimization and robustness [3].

Adding or removing swarm members does not decrease the effective functionality of the collective behaviour. For this reason swarm systems are extremely scalable and flexible. In addition multiple simple robots are often more cost effective than a single complex one.

There are several projects in the field of underwater robot swarms. The CoCoRo project [4] is an underwater robot swarm that contains heterogeneous members of AUVs. The CoCoRo swarm is used for underwater monitoring and searching. The swarm consists of three parts, the base station at the surface, a relay-swarm that serves as a node connection between the base station and a ground-swarm that performs the tasks at the sea bed. Several papers present the Serafina project [5], [6], [7]. The Serafina project aims for large scale and fault-tolerant swarms. Communication is used for localisation of the nearly swarm members. To enable distance measurements each AUV has four hydrophones, two as receivers and another two as projectors to obtain angle and posture estimations by using Maximum Length Sequence (MLS) signals [8]. In [9] and [10], swarm techniques were introduced that allow a small number of underwater robots to survey and explore the environment using certain formations, e.g. triangular formation, or to create polygonal formations around a specified leader robot. Then the leader robot tracks environmental isocontours.

This paper presents a concept to create a swarm of AUVs in a V-formation. Depending on the energy capacity the swarm reconfigures the position of the AUVs. The different energy levels can so be balanced because of the different energy consumptions some tasks require. Holding a certain depth level requires more energy than floating on the water surface. The swarm itself consists of homogeneous AUVs of the type MONSUN II that is especially designed and developed for usage in a swarm. Since localisation by GPS is not possible under the water surface, the swarm uses acoustic communication to solve this problem. Several AUVs are on the surface and receive GPS data. The dived robots receives the data from the above AUVs via an acoustic modem. From time of arrival and signals from different locations one can calculate the estimated position of the underwater AUVs relative to the GPS position of the AUVs on the surface. Furthermore the use of formations and a clustering of the robots in one place gives the possibility to survive failures and achieve a stable network state.

The remainder of this paper is structured as follows. Section 2 describes the AUV MONSUN II that is used for performing autonomous underwater tasks in a homogeneous swarm.

Section 3 describes our approach for an energy-efficient and fault-tolerant swarm behaviour and first results obtained by simulation. A summary of the work and an outlook of future developments are presented in Section 4.

II. MONSUN II Underwater Robot

Fig. 1. The AUV MONSUN II with its small dimensions of a length of 60 cm and a diameter of 10 cm. The whole robot has a light weight of 4 kg and can be managed by a single person.

The main objective of MONSUN II (**see Figure 1**) was to design a small and inexpensive underwater robot for swarm usage [11], [12]. The dimensions of MONSUN II are 60 cm in length and 10 cm in diameter and a weight of approx. 4 kg. The operational depth is approximately up to 10 meters therefore the main operation areas are local waterbodies like lakes, harbours and coastal areas. It is equipped with six brush-less motors, four of them mounted vertically and two horizontally. The interior hardware system has a modular slot-in system allowing an easy way to exchange or extend the hardware system by adding various pcb boards. Hence the hardware enables the user to a fast repair in failure cases.

To recognize the other members of the swarm MONSUN is equipped with a 1280x1024 pixel camera located at the front of the AUV. In both front fins are two infra-red distance sensors integrated to avoid lateral obstacles or collisions with other members of the swarm. An accurate temperature compensated pressure sensor measures the depth with a resolution of 1.2 cm. Due to drifts that pose an imbalance of movement, MONSUN has an Inertial Measurement Unit (IMU) and an attitude and heading reference system (AHRS) [14].

The equipped underwater modem enables the robot to use simple packet based peer-to-peer communication with an achievable data rate up to 1 kbps. It is sending in a frequency range of 15 kHz up to 30 kHz using frequency hopping (FHSS) to avoid mirroring and erasing effects. The signature of the receiver is used for addressing as well as for spreading / despreading the message to achieve a lower data rate but higher reliability by automatic error-correction. Furthermore the signal of the modem can be used for signal strength measurements to calculate distances between swarm members by trilateration.

III. Behaviours

In this section we introduce an energy-efficient swarm behaviour that consists of four phases. In the first phase the robots begin to form a V-formation of the swarm at the surface, using the estimated distance and angles between the robots gathered by a GPS sensor. To create the formation, only few information are needed: Each robot needs to be able to determine the position and orientation of its successor in the V-formation to create a relative localisation (relative distance and angle). Furthermore each robot has a different ID so others can identify it and the communication can be managed. Then each robot starts to broadcast its position and orientation. This can be done via Wi-Fi, because the AUVs are still at the surface. The robot with the highest ID will be elected the master and it will lead the swarm towards a given goal. The peer-to-peer communication is organized in different levels (**see Figure 2**). The leader communicates with all swarm members. The lower level of the V-formation communicates only with the leader and their own lower level. Furthermore a communication in between a level is not allowed. The master checks if the communication link between itself and the other members is active. Therefore the other members reply with a simple alive message for a request message from the master. When one member is not answering it can be assumed that its lost and the master has to reconfigure the swarm. Since the master has information about previous position of the lost member it can publish a command to the follower of the lost robot to take its location and angle in the formation. This makes the swarm more robust to member loss which increases the overall fault tolerance.

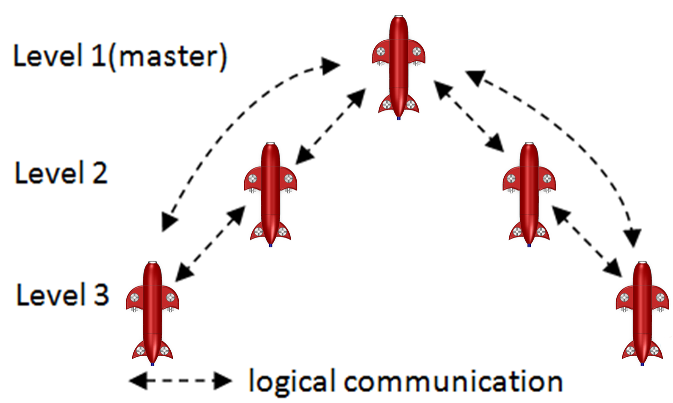

Fig. 2. Illustration of the logical layer based communication in a MONSUN swarm.

The behaviour of the single members is described as follows. The master robot sends periodically to all swarm members the position it should take in the formation and the called members adjust their speed and orientation to stay at their given position. The consisting distances and angles of

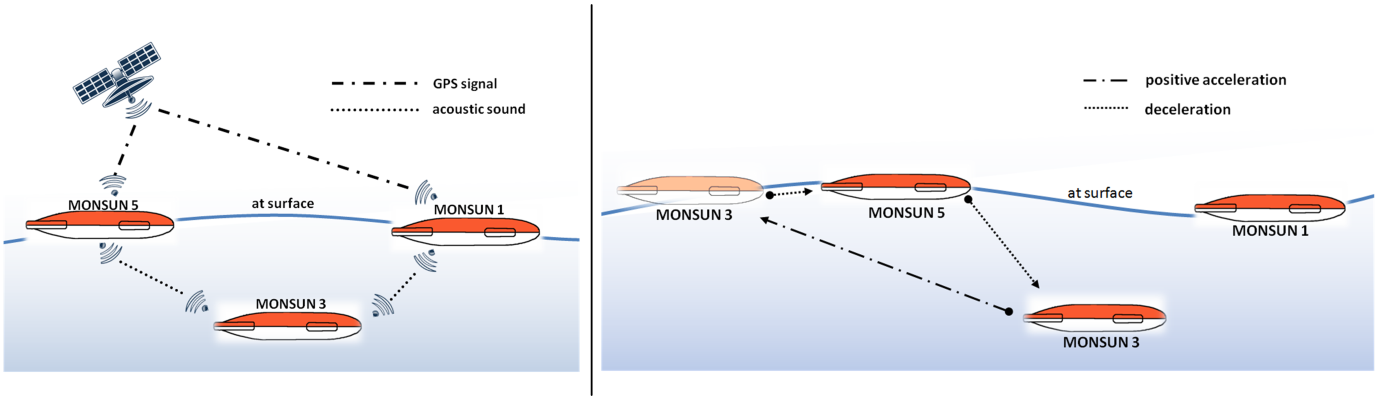

Fig. 3. Left: The side view of the swarm that shows MONSUN number three that has reached the required depth and is in survey mode on the *lower* layer. The other MONSUNs remain at the surface and create the *upper* layer of the swarm that would function as an energy reserve. Beside that they send the GPS data to the *lower* layer through an acoustic modem. Right: The exchange process between MONSUN number three and five. The submerged robot reduces speed to surface behind MONSUN number five. Robot number five then submerges to recapture the position of robot number three.

the robots between each other are maintained during the movement of the swarm. The occurrence of environmental obstacles leads the whole swarm to a avoidance behaviour and an adaptation to the current situation.

Still at the surface, the robots are in the so called safe mode. The energy consumption in this phase is at the lowest level because of the usage of only two horizontally mounted thrusters for the propulsion. Moreover, some system functions, such as the image processing unit and pressure sensing can be disabled. This increases the overall operating time of the swarm. After achieving the required stability of the V-formation like an acceptable margin of distance and orientation error the next phase will be started.

The second phase includes the needed diving behaviour of a subset of swarm members to be able to perform submerged tasks, like inspections or monitoring tasks. Therefore a modified behaviour is needed. Assuming that the total number of swarm members is greater than three robots, the swarm will be divided into two layers - the *upper* and *lower* layer. Furthermore to achieve an underwater localisation of the robots, the number of entities at the surface has to be at least three. The swarm members at the surface perform the phase one behaviour and activate the acoustic modems to propagate their global positioning information to the submerged swarm members. These have to localize themselves under water and estimate their behaviour depending on the whole swarm (**see Figure 3**). Localization under water can be achieved by several solutions like in [13] and is not considered further. The robots of the *lower* layer have to enable additional systems, e.g. the vertical directed thrusters to control their depth. The usage of the MONSUN GPS at the surface consumes approx. 10 mA which is a small part of energy needed for the four vertical directed thrusters for depth control. This behaviour produces a difference in energy consumption between the different layers. Moreover, the robots are not subject to the same environmental conditions. Thus, the *upper* layer consumes less energy then the *lower* one. This discrepancy in energy consumption can be used in the next stage, to acquire a longer mission time and tolerance of failures.

The third phase is the most important one for energy management. Several swarm members are entering the *lower* layer. Among others they start to send information about their battery status to the swarm. If the whole swarm is performing the mission in the same separation, the energy level of the *lower* layer decreases more faster then the *upper* layer. Therefore the swarm members at the surface can act as an energy reservoir for the *lower* layer, for increasing the mission time and preventing failures. The *upper* layer is an active part of the V-formation and traverses the path together with the *lower* layer.

If for example the robot number three of the *lower* layer has a low energy level (less than 20%), then the process of exchange of two members of the swarm e.g. number three and five is as follows (**see Figure 3**). The robot number three reduces the speed to surface behind the robot number five avoiding collisions with other swarm members. Then it will change its mode from survey mode to safe mode receiving and sending current GPS data. In addition, the IDs of the exchanging robots have to be changed. Thus robot number three (previously five) starts the process of diving down and takes the position of the former robot three. After the swap is completed the swarm robots will reconfigure the V-formation to correct their positions. The exchange process will be repeated by other survey mode robots when they have low power, to enlarge the overall mission time and avoid faults from low supply voltage of the robot sensors and actors.

In the fourth and last phase the general energy level of the swarm robots is becoming very low. A sufficient amount of energy should be left so the swarm can return to the home base. The lower layer members have to surface by turning off the vertically directed thrusters. This is possible due to the positive buoyancy of the MONSUN robot.

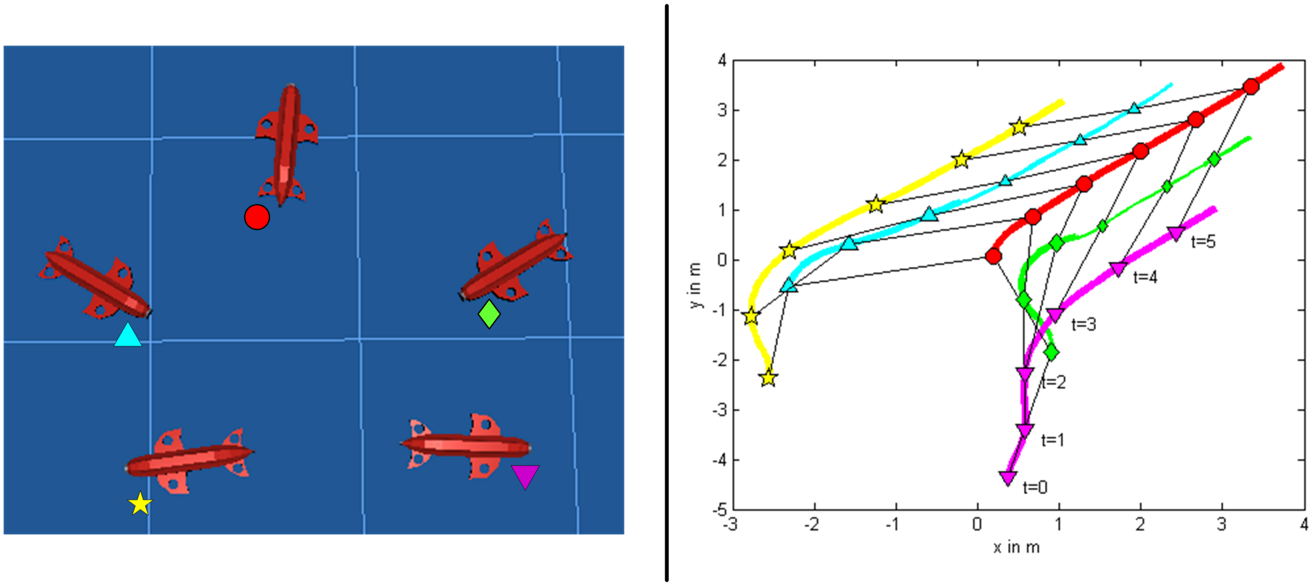

Fig. 4. First experiments with three MONSUNs were simulated performing a drive in a predefined V-formation to reach a given goal position. The right plot shows the different positions of the robots at different time steps. [12]

The evaluation of the mentioned behaviour is still in progress and already done in a simulation environment. We are using the MArine Robotics Simulator (MARS) which is a Hardware-in-the-Loop real-time simulation environment for multiple AUVs developed at our institute. The **Figure 4** shows a scene of the simulation and a time plot of the different positions of the swarm members. The task was to reach a goal position in the scene in a predefined V-formation. Phase 1 and Phase 2 are active in this case. The path is computed by the master robot as a minimal distance estimation and the swarm members adapt their movement depending on the information from the swarm leader.

IV. Summary and Outlook

Summarized this paper presents a method to achieve an energy-efficient and fault-tolerant swarm behaviour for underwater inspection tasks and environmental monitoring. Currently a simulation with the MONSUN II underwater robots is done. The swarm successfully forms a V-formation and several members dive into the lower layer to perform their monitoring tasks. The swarm reconfigures itself like described above for increasing the overall mission time and tolerance faults. The next steps are a simulation of the remain two phases and first experiments in the reality with the MONSUN II underwater robots.

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