A Robust Acoustic-Based Communication Principle for the Navigation of an Underwater Robot Swarm

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***Abstract*—This paper presents a robust acoustic-based communication principle for the localization and navigation of an underwater robot swarm in featureless environments. With the help of acoustic modems and two robots at the surface with available GPS positions, a number of various submerged autonomous underwater vehicles (AUVs) can be navigated to fulfill different tasks in underwater inspection and monitoring in a V-shaped formation. The principle was implemented using MONSUN underwater robots and tested under real conditions in a shallow waterbody.**

I. Introduction and Related Work

Autonomous robots are playing an increasingly important role in the area of environmental monitoring and inspection tasks. Especially the development of advanced communication methods allows for a highly complex capability of the cooperation of robotic devices. Hence, with the help of suitable sensors, it is possible to autonomously observe the environment and interact with it.

In the field of underwater robotics, communication is highly restricted due to the characteristics of water, which absorbs high-frequent signals such as WiFi. Therefore, an acoustic communication with specialized modems is often used. Most commercially available underwater robots, such as REMUS [1], are equipped with very specialized sensors to fulfill most requirements of underwater inspection tasks, but high unit costs limit their deployment to only few AUVs. However, for the monitoring of larger areas, the deployment of a swarm of underwater robots has many benefits.

The CoCoRo Swarm project introduced an underwater robot swarm to study basic swarm behaviours, but due to limited computational power and sensor payload, they are not suited for large scale monitoring missions [2]. In contrast, the Ocean Lab Data Driver [3] has on-board sensors for environmental monitoring, but has no means to communicate underwater and relies on radio communication at the surface. The company Hydromea from Lausanne, Switzerland is currently working on the flexible AUV called VERTEX for environmental monitoring which shall also operate in a swarm [4]. In the Serafina project [5] basic algorithms and concepts for AUV swarms have been proposed. The SEMBIO AUV [6] developed at our institute in a companion project is also swarm-capable, but mainly designed for energy efficiency and has not been operated as a swarm yet.

Fig. 1. The MONSUN underwater robot developed by the Institute of Computer Engineering of the University of Lübeck. With a length of 80 cm, it is small in size and actuated with six brushless motors, four directed in the vertical plane and two directed in the horizontal plane. They are placed at the fins enabling high maneuverability. For the behaviors described in this paper, it is equipped with a large antenna for WiFi communication at the surface and an acoustic modem at the bottom of the AUV at its right side (transducer not shown).

This paper presents an approach of a robust communication principle for AUVs consisting of underwater acoustic and wireless network-based links, which allows for continuous navigation of a swarm of robots. The principle is tested using our MONSUN AUVs and first results are presented.

II. MONSUN Underwater Robot

Nowadays underwater robots are characterized mainly by a powerful control unit placed in a highly pressure-resistant hull. They are actuated by a strong propulsion system which allows for deployments in open sea environments. Most common

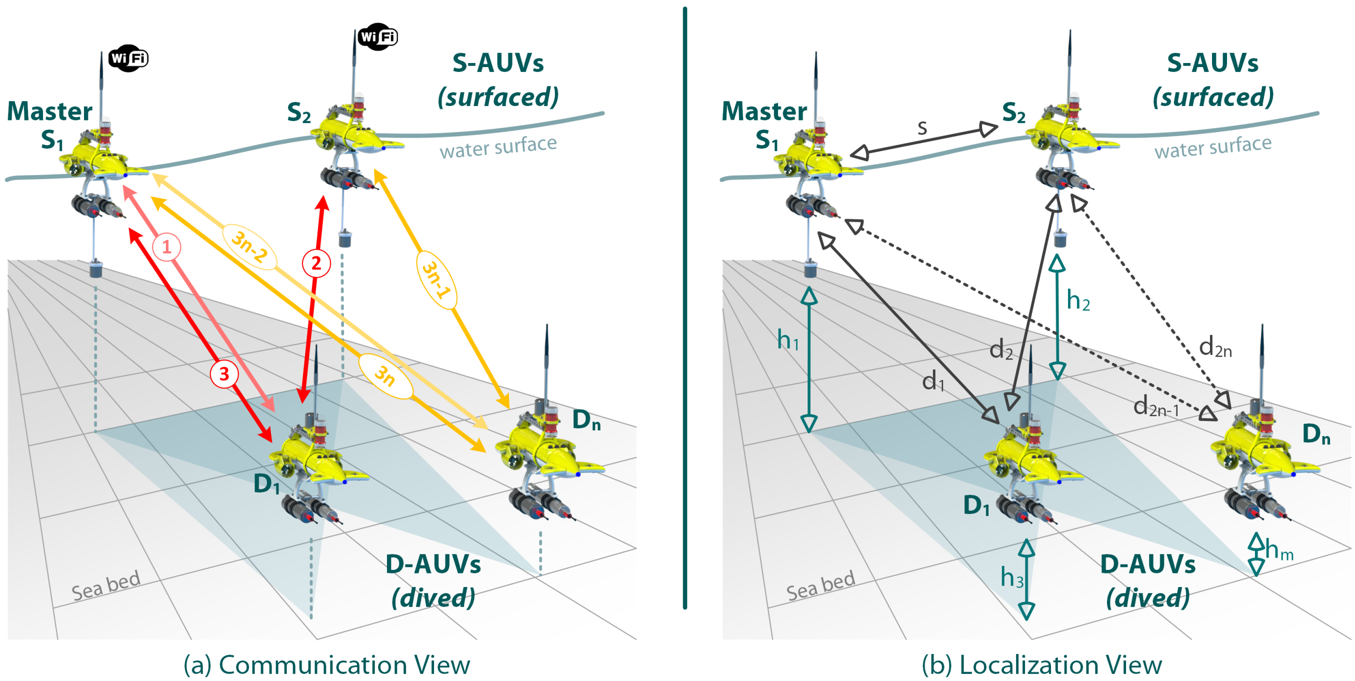

Fig. 2. Communication principle of the message exchange sequence of a robot swarm. The robots at the surface build a V-shaped formation together with each submerged robot. (a) The robots at the surface S_1 and S_2 are able to exchange data via WiFi. All communication with submerged members of the swarm needs to be performed via acoustic modems. The master S_1 communicates in message-triples with the dived MONSUN robots. For n dived AUVs the message complexity adds up to $3\,n$. (b) The localization for dived AUVs is based on surface reference values. In case three reference points were used, the exact position of the submerged MONSUN could be triangulated. In order to reduce the needed amount of surface vehicles only the two surface AUVs S_1 and S_2 are used. The depth, e.g. h_3, can be determined by the pressure sensor of MONSUN . The distances to the surface AUVs can be computed using the round trip time of the messages. By using this information the position uncertainty is reduced to two points; one in front and one behind the surface vehicles. By providing a known start position for the formation one is hence eliminated and the position can be determined relative to S_1 and S_2.

systems are not suitable for shallow water bodies due to large scale factors and limited maneuverability. To overcome this limitations, the Institute of Computer Engineering of the University of Lübeck has developed the MONSUN underwater robot, a small, flexible, and modular AUV for various underwater inspection tasks [7]. The robot is actuated with six brushless motors, four of them placed vertically at the robot's fins for posture and depth control and two of them placed in the middle of the robot for movements in the horizontal plane. With a length of $80\,\mathrm{cm}$, it is small in size and its battery capacity of up to $60\,\mathrm{Wh}$ allows for an operation time of up to $5\,\mathrm{h}$ with an average speed of $1.5\,\mathrm{kn}$. As computational unit, a Raspberry Pi 3 with a Quad Core Broadcom BCM2837 64bit CPU clocked at $1.2\,\mathrm{GHz}$ and 1GB RAM running Linux Ubuntu is chosen. It allows the use of the Robot Operating System (ROS) [8], which accelerates the software developing process due to open source community programs and algorithms.

Underwater robots can be deployed in different kinds of inspection and monitoring tasks, e.g. searching for sunken objects or measuring different environmental parameters. The MONSUN robot was developed in a forward-looking modular way, allowing for an adaptation of the robot for a large portfolio of applications. It involves an expansion set with different hardware-based enhancements in stand alone modules which can be mounted at different docking points at the robot [9]. The modules are categorized in sets for environmental monitoring, communication, and navigation including image processing capabilities and it is possible to equip robots with different configurations without interfering with basic robot behaviours.

Currently, the Institute of Computer Engineering has constructed a total number of five MONSUN AUVs. Two of them were used as part of the international expedition Clockwork Ocean in June 2016 and proved the usability and robustness of the system [10]. The aim of the expedition was to survey effects and characteristics of submesoscale eddies in the Baltic sea, for the first time with a combination of measurements from various platforms. First results are presented in a previous paper [11] showing successful measurements of thermal structures in the water column.

The MoSAIk project [12] aims to research the usage of MONSUN AUVs for environmental monitoring in harbour areas and inland waters. In these areas, regular water quality monitoring as well as thorough measurements after accidents or suspected contaminations take place. Leaking ships, loading incidents, or sewage contamination of surrounding industry are potential risks. After ship collisions, the presence and extent of spillages of oil or other hazardous substances must be identified. Current monitoring systems consist of stationary measuring stations, taking manual samples, and the use of divers in the event of accidents or other acute pollution threats. Stationary systems lack spatial resolution and as a result have reduced detection rates and can not localize the source of a spillage. Taking manual samples leads to a low spatial and temporal resolution and is associated with high labor costs. Divers are only brought into action if it is required due to an accident or environmental disaster and if the safety of the divers can be ensured. The usage of a swarm of MONSUNs is not endangered by these drawbacks. The AUVs can take measurements at the surface as well as in multiple depths with environmental sensors that can be equipped specifically for the expected pollution. Due to their small size and low weight, they can easily be deployed by a few operators without exposing any risk for the involved persons. The higher spatial and temporal resolution that can be achieved with this system also enables a more complete monitoring of vulnerable areas.

A key technology for a reliable use of underwater robot swarms is a stable communication between the entities under water and at the surface. Therefore, the MONSUN AUVs use a combination of WiFi communication at the surface and acoustic modems from Evologics while diving [13]. The modems achieve a data rate of up to $13.9\,\mathrm{kbit/s}$ and operate in a frequency band from 18 to $34\,\mathrm{kHz}$ which enables underwater communication to coordinate and navigate the swarm on the one hand and an online data transmission to the surface on the other hand. The modems were placed outside the hull at the bottom of the AUV with a separate transducer pointing downwards at a $50\,\mathrm{cm}$ extension rod. A principle for robust and fault-tolerant under water communication using these modems is introduced in this paper.

III. AUTONOMOUS INSPECTION TASKS

Utilizing AUV swarms for inspection and monitoring tasks has many advantages compared to a single robot performing the task. Several AUVs are able to cover a larger area and can produce redundant data. In case of a robot failure in the swarm, the mission does not need to be aborted, it just decreases in efficiency. In this paper, an approach for swarm-based navigation is presented that can be applied to environmental monitoring tasks. To provide a thorough coverage of a waterbody, the AUVs are supposed to traverse the area in a formation. Some AUVs are navigating with a set distance at the surface to given GPS coordinates. Additional MONSUN AUVs are submerged and follow the course of the surface robots, e.g. in a V-formation. An alteration of the course needs to be communicated between all members of the swarm. The depth of the submerged AUVs can be set to layers of the water column relevant for the survey. The measured data often need to be georeferenced in order to be evaluated in various contexts. Samples taken by a MONSUN at the surface can easily be referenced due to the built-in GPS. The submerged AUVs, however, do not have access to a GPS signal and hence the data cannot be referenced in this way.

For effective and efficient swarm behavior, a reliable communication channel as well as precise localization is required. For the communication with submerged robots, traditional WiFi channels cannot be used; instead an acoustic channel is utilized to distribute mission specific data. For the localization at the surface, GPS is accurate enough, but in a submerged state, MONSUN lacks typical sensors such as sonars and Doppler velocity logs in order to keep the swarm cost efficient. Instead, the acoustic channel is used for this purpose as well. By measuring the parameters needed to calculate the speed of sound underwater and the round trip time of an acoustic message, it is possible to determine the distance of transmitter and receiver. Due to characteristics of the acoustic underwater channel, only two AUVs can communicate and measure the distance at a time, with the exception of broadcast messages. If two robots transmit data at the same time, the signals would interfere with each other, possibly resulting in the receiver not being able to decode either messages. Hence, in this case, a medium access strategy for the acoustic channel and the distribution of messages would be needed.

IV. COMMUNICATION PRINCIPLE

The localization and communication concept of MONSUN assumes that some MONSUN AUVs stay at the surface (S-AUVs) and the others dive to a given depth (D-AUVs). The S-AUVs obtain their positions by GPS and communicate with each other and a control station at a boat or at shore by WiFi. S-AUVs and D-AUVs communicate with each other by acoustic modems. The D-AUVs can easily measure their depth by pressure sensors and keep it stable by a depth control algorithm. Therefore, a 2D localization of the D-AUVs relative to the S-AUV in the corresponding plane is sufficient for them to compute their 3D positions. To achieve this, the distance d to the S-AUVs at the surface is used. This distance can be obtained by the acoustic modems via the round trip time of a sent message and its acknowledgement from the receiver. The Evologics S2C M 18/34 modems used for MONSUN support this feature.

Based on the distance measurements, various protocols and methods are possible. A simple and robust communication principle for V-formations is proposed in this paper (Figure 2). It assumes that two S-AUVs stay at the surface, one of them taking over the role of a master. Via GPS, both know their absolute positions and, from this, their relative distance s to each other. Behind the two S-AUVs, a D-AUV forms a V-formation with them. Up to n D-AUVs can be used, each with its own V-formation. The V-formations are first built up at the surface with all AUVs using GPS for their positions. Then the D-AUVs D_i submerge to their given depths h_i. Also given are the desired distances d_i^* to the two S-AUVs S_1 and S_2. The master S_1 then initiates the following simple protocol.

First, S_1 sends message 1 to D_1, which contains among others the desired course, speed, and distances of the formation. D_1 then sends message 2 to S_2 and finally message 3 to S_1. It should be noted that for each message, the modem of the receiver automatically generates an acknowledge message back to the sender. Thus, the transmitting modem can measure the round trip time. This is then used by the sender to compute the distance to the receiver. In this case, D_1 can compute distance d_1 to master S_1 and by sending message 2 to S_2 also distance d_2. Having both distances, D_1 can control its speed and course such that the desired distances d_1^* and d_2^* are kept and thus the V-formation is maintained.

To control the speed, the measured distances d_1 and d_2 are compared with the required distances d_1^* and d_2^*. If the measured distances are smaller than the required ones, D_1 is too close to S_1 and S_2 and has to reduce its speed. If they are greater, D_1 is too far away and the speed has to be increased.

For the course, the simplest case is that D_1 shall stay on a middle line between S_1 and S_2. In this situation, the course has to be controlled such that both measured distances stay equal, i. e. $d_1 = d_2$. If d_1 is shorter than d_2, D_1 has to turn to the right, and if d_1 is longer than d_2 to the left. This simple principle can be generalized to the case where d_1^* and d_2^* are different, i. e. D_1 shall stay on a line on the left or right behind S_1 and S_2.

It should be noted that these are not typical closed feedback control loops, but D_1 continues to drive with its course and speed autonomously in case no distance measurements are available due to lost messages. The distance measurements are only used for course and speed corrections whenever measurements are available in order to keep the V-formation.

This simple protocol can easily be extended to n D-AUVs, which are then addressed by the master round robin. For each D-AUV, only 3 messages are required which yields a total complexity of $3\,n$ messages for n D-AUVs. It should be noted that only point-to-point messages are used which are sent strictly sequentially. Complicated media access protocols are thus not necessary. The prize is the linear growing complexity with the number of D-AUVs which limits the scalability. However, up to $n = 5$ D-AUVs (meaning a position update each $7.5\,\mathrm{s}$) seems realistic, assuming $0.5\,\mathrm{s}$ per message which is typical for the used Evologics modems. It is also possible to build V-formations with the D-AUVs in front of the S-AUVs instead of behind them. For a larger number of AUVs, several clusters of V-formations can be used while the masters of each communicate by WiFi.

Unfortunately, acoustic communication is rather unreliable under water, e.g. messages often get lost. Therefore, the D-AUVs also receive their required course and speed from the master by message $3\,n$ and keep them using their compass and inertial measurement unit (IMU) in case the communication to the master is interrupted, e.g. they continue their navigation along a straight path autonomously until communication is up again. Unfortunately, this autonomous navigation is rather inaccurate due to sensor noise and drift. The protocol is, however, very robust, since the master initiates always new rounds, also in case of lost messages. By this, even after longer outages the course and speed control by the distances is automatically continued and an accurate navigation re-established.

Also a lost D-AUV can easily be tolerated, since the D-AUVs are addressed in independent rounds by the master. In the event of failures, the D-AUV surfaces in most cases automatically due to its positive buoyancy, while the rest of the formation continues working. In case of a failed S-AUV, a D-AUV can emerge and take over its role. Thus, fault tolerance for S-AUVs is also achieved.

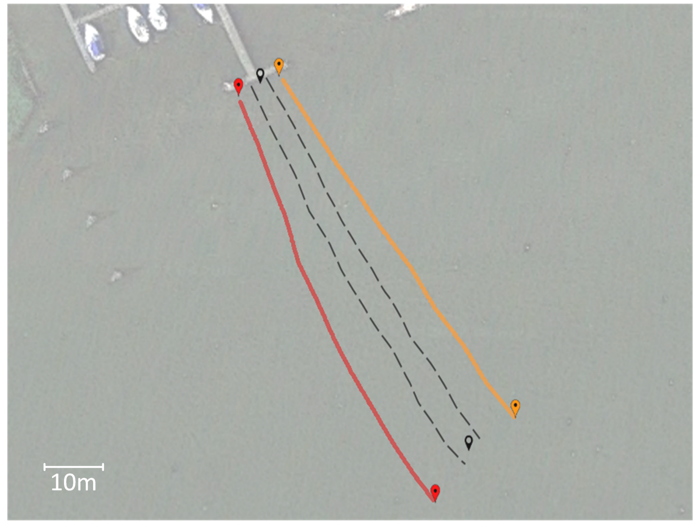

Fig. 3. Results of a test scenario with three formation building MONSUN robots moving in a V-formation in a shallow waterbody. Two robots drive next to each other at the surface, while the third AUV dives behind them at a depth of $1\,\mathrm{m}$. Depicted in orange is the course of the master AUV and in red the one of the second surface AUV. In a corridor marked with black dashed lines the course of the submerged robot is illustrated. The accuracy of the underwater position is dependent on the GPS deviations, the accuracy of the acoustic distance measurements and the reliability of the acoustic communication channel. In average the corridor has a width of $4.6\,\mathrm{m}$.

It should be noted that messages $3n-2$ and $3n-1$ can also be used for sending payload data (e.g. measurement values from payload sensors) from the D-AUVs to the S-AUVs, which in turn can transmit this data by WiFi to a user station.

V. EXPERIMENTS AND RESULTS

The communication principle was tested in a shallow waterbody called *Ratzeburger See*, a lake of $14\,\mathrm{km}^2$ located near Lübeck, Germany. Three MONSUN AUVs were launched at a peer next to each other and were supposed to move away in a V-formation along a straight line in south-east direction. As an auxiliary condition, the outer MONSUN AUV needed to move in parallel with an inter-AUV distance of $20\,\mathrm{m}$. With a point of view situated on the peer, the left MONSUN was navigated to a set of GPS coordinates, while the right AUV tried to reach the desired distance by compensation movements. A straight line was chosen as a course due to its suitability to test the reliability of the acoustic link as well as the communication principle. Furthermore this scenario poses relatively moderate requirements on the feedback motion controller. It should be noted that the speed correction was not yet used during this experiment. After the mission start, the third AUV in the middle behind the other two AUVs submerged with a delay of $10\,\mathrm{s}$ to a depth of $1\,\mathrm{m}$ before starting to follow the surfaced robots while trying to maintain an equal distance to both building a V-formation. The surfaced AUVs continuously measured their position with the built-in

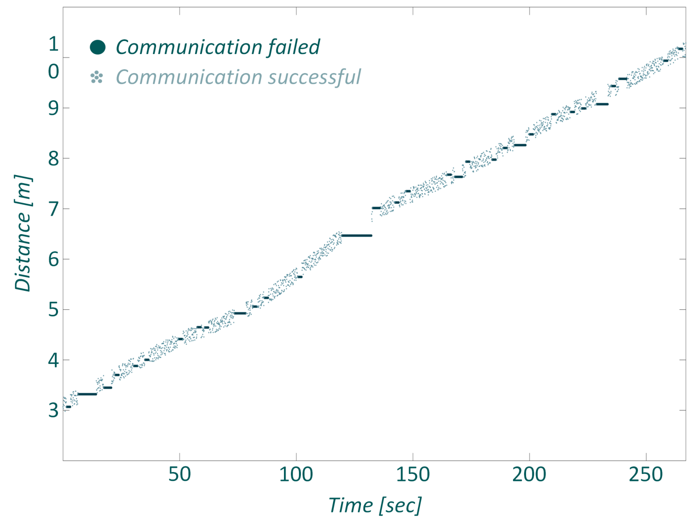

Fig. 4. This plot shows the measured distance of the submerged MONSUN from the robot to its right at the surface while diving in formation. The desired distance of 10 meters was reached after 4 minutes. The acoustic distance measurements variate on the average for not more than 20 cm. The cases of communication outage are depicted as bold straight lines compared to the lighter scatter plots. It was observed that communication outages are commonly appearing as cluster. During the test run, a total of 78 % of acoustic communication messages reached their destination. The longest acoustic outage lasted 13 s.

GPS and communicated via WiFi to reach a target distance of 20 m despite the presence of wind and waves. The diving MONSUN utilized its acoustic modem to repeatedly measure the distances to the two surfaced AUVs in order to follow them in a V-shaped formation.

The total length of the test track was 100 m and is illustrated in Figure 3. The course of the master AUV is depicted in orange, with the other surface AUV being red. At the start of the mission, these two AUVs had an inter-AUV distance of 8 m at the peer and the desired distance of 20 m at the end of the mission. While the master AUV took a straight course to the target, the other surface AUV needed to compensate while maintaining a parallel course. It took around two thirds of the mission time to reach the desired distance. The track of the diving AUV is shown in black. Instead of a drawn-through line, two dashed lines mark a corridor where the MONSUN was believed to be situated. Without being able to receive GPS coordinates in a submerged state, a ground truth could only be taken at the start and the end of the track, where the robot surfaced. The width of the corridor was calculated using the GPS deviation of the surface vehicles and the inaccuracy of the acoustic modems as well as the current reliability of the acoustic channel. In average, the corridor had a width of 4.6 m. This accuracy is comparable to most GPS systems.

Figure 4 shows the acoustically measured distance of the submerged AUV to the surface robot to its right. The desired distance of 10 meters was reached after 4 minutes. The measured distances are depicted as a scatter plot that shows a mean variation of only 20 cm. Considering this accuracy, the GPS uncertainty has a far higher influence on the localization of the submerged AUVs. In the course of the test run, a total of 78 % of acoustic communication messages reached their destination. Communication outages are displayed in the plot as bold straight lines, since no new distance measurements could be made. It could be observed that outages appeared in clusters. This could mean that the highest influence on the channel reliability are changing physical conditions. The longest acoustic outage lasted 13 s. For outages of comparable lengths, the AUVs are easily able to navigate without reference values from the surface by using their own sensors.

VI. CONCLUSION

This paper presents an approach and first results of an acoustic-based communication principle for the navigation of an underwater robot swarm. The approach is specifically designed to work with unreliable acoustic communication. We have proved the basic suitability of our concept under realistic conditions. The next steps are to further develop the navigation system to allow for more advanced paths and formations.

VII. ACKNOWLEDGEMENT

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