Networking Autonomous Underwater Vehicles to Automize Cooperative Missions

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***Abstract*—Research regarding AUVs has increased over the past decades. The interest is driven by the possibility to automatize underwater missions, requiring human interaction only at the base station for supervision. This avoids putting humans at risk, e.g., for mine countermeasures. Since AUVs are also relatively inexpensive and their mostly customizable equipment offers a range of applications, they are attractive from an economic perspective as well. This paper aims to provide an introduction to the networking of autonomous underwater vehicles to enable cooperative missions such as cooperative hunting. To give an overview, navigation methods and underwater acoustic communication, which is challenging due to multiple factors, are explained. Building upon this, different manifestations of underwater acoustic network architectures with autonomous underwater vehicles as mobile nodes are presented. We show numerous applications in which networked AUV swarms provide a significant benefit.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are unmanned, self-propelled vehicles designed to accomplish a predefined task in a self-organized way. AUVs have gained increasing popularity over the past years, in line with autonomous 'vehicles' on terrestrial areas and in aerial space [1]. AUVs, in comparison to submarines, automatize tasks, without the need for human assistance underwater, making such missions less expensive. The machines can also replace divers for dangerous missions, such as mine reconaissance, and conduct pipeline inspections for offshore oil platforms or even small repairs [2]. Advances in underwater communication techniques have enabled increasingly complex and flexible networks. The underwater communication usually uses acoustic signals, while on the surface radio signals are transmitted. These networks, so-called underwater acoustic sensor networks (UASN), can be enhanced using AUVs for, e.g., maintenance of their submarine infrastructure or accomplishment of specific other tasks, as will be mentioned in the following. Communication plays an important role for AUV operations regarding data retrieval, recharging, but most importantly also regarding the navigation of AUVs [2]. AUVs have a wide range of possible applications and tasks in different areas. The fact that they are able to act without human interaction and their relative inexpensive deployment contributed to an increasing popularity over the past decade [2]. In the following, selected real-world use cases of AUVs are listed. The main contribution of this paper is to present numerous applications like those, in which networked AUV swarms provide a significant benefit.

Security — *Underwater surveillance:* AUVs as part of an underwater network detect and classify submarines [3].
Mine reconnaissance: Equipped with optical and acoustic sensors, multiple AUVs cooperate to detect mine-like objects by high resolution imaging. Special sensors are necessary to detect in-volume mines [3].
Research — *Seafloor mapping:* The motivation behind creating seafloor maps and high quality images of the ground stems from detecting and localizing possible dangers for marine traffic (such as icebergs), exploring natural underwater resources or determining potential offshore construction sites [2], [4].
Industry — *Offshore maintenance:* AUVs are utilized to perform minor underwater repair works or inspections at offshore facilities. For example, AUVs specifically developed for pipeline inspection may be used for offshore oil platforms or windmill parks. The AUVs scan for corrosion and for deformations independently from surface vessels or the base for up to 24 hours [2].

This paper will first give an introduction to underwater acoustic sensor networks in Section II. Section III describes multiple cooperative missions using AUV swarms. The paper is concluded in Section IV.

II. UNDERWATER ACOUSTIC SENSOR NETWORKS

Advances in underwater communication techniques have enabled increasingly complex and flexible networks. The underwater communication usually uses acoustic signals, while on the surface radio signals are transmitted. These networks, so-called underwater acoustic sensor networks (UASN), can be enhanced using AUVs for, e.g., maintenance of their submarine infrastructure or accomplishment of specific other tasks, as aforementioned in Section I. Communication plays an important role for AUV operations regarding data retrieval, recharging, but most importantly also regarding the navigation of AUVs [2].

A. Common Navigation Methods

AUV communication and navigation are closely interrelated and often share the same channel. Navigation methods need accurate localization data for each target AUV. The choice of the navigation function or path planning algorithm influences the energy efficiency, obstacle avoidance ability, and adaptability of the operation [5]. Section III will introduce research on AUV swarm organization, which requires the understanding of some localization basics in AUV operations. There exist two major categories of localization methods relevant for Section III.

Inertial/dead reckoning positioning relies hardware-sided on the inertial measurement unit (IMU). The IMU provides measurements of a combination of accelerometers and gyroscopes. These measurements support dead reckoning, which describes the situation when an AUV navigates autonomously, without additional positioning support from a surface vessel. Dead reckoning suffers from unbounded growth of positioning error due to its cumulative nature [6].

Acoustic positioning measures the time of flight of an acoustic signal from a transponder with known GPS data, used as reference for relative positioning. For ultra-short baseline and short-baseline, the reference usually is a surface ship.

- Ultra-short baseline (USBL): Transducers on the baseline are maximum 10 cm apart.
- Short baseline (SBL): Distance of transducers is the ship length.
- Long baseline (LBL): Transducers are beacons located on the seafloor and triangulation is used for positioning.
- Acoustic modem: Rely on inter-AUV communication via acoustic modem instead of stationary sensors. This way, AUVs can exchange positions directly [6].

B. Architecture

In general, the UASN consists of the following components: underwater sensors at fixed positions, a main node, a surface buoy, and a base station. The sensor nodes report to a main node which in turn communicates with a surface buoy. In this configuration, the surface buoy acts as a gateway to the base station (a manned surface vessel or on-shore facility). This type of UASN is built as an 2D architecture. If the UASN additionally contains sensors which can vary their depth by moving vertically, it is called a 3D UASN (Figure 1). Within this architecture, AUVs act as mobile nodes [7].

C. Topologies

The topology shifted from fully connected peer-to-peer networks towards clustered topologies for scalability reasons. Clusters may consist of, e.g., an AUV and stationary sensors, respectively. Within clusters, time-division multiple access is used to regulate the access to the acoustic channel [9].

D. Challenges in Network Design

Designing UASN presents very particular challenges, due to the characteristics of the submarine environment, compared to terrestrial networks [10]. This section provides an overview of the most critical aspects of underwater communication. As reference [10] summarizes: 'Most of the described factors are caused by the chemical-physical properties of the water medium such as temperature, salinity and density, and by their spatio-temporal variation'.

To be able to fulfill tasks in the aforementioned applications of AUVs, it is desirable to cover large underwater areas in sparse network deployments. AUV as well as stationary sensors can act as relay nodes (hops). The distance between the nodes of the network is limited by the range of acoustic signals (around 20 km for long range communication, at cost of an increasing propagation delay). However, radio waves are only used at the surface level, but are usually infeasible underwater, because the distance they can travel underwater is smaller compared to acoustic signals [2]. The usage of optical methods is also subject to research, even though the range is shorter than the acoustic signal [11].

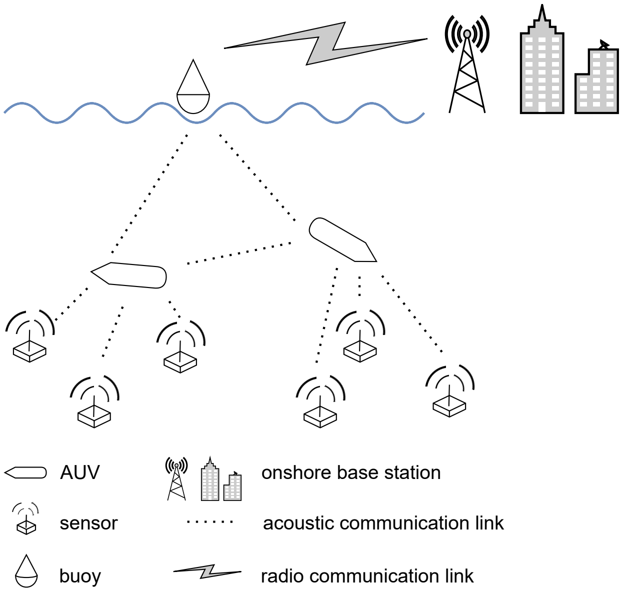

Fig. 1. A general underwater communication architecture [8]

Additionally, sound travels slower than speed of light by a factor of $2 \cdot 10^5$, leading to large propagation delays (speed of sound in seawater, e.g., 1.5 km/s), i.e., the change in frequency of the acoustic signal moving relative to the observer [12]. Another difficulty arises from the very *limited bandwidth* of the underwater acoustic channel, resulting in low transmission rates (as an example: 100 kbit/s for ranges $\leq$ 1 km, 10 - 50 kbit/s for medium ranges up to 10 km, and 10 kbit/s at 20 km). UASNs also suffer from high bit error probability due to fluctuations in phase and amplitude underwater [12].

Multipath interference, *fading*, and *shadow zones* are common phenomenons in UASN. *Multipath interference* describes the reflection of a signal causing the signal to arrive at the receiver via multiple paths. Under water, reflections may be caused by the surface, the seafloor, or obstacles and are time-varying. The signal reaches the receiver via different paths with different time delay, which can cause fading. Furthermore, this in turn may causes shadow zones - regions, where the signal is not traceable at all. The latter eventually destroys the network connectivity [10].

Not only the communication channel itself presents challenges to the engineers, but also considerations regarding the energy consumption and recharging must be taken into account. AUVs only have limited energy storage capabilities, namely their on-board batteries and need to be able to surface at recharging stations in time. Lastly, sound signals affect submarine environment. Animals such as dolphins use acoustic communication. Therefore, the frequencies for AUVs must be carefully chosen to fulfill ecological requirements [10].

E. Underwater Acoustic Protocol: the JANUS Standard

Research on AUV development and deployment has been conducted for over five decades [13]. However, no official, international standard for underwater communication existed to support interoperability, until 2017 JANUS was included in the NATO Standardization Agreement (STANAG). JANUS (named after the Roman god of beginnings and gate opener) was developed by the NATO Centre for Maritime Research and Experimentation as a multiple-access acoustic protocol with possible applications both in military and civilian missions. It is characterized by its robustness and 'can easily be adopted by a wide range of existing systems' [14]. By including this protocol in detail in this paper, the intention is to give an example of how acoustic communication can be implemented and how acoustic signal processing itself works [14].

JANUS is robust against multipath interference by using frequency-hopping binary frequency shift keying (FH-BFSK) on the physical layer. 'Frequency hopping is the periodic changing of the carrier frequency of a transmitted signal.' [15]. Binary frequency shift-keying (BFSK) uses a pair of discrete frequencies to transmit binary information [15].

Figure 2 shows the transmission sequence and acoustic waveform generation of a 64-bit JANUS Baseline packet. A Cyclic Redundancy Checksum (CRC) is generated to ensure data integrity. The requirement to handle frequency fading is met by using a 2:1 convolutional encoder.

Optionally, three wake-up tones may be generated before the transmission, in case that hardware within the network is in sleep mode to save energy. This step should be completed in time before the preamble starts, to allow the hardware to wake up. The 32 chip ('chip' replaces the term 'bit' on the physical layer, both referring to binary data) preamble serves as synchronization mechanism, before the actual payload is transmitted as a sequence of tones. The above described phases are executed parallel to the generation of the 32 chip preamble and - if selected - wake-up tones, to ensure that the actual payload can be appended directly, without time delay. The order of tones for the payload encoding is chosen to avoid multipath interference or collision with JANUS packets from other users. The chosen frequency band **Bw**, about 1/3 of the center frequency **Fc** (default: Fc = 11520Hz, Bw = 4160Hz), yields the chip duration **Cd** and the frequency slot width **FSw** (default: FSw = 160Hz, Cd = 6.25ms). The chip sequence may be transmitted using Tukey windowing to minimize the sidelobes of the square wave signal. Sidelobes are the consequence of sharp edges in signal modulation [16] and are minimized to distinguish the signal from external interference. After the baseline JANUS packet, the message's 'body', i.e., user-specified payload, may be appended [14].

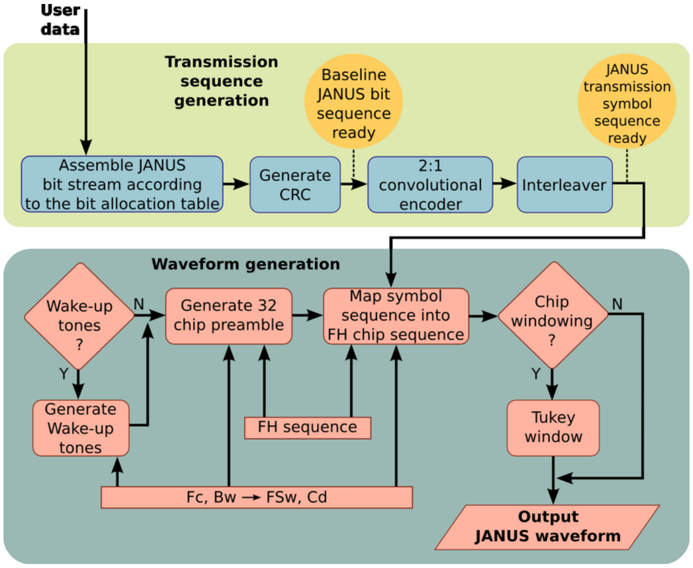

Fig. 2. JANUS packet generation [14]

F. Routing Protocols

An important, complex control mechanism for adjustments in networks are routing protocols. They can improve the overall efficiency and are designed to adapt to the specifics of the network. For UASN, there already exists a number of protocols, which to present would have been out of the scope for this paper. The routing protocols should satisfy the condition of robustness in case of intermittent connectivity and in event of connectivity loss should not provoke immediate retransmissions due to the limited bandwidth [7].

III. COOPERATIVE MISSIONS

Underwater communication, as stated before, is key to efficiently deploy more complex autonomous underwater operations, whether the goal is to transmit data as reliably as possible, or to extend the operation to coordinated, multiple AUV tasks. Some advantages of networking multiple AUVs are, that firstly completely new tasks can be fulfilled, such as hunting [5], which would not be possible otherwise. Secondly, it has been shown that AUVs position themselves more accurately, if they are able to exchange location data. This approach works even if communication with surface vessels is not possible (e.g., ice-field operations) [17]. Lastly, existing tasks can be completed in a more efficient and faster manner, e.g., seafloor mapping [4]. Research on coordinated AUV operations has become increasingly relevant and widespread, because of those promising features. This section points out selected coordinated missions of AUVs. The first research topic is the formation of multiple AUVs, followed by the use cases seafloor mapping and hunting.

A. Formation

The formation of multiple AUVs on a coordinated mission can take communication constraints (limited bandwidth, large propagation delays) into account and is thereby a dedicated field of research [2].

In [18], the authors present a formation-flying algorithm which approaches the challenges of the acoustic channel by minimizing the overall acoustic communication. The authors' idea is to benefit from proximity to reduce data transmission time and reaction time among the AUVs. In case that a vehicle drops out of the formation (e.g., due to loss of communication), the formation can also be recovered quickly when the vehicles remain in close proximity at all times.

The formation consists of one leader and a number of followers. The leader uses acoustic long baseline for navigation, the followers use long baseline measurements of their inertial position and the leader position. If communication with the leader is lost, any other AUV may take over this position. If all communication among the AUVs is lost, however, all AUVs independently fulfill their respective tasks, localizing themselves with their inertial LBL. The AUVs must keep a certain distance to each other and the leader, due to formation constraints and also due to their configuration. The distance is calculated relative to the leader only, the leader serves as central measurement point for all followers. If necessary, the distance is corrected via change of velocity. The acoustic communication only takes place in form of 'intermittent broadcasts from the leader' [18].

In [4], a swarm of AUVs is used to experimentally increase the overall covered area in seafloor observation missions. For this purpose, the AUVs are divided into two groups, the main group and the sub group, respectively. Principally, the procedure is described as follows: The main group consists of the AUVs which act as alternating landmarks in the formation. At any time, a single AUV takes the position of a landmark and remains stationary at the seafloor for that time. All AUVs calculate their state from the ground velocity, the angular velocity and their relative positioning with this landmark AUV A1. The AUVs can move and observe the area around the landmark within the communication range. To switch the landmark position, another AUV A2 from the main group lands in some distance to A1. Then A2 performs multiple positioning calculations relative to A1 to reduce uncertainties in positioning. A2 sends its compressed state to A1. During this role transfer, the AUVs - except A1 and A2 - use their own navigation system. After the transfer, all AUVs except A2 can move again, relative to the new landmark A2.

B. Simultaneous Localization and Mapping

Research for multi-AUV deployment has also adopted methods and integrated experimental results from terrestrial multi-robot systems. An example is the simultaneous localization and mapping technique (SLAM), where robots need to create a map and localize themselves within the map concurrently. The map is created by observing landmarks, e.g., detected by side-scan sonars. It was shown in terrestrial experiments, that the robots can improve their own state estimates and the environmental observations if they share data [17]. As [17] states: '(...) terrestrial CSLAM systems are built upon assumptions of communications throughput and bandwidth, which are unattainable underwater.' This enforces adaptations of the traditional, terrestrial tested CSLAM. In this section, a CSLAM process developed for AUVs is presented.

Reference [17] proposes '(...) a framework for cooperative SLAM (CSLAM) for multiple AUVs communicating only through acoustics.' Therefore, a surface vessel becomes expendable, which is advantageous when an AUV mission requires covertness (security use case) or the mission takes place in inaccessible areas (ice-fields). The authors specifically generate the communication packets to match with the constraints of the underwater channel, mainly severely limited bandwidth and packet loss ('develop the first multi-AUV CSLAM algorithm that is specifically designed to operate solely with low-bandwidth acoustic communications.' [17]).

The authors state, that the communication packet size in their proposed method increases linearly with the number of observations since the last successful message passing and constantly with the number of AUVs in the network. This is advantageous in presence of the limited bandwidth of the acoustic channel, because the overhead is not growing extensively. This is achieved by reducing packet size with an optimal marginalization of intermediate pose estimates and converting the result into a sparse matrix. The pose is determined by six degrees of freedom (three for orientation and three for translation, respectively). Access to the acoustic channel is regulated using time-division multiple-access with statically assigned slots.

AUVs can make observations of each other either by direct or indirect encounters. When the AUVs calculate the relative range of each other after acoustic packet transmission, it is a direct encounter. For that purpose, the AUVs are equipped with synchronized clocks and calculate the time of flight of communication packets. Otherwise, the AUVs can calculate relative measurements from observing the same landmark in the underwater environment (indirect encounter).

The approach uses decentralized estimation, avoiding single points of failure. Each AUV keeps track of its own trajectory, the poses of other AUVs, and the detected landmarks. This system is represented in a special data structure for probabilistic relationships, approved of in terrestrial SLAM: the so-called factor graph. Factor graphs are bipartite, undirected graphs, with variable nodes as one set of nodes, and factor nodes as the other set. Factors are functions of only the adjacent variables [19]. In this instance, the functions are odometry, relative range measurements from time of flight, landmark observations, GPS positioning data, and the resulting matrix from the marginalization step. The GPS data may be obtained (at surface) periodically or at least once before deployment to get the initial relative distances between the AUVs.

The poses of the other AUVs are always obtained at communication time. To achieve consistency of the factors among all AUVs, the method implements a contact book for each AUV, containing the most recent confirmed (= acknowledgment packet received) in- and outgoing contacts. Since the AUVs broadcast packets, it would not be possible to track the interactions otherwise. The contact points serve as reference for generating the local factors, which are to be transmitted. Additionally, the system does not fail if outgoing packets or their acknowledgments are dropped.

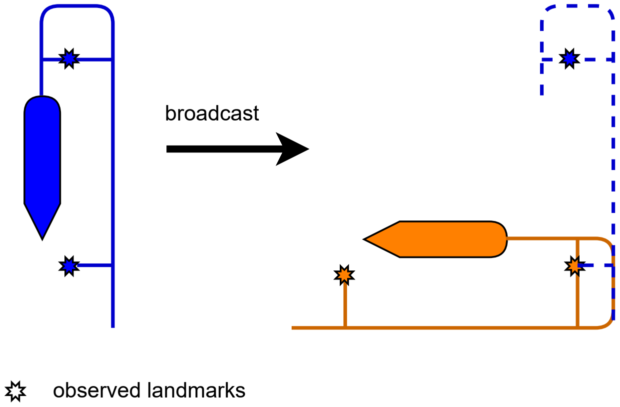

Fig. 3. CSLAM data exchange at communication time t_1, adopted from [17]

Figure 3 visualizes the process of coordinated simultaneous mapping and localization using a simple scenario with two AUVs (AUV_1, orange and AUV_2, blue). Both are scanning the seafloor and add the detected landmarks to their local map (line in their respective color). From left to right: at a certain time, t_1 AUV_2 makes a broadcast, which AUV_1 receives. The receiver now calculates the relative distance to AUV_2 (localization), using time of flight, and integrates the landmarks detected by AUV_2 in its local map (dotted line).

To validate the bounded uncertainty of the CSLAM approach in [17], MOOS, an open source software framework developed by MIT was used. Two vehicles were simulated for three cases within a predefined mapping area: no communication, application of the proposed scheme, and full bandwidth simulation (which is unfeasible in a real-world scenario). The parameters for the proposed scheme were chosen as follows: packet transmission every 10s, drop rate 50% and maximum packet size of 192 bytes. The results showed that uncertainty was bounded and close to the full bandwidth simulation result, but without communication the uncertainty was unbounded.

C. *Cooperative Hunting Using Artificial Intelligence*

The usage of cooperative AUVs is especially of interest for search tasks (such as mine reconaissance), because of the wider area the AUVs can span together within a shorter timeframe [4]. Closely related to searching a moving target are hunting tasks. The research of automated underwater hunting aims to extend the search of static targets by dynamic algorithms, to adjust the task assignment and path planning according to the changing position of the target. Additionally, the target is 'captured' at the end, i.e., surrounded by AUVs to prevent it from moving. Possible applications can be found in the security section, comparable to those of unmanned aerial vehicles (UAV), which have been enabled to capture/destroy non-cooperative drones [20]. Under water, the targets could be robot fishes, other AUVs, or submarines [2], [5]. In what follows, we will describe the work of [5] in more detail.

In the aforementioned research, the authors present a solution for cooperative hunting, taking into account groups of AUVs with different speed, intelligent evaders, and obstacles. The implementation consists of two main components: the dynamic formation algorithm, to determine which of the AUVs form a team to hunt an evader, and the path planning itself, which combines a Glasius-inspired neural net (GBNN) with a belief function. After the AUVs have located an evader, the dynamic hunting algorithm is applied, yielding the team scheduled to hunt the evader. Then, the path is planned to capture the evader. These steps are repeated until all evaders are captured. The proposed methodology can be applied to both the 2D scenario (ground hunting, at seafloor level) as well as the 3D environment. In 2D, four AUVs per team are necessary to surround the target, while in 3D six AUVs are required (additionally one above, one below the target). Intelligent evaders are assumed to take two different basic approaches (in 2D) to flee from the AUVs: in the first case, the AUVs have not yet formed a cycle around the target. The target will therefore try to escape in the opposite direction. If, in the second case, the AUVs are forming a cycle, the evader is assumed to choose the path between the two AUVs with the largest distance.

Search for evaders: Approaches for this initial phase are described, by the authors, in a previous publication [21]. To exploit the potential for high parallelism and avoid double searching of the same space, the underwater search space is divided into equally sized subspaces. These are assigned to the AUVs in a shortest-distance competition. The AUVs navigate through their respective space, using a combination of a self-organising map and a GBNN to achieve a high coverage rate and avoid obstacles. Only the total number of targets and the boundaries of their respective search space are known beforehand. Targets are detected by, e.g., side-scan sonars, so the AUVs must be capable to recognize a target in some way.

Dynamic hunting alliance formation: The hunting alliance formation stage chooses the evader with the least estimated hunting time, computed under consideration of the velocity and distance of the AUVs, to be hunted first. Also, the team of AUVs to hunt this evader is formed.

Path planning: After the team formation, the AUVs need to plan their way to follow and eventually catch up to the evader. The planning must be completed fast, to adapt if necessary to the moving target. The authors propose the combination of a neural net, GBNN, and a belief function. Neural nets stem from the area of artificial intelligence and model the human brain. Visually spoken, it consists of 'neurons' connected by 'synapses' [22]. For the underwater path planning, the neurons represent single cells in a grid overlay of the environment and can take a value ('activity') in the interval [0,1]. The higher the activity of a neuron, the more an AUV will be drawn towards that cell. Belief functions are applied to a subset of a set of possibilities, and their result represents the (subjective) belief that the true possibility is part of this subset [23]. The authors chose the belief function, because it '(...) has the advantages of quick response, small calculation and certain obstacle avoidance ability' [5], while the GBNN requires more complex calculations and therefore introduces a delay between change of environment and reaction to that change.

The path planning processes as follows: while the AUV is still not close to the target, the belief function effect is larger than the GBNN effect to steer the AUV in the general direction of the target. That is achieved by keeping the value of the GBNN neurons representing free cells far away from the target small, and increasing the value only when the AUV gets closer to the target. Then, the GBNN effect in turn is larger than the belief function effect, hence taking charge of steering the AUV into the direction of the previously 'assigned' target. Simplified, the neurons representing free cells have increasing values when approaching the target and the values of free cells are always greater than zero, whereas the neurons representing occupied cells (occupied by, e.g., other AUV or obstacles) have a value of zero. The belief function is less than zero at occupied cells. That means AUVs follow cells with increasing neural activity while obstacles are avoided.

Capture: The hunting of one evader is completed upon successful capture. That is, in the 3D scenario, the AUVs either form a circle around the target 'close enough' [5] and one above, one beneath the target . For the 2D scenario, four AUVs are required to surround the target. Applying to both cases, if there exists an obstacle, blocking at least one direction, the number of AUVs may be reduced.

Finally, the method showed better results in a 2D Matlab simulation than comparable methods. The compared variable was the average distance each AUV completed before all evaders were captured. For the 3D scenario, no quantitative comparison could be presented, because only the proposed algorithm managed to complete the hunting task successfully.

Regarding the utilization of inter-AUV communication, the challenges in underwater communication are not discussed, except for explaining the choice to use competition-based functions (fastest AUV wins) for cooperation instead of negotiation (make a joint decision), because the latter produces too much load for the acoustic channel.

IV. CONCLUSION

This paper provides an introduction to the networking of AUVs into swarms. We present different missions such as formation, seafloor mapping, and cooperative hunting, which can benefit from networked AUV swarms. For instance, the hunting operation is a very specific use case, developed for counteraction against microrobot fishes. This use case shows, how neural nets can successfully take over the task of path planning for a team of AUVs. As part of future work, we will show how software-defined networking can be used for underwater acoustic sensor networks and we will simulate cooperative missions in the network simulator OMNeT++.

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