Received July 1, 2019, accepted July 16, 2019, date of publication July 19, 2019, date of current version August 7, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2929932

An Overview of Next-Generation Underwater Target Detection and Tracking: An Integrated Underwater Architecture

HUMA GHAFOOR[1] AND YOUNGTAE NOH[2]

[1]School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Islamabad 44000, Pakistan
[2]Department of Computer Engineering, Inha University, Incheon 22212, South Korea

Corresponding author: Huma Ghafoor (huma.ghafoor@seecs.edu.pk) and Youngtae Noh (ytnoh@inha.ac.kr)

This work was supported by INHA UNIVERSITY Research Grant.

ABSTRACT Military forces of every country are trying their best to protect their motherland from the attackers. With advancement in marine technology, it has become critical to detect and track the target by obtaining active measurements before it is close enough to attack. The utilization of unmanned underwater vehicles for target tracking behavior is gaining great attention due to continuous advancement of underwater vehicular technology. Nevertheless, safe and stable communications issues among different acoustic devices are still under active investigation to reach a robust, secure, and flexible underwater networking. Moreover, due to harsh underwater environment, acoustic simulations are also time-consuming; therefore, an accurate model for target detection and tracking is a necessity. Apart from the harsh environment of underwater networks, various technologies emerging for terrestrial networking are also becoming the part of underwater networking. For instance, cognitive acoustic networks, software-defined networks, network function virtualization, cloud computing, fog computing, and internet of underwater things; all are leading to trusted next-generation underwater networks. In this paper, we first provide a comprehensive survey of unmanned underwater vehicles and different ray tracing models essential in target detection and tracking that answers several questions regarding the current necessities of underwater networks and finally, provides a solution that opens several doors for research community to excel in this area.

INDEX TERMS Internet of underwater things (IoUT), ray tracing models, underwater acoustic networks (UAN), unmanned underwater vehicles (UUV).

I. INTRODUCTION

The networking in the ocean is an advancing technology that has been drawing abundant attention for the last two decades. A technology that allows communication among different acoustic users dealing with different applications that ranges from the depths of the ocean to the sea surface is called as underwater acoustic network (UAN). Due to the limitations of resources and complexity of ocean environment, wide-range of efforts has been dedicated to tackle the problems of communications in underwater networks [1]–[4]. Similarly, the target detection and tracking in the ocean is becoming a critical issue due to increased demand of attaining manageable development of ocean resources. We consider target detection and tracking as a communication problem, since several entities need to be involved to make the detection process secure and reliable.

Target tracking is one of the important applications of underwater wireless sensor networks (UWSNs). It is a sophisticated process that estimates the state (position, velocity, acceleration) of single or multiple moving targets by conducting the possible measurements that can be available from different types of sensors. Different unmanned underwater vehicles (UUVs) can be used to detect the underwater targets that cannot be detected by fixed sensor nodes. Literature has several sonar-based target tracking algorithms that utilize underwater vehicles (mostly autonomous underwater vehicles (AUVs)) to submerge the equipment into water [5]. Sonar systems have the capability of estimation of both spatial and temporal wave fronts however, the most essential mission of sonar arrays is the estimation of direction-of-arrival (DOA), i.e. bearing information [6]. Two types of sonar systems are

The associate editor coordinating the review of this manuscript and approving it for publication was Fang Yang.

available for underwater target tracking: a sonar system that listen the echoes after transmitting the pulses is known as active sonar whereas the one who detects the noise made by others is called passive sonar.

Active sonar systems provide both range and bearing information [7]. Three different types of active sonar systems are used to detect and track the target: monostatic (both transmitter and receiver are co-located), bistatic (receiver is separated from transmitter), and multi-static (one transmitter and multiple receivers). To estimate the target bearing and range with special diversity, a broadband signal model is used that has been proved in the simulation results of [8]. Passive sonar systems only provide bearing information. Solving bearing ambiguity is the most common issue of passive sonar systems. The systems have arrays of linear geometry that causes difficulties in distinguishing the signals; either they are originating from the right or left of the arrays [7]. Passive sonar systems are used to analyze the features of UUVs especially AUVs. Due to the advantages of target tracking based on three-dimensional (3D) measurements and sensor management, active sonar systems have received great attention over passive sonars [9], [10].

However, due to the advancement in technology, the smart next-generation underwater devices are stealthy which cause difficulty for the defense agencies to predict the sounds or echoes of the target on time. This leads to another reason that passive sonar is not suitable for robust detection in the modern next-generation underwater technology. Sound propagation in the ocean is affected by several acoustic properties of the medium. To have timely measurements, the tracer should be fast and flexible [11]. Several ray tracing models have been developed to provide acoustic simulations timely. Though, the accuracy of any ray tracing model depends on the validity and implementation of the ray theory. A few simulators/emulators (UnetStack, DESERT, WOSS, and SUNSET [12]–[15]) for underwater communication systems have been designed to conduct experiments and test the validity of different algorithms. Nonetheless, before choosing a simulator/emulator, an accurate emulation of sound propagation and channel model is a significant choice to provide an accurate picture of UAN.

Various novel techniques and standards have been proposed recently that play a crucial role in building next-generation underwater networks [5], [16], [17]. Likewise, terrestrial communication systems, interoperability issues due to several underwater communication approaches based on different proprietary protocols have been aroused in underwater communication systems. Underwater cognitive acoustic network (UCAN) and software-defined underwater network (SDUN) are two emerging technologies that resolve the interoperability issues in underwater communication systems. Moreover, network function virtualization (NFV) along with cloud and fog computing, the components of internet of underwater things (IoUT), are becoming popular to explore numerous underwater applications and resources and to resolve various issues (especially energy consumption and latency) in this challenging domain.

The key contributions of this paper are as follows:

i A thorough review of unmanned underwater vehicles utilized for target detection and tracking and analysis of their characteristics along with existing issues are presented.

ii We discuss several ray tracing models with the purpose of their development, features, and the open challenges for the designer to modify the existing issues in their codes.

iii A novel next-generation underwater target detection and tracking technique is proposed to open several doors for research community to excel in this area. The proposed solution considers several acoustic devices at different control layers to integrate SDN, NFV, and fog computing in underwater networks to reduce complexities in the existing infrastructure.

The remainder of the paper is organized as follows. An overview of unmanned underwater vehicles used for detecting and tracking the targets is presented in Section II. In Section III, we discuss the ray-tracing models essential in target detection and tracking, while Section IV first gives a brief introduction of each of the novel terminologies discussed in Section I, the literature using these notions to improve underwater communications, and lastly provides the solution for next-generation underwater target detection and tracking. Finally, Section V concludes the paper.

II. UNMANNED UNDERWATER VEHICLES FOR TARGET DETECTION AND TRACKING

Unmanned underwater vehicles (UUVs) are becoming part of underwater surveillance systems due to their persistency of monitoring a specific area with low costs [18]. UUVs are evolving as Navy's seaborne which is equivalent to Air Forces' drones [19]. A target tracking scheme using UUV to resolve bearing ambiguity for unique passive sonar system by executing maneuver after target detection is proposed in [7]. The system was unique because the arrays were originally designed for active sonar system and was repurposed for passive sonar system. Maneuver was executed due to the incapability of passive sonar systems to distinguish between port and starboard sides of arrays. Due to repurpose system, the performance was not good, but the system has advantage of target tracking with low cost due to not demanding any additional sensors. A coordinated scheme to track a maneuvering target by multiple UUVs with variable velocity and time delays is proposed in [20]. To achieve the goal, the information of neighboring UUV state, target state, and target acceleration is required. The scheme does not assure stability due to not considering time-varying factors of switching topology. The self-localization of UUV with a bounded estimation of its position based on signals from sources of opportunity (SOOs) is presented in [21]. The technique considers waveguide invariant and Doppler Effect and is known as waveguide invariant Doppler-based localization (WI-DBL) technique. The simulation results show that position estimation is reliable with less error in shallow water whereas deep water environment has some limitations. Three types of UUVs are equivalent to the drones of the sea: AUVs, remotely operated vehicles (ROVs), and gliders [19].

A. AUTONOMOUS UNDERWATER VEHICLES (AUVs)

AUVs seem to be a practical device for monitoring, observing and inspecting the ocean. These are autonomous vehicles that propel themselves through the water for durations of few hours to numerous days without the need of their dropping vessels. AUVs move at the speeds of almost 1.5 to 2.0 m/s on fixed trajectories. They are battery-powered vehicles with high energy density. However, high cost is required to provide enough energy for the completion of the whole mission, as duration of batteries is limited. Due to these batteries, AUVs have light-weight power sources where docking stations are required to recharge the batteries [22]. AUVs need less turning time to make 180-degree shift and may provide covert and silent operations such as mine hunting [23]. There are also some operative and deployable limitations that do not allow AUVs to move in areas of high military, shipping, or fishing activity [24]. Nevertheless, to perform several underwater tasks in a fully automated mode, AUVs are emerging as an efficient and reliable solution for various underwater complexities. The development of AUVs was started in 1990s at the research centers for gathering data and performing tasks that could not have been done in any other way [25].

To track the movement of AUVs working as receivers for multi-static sonar surveillance network, a data-driven nonmyopic approach has been proposed in [26]. The objective of the algorithm was to minimize the expected estimate error generated by the onboard tracker while locating the target. Error minimization is significant in state estimation of targets for maintaining tracks. The algorithm performs better for making decision about AUV by estimating tactical situation with a drawback of an increase in computational overhead. The results are the first successful demonstration at sea to control real-time movement of AUVs in a realistic surveillance scenario. However, a framework to deal with multiple tracks depending on the growing tactical scenarios is yet to be developed. A total of 25 experts that are part of development in adaptive mission planning (AMP) have reviewed a survey to find the answer why AUVs have not yet been deployed for AMP [27]. It was difficult for them to find clearly a single cause for failure to implement AMP; however, the main reason is the lack of demonstrations.

The authors in [28] used AUV to bridge the gap that hinders cooperation among vehicles of different architectures and modems. An AUV developed and built by the Department of Industrial Engineering of the University of Florence, MARTA AUV was particularly used to allow cooperation and data transmission among vehicles of multi-vendors modems. The experiments conducted with the help of SUNSET Software Defined Communication Stack (SDCS) framework (University of Rome La Sapienza) that opens doors for complex networking scenarios where heterogenous vehicles and systems are deployed. Another scheme proposed in [29] to solve the target tracking problem of AUVs in 3D space considered three-layer neural network and an adaptive robust controller to overcome the hindrances caused by wind, waves, and other environmental factors. The scheme assumes that AUVs are equipped with range and heading sensors, however for real implementation these sensors are of vital importance. Among several algorithms that exist in literature to track single vehicle, fleets of AUVs are also used to achieve the same goal.

A novel method [30] for the tracking of multiple AUVs is based on Probability Hypothesis Density (PHD) filter to predict the position as well as velocities of the vehicles. This is the first AUV tracker that tracks multiple vehicles in real scenarios and its validity has been approved through successful experiments. However, the scheme is limited to only underwater robotics. A passive method known as Reverse Bearing Only Target Motion Analysis (Reverse BO-TMA) for the self-localization of AUV is presented in [31] that allows AUV to maintain its distance from the source vehicle without requiring any cooperation. The accuracy of the method has been validated both numerically and experimentally; however, the method does not support inertial navigation system of AUVs. Another mathematical model is presented in [32] to analyze the probability of detection of mobile target by using AUVs. The method uses a passive sonar system to analyze the features of AUV. Likewise, for active sonar, a coherent-noncoherent joint processing framework is proposed in [8] to detect a small target in shallow water.

B. REMOTELY OPERATED VEHICLES (ROVs)

ROVs are human-controlled and tether-dependent vehicles that remain tethered to the source vessel and used mostly in applications where continuous supervision of manpower is required. These vehicles are generally equipped with cameras and can travel in the ocean as far as their tether let; therefore, they are mostly used in applications where visual information is required. They have continuous power sources used for both electrical power and communications [22]. Due to their tethered factor, ROVs draw more power and noise, and can communicate real-time data [24]. They move with less speed and have limited spatial range than AUV. They have high risks of tether's failure and are heavy weight vehicles due to the requirement of tether management system (TMS). They have high turning times typically of 4 – 6 hours [33]. A 3D model-based matching method and Real-time Multi-step Genetic Algorithm (GA) for vision-based real-time estimation of target's position and orientation by using a ROV is presented in [34]. The experimental results conducted in a pool showed that the system is robust and accurate enough to overcome environmental hindrances that not only affect the images but also the vehicular movement. An integrating scheme is proposed in [35] to emphasize the challenges of deploying,

TABLE 1. Characteristics of unmanned underwater vehicles.

UUVs	Staying Period	Energy Consumption	Speed	Features	Merits	Demerits
AUVs	Long	less than ROVs	fast (1.5 – 2 m/s)	○ Fixed trajectories ○ Active power propelled system ○ autonomous	○ autonomous ○ no need of dropping vessel ○ having fixed trajectories ○ propel for few hours to numerous days ○ high speed from 1.5 to 2.0 m/s ○ battery-powered vehicle ○ light-weight power source ○ high energy density ○ perform covert and silent operations ○ less turning time	○ limitations to move in specific areas ○ limited durations of batteries ○ high cost required to provide enough power for mission completion ○ for continuous power source, docking stations are required
ROVs	Short	high	less than AUVs	○ Vision-based monitoring ○ Human-controlled ○ Travel as far as tether let	○ Tether-powered vehicles ○ Continuous power source due to tether ○ Used for both electrical power and communications	○ Travel as far as tether let ○ Risk of breakdown of tether ○ Noisy operations ○ Heavy weight due to tether management system ○ Low speed ○ High turning time
Gliders	Long	less than AUVs and ROVs	less than AUVs and ROVs	○ Not fixed trajectories ○ Difficult to control ○ Lack of power propelled system	○ Stay for long periods ○ Having undulating trajectories	○ Not fast ○ High cost required to provide enough power ○ Difficult to control

developing, and testing 3D electromagnetic sensors on different ROVs and AUVs. The objective is to enhance target detection, tracking, and classification for specific underwater defense scenarios and missions.

C. GLIDERS

Gliders have the capability to stay in the ocean for long periods with less energy consumption as compared to other two UUVs. Gliders have undulating trajectory as they propel through water using a buoyancy engine. They are not as fast as other UUVs therefore are difficult to control due to lack of power force systems. A recently developed wave glider [36] has the potential to become an important part of acoustic applications as it is mobile and could coordinate with the other ocean devices accordingly. Also, it could reduce energy costs for long durable missions. A novel hybrid heading tracking control algorithm to advance the flexibility and robustness of heading control of underwater glider is presented in [37]. Heading tracking control considers all the present and future information about the target area by reflecting the planned behavior during a mission [38]. Peter-II 200 was used to model the controller and an adaptive fuzzy incremental PID (AFIPID) along with an anti-windup (AW) compensator was considered in this algorithm. The results showed that with AFIPID and AW compensator, desired heading can be maintained even in harsh underwater environment. Due to the self-adaptation of parameters controlled by AFI system, the cost for testing underwater glider in the ocean can be reduced. A summary of all the schemes described in this section is given in Table 2.

In a nutshell, due to autonomy and the active power propelled system of AUVs, they are the best suited UUVs for underwater target tracking (see Table 1). AUVs are used to classify targets (either hidden in the depths, rocks or locate at the sea surface) due to having capability of reaching the depths of the oceans. But AUVs have the battery charging issues, which need to be considered while proposing a novel next-generation target detection and tracking scheme. Also, energy consumption is a critical issue in underwater sensor networks; therefore, integration of different novel technologies is required to solve this issue for oceanic environment. Here, we briefly discuss the existing solutions in literature for the issues of underwater energy consumption.

Ambient energy harvesting joined with supercapacitors is an up-and-coming technology to remove the necessity of using batteries and entrust only harvested energy for operational purposes [39]. Solar energy is the promising energy harvesting technique for terrestrial networks. It can be employed in IoUT with solar-powered AUVs. Solar-powered AUVs need to operate on the sea surface for battery charging via solar energy input. Other energy harvesting techniques for IoUT can be piezoelectric energy harvesting and ocean thermal energy [40]. Energy consumption is a critical issue in target tracking that can be resolved by implementing energy-efficient algorithms for target tracking. An adaptive sampling algorithm for target tracking is proposed in [41] that considers two-input-single-output fuzzy logic controller. The algorithm maximizes the energy efficiency by designing an adaptive sampling interval adjustment (ASIA) method and balances the energy consumption by developing

TABLE 2. Summary of related target tracking schemes.

Target Tracking Schemes	Strengths	Drawbacks
[7]	Unique, low cost target tracking scheme repurposed for passive sonar system	Due to repurpose system, performance was not good
[20]	Coordinated multiple UUVs	Not assure stability
[21]	Self-localization of UUV, reliable estimation, and less error in shallow water	Limitations in deep water
[26]	Data-driven nonmyopic approach to minimize expected estimate error	Increase in computational overhead
[27]	Survey to find why AUVs fail to deploy in adaptive mission planning	Lack of demonstrations
[28]	Cooperation among vehicles of multi-vendor modems	a specific AUV was used
[29]	Target tracking in 3D space	Range and heading sensors assumption
[30]	Tracking of multiple AUVs to predict vehicles' positions and velocities, experiment successfully	Limited to underwater robotics only
[31]	Passive method for self-localization of AUV, accurate method that maintains distance without any cooperation	Not support inertial navigation system of AUVs
[32]	Detection of mobile targets using AUVs	Only applicable for passive sonar systems
[8]	Joint processing framework	Not tested for passive sonar systems
[34]	Vision-based real-time estimation of target's position using ROV with robustness and accuracy of handling hindrances	Experiment was conducted in pool
[35]	Integrating sensors on different ROVs and AUVs	Tested only for specific scenario
[37]	Hybrid heading tracking control algorithm that reduces cost due to self-adaptation of parameters	Planned behavior was considered during a mission

a dynamic uncertainty threshold adjustment (DUTA) method. The authors prove 36% of energy saving in different tracking areas through simulation results.

A 3D underwater target tracking (3DUT) algorithm [9] is proposed to minimize energy consumption by incorporating a target-movement-based duty-cycle mechanism. The approach is an efficient alternate for sonar-based target tracking algorithms. Another adaptive method based on Kalman filter to minimize energy consumption in 3D underwater environment for target tracking is proposed in [42]. The method uses sleep/wake plan to track the mobile target with the trilateration method. The results show reduction in energy consumption by 33% and improvement in location error by 45%. An active detection on virtual time reversal (ADVTR) method is proposed in [43] to consider AD for channel estimation and VTR for focusing when the source-receive array (SRA) receives the reflected signal of target. Bellhop simulator was used to verify improvement in the energy of SRA and accuracy of estimating target.

All these energy-efficient protocols have been proposed with some specific designed purposes to show improvement in the overall system. None of the schemes discussed above have been considered all the aspect of target detection and tracking algorithms. The target tracking using underwater sensor networks has been gaining great attention due to low cost, medium level precision and complexity, rapid deployment, self-organized nature, real-time monitoring, and wide-range distribution [5], [44]. Therefore, we consider underwater sensor networks as a viable solution in the next-generation target detection and tracking integrated scheme. The integration helps resolving different issues that will be explained in Section IV.

III. RAY-TRACING MODELS

Simulators would always be chosen based on the parameters required for a user going to perform an experiment. Due to complex underwater environment, acoustics simulations are time consuming; therefore, to provide precise acoustics simulations a vital and accurate model is required. The thorough description of how sound propagates through the ocean medium is finely described by ray tracing models [45]. For short-range calculation, where the sound speed profile (SSP) and the bottom profile are considered flat, a single profile program can be used. However, for long-range calculations, where both the SSP and bottom profiles vary, an advance all-purpose program is required [46]. To determine the ray coordinates, solution of ray equations is the basic requirement of ray tracing [47]. A full 3D modeling is important for rays that travel several kilometers with vertical fluctuations. A tracer should be very fast and flexible simultaneously to handle propagations timely [11]. This section provides several ray tracing models that are available for underwater simulations. All the following models were developed to tackle the hardest problem of ray tracing i.e., the calculation of eigenrays along with other challenges [48].

A. HAMILTONIAN 3D RAY TRACING PROGRAM FOR THE OCEAN (HARPO)

HARPO is a fully 3D ray tracing program to model very long-range acoustic paths for long-term monitoring of global warming effects. This concept of long-range ocean warming was described by Munk and Forbes [49] and summarized by Gibbons [50]. The longest paths reveal some chaotic behavior that need to be suppressed by using this tracing model; however, the suppression degrades the model practicality.

Also, 3D modeling is more likely to create chaotic behavior than 2D modeling; nevertheless, 3D modeling keeps the practicality of the model. HARPO has the characteristic to solve Hamilton equation on an elliptical Earth. But, these calculations of ray paths on curved Earth present complexities. Six variables are used to define ray trajectory in 3D by using non-linear Hamiltonian equations, where three define the position (radius, colatitude, longitude) and other three define the local components of the wavenumber. The interest of the developers of HARPO is to model the long-range sound propagation topology closely related to the geometry of the planet as it provides best topology. The accuracy of the model is limited to moderate ocean environment and it does not consider bathymetry effects. Also, HARPO does not generate eigenrays products (e.g., transmission loss, multipath travel time, phase, and propagation direction). Alternative software is still required to overcome the flaws of HARPO as it does not seem to be a viable model for long-range monitoring when it comes to execute it for non-smooth oceanic medium [11].

B. EIGENRAY ACOUSTIC RAY TRACING

The model was developed at Applied Physics Laboratory, University of Washington [51] and used for long-range acoustic transmission in the deep ocean. The model uses cubic spline methods to calculate SSPs and the derivative of sound speed gradient. To provide accuracy with less overhead, the model introduces prearranged user-specified step size for efficient and accurate calculations in comparison to adaptive step size. The model introduces caustics (points where intensity goes to infinity as per ray theory) when SSPs move from one profile to another in an intermittent manner, therefore a constant sound speed gradient between SSPs is an essential requirement to be implemented. The calculation of sound speed and sound speed gradient depends on 3D matrix of depth, range, and six variables at those depths and ranges. These six variables are sound speed, sound speed gradient, sound speed second derivative with depth, horizontal derivative of sound speed, horizontal derivative of sound speed gradient, and the constant. The code for this model is unstable, and it provides flexibility with an open invitation to any user for modification and accuracy. Also, a more efficient adaptive step size method and handling of SSPs at irregular depths are still required to be developed.

C. WAVE-FRONT QUEUE 3D (WaveQ3D)

WaveQ3D is a 3D ray tracing model especially designed for active sonar simulation systems and distributed as part of Under Sea Modeling Library (USML). It is based on ray theory where other models (*e.g.*, parabolic equation and normal mode) exhibit low performance for frequencies above 1000 Hz. The objective of this model is to generate transmission loss eigenrays accurately only for coastal scenarios. Moreover, it generates other eigenrays products also *i.e.*, multipath travel time, phase, and propagation direction. WaveQ3D enhances Gaussian beam techniques to make it applicable for lower frequencies also. These Gaussian beam techniques are based on Gaussian Ray Bundling (GRAB) [52], [23]. Due to its unique characteristic of enhances Gaussian beam techniques; it can solve Eikon equation in spherical Earth coordinates, thereby supporting out-of-plane 3D effects. Real time active sonar simulation systems exhibit better performance when the number of targets to be detected is smaller than the number of ray tracing points. However, WaveQ3D does not support this assumption for planned missions. With an increase in number of targets, WaveQ3D performs faster with less overhead based on each target. The accuracy of this model for sea surface is not yet guaranteed [54].

D. THE BELLHOP RAY TRACING MODEL

An effectual ray tracing program written in FORTRAN by Michael Porter is designed for 2D ray tracing for a given SSP and sound speed field (SSF) with different range-dependent boundaries (surface and bottom) in the ocean. Along with FORTRAN sources, MATLAB functions to present ray coordinates and transmission loss are also provided. It can be implemented in Python too [55]. The solution of dynamic ray equations is required for transmission loss or acoustic pressure. Bellhop integrates both ray and dynamic equations. The input files include depth, sound speed, surface type, attenuation, surface shape, directional sources specifications, and geo-acoustic properties. However, in the simplest case, environmental file is the only input file that includes SSP and bottom information. The output files include ray coordinates, travel time, amplitude, eigenrays, acoustic pressure, and transmission loss. The different provisions of range-dependent input and output files are shown in Table 3. Like WaveQ3D, the Gaussian beam techniques [56], [57] are used to calculate acoustic pressure in BELLHOP ray tracing model with different approximations such as, geometric beams [54], beams with ray-centered coordinates, beams with Cartesian coordinates, and Gaussian ray bundles approximation [58]. Therefore, the model can handle shadows and caustics with the help of Gaussian beam techniques. For some specific applications, where accuracy is crucial, geometric beams approximations cannot be adequate. Therefore, the model provides a set of other approximations in addition to geometric beams which is the default option. Bellhop exhibits slow performance if the number of sound speed points increases [47], [55]. A BELLHOP3D has been distributed for 3D Gaussian ray tracing model. The model has several approximations for different approaches that do not assure its accuracy nevertheless, this is an opening towards a benchmark solution for several 3D models [59].

E. HORIZONTAL – GRADIENT ACOUSTICAL RAY – TRACE PROGRAM TRIMAIN

A FORTRAN-IV program (initially written as FORTRAN-63 [60]) is used to compute intensity level, travel time, and source and receiver angles for individual eigenrays. Ray paths are calculated in a 2D medium with varying SSP. The velocity is assumed to be constant in piecewise

TABLE 3. Characteristics of ray tracing models.

Ray Tracing Models	HARPO	Eigenray	WaveQ3D	BELLHOP
URL	http://oalib.hlsresearch.com/Rays/harpo.htm	http://staff.washington.edu/dushaw/AcousticsCode/EigenRay.html	http://oalib.hlsresearch.com/Rays/USML/usml_frontpage	http://oalib.hlsresearch.com/Modes/AcousticsToolbox/
Purpose	To model very long-range acoustic paths	long-range acoustic transmission in deep ocean	Designed for active sonar simulation systems	Designed for 2D ray tracing, 3D is available for 3D Gaussian ray tracing model
pros	Fully 3D 3D modeling keeps practicality Solve Hamilton equation	accurate, less overhead, flexible for modification	• 3D model • Ray theory-based model • Faster, less overhead • Generate eigenrays for coastal scenarios only • Enhances Gaussian beam techniques • Support out-of-plane 3D effects due to solving Eikon equation	• Integrates both ray and dynamic equations • Can be implemented in Python • Enhances Gaussian beam techniques
cons	• Chaotic behavior suppression degrades model practicality • Not a working model • Introduce complexities to compute ray paths • Accuracy is limited to moderate ocean environment • Does not consider bathymetry effects and generate eigenrays products • An extensive modification is required	• code is unstable • inefficient adaptive step size method	• Does not support target detection for planned mission with large number of tracing points • Accuracy is not guaranteed	• Geometric beam approximations cannot be adequate for specific applications • Exhibit slow performance with increase in sound speed points • 3D model does not assure accuracy
Input file	SSP, range, depth, environmental file	SSP, range, depth, bathymetry	SSP, depth, range	Environmental file along with additional files Additional files can be: • if bottom is range-dependent, add bathymetry file • if sound speed is range-dependent, add an SSP file with the sound speed tabulated on a regular grid. • if a specific arbitrary bottom reflection coefficient is required to characterize the bottom, then bottom reflection coefficient file with angle-reflection coefficient pairs defining the reflectivity must be provided by the user. • having option of providing a top reflection coefficient and a top shape (called an altimetry file).
Output file	Latitude, longitude, altitude	Eigenrays	eigenrays	• ray coordinates, travel time, amplitude, eigenrays, acoustic pressure, transmission loss • Different output files depending on the options: • Ray tracing option • Eigenray option

Ray Tracing Models	TRIMAIN	VirTEX	TV-APM	TRACEO3D
URL	http://oalib.hlsresearch.com/Rays/trimain/	http://oalib.hlsresearch.com/Rays/VirTEX/VirTEX_20110708.zip	http://oalib.hlsresearch.com/Rays/tvapm.zip	http://www.siplab.fct.ualg.pt/models.shtml
Purpose	Compute intensity level, time and angles for individual eigenrays in 2D medium	Developed to model arbitrary motion of underwater time-varying environments	To generate channel responses for mobile nodes in realistic environment	To envisage acoustic pressure and velocity within both surface and bottom range-dependent boundaries
pros	• No limitations for SSPs • Different rays can be traced at the same time • Presents variable-bottom • Caustics are solved • Modifications are open	Allow post-processing of multiple ray tracing programs	Handle too large velocities	• Originally designed for 2D modeling but, assure out-of-plane propagation of 3D bathymetry • Handle sound propagation in different environments • Solve both Hamilton and Eikon equations as well as both dynamic and ray equations • Goes outside of Bellhop characteristics
cons	Discontinuous velocity at triangular boundaries	• Dependent on Bellhop • Does not consider every aspect of acoustic channel	• Dependent on Bellhop • No warranty • Shear and range dependent bottom properties, non-linear velocities and arrays, swells are not supported	
Input file	Depth, frequency, surface and bottom loss, volume attenuation	Depth, SSP	SSP, bathymetry	Blocks of input files (source, SSP, altimetry, array)
Output file	Eigenray, transmission losses, surface and bottom reflections	eigenray	Channel impulse responses	Rays, arrivals, amplitudes, acoustic pressure and partial velocity components

linear functions of depth and range. The constant velocity is continuous in a triangular region however; its gradient is discontinuous at the triangular boundaries. TRIMAIN has the following features:

- No limitations for SSPs are introduced in this program. Also, SSPs are presented as a function of range and depth.
- Different rays can be traced at the same time.
- The program presents variable-bottom in piecewise linear function of depth.
- The sea surface is flat with a user-specified constant reflection coefficient and phase shift.

The program uses depth, frequency, surface loss, bottom loss, and volume attenuation as input files and transmission losses, surface and bottom reflections, eigenray as output files. There are some cautions to run this program, otherwise the program ends at any point during simulations. The number of input points in SSP is limited to 50. Source depth and sound speed depth should be different. 1000 rays should be traced by the program. The program uses original ray theory. Modifications are open for any interested user. Caustics are solved in this program by throwing the eigenray out for those two rays whose depth is 0.001 meter close to each other [46].

F. VIRTUAL TIMESERIES EXPERIMENT (VirTEX)

VirTEX [61] was developed to model arbitrary motion of underwater time-varying environments and to calculate post-processing of multiple ray tracing programs (more specifically BELLHOP ray tracing program). Two novel and efficient modifications of VirTEX models to calculate single ray tracing for platform and sea surface motion respectively are:

- VirTEX Extra-Lite (platform motion)
- VirTEX Lite (sea surface motion)

Along with post-processing of single ray tracing, VirTEX Extra-Lite accomplishes only fixed source and receiver motion modeling with less computational resources, whereas VirTEX Lite is capable of handling both steady motion of source and receiver and unsteady motion of sea surface with greater resources than VirTEX Extra-Lite. VirTEX and its variants are dependent on BELLHOP ray tracing program. The model does not consider every aspect of underwater acoustic channel.

G. THE TIME VARIABLE ACOUSTIC PROPAGATION MODEL (TV-APM)

TV-APM [62] considers realistic environment that generates channel responses for mobile nodes. The simulator which was partially developed by 7th European Framework Program has a set of MATLAB files and data configuration files. The MATLAB files include configuration parameters that define initial positions, linear velocities, and wind parameters, whereas, data configuration files include the sea surface, bathymetry, SSP, and the transmitted signal. To simulate signal propagation dynamically, it runs Bellhop ray tracing model with the following conditions:

- A 3D box with user specified bathymetry and surface wave is a must to place source and array.
- Both positions and velocities are updated with transmission time.
- A user specified SSP is required.
- A user-specified transmitted signal is required.

The simulator generates the following output files: channel impulse responses and output signals. The simulator allows users to modify the parameters and configurations according to their experimental requirement. The simulator has no warranty; therefore, users are warmly welcome to fix bugs and improve the internal workings of the simulator. The simulator can handle too large velocities with the condition of enlarging run time and memory space. Shear and range dependent bottom properties, non-linear velocities and arrays, and swells are not supported by TV-APM.

H. TRACEO3D RAY TRACING MODEL

A ray tracing model developed at the Signal Processing Laboratory (SiPLAB) of the University of Algarve was designed to envisage acoustic pressure and velocity within both surface and bottom range-dependent boundaries. TRACEO was originally designed for 2D modeling and written in FORTRAN 77 however, it can surely model sound for out-of-plane propagation with simplest cases of 3D bathymetry (validity of 3D predictions). The purpose of this model is to calculate eigenrays with a specific set of SSPs or SSFs. The model can handle sound propagation in different environments with different applications; such as wavy surfaces, complex bathymetries, depth and range variations of SSPs, etc. in the areas of geo-acoustics, vector sensor arrays, and acoustic barriers, which the current existing models cannot handle. It also considers complex scenarios of earth's curvature to solve Hamiltonian equation like HARPO and Eikon equations like WaveQ3D in addition to the Lagrange formalism. It has the characteristic of solving ray equations as well as dynamic equations. The input and output files are described in Table 3. Like other models, TRACEO also handle the caustics with the help of Gaussian beam techniques. The model takes assistances from Bellhop ray tracing model, but it goes outside bellhop due to the following advancements:

- Handling set of both analytical and tabular SSPs.
- One or more targets can be positioned between the source and the array of receivers.
- Handling boundaries with range-dependent properties (shear velocity, attenuation) and with being absorbed by partially or totally reflective waveguide.

TRACEO3D has been validated by Calazan and Rodríguez [63] as a most vital and accurate model to handle underwater noise while predicting sound propagation efficiently [45].

Numerous ray tracing models with their codes are available, but none of them satisfy all the demands of underwater acoustic monitoring for different environments. Bellhop has been considered as an accurate ray tracing model due to its characteristics of providing accurate modeling of sound propagation and acoustic channel. However, its 3D model does not assure accuracy. TRACEO3D is an advancement of Bellhop ray tracing tool as it assures out-of-plane propagation for 3D environment. Nevertheless, a fast, flexible, and accurate code is an essential requirement to handle several challenges for 3D modelling of next-generation underwater target detection and tracking architecture.

IV. NEXT-GENERATION UNDERWATER TARGET DETECTION AND TRACKING SCHEME

In this section, we first briefly discuss the novel terminologies (UCANs, SDUN, IoUT, NFV, cloud and fog computing), the literature using these notions to improve underwater communications, and then we provide the solution for next-generation underwater target detection and tracking.

A. UNDERWATER COGNITIVE ACOUSTIC NETWORK (UCAN)

Among various challenges of underwater environment such as severe path loss, long propagation delay, less propagation speed, limited spectrum is the one that causes hindrance in communications. Due to the high competition of sharing acoustic spectrum among various acoustic users, safe and stable communications become a great challenge for this highly challenging environment. The underwater communications systems include both natural acoustic systems (e.g., marine mammals) and artificial acoustic systems (e.g., sonar systems). The medium of communication for both natural and artificial systems is acoustic waves, thereby triggering high competition for all acoustic users to efficiently utilize the limited spectrum. Consequently, UCANs which implement cognitive acoustic (CA) capabilities are becoming popular to overcome the issues of spectrum scarcity in underwater networks. UCANs allow acoustic users (secondary users) to utilize the spectrum in a friendly manner, ensuring that primary user (licensed user) activity is secured. This means that the two acoustic users can only communicate with each other if both have consensus on common idle spectrum. But these networks are still under investigation because proposing a cognitive underwater protocol that considers the limited spectrum issue to meet the increasing demands of different acoustic users for different applications and services is highly challenging. Therefore, the research in this area is at its infancy. Very few medium access control (MAC) and network layer protocols proposed for UCANs are listed in [64]–[67].

B. SOFTWARE-DEFINED UNDERWATER NETWORK (SDUN)

Software-defined networking (SDN) has been announced as a flexible, efficient, and vendor independent technology. To engulf the constrained nature of underwater networks, the decoupling of control plane from the data plane enhances network compatibility with efficient utilization of resources and proper time management. SDN overcomes the hindrances of integration of various underwater devices to make safe and stable networking. SoftWater [68] is the first next-generation underwater communication system that integrates network function virtualization (NFV) to incorporate new underwater communication solutions. Due to this architecture, several underwater applications that operate on different communication technologies (acoustic, optical or radio waves) can be supported simultaneously. The physical-layer adaptation mechanisms are proposed in [69] to allow either seamless switching between different underwater technologies (such as orthogonal-frequency-division-multiplexing (OFDM) and direct-sequence-spread-spectrum (DSSS)) or joint adaptation of communication parameters (such as modulation constellation and channel coding rate). They present a new high-rate software-defined acoustic modem (SDAM) with real time adaptation capabilities and evaluate it in both indoor and outdoor environments. A multi-controller SDN-based UASN framework [70] is designed to present a load balancing mechanism with UASNs hypervisor. UASNs hypervisor is a simulation program that is developed and implemented to improve UASN performance.

C. INTERNET OF UNDERWATER THINGS (IoUT)

A network of smart-interconnected nodes that helps enabling numerous unexplored underwater applications and resources is called IoUT. The smart devices in IoUT improve numerous applications in smart coastal cities including target detection and tracking. These applications include environmental monitoring, underwater exploration, disaster prevention, military and others navigation and location applications [71]. Due to sparse network condition in IoUT, autonomous underwater vehicles (AUVs) can be used to establish stable connections between nodes far away from each other. IoUT is a three-layered architecture, first described in 2012 [40] that fulfill the demands of application users. The perception layer includes sensors, vehicles, and stations that are responsible for collecting data. The middle layer *i.e.*, the network layer includes internet, wired/wireless networks, cloud computing platforms, and so on for transmitting information from the perception layer, and the application layer satisfies diversified demands of different users.

D. NETWORK FUNCTION VIRTUALIZATION (NFV)

NFV is a concept of virtualization of network resources into software-based network functions [17] which is at its early stage for terrestrial sensor networks. NFV provides the services in virtual machines that perform different operations. NFV can use SDN as a part of service function chaining (SFC), and SDN can provide connectivity between virtual network functions (VNFs) [72], [73]. A VNF is the virtualization of specific network function that should function autonomously. Both SDN and NFV are complementary to each other, by this means they can be applied to network of different types and can be used in simplifying network management. Therefore, for the real-time implementation of next-generation underwater sensor networks, integration of NFV and SDN facilitates multiple underwater applications under the same infrastructure.

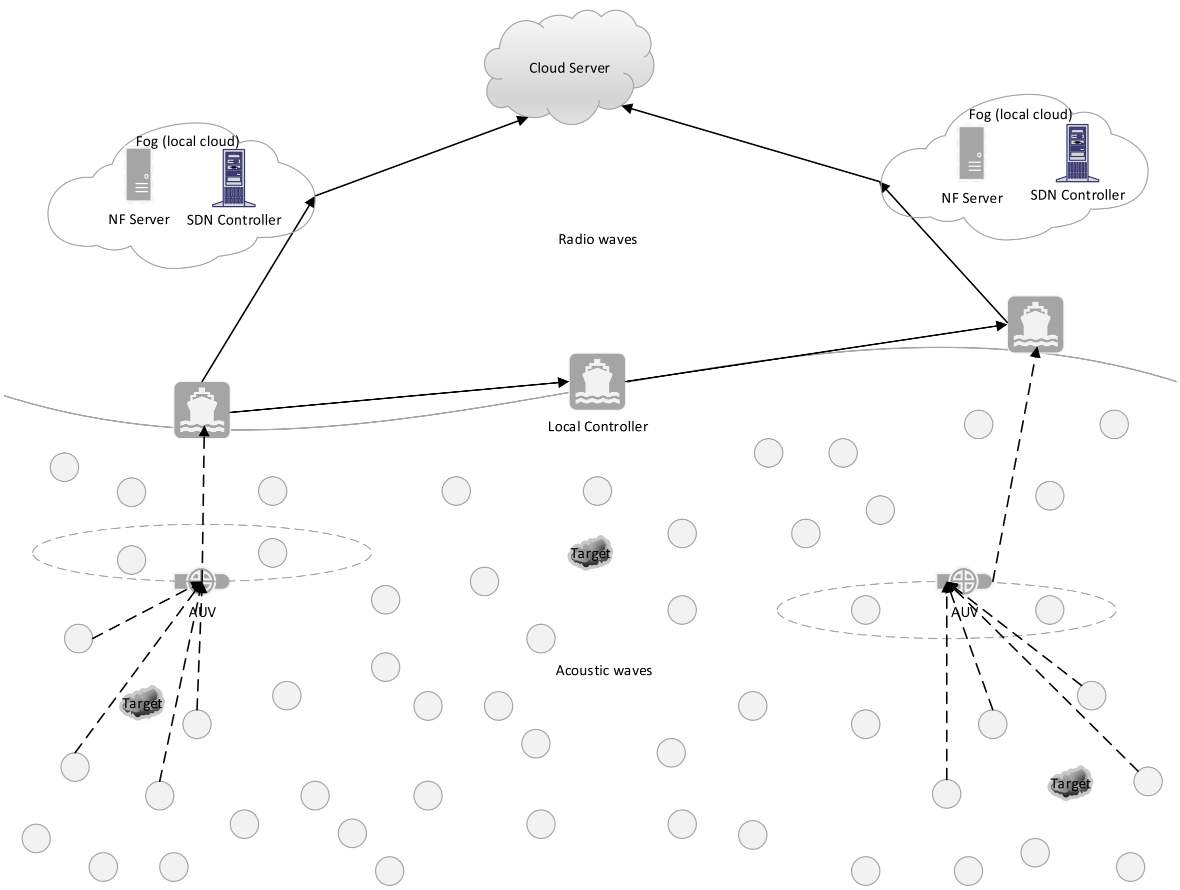

FIGURE 1. Next-generation underwater target detection and tracking scheme.

E. CLOUD AND FOG COMPUTING

Cloud computing for underwater networks seems to be the best candidate to distribute and visualize the complex data collected from the oceans through the gateways (surface buoys or AUVs). An intelligent context-aware middleware [74] is proposed to combine underwater sensor network and cloud computing that supports different underwater applications through multi-agents. Another method [75] connects underwater sensor network to the cloud by means of a wireless transceiver to elaborate and analyze the data. An integration of ocean and cloud computing is proposed in [76] to sense, identify, and predict the multi-sensor data. All these research works transfer data to the cloud by means of gateways. Likewise, terrestrial communications, plethora of underwater devices increase the amount of data to be transferred to the cloud, which might cause congestion and bottleneck at the gateways. Therefore, fog computing and edge computing notions can be applied in underwater networks to overcome the issues of cloud computing. We will discuss it further in our proposed scheme below.

Taking advantages form all the novel notions such as SDN, NFV, fog, and cloud computing, we propose novel target detection and tracking scheme. The scheme considers underwater sensor nodes as the fundamental units that sense the presence of the target and report the sensing results to any of the AUV moving around the cluster of the sensor nodes. The AUV collects the sensing results, apply any information gathering algorithm such as decision-based methods or neural networks, and forward the collaborative output to the next-level AUV as shown in Fig. 1 to reach the local controller (any surface buoy).

Different surface buoys communicate with the SDN controller on land that is inside the fog cloud. The fog cloud serves as the local cloud to provide flexibility among different services and to preserve network latency. Each fog cloud forwards the collected data to the server cloud. This is next-generation hybrid underwater communications where both acoustic and radio waves serve as a medium of communications. The NFV hypervisor inside each fog cloud is responsible for launching different underwater application services such as surveillance, monitoring, safety, oceanographic, and oil inspection. SDN controller is responsible for monitoring these application services.

The integration of these different notions in next-generation underwater target detection and tracking systems allow any node of interest for any other service to collect information from any fog cloud and take full advantage of the whole network. This scheme allows detecting either a single or multi, mobile or fixed target, by collecting the sensing information at nearby AUVs which forwards the collected data to the local/server cloud for stronger processing. The cloud then estimates the position of the target and predicts its trajectory more accurately. The scheme does not involve a single entity; it is a hybrid communication of several underwater devices such as sensors, AUVs, surface buoys, and base stations on land, each performing the tasks in a collaborative manner. Therefore, we can say that, this is an alternative solution to detect and track the mobile target more accurately and precisely.

The problem of energy consumption for sensor nodes can be overwhelmed by utilizing the waking-up sleep mechanism [77], [78] where only those sensor nodes near the area where the target is moving, or static keep themselves activated. The other energy-efficient target detection and tracking algorithms described in Section II can be used to solve this issue. Also, SDN controller along with virtualization hypervisor, i.e. fog cloud is responsible for adjusting the energy level of each underwater sensor node [79].

V. CONCLUSION

We introduce a novel integrated solution for next-generation underwater target detection and tracking by integrating SDN, NFV, cloud and fog computing intending to resolve the existing underwater issues. AUVs are emerging as an efficient and reliable solution for various underwater complexities and will continue playing a significant role in the exploration and monitoring of underwater systems and resources. The integration allows any acoustic device of interest for any other service to collect information from any fog cloud and take full advantage of the whole network. Likewise, terrestrial networks, SDN and NFV can also be used in underwater networks to resolve energy and time constrained issues. An overview of different unmanned underwater vehicles utilized for target tracking for various algorithms in the literature is presented. We also discuss various ray-tracing models essential in target detection and tracking and provide their purpose of development along with advantages and disadvantages. It remains as our future work to test our proposed solution using TRACEO ray tracing.

REFERENCES

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Netw.*, vol. 3, no. 3, pp. 257–279, Mar. 2005.

[2] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li, "Research challenges and applications for underwater sensor networking," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2006, pp. 228–235.

[3] M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," *Marine Technol. Soc. J.*, vol. 42, no. 1, pp. 103–116, 2008.

[4] L. Liu, S. Zhou, and J.-H. Cui, "Prospects and problems of wireless communication for underwater sensor networks," *Wireless Commun. Mobile Comput., Underwater Sensor Netw., Archit. Protocols*, vol. 8, no. 8, pp. 977–994, 2008.

[5] K. Munasinghe, M. Aseeri, S. Almorqi, M. F. Hossain, M. B. Wali, and A. Jamalipour, "EM-based high speed wireless sensor networks for underwater surveillance and target tracking," *J. Sensors*, vol. 2017, Feb. 2017, Art. no. 6731204.

[6] E. Dalberg, A. Lauberts, R. K. Lennartsson, M. J. Levonen, and L. Persson, "Underwater target tracking by means of acoustic and electromagnetic data fusion," in *Proc. 9th Int. Conf. Inf. Fusion*, Jul. 2006, pp. 1–7.

[7] A. Wolek, B. R. Dzikowicz, J. McMahon, and B. H. Houston, "At-sea evaluation of an underwater vehicle behavior for passive target tracking," *IEEE J. Ocean. Eng.*, vol. 44, no. 2, pp. 514–523, Apr. 2019.

[8] X. Pan, J. Jiang, S. Li, Z. Ding, C. Pan, and X. Gong, "Coherent and noncoherent joint processing of sonar for detection of small targets in shallow water," *Sensors*, vol. 18, no. 4, p. 1154, Apr. 2018.

[9] G. Isbitiren and O. B. Akan, "Three-dimensional underwater target tracking with acoustic sensor networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3897–3906, Oct. 2011.

[10] S. Kim, B. Ku, W. Hong, and H. Ko, "Performance comparison of target localization for active sonar systems," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 44, no. 4, pp. 1371–1380, Oct. 2008.

[11] G. Dworski and J. A. Mercer, "Hamiltonian 3-D ray tracing in the oceanic waveguide on the ellipsoidal Earth," Univ. Washington Appl. Phys. Lab., Seattle, WA, USA, Tech. Rep. APL-UW TR8929, Dec. 1990.

[12] M. Chitre, R. Bhatnagar, and W.-S. Soh, "UnetStack: An agent-based software stack and simulator for underwater networks," in *Proc. Oceans St. John's*, Sep. 2014, pp. 1–10.

[13] F. Guerra, P. Casari, and M. Zorzi, "World ocean simulation system (WOSS): A simulation tool for underwater networks with realistic propagation modeling," in *Proc. 4th ACM Int. Workshop Underwater Netw. (WuWNeT)*, Berkeley, CA, USA, Nov. 2009, Art. no. 4.

[14] F. Campagnaro, R. Francescon, F. Guerra, F. Favaro, P. Casari, R. Diamant, and M. Zorzi, "The DESERT underwater framework v2: Improved capabilities and extension tools," in *Proc. IEEE 3rd Underwater Commun. Netw. Conf. (UComms)*, Aug./Sep. 2016, pp. 1–5.

[15] C. Petrioli, R. Petroccia, J. R. Potter, and D. Spaccini, "The SUNSET framework for simulation, emulation and at-sea testing of underwater wireless sensor networks," *Ad Hoc Netw.*, vol. 34, pp. 224–238, Nov. 2015.

[16] H. Ghafoor and I. Koo, "Cognitive routing in software-defined underwater acoustic networks," *Appl. Sci.*, vol. 7, no. 12, p. 1312, Dec. 2017.

[17] H. Luo, K. Wu, R. Ruby, Y. Liang, Z. Guo, and L. M. Ni, "Software-defined architectures and technologies for underwater wireless sensor networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2855–2888, 4th Quart., 2018.

[18] G. Ferri, A. Munafò, A. Tesei, P. Braca, F. Meyer, K. Pelekanakis, R. Petroccia, J. Alves, C. Strode, and K. LePage, "Cooperative robotic networks for underwater surveillance: An overview," *IET Radar, Sonar Navigat.*, vol. 11, no. 12, pp. 1740–1761, Dec. 2017.

[19] R. W. Larson, "Disruptive innovation and naval power: Strategic and financial implications of unmanned underwater vehicles (UUVs) and long-term underwater power sources," Ph.D. dissertation, Massachusetts Inst. Technol., Cambridge, MA, USA, 2014.

[20] Z. Yan, X. Liu, J. Zhou, and D. Wu, "Coordinated target tracking strategy for multiple unmanned underwater vehicles with time delays," *IEEE Access*, vol. 6, pp. 10348–10357, 2018.

[21] A. Young, J. Soli, and G. Hickman, "Self-localization technique for unmanned underwater vehicles using sources of opportunity and a single hydrophone," in *Proc. OCEANs*, Anchorage, AK, USA, Sep. 2017, pp. 1–6.

[22] X. Wang, J. Shang, Z. Luo, L. Tang, X. Zhang, and J. Li, "Reviews of power systems and environmental energy conversion for unmanned underwater vehicles," *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 1958–1970, May 2012.

[23] P. E. Hagen, N. Størkersen, B.-E. Marthinsen, G. Sten, and K. Vestgård, "Rapid environmental assessment with autonomous underwater vehicles—Examples from HUGIN operations," *J. Marine Syst.*, vol. 69, nos. 1–2, pp. 137–145, Jan. 2008.

[24] R. B. Wynn, V. A. I. Huvenne, T. P. Le Bas, B. J. Murton, D. P. Connelly, B. J. Bett, H. A. Ruhl, K. J. Morris, J. Peakall, D. R. Parsons, E. J. Sumner, S. E. Darby, R. M. Dorrell, and J. E. Hunt, "Autonomous underwater vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience," *Marine Geol.*, vol. 352, pp. 451–468, Jun. 2014.

[25] T. Crees, C. Kaminski, J. Ferguson, J. M. Laframboise, A. Forrest, J. Williams, E. MacNeil, D. Hopkin, and R. Pederson, "UNCLOS under ice survey—An historic AUV deployment in the Canadian high arctic," in *Proc. Oceans MTS/IEEE Seattle*, Sep. 2010, pp. 1–8.

[26] G. Ferri, A. Munafò, and K. D. LePage, "An autonomous underwater vehicle data-driven control strategy for target tracking," *IEEE J. Ocean. Eng.*, vol. 43, no. 2, pp. 323–343, Apr. 2018.

[27] M. P. Brito, R. S. Lewis, N. Bose, and G. Griffiths, "Adaptive autonomous underwater vehicles: An assessment of their effectiveness for oceanographic applications," *IEEE Trans. Eng. Manag.*, vol. 68, no. 1, pp. 98–111, Feb. 2019.

[28] A. Ridolfi, D. Spaccini, F. Fanelli, M. Franchi, N. Monni, L. Picari, C. Petrioli, and B. Allotta, "An autonomous underwater vehicle and SUNSET to bridge underwater networks composed of multi-vendor modems," *Annu. Rev. Control*, vol. 46, pp. 295–303, Oct. 2018.

[29] O. Elhaki and K. Shojaei, "Neural network-based target tracking control of underactuated autonomous underwater vehicles with a prescribed performance," *Ocean Eng.*, vol. 167, pp. 239–256, Nov. 2018.

[30] J. Melo and A. C. Matos, "Tracking multiple autonomous underwater vehicles," *Auton. Robots*, vol. 43, no. 1, pp. 1–20, Jan. 2019. doi: 10.1007/s10514-018-9696-7.

[31] T. Alexandri and R. Diamant, "A reverse bearings only target motion analysis for autonomous underwater vehicle navigation," *IEEE Trans. Mobile Comput.*, vol. 18, no. 3, pp. 494–506, Mar. 2019.

[32] P. Sun and A. Boukerche, "Modeling and analysis of coverage degree and target detection for autonomous underwater vehicle-based system," *IEEE Trans. Veh. Technol.*, vol. 67, no. 10, pp. 9959–9971, Oct. 2018.

[33] T. Chance, A. Kleiner, and J. Northcutt, "The autonomous underwater vehicle (AUV): A cost-effective alternative to deep-towed technology," *Integr. Coastal Zone Manage.*, vol. 2, no. 7, pp. 65–69, 2000.

[34] M. Myint, K. Yonemori, K. N. Lwin, A. Yanou, and M. Minami, "Dual-eyes vision-based docking system for autonomous underwater vehicle: An approach and experiments," *J. Intell. Robotic Syst.*, vol. 92, no. 1, pp. 159–186, Sep. 2018.

[35] G. Schultz, J. Keranen, C. Bassani, M. Cook, and T. Crandle, "Littoral applications of advanced 3D marine electromagnetics from remotely and autonomously operated platforms: Infrastructure and hazard detection and characterization," in *Proc. Oceans Conf.*, Aberdeen, U.K., Jun. 2017, pp. 1–7.

[36] B. Bingham, B. Howe, N. Kraus, L. E. Freitag, K. Ball, P. Koski, and E. Gallimore, "Passive and active acoustics using an autonomous wave glider," *J. Field Robot.*, vol. 29, no. 6, pp. 911–923, Nov. 2012.

[37] H. Sang, Y. Zhou, X. Sun, and S. Yang, "Heading tracking control with an adaptive hybrid control for under actuated underwater glider," *ISA Trans.*, vol. 80, pp. 554–563, Sep. 2018.

[38] Z. Zeng, K. Sammut, F. He, and A. Lammas, "Efficient path evaluation for AUVs using adaptive B-Spline approximation," in *Proc. Oceans Conf.*, Virginia Beach, VA, USA, Oct. 2012, pp. 1–8.

[39] W. K. G. Seah, Z. A. Eu, and H.-P. Tan, "Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP)—Survey and challenges," in *Proc. 1st Int. Conf. Wireless Commun., Veh. Technol., Inf. Theory Aerosp. Electron. Syst. Technol.*, May 2009, pp. 1–5.

[40] M. C. Domingo, "An overview of the Internet of underwater things," *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 1879–1890, 2012.

[41] Y. Sun, Y. Yuan, X. Li, Q. Xu, and X. Guan, "An adaptive sampling algorithm for target tracking in underwater wireless sensor networks," *IEEE Access*, vol. 6, pp. 68324–68336, 2018.

[42] M. Poostpasand and R. Javidan, "An adaptive target tracking method for 3D underwater wireless sensor networks," *J. Wireless Netw.*, vol. 24, no. 8, pp. 2797–2810, Nov. 2018.

[43] H. Jing, H. Wang, Z. Liu, and X. Shen, "DOA estimation for underwater target by active detection on virtual time reversal using a uniform linear array," *Sensors*, vol. 18, no. 8, p. 2458, Jul. 2018.

[44] J. Luo, Y. Han, and L. Fan, "Underwater acoustic target tracking: A review," *Sensors*, vol. 18, no. 1, p. 112, Jan. 2018.

[45] R. M. Calazan and O. C. Rodríguez, "TRACEO3D ray tracing model for underwater noise predictions," in *Technological Innovation for Smart Systems. DoCEIS* IFIP (Advances in Information and Communication Technology), vol 499, L. Camarinha-Matos, M. Parreira-Rocha, and J. Ramezani, Eds. Cham, Switzerland: Springer, 2017.

[46] B. G. Roberts, Jr., "Horizontal-gradient acoustical ray-trace program TRIMAIN," Naval Res. Lab., Washington, DC, USA, NRL Rep. 7827, Dec. 1974.

[47] O. C. Rodriguez, "General description of the BELLHOP ray tracing program, version 1," Dept. Phys., Signal Process. Lab., Univ. Algarve, Faro, Portugal, Tech. Rep., 2008.

[48] O. C. Rodriguez, "The TRACEO ray tracing program," Dept. Phys., Signal Process. Lab., Univ. Algarve, Faro, Portugal, Tech. Rep., 2011.

[49] W. H. Munk and A. M. G. Forbes, "Global ocean warming: An acoustic measure?" *J. Phys. Oceanogr.*, vol. 19, pp. 1765–1778, Nov. 1989.

[50] A. Gibbons, "What's the sound of One Ocean warming?" *Science*, vol. 248, no. 4951, pp. 33–34, 1990.

[51] B. D. Dushaw and J. A. Colosi, "Ray tracing for ocean acoustic tomography," Appl. Phys. Lab., Univ. Washington, Seattle, Washington, Tech. Rep. APL-UW TM 3-98, 1998.

[52] V. Červený, M. M. Popov, and I. Pšenčík, "Computation of wave fields in inhomogeneous media—Gaussian beam approach," *Geophys. J. Roy. Astronomical Soc.*, vol. 70, no. 1, p. 109, Jul. 1982.

[53] H. Weinberg and R. E. Keenan, "Gaussian ray bundles for modeling high-frequency propagation loss under shallow-water conditions," *J. Acoust. Soc. Amer.*, vol. 100, no. 3, pp. 1421–1431, Apr. 1996.

[54] S. M. Reilly, "WaveQ3D: Fast and accurate acoustic transmission loss (TL) eigenrays, in littoral environments," Dept. Ocean Eng., Univ. Rhode Island, Kingston, RI, USA, Tech. Rep., 2014.

[55] M. B. Porter, "The BELLHOP manual and user's Guide: PRELIMINARY DRAFT," Heat, Light, Sound Res., Inc. La Jolla, CA, USA, Tech. Rep., Jan. 2011.

[56] M. B. Porter and H. P. Bucker, "Gaussian beam tracing for computing ocean acoustic fields," *J. Acoust. Soc. Amer.*, vol. 82, no. 4, pp. 1349–1359, Oct. 1987.

[57] F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt, *Computational Ocean Acoustics* (Modern Acoustics and Signal Processing), New York, NY, USA: Springer, 1994.

[58] M. B. Porter and Y.-C. Liu, "Finite-element ray tracing," in *Theoretical and Computational Acoustics*, vol. 12. World Scientific: Singapore, 1994, pp. 947–956.

[59] M. B. Porter, "BELLHOP3D user guide," Heat, Light, Sound Res., San Diego, CA, USA, Tech. Rep.2016 7 25, 2016.

[60] E. L. Wright, "Ray tracing with horizontal and vertical gradients," *J. Acoust. Soc. Amer.*, vol. 48, no. 1A, p. 92, Jul. 1970.

[61] J. C. Peterson and M. B. Porter, "Virtual timeseries experiment (VirTEX)—Quick start," Tech. Rep., Jul. 2011. [Online]. Available: http://oalib.hlsresearch.com/Rays/VirTEX/README.pdf

[62] O. C. Rodriguez and A. J. Silva, "The time variable acoustic propagation model (TV-APM)," Signal Process. Lab., Universidade do Algarve, Faro, Portugal, Tech. Rep., 2012.

[63] R. M. Calazan and O. C. Rodríguez, "TRACEO$_3$D ray tracing model for underwater noise predictions," in *Technological Innovation for Smart Systems* (IFIP Advances in Information and Communication Technology), vol. 499, L. Camarinha-Matos, M. Parreira-Rocha, and J. Ramezani, Eds. Cham, Switzerland: Springer, 2017.

[64] Y. Luo, L. Pu, Z. Peng, and J.-H. Cui, "Dynamic control channel MAC for underwater cognitive acoustic networks," in *Proc. IEEE INFOCOM 35th Annu. Int. Conf. Comput. Commun.*, San Francisco, CA, USA, Apr. 2016, pp. 1–9.

[65] Y. Luo, L. Pu, H. Mo, Y. Zhu, Z. Peng, and J. Cui, "Receiver-initiated spectrum management for underwater cognitive acoustic network," *IEEE Trans. Mobile Comput.*, vol. 16, no. 1, pp. 198–212, Jan. 2017.

[66] X. Li, Y. Sun, Y. Guo, X. Fu, and M. Pan, "Dolphins first: Dolphin-aware communications in multi-hop underwater cognitive acoustic networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2043–2056, Apr. 2017.

[67] H. Ghafoor, Y. Noh, and I. Koo, "OFDM-based spectrum-aware routing in underwater cognitive acoustic networks," *IET Commun.*, vol. 11, no. 17, pp. 2613–2620, Nov. 2017.

[68] I. F. Akyildiz, P. Wang, and S.-C. Lin, "SoftWater: Software-defined networking for next-generation underwater communication systems," *Ad Hoc Netw.*, vol. 46, pp. 1–11, Aug. 2016.

[69] E. Demirors, G. Sklivanitis, T. Melodia, G. E. Santagati, and S. N. Batalama, "A high-rate software-defined underwater acoustic modem with real-time adaptation capabilities," *IEEE Access*, vol. 6, pp. 18602–18615, 2018.

[70] J. Wang, S. Zhang, W. Chen, D. Kong, X. Zuo, and Z. Yu, "Design and implementation of SDN-based underwater acoustic sensor networks with multi-controllers," *IEEE Access*, vol. 6, pp. 25698–25714, 2018.

[71] C.-C. Kao, Y.-S. Lin, G.-D. Wu, and C.-J. Huang, "A comprehensive study on the Internet of underwater things: Applications, challenges, and channel models," *Sensors*, vol. 17, no. 7, p. 1477, Jun. 2017.

[72] M. S. Bonfim, K. L. Dias, and S. F. L. Fernandes, "Integrated NFV/SDN architectures: A systematic literature review," 2018, *arXiv:1801.01516*. [Online]. Available: https://arxiv.org/abs/1801.01516

[73] Alcatel-Lucent, "The right SDN is right for NFV," Alcatel Lucent, Boulogne-Billancourt, France, Strategic White Paper MKT 2014097243EN, Sep. 2014. [Online]. Available: https://www.tmcnet.com/tmc/whitepapers/documents/whitepapers/2014/10695-nfv-insights-series-right-sdn-right-nfv.pdf

[74] C. Srimathi, S.-H. Park, and N. Rajesh, "Proposed framework for underwater sensor Cloud for environmental monitoring," in *Proc. 5th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Da Nang, Vietnam, Jul. 2013, pp. 104–109.

[75] G. Suciu, V. Suciu, C. Dobre, and C. Chilipirea, "Tele-monitoring system for water and underwater environments using cloud and big data systems," in *Proc. 20th Int. Conf. Control Syst. Comput. Sci.*, Bucharest, Romania, May 2015, pp. 809–813.

[76] J. Liu, K. Guo, and J. Cui, "Cloud-ocean computing: A new scheme of marine data processing," in *Proc. 13th ACM Int. Conf. Underwater Netw. Syst.*, Shenzhen, China, Dec. 2018, Art. no. 47.

[77] C. H. Yu, K. H. Lee, J. W. Choi, and Y. B. Seo, "Distributed single target tracking in underwater wireless sensor networks," in *Proc. SICE Annu. Conf.*, Aug. 2008, pp. 1351–1356.

[78] A. Kumar and K. M. Sivalingam, "Target tracking in a WSN with directional sensors using electronic beam steering," in *Proc. 4th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Jan. 2012, pp. 1–10.

[79] H. Gebre-Amlak, S. Lee, A. M. A. Jabbari, Y. Chen, B.-Y. Choi, C.-T. Huang, and S. Song, "MIST: Mobility-inspired software-defined fog system," in *Proc. IEEE Int. Conf. Consum. Electron. (ICCE)*, Las Vegas, NV, USA, Jan. 2017, pp. 94–99.

HUMA GHAFOOR received the B.Sc. degree in electronics engineering from the NFC Institute of Engineering and Technology, Multan, Pakistan, in 2009, the M.S. degree in communication systems engineering from the School of Electrical Engineering and Computer Science, National University of Sciences and Technology (NUST), Islamabad, Pakistan, in 2012, and the Ph.D. degree in electrical engineering from the School of Electrical Engineering, University of Ulsan, South Korea, in 2018. She is currently an Assistant Professor with the School of Electrical Engineering and Computer Science, NUST. She was a Postdoctoral Researcher with the Networked Systems Laboratory, Inha University, South Korea, until January 2019. Her research interests include vehicular ad hoc networks, underwater sensor networks, and software-defined networking with a focus on cognitive networking protocols.

YOUNGTAE NOH received the B.S. degree in computer science from Chosun University, in 2005, the M.S. degree in information and communication from the Gwangju Institute of Science Technology (GIST), in 2007, and the Ph.D. degree in computer science from the University of California at Los Angeles (UCLA), Los Angeles, in 2012. Before joining Inha University, he was a Staff Member with Cisco Systems, until 2014. He is currently an Assistant Professor with the Department of Computer Science and Engineering, Inha University. His research interests include data center networking, wireless networking, future Internet, and mobile/pervasive computing.