J. Ocean Univ. China (Oceanic and Coastal Sea Research)
DOI 10.1007/s11802-012-2111-7
ISSN 1672-5182, 2012 11 (4): 436-450
http://www.ouc.edu.cn/xbywb/
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Review

Three-Dimensional Ocean Sensor Networks: A Survey

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(Received July 17, 2012; revised September 3, 2012; accepted September 25, 2012)

Abstract The past decade has seen a growing interest in ocean sensor networks because of their wide applications in marine research, oceanography, ocean monitoring, offshore exploration, and defense or homeland security. Ocean sensor networks are generally formed with various ocean sensors, autonomous underwater vehicles, surface stations, and research vessels. To make ocean sensor network applications viable, efficient communication among all devices and components is crucial. Due to the unique characteristics of underwater acoustic channels and the complex deployment environment in three dimensional (3D) ocean spaces, new efficient and reliable communication and networking protocols are needed in design of ocean sensor networks. In this paper, we aim to provide an overview of the most recent advances in network design principles for 3D ocean sensor networks, with focuses on deployment, localization, topology design, and position-based routing in 3D ocean spaces.

Key words ocean sensor networks; underwater sensor networks; three-dimensional sensor networks; ocean applications; 3D deployment; topology design; localization; position-based routing

1 Introduction

Nearly 71% of the Earth's surface is covered by water. The deep ocean is a vast and mostly unexplored habitat on our planet. Recently, there has been a growing interest in exploring and monitoring ocean environments for scientific exploration, commercial exploitation, or defense and security purposes. Ocean sensor network (OSN), formed by underwater networks of distributed sensors, is an ideal system for this type of extensive monitoring and exploration tasks.

Ocean sensor network is a type of underwater wireless sensor network (UWSN) (Akyildiz *et al.*, 2005; Cui *et al.*, 2006; Akyildiz *et al.*, 2007; Heidemann *et al.*, 2012), which is generally formed by various ocean sensors, stationary moorings, autonomous underwater vehicles, surface research vessels, or even coastal radars and large gliders. Different types of underwater devices in an OSN can communicate with each other *via* underwater communication techniques to form an underwater wireless network, while different types of ocean sensors can perform various sensing and monitoring tasks for marine applications. With the great potential to enable a wide range of applications and enhance the ability to observe and predict the ocean environments, ocean sensor network has recently become an extremely hot research area around the world.

However, due to the unique characteristics of underwater communication channels (Sozer *et al.*, 2000; Chitre *et al.*, 2008), such as low communication bandwidth, severe fading and multipath effects, large propagation delay, and high error rate, efficient and reliable underwater communication in ocean sensor networks is very challenging and significantly different from the one for terrestrial wireless sensor networks. The typical underwater communication is based on acoustic wireless communication (Sozer *et al.*, 2000; Chitre *et al.*, 2008). Underwater communication was first used in the military such as in the submarine communication system developed in the United States around the end of the Second World War. With continued research over these years, different new physical layer or link layer techniques (such as modulation, coding, multiple access, media access, error detection and recovery) have been developed to improve the performance of acoustic communication in salty ocean water. For more details on these techniques, please refer to survey papers by Sozer *et al.* (2000), Akyildiz *et al.* (2007), Chitre *et al.* (2008) and, Heidemann *et al.* (2012). In this paper, we instead focus on recent advances of network design principles (such as deployment, localization, topology control, and routing) for ocean sensor networks.

Notice that most existing wireless sensor network systems and protocols are based on two-dimensional (2D) design, where all sensor nodes are distributed in a two dimensional plane. This assumption is justified for applications where sensor nodes are deployed on earth surface and where the height of the network is smaller than

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transmission radius of a node. However, this 2D assumption may no longer be valid in ocean sensor networks, where sensors are distributed over a three-dimensional (3D) space and the difference in the third dimension (depth) is too large to be ignored. Sensor network problems in 3D have not been adequately analyzed until recent. Unfortunately, the design of 3D networks is surprisingly more difficult than the design in 2D (Wang, 2013). Many properties of the 3D network require additional computational complexity, and many problems cannot be solved by extensions or generalizations of 2D methods. In facing up to these challenges, there have been new network protocols and algorithms specifically designed for 3D sensor networks by exploring rich geometric properties of 3D sensor networks. In this paper, we aim to provide an overview of the most recent advances in network design principles for 3D ocean sensor networks, with focuses on deployment, localization, topology design, and position-based routing in 3D ocean spaces.

The remainder of this paper is organized as follows. In Section 2, we introduce some examples of current applications or systems of ocean sensor networks. In Sections 3, 4, 5 and 6, we discuss 3D deployment, localization, topology design, and position-based routing for 3D ocean sensor networks in detail, respectively. Finally, we conclude the paper in Section 7.

2 Ocean Sensor Network Applications

Applications of ocean sensor networks include oceanographic data collection, scientific ocean sampling, pollution and environmental monitoring, ocean climate recording, marine commercial operations, offshore oil exploration, disaster prevention, assisted navigation, distributed surveillance, *etc.* These applications can be roughly categorized into three classes: scientific applications, industrial applications, and defense applications (Heidemann *et al.*, 2012). Since many new applications are emerging, it is infeasible to give an exhaustive list of ocean sensor network applications. Next, we briefly review some representative examples in each class.

2.1 Scientific Applications

Scientific applications of ocean sensor networks mainly serve to observe the ocean environment for various scientific research purposes. Possible sensing objectives of ocean sensor networks include geological processes on the ocean floor, ocean water characteristics (temperature, salinity, oxygen levels, bacterial and other pollutant content, *etc.*), activities of marine animals (microorganisms, fish, or mammals). Next, we describe two example systems of ocean sensor networks in scientific applications.

Autonomous Ocean Sampling Network (AOSN): Ocean phenomena such as fronts, wind-driven red tides and mixing upwelling are rapidly changing dynamic processes with highly spatial and temporal characteristics. With the regular static mooring sensing system, it is difficult to observe these dynamic ocean phenomena (Zhang *et al.*, 2012). Curtin *et al.* (1993) proposed the AOSN concept which leverages autonomous mobile platforms to observe dynamic ocean fields. Sampling of the high gradients associated with the front is done with several autonomous underwater vehicles (AUVs) as well as with distributed acoustic and point sensors. The vehicles traverse the network recording temperature, salinity, current velocity, and other items, relaying key observations to the network nodes in real time and transferring more complete data sets after docking at a node. Each network node consists of a base buoy or mooring containing an acoustic beacon, an acoustic modem, point sensors, an energy source and a selectable number of AUV docks. Acoustic transmission loss along the many inter-nodal paths is measured periodically. A central location, either one of the nodes and/or onshore, processes the information in nearly real time to guide vehicle sampling. One of the major milestones for AOSN is the automated control of multiple, mobile sensors for weeks using spatial coverage metrics (Curtin and Bellingham, 2009). Control of an array of platforms (gliders) constrained to a fixed sampling pattern for a month has been demonstrated with no person in the loop (Paley *et al.*, 2008).

Coastal Ocean Monitoring and Prediction System (COMPS): The COMPS (Weisberg *et al.*, 2009) is a contributor toward an emergent Regional Coastal Ocean Observing System for the southeastern United States. The system is intended to provide a supportive framework for red-tide prediction as well as for other coastal ocean matters of societal concern. The coastal ocean element of COMPS is comprised of: 1) buoys with acoustic Doppler current profilers for full water column currents, temperature and salinity sensors at a few discrete depths, and surface meteorological sensors; 2) high frequency radar for surface current mapping; 3) bottom stationed ocean profilers (BSOP) for discrete profiles of temperature and salinity; and 4) various data analysis products. A total of six buoys with real-time telemetry are presently maintained, five with surface meteorological measurements in addition to in-water sensors. In addition to these surface moorings with telemetry four other (subsurface) moorings are also maintained. The subsurface wave sensors are linked by acoustic modems to either a surface buoy or a fixed tower at two experimental near shore sites. COMPS is also planning to deploy BSOP in conjunction with gliders. By combining the attributes of BSOP (synoptic sampling at high vertical resolution, but limited horizontal resolution) with those of gliders (high spatial resolution, but non-synoptic sampling), the intention is to provide three dimensional maps of temperature, salinity and other data fields for description and assimilation into models.

2.2 Industrial Applications

Industrial applications of ocean sensor networks are mainly associated with monitoring and controlling underwater commercial activities, such as installation of underwater equipment related to oil or mineral extraction, underwater pipelines, or commercial fisheries. Different from scientific applications, industrial applications usually involve control and actuation components (Heidemann *et al.*, 2012). Here, we just review an example system used for pipeline monitoring.

With the increasing demand for energy and water in the world, petroleum, natural gas, and water resources and facilities have become important assets for most countries. One of the major facilities for using these resources is pipelines and a large portion of these pipelines are deployed under ocean water. Two types of threats may occur in pipeline-laying infrastructures: intentional and non-intentional (Mohamed *et al.*, 2011). Intentional threats include terrorist attacks or illegal tapping. Non-intentional threats may occur due to accidents such as ships crashing onto a pipeline, human mistakes in the pipeline operation or maintenance, or natural disasters such as those associated volcanoes and earthquakes. Therefore, it is crucial to keep monitoring the health of every underwater pipeline and preventing or detecting any possible threat. Manum and Schmid (2007) reported an acoustic ocean sensor network used for monitoring vibrations in the Langeled Pipeline installed at a depth of 800–1100 meters on a hilly and rocky seabed. Several segments of the pipeline are not in contact with the seabed. With strong sea currents, high vibrations may be induced in these free segments. This introduces high and risky pressure on the pipeline segments. The monitoring network consists of autonomous synchronized wireless acoustic nodes. These nodes use acoustic Clamp Sensor Packages (CSP) mounted on the pipeline at regular intervals and Master Sensor Packages (MSP) for monitoring the vibrations in longer pipeline free segments. The CSPs are equipped with batteries that last for six months. Remote operating vehicles are used to replace dead nodes.

2.3 Defense Applications

Defense applications of ocean sensor networks include safeguarding or monitoring port facilities or ships in harbors, detecting and removing sea mines, providing communication with submarines and divers, and assisting navigation of battle ships or submarines in enemy's sea areas.

Detecting, classifying, and tracking underwater targets are indispensable components of modern underwater defense systems. Using traditional sonar arrays may be difficult and impractical in some mission-critical scenarios, because they should be mounted on or towed by a ship or a submersible. Alternatively, acoustic ocean sensor networks offer a promising approach (Isbitiren and Akan, 2011). Cayirci *et al.* (2006) introduced a classification-mining-based detection and classification scheme for tactical ocean sensor networks, in which mechanical, radiation, magnetic and acoustic micro-sensors are used. Their scheme first detects a target in the vicinity based on the readings of radiation and mechanical sensors. Then the detected target is classified into one of the following target types based on the data coming from acoustic and magnetic micro-sensors: a diver, a SEAL delivery vehicle, a submarine or a mine. Barr *et al.* (2011) presented the first set of results for constructing a barrier to detect intruding submarines in a 3D sensor network where sensor nodes are distributed randomly and uniformly. Their deployment method guarantees to create a vertical barrier without any hole.

Seaweb (Rice, 2007) is an example of a large-scale ocean sensor network used for defense, which is being developed by the US Navy since the 1980s. It employs AUVs, gliders, buoys, repeaters and ships where the component devices communicate *via* telesonar, radio or satellite links (see Fig.1 for an illustration). Telesonar

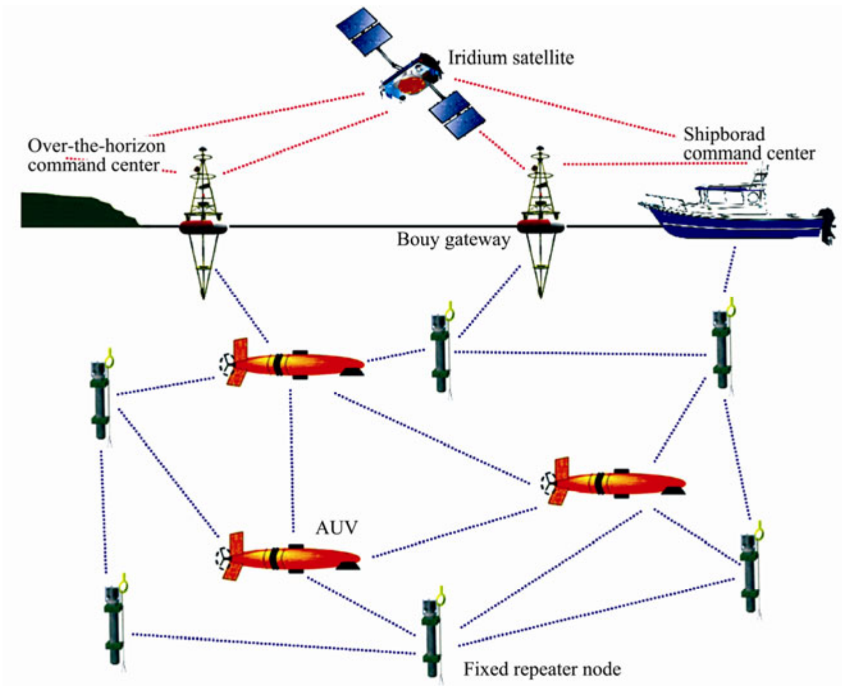

Fig.1 Seaweb network in the Eastern Gulf of Mexico, including three AUVs, six repeater nodes, and two gateway buoys (Rice, 2007).

links enable underwater communication, radio links are used only by the devices on the surface to communicate with the command center on the ship, and the on-shore command center is accessed *via* satellite links.

3 3D Deployment of Ocean Sensor Networks

Ocean sensor networks are usually deployed in 3D underwater spaces, except for a few sensor networks deployed only on the surface (Guo *et al.*, 2008) or at the bottom (Akyildiz *et al.*, 2007) of the ocean. Due to the wide range of applications of ocean sensor networks, there are different ways to deploy underwater sensors in ocean environment. Based on the mobility of nodes, we can roughly categorize them into three groups: static deployment, semi-mobile deployment, and mobile deployment. We will review several different 3D deployment methods of ocean sensor network in this section.

Besides mobility, other important parameters that characterize a deployment include network density, coverage, and number of nodes. Compared to those for terrestrial sensor networks, underwater deployments are generally less dense, of longer range, and with significantly fewer nodes. However, it is also envisioned that a large scale of 3D ocean sensor network can become a reality in near future and be useful for more complex tasks and applications.

3.1 Static Deployment

In the 3D ocean environment, ocean sensors can float at different depths to observe a given phenomenon. One possible deployment method (Cayirci *et al.*, 2006) is to attach each ocean sensor to a surface buoy and control the length of the wire to adjust the depth of each sensor. This solution enables an easy and quick deployment of a 3D sensor network, but also suffers from certain weaknesses; for instance, multiple floating buoys may obstruct ships navigating on the sea surface or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering (Pompili *et al.*, 2009). Akyildiz *et al.* (2005) proposed another solution that sensors can be anchored to the seafloor and equipped with a floating buoy that can be inflated by a pump. The buoy pulls the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire that connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor. In both of these solutions, ocean sensors are static after the initial deployment.

3.2 Semi-Mobile Deployment with Depth Adjustment

If the sensor nodes have the ability to adjust their positions underwater, it will be easier for water column profiling and 3D network deployment. Although the mobility of ocean sensors is limited with the current technology, some devices have been constructed to implement depth adjustment. For example, Howe and McGinnis (2004) developed a water column profiler which travels along the mooring cable of their system and is able to be recharged inductively on the surface platform. The LEO-15 platform developed jointly by WHOI and Rutgers University has a bottom-mounted winch system for water column profiling (Glenn *et al.*, 2006). Detweiler *et al.* (2012) developed a depth adjustment system that is a winch-based module and can be incorporated into the core AquaNode system to enable depth adjustment in water of up to 50 m deep. The depth adjustment system enables the ocean sensors to be deployed with a desired geometry which can improve sensing and communication over the whole region. Moreover, this system makes localization and recovery/deployment of large systems much easier than traditional static ocean sensor networks.

One of the ocean monitoring systems employing such profiling floats is the Argo Project (Argo Science Team, 1998). Argo is a global array of 3000 free-drifting profiling floats that collect high-quality temperature and salinity profiles from the upper 2000 m of the ice-free global ocean and current profiles from intermediate depths. The deployments began in 2000 and continue today at the rate of about 800 floats per year. The floats will cycle to 2000 m depth every 10 d, with 4–5 year lifetimes for individual instruments. At typically 10-day intervals (as shown in Fig.2), the floats pump fluid into an external bladder and rise to the surface over about 6 h while measuring temperature and salinity. Satellites determine the position of the floats when they surface, and receive the data transmitted by the floats. The bladder then deflates and the float returns to its original density and sinks to drift until the cycle is repeated. Floats are designed to make about 150 such cycles. Although Argo floats do not form a network because there is no communication between the floats. Their depth adjustment system is quite mature and can be transformed to 3D ocean sensor nodes.

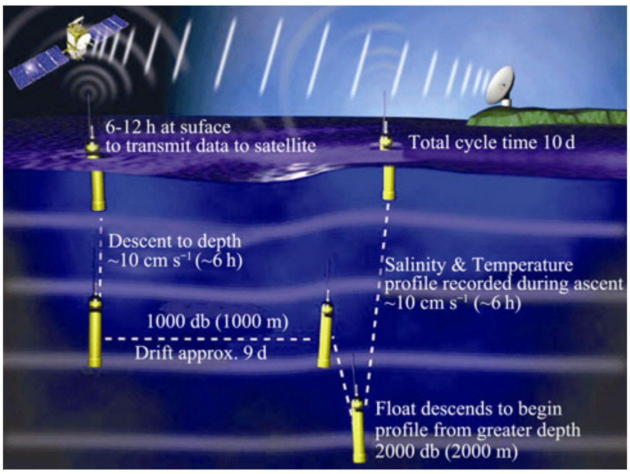

Fig.2 Park and profile mission operation in Argo project (http://www.argo.ucsd.edu/How_Argo_floats.html).

3.3 Mobile Deployment

In mobile ocean sensor networks, sensors can be attached to AUVs, low-power gliders, or unpowered drifters. Therefore, the sensors can move vertically and horizontally in the ocean. Since the underwater instruments are fairly expensive and the costs quickly rise for deep water, mobility is useful to maximize sensor coverage with limited hardware. For example, inexpensive AUVs can carry multiple ocean sensors and reach any depth in the ocean. But mobility also raises challenges for localization and maintaining connectivity. Recently, there are several new studies on how to intelligently control multiple AUVs to coordinate with ocean sensors and perform sensing, localization, and communication tasks. Since energy for communications is usually plentiful in AUVs compared with ordinary sensors, they can play more important roles than ordinary ocean sensors in collecting, processing, and managing the desired data. One of such examples is a marine vehicle sensor network proposed by Zhang *et al.* (2012). Their overall integration of ocean phenomena observation system includes multiple marine AUVs equipped with various sensors. Multiple AUVs can transmit information to each other through acoustic communications. They are smartly controlled and work together to complete the overall observation mission.

3.4 Hierarchical and Heterogeneous Deployment

Due to the variety of ocean environment and applications, different deployment methods of ocean sensor network could be used. In many applications, multiple heterogeneous deployment methods can be combined and co-exist in large-scale ocean sensing platforms. For example, in Seaweb network (Rice, 2007), as shown in Fig.1, multiple AUVs, underwater repeater nodes, and gateway buoys are used in 3D ocean networks. In addition, hierarchical architecture can be used to form the 3D ocean sensor network. For example, Alam and Haas (2010) described a hierarchical ocean sensor network where a small number of robust and powerful nodes form the backbone to route sensing data towards a sink node while actual sensing is done by a large number of inexpensive and failure-prone sensor nodes. A placement strategy is provided to minimize the number of backbone nodes while keeping the network fully functional. In summary, hierarchical and heterogeneous deployment is envisioned more suitable for large-scale ocean sensor networks.

4 3D Localization

Localization is one of the fundamental tasks in designing ocean sensor networks (Erol-Kantarci *et al.*, 2011; Tan *et al.*, 2011) or general wireless sensor networks (Wang and Li, 2009). Location information can be used in many tasks of ocean sensor networks such as event detecting, target/device tracking, environmental monitoring, tagging raw sensing data, and network deployment. Moreover, location information can also be used by networking protocols to enhance the performance of ocean sensor networks, such as routing packets using position-based routing or controlling the network topology and coverage using geometric methods.

It is more challenging to locate nodes in underwater environments than in terrestrial environments. First, GPS signal does not propagate through water and RF signal cannot be used since it will be absorbed by water. Thus, acoustic signal is usually the best choice in underwater environments. Second, several alternative cooperative positioning schemes are not applicable in practice due to acoustic channel properties (such as low bandwidth, high propagation delay and high bit error rate). Since the velocity of acoustic signal can change with salinity, pressure and temperature, it is difficult to get quite precise ranges between nodes underwater. Last, the 3D deployment of ocean sensor network requires more anchor nodes to locate nodes in 3D ocean space. All these make accurate localization in the ocean a challenging task.

Recently, a large number of localization techniques have been proposed for ocean senor networks or underwater sensor networks. Most of these methods can be classified into two categories: range-based methods and range-free methods. Range-based methods utilize time of arrival (ToA), time difference of arrival (TDoA), or angle of arrival (AoA) to measure distances or angles between nodes and then use these distance or angle estimations to compute positions of nodes. Usually, in range-based methods, a certain number of anchor nodes (or called reference nodes) are used, with their positions known beforehand and the capacity to send beacon messages to other nodes being given. However, in some applications, the cost and limitations of the hardware on sensing nodes prevent the use of range-based localization schemes, depending on absolute point-to-point distance estimates. Therefore, the other type of localization methods, range-free method, does not employ accurate measurement techniques; instead, it uses alternative methods such as hop-count or areas to locate nodes with less expense. Such coarse accuracy is sufficient for some of ocean sensor network applications.

Depending on the mobility of anchor nodes, localization methods can also be categorized into static localization methods and mobile localization methods. In static localization methods, all anchors are stationary and the estimated distances from sensors to anchors are used for determining locations of sensors. However, in such methods, some sensor nodes may not be uniquely determined because there are no sufficient anchor nodes. One possible solution is deploying a great number of anchors to avoid such situation. However, this brings high cost, especially for ocean sensor networks. One efficient way to address this problem is to introduce mobile anchor nodes. These mobile anchors can move around in the network and know their positions at a certain or any time. The beacon signals sent by the mobile anchor include its position. When a sensor hears the beacon signals from mobile anchors, more information can be obtained for localization, thus this improves the accuracy of localization. Several AUV-aided localization methods use AUVs as the mobile anchors. For example, Erol *et al.* (2007b) proposed to use a single AUV to aid the localization of underwater sensors. When AUV is on the surface of water, it can receive signals from GPS and get its position. Then the AUV dives into water and follows a known trajectory. While AUV is moving among sensor nodes, it broadcasts some information containing the present position of AUV. When a sensor node receives a signal from AUV, it can measure the distance to AUV and get the position of AUV. If the node obtains enough distances to AUV and positions of AUV, it can compute its position by using trilateration. A similar method (called Dive'N'Rise, where the mobile anchors are sinking and rising in the water and broadcast their positions) was adopted by Erol *et al.* (2007a).

Finally, localization algorithms can also be grouped under centralized methods and distributed methods. Centralized methods usually collect all kinds of information and send them to a centralized entity (a sink or command center) where the location of each sensor is calculated. Then the location information can be sent to each sensor or used for data analysis. Distributed methods allow each sensor to perform localization individually and collaboratively. There is no single centralized entity and algorithms are executed distributively without a global infrastructure. Usually, distributed methods are preferred over centralized methods since the former can provide real-time dynamic location information for large-scale ocean sensor networks.

To fulfill different requirements of localization tasks in ocean sensor networks, various 3D localization methods have been proposed. Table 1 summaries some of them. For more detailed techniques, please refer to more comprehensive surveys (Erol-Kantarciz *et al.*, 2011; Tan *et al.*, 2011; Han *et al.*, 2012).

Table 1 Summary of existing localization methods for 3D ocean sensor networks

3D localization method	Mobile or static sensor	Anchor	Ranging technique	Distributed or centralized	Message from sensor
Motion-aware self localization (Mirza and Schurgers, 2008)	Mobile	No anchors	ToA	Centralized	Active
3D multi-power area localization (Zhou *et al.*, 2009)	Static	Surface buoys, DETs	Range-free	Centralized	Active
Collaborative localization (Mirza and Schurgers, 2007)	Mobile	No anchors	ToA	Centralized	Active
AUV-aided localization (Erol *et al.*, 2007b)	Static	Propelled mobile anchor (AUV)	ToA	Distributed	Silent
Localization with directional beacons (Luo *et al.*, 2010)	Static	Propelled mobile anchor (AUV)	Range-free	Distributed	Silent
Dive and rise localization (Erol *et al.*, 2007a)	Mobile or static	Non-propelled mobile anchors	ToA	Distributed	Silent
Multi-stage localization (Erol *et al.*, 2008)	Mobile	Non-propelled mobile anchors and reference nodes	ToA	Distributed	Active
Large-scale hierarchical localization (Zhou *et al.*, 2007)	Static	Surface buoys, underwater anchors and reference nodes	ToA	Distributed	Active
Detachable elevator transceiver (DET) localization (Chen *et al.*, 2009)	Static	Surface buoys, DETs, underwater anchors and reference nodes	Not specified	Distributed	Active
3D underwater localization (Isik and Akan, 2009)	Semi-static or mobile	Three initial anchors and reference nodes	ToA	Distributed	Active
Underwater positioning scheme (Cheng *et al.*, 2008)	Static	4 stationary anchors	TDoA	Distributed	Silent
Wide coverage positioning System (Tan *et al.*, 2010)	Static	4 or 5 stationary anchors	TDoA	Distributed	Active
Large-scale localization scheme (Cheng *et al.*, 2009)	Static	Stationary anchors	TDoA	Distributed	Active
Underwater sensor positioning (Teymorian *et al.*, 2009)	Static	Stationary anchors	ToA	Distributed	Active
Scalable localization with mobility prediction (Zhou *et al.*, 2008)	Mobile	Surface buoys, underwater anchors and reference nodes	ToA	Distributed	Active

5 3D Topology Design

Network topology is always a key functional issue in design of wireless networks. For different applications, network topology can be designed or controlled for different objectives (such as power efficiency, fault tolerance, and throughput maximization). Topology design for 2D wireless sensor networks (Wang, 2008) has been well studied. However, 3D environment introduces new challenges to topology design for ocean sensor networks in terms of connectivity, coverage and energy efficiency. Connectivity of the underlying topology enables ocean sensors to communicate with each other, while sensing coverage reflects the quality of surveillance. Surprisingly, topology design of 3D networks is more difficult than the one in 2D (Wang, 2013). Many desired properties of topologies require additional computational complexity, and simple extensions or generalizations of 2D methods may not work in 3D.

5.1 3D Topology Design for Coverage

Providing full coverage of the deployment region or a certain target region is one of the key goals in sensor network design, especially for those surveillance or monitoring applications. Different topologies of a sensor network can provide different levels of coverage to the region. If ocean sensors can adjust their positions, one of topology design tasks is how to control them to provide full coverage. Akkaya and Newell (2009) proposed a self-deployment scheme for underwater sensor nodes in 3D environment. The nodes are assumed to have the ability to adjust their depth. Based on a local agreement to reduce the sensing overlaps among the neighboring nodes, the nodes continuously adjust their depths until there is no room to improve their coverage. Cayirci *et al.* (2006) introduced a distributed 3D space coverage scheme for tactical underwater sensor networks where sensor nodes transmit their data packets through the antenna in surface buoys. Although sensor nodes are randomly deployed, they can be lowered at any depth. The scheme finds out an appropriate depth for each node such that the maximum 3D coverage of the field is maintained. Their algorithm can rearrange the depths of sensor nodes as they are moved by currents, winds or other reasons. Pompili *et al.* (2009) also proposed three deployment strategies for 3D underwater sensor networks to obtain full coverage of a 3D region: 3D-random, bottom-random, and bottom-grid strategies. In all these deployment strategies, winch-based sensor devices are anchored to the bottom of the ocean in such a way that they cannot drift with currents. Sensors can adjust their depth and float at different depths in order to observe a given phenomenon or coverage. Sensors are assumed to know their positions by exploiting 3D localization techniques. Watfa and Commuri (2006a, 2006b) also studied the coverage problem for general 3D sensor networks with high deployment density. Their methods can choose a subset of sensors to be alive and provide full coverage to the whole 3D region.

5.2 3D Topology Design for Connectivity and Coverage

While maximizing the total network coverage is necessary for being able to monitor any event at every spot of the region, maintaining connectivity is crucial for continuous data gathering from all sensors. Since today sensor nodes deployed in 3D underwater space are expensive, deploying the minimum necessary to achieve both coverage and connectivity is important for economic reasons. Alam and Haas (2006) first studied the 3D topology problem for both connectivity and coverage, and they proposed a placement strategy based on Voronoi tessellation of 3D space, which creates truncated octahedral cells. In their truncated octahedron placement strategy, the transmission range must be at least 1.7889 times the sensing range in order to maintain connectivity among nodes. If the transmission range is between 1.4142 and 1.7889 times the sensing range, then a hexagonal prism placement strategy or a rhombic dodecahedron placement strategy can be used instead. Bai *et al.* (2009a, 2009b) studied a more general problem of how to construct a 3D topology with k-connectivity and full-coverage by using the least number of sensors. They design and prove the optimality of 1-, 2-, 6-, 14-connectivity patterns under any value of the ratio of communication range over sensing range, among regular lattice deployment patterns. They also proposed a set of patterns to achieve 3- and 4-connectivity patterns and investigate the evolutions among all the proposed patterns. Ammari and Das (2010) extended the coverage and connectivity problem by considering k-coverage in 3D sensor networks and proposed the Reuleaux tetrahedron model to guarantee k-coverage of a 3D field. Based on the geometric properties of Reuleaux tetrahedron, they derived the minimum sensor spatial density to ensure k-coverage of a 3D space. Aslam and Robertson (2010) considered how to find a subset of sensors in a densely deployed 3D sensor network to guarantee the coverage and connectivity. Their distributed coverage algorithm allows sensors to form a 1-covered and connected topology by exchanging messages based on the local information.

5.3 3D Topology Control for Connectivity and Power Efficiency

Topology control technique is to let each sensor node locally adjust its transmission range and select certain neighbors for communication, while maintaining a structure that can support energy efficient routing and improve the overall network performance. For a 3D sensor network modeled by a unit ball graph (UBG) where each sensor has the same maximum transmission range, topology control aims to build and maintain a sparse 3D subgraph of the UBG as the underlying topology for the network. The constructed 3D topology should preserve connectivity, support energy-efficient routing, and conserve energy. Here, a 3D topology is energy efficient if the total energy consumption of the least energy cost path between any two nodes in final topology should not exceed a constant factor of the energy consumption of the least energy cost path in the original network modeled by UBG (Li *et al.*, 2001). Such topology and the constant factor are called an energy spanner of UBG and its energy stretch factor, respectively. An energy spanner keeps the possibilities of energy-efficient routing. In addition, the construct algorithm is preferred to be localized, *i.e.*, every node can decide all links incident on itself in the topology by only using local information.

Although geometric topology control protocols (Wang, 2008) have been well studied in 2D networks, current 2D methods cannot be directly applied in 3D networks. There is no embedding method mapping a 3D network onto a 2D plane so that the relative scale of all edge length (or energy) is preserved and all 2D geometric topology control protocols can still be applied for energy efficiency (Wang *et al.*, 2008a). Next, we introduce a few 3D geometric topologies for 3D sensor networks.

It is very natural to extend the 2D related neighborhood graph (RNG) (Toussaint, 1980) and Gabriel graph (GG) (Gabriel and Sokal, 1969) to 3D (Wang *et al.*, 2008a). The definitions of 3D RNG and 3D GG are as follows (see Fig.3): an edge $uv \in$ RNG if and only if the intersection of two balls centered at u and v with radius of length as the distance between u and v does not contain any node from the set V; an edge $uv \in$ GG if and only if the ball with edge uv as a diameter contains no other node of V. Based on their definitions, 3D RNG and 3D GG can be easily constructed using 1-hop neighbors' position information. 3D RNG and 3D GG both contain the minimum spanning tree (MST), which indicates that they are connected if the UBG is connected. However, both of them do not have bounded node degree. It can be proved that RNG is not an energy spanner, while GG is an energy spanner with the energy stretch factor of one. In other words, all edges in the least energy path in UBG are kept in 3D GG.

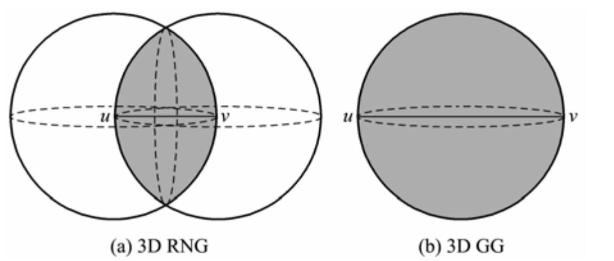

Fig.3 Definitions of 3D RNG and 3D GG: shaded areas are empty of nodes.

Since both 3D RNG and 3D GG cannot bound node degree, it is also interesting in extending Yao graph (Yao, 1982; Li *et al.*, 2001) to 3D. 3D Yao structures can use certain types of 3D cones to partition the transmission region of a node (which is a sphere), and inside each 3D cone the node only keeps a link to the nearest neighbor. If the number of such 3D cones is bounded by a constant k, 3D Yao structures can bound the node out-degree by k. 3D Yao structures can be categorized into two sets based on their partition methods: fixed partition and flexible partition. In fixed partition, 3D cones from one node do not intersect with each other and the partition method is the same for all nodes. Wang *et al.* (2008a) proposed two such methods to divide the transmission range of a node into 32 or 56 3D cones (as shown in Figs.4(a) and 4(b)). The resulting directed Yao graphs are denoted by FiYG_{32} and FiYG_{56} respectively. Kim *et al.* (2010) proposed another fixed partition method: localized Yao-based structure with Platonic solid (PYG). To construct PYG, each node divides the 3D sphere neighborhood into k equal cones by using a regular k-polyhedron and selects the nearest neighbor in each cone. The resulting directed graph is denoted by PYG_k. Possible polyhedrons include tetrahedron, cube, octahedron, dodecahedron and icosahedron. Figs.4(c) and 4(d) illustrate partition examples with an octahedron $k=8$ and a dodecahedron $k=12$. In flexible partition based method (Wang *et al.*, 2008a), identical 3D cones with a top angle θ are used to partition the transmission ball (as shown in Fig.5(a)) and where to define these cones depends on the locations of neighbors around node u (*i.e.*, different nodes may get different partitions). Here θ is an adjustable parameter. Clearly, larger θ leads to lower node out-degree at each node. In flexible partition method, the 3D cones are allowed to be overlapping as shown in Fig.5(b). Wang *et al.* (2008a) proposed three different methods to perform such a partition. Two of them can bound the node out-degree. Let FlYG_θ denote the structures from these methods. For all of these 3D Yao

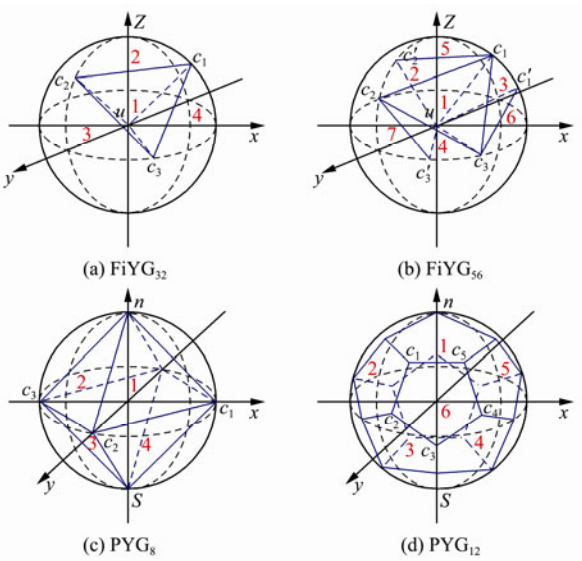

Fig.4 Definitions of 3D Yao structures with fixed partitions: (a) and (b), partitions of the 1/8 sphere in FiYG; (c) and (d), partitions using an octahedron or a dodecahedron for PYG.

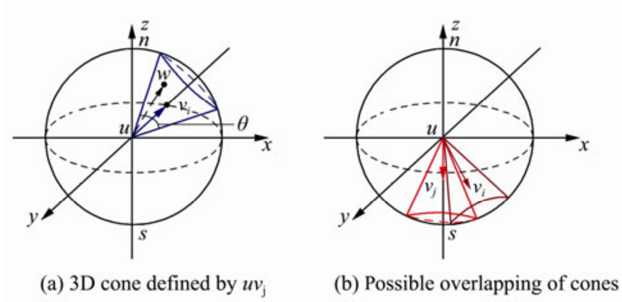

Fig.5 Definitions of 3D Yao structures with flexible partitions FlYG_θ.

structures (FiYG_k, FlYG_θ and PYG_k), they are energy spanners of UBG when k is large enough or θ is small enough. In addition, all of them can be easily constructed based on 1-hop information. Similar to 3D Yao structures, the cone-based topology control (CBTC) protocol (Wattenhofer *et al.*, 2001) has been generalized to 3D by Bahramgiri *et al.* (2002), Ghosh *et al.* (2007), and Poduri *et al.* (2009) to preserve connectivity. Basically, each node u increases its transmission power until there is no empty 3D-cone with angle degree α, *i.e.*, there exists at least a node in each 3D-cone of degree α centered at u, if $\alpha \le 2\pi/3$. Even though these approaches can guarantee connectivity, the gap detection algorithm applied to check the existence of the empty 3D-cone of degree α is complicated. Their time complexities are much larger than those of 3D Yao structures. If both in-degree and out-degree need to be bounded, 3D symmetric Yao graph or 3D Yao and reverse Yao graph (Li *et al.*, 2012) can be applied.

So far, we have introduced several localized 3D geometric structures. Some of them have bounded node degree, and some of them are energy spanners of UBG. Notice that all listed topologies only need 1-hop neighbor information to be constructed, *i.e.*, all construction algorithms are localized algorithms. Thus, when nodes move, the updates of these topologies can be efficiently performed in a local area without any global affects.

5.4 Handling Fault Tolerance and Shadow Zone

In order to be power efficient, traditional topology control algorithms try to reduce the number of links, and thereby reduce the redundancy available for tolerating node and link failures. Thus, the topology derived from such algorithms is more vulnerable to node failures or link breakages. Fortunately, most of the 3D structures we introduced so far can be easily extended to support fault tolerance. To achieve both sparseness and fault tolerance, Wang *et al.* (2009) extended 3D RNG, 3D GG, and 3D Yao structures to support fault tolerance by a simple modification of their definitions. The new 3D topologies not only guarantee *k*-connectivity of the network, but also ensure the bounded node degree and constant energy stretch factor even under *k*-1 node failures. A similar idea has been used by Bahramgiri *et al.* (2002) for 3D CBTC.

The spatially-variant underwater channel can also cause the formation of shadow zones, which are time-variant areas where there is little signal propagation energy due to the refraction of signals by the sound speed fluctuation (Preisig, 2007). Shadow zones can cause high bit error rates, losses of connectivity and dramatically impact communications performance. Domingo (2009) proposed a distributed adaptive topology reorganization scheme that alleviates the effects of energy limitations and is able to maintain connectivity between sensor nodes in 3D underwater sensor networks in the presence of shadow zones. It can estimate when the shadow zones have disappeared using double sensor units to re-establish communication very quickly through the original acoustic wireless links.

6 3D Position-Based Routing

Routing is another challenging task in ocean sensor networks, which aims to delivery packets from a source node to a destination node *via* multihop relays. Pompili and Akyildiz (2009) have shown that traditional terrestrial routing solutions (such as classical proactive and reactive protocols) may not be suitable for underwater networks due to slow propagation of acoustic signals and high latency of path establishment and maintenance. The geometric nature of the multi-hop sensor networks provides a promising idea: position-based routing (also called geometric routing, georouting, or geographic routing). Position-based routing protocols do not need the dissemination of route discovery information, and no routing tables are maintained at each node. They only use the local position information at each node and geometric properties of surrounding neighbors to determine how to route the packet. This leads to lower overhead and higher scalability, and makes such routing protocols suitable for ocean sensor networks. In this section, we focus on reviewing different 3D position-based routing techniques to achieve sustainability and scalability in large-scale 3D sensor networks. Many of them can be directly used in 3D ocean sensor networks. Notice that there are also other types of routing solutions (no position information is used) for 3D ocean sensor networks; however, due to space limitation we could not include them within this survey.

6.1 3D Greedy Routing

Most classical and widely used position-based routing is greedy routing, in which a packet is greedily forwarded to the closest node to the destination in order to minimize the average hop count. Greedy routing can be easily extended to 3D cases. Actually, several under-water routing protocols (Pompili and Melodia, 2005; Xie *et al.*, 2006) for underwater sensor networks are just variations of 3D greedy routing. Fig.6 illustrates the basic idea of 3D greedy routing. Let t be the destination node. As shown in Fig.6(a), current node u finds the next relay node v that is the closest to t among all neighbors of u. But, it is easy to construct an example (see Fig.6(b)) to show that greedy routing will not succeed to reach the destination but fall into a local minimum (at a node without any 'better' or 'closer' neighbors). This is true for both 2D and 3D networks. To guarantee packet delivery of 3D greedy routing is not straightforward and much more challenging than in 2D greedy routing. In 2D networks, face routing can be used on planar topology to recover from the local minimum of greedy routing and guarantee the delivery (Bose *et al.*, 1999). However, there is no planar topology concept any more in 3D networks, thus, face routing cannot be applied directly to help 3D greedy routing get out of local minimum. Most importantly, Durocher *et al.* (2008) have proved that there is no deterministic localized routing algorithm for general 3D networks that guarantees the delivery of packets. Here, a routing algorithm is localized if the decision to which node to forward a packet is based only on: the information in the header of the packet and the local information gathered by the node from a small neighborhood (*i.e.* 1-hop neighbors of the node).

One simple way to guarantee the packet delivery for greedy routing in 3D networks is letting all nodes have sufficiently large transmission range to avoid the existence of local minimum. It is clear that this can be achieved when the transmission range is infinite. Given a set of sensors V in a 3D sensor network, let the critical transmission range (CTR) for 3D greedy routing be the smallest transmission range that can guarantee the delivery of packets between any source-destination pair of nodes among V. Wang *et al.* (2008b, 2010) studied the CTR of 3D greedy routing in large-scale random 3D networks. When a set V of n sensor nodes uniformly distributed in a compact and convex 3D region with unit-volume and each node has a uniform transmission range

r_n, the CTR for 3D greedy routing is asymptotic almost surely at most $\sqrt[3]{3\beta \ln n/(4\pi n)}$ for any $\beta>\beta_0$ and at least $\sqrt[3]{3\beta \ln n/(4\pi n)}$ for any $\beta<\beta_0$, where $\beta_0=3.2$. This theoretical result answers a fundamental question about how large the transmission range should be set in a 3D sensor networks, such that 3D greedy routing guarantees the delivery of packets between any two nodes.

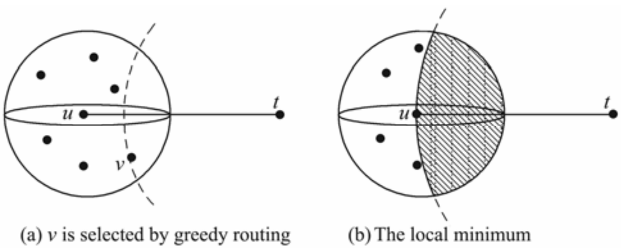

Fig.6 Illustration of 3D greedy routing.

6.2 3D Routing *via* Mapping and Projection

Since face routing can always find a detour out of the local minimum for greedy routing in planar 2D networks (Bose *et al.*, 1999), it is natural to project the 3D network onto a 2D space (as shown in Fig.7(a)) and use face routing in the 2D plane. Kao *et al.* (2005) and Abdallah *et al.* (2007) have proposed several 3D position-based routing protocols using this idea. However, as shown in Fig.7(b) (Kao *et al.*, 2005), a planar graph cannot be extracted from the projected graph. It is clear that removing either $v'_1v'_2$ or $v'_3v'_4$ will break the connectivity. Kao *et al.* (2005) and Abdallah *et al.* (2007) also proposed face coordinate routing (CFace) which first projects the network onto the *xy* plane and runs face routing on it. If the face routing fails on the projected graph, it will project the network onto the second plane (the *yz* plane). If the face routing fails again, the network is projected onto the third plane (the *xz* plane). However, if the face routing fails on the third plane, this method fails. In 2D, several greedy embedding algorithms (Kleinberg, 2007; Zhang *et al.*, 2007; Sarkar *et al.*, 2009) can embed the 2D network into certain space such that greedy routing guarantees delivery in the new virtual space. Unfortunately, none of the greedy embedding algorithms in the literature can be extended from 2D to 3D general networks.

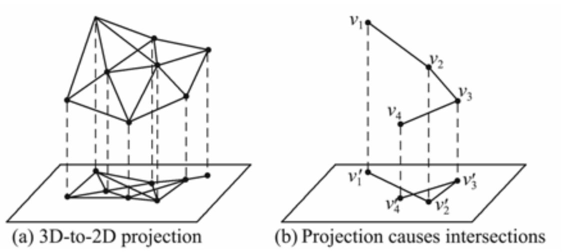

Fig.7 Simple projection from 3D to 2D does not work.

6.3 Randomized 3D Greedy Routing

Since no deterministic localized position-based routing can guarantee the packet delivery (Durocher *et al.*, 2008), randomized algorithms become possible solutions. Abdallah *et al.* (2006) proposed a new randomized position-based routing for 3D networks, called randomized AB3D routing. AB3D algorithm selects the next hop *x* randomly from three candidate neighbors of the current node *u* (the node nearest to the destination *t* (denoted by *a*), the node chosen by 3D greedy from all neighbors of *u* above or below the plane defined by *a*, *u* and *t*. The probabilities to choose *x* from these three candidates could be the same or related to their angles or distances to the destination. However, such routing method does not have any performance guarantee. Flury and Wattenhofer (2008) explored using random walks to escape from the local minimum and proposed a greedy-random-greedy routing method. The packet is first forwarded greedily until a local minimum is encountered. To resolve the local minimum, a randomized recovery algorithm based on random walks kicks in. Whereas a packet moving around randomly in the network may seem very inefficient and too simplistic, they do propose several techniques to make random walks more efficient. They proved that the expected number of hops needed for the random walk method is in the square of the optimal localized routing algorithm. However, in practice, this randomized method still often leads to high overhead or long delay in 3D networks.

6.4 3D Greedy Routing over Constructed Structures

Guarantee delivery can also be achieved at the cost of more (non-constant-bounded) storage space by constructing certain routing structures. For example, Lam and Qian (2011) used a virtual Delaunay triangulation to aid position-based routing, while Zhou *et al.* (2010) used hull tree structures (spanning trees) to store possible routes around the void.

Lam and Qian (2011) proposed multi-hop Delaunay triangulation (MDT) routing over a virtual Delaunay triangulation. In a *d*-dimensional Euclidean space, a Delaunay triangulation is a triangulation such that there is no point in *V* inside the circum-hypersphere of any d-simplex. In 3D space, the 3-simplex is a tetrahedron. Morin (2001) has proved that 2D greedy routing can guarantee the packet delivery on 2D Delaunay triangulation. This is also true in 3D space. However, building the Delaunay triangulation needs global information and the length of a Delaunay edge could be longer than the maximum transmission range. The key idea of the MDT method is to relax the requirement that every node be able to communicate directly with its neighbor in Delaunay triangulation. In a MDT, the neighbor of a node may not be a physical neighbor. A virtual link represents a multi-hop path between them. When the current node *u* has a packet with destination *t*, it forwards the packet to a physical neighbor closest to *t* if *u* is not a local minimum; otherwise the packet is forwarded *via* a virtual link to a multi-hop Delaunay neighbor closest to *t*. MDT can guarantee the packet delivery using a finite number of hops. However, the construction and maintenance of the MDT at each node are not purely localized.

Zhou *et al.* (2010) also proposed a position-based routing method (3D Greedy Distributed Spanning Tree Routing, GDSTR-3D), which uses two hull trees (both spanning trees) for recovery from local minimums. For each tree, each node stores two 2D convex hulls to aggregate the locations of all descendants in the subtrees rooted at the node. The two 2D convex hulls approximate a 3D convex hull at each node to save the storage space. GDSTR-3D forwards packets greedily as long as it can find a neighbor closer to the destination than the current node. If the packet ends up in a local minimum, the node then attempts to forward the packet to a neighbor that has a neighbor closer to the destination than itself. If this 2-hop greedy routing still fails, GDSTR-3D switches to forwarding the packet along the edges of a spanning tree which aggregates the location of the nodes in its subtrees using two 2D convex hulls. Since the spanning tree can always reach the destination if the network is connected, GDSTR-3D can always guide the packet to escape from the local minimum and guarantee the delivery. However, in the worst case routing with the hull tree degrades to depth first search, so the routing path could be long and the storage in a node can be very large. In addition, some nodes (such as the roots of trees) will be heavily loaded.

6.5 Hybrid 3D Greedy Routing

There are also hybrid greedy routing methods which combine various solutions above. For example, Abdallah *et al.* (2006) also combined their randomized routing method with the projection-based face routing (Kao *et al.*, 2005; Abdallah *et al.*, 2007). Xia *et al.* (2011) recently proposed a hybrid 3D greedy routing, which uses both a constructed routing structure (unit tetrahedron cell) and a projection method (volumetric harmonic mapping). We now briefly review their routing methods. First, a unit tetrahedron cell (UTC) mesh structure is constructed from all 3D nodes. A UTC is a tetrahedron formed by four network nodes, which does not intersect with any other tetrahedrons. The union of all UTCs forms the mesh structure. Second, a face-based greedy routing is proposed to delivery packets within the internal (non-boundary) UTC. The idea is very like the face routing in 2D. The face-based greedy routing will pass a sequence of faces which intersect with the line segment between the source and destination. It can be proved that such face-based greedy routing does not fail at a non-boundary UTC. Third, to handle the possible failure of greedy routing at boundaries, the proposed method maps the whole UTC mesh using volumetric harmonic mapping under spherical boundary condition so that the boundary nodes are now on a surface of a sphere. This can guarantee the node-based greedy routing can reach any boundary node successfully. Last, a hybrid greedy routing is proposed, which alternately uses face-based greedy for internal UTCs and node-based greedy for boundary UTCs. Face-based greedy can guarantee the delivery in non-boundary UTCs. When the packet fails at a boundary UTC, node-based greedy is applied to escape the void. Since the boundary has been mapped to a sphere, node-based greedy routing always succeeds on a boundary. When it is possible, it switches back to face-based greedy to route the packet towards the destination. However, the complexity of this proposed method (such as spherical/volumetric harmonic mapping) still makes it not very practical. In addition, how to handle multiple inner holes and routing across them is still not clear.

In this section, we briefly review existing geometric solutions for designing 3D position-based routing to guarantee the packet delivery in 3D wireless sensor networks. Table 2 provides a summary and comparison of these solutions. Most of these techniques can be applied in static 3D ocean sensor networks. Note that certain performances of position-based routing protocols are relying on the accuracy of node position information. Therefore, 3D localization techniques we introduced in Section 4 are usually used together with 3D position-based routing in 3D ocean sensor networks. Beyond the goal of delivery

Table 2 Summary of existing geometric solutions for 3D position-based routing aiming to improve or guarantee the packet delivery in 3D wireless sensor networks

3D Position-based routing	Enlarging TrX range	Projection-based method	Randomized method	Constructed structure	Hybrid Method	Localized method	Delivery guarantee
3D Greedy routing						Yes	
CTR of 3D greedy routing in random networks (Wang *et al.*, 2008b, 2010)	Yes					Yes	Yes (with high prob.)
Face coordinate routing (CFace) (Kao *et al.*, 2005; Abdallah *et al.*, 2007)		Yes (mapping to 2D)				Yes	
Randomized AB3D routing (Abdallah *et al.*, 2006)			Yes			Yes	
Hybrid AB3D-CFace routing (Abdallah *et al.*, 2006)		Yes (mapping to 2D)	Yes		Yes	Yes	
Greedy-random-greedy (Flury and Wattenhofer, 2008)			Yes			Yes	Yes
Multi-hop delaunay triangulation routing (Lam and Qian, 2011)				Yes (virtual Delaunay triangulation)			Yes
Greedy distributed spanning tree routing GDSTR-3D (Zhou *et al.*, 2010)				Yes (spanning trees)			Yes
Volumetric harmonic mapping based greedy routing (Xia *et al.*, 2011)		Yes (volumetric harmonic mapping)		Yes (unit tetrahedron cells)	Yes		Yes

guarantee, there are also other design goals for 3D position-based routing, such as energy efficiency (Wang *et al.*, 2011), robustness and reliability. In addition, there are other types of 3D routing protocols (such as delay tolerant routing protocols (Guo *et al.*, 2010; Rahim *et al.*, 2011)) for ocean/underwater sensor networks, which may not rely on the position information. Due to space limitation, we could not include them within this survey.

7 Conclusion

With the growing ocean applications, new 3D ocean sensor network systems have been developed and deployed in recent years. Due to the unique characteristics of underwater acoustic channels and the complex deployment environment in 3D ocean spaces, various efficient and reliable 3D communication and networking protocols have been proposed. In this paper, we present an overview of the most recent advances in network design principles for 3D ocean sensor networks, with focuses on deployment, localization, topology design, and position-based routing in 3D ocean spaces. We strongly believe that more promising developments and significant improvements of ocean sensor network systems will be achieved over the next decade. This will greatly enhance humans' abilities in exploration and exploitation of the ocean.

Acknowledgements

The work of Y. Wang was supported in part by the US National Science Foundation (NSF) under Grant Nos. CNS-0721666, CNS-0915331, and CNS-1050398. The work of Y. Liu was partially supported by the National Natural Science Foundation of China (NSFC) under Grant No. 61074092 and by the Shandong Provincial Natural Science Foundation, China under Grant No. Q2008E01. The work of Z. Guo was partially supported by the NSFC under Grant Nos. 61170258 and 6093301. This work was partially done when Y. Liu visited the Department of Computer Science, University of North Carolina at Charlotte, with a scholarship from the China Scholarship Council.

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(Edited by Xie Jun)