AUTONOMOUS UNDERWATER VEHICLE PATH PLANNING DATA AGGREGATION SCHEME FOR UNDERWATER LINEAR SENSOR NETWORK

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ABSTRACT

Linear Sensor Networks (LSNs) are often utilized for monitoring and surveying linear structure material such as pipelines, roads, and demarcation of borders. The Under Water Linear Sensor Network (UWLSN) is facing the challenges of limited capability such as bandwidth due to the acoustic signal. In addition, the way and manner of the sensor nodes that are deployed, and data collection that are conducted contribute to the delay in the data delivery to the sink node. Existing deployment strategies forward data to a higher capacity node in order to forward to an Autonomous Underwater Vehicle (AUV) or the sink node. However, these approaches cause delay and do not guarantee data delivery to the sink. The problem could be due to both the higher capacity node and autonomous vehicle that might deviate due to water currents, hence leading to entrapment or local maxima. In addition, existing path planning algorithms do not consider the network coverage of heterogeneous sensor nodes. Consequently, it is important to employ a path planning strategy that utilizes AUV with a unique path movement to collect data with minimum delay and higher data delivery ratio. This research designed and developed an AUV Path planning Data Aggregation Scheme (APDAS) to handle heterogeneous and long distance pipeline sensors without depleting a large amount of sensor energy in UWLSN. The APDAS includes node distribution and path planning strategies for AUV. The node distribution was performed based on the capability and signal coverage of the heterogeneous nodes. Furthermore, the path planning concept was based on sinusoidal sine wave movement for effective traversal of forwarding nodes at the base of the pipeline. Extensive simulation experiments were performed in order to benchmark the performance of the proposed APDAS scheme against baseline schemes. The results of the simulation were evaluated based on Packet Delivery Ratio (PDR), End-to-End Delay (E2ED), and throughput with performance improvements of 13%, 17.8%, and 14.1%, respectively. APDAS was compared with the existing schemes namely, Minimizing Deep-sea Data Collection Delay with Autonomous (MDD-CDA) underwater vehicles and Scalable Heterogeneous Nodes Deployment (SHND) algorithm for monitoring of long-range underwater pipeline. The results obtained were based on the average of both MDD-CDA and SHND, and the percentage was estimated in order to increase the packet delivery while reducing the E2ED and throughput. Thus, the findings have shown the APDAS scheme significantly improved the packet delivery rate and reduced delay during data collection in UWLSN.

ABSTRAK

Rangkaian Sensor Linear (LSN) sering digunakan untuk memantau dan mengukur bahan struktur linear seperti saluran paip, jalan raya, dan penandaan sempadan. Rangkaian Sensor Linear Dalam Air (UWLSN) menghadapi cabaran keupayaan terhad seperti jalur lebar disebabkan oleh isyarat akustik. Di samping itu, cara dan cara nod sensor yang digunakan dan pengumpulan data yang dilakukan menyumbang kepada kelewatan penghantaran data ke nod sink. Strategi penyebaran sedia ada menyambung data ke nod kapasiti yang lebih tinggi untuk meneruskan ke *Autonomous Vehicle Underwater* (AUV) atau nod sink. Walau bagaimanapun, pendekatan ini menyebabkan kelewatan dan tidak menjamin penghantaran data ke sink. Masalahnya mungkin disebabkan kedua-dua nod kapasiti yang lebih tinggi dan kenderaan autonomi yang mungkin menyimpang disebabkan oleh arus air, oleh itu membawa kepada pemerangkapan atau *maxima* tempatan. Di samping itu, algoritma pelan laluan sedia ada tidak menganggap liputan rangkaian nod sensor heterogen. Oleh itu, adalah penting untuk menggunakan strategi perancangan laluan yang menggunakan AUV dengan pergerakan laluan unik untuk mengumpul data dengan kelewatan minimum dan nisbah penghantaran data yang lebih tinggi. Kajian ini mereka bentuk dan membangunkan skim pengumpulan data perancangan jalur kelewatan menggunakan AUV (APDAS) untuk pemantauan sensor saluran paip heterogen dan jarak jauh tanpa mengurangkan jumlah tenaga sensor di UWLSN. APDAS termasuk pengedaran nod dan strategi perancangan laluan untuk AUV. Pengagihan nod dilakukan berdasarkan keupayaan dan liputan isyarat nod-nod yang heterogen. Tambahan pula, konsep perancangan laluan adalah berdasarkan pergerakan gelombang sinus sinusoidal untuk traversal penghantaran nod yang berkesan di dasar saluran paip. Eksperimen simulasi yang meluas dilakukan untuk menanda aras prestasi skim APDAS yang dicadangkan terhadap skim asas. Keputusan simulasi dinilai berdasarkan Nisbah Pengiriman Paket (PDR), Kelewatan Akhir (E2ED), dan daya tampung dengan peningkatan prestasi masing-masing sebanyak 13%, 17.8%, dan 14.1%. APDAS dibandingkan dengan skema yang sedia ada termasuk Mengurangkan Kelewatan Pengumpulan Data laut dalan dengan kenderaan bawah laut Autonomi (MDD-CDA) dan Algoritma Penyebaran Nod Heterogen Berkala untuk pemantauan saluran paip bawah air (SHND). Hasil yang diperoleh adalah berdasarkan pada purata MDD-CDA dan SHND, dan peratusan dianggarkan untuk meningkatkan penghantaran paket sambil mengurangkan E2ED dan penghantaran. Oleh itu, skim yang dicadangkan dengan ketara dapat meningkatkan kadar penghantaran paket dan mengurangkan kelewatan semasa pengumpulan data di UWLSN.

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LIST OF ABBREVIATIONS

2H-ACK	-	Hop-by-Hop ACKnowledgement
APPER	-	AUV Path Planning Efficient Routing
Aqua-Sim	-	Aquatic Simulator
AUV	-	Autonomous Underwater Vehicle
BSN	-	Basic Sensor Node
CAR	-	Chain-based Anonymous Routing
CNs	-	Courier Nodes
CO-AUV	-	Comparison Optimization AUV
DCS	-	Data Communication Scheme
DDG-AUV	-	Distributed Data-Gathering AUV
DDN	-	Data Dissemination Node
DGPS	-	Differential Global Positioning System
DLA	-	Distributed Learning Automation
DRN	-	Data Relay Node
DTT-CBF	-	Distributed Tracking Target Consensus Bayesian Filtering
DUCS	-	Distributed Underwater Clustering Scheme
E2ED	-	End to End Delay
FDI	-	Fault Detection and Identification
FPIM-WSN	-	Framework for Pipeline Infrastructure Monitoring WSN
GloMoSim	-	Global Mobile Information System Simulator
GPRS	-	General Packet Radio Service.
GPS	-	Global Positioning System
IOPMIMS	-	Integrated Oil Pipeline Monitoring Incident Mitigation System
LSN	-	Linear Sensor Network
LWSN	-	Linear Wireless Sensor Network
M3D-UAV	-	Mobile 3D UAV
MAC	-	Medium Access Control
MDD-CDA	-	Minimizing Deep-sea Data Collection Delay with Autonomous underwater vehicles
MC-UAV	-	Multi- Cooperative UAV
MP-MUAV	-	Monitoring Pipeline- Multi-UAV
NCC	-	Network Control Center

NS-2	-	Network Simulator 2
NSGA-II	-	Non-dominant Sorting Genetic Algorithm 2
OMNET++	-	Objective Modular Network Testbed in C++
OPNET	-	Optimized Network Engineering Tool
OTCL	-	Object-oriented Tool Command Language
PDR	-	Packet Delivery Ratio
PPS-AUV	-	Path Planning Surface AUV
PP-UAV	-	Planning for Photovoltaic UAV
PSO	-	Particle Swamp Optimization
QPSO	-	Quantum-behaved Particle Swarm Optimization
QualNet	-	Commercial Version of GloMoSim
RF	-	Radio Frequency
RFID	-	Radio Frequency IDentification
RNs	-	Relay Nodes
SHND	-	Scalable Heterogeneous Node Deployment
SNs	-	Sensor Nodes
SPAMMS	-	Sensor-based Pipeline Autonomous Monitoring and Maintenance System
TCL	-	Tool Command Language
UAS	-	Unmanned Aerial System
UAV	-	Unmanned Aerial Vehicle
UDP	-	User Datagram Protocol
ULSNs	-	UAV-based LSNs
UW-LSN	-	Underwater Wireless Linear Sensor Network
UWSN	-	Underwater Wireless Sensor Network
WSN	-	Wireless Sensor Network

LIST OF SYMBOLS

$Avt(t)$	-	Average Time
D_n	-	Total number of DDN nodes
R_D	-	Communication Range of each DDN
R_d	-	Range of each DDN node
R_s	-	Communication Range of each sink
T_0	-	Overshoot threshold
X_{max}	-	Maximum range of the $x - axis$
Y_{max}	-	Maximum value of the $y - axis$ (Water surface)
Y_p	-	Path of UAV on $x - axis$
d_D	-	distance between two DDN nodes
d_p	-	Distance between two peaks of AUV path
d_r	-	Distance between the range of DDN and the range of sink node
L	-	Total Pipeline length
N	-	Total number of BSN nodes
PR	-	Packet Received
PS	-	Packet Sent
S	-	Set of sinks (S_1, S_2, S_3 ...)
$X\ initial$	-	x coordinate of first DDN

CHAPTER 1

INTRODUCTION

1.1 Overview

Global offshore oil production in 2015 was the highest level since 2010, and accounted for nearly 30% of total global oil production (Global Crude Oil Production, 2016). The total crude oil production is more than 27 million barrels per day (mbd) from more than 50 different countries (Global Crude Oil Production, 2016). Structure of these offshore rigs and connecting pipelines are very complex and spread over a very large area. Maintaining and monitoring of the pipelines is challenging due to the harsh environment. Monitoring of offshore pipelines is very important to save natural resources, the environment, and wildlife. Thus, most of the installations of infrastructures are done on the coast and if there is any damage, the impact can be massive. In addition, the concentrations of pipelines are very dense and complex on both onshore and offshore which are connected to each other (Dey *et al.*, 2004). For these reasons, any damage, leakage or fault needs to be detected and fixed as soon as possible (see Figure 1.1 for illustration of underwater pipeline). Underwater communication was first explored in the World War II when American war ships used to communicate to the control station on island (Ayaz *et al.* 2011). Insufficient technology and equipment was a major hurdle in communication performance. After communication technologies thrive, researchers have explored the underwater communication domain. Several communication strategies and architectures have been explored, specifically for underwater due to the unique nature of water as a wireless communication channel. Consequently, routing algorithms for Underwater Wireless Sensors Network (UWSN) are required for a successful communication

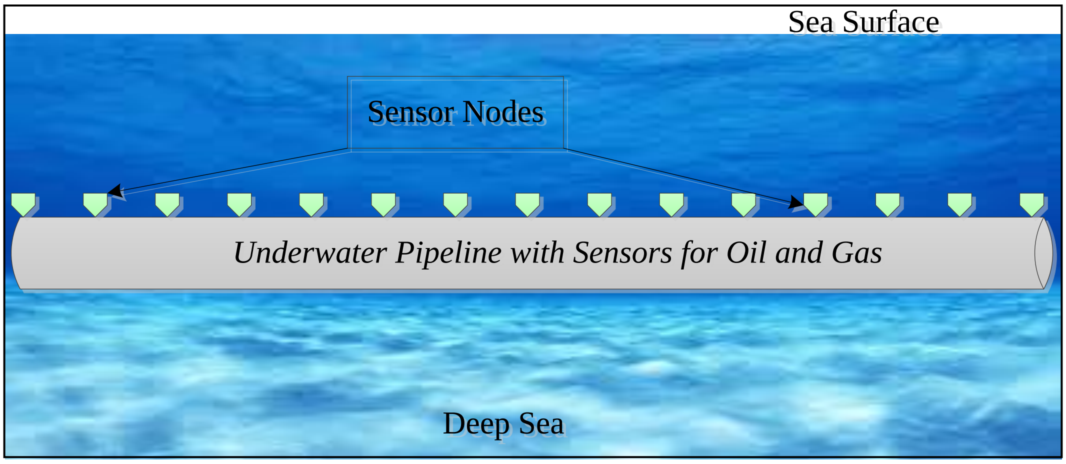

Figure 1.1 Underwater Pipeline with Sensors

Due to underwater environment restrictions and computing capabilities, UWSNs are different from Wireless Sensor Networks (WSNs). Thus, WSN routing protocols are not feasible for UWSN applications (Ayaz *et al.*, 2011). Underwater sensor nodes are limited in bandwidth, transmission power, energy, and memory. Hence, these limitations have led to many issues in the design of UWSNs. Accordingly, data transmission mechanisms between ordinary nodes and sinks need to be designed based on some suitable criteria such as shortest paths, in order to achieve optimal data forwarding towards destination, which improves network efficiency. The UWSNs communication models are based on acoustic channels, which have many challenges namely, propagation delay, which is five times higher than the radio frequency, frequent movement of the water affects acoustic signal, which increase bit error rates, and high deterioration of signal strength in underwater communication (Ayaz and Abdullah, 2009). Considering the acoustic communication having limited bandwidth, underwater sensor nodes face higher delay and it is impractical to use Radio Frequency (RF) in underwater environment for information gathering. Therefore, higher latency and proper node deployment are the main design challenges of underwater sensor networks. One kind of UWSN is the Underwater Wireless Linear Sensor Network, (UW-LSN) which also faces many challenges in monitoring the underwater linear structures such as underwater pipelines. The inspection of underwater pipeline's health is a critical task requiring active, frequent and event based monitoring process. Such monitoring process becomes highly expensive, risky and unreliable by using human intervention, tools, or robot systems.

Moreover, the network topology for data forwarding plays a key role in the design of any network and has a major contribution to the network performance (Smith *et al.,* 2002). UWSNs, UW-LSNs and its deployment are discussed in detail in Chapter 2. There are two types of deployment areas, dense sensors deployment, and sparse sensors deployment; the dense sensors deployments are mainly used when a large numbers of sensors are utilized for small coverage area while the sparse sensors deployment schemes utilize high capacity sensors placed at a longer distance to cover a large area. In order to achieve optimal data delivery, there is a need for routing scheme that performs better in the acoustic environment. Meanwhile, several routing schemes have been suggested in the previous literature including geographic routing, and opportunistic routing. Geographic routing relies on geographic position information. It is mainly proposed for wireless networks and based on the idea that the source node sends a message to a geographic location of the destination instead of using the node address. Geographic routing is important because it is a concept that relates to sensor localization (positioning), which is a concept in AUV operation. Opportunistic routing has proven its efficiency in underwater data forwarding (Coutinho and Boukerche, 2017). It is a data packet forwarding process that employs broadcasting concept for efficient routing. Several studies, such as Lee *et al.* (2010), Ayaz *et al.* (2011), Noh *et al.* (2013) and Coutinho *et al.* (2016) have considered the opportunistic routing approach for data forwarding in underwater communication. The opportunistic routing takes advantage of the broadcast nature of the wireless network for enhancing data delivery. In opportunistic routing, each node broadcasts the packet to a set of nodes that are within its neighbourhood and in the forwarding direction to the sink node. Hence, there is more retransmission that causes high overhead. Opportunistic routing achieves higher data delivery in the underwater acoustic transmission and is suitable for linear sensor network.

A distributed topology is a deployment approach whereby an ordered list of all the nodes in the network is uniformly arranged. In distributed topology, heterogeneous node deployment has a central role within network design as different types of nodes perform different functions in network field, so their proper deployment is highly important. Accordingly, placement of the appropriate node in UW-LSN for pipeline monitoring is challenging in distributed topology-based routing protocols (Aziz *et al.,* 2013; Domingo and Prior, 2007; Jawhar *et al.,* 2012;

Wang *et al.,* 2007). The design of UW-LSNs derived from Linear Sensor Networks (LSNs) is a routing protocol that is classified into autonomous underwater vehicles (AUV), chains, distributed topology, and jump-based communication types. Autonomous Underwater Vehicle (AUV) is a computerized managed system that is self-operative for the purpose of collecting sensing data in the deep-sea environment (Fiorelli *et al.,* 2006; Paul *et al.,* 2014). In the underwater environment, the sensors installed on the pipeline are required to forward information from the base of the sea to the top of the sea level. However, the transmission capacity of the sensor node is limited and forwarded data might not get to the sink node at the top of the sea (Akbar *et al.,* 2016). Therefore, there is need for a more powerful sensor node called AUV, which can dive into the sea as deep as 6000 meters (Nyrkov *et al.,* 2017). The AUV is a self-powered system that can traverse a longer distance pipeline. Sensor nodes are utilized to monitor different parameters regarding the pipeline and its environment. It is assumed that sensors are installed in a very remote area with harsh condition and left unattended (Ali *et al.,* 2015). The connection between the sensor node and AUVs as well as the connection between AUVs and the sink is often an acoustic communication. The connection between the sink and Network Control Centre (NCC) can employ any type of communication technology.

1.2 Problem Background

Underwater sensor nodes are embedded to the pipeline for monitoring purpose. The data collected during the monitoring are forwarded from the depth of the sea to the sea surface. Due to restricted data rate constraints in underwater acoustic communication, delay has a great impact in UW-LSN applications for efficient data forwarding. Underwater acoustic sensor nodes are typically having low bandwidth and expected to face higher delay issues. Therefore, acoustic communication is a limited channel and has to be managed properly for efficient data forwarding in large scale UW-LSN. Besides, it is a difficult task in underwater environment to assure reliable chained links for data communication especially for large scale LSN with minimum delay in packet delivery. Keeping in view the issues discussed, it is still hard to find an efficient LSN routing protocol, for the monitoring of thousand kilometres long and deep sea oil and gas pipeline leakage, in order to maintain the communication between underwater sensors with delay and energy constraint. The node deployment of LSN is normally predefined for different kinds of applications while LSN routing protocols explore channel characteristics, signal, and node distribution components for minimizing energy consumption. Different chains, autonomous vehicles and distributed topology discovery based schemes are proposed by several researchers for improving network scalability and minimizing delay. There are many critical issues that need to be considered while designing UWSN protocols, such as proper deployment of sensors (Khan *et al.,* 2015; Han *et al.,* 2013; Owojaiye and Sun, 2013), unique addresses for each sensor (Ayaz and Abdullah, 2009a; Jawhar *et al.,* 2008; Sarr *et al.,* 2012) and efficient routing mechanism (Pompili, 2009; Kheirabadi, 2013).

In the existing routing schemes for data forwarding such as in Abbas *et al.* (2016), the method considers scalability in node distribution with heterogeneous nodes. The unequal-capacity nodes are spread based on their different capacity of transmission coverage. The nodes with higher capacity are utilized as relaying node and dissemination node, while the smaller capacity nodes are used as the basic sensing node. In the proposed deployment method, the sensor node spacing is equal, which might not be effective because smaller nodes that become weak in terms of energy capacity cannot transmit to a longer distance. Considering the deployment methods, the employed distribution strategies still encounter a significant amount of data error and propagation delay due to deployment spacing and data forwarding technique. Thus, a proper node distribution in required in order to attain scalability.

Another scheme for data collection is named AUV-based data collection in a linear sensor network (Khan *et al.,* 2015). Homogenous types of sensor node are placed in a straight line on the pipeline for sensing data. An AUV known as mobile node moves in a straight line above the sensor node to collect the data. However, the straight path movement might not be feasible since there is frequent water current (Garau *et al*., 2009), which displace the position of AUV during data collection. Another issue is that it takes long time to arrive at the collected data to the sink so there might be a chance of error occurring in the data forwarding that leads to loss of data. Further, data collection from a specific node is difficult, since there is need for the AUV to move across all the nodes on the pipeline and also navigate to the sink for data forwarding. Therefore, there is need to explore another method of path planning that resist the force of water current and reach data to the sink efficiently. In addition, Zheng *et al.* (2017) suggested a delay-aware data reporting using AUV based on linear distributed sensors in the underwater environment. It focused on Minimizing Deep-sea Data Collection Delay with Autonomous underwater vehicles (MDD-CDA). The challenge is to forward timely sensor data by addressing the acoustic transmission delay in an ocean. The AUV is utilized for the deep-sea data collection in 3-dimensional or 2-dimensional interplanetary navigation as the concept for the path planning in such a way that the AUV traverses nodes during data collection. This is from the relay sensor nodes to the sink at the water surface. However, the interplanetary path planning strategy lacks the consideration of different signal coverage, which is very important in an heterogeneous sensor deployment. Therefore, there is need to further explore how to efficiently utilize AUV since one of the major advantages of AUV is the localization of sensor's position along with the ability to follow a path trajectory (Luo *et al.*, 2010). Hence, there is need to explore a suitable data aggregation scheme in underwater pipelines.

Several studies such as Lee *et al.* (2010), Ayaz *et al.* (2011), Noh *et al.* (2013) and Coutinho *et al.* (2016) have employed opportunistic routing approach for data forwarding in underwater data communication. The routing approach takes advantage of the broadcast nature of the wireless network for enhancing data delivery. In opportunistic routing, each node forwards packet to a set of nodes that are within it neighborhood and in direction of the sink node. Hence, there is lower overhead because of fewer retransmissions. Opportunistic routing approach achieves high data delivery in the UWSNs. To improve on the strengths of the opportunistic routing approach, a proper deployment of AUVs, and unique path for each AUV, routing mechanism between AUVs and SNs, are required.

In the proposed solution, the network setup is similar to that of Abbas *et al.* (2016) but with modification of sensor node distribution spacing, and the introduction of AUV path-planning concept for data collection scheme. Currently, the data forwarding and monitoring techniques (Jawhar *et al.,* 2013; Jawhar *et al.,* 2007; Mohamed *et al.,* 2010; Umar *et al.,* 2015) for UW-LSN routes managements might have delay and data error. Data error occurs when the received data is not completely the same as the transmitted data. There for more improvement is required.

1.3 Problem Statement

This research addressed the problem of higher delay faced by the existing data aggregation schemes for underwater pipeline sensor network. For efficient data delivery, three critical aspects are considered in this research: scalable nodes deployment, path planning of AUV and aggregated data forwarding. The existing deployment strategies are faced with complex communication process because nodes have to send data to other nodes across the pipeline, which deplete the energy of most nodes and lead to delay. Further, the data forwarding procedure experiences packet error/loss in the process of data packet forwarding. Unlike the classical data forwarding schemes, AUV-based data collection schemes have proved to be more adaptable to the underwater pipeline harsh environment. However, most of the existing AUV-based data collection schemes employ straight path planning, which collect data from pipeline-sensors and forward to the sink node, but experience delay and loss of some data due to AUV Path Planning mechanism. Additionally, the available sensor node deployment strategies do not consider explicit variable transmission coverage of heterogeneous nodes with respect to AUV path planning, which lead to packet loss in the data collection process. Furthermore, the existing opportunistic routing scheme employed for the data collection increase end-to-end delay due to neighbor node waiting for a packet to reach the furthest node during packet forwarding.

1.4 Research Questions

Based on the discussion in problem background and problem statement, the following research questions are formulated as:

i. How can heterogeneous sensors be deployed while considering their different transmission coverage and conforming to AUV path planning to achieve higher packet delivery ratio?
ii. How can path planning algorithm for AUV navigation be constructed in order to enhance data aggregation performance?
iii. How can the aggregated data be forwarded between the basic sensing nodes to the relay node and dissemination node up to the AUV and to the sink at the surface of the sea, which reduces delay?

1.5 Research Aim

The aim of this research is to propose an efficient data aggregation scheme for autonomous underwater linear sensor network, which is an efficient data forwarding scheme for long-range underwater pipeline that uses AUV to maximize the packet delivery ratio and minimize the delay between underwater heterogeneous linear network nodes and sinks.

1.6 Research Objectives

The subsequent research objectives are proposed to achieve the aim of the research. These objectives are considered in the perspective of the research questions mentioned in Section 1.4.

i. To enhance a scalable heterogeneous sensor node deployment strategy considering the AUV path planning and the transmission coverage of sensor nodes that reduces delay in aggregated data forwarding.
ii. To enhance a path planning scheme for AUV to increase coverage of the underwater pipeline monitoring area.
iii. To enhance an aggregated data forwarding scheme based on opportunistic routing approach in large scale UW-LSN that reduces delay.

1.7 Research Contributions

The contribution of this research is summarized as follows:

i. AUV path planning scheme with heterogeneous node deployment strategy that minimizes delay for underwater pipeline data aggregation.
ii. An enhanced path planning scheme for an autonomous underwater vehicle that has lower delay in underwater pipeline data aggregation.
iii. An enhanced data aggregation scheme that has higher packet delivery ratio and considers large-scale coverage of the underwater linear sensor network by using AUV.

1.8 Research Scope

The scope of the research covers the following.

i. This research focuses on design and development of UW-LSN where a single AUV and limited number of underwater sensors are used to cover long-range pipeline.
ii. This research only focuses on deep-sea underwater sensing environment and sparse deployment of underwater sensors.

iii. In this research, only the coastal area starting from the seacoast to 100 KM into the deep sea to monitor offshore pipeline is considered.

1.9 Research Significance

This research contributes significantly to the field of underwater pipeline monitoring, which could be crude oil pipeline, water pipeline and other important pipelines carrying natural resources. Thus, the research focuses on efficient data aggregation scheme, which is capable of deploying heterogeneous types of sensors and optimize the path discovery for AUV. The proposed scheme enables a more efficient linear pipeline monitoring in underwater environment. Therefore, monitoring of pipeline leakage and destruction can be carried out in real time. Hence, it could reduce loss of natural resources and in turn increase revenue generation.

1.10 Thesis Organization

The rest of the thesis is organized and structured as follows:

Chapter 2: Presents an extensive literature review of the underwater sensor network and UW-LSN routing techniques and management concepts and research challenges. In addition, the proposed solutions and their limitations were discussed.

Chapter 3: Presents the research methodology and the general architectural design of each phase. It discusses problem formulation based on the literature review chapter. The simulation setup parameters were presented along with the performance evaluation criteria. In the end, the research plan has been explained in detail.

Chapter 4: Presents the detailed design and development of the AUV path planning scheme. The network model, path planning algorithm and the data collection algorithms are discussed in detail.

Chapter 5: Presents the performance and evaluation of results obtained from the simulation implementation. The analysis of the result is based on traffic load and the benchmarking with existing schemes considering two metrics, namely, packet delivery ratio and end-to-end delay.

Chapter 6: Provides a summary of research achievements, conclusion and future research directions in AUV path planning based efficient routing scheme.

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