A HYBRID MULTI-OBJECTIVE OPTIMISATION FOR ENERGY EFFICIENCY AND BETTER COVERAGE IN UNDERWATER WIRELESS SENSOR NETWORKS

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ABSTRACT

Underwater wireless sensor networks (UWSNs), which benefit ocean surveillance applications, marine monitoring and underwater target detection, have advanced substantially in recent years. However, existing deployment solutions do not satisfy the deployment of mobile underwater sensor nodes as a stochastic system. Internal and external environmental problems concern maximum coverage in the deployment region while minimising energy consumption. To fill this gap, this research proposes and implements a multi-objective optimisation solution to balance conflicts concerning node deployment objectives. First, this research analyses the existing mobile underwater node deployment algorithms to identify the significant problems in existing solutions. Next, it establishes the research problems by implementing various existing algorithms using comparative analysis. Based on that analysis, this research suggests a hybrid algorithm: the Multi-Objective Optimisation Genetic Algorithm based on Adaptive Multi-Parent Crossover and Fuzzy Dominance (MOGA-AMPazy). The method adapts the original Non-Dominated Sorting Genetic Algorithm II (NSGA-II) by introducing a hybridisation of adaptive multi-parent crossover genetic algorithm and fuzzy dominance-based decomposition techniques. The algorithm introduces the fuzzy Pareto dominance concept to compare two solutions and uses the scalar decomposition method when one solution cannot dominate the other in terms of the fuzzy dominance level. The solution also proposes adaptive multi-parent crossover (AMP) to balance exploration and exploitation with new offspring, changing the number of parents involved in the crossover based on the execution of the new generation. The solution is further improved by introducing prospect theory to guarantee convergence through risk evaluation. The results obtained are then analysed to assess the proposed solution's performance in obtaining each deployment objective's optimal value. Finally, the proposed algorithm's effectiveness regarding node coverage, energy consumption, Pareto-optimal value, and algorithm execution time is validated using three Pareto-optimal metrics: including inverted generation distance (IGD), hypervolume, and diversity. Furthermore, this research utilises five commonly used two-objective ZDT test instances as benchmark tests, namely ZDT-1, ZDT-2, ZDT-3, ZDT-4, and ZDT-6. These tests use specific problem characteristics to impose the underlying proposed solution as well as three other systems. Pareto-optimal values obtained indicate that the proposed solution has almost complete coverage involving the actual Pareto front. Furthermore, all analysis and evaluation attributes indicate that the MOGA-AMPazy deployment algorithm can handle the multi-objective underwater sensor deployment problem better than other solutions. Thus, MOGA-AMPazy provides an efficient and comprehensive deployment solution for mobile sensor nodes in UWSNs. This study makes several noteworthy contributions to the body of knowledge concerning UWSNs, and it provides an excellent multi-objective representation to decision-makers or mission planners to monitor the region of interest (RoI).

Keywords: Mobile sensor nodes, Multi-objective optimisation, Ocean surveillance, Sensor deployment, Underwater wireless sensor networks.

HIBRID PENGOPTIMUMAN BERBILANG-OBJEKTIF UNTUK KECEKAPAN TENAGA DAN LIPUTAN DALAM RANGKAIAN SENSOR BAWAH AIR TANPA DAWAI

ABSTRAK

Rangkaian sensor tanpa dawai bawah laut (UWSNs), yang memanfaatkan aplikasi pengawasan lautan, pemantauan marin dan pengesanan sasaran bawah air, telah maju dengan ketara dalam beberapa tahun kebelakangan ini. Walau bagaimanapun, penyelesaian penyebaran sedia ada tidak memenuhi penggunaan nod sensor bawah air mudah alih sebagai sistem stokastik. Masalah persekitaran dalaman dan luaran melibatkan liputan maksimum di kawasan penempatan sambil meminimumkan penggunaan tenaga. Untuk mengisi jurang ini, penyelidikan ini mencadangkan dan melaksanakan penyelesaian pengoptimuman berbilang objektif untuk mengimbangi konflik mengenai objektif penyebaran nod. Pertama, penyelidikan ini menganalisis algoritma penyebaran nod bawah air mudah alih sedia ada untuk mengenal pasti masalah penting dalam penyelesaian sedia ada. Seterusnya, ia mewujudkan masalah kajian dengan melaksanakan pelbagai algoritma sedia ada menggunakan analisis perbandingan. Berdasarkan analisis itu, penyelidikan ini mencadangkan algoritma hibrid: Algoritma Genetik Pengoptimuman Pelbagai Objektif berdasarkan Penyesuaian Lintas Berbilang-Induk dan Kedominan Kabur (MOGA-AMPazy). Kaedah ini menyesuaikan Pengisihan Tak-Terdominan Algoritma Genetik II (NSGA-II) asal dengan memperkenalkan penghibridan Algoritma Genetik Pengoptimuman Pelbagai Objektif berdasarkan Penyesuaian Lintas Berbilang-Induk dan Kedominan Kabur. Algoritma ini memperkenalkan konsep penguasaan Pareto kabur untuk membandingkan dua penyelesaian dan menggunakan kaedah penguraian skalar apabila satu penyelesaian tidak dapat menguasai yang lain dari segi tahap penguasaan kabur.

Penyelesaian itu juga mencadangkan Penyesuaian Lintas Berbilang-Induk (AMP) untuk mengimbangi penerokaan dan eksploitasi dengan anak baharu, menukar bilangan induk yang terlibat dalam lintas berdasarkan pelaksanaan generasi baharu. Penyelesaian itu dipertingkatkan lagi dengan memperkenalkan teori prospek untuk menjamin penumpuan melalui penilaian risiko. Keputusan yang diperoleh kemudian dianalisis untuk menilai prestasi penyelesaian yang dicadangkan dalam mendapatkan nilai optimum setiap objektif penyebaran. Akhir sekali, keberkesanan algoritma yang dicadangkan berkenaan liputan nod, penggunaan tenaga, nilai Pareto-optimum dan masa pelaksanaan algoritma disahkan menggunakan tiga metrik Pareto-optimum: termasuk Penjanaan Jarak Tersongsang (IGD), Hiperisipadu dan Kepelbagaian. Selain itu, penyelidikan ini menggunakan lima contoh ujian ZDT dua objektif yang biasa digunakan sebagai ujian penanda aras, iaitu ZDT-1, ZDT-2, ZDT-3, ZDT-4 dan ZDT-6. Ujian ini menggunakan ciri masalah khusus untuk mengenakan penyelesaian cadangan asas serta tiga sistem lain. Nilai Pareto-optimum yang diperoleh menunjukkan bahawa penyelesaian yang dicadangkan mempunyai liputan hampir lengkap yang melibatkan bahagian hadapan Pareto sebenar. Tambahan pula, semua sifat analisis dan penilaian menunjukkan bahawa algoritma penyebaran MOGA-AMPazy boleh menangani masalah penyebaran sensor bawah air berbilang objektif dengan lebih baik daripada penyelesaian lain. Oleh itu, MOGA-AMPazy menyediakan penyelesaian penyebaran yang cekap dan komprehensif untuk nod sensor mudah alih dalam UWSN. Kajian ini memberikan beberapa sumbangan penting kepada badan pengetahuan mengenai UWSN, dan ia menyediakan perwakilan berbilang objektif yang sangat baik kepada pembuat keputusan atau perancang misi untuk memantau kawasan sekepentingan (RoI).

Katakunci: Nod sensor bergerak, Pengotimuman berbilang-objektif, Pengawasan lautan, Penyebaran sensor, Rangkaian sensor bawah air tanpa dawai.

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LIST OF ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
AI	Artificial intelligence
APF	Artificial Potential Field
ASVs	Autonomous Surface Vehicles
AUVs	Autonomous Underwater Vehicles
CG	Computational Geometry
DABVF	Distributed node deployment algorithm
DT	Delaunay Triangulation
FDDA	Fully Distributed Deployment Algorithm
IoT	Internet of Things
IP	Internet Protocol
M-UW	Mobile Underwater
M2M	Machine-to-Machine
PSO	Particle swarm optimization
ROVs	Remotely Operative Underwater Vehicles
SOFAR	Sound Fixing and Ranging
VD	Voronoi Diagram

VFRBEC Virtual forces redeployment algorithm based on energy consumption

CHAPTER 1: INTRODUCTION

This chapter presents an overview of the research carried out in this thesis, and it is organised as follows: Section 1.1 discusses the background of mobile underwater wireless sensor node (UWSN) deployment, purposes and perspectives. Next, Section 1.2 describes the motivation for this research work. Section 1.3 states the problem concerning node coverage and energy consumption. The research objectives are presented in Section 1.4, and Section 1.5 provides an overview of the research methodology chosen to achieve the defined objectives. Finally, Section 1.6 outlines the structure of the thesis.

1.1 Background

This section presents an overview of UWSNs, mobile underwater (M-UW) sensor node deployment, and multi-objective optimisation to provide fundamental knowledge on the research domain. A UWSN is a network of intelligent sensors and instruments intended to interact collaboratively via wireless connections to monitor tasks across a particular area (Akyildiz, Pompili, & Melodia, 2005). UWSN architecture is categorised according to type, sensor node network capabilities, and the spatial coverage of the application.

The static sensor node is usually placed on the seafloor in a two-dimensional (2D) region. It uses multi-hop communication among several clusters to connect with a sink node for data transfer (Felemban, Shaikh, Qureshi, Sheikh, & Qaisar, 2015). A static three-dimensional (3D) design, on the other hand, uses inflatable buoys to attach the system to the bottom and deploys sensors at various depths by changing cable length. The sensor nodes in the mobile architecture are free to move around, thereby allowing for dynamic changes in network structure. The mobile node needs two transceivers to maximise network data collection efficiencies. Remotely operated underwater vehicles (ROVs) , autonomous underwater vehicles (AUVs), and sea gliders are all part of it.

However, (Mohamed, Hamza, & Saroit, 2017) emphasised that, due to changes in mobility characteristics, mobile node features require special attention to ensure complete network coverage. A hybrid architecture, on the other hand, mixes static and mobile sensor nodes to accomplish particular functions. In a hybrid system, mobile nodes may serve as routers or controllers, communicating with static or standard sensors for data sensing. Scientific research institutions as well as public and private-sector industries, including maritime surveillance, have increased interest in UWSNs and robotics.

Communicating via wireless technology, sensor nodes placed across a wide region gather useful data from the sensor field in mobile underwater sensor networks. A sensor must be placed in a contextually suitable position before it can give useful data to the system, and many wireless sensor systems – particularly those used for remote monitoring and surveillance – can be placed in hazardous areas, most often without human intervention. Node deployment is regarded a crucial process in underwater sensor networks. It supports many important functions, such as routing protocol, localisation and network architecture, and it has a major effect on network performance. Sensor nodes in mobile deployments may operate freely in any orientation. In UWSNs, the majority of mobile deployment algorithms have focused on decreasing energy usage while increasing coverage and connectivity. Based on the current knowledge about the target, an underwater mobile sensor may adjust the initial node location; such relocation seeks to achieve an expected end configuration (Vilela, Kashino, Ly, Nejat, & Benhabib, 2016). Reorganisation or redeployment is necessary after adjustments have been made to the networks, often because of sensor failure (e.g. malfunction, power reservation) or target detection.

The research scope of this study encompasses homogeneous mobile sensor nodes. All sensor nodes are expected to have the same sensing, communication, computing and mobility features. Each node's sensing and communication coverage is expected to be ideal, which means that both coverage areas have a circular shape with no irregularity. Error-free data transmission and node position determination is another assumption. It is further assumed that each node possesses local information from neighbouring nodes within the direct communication range. Mobile sensor nodes can adjust their locations, consequently changing network topology. The topological changes are generally because of deteriorated underwater environments and the occurrence of certain events. As a result, the deployment solutions for mobile sensor nodes in the area of interest must address a variety of difficulties and concerns. In this research, a suite of multi-objective evolutionary algorithms is developed for coverage and energy consumption problems. Performance is evaluated using coverage rate, node energy consumption, Pareto optimal metrics, and execution time.

1.2 Research Motivation

This section describes the motivation for mobile sensor node deployment concerning UWSN technologies.

Some regions are particularly vulnerable to border encroachments and traditional threats such as kidnappings, illegal immigration and smuggling. Furthermore, regional authorities face a number of challenges in monitoring such locations. In many cases, funding has been increased, but has not been used optimally, because not all available assets are suitable to detect intruders at the border. Therefore, this study proposes mobile sensors in UWSNs as an alternative solution to assist authorities in monitoring locations without requiring a physical human presence at all times.

The wireless sensor network (WSN) is one emerging technology that has received particular attention from researchers and professionals alike (Jiang, Xu, & Wu, 2016). Market research by the firm (MarketsandMarkets, 2019) highlights the importance of wireless sensor technology. The WSN industry is expected to reach a market value of

USD 93.86 billion by 2023, up 18.55% from USD 29.06 billion in 2016. Data released by Market Watch (MarketWatch, 2019) also supports the growth rates for the forecast period. Wireless technology adoption and cost reduction are the main factors boosting market value. According to the report, demand is growing every year due to the compatibility and wide application of WSN in various fields. The report also affirmed that UWSN contributes to market growth, especially in monitoring specific areas using sensors and vehicles for data collection.

Furthermore, scientific research institutions – including maritime surveillance and the public and private sectors – have shown increasing interest in UWSNs and the robotics market. UWSN technologies are deployed and operated deep underwater with sensors that communicate via acoustic signals. Overall, these reports indicate that awareness of UWSN technology has increased significantly, sparking interest among researchers and offering better business opportunities in the industrial world. Due to enormous technical developments in UWSN, sensors are smaller, smarter, more adaptable, more energy-efficient, have improved processing power, and can operate underwater in different circumstances. UWSN technology is also connected with the Internet of Things (IoT) , internet protocol (IP)-based systems , and machine-to-machine (M2M) real-time monitoring frameworks (Lazaropoulos, 2016).

Consequently, according to (Ullah, Liu, Su, & Kim, 2019), many undiscovered resources – especially seas, sensors and sensor networks – warrant continuous study and investigation. In particular, UWSN theories and applications require further study and evaluation, given that UWSNs have shown substantial market growth worldwide. However, a wide variety of application needs have imposed critical limitations on network job performance and sensor node capabilities in the monitored area; research works have paid minimal attention to deploying multiple mobile sensor nodes in UWSNs with multiple-objective solutions.

Typically, the nodes in a practical surveillance network are sparsely distributed and use mobility as well as high-level coordination to provide a lower surveillance cost per unit area. For such a network to be feasible, a dynamic control system is needed to coordinate the autonomous vehicles using all available target information. The control and deployment system must balance multiple objectives while maximising network coverage, energy consumption, and hold time when performing this allocation. The techniques proposed in this research provide steps for AI-driven emerging technologies concerning autonomous vehicles for ocean applications. According to (Gartner, 2018), the first trend in strategic technology is that of autonomous objects using artificial intelligence (AI) to drive new hardware and software systems on land, in the air, or underwater.

1.3 Statement of the Problem

The mobile underwater sensor deployment problem comprised several factors. Causes trigger events; some causes may trigger the same event. Considering numerous causes and generalising the causes that trigger such events is essential to provide an accurate solution.

Underwater mobile sensor node deployment involves several challenges. Notably, existing mobile underwater sensor node solutions have enormous power needs to maximise network coverage; arbitrary movement of underwater mobile nodes or vehicles may cause swift and unpredictable changes to network topology. Thus, every time a node moves out of place, the network topology must be re-calculated and re-distributed. The network may also experience redundancy or coverage gaps due to the likelihood of sensor failure, destruction, or unusual events. Therefore, nodes require immense energy to communicate with the deployed sensors. In a centralised approach, every sensor node must send its position information to a control centre. The control centre then performs computations based on global information about the network topology before instructing the nodes about subsequent directions and movement. An increase in the number of mobile sensor nodes