Agent-Based Petroleum Offshore Monitoring Using Sensor Networks

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Abstract

This paper investigates the architecture and design of agent-based sensor networks for petroleum offshore monitoring. A few challenges to monitor the reservoir, wellbore and wellhead are identified. Moreover, the necessary components for a reliable, precise, and accurate monitoring are suggested. The paper describes the architecture of the routing agent and discusses the cross layer optimization issues for query processing. The paper also provides the software design and components for a web-based continuous monitoring application.

KEY WORDS
Petroleum offshore, sensors, agent, query optimization

1. Introduction

Due to recent advances in electronics and Micro-Electro-Mechanical Systems (MEMS), it is feasible to integrate computing and storage resources with the typical monitoring sensors. These smart sensors can be connected using a serial cable, Ethernet cable, radio, acoustics, or any other physical medium of connectivity. Due to a network of sensors, it is possible to provide real-time continuous monitoring, which is precise, accurate, reliable, as well as inexpensive [1, 2]. Sensor networks promise efficient solutions for various applications such as military, security, automation, energy resources, and environmental monitoring.

This paper investigates the design and challenges of using sensor networks for petroleum reservoir and offshore monitoring. Although significant advances have been made in the areas of remote sensing and petroleum reservoir monitoring, much of these technologies remain untouched by the petroleum industry [3]. Similarly, great advances have been made in the environmental sector but most of them have not permeated into the petroleum industry.

Although offshore petroleum developments are huge revenue generating projects that provide numerous job opportunities, the projects inevitably involve risk from identified and unidentified impacts, as well as from cumulative impacts. The proposed remote sensing system will address the requirements and incorporate technologies for transmitting both downhole and wellhead data (chemical analysis of oil, gas, water, and solid) for real-time access from any desired location.

The petroleum offshore monitoring application will be based on a heterogenous environment that will consists of several independent sub-networks. There is a need for an agent-based middleware framework that will provide the abstraction for the different technologies used in reservoir, wellbore and wellhead. One promising solution is to use an agent-based approach [4], where the agent has the ability to communicate with all the sensors in the environment, create clusters and sub-networks, learn about the status of all sensors, analyze the decisions, and acts autonomously. The architecture of the proposed agent has several components. One of its main components is the learning capability, which can be implemented by a Genetic Algorithm (GA) technique. The agent acts as a mediator between the administrator and the sensor network environment. This agent provides real-time solutions for energy-efficient query processing and data dissemination. The agent-based architecture will use a database approach where the users will be unaware of the implementation details. In other words, users would be able to query the network without worrying about the energy efficient query processing and routing techniques. The query and routing agents would be responsible for query processing and data dissemination respectively. Moreover, the application developers could easily build web-based or standard applications for the given sensors, without going into the hardware, routing, or sensor details.

The remaining paper is organized as follows: Sec. 2 introduces database, routing and intelligent agent techniques for sensor networks. Sec. 3 describes the requirements and challenges of monitoring petroleum offshore reservoir. The agent-based architecture is described in Sec. 4. A sample prototype implementation is given in Sec. 5. Finally Sec. 6 concludes the paper.

2. Sensor Networks

Sensor networks consists of numerous sensors that produce continuous data streams. Due to the inherent nature of sensor networks, the database approach is preferred to execute different queries for the sensor data streams. Moreover, the database approach provides an abstraction for the data storage, allocation, and distribution. For a user, all the data appears to be local and all the queries could be performed without writing any energy efficient algorithm. A few database approaches for sensor networks are described below. Madden et al. [5] proposed a Tiny Aggregation (TAG) Service for data aggregation. This approach provides a declarative interface for the data collection and in-network aggregation. It performs intelligent distributions of queries and executes them efficiently by optimum utilization of constrained recourse of the network. At each node, irrelevant data is discarded; the relevant data are merged using aggregate functions. Yao and Gehrke [6] proposed a layered architecture consisting of application, routing and query proxy layers. The query proxy layer is present on each sensor node and connects the application and routing layers.

For data dissemination, we describe a few cluster-base approaches. For instance, Heinzelman et al. [7] described the LEACH protocol, which is a hierarchical self-organized cluster-based approach for monitoring applications. The data collection area is randomly divided into several clusters, where the number of clusters are pre-determined. Based on time division multiple access (TDMA), the sensor nodes transmit data to the cluster heads, which aggregate and transmit the data to the base station. Bandyopadhyay and Coyle [8] described a multi-level hierarchical clustering algorithm, where the parameters for minimum energy consumption are obtained using stochastic geometry.

In another direction, Jin et. al [9] have used GA for energy optimization in wireless sensor networks. In their work, GA allowed the formation of a number of pre-defined independent clusters which helped in reducing the total minimum communication distance. Their results showed that the number of cluster-heads is about 10% of the total number of nodes. The pre-defined cluster formation also decreased the communication distance by 80% as compared with the distance of direct transmission. Ferentionos et. al [10] extended the attempts proposed by Jin *et. al* [9] by improving the GA fitness function. The focus of their work is based on the optimization properties of genetic algorithm.

In this paper, we propose an agent-based architecture to design and implement petroleum offshore monitoring application. A query agent is used for heuristics-based query optimization and a routing agent creates energy-efficient clusters and sub-networks for data dissemination.

3. Offshore Monitoring Application

In this section we briefly describe the requirements of offshore monitoring application. The sensor network monitoring would be deployed at three levels: reservoir, wellbore and wellhead, as shown in Fig. 1. Conventional sensors for temperature, resistivity, density and sonic data provide valuable information about the reservoir; however, generally the information is collected only near the wellbore. In Fig. 1, these conventional sensors are shown as triangles, which are deployed as clusters around the wellbore, along the pipline, as well as scattered around the environment. A base station, shown as a hexagon in Fig. 1, receives the data by multi-hop communication. As the sensors are deployed around the wellbore and the pipline, the complete diagnostics about the condition of the interior of the reservoir is usually not monitored.

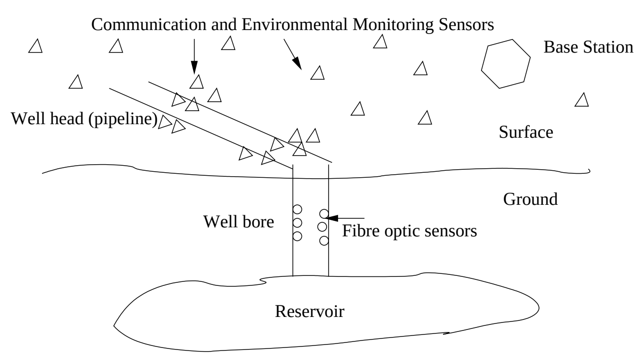

Figure 1. Reservoir, wellbore and wellhead.

For example, conventional seismic technology has a resolution of 20m for the reservoir region. While this resolution is sufficient for exploration purposes, it falls short of providing meaningful results for petroleum field development, for which 1 m resolution is necessary to monitor changes (with 4*D* seismic) in a reservoir. For the wellbore, a resolution of 1 mm is necessary. This can also help detect fractures near the wellbore.

The current technology does not allow one to depict the reservoir, the wellbore, or the tubular with acceptable resolution. In order to improve resolution within a wellbore, acoustic response from multiple sources will be analyzed. Instead of using a single powerful sensor or a data logger, we propose to use a network of multiple low-power smart sensors. The sensor network will be more reliable and precise. Moreover, the sensor network will assist to identify the less obvious parameters. In addition, fiber-optic detection of multiphase flow will be investigated. Thus, a network of heterogenous sensors will be needed to monitor the reservoir and tubular.

In order to remain competitive in today's global economic environment, owners of civil structures need to minimize the number of days their facilities are out of service due to maintenance, rehabilitation or replacement. Indicators of structural system performance are needed for the owner to allocate resources toward repair, replacement or rehabilitation of their structures. To quantify these system performance measures requires structural monitoring of large civil structures while in service. The proposed application will incorporate a structural monitoring system to integrate fiber optic sensor systems, remote monitoring communication systems, intelligent data processing system, damage detection and modal analysis system and non-destructive evaluation system. A similar system of monitoring devices, which will be capable of detecting signs of stress corrosion cracking will be developed. A fiber optic-based sensor system, and remote monitoring communication system, will allow the monitoring not only of the internal operating pressures, but also the residual stress levels, which are suspected for the initiation and growth of near-neutral pH stress corrosion cracking. The deliverable of this task is a technology that would monitor offshore structures in realtime.

Figure 1 shows the fiber optic-based sensors as circular objects within the wellbore. These fiber optic-based sensors act as a separate subnet, which is also connected to the base station. The base station is equipped with the necessary software and hardware to receive packets from different types of sensors and communication technologies.

4. Agent-based Architecture

In this section, we briefly describe the environment with special focus on the routing agent architecture. Our agent-based environment for sensor networks is shown in Fig. 2. It consists of four entities including: user, user application, software agents, and sensor nodes. The user is the administrator who manages the network. Application is the gateway for the user to submit queries and get results. Agents are the intelligent entities that are able to respond to the user needs and relieve the user from being the controller. Sensor nodes are physical entities that are able to read different phenomenon from the environment.

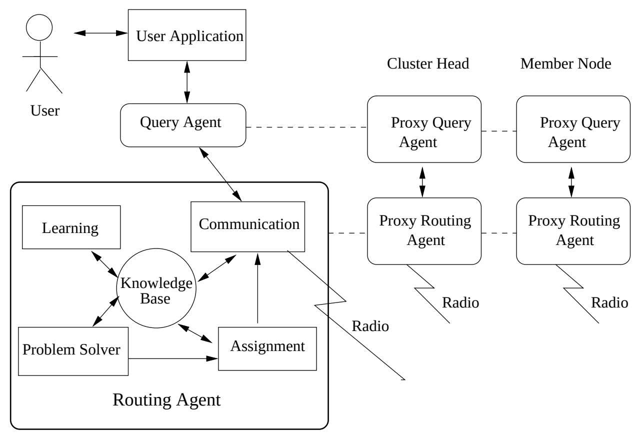

Figure 2. The Environment.

The routing agent at the base station performs computation intense intelligent operations, such as GA operations. However, as sensor nodes have limited energy supply, a sensor node is equipped with a proxy routing agent. Although the proxy agent has the same structure as the routing agent at the base station, the functionality of the proxy agent is adapted according to the requirements. A query agent is responsible to send queries and receive the results. Similar to routing agents, the sensor nodes are equipped with proxy query agents.

4.1. Query Communication Path

Using one of the standard interfaces such as a desktop, a tablet PC, or a personal digital assistant (PDA), a user initiates a query to the sensor network application. The application sends the query to the query agent of the base station. The query agent sends the query to the routing agent's communication component. When the routing agent receives the query, it forwards it to the sensor network as packets. Since the sensor network application will consist of various types of sensors and communication technologies, the communication component will act as a bridge between different forms of sensor subnets. The communication component will forward the packets in formats that are applicable for the corresponding connected sensor subnets. For instance, the wellbore structural monitoring will include fiber optics sensor subnets; whereas the wellhead will be monitored by the remote communication and conventional sensor subnets.

The network is divided into several subnets based on the communication technology. Moreover, for energy-efficient routing the subnet is divided into several clusters, where each cluster is managed by a cluster head. The cluster head is responsible to collect sensor data from the cluster members. Then, the sensor data is aggregated and transmitted to the base station. Although the clusters are self-organized, the base station can assist in the formation of clusters and the creation of transmission schedules.

When the routing agent sends packets to the sensor subnets, the agent updates its knowledge with the user queries and interests. At the sensor nodes, the routing agents' communication components receive the query packets and forward the queries to the query agents, which are responsible for retrieving the results. The query agents send their results to their cluster heads through their routing agents. The query agents at the cluster heads aggregate the query results and send their aggregated results to the query agent at the base station through their routing agent.

4.2. Routing Agent Architecture

The proposed routing agent architecture consists of several components to perform real-time energy efficient routing decisions. The routing agent has four executable components and a knowledge base repository, as shown in Fig. 2. The routing agent components are as follows: a) learning, b) problem solver, c) assignment, and d) communication.

The routing agent's *learning* component uses GA to provide an optimum network configuration for an optimum number of future transmissions. First, it creates an initial population with a large number of clusters, where the available nodes and start energies are obtained from the knowledge base repository. Then, several generations are created to produce an optimum chromosome. The optimum solution provides the complete network details: the number of cluster heads, the members of each cluster head, and the number of transmissions for this configuration. The optimum solution is stored in the knowledge base. In addition to optimum solutions, the knowledge base repository contains all the information about the network conditions, user applications, types of sensor subnets, wellbore profile, pipeline condition, and other related reservoir details.

The *problem solver* component is a decision maker that analyzes the contents of the knowledge base to choose an optimum routing plan for an optimum number of future transmissions. Moreover, the problem solver performs the functions of damage detection, modal analysis, and non-destructive system evaluation. In other words, as the routing agent performs cross layer optimization, the optimization includes the data dissemination, as well as estimation of data uncertainty, reliability, and accuracy. The problem solver component sends the decision to the *assignment* component. The assignment component assigns or delegates the responsibilities to the sensor nodes. For instance, in case of warning or alerts, the assignment operator sends the alerts messages to the suitable agents or entities. The assignment component sends the messages to the *communication* component.

The communication component creates packets that are transmitted to the desired sensor nodes. The communication components of the proxy routing agents (at the sensor nodes) receive the packets broadcasted by the routing agent at the base station. The agents at the proxies record the appropriate network and cluster information in their knowledge base repositories.

The proxy routing agents transmit packets according to the given plan for a given number of transmissions. Once the current plan is completed, the problem solver component chooses another plan from the knowledge base and the network is reconfigured (or assigned) according to the new plan. A round is defined as a time interval in which a new optimum plan is generated and the optimum number of transmissions are transmitted according to the given plan. The time interval between successive transmissions is an application dependent parameter and can be adjusted by the user.

5. Implementation

We have implemented a prototype application to monitor the environmental conditions of a campus building. This prototype application will be extended for petroleum offshore monitoring. In this section, we describe the implementation details that will assist in the design of future work. Our agent-based query processing application is implemented using Tmote^{TM}Sky model motes by Moteiv.

Client Mote Software. When the motes are first started they directly transmit to the base station with a poll frequency of one minute. This is a relatively neutral starting state and will be needed until the routing agent transmits the first broadcast that contains the query execution plan and the routing information. Once a query is received from the base station, the motes start using the query execution plan. The query packet contains information such as poll frequency, poll count and threshold values for the sensors. During the duration of the query, the radio is turned off when not transmitting to conserve power. This means that no other queries can be received until the currently active query is completed.

Server Software. The application comprises three main components for the server software. First, the DBMS stores the data received from the client motes. Second, Apache Tomcat servlet container hosts the web application. Finally, TinyOS environment of the connected mote acts as a base station to receive data from the client motes.

Web Application. The web application indicates the potential requirements for a WSN-based application. It is by no means authoritative; however, it provides a simple query interface and graphs, as well as tables to display the data received by the client motes.

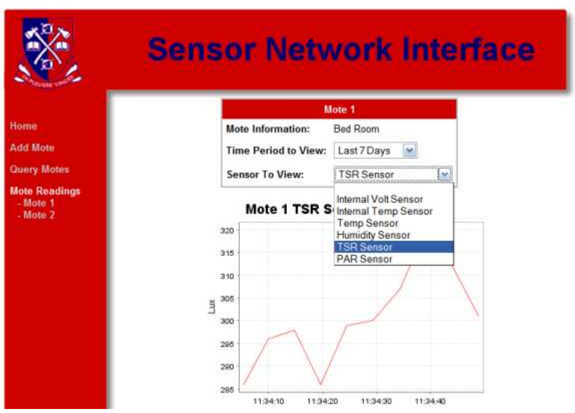

Figure 3. Sample Data Visualization

Figure 3 shows a sample visualization of the data obtained from the motes. Due to the limited space, the implementation details are very limited. There are options to narrow down the amount of data displayed in the graph; this option becomes more important as the data collection grows.

6. Conclusion and Future Work

Our proposed agent-based monitoring of petroleum offshore reservoirs, wellbore, wellhead, and pipeline uses different types of sensor networks. The agent-based architecture provides seemless integration of these heterogenous sensor subnets. This work will be extended to incorporate the design and implementation of the required sensor subnets. The communication components for the different sensor subnets will be investigated. Finally, the implementation issues will be provided in the future work.

The proposed remote sensor monitoring application will reduce the operating cost of petroleum offshore monitoring. Moreover, the real-time continuous monitoring will facilitate in implementing the suggested guidelines for safety and in avoiding the environmental hazardous conditions.

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