An Algorithm of three-Dimensional Sensor Network Deployment for Petroleum and Gas Pipeline Monitoring Systems

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Abstract. Pipeline systems are widely used for transportation of petroleum and natural gas. It is clear that a continuous and automatic monitoring system is very necessary for petroleum and gas pipeline system. This paper describes an algorithm of 3D sensor node deployment based on petroleum and gas pipeline architecture and three-tiered network architecture, which was described with the C language pseudo-code. The network coverage performance and connection performance for petroleum and gas pipeline system were discussed and we give the evaluation methods of 3D sensor node deployment algorithm.

Introduction

Wireless sensor networks (WSNs) consist of a large number of resource-limited sensor nodes. Each node is equipped with various types of sensors, computation units, storage devices, communication modules and battery units which enable nodes to be randomly and determinately deployed to cooperatively sense, compute, and transmit all types of monitored data. At present, WSNs already have many civil and military applications, such as health-care, environmental monitoring, scientific exploration and battle surveillance. etc. [1]

Transmission pipelines for oil and gas are an important part of national energy-transportation infrastructure vital to the national economy and pipelines are the most economical way to transport large quantities of oil and gas. Compared to shipping by railroad and highway, pipeline systems have lower cost and higher capacity. But these pipelines are operated at high pressure, large temperature difference and chemical corrosion. Therefore, pipelines management is confronting substantive pressure at the aspect of pipeline state monitoring, such as pipeline leak, pressure monitoring, flow monitoring, temperature monitoring, pipeline corrosion and environmental pollution that will affect the pipeline safety and transportation efficiency. WSNs can be used to ensure the efficiency and safety of pipeline without costly expansion [2], which can effectively improve the level of management. In this paper, we study an algorithm of 3D sensor nodes deployment based on the characteristics of pipeline architecture.

System Architecture and three-Dimensional Sensing Coverage based on WSNs

In this section, we describe the oil and gas pipeline architecture, network architecture and analyze three dimensional sensing coverage model based on WSNs.

A. The oil and gas pipeline architecture and network architecture

Oil and gas pipeline monitoring network requires vast longevity sensor nodes to seamlessly cover the overall pipeline. Figure 1 shows the architecture of pipeline and a three-tiered network architecture [3], which includes sensor nodes, intermediate stations sink nodes and pipeline monitoring control center.

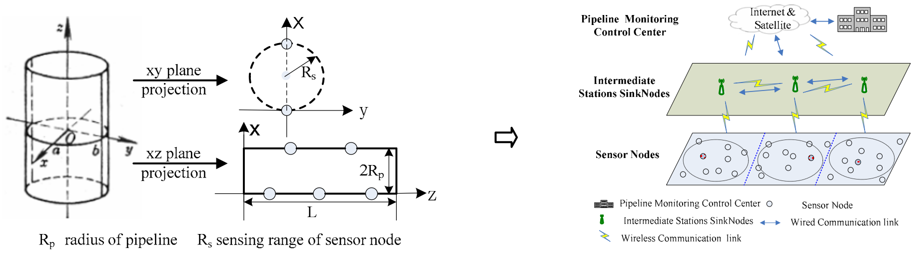

Fig 1. The oil and gas pipeline architecture and a three-tiered network architecture

The bottom tier consists of vast ordinary sensor nodes deployed on the surface of the pipelines which are used to sense the real time pipeline state information. Each node has restricted computing ability, storage ability and battery power supplies. In the middle tier, sink nodes are installed at initial injection station, compressor/pump station, partial delivery station, valve station and final delivery station [2]. Each sink has abundant computing and storage resource compared to the bottom tier node which can analyze the data from the bottom tier nodes and uploading the data to pipeline monitoring control center. These all sinks form a middle tier network via the satellite communication or internet communication.

B. The three-dimensional sensor node coverage on the surface of oil and gas pipelines

Oil and gas pipelines are made from steel or plastic tubes with the radius (refer as R_p) typically from 0.1m to 2.5m [2].and the effective sensing range (refer as R_s) of sensor node is between 0 m and 100 m. In this research, we project the three-dimensional pipeline space into two two-dimensional planes which is as shown in figure 2. It is clear that a single sensor node can cover the pipeline completely in XY plane and the XZ plane needs multi-nodes deploy collaboratively.

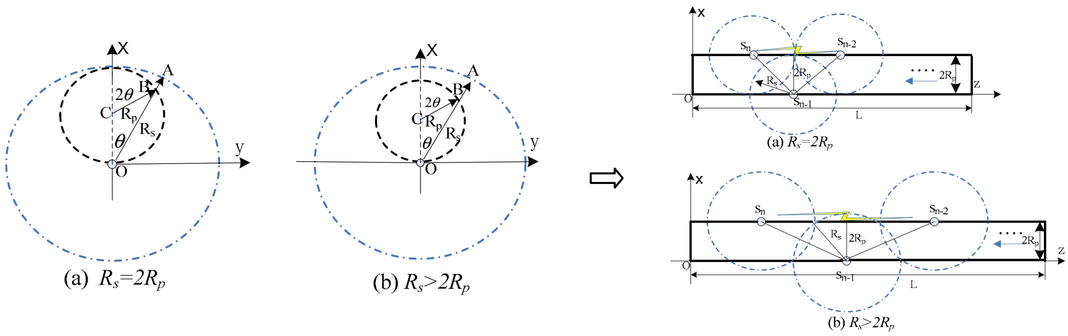

Fig 2. The coverage in the XY plane and XZ plane for oil and gas pipeline sysem

Proposed Algorithm of Sensor Nodes Deployment for Oil and Gas Pipeline System

This section presents the network coverage performance analysis and gives a complete 3D nodes deployment algorithm description with the C language pseudo-code.

A. The number of sensor nodes

In figure 2,we can clearly know that $|S_nS_{n-2}| = 2(R_s + \sqrt{R_s^2 - 4R_p^2})$, If we let L denotes the length of pipeline which needs to be overall covered, the number of nodes (refer as N_s) can be expressed as follow.

$$N_s = \lceil 2L/|S_nS_{n-2}| \rceil + 1 = \left\lfloor L/(R_s + \sqrt{R_s^2 - 4R_p^2}) \right\rfloor + 1 \quad (1)$$

B. Coverage efficient and redundancy coverage

The coverage is seamless that produces the intersection of the sensing spaces of different sensor nodes. We define the coverage efficient (refer as τ) which is expressed in equation (2).

$$\tau = \frac{V_p}{V_m} = \frac{L\pi R_p^2}{4\pi R_s^3 N_s/3} = \frac{3LR_p^2}{4R_s^3 N_s} \approx \frac{3}{4}(\frac{R_p}{R_s})^3 \quad (2)$$

In the equation (2), V_p indicates the volume of pipeline, and V_m denotes the max coverage volume of these sensor nodes. Especially, when $R_s \geq 2R_p$, $\tau \leq 37.5\%$.

In the figure 2, It is clear that the 1-coverage is 100%. and the 2-coverage (refer as k_2) can be presented as equation (3).

$$k_2 = \frac{(N_s - 1)V_c}{V_p} \le \frac{(L/(R_s + \sqrt{R_s^2 - 4R_p^2}) + 1)2\pi h^2 (3R_s - h)/3}{L\pi R_p^2} \le \frac{0.65 L\pi R_p^2}{L\pi R_p^2} = 0.65 \quad (3)$$

In the equation (3), V_c denotes the redundancy coverage volume of these sensor nodes. h denotes the height of spherical crown. Especially, when $R_s \ge 2R_p$, $k_2 \le 65\%$. And we can easily get the result that $k_n = 0, n = 3,4,...,n$ according figure 2.

C. Algorithm decription with the C language pseudo-code

Input: pipeline spatial parameters(R_p,L),effective sense radius (R_s) and communication radius (R_c)
Output:the required number of sensor node (N_s), coordinate matrix P[N_s][3].and P[i][0] denotes the X axis of node S_i(i=0,N_s-1).In the same way,P[i][1] denotes the Y axis and P[i][2] denotes the Z axis.

```
Main()
{int L,Rp,Rs,Rc,Ns;
Num();   //output the number of sensor node (Ns) for oil and gas pipeline monitoring system
Pos(Ns);  //output the coordinate matrix P[Ns][3]    }

Function Num()
{int ds;    ds =| SnSn-2 |= 2(Rs + sqrt(Rs^2 - 4Rp^2)) ;   Ns = |L/(Rs + sqrt(Rs^2 - 4Rp^2))| +1;  }

Function Pos(Ns)
{int i,P[Ns ][3];
For(i=1;i<=Ns;i++)
{if  i%2==0 P[i-1][0]= 2Rp else P[i-1][0]=0  ; // the coordinate of x axis
P[i-1][1]=0 ;              // the coordinate of y axis
P[i-1][2]= (i-1)* ds /2 ;   // the coordinate of z axis   }  }
```

Network Connectivity Performance Analysis

A. Communication model

The communication model describes the quality of communication of sensor node which is a basic network performance.

$$C(s_i,s_j) = \begin{cases} 1 & 0 \le d(s_i,s_j) \le R_{c1} \\ \frac{E_{ir}}{E_i} e^{-\lambda(d(s_i,s_j) - R_{c1})} & R_{c1} < d(s_i,s_j) \le R_{c2} \\ 0 & R_{c2} < d(s_i,s_j) \end{cases} \quad (4)$$

In equation (4), $C(s_i,s_j)$ denotes the communication quality from node S_i to S_j. R_{c1} defines the starting of uncertainty in sensor detection and R_{c2} is the maximum sensing range of the node. Generally, $R_{c1} \le 70\ m$, $R_{c2} \le 100\ m$. E_{ir} denotes remainder energy of sensor node S_i. E_i denotes the initial energy of sensor node S_i. The parameter λ is denotes degree of attenuation of signal intensity based on communication distance according to the physical properties of the sensor. The typical value of λ is 1 [4].

B. Network connection performance

The communication quality of sensor node S_i based on equation (4) is $C_i = \frac{1}{m-1}\sum_{j \ne i}^{m} C(s_i,s_j)$,m denotes the number of communicable neighbor sensor node of node S_i. And the network connection performance can be described as equation (5).

$$C = \frac{1}{N_s}\sum_{i=1}^{N_s} C_i \quad (5)$$

Generally, the condition of $R_c >= 2R_s$ is both necessary and sufficient to ensure that complete coverage of a three-dimensional space implies connectivity in the network [5]. In most cases, the condition of $R_c >= 2R_s$ is accessible for oil and gas pipeline.

C. The influence of energy consumption on network connection performance

Every sensor node has the same initial energy (refer as E_i) and the same connection performance accoring to equation (5) at the start of the network to work. But, As time went on, the remainder energy of sensor node (refer as E_{ri}) will be far different because the unbalance energy consumption. So the connection of sensor node will be different too. In order to accurately evaluate network connection performance, we design the Ns×7 network connection performance matrix which is described as equation (6). The matrix C[i][0] denotes identifier of node S_i (i=0,N_s-1). C[i][1,2,3] denotes the X,Y,Z axis of node S_i (i=0,N_s-1). In the same way, C[i][4] denotes the connection of node, C[i][5] denotes the remainder energy of node and C[i][5] denotes the network route path.

identifier of node | X,Y,Z coordinate of node | connection of node | energy of node | route path of node

$$C=\begin{bmatrix} 1 & X_1 & Y_1 & Z_1 & C_1 & E_1 & R_1 \\ 2 & X_2 & Y_2 & Z_2 & C_2 & E_2 & R_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ N_s & X_{N_s} & Y_{N_s} & Z_{N_s} & C_{N_s} & E_{N_s} & R_{N_s} \end{bmatrix} \quad (6)$$

Summary

In this work, three-dimensional sensor node coverage has been carefully analyzed based on the architecture of oil and gas pipeline. And network coverage performance was discussed carefully. At last, a complete algorithm description with the C language pseudo-code was presented. In the future, we plan to make investigation of data storage, data fusion and delay performance based on three-dimensional sensing coverage for oil and gas pipelines.

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