Water supply network monitoring based on Demand Reverse Deduction (DRD) technology

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Abstract
DRD technology is a new method to calculate the node water demand based on the monitoring node pressure of the water supply network. This method is able to acquire the water consumption in every node of the monitoring area. Therefore, no flow meter is needed to install on the main pipes. This paper describes the technical details of DRD application and the design of monitoring platform based on wireless sensor network (WSN). A case study is carried out in an actual water supply network and the result shows this method is accurate enough to provide decision support for water supply network management.

Keywords: Water supply network, Demand Reverse Deduction (DRD), Wireless Sensor Network (WSN), pressure monitoring;

1. Introduction

Water supply network is one of the most important municipal infrastructures. However, constant pipe networks expansion and lacking of monitoring result in a lot of acute problems in the water supply network, such as high leakage rate and energy consumption. Water pressure and flow are the most frequently used parameters in water supply network management. For example, the District Metered Area (DMA) night minimum flow analysis [1], the traditional way for water loss detection, needs to install a lot of flow meters. However, the scale of the network are so large and buried underground that difficult to access for monitoring. In this circumstances, DRD technology is proposed to provide a new idea for water supply network management [2-4]. DRD is a method to calculate the node demand based on the monitoring node pressure of the pipe network system. Because the cost of pressure monitoring is much lower than that of flow monitoring, it is reasonable to carry out water pressure monitoring instead of flow monitoring.

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monitoring. Meanwhile, pressure monitoring is a relatively easy task that the sensors can be installed on the fire hydrants. So it is feasible to apply the Wireless Sensor Network (WSN), a low cost monitoring system, to the enormous water supply network.

This paper describes DRD technology and its application in water supply network monitoring. Section 2 describes DRD and its related technologies in detail. Section 3 makes a brief induction of the water pressure monitoring system based on WSN. Section 4 illustrates the application effects through a case study. And section 5 concludes the paper.

2. DRD and related technologies

Water demand is a crucial parameter for it is the basis of pump operation, optimal scheduling and leakage detection of water supply network. Two traditional ways to get the water demand are flow monitoring and demand prediction. For the former, it is impractical to install flow meters for all the metered areas because the device and installation costs are very high. The latter is usually based on a great number of historical water consumption data. And the typical prediction models, such as Artificial Neural Network (ANN) Model [5] and Grey Model (GM) [6], are essentially time-series and black box models. The biggest drawback of this approach is the forecast highly depends on historical water consumption data while ignoring the hydraulic process in pipes. Moreover, the result is just a regional demand prediction and the water demand in specific node is still unknown. In this situation, DRD technology is developed to make a more accurate quantitative analysis for the node water demand. This approach takes advantage of the highly accurate monitoring pressure data and the water demand calculation is fully based on hydraulic theory.

2.1. DRD introduction

Water supply network hydraulic calculation commonly adopts Hazen-Williams formula as follows:

\[ H_i - H_j = \frac{10.67L_{ij}q_{ij}^{1.852}}{C_{ij}^{1.852}D_{ij}^{1.852}} \]  

(1)

Where \( H \) is the water head of the node (m), \( L \) is the pipe length between two nodes (m), \( q \) is the pipe flow rate (m³/s), \( C \) is Hazen-Williams constant that represents the pipe inner wall roughness, \( D \) is the pipe inner diameter (m), \( i \) and \( j \) are the node IDs.

The pipe length \( L \) and diameter \( D \) are known by checking the design drawings. The pipe \( C \) value changes slowly which is regarded as a constant in a short term and can be obtained through clustering analysis (see section 2.3). Some of the nodes’ water heads are collected by the on-line monitoring system. And others can be calculated by interpolation method. In this way, the flow in every pipe can be reversely calculated by formula (1). Assume the flow towards the node is positive and out of the node is negative. According to the law of mass conservation, the node water demand can be calculated as follows:

\[ Q_i = \sum_{j=1}^{n} q_{i,j} \]  

(2)

Where \( Q \) is the node water demand (m³/s), \( n \) is the number of pipes connected with the node.

2.2. Meshing and interpolation method

For the actual water supply network, it is impossible to monitor all nodes’ pressures. The interpolation method takes full use of the limited number of monitoring data to simulate the entire network pressure state. In a single pipe, the water head decreases linearly along with the flow direction. But in the system of multi-pipe with demand nodes, the water head variation is non-linear. The branch-shaped pipeline as shown in the bottom of Fig.1 consists of 5
water demand nodes, 4 pipes, 1 pump and 1 reservoir. The water demand in each node is 50L/s and the length of each pipe is 1000m. Node 2, 4 and 6 were selected as monitoring nodes. Liner Interpolation, Cubic Spline Interpolation and Cubic Polynomial Interpolation were adopted separately and the calculation result is shown in Fig.1. Compared with the latter two methods, the calculation result of Liner Interpolation had poorer accuracy. This is because the function of the latter two methods is continuous and smooth in the interpolation interval, so they have a better reflection of the water head variation characteristics in complex pipe networks. Among these methods, the Cubic Polynomial Interpolation performed best. So it was selected as the priority method.

![Fig. 1. The comparison of calculation results in different interpolation methods](image)

Since the actual water supply network is usually designed as loops and its topology is always very complicated, the Digital Network (DN) is proposed to make the mathematical description for them. DN consists of node geographical coordinates, network topology and monitoring pressure data. In DN, the monitoring pressure data is discrete and the pipe network topology is complicated. Therefore, we divide the network topology into grids for high-precision estimation of water head on the entire pipe network. Delaunay triangle is used to construct irregular triangular grids for the pipe network topology. Compared with other meshing methods, it has some unique advantages [7]:

- **Uniqueness**. For the same set of data, the Delaunay meshing result is unique regardless of the method. This advantage ensures a stable data computing structure.
- **Empty circumcircle**. Each of triangle’s circumcircle doesn’t contain other monitoring nodes. This character eliminates data redundancy so that the computational efficiency is improved greatly.
- **Convex polygon**. The boundary formed by Delaunay triangle grids is a convex polygon and the interpolation calculation occurs within its borders. Thus, it avoids the uncertainty brought by extrapolation.
- **Low impact**. When add or delete a node or change its location, there is only influence on its neighbor nodes. So it is convenient to make some adjustment for the layout of monitoring nodes.

Delaunay triangular grids employ corresponding resolutions to describe areas with different nodes densities in order to get in harmony with water supply network topology. They represent linear features as well as easily constitute arbitrary shapes. Thus, water supply network, an irregular linear system, is well described by Delaunay triangular grids.
2.3. Pipe friction coefficient clustering analysis

Pipe friction coefficient $C$ is an important parameter for pipe network hydraulic calculation. However, until now, there is no theoretical or empirical formula to calculate the $C$ value. What’s more, it is impractical to measure all pipes’ $C$ values because the scale of water supply network is huge. As it is known, the pipe $C$ value is decided by its diameter, material, water quality and service time, and pipes with similar attributes as mentioned should have similar $C$ values. In order to reduce the number of measuring pipes, a clustering method is proposed to cluster similar pipes into one class in which all the pipes share the same $C$ value. In this case, only the “central pipe” of its class needs to be measured or estimated.

Fuzzy C-means (FCM) clustering method is adopted to cluster these pipes. The advantage is the method introduces a fuzzy rule to describe the affiliation uncertainty when clustering. In this way, the degree of affiliation is no longer a fixed target of 0 or 1, but a proper value in the interval of 0-1. FCM clustering algorithm objective function is as follows:

$$\min J = \sum_{k=1}^{n} \sum_{i=1}^{m} (a_{ik})^w d_{ik}^2$$  \hspace{1cm} (3)

Where $n$ is the sample size, $m$ is the number of clusters, $a_{ik}$ is the affiliation degree of the sample $k$ to the cluster $i$, $w$ is the weight coefficient, $d_{ik}$ is the Euclidean Distance between sample $k$ and the centre of cluster $i$.

The affiliation degrees of all the samples constitute a fuzzy dividing matrix $A = \{a_{ik}\}$. FCM algorithm optimizes the clustering result by constantly revising the clustering center $XC_i$ and dividing matrix $A$. Its iterative calculation formulas are as follows:

$$a_{ik}(t) = 1 / \sum_{j=1}^{m} \left[ \frac{d_{jk}(t)}{d_{jk}(t)}^{2} \right]$$  \hspace{1cm} (4)

$$XC_i(t + 1) = \frac{\sum_{k=1}^{n} (a_{ik}(t))^w x_k}{\sum_{k=1}^{n} (a_{ik}(t))^w}$$  \hspace{1cm} (5)

Where $x_k$ means the sample $k$, $t$ is the number of iterations. The meaning of other symbols is the same as above. The following is the calculation process:

- Step 1: Set the number of clusters and permissible error $\epsilon$ for stopping iteration.
- Step 2: Initialize the fuzzy dividing matrix $A$ and clustering center $XC_i(0)$.
- Step 3: Calculate the Euclidean Distance between each sample and each cluster center.
- Step 4: Update the dividing matrix $A$ and cluster center $XC_i(0)$.
- Step 5: If $\| XC_i(t) - XC_i(t+1) \| < \epsilon$, stop calculation. Otherwise, return to step 3 and keep computing until getting the final result.

3. Monitoring platform

In order to apply DRD technology to water supply network management, a large-scale on-line monitoring platform needs to be built for water pressure data acquisition. The current commercial on-line monitoring solution usually equips a remote communication module with each monitoring node. This way makes the single monitoring node a high hardware cost and a large power consumption so that it is not suitable for large-scale and low-cost monitoring requirements of water supply network. In this condition, the WSN technology is recommended to build the monitoring platform. WSN technology is able to construct a strong sensing network at a very low cost to meet the demands of DRD application. Since only water pressure needs to be monitored, the fire hydrants are selected to
install the monitoring nodes. In this way, it is not only convenient to manage and maintain these monitoring devises, but also prevents the transmission signal from being shielded.

3.1. Monitoring node design

According to the role in WSN, the monitoring nodes are divided into Multi-hop Node and Gateway Node. Multi-hop Node is responsible for data transmission with its neighbor nodes through 2.4 GHz ZigBee. The advantage is ZigBee is a short-range and very low-power wireless communication protocol. For example, the Multi-hop Node typical transmit current is about 27mA, receiving current is around 20mA and the pressure sensor’s working current is 20mA which means the total current for data transmitting period is about 47mA and data receiving period is about 40mA. A battery with capacity of 3000mA • h can drive this node at least for 60h. In fact the monitoring system only needs collect data for a few times a day, assume data acquisition frequency is 10 times a day and 60s for one time, thus this node is able to work 360 days without battery replacement.

Both the Multi-hop Node and the ZigBee module of Gateway Node are built on the CC2530 System on Chip (SoC) which integrates the enhanced 8051 CPU, 256 KB programmable flash memory, 8 KB ultra-low-power SRAM, 32 MHz and 32.768 KHz crystal oscillators, an antenna interface and 21 I/O interfaces. The reason choosing this SoC is it is fully compatible with ZigBee protocol and capable to build a wide-area sensor network at a very low hardware cost. Gateway Node adopts Atmel Atmega 128 chip as the converter motherboard which is in charge of ZigBee and GPRS protocol converting, and the GPRS communication module is based on Chipcon SIM300 chip system. In addition, all the monitoring nodes are water-proof packaged to meet the outdoor working conditions. The monitoring nodes’ software development takes IAR Embeded Workbench integrated developing environment as the platform and the programming is based on Texas Instruments Z-Stack 2007 protocol stack.

3.2. Network design

The outdoor fire hydrants are normally laid along the roads and the distance between two is less than 120m which is in the communication range of ZigBee. Therefore, this paper recommends the monitoring nodes are installed on outdoor fire hydrants to collect water pressure data. The Multi-hop Nodes establish a multi-hop, ad hoc network and pass their data one by one. Then the Gateway Node installed in a proper place collects all the delivered data and uploads them into the Internet through GPRS service. In the meantime, the server in data center makes a connection with the Gateway Node through the Domain Name Service (DNS) to download the field data and issue directives. Finally, the field data are processed by DRD technology and the results are published on the website so that other terminal devices can login to query the running status of water supply network. When a network node is suddenly out of work, the data transmission route will change automatically to skip over the broken nodes and a warning massage displays in the data center to show the detailed information.
4. Case study

This paper takes a regional water supply network in Shenzhen city as an example to study the application of DRD technology. The topology of this pipe network was simplified that only the main pipes were reserved. As shown in Fig.3, the pipe network system consists of 2 reservoirs, 324 demand nodes and 416 pipes. The district specified in Fig.3 is densely populated and has large water consumption. Leakage and pipe burst happen frequently, so this part in the system was selected to be the study area. The study area contains 190 demand nodes and 250 pipes and the WSN on-line monitoring platform was applied. 24 monitoring nodes were set in this area which the border points, extreme pressure points, terminal points and entrance points of large consumer were prior.

Before calculating each node water head via interpolation, the pipe network topology was divided into grids by Delaunay triangulation. The calculus of interpolation was just implemented in these irregular triangular grids. Cubic Polynomial Interpolation method was adopted because of its higher accuracy as mentioned before. The calculation result was displayed in form of contour lines which gives an intuitive description of the water head state in the study area. As shown in Fig.4, darker lines means higher water head while more intensive of contour lines indicates greater water head loss.

![Fig. 3. (a) The network topology; (b) the study district.](image-url)
To calculate the water demand of each node, the friction coefficient (C value) of each pipe is necessary. This study used FCM clustering method to classify these pipes according to their attributes of diameter, material and service time. Only the C values of the pipes closest to cluster center were measured and the C values of cluster center was calculated based on these measured values. In this study area, there are 4 kinds of pipes that is steel pipes, cast iron pipes, ductile iron pipes and fiberglass pipes. The minimum pipe diameter is 300mm while the maximum is 2200mm. After several rounds of repairing and expansion, the pipes service time ranges from 5 to 30 years. When applying FCM algorithm to clustering analysis, the weight coefficient \( w \) took 2, a recommended value of this algorithm, and the iterative termination error \( \epsilon \) took \( 10^{-5} \). The pipe materials were in form of text that was unable to calculate directly, so 1,2,3,4 were adopted to represent the steel, cast iron, ductile iron, fiberglass respectively. Data normalization utilized 0-1 method namely the raw data were normalized to standard data which the mean value was 0 and the standard deviation was 1. The number of clusters was determined as 8 according to the result of objective function value and uncertainty analysis. Table 1 shows the result of clustering and central C values in each cluster.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Diameter (mm)</th>
<th>Material</th>
<th>Service time (years)</th>
<th>Number of pipes</th>
<th>Central C value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2002</td>
<td>1.99</td>
<td>11.5</td>
<td>19</td>
<td>133</td>
</tr>
<tr>
<td>2</td>
<td>1833</td>
<td>2.02</td>
<td>12.3</td>
<td>23</td>
<td>128</td>
</tr>
<tr>
<td>3</td>
<td>1560</td>
<td>2.03</td>
<td>9.4</td>
<td>33</td>
<td>129</td>
</tr>
<tr>
<td>4</td>
<td>1008</td>
<td>2.00</td>
<td>16.7</td>
<td>40</td>
<td>112</td>
</tr>
<tr>
<td>5</td>
<td>872</td>
<td>1.87</td>
<td>20.5</td>
<td>27</td>
<td>117</td>
</tr>
<tr>
<td>6</td>
<td>653</td>
<td>1.93</td>
<td>17.2</td>
<td>21</td>
<td>113</td>
</tr>
<tr>
<td>7</td>
<td>540</td>
<td>1.99</td>
<td>10.2</td>
<td>42</td>
<td>101</td>
</tr>
<tr>
<td>8</td>
<td>423</td>
<td>2.98</td>
<td>23.1</td>
<td>45</td>
<td>97</td>
</tr>
</tbody>
</table>

After obtaining the C value of each pipe, the water consumption in each node was calculated by formula (1) and (2). The node in the water supply network takes charge of supplying water for a region and there has been equipped with flow meters for water consumption measurement in the entrance of every building. Therefore, a comparison can be made between the meter readings and the calculated water consumption of the node by DRD. When there is an obvious difference between the two, water loss or flow meter malfunction probably occurs in this region. By this
means, not only the water loss region is able to be located, but installing flow meters for the large-diameter main pipes is avoided. The study area was monitored through the on-line monitoring system for 24 hours and the flow meter readings in Node A and Node B (see Fig.3) was gathered at the same day for data validation. Fig.5 compares the calculated and actual measured water consumption curves. The result shows the calculated curve trend is basically consistent with the measured curve. The errors between calculated and measured daily water consumption for Node A and Node B are 4.3% and 7.1% respectively which is accurate enough to provide guidance for water supply networks management.

![Fig. 5. Calculated and measured water consumption curves in 24hr of node A and node B](image)

5. conclusion

This paper describes a new water supply network monitoring pattern based on DRD and WSN technology in detail. It includes pipe network topology meshing method, water head interpolation, friction coefficients clustering analysis, water consumption calculation and WSN pressure monitoring platform.

A case study is carried out to illustrate the application of this pattern which indicates two advantages. First, the water head contour line graph from interpolation method provides an intuitive description of the network pressure state. The overall aware of the water head in the pipe network can act as an effective decision support for water supply optimal scheduling, pipe burst forewarning, malfunction diagnosis. Second, water consumption in each node is not estimated based on historical data, but the quantitative analysis based on the hydraulic calculation. This method has a high calculation accuracy for daily total water consumption and the calculated 24-hour variation trend is basically consistent with the actual one. And during the water consumption trough period in wee hours, the node water consumption calculation is highly accurate. However, during the peak water usage period, the calculation has a greater error. Therefore, the water loss detection is recommended to implement in wee hours. Because the accuracy of water consumption calculation is directly related to the precision of water head interpolation. So, in order to make an improvement of this technology, future study will focus on the optimization layout for monitoring nodes and the research of interpolation methods.

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