Internet of Thing System to Extract Hierarchical Healthy and Efficiency Information for Pump Station Optimization

Haoran Feng
Joint Laboratory of National Engineering Research Center for Software Engineering and Hanpu Intelligent
Peking University, Beijing, China
haoran@pku.edu.cn

Yongcai Wang
Department of Computer Sciences
Renmin University
Beijing, China
ycw@ruc.edu.cn

Lifeng Qiao
Beijing Ganwei Technology Development Company Limited
Beijing, China
qiaolf@ganweitech.com

Jiajun Zhu
Department of Computer Sciences
Renmin University
Beijing, China
kongqizhu@ruc.edu.cn

ABSTRACT

Pump stations provide water supply and dispatching functions in industry plants. Smart and sustainable operations of the pump stations plays a critical role for production safety and efficiency. This requires the real-time states of the pump stations to be tracked for situation awareness. However, the pump stations contain serial/parallel pumps, pipes, valves, and other devices, whose states are tightly coupled due to the hydrodynamics of the fluid. This paper reports the design, development, and knowledge learned from practical deployment of an Internet of Things (IOT) system in Baotou steel plant, China. We spent more than half a year to deploy a IOT system containing several hundreds of sensor nodes. The IOT system is designed to provide healthy and sustainability information of pump stations in three levels: 1) pump level; 2) pump station level, and 3) system level. The IOT system helps to discover originally unaware problems of the pump stations, and shows potential directions of using IOT and Big data analysis for smart pump station operations.

Keywords

Internet of Things, Pump Station, Sustainability, Intelligent, Cyber-Pysical System

1. INTRODUCTION

Pump stations are fundamental supporting system in many industry plants, which play vital role for water supplying and dispatching[10, 7]. For processing the massive volume of water, pump stations are major course of electrical energy consumption in the production systems. For example, in Baotou Steel Plant, one of the largest steel company in the north China, the annual water drilling from Huang River is nearly 0.1 Billion tons[3]. These water is drilled, pumped, transported, and dispatched through nearly twenty pump stations distributed in the company area. The annual electrical energy consumption by these pump stations is nearly 0.2 billion Kwh. Therefore, the lifetime operating cost of a pumping station is about a hundred times its initial deployment cost, because the energy-intensive processing of water pumping.

At the same time, because of the high speed rotation of the impellers in the pumps, the pumps are prone to different kinds of runtime faults, such as faulty bearing, defection on the impeller and cavitation etc [5]. For keeping production safety and efficiency, pump state checking, health monitoring, maintenance and pump repairing are major costs in pump station operation [4]. Therefore, the smart and sustainable operations of pump stations is substantial for not only energy saving but also for productivity improvement.

Situation awareness is the first step requirement for pump station optimization. This is generally carried out by deploying sensors and Internet of Things systems to monitor the working states of different devices[1, 6, 14]. But the goal of situation awareness is not to easily track the working states of the devices, because the rough data is meaningless. The major task is to extract run-time state knowledges by fusion of the noisy sensor data[2]. Such knowledge includes the healthy and efficiency states of the pump stations, the pumps and other devices. In practice, a pump station is composed by several parallel/serial pumps, pipes, valves, ponds, and other devices. The states of these devices are tightly coupled by the hydrodynamics of the fluid[8, 11, 12]. How to monitor and extract healthy and efficiency states for the pump stations is therefore an important problem. Some recent work presented the energy efficiency state monitoring and optimization for subway HVAC system[13] The learned model generally needs to be online adapted. A simplex based online learning model adaptation problem was investigated in previous works[9].

This paper reports the design and development of an IOT

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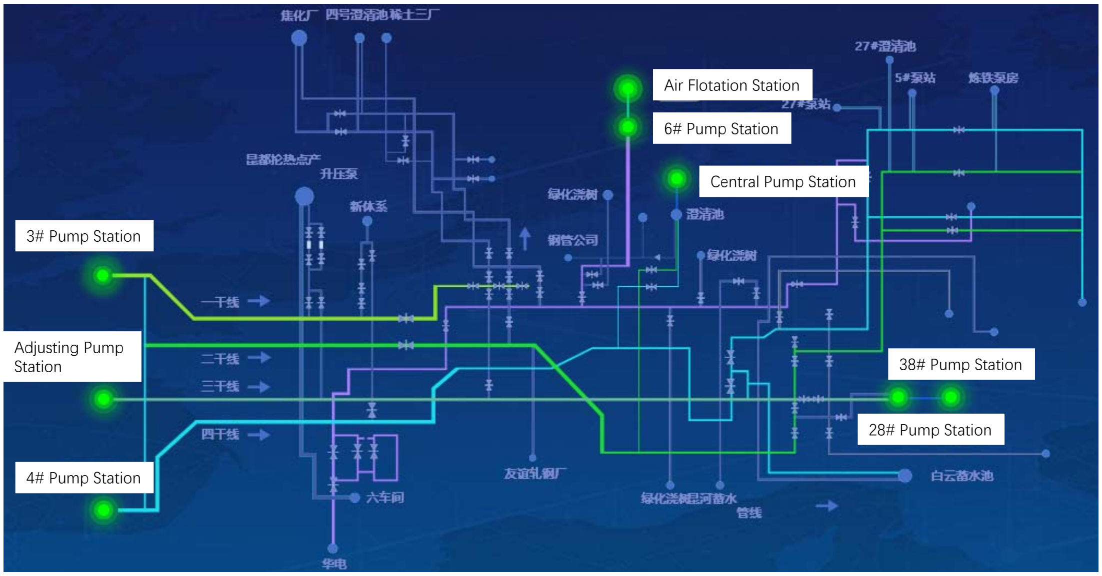

Figure 1: The topology of water supplying network in Baotuo Steel Plant

system for monitoring the run-time states of the pump stations in Baotou steel company. The IOT system is deployed in four pump stations. It is designed to extract the healthy and efficiency states of the pump stations from three levels: (1) water transportation system level; (2) pump station level; (3) pump level. By more than half a year's deployment and testing, several hundreds of sensors are deployed and massive data is collected. Data is collected into a cloud server and is stored into database, where data analysis is carried out to extract healthy and efficiency state of three levels. Then the raw data and extracted state data are rendered in a web-based state tracking system.

The remainder sections of this paper are organized as following. The design methodologies of the system are introduced in Section 2. System implementations are introduced in Section 3. Hierarchical healthy and efficiency state analysis methods are introduced in Section 4. The run-time results are reported in Section 5. The paper is concluded with discussions of IOT system for smart pump stations in Section 6.

2. SYSTEM DESIGN METHODOLOGIES

The whole system is developed by improving the hardwares, software and information systems of existing pump stations in Baotou Steel Plant. The goal of pump station optimization is to reduce the operation cost of the water supplying system while meeting the requirements of water supplying for not only steel production but also for living usage in the company area.

2.1 Water Supplying Requirements

The first goal of pump station operation is to satisfying the requirements of the steel production systems. The topology of the water supplying network in Baotuo Steel Plant is rendered in Fig.1. The pump stations supply water for the steel production system and for living usage. The 3# *Pump Station*, 4# *Pump Station* and *Adjusting Pump Station* are major water drilling stations, which drill water from Huanghe River and pump the water through main transportation lines towards the company. The *Air Flotation Station*, 6# *Pump Station* and *Central Pump Station* are supplying water to the production system and living areas. The 28# *Pump Station*, 38# *Pump Station* are pumping water to production system and water storage. The detailed requirements to these pump stations are given in Table 1.

2.2 Cost Composition of Pump Stations

The second goal of pump station optimization is to reduce the operation cost and to improve the energy efficiency of the pump stations. The operation costs of pump stations can be decomposed into four aspects:

- Cost of electrical energy consumption.
- Cost of water consumption and water waste.
- Human cost for operating.
- Spare parts cost for reparation

To reduce the operation costs, we need to improve the energy efficiency of the pumps. This can be done by adjusting the valves and by controlling the speeds of the motors. We also need to avoid severe system faults for guarantee productivity. Therefore, the fundamental problem of pump station optimization is to improve the efficiency and healthy of the pump stations.

2.3 Hierarchical Efficiency and Healthy

We developed IOT system to extract the efficiency, healthy states of the water supplying system from three levels:

1. System level: the overall efficiency and healthy state of the water supplying system.
2. Pump station level: the efficiency and healthy state of each pump station.
3. Pump level: the efficiency and healthy state of each pump in each pump station.

The system level reports the state of overall water supplying system to the company managers, so that they can quickly know the overall water system states. The pump station level is an overall evaluation to all the pumps in the station.

The pump states are evaluated by the working point of the pump and by healthy evaluation by processing the sensor data of the pumps.

3. HIERARCHICAL STATE MONITORING

The IOT system is developed to monitor the working states of pumps, motors, valves, and pipes. The monitored data is collected by the edge computer and finally collected to a cloud server. The data is then processed to extract the healthy and efficiency information of different levels.

3.1 Pump States Monitored by IOT

Fig.2 shows two pumps in the pump station. Sensors are deployed to monitor the 1) the axis temperature; 2) the water pressure before and after the pump; 3) the water flow; 4) variation at three points; 5) the open rate of the valves; 6) the real-time voltage of pump; 7) the real-time current of pump; 8) pump rotation speed;

Figure 2: Pumps

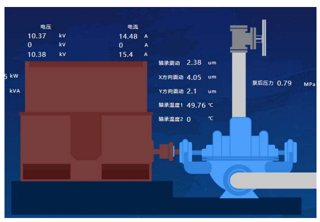

Figure 3: A pump's states monitored by the IOT system

The sensor data is collected to an edge computer at the controller box and then reported to the cloud server. The monitored pump state is shown in Fig.3. We can see the real-time information of the pump and the motors.

3.1.1 Evaluate of Pump Efficiency

The pump efficiency is calculated based on the efficiency curve of the pump, which is provided by the pump company. The pump efficiency is

$$\eta = \frac{N_{out}}{N_{in}} = \frac{2.778 \cdot Q \cdot H}{\sqrt{3} \cdot U \cdot I \cdot \cos\theta} \tag{1}$$

where Q is the real-time flow; H is the pump head which equals the outlet pressure minus the inlet pressure; U is the voltage; and I is the current. So based on the monitored values of Q, H, U and I, the working point and the efficiency of the pump can be calculated. Fig.4 a) shows the real-time working point of a pump on its efficiency curve.

Pump Station Name	Flow Requirement (m3/h)	Pressure Requirement (Mpa)
28# Station	800-1650	0.8-0.9
38# Station	900-1500	0.12-0.2
3# Station		
4# Station	900-12600	0.74-0.78
Adjusting Station		
6# Station	1000-1300	0.53-0.60
Air Floating Station	300-500	0.15
Central Station	200-700	0.2-0.3

Table 1: Water supplying requirements

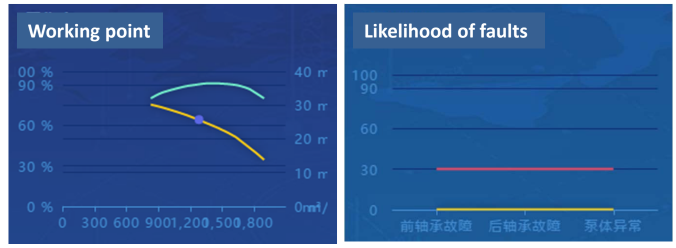

Figure 4: The real-time monitored healthy and efficiency states of a pump

3.1.2 Evaluate of Pump Healthy

The pump healthy is evaluated based on the likelyhood of happening pump faults. We reported the online pump faults detection method in our early work[5]. The machine learning method is applied to evaluate the likelihood that the pump is running into different kinds of fault states. The system can conduct real-time fault diagnosis in real-time.

3.1.3 Pump Healthy and Efficiency Statistics

Based on the real-time pump healthy and efficiency data, the pump healthy and efficiency states are smoothed overtime to generate more reliable state estimation. The fault diagnosis tool and preventive maintenance tool also generate issues to notify the manager to conduct pump maintenance. The overall pump health, efficiency states and the issue tracker are shown in Fig.5.

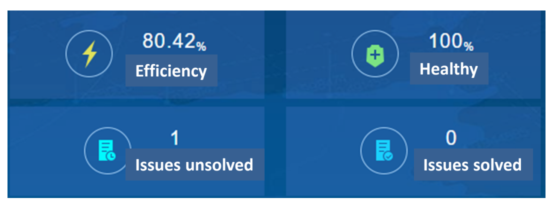

Figure 5: The calculated pump healthy and efficiency states

3.2 Pump Station State Monitoring

Based on the collected pump states, the second level is to monitor the states of the pump stations.

3.2.1 Composition of Pump Station States

The states of a pump station are composed by the states of multiple pumps. Fig.6 shows the monitor states of a pump station. The pump station contains five pumps. The Q, H, U, I values of different pumps are collected and rendered in real-time. The pump station also contains a set of valves. The real-time states of the valves are also rendered. The surface level of the water pool, the states of the frequency controller are also collected and rendered in real-time.

3.2.2 Efficiency of a Pump Station

The efficiency of the pump station is evaluated by the average efficiency values of all the pumps in the station.

Figure 6: The monitored real-time data of the pump station

3.2.3 *Healthy of a Pump Station*

The healthy of a pump station is decomposed into the healthy information of all the pumps in the station.

3.2.4 *Supply Requirement Satisfaction Rate*

Whether the water supply of the pump station can satisfy the water usage requirement is an important performance of the pump station. Therefore, the rate of supply requirement satisfaction is evaluated based on the proportion of points that satisfy the water pressure and flow requirements over all the measured data points.

3.2.5 *Water Usage Per Ton Steel Production*

The water usage for per ton steel production is an important indicator of the water saving performance. Thus, it is evaluated as an state factor of the pump station.

These pump station states are shown in Fig.7. The pump station states can be seen clearly from these statistical results, which is convenient for the pump station managers.

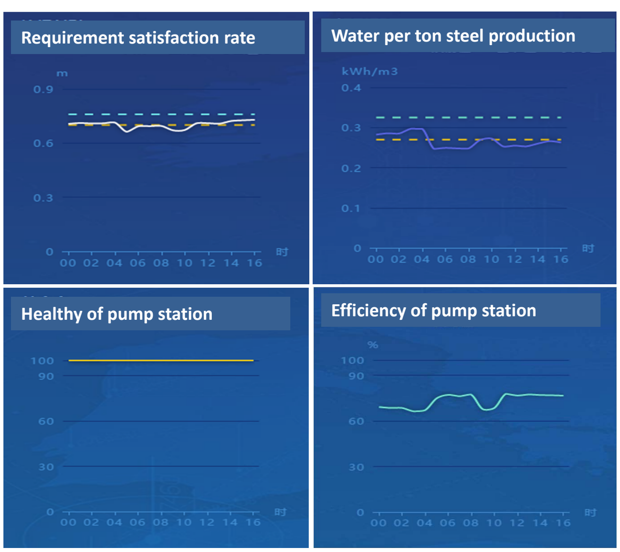

Figure 7: The calculated states of the pump station

3.3 State of Overall Water Supplying System

The top level represent the states of the whole water supplying system, which provides summarized information of water supplying system to the company managers. The topology of overall water supplying system is shown in Fig.1. The following performances are summarized for the whole water supplying system.

1. *The supply requirement satisfaction rate of the whole system*, which is calculated by the average water supply requirement satisfaction rates of all the pump stations.

2. *Water usage per ton steel production*, which is calculated based on the water usage of the whole company and the steel production information.

3. *The system healthy state*, which is calculated by the average of healthy rates of pump stations.

4. *The energy saving rate*, which is calculated by comparing the energy per ton of steel production divided by the energy per ton of steel production before the system deployment.

All these information is rendered in real-time and stored into databased for querying at any time.

4. SYSTEM DEPLOYMENT

4.1 Deployed Sensors and Hardware

Based on above design methodologies, the IOT system is deployed to monitor the pump station states. The details of IOT system deployment is given in Table 2. The table lists the number of sensors, controllers, edge computers, pump devices and cloud system deployed to monitor the states of water supplying system.

	Description	Number
Sensing System	Pressure sensor	54
	Axis temperature sensor	28
	Temperature sensor	76
	Vibration sensor	39
	Liquid level sensor	66
	Data collector	3
Pump devices	Variable frequency pump	14
	Motor	5
	Adjustable Valves	20
Edge System	Edge device for data collection and control	29
	Pump station controller	8
Cloud System	Cloud platform	1
	Database	1

Table 2: Details of deployed sensors, controllers, edge computer and cloud server

4.2 The Data Processing System

The sensor data of a pump is collected by edge computer located in the pump controller. The edge computer receives the real-time sensor data and conducts basic data smoothing and aggregation. It assigns the time label, pump label to the sensor data and then report the sensor data to the remote data server. Kafka streaming is used to collect sensor data to the database and Mogodb is used for data storage and data querying.

4.3 System State Tracking Results

Using above mentioned system, we track the healthy and efficiency states of the water supplying system for the eight pump stations. For space limitation, we only plot the one-week state tracking result of 38# pump station. The result is given in Fig.8. We can see the water supply satisfaction rate, the traces of water flow and the efficiency curve of the pump station can be seen clearly, which provide important tool and first-hand information for the optimization of pump station operation.

Figure 8: System state tracking result

5. CONCLUSION

This paper reports the design and development of IOT system for extracting hierarchical healthy and efficiency states of pump stations. These state information are crucial for the optimization of pump station operation. We report the methodologies of representing system states from three levels, namely the water supply system level, the pump station level and the pump level. We provide the practical method to calculate the healthy and efficiency states in these three levels. Then the deployment details of the IOT system is introduced and the results obtained by the IOT system is introduced briefly.

From the practical deployment of IOT system for the pump stations we have learn important knowledge and practical problems in conducting such kind of systems. The sensor data and monitoring point association is a key problem which must be paid attention during system development. Data filtering and outliers detection are also important in practical systems. In future, we will conduct deep mining on the collected data from the system and research on the optimization of pump station based on the tracked system states.

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7. REFERENCES

[1] M. Abdelhafidh, M. Fourati, L. C. Fourati, and A. Chouaya. Internet of Things in Industry 4.0 Case Study : Fluid Distribution Monitoring System. In *Computer Science & Information Technology (CS & IT)*, pages 01–11. Academy & Industry Research Collaboration Center (AIRCC), Nov. 2017.

[2] B. Ao, Y. Wang, L. Yu, R. R. Brooks, and S. S. Iyengar. On precision bound of distributed fault-tolerant sensor fusion algorithms. *ACM Comput. Surv.*, 49(1):5:1–5:23, 2016.

[3] Chinadaily. Baotou Iron and Steel Group (Baotou Steel).

[4] M. Cieslak. Life cycle costs of pumping stations. *World Pumps*, 2008(505):30–33, Oct. 2008.

[5] H. Feng, Y. Wang, and J. Zhu. Multi-kernel learning based autonomous fault diagnosis for centrifugal pumps. *The 2018 International Conference on Control, Automation and Information Sciences*, 2018.

[6] M. Fourati, L. C. Fourati, and A. Chouaya. Internet of Things in Industry 4.0 Case Study: Fluid Distribution Monitoring System, 2017.

[7] N.-S. Hsu, C.-L. Huang, and C.-C. Wei. Intelligent real-time operation of a pumping station for an urban drainage system. *Journal of Hydrology*, 489:85–97, May 2013.

[8] M. Koor, A. Vassiljev, and T. Koppel. Optimization of pump efficiencies with different pumps characteristics working in parallel mode. *Advances in Engineering Software*, 101:69–76, Nov. 2016.

[9] Z. Lei, X. Ye, Y. Wang, D. Li, and J. Xu. Efficient online model adaptation by incremental simplex tableau. In *Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence, February 4-9, 2017, San Francisco, California, USA.*, pages 2161–2167, 2017.

[10] S. Mambretti and E. Orsi. Optimizing Pump Operations in Water Supply Networks Through Genetic Algorithms. *Journal of American Water Works Association*, 108(2):E119–E125, Feb. 2016.

[11] M. A. Moreno, P. A. Carrilő́n, P. Planells, J. F. Ortega, and J. M. Tarjuelo. Measurement and improvement of the energy efficiency at pumping stations. *Biosystems Engineering*, 98(4):479–486, Dec. 2007.

[12] W. S. Ngueya, J. Mellier, S. Ricard, J. Portal, and H. Aziza. Power efficiency optimization of charge pumps in embedded low voltage NOR flash memory. In *2017 IEEE Nordic Circuits and Systems Conference (NORCAS): NORCHIP and International Symposium of System-on-Chip (SoC)*, pages 1–5, Oct. 2017.

[13] Y. Wang, H. Feng, and X. Xi. Monitoring and autonomous control of beijing subway hvac system for energy sustainability. *Energy for Sustainable Development*, 39:1 – 12, 2017.

[14] M. Zarei, A. Mohammadian, and R. Ghasemi. Internet of things in industries: A survey for sustainable development. 10:419–442, Jan. 2016.