Smart City Application and Analysis: Real-Time Urban Drainage Monitoring by IoT sensors: A case study of Hong Kong

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Abstract – **Heavy downpours always bring trouble to Hong Kong during the rainy season. Severe rainfalls and flooding will delay the transportation, cause the loss of property or even kill lives. However, there is limited research that investigated the problems of the drainage system and stormwater management. Regarding the Internet of Things (IoT) development and successful example of IoT application, Hong Kong has the potential to become a smart city. The smart drainage system is one of the possible research directions. A prototype IoT system is decided with hardware and software. Experiments are conducted to collect the data. The data is then used to train the Artificial Neural Network. The analysis and predictive maintenance solutions are proposed to help the stormwater and drainage management. The results show that a well-trained algorithm can predict the drainage situations. The cross-validated results showed that it is reliable and able to predict most of the testing inputs. This paper aims at benefit to Hong Kong drainage service and the society.**

Keywords – **IoT, Artificial Neural Network, Smart City, Urban Drainage system, Sensor Application**

I. INTRODUCTION

Hong Kong is situated in the sub-tropical zone. The sub-tropical climate and tropical cyclone bring Hong Kong to heavy downpours during the rainy season. The average annual rainfall is about 2400 millimetres, one of the highest among the cities in the Pacific Rim. Heavy rainstorms also bring flooding troubles to low-lying rural areas and natural flood-plains in the northern part of the territory and parts of the older urban areas. Severe rainfalls and flooding threaten the residents' living conditions from disconnecting transportation, losses of the public, personal property and even lives. The typhoon causes destructions, flooding villages and uprooting trees to the cities. Hence, global warming is causing adverse effects on the planet, increasing average temperature, rising sea level, extreme weather events, etc. The climate change also brings significant problems to Hong Kong with higher rainfall intensity and rising sea level [1]. The rainfalls are generally increasing in Hong Kong, and the hourly rainfall record has been broken for several times. The urban areas even holding higher increasing trend of rainfalls than the countryside because of the urbanisation. It brooks no delay to handle the challenge of flood prevention and urban drainage reinforcement due to the climate change and the urban developments. Currently, Climate Ready has proposed "Hong Kong's Climate Action Plan 2030+", which suggested a smart, green and resilient (SGR) city strategy framework. It highlighted that the threats of climate change are pressing and listed the government's initiatives which have been processing to face the climate change such as Happy Valley underground Stormwater Storage Scheme, Kai Tak River revitalisation. It is required to consider the climate adaptation of Hong Kong and prevent Hong Kong from the major flooding issues [2].

The IoT has gained significant attention over the past decade [3]. The IoT systems are connecting sensors to the Internet and applying to efficient and effective resource management in Smart Cities. Today, infrastructure, platforms, and software applications are offered as services using cloud technologies. Hong Kong can refer foreign countries especially western countries' successful cases and build the smart city with IoT.

Therefore, this paper studies the real-time drainage system as a prototype of Smart City. The climate always brings Hong Kong with heavy rainstorms and serious problem of flooding, especially during the rainy season. Climate change and urbanisation even aggravate the flooding issues. It threatens residents from disconnecting transportation, losses of property and lives. This paper investigates the current drainage system. Few major problems are found and needed to be solved, including limited long-term improvement project, perpetually reinforcement of drainage, identically sensor for monitoring.

In addition, the paper reviews the current improvement measures of the drainage system. Afterwards, it pertains to develop an underground sensing system to collect environmental information by integrated sensor modules, such as water flow sensors and water level sensors with the Raspberry Pi small single-board computers to collect the data and monitor the system. The IoT concept was applied to construct an effective, real-time and smart drainage system in order to solve the above problems. Further analysis of sensors' data is conducted by Artificial Neural Network (ANN).

There are total four layers, including Perception layer, network layer, Internet layer and Application layer, combined as a prototype of the smart IoT application for Hong Kong's drainage system. The new technology and machine learning help to innovate and create the novel solution to the flooding problem in Hong Kong.

Experiments are set up to demonstrate this suggested system.

II. PROBLEM FORMULATION

A. Description of the problems of current scheme for distribution of rainfalls and current approach for flood surveillance in Hong Kong

There are several schemes which taken by Drainage Services Department (DSD) to resolve the flooding problems in Hong Kong [4]. The department has studied the flooding prevention strategy and the Drainage Master Plan (DMP) studies [5]. The studies covered eight major catchment areas and examined the suitability of current drainage systems for long-term improvement and fulfilling the standards. Implementation and improvement should be followed upon completion of the DMP study. DSD have constructed and operated four drainage tunnels namely Hong Kong West Drainage Tunnel, Lai Chi Kok Drainage Tunnel, Tsuen Wan Drainage Tunnel and Kai Tak Transfer Scheme, with a total length of about 20 km. Intakes, interceptions, and pumping were set up to help the stormwater delivery. The Drainage Tunnel can divert the stormwater from the upland area and discharge to the sea directly to prevent the flooding risk of the downstream urban area in the long-run. DSD also carried out the three stormwater storage schemes, including Tai Hang Tung stormwater storage tank, Sheung Wan Stormwater Storage Scheme, and Happy Valley Underground Stormwater Storage Scheme. The stormwater storage can temporarily store and share part of the stormwater runoff and control the flow rate of the downstream drainage system to relieve the burdens. The water will finally be discharged to the adjacent sea. The storage schemes can reduce the risk of flooding effectively. Although DSD proposed their projects to prevent the flooding problems of low-lying areas, it only serves distinct regions. Drainage tunnels and stormwater storage tanks can only collect water from adjacent areas. There are not enough tunnel and storage tanks to cover Hong Kong's boundary.

The urban areas have equipped with stormwater drainage systems during the urbanisation. Some old towns' drainage systems were built decades ago, such as Mong Kok and Sheung Wan. Modifications, improvement, and extensions had been made to drainage systems. The expansion of the urban area aggravated the risks of flooding. Thus, the current drains and pipes are no longer sufficient to meet the current flood protection standards. The low-lying areas will be plagued by the serious flooding during heavy downpours and high tide. Other than the master project, DSD is also conducting general reinforcement of drains regularly, including preventive maintenance programmes of inspection, desilting, and repair. The reinforcement can alleviate the deterioration of the drainage system. However, the maintenance programmes or regular checks can only be scheduled by the completion date of the drains but cannot indicate the distinct drainage or flooding blackspots. Further actions needed to be taken to deal with the flooding problems. The Hong Kong Observatory (HKO) will issue warnings on rainstorm and flooding based on the weather condition. These warnings include Rainstorm Warnings, Special Announcement on Flooding in the Northern New Territories and Storm Surge Information under Tropical Cyclones Warning Signals. Thus, the warnings can alert residents, and they can take appropriate precautionary measures. For drainage monitoring, DSD will conduct the closed-circuit television (CCTV) surveys for partly drains before rainy season since man-entry inspections are not possible. Thus, further work can be done by the CCTV surveys. Water level sensors have been applied to several areas. The flood warning systems have been installed in the flood-prone areas to inform the residents when the flood water reaches a predetermined alert level of the water level sensor. The system can alert them before flooding occurs and they can take precautionary measures. A Government report stated that the progressing Happy Valley Underground Stormwater Storage Scheme have installed the real-time water level sensor to monitor the water level of intakes and decide the necessity of opening the tank [6]. Moreover, Emergency and Storm Damage Organisation in DSS will monitor the water levels of major rivers and channels under the Flood Monitoring and Reporting System when there are emergencies.

Unfortunately, the HKO warnings can only remind Hong Kong residents generally. It cannot provide real-time checking of specific areas. Moreover, DSD only applies water level sensor in few major areas and stormwater storage tanks. Monitoring the underground environment is the key point to prevent and predict the possible accidents or drain blockages, it is necessary to have an underground sensing network to provide real-time monitoring drainage. Various and more type of sensors should apply to the drainage system to monitor the pipes condition or water flow conditions.

III. METHODOLOGY

A. System Architecture of the Drainage Monitoring System

In the aforementioned problems, we designed an IoT sensor network and propose a predictive maintenance strategy for the current drainage system in Hong Kong. It hopes to enhance the efficiency of flood handling.

The proposed system architecture and conceptual map of Real-Time Urban Drainage Monitoring (RTUDM) are presented in this chapter. Four layers are designed for this IoT model. The system architecture consists of perception layer, network layer, Internet layer and service layer. The real-time sensor's data can be transferred between these layers and be analysed by the RStudio to compute the predictive result. The IoT System is built to collect and transfer data.

Firstly, perception layer mainly focuses on data collection. Two sensors are set up in this simulated drainage system, including water flow sensor, water level sensor. They will output the signals to Raspberry Pi, which is common single-board computers for IoT development, with a solderless breadboard and other equipment. Python program is written to collect the instant data from the two sensors. The program helps the application layer to complete the major function of data collection and presentation. The Raspberry Pi and the sensors acted as a sensor hub, and it is connected to the nearby router or gateway by WiFi to transfer data. The setup procedures, programming libraries, and the logic will be introduced afterwards.

Secondly, the Network layer helps to communicate the Local Area Network (LAN) with Wide Area Network (WAN). As the sensor hub is located on the local network, the data should be sent out and gathered with other data. Routers are the network infrastructure device which directs packets through the computer networks [7]. The sensors' data can transfer through the path to the Internet. The WAN covers large geographical distances. Thus, the whole drainage network's data can be collected and be monitored. Practically, the municipal wireless network (citywide WiFi network), is constructing and going to cover the city. The sensor hub can fully apply the advantage and implement this smart city application.

Thirdly, Internet layer provides the cloud storage. This layer is responsible for receiving data information from the network layer and store into the database. The cloud platform performs the easy and quick storage of data [8]. Data can be grouped into the cloud and used for further analysis. For this project, Google Drive Application Programming Interface is called, and the sensor hub can send data through the network to the google spreadsheet. The real-time synchronisation can be embodied by the cloud technology.

Finally, the application layer performs the analytic function. This layer is also connected to the Internet to obtain the data. RStudio is the application which used to analyse the data. Some libraries are applied in the written R program. The important libraries include "gsheet" and "neuralnet". ANN is applied to solve the flooding and problems by indicating the drainage situation intelligently. This machine learning technique provides the predictive maintenance results. Officers of DSD can base on these results to give the corresponding strategy of handling.

These four layers, including perception layer, network layer, internet layer and application layer, combined as a prototype of the smart IoT application for Hong Kong's drainage system. The new technology and machine learning help to innovate and create the new solution to the flooding problem in Hong Kong. Experiments are set up to demonstrate this suggested system. **Fig. 1** shows the conceptual map of the newly designed IoT model for the urban drainage system.

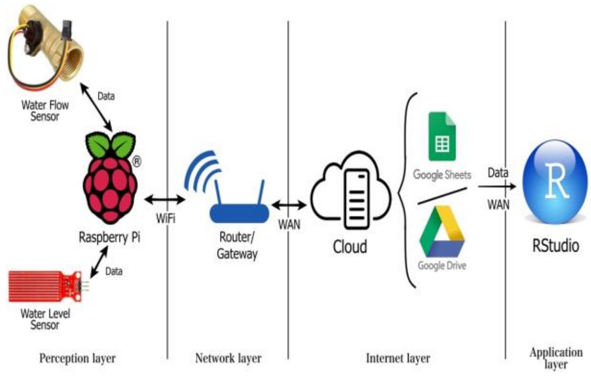

Fig. 1. The IoT model for the urban drainage system

B. Drainage situation analysis with ANN

ANN will be used as a tool to analyse the system data. ANN is a computational model to simulate the structure and functions of the human brain. It can change or learn based on that input and output. The artificial neural network is constructed by RStudio and R programming language in this research. The time series data, including FlowSensor.Data1 to FlowSensor.Data10, and discrete data, The time series data, including FlowSensor.Data1 to FlowSensor.Data10, and discrete data, including Total.Liters, Level.Sensor, Inflow, Difference, will be set as the input neurons.

According to **Fig. 2**, There will be total 14 input neurons in the input layer. The four situations Absorbent, Blockage, Cloggy and FreeFlow will be set as the output neurons in the output layer.Formula below shows that the outputs will follow the input data.

formula.bpn = Absorbent + Blockage + Cloggy + FreeFlow ~ FlowSensor.Data1 + FlowSensor.Data2 + FlowSensor.Data3 + FlowSensor.Data4 + FlowSensor.Data5 + FlowSensor.Data6 + FlowSensor.Data7 + FlowSensor.Data8 + FlowSensor.Data9 + FlowSensor.Data10 + Total.Liters + Level.Sensor + Inflow + Difference (1)

The setting of the hidden layer will also be introduced. The neural network will follow the logistic function as the activation function and sum of squared errors as the error function. It also follows the resilient backpropagation with weight backtracking. The resilient backpropagation can help to back propagated to all the neuron units, adjust the weights and improve the network performance after identifying the error of out nodes [9]. Regarding the outcome and analysis, predictive maintenance of flow control has been performed.

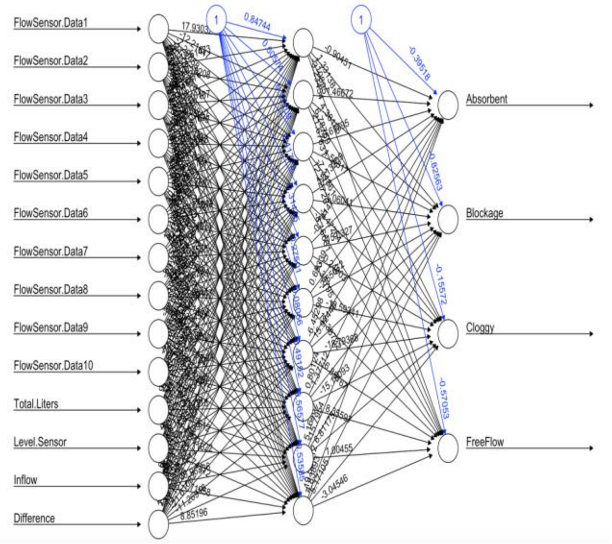

Fig. 2. ANN structure of the model

IV EXPERIMENT

These experiments aim at simulating the current Hong Kong Drainage System and collecting the results of different waste flow situations. It sets some of the hypothesis before experimenting assuming that the drainage is blocked before the data-driven sensor, assuming that another sensor is set up before the data-driven sensor and that sensor can collect the inflow data, assuming that no water is leaked out from the drains and no other factors affecting the experiment. By considering these hypotheses, it can conduct the experiments and locate the blocked point of the drains with the hardware and software.

Four situations are designed to be examined. Still, it is only considering the worst-case situation. If the mixture of blockage and absorbent, then it must be blockage. It is going to conduct the experiments with 100 trials for each of the situations. Totally 400 times of valid trials will be taken. The experiments are set following the setting of **Fig. 3**. Pipes with the diameter of 2cm, water flow sensor are interconnected. They are used to simulate the smart drainage system, and water is poured from the entry of the drain and delivered from the top to the bottom following the water flow direction which has been shown in **Fig. 3**. Water will pass through the water flow sensor and trigger the sensor readings. Water will finally flow out from the pipe and go into the cylinder plastic box. The cylinder plastic box with the diameter of 7 cm is simulating the stormwater storage tank of the current drainage system. The water level sensor can detect the water level and the water outflow. Data from the experiments will be captured.

Four possible drainage situations are introduced and illustrated below:

Free Flow: When the drain is unimpeded, which mean it is free from congestion and without obstacles, stormwater can go into the drain with at any time and any amount. The experiments are conducted in a normal setting as **Fig. 3**.

Blockage: When the drain is impeded, and there are solid obstacles inside the pipe (i.e., Plastic), water cannot pass through the obstacles, and the excess water will pour out and become the surcharge. The experiments setting is shown as **Fig. 4**. The small arrow illustrated the outflow directions of the surcharge.

Cloggy: Water can pass through the drain, and the drain is unimpeded originally. However, when sediments go into the drain, it begins to clog and jam the drain. The sediments will finally block the drain and water can no longer pass through the drain and water will pour out from the drain, as shown in **Fig. 4**. A tea bag is put inside the pipe and sand will be added together with water. The small arrow illustrated the outflow directions of the surcharge.

Absorbent: There are absorbents (i.e., Tissue, Cotton) inside the drain. When water delivers into the drain, water will be absorbed, pour out from the entry or flow out from the drain. The experiments are conducted as the setting in **Fig. 4**.

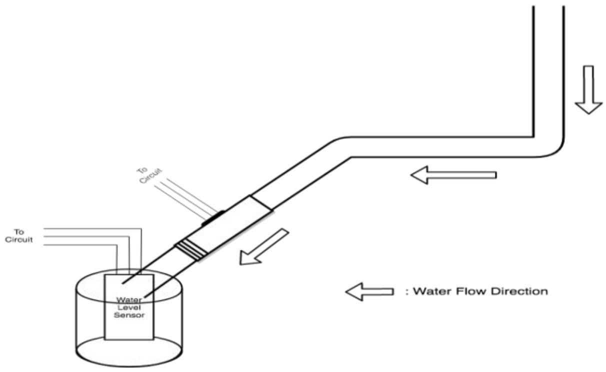

Fig. 3. Setting of the experiments

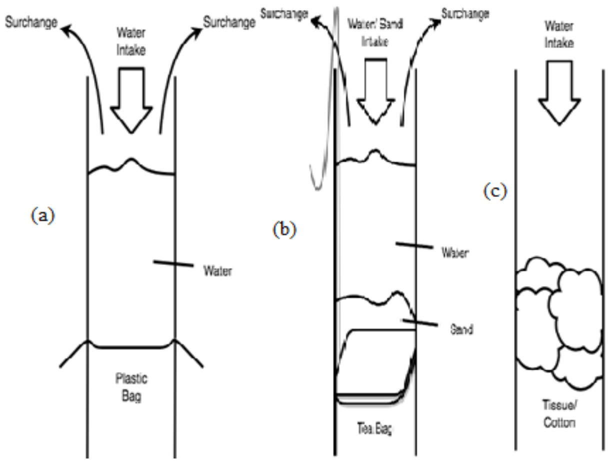

Fig. 4. Setting of blockage, cloggy and absorbent siutations

V. RESULTS

A. The ANN Results

100 results were collected for each situation. Totally 400 raw results were saved into google sheet and then imported into RStuido. After importing the data from

google sheet, ANN analysis is conducted. The results are followed. The default setting of the ANN includes ten hidden neurons in one hidden layer, and 80% of the data is used to train the ANN as shown in **Fig. 2**. There are 14 input nodes in the input layer. FlowSensor.Data1 to FlowSensor.Data10 are time series data inputs while Total. Liters, Level. Sensor, Inflow and Difference are discrete data input. There are four nodes on the output layer including Absorbent, Blockage, Cloggy and FreeFlow four situations. Ten hidden nodes are set in the hidden layer. The numbers above the black lines are the weighting of each node, and the blue line represent the bias. There are total 80 testing data was used to test the ANN. 79 situations have predicted. **Fig. 5** shows that one situation was wrongly predicted. 20 Absorbent, 23 Blockage, 15 Cloggy and 20 Freeflow situations are successfully predicted which same as the real situations given. The result of the simple test has 0.0125 error rate.

```
           predict
real         Absorbent Blockage Cloggy FreeFlow
  Absorbent 0       20        0      0        0
  Blockage  0        0       24      0        0
  Cloggy    1        0        0     15        0
  FreeFlow  0        0        0      0       20
> sum(test$Situation != pred.result$Situation)/sum(table)
[1] 0.0125
```

Fig. 5. The classification results

B. Cross-Validation Result

Cross-validation method is used to tune the parameter (i.e. number of neurons). The mean error rate of cross-validation is computed, and min test error is calculated for 1-15 number of hidden neurons. The test error against hidden neurons graph is shown in . The graph shows that the error is high when there is a small number of hidden neurons. The mean test error results are shown in **Fig. 6**. The results show that 7, 8, 9, 13, 15 number of hidden neurons can produce smallest error rate of 0.01. It is decided to use nine hidden neurons to build the ANN. The data have been derived into five folds. Artificial Neural Networks have been build using the cross-validation method. The test result of fold 1, fold 2, fold 3, fold 4, and fold 5 in ANN 1 to 5 are shown respectively, with the error rate of 0.0250, 0.0125, 0.0000, 0.0000 and 0.0125, and 0.1 error on average. Some of the error coming from unpredictable results and other coming from the wrong predictions. Most of the predictive results are equal to the real results. The system obtained total 99% accuracy.

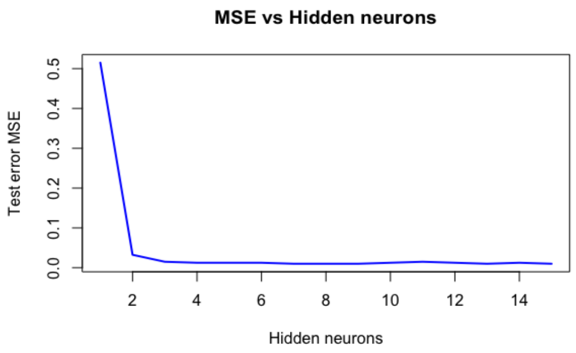

Fig. 6. Cross-validation error against the hidden neurons graph

VI. CONCLUSION

This project developed the prototype of the smart city drainage monitoring system in order to estimate the drainage situation. First, the Raspberry Pi will be connected with sensors and ADC. After the hardware setup, the software setup will be started. The operator will create the Google Sheet with different variables so that the data can be set to the spreadsheet. Then the Python program and R program will be written. After creating the programs, experiments can be conducted. Data will be collected. Finally, the data will be analysed and used to predict the results with ANN. The system included both hardware, software and setup of the prototype drainage network. They are used to simulate the smart drainage system. The sensors, Raspberry Pi and monitoring computer, are interconnected with the network. Therefore, the system can collect and analyse different data including the flow sensor and water level sensor data.

For the analysis, the result shows that the trained networks have average 0.1 error rate and conducting 99% accuracy by using cross-validation method. Therefore, the prototype model is reliable to provide the predictive solutions, and it gives the right results most of the time. Since the ANN is trained with both time series data and discrete data, the successful predictive results imply that the combined ANN is workable. It can be applied to the smart drainage management and predict the situation results from real-time data. The prototype drainage system is feasible to provide predictive maintenance solution for the flooding problem. The artificial neural network can detect the satiation of the drain by reviewing the data from the water flow sensor and water level sensor.

The system can be a reference for urban planning. Hong Kong DSD will cooperate will Hong Kong Development Bureau for urban planning. They need to decide the setting of the drainage system. By considering this application, the efficiency of the urban drainage system can be increased. DSD and the Development Bureau can reconsider the urban planning and drainage planning if the practical, smart drainage system is designed in further stage. Moreover, the prototype drainage system can be a foundation for optimising the urban drainage system. IoT and smart city are trends of current technology [9]. The newly designed IoT system is able to optimize the drainage system by real-time monitoring solutions. It also fills the research gap of the drainage system and helps to face the stormwater management challenge of Hong Kong [10].

The application of the smart drainage system can help to handle the emergent situations instantaneously. There are the different situations regarding flooding problem. In current practices, the DSD will be noticed by the public with the flooding problem. The new system can automatically detect the situations and DSD can take instant action to handle the problem. Suggestions can also be given following the analysis and classifications.

ACKNOWLEDGEMENT

The research is supported by The Hong Kong Polytechnic University. The authors would like to thank the Research Committee and the Department of Industrial and Systems Engineering of the Hong Kong Polytechnic University for support of this project.

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