A Cyber Physical Networking System for Monitoring and Cleaning up Blue-green Algae Blooms with Agile Sensor and Actuator Control Mechanism on Lake Tai

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***Abstract* – Nowadays, the harmful blue-green algae blooms on lakes threaten the daily life of millions of people in China. We designed and developed a cyber physical networking system on Lake Tai for the monitoring and cleanup of the water blooms which is at work in Wuxi City, Jiangsu Province. We designed the sensor device and algorithm to monitor the order of severity of algae bloom. A GIS-based management website is built for the end user to monitor the whole system. In this paper, we focus on the agile sensor and actuator control (ASAC) mechanism to dispatch salvaging boats. The location area and the order of severity of a water bloom change rapidly with the climatic, the terrain and the sewage disposal system. The location and the capacity of salvaging boat are also in changing when the system is running. ASAC is designed to generate optimal dispatch plan in the changing environment. This mechanism also balances workloads among the boats and among the algae factories to achieve an overall high working efficiency. Through the tests in the real system, ASAC largely saved human resource and increased the work efficiency in the cleaning up process.**

I. INTRODUCTION

Blue-green algae can become very abundant in warm, shallow, undisturbed surface water that receives a lot of sunlight. When this occurs, they can form a surface water bloom that discolors the water and naturally produces toxins that attack the liver, nervous system or the skin as shown in Fig.1. In May 2007, Lake Tai, China's third-largest freshwater lake was overtaken by the algae bloom. The rendered water is undrinkable for about 10 days, which affects more than one million residents in Wuxi City, Jiangsu Province. Recently, the serious blooms of blue-green algae also occur in many other lakes and streams in the world.

Fig.1. Blue-green algae and the water blooms

The class of algae can be well detected in laboratory using DNA/RNA Biosensor [1] and laser fluoro-sensor [2]. But the lab analyzers can hardly be applied in the real monitoring and clean-up system because of high requirement for the experiment conditions and long detection time. Online blue-green algae sensing device [3][4] is widely used for the measurement of total chlorophyll, pycocyanin and phycoerythrin. But these parameters can not accurately alert the degree and location of the blooms because the degree and location of blooms change with the temperature, wind and water stream. Therefore the changing environment makes it difficult to get the accurate monitoring result in real-time. To clean up the water bloom, the local government has built a fleet with about one hundred salvaging boats. Eight blue-green harvesting factories have been built to dehydrate and reuse the water blooms. The control mechanism for dispatching boats to do the clean-up job is a bottleneck in the whole system, because the states of the system units, such as the locations of the salvaging boats and the capacity to store the blue-green algae in the harvesting factory, are also changing dynamically.

Recent research works [5-7] have shown the abilities to reconfigure the parameters of sensors according to the changing environment. Usually, the control mechanism in these papers maintains its state based on the data obtained from the sensors and configures the remote devices with parameters that satisfy a constraint optimization problem derived from the current system state and the requirements of users. However, we identify two problems in these works: firstly, the actuators are seldom considered together with the reconfiguration of sensors. Actually, the actions of actuators generate large influence in many cyber physical systems. Secondly, the fidelity of the sensing data or the interesting event changes rapidly in some systems. The time delay between the event detection and the decision often leads to the non-optimal schedule plan.

In this work, we build a monitoring and self-driven cleanup system for blue-green algae blooms on Lake Tai, which physically consists of 11 sensing stations, 31 salvaging boats and 8 algae harvesting factories. The goal of this system is to: (1) monitor the occurrences of blue-green algae water blooms and estimate the order of severity of water bloom. (2) Automatically dispatch the salvaging boats to clear off the algae scrums according to the agile sensing and actuator control mechanism. The system also sends the source water with algae to the algae harvesting factory and then produces the natural organic fertilizer with the dry algae. This system is now serving the daily work of Wuxi Municipal Water Conservancy Bureau and largely saves manpower used in monitoring and cleaning up algae blooms.

Our contributions are two-folds: 1) we develop the water blooms estimation device, the main control box of sensing station, the location and communication device on the salvaging boat. The real running system is completely

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automatic. 2) We design an agile sensing and actuator control mechanism (ASAC) which can catch the changes of the target event and the action of the actuators before the schedule plan is generated. Then ASAC generates the optimal dispatch solution for salvaging boats using programming approach.

The reminder of this paper is organized as follows: in Section II, we discuss the related work. Section III presents the architecture, design and deployment of the system on Taihu Lake. In Section IV, we detail the design and implementation of ADAC. The performance of the real system is shown in Section V. Finally, we conclude in section VI.

II. RELATED WORK

Recent works focus on the adaptive sampling are the significant steps in the direction to build an agile cyber physical networking system. The Glacsweb system [5], deployed motes to collect the environmental data related to glaciers which it transmits to the server so that the data can be used by the scientists. The sensors use a Bayesian linear model to forecast values and decide the next sample time based on the estimated information gain of these values. Lance [6] introduced utility-based controllers, which focus on the cost of download of each data unit in the context of data acquisition. Values and costs are taken into account to determine download scores. Not all the data acquired by the users can be transmitted to the base station. In [7], the authors proposed ADAE, a utility-based controller that adaptively configures motes in a changing environment. ADAE presents three-tier architecture to organize the complexity of communicating with motes, representing the sensor network state and the user requirements, generating constraint optimization problems to determine the configuration parameters. However, these works do not consider the sensors and actuators together. The reconfiguration plan is made according to the dynamic events and the user's requirements without considerations in the dynamic state of the whole autonomous system.

III. SYSTEM DESIGN AND IMPLEMENTATION

The system architecture is shown in Fig. 2. Our system is composed of four main parts: (1) the blue-green algae water blooms estimation device and algorithm, (2) the sensing station built in and along Lake Tai, (3) The self-driven algae cleanup subsystem using salvaging boats and algae harvesting factory and (4) the GIS-based management website. The several kinds of sensing data and the location information of the salvaging boats are transmitted through 3G mobile network. The information center stores and analyzes the received data. When bloom area goes beyond the threshold, a dispatching schedule of the salvaging boats (also called as cleanup schedule) is generated. The navigating commands are sent to the target boats immediately and the algae harvesting factory is informed to prepare the capacity for the forthcoming water with blooms.

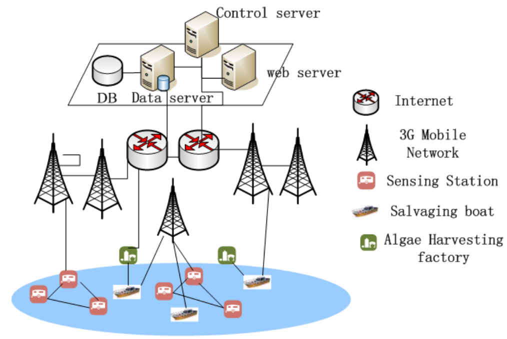

Fig.2. The system architecture

A. Water Bloom Estimation

We design a device for the water bloom estimation. This device consists of a camera and an ARM-based control board. The camera is operated by the control board to capture the image of the water surface periodically. The control board analyses these images.

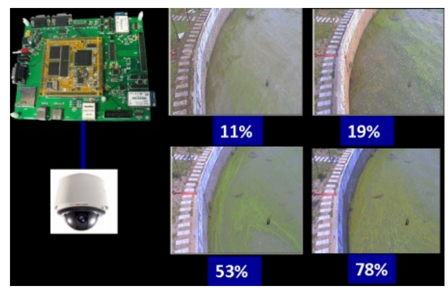

Fig.3. The estimation device and the algorithm result for water blooms

An algorithm is designed to estimate the area of the water bloom considering the color and texture. The statistical color feature and texture feature of blue-green algae is analyzed. The identified pixel is regarded as part of the water blooms. We give the result in percentage to explain the relative area of water blooms in the water. The typical result is shown in Fig.3.

B. Sensing Station

The system has two kinds of sensing station: the first kind is built in the water as shown in the left of Fig.4. It consists of four major components: (1) the digital camera with 22x optical zoom for the water bloom estimation; (2) the solar cell and the storage battery; (3) the multiple-parameter water sondes and (4) the main control box. The second kind of sensing station is built on the shore as shown in the right of Fig.4. This kind does not have the multiple-parameter water sondes.

Fig. 4. The sensing station in the water and on the shore of Lake Tai

The main task of the sensing station is to capture the image of water surface and monitoring the water parameters. The data is sent back through the 3G network. The embedded program in the control board can be updated remotely. So we can change the monitor schedule according to the user's requirement.

C. Control Subsystem for Algae Cleanup and Recycling

The algae salvaging boat is widely used in the Lake Tai in recent years. However, the job of dispatching these boats is finished manually. We equipped the boat with a location and communication device which has a GPS module and a CDMA2000 module. So the location data of the boats can be collected, and meanwhile the navigation instruments can be sent to the boat by SMS or real-time Voice. The sailors are trained to follow the instructions from the command center and communicate with each other when necessary. When a sensing station finds that bloom area goes beyond the threshold, a dispatching schedule module is triggered. The design of this module is discussed in Section IV.

Fig. 5. The salvaging boat for blue-green algae water blooms; the location and communication device on the boat

The system also adaptively controls the recycling process of algae. When the salvaging boats are sent out, the enough capacity is reserved in appointed algae harvesting factory. There are 8 factories in our system. We monitor the real-time facility's occupancy rates of every factory and balance the workload among them. After the dry algae are produced, they are sent to the fertilizer plant as the raw material of the natural organic fertilizer.

D. GIS-based Management Website

We develop a GIS-based management website for the end user to monitor the running of the whole system. All the sensing stations, the cleanup schedule generated, the algae harvesting factory and the salvaging boats are displayed in the map. The real-time sensing data, the location information of boats and the video stream from the camera can be queried from the webpage. We also provide the data analyzing and reporting module in this website.

IV. ASAC: Agile Sensing and Actuator Control Mechanism

ASAC faces two challenges in design of the cyber physical networking system on the Lake Tai.

First, the dynamic changes of the water bloom often lead to a failed schedule plan of the salvaging boats. The location, area and the order of severity of a water blooms changes rapidly with the climatic, the terrain and the sewage disposal system.

Second, the system state is changing with the clean-up process runs. Every boat is moving on the Lake and the produce state of the algae harvesting factory is also changing timely. To generate an optimal schedule solution for a clean-up case of water blooms, the optimizing algorithm should know the current state of the event and the system state.

In this section, we discuss the design of ASAC. Three main parts are detailed: the system models, the architecture of the control mechanism and the optimizing method.

A. Models

In this subsection，We introduce the three models used in the ASAC control mechanism.

Firstly, we need an event model to describe the happening of a water bloom. The model should directly tell the order of severity of the water bloom of blue-green algae. According to the suggestions of the salvors on boats, we evaluated the water bloom event as follows:

$$W = (L_w, A_w, D_w, S_w)$$

Where a running water bloom event of the blue-green algae is consisted of four parts: L_w is the GPS locations of the sensor which discover the happening of the water bloom; A_w is the area of the water bloom on the water surface; D_w is the depth of the water bloom and S_w the order of severity of the water bloom. Unusually, S_w is an estimated value normalized in $[0,1]$, which is provided by the sensor directly.

Secondly, the clean-up job of the blue-green algae is mainly finished by the salvaging boats. One of the schedule tasks of the control mechanism is to guide the boats to clean the water blooms with minimum cost. So we define the boat's model as follows:

$$b = (L_b, V_b, C_b, S_b, P_b, B_b)$$

Where a working boat is defined as a 6-tuple: L_b is the GPS location information which is gotten from the GPS device installed on the boat; V_b is the sail speed of the boat; C_b is the left capacity of the boat to store the water blooms. S_b is the salvaging speed of the boat; P_b is the cost of the running boat per hour which is consisted of two parts, the human resource cost and the energy cost. B_b is a Boolean variable to indicate if the boats are free for schedule.

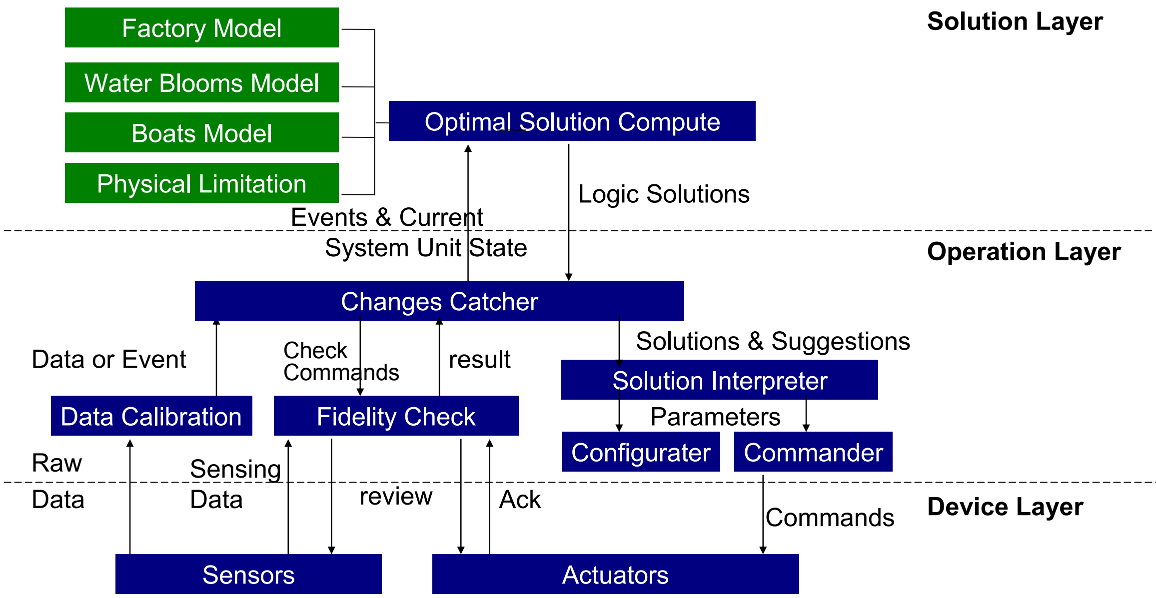

Fig. 6 The architecture of ASAC

Thirdly, in order to destroy and reuse the water blooms, all the water blooms in the liquid form should be dehydrated in the algae harvesting factory. Government has built eight factories around the Taihu Lake. Every Factory has its maximum harvesting capability. To keep the clean-up workflow running smoothly, ASAC should consider where the full salvaging boats are going to unload the water blooms. We define the harvesting factory model as follows:

$$F = (L_F, V_F, C_F)$$

Where a harvesting factory is defined in three parts: L_F is the GPS locations of the factory; V_F is the dehydrating speed of the factory; C_F is the left capacity of the factory.

Finally, we assume that the events of water bloom happen in sequence. The sensors can finish the sampling, storing and transmitting task itself. All the sensors have the same sample rate. The server running the control algorithm can communicate with any sensor at any time to read the sensor for the real-time sample value. These assumptions are also the real situations in Smartlake.

B. Control Mechanism

As shown in Fig. 6, ASAC is divided into three layers:

The device layer contains the sensors and actuators which can report data and receive the commands from different upper modules.

The operation layer checks the raw sensing data, the fidelity of the sensors and actuators, and the changes of the environment and system state. When the new water blooms are identified and confirmed, the event and all the state of the system units are passed to the solution layer. After the logic solution is passed down, the operation layer analyzes the solution and generates the configure parameters for the sensors and the commands for the actuators. The critical module in this layer is the changes catcher module (CCM) which is designed for the dynamic environment.

The solution layer gets the data and system state from the lower layer and uses the programming method to generate the optimal solution. The system models are employed by the generator and the physical limits is considered in the programming approaches.

The raw data is collected by the sensors and transmitted to the Data Calibration modules in the operation layers. After the calibration, the data is sent to the Changes Catcher modules. CCM uses the fidelity modules to check the events and the system state. For the events, the fidelity module cares about changes of water blooms in attributes of the area, locations and so on. For the system states, the changes of models of boats and the factories is collected by the real-time query to the remote units. In the purpose of generally applying, CCM can use different check methods for different events and systems. The check rules are regarded as a plug-in software in the implementation. Considering rapid dynamic changes of the water blooms events and the mobile characters of the boats, the reviewing period of CCM is set to be very short. Since the optimal solutions generator takes time to get the result, a call-back review process is arranged for the specific system, which means the CCM will check the changes again after a candidates schedule plan is generated and this plan will be canceled if the changes is considered to be big. For example, in the real system, when the areas of the water blooms become bigger, more boats are needed. The solution with less boat will be canceled. When a boat which is moving more near than the one in the candidate plan appears, the optimal solution generator should be called again. We set a maximum reaction time for the generator and CCM to avoid the endless-loop between them when the changes is too frequency. Once the reaction timer fires, the CCM should pass the current solution to the next modules and meanwhile CCM will generate a new suggestion for the sensors to adjust the monitoring parameters such as the sampling rate or the threshold for the event detection. CCM also record the time between the two fires of reaction timer. If the length is beyond the threshold, the suggestion in negative direction will be generated.

When the logic solution and the suggestions are passed to the interpreter, the solution and suggestions are analyzed into the new configuration parameters for sensors and the new commands for the actuators. In the system on Lake Tai, the sensors can be reconfigured remotely. The commands are sent to the communication device on the boats. The drivers are suggested to follow these guiding messages.

C. Optimizing Method

The optimal solution generator is designed to use different programming solvers in the plug-in form. The requirement of final users can be formulated to different optimizing problems. Usually, the linear programming and integer linear programming problem is preferred because of the low computing complexity and many well-built solvers.

In the SmartLake system, the optimizing target changes according to the season, because the water blooms of blue-green algae often lead to the water crisis in the summer and autumn, but the situation is relatively secure in the winter and spring. Therefore, we designed four seasonal optimal solution generator for the system.

For example, the solution for winter and spring is to minimizing the clean-up cost. the optimizing target is the total cost of the solution for the clean-up process of water bloom. The constrains should include：1) the boats with enough free capacity should be sent to solve this event. 2) the order of severity of water blooms should beyond the preset threshold. There are also others constrains according to the real system situations, such as the workload and the work-time constrains for the boat and workers.

V. PERFORMANCE OF REAL SYSTEM

The real system ran on the Lake Tai in Wuxi City, Jiangsu Province since the June 2010. This system is part of the whole environment conservation system of Lake Tai supported by Wuxi Municipal Water Conservancy Bureau. The performance of the real system is demonstrated in two parts.

A. The Performance of Monitoring

Usually, sensors on the lake report the data every 10 minutes. The sampling rate is updated according to situation of growth of blue-green algae. A small number of data packets lost in the transition process. The Figure 7 shows the typical changes of the monitoring of a day in the summer. Water blooms occur with possibility in the 12:00 to 14:00 in a day because the strong sunlight leads to the high water temperature. The waters around the LABAKOU monitoring station is more likely to suffer the water blooms than the water around the GUHUSHUICHANG monitoring station, because LABAKOU lies in the quite bay with less water flow.

Figure 8&9 show the daily average value and the maximum value collected by these two stations. The water blooms occurs with high possibility in the hottest days from he late t August to the early September. We can also conclude that GUHUSHUICHANG area has a better water quality.

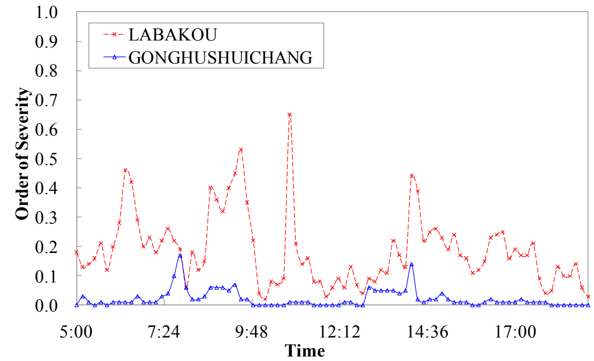

Fig. 7. The monitoring data of on 31/7/2010

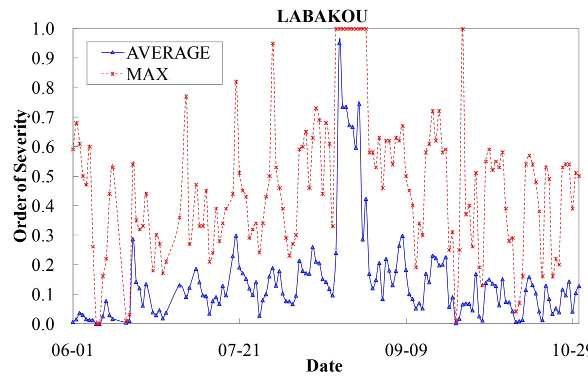

Fig. 8. The monitoring data from 1/6/2010 to 29/10/2010 on the monitoring station of LABAKOU

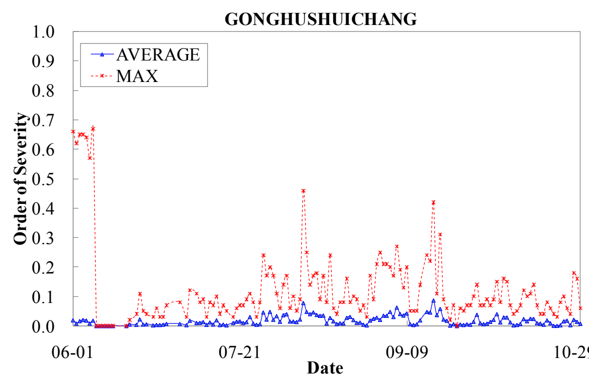

Fig. 9. The monitoring data from 1/6/2010 to 29/10/2010 on the monitoring station of GONGHUSHUICHANG

B. The Performance of ASAC

TABLE I
THE NUMBER OF CALLS BY ASAC

Model / Boats	ASAC Call	
	19/9/2010	20/9/2010
Boat009	49	25
Boat057	2	4
Boat043	51	34
Boat072	38	30

In the early phase from June to August, the system ran without the ASAC autonomous control subsystem. The schedule plan is generated by the officer manually in the monitoring center. The manual schedule is a preset plan. It divided the Lake Tai into areas which has prearranged boats works in. These boats are responsible for the cleaning job in this area. The officer will call the boats in other area to help the busy area only when he realize that the water blooms is hard to clear off by the local boats. So the work efficiency of the clean-up system is highly depending on the human experience and the workload is unbalanced between boats.

We tested the ASAC in several days The schedule calls of four boats is listed in Table I. ASAC largely saved human resource and increased the work efficiency in the cleaning up process. To keep the whole system work steadily, the government planned to use ASAC to reduce the manual intervention gradually this year.

VI. CONCLUSIONS

In this paper, we present the cyber physical networking system to monitor and automatically clean up water blooms on Lake Tai. The system detects the occurrence of the blue-green algae water blooms and dispatch salvaging boats based on the ASAC mechanism. Facing the changing environment, ASAC checks the changes of events and the system state in an adaptive way. Then ASAC generates the optimal dispatch plan using programming approach and confirm the reconfiguration and the commands are executed by the sensors and actuators. The performance is tested in the real system. In the future, we will attempt to improve the interaction between the devices and the control mechanism. The intelligent algorithm for self-update and self-repair should be investigated.

ACKNOWLEDGMENT

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