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An Intelligent Environmental Monitoring System Based on Autonomous Mobile Robot

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***Abstract*— Monitoring indoor environmental state of large communication rooms, warehouses and power stations is an important task. Based on mobile robotics, we have developed an intelligent environmental monitoring system. In this system, a mobile robot carrying a number of sensors autonomously navigates and dynamically sample the environmental data including the temperature, humidity and airflow velocity. The system outputs the environmental parameters in appropriate modes such as clouds. In this paper, we present the development of this monitoring system, its working principle and application effectiveness. It has been shown how a mobile robot can be used to as a novel application in industry environments.**

***Index Terms*— Environmental monitoring, Mobile robot, Autonomous navigation, Environmental cloud, Visual slice analysis**

I. Introduction

In the past decades, great progress in robotics has been achieved. With the development of mobile robots, they are widely used in indoor and outdoor environments for home and social services, surveillance, monitoring, exploring resources, rescuing, anti-territory and so on [1], [2], [3], [4]. Mobile robots can be used as fundamental data gathering tools to monitor environmental conditions [5], [6], [7]. Example applications include indoor monitoring (e.g., large communication rooms, warehouses, power stations, computer barns and so on) and outdoor monitoring (e.g., tracking water surface blooms and pollution spread, building gas concentrate gridmaps [8], [9], [10], ocean floor sampling, volcanoes activities and so on). The system proposed in this paper aims to resolve some issues of indoor environmental monitoring.

Master control and relay stations are core areas for telecommunication networks, and most sensitive communication devices must run under strict environment conditions in order to ensure communication reliability and safety. It is necessary to monitor strictly environmental parameters such as temperature, humidity, airflow velocity and the like. The areas of large communication stations (refer to Fig. 1(a)) are usually several hundred square meters and even up to thousand square meters. Similar environments are warehouses, power stations, computer barns and automation workshops (see Fig. 1(b),(c),(d)). The monitoring task for them is usually completed by manual methods or semi-autonomous methods (e.g., Trolley in Fig. 2(a)). The operator utilizes trolley equipped with sensors to collect environmental parameters, and records the data in a laptop or a desktop computer. The manual method has the following shortcoming:

- Tedious collecting and analysis process, low efficiency, and high time-consumption and labor-consumption.
- Lacking of adaptation to some special or hazard environments. For example, some environments are sealed and filled with nitrogen (to ensure stable operation

(a) Communication rm

(b) Warehouse

(c) Power station

(d) Auto-workshop

Fig. 1. Some typical indoor environments to be monitored

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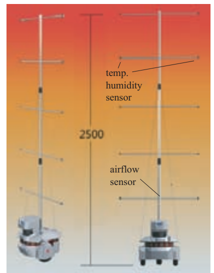
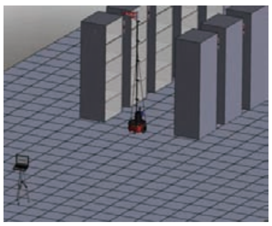
(a) Trolley

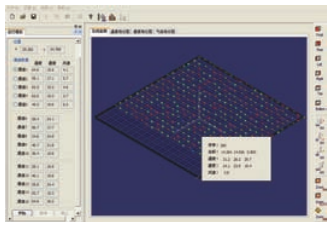
(b) Our system



(c) Sensor layout



(d) Work scene



(e) The post-processing system

Fig. 2. Environmental monitoring systems: (a) A manual monitoring system, (b)-(d) our system, its layout and GUI.

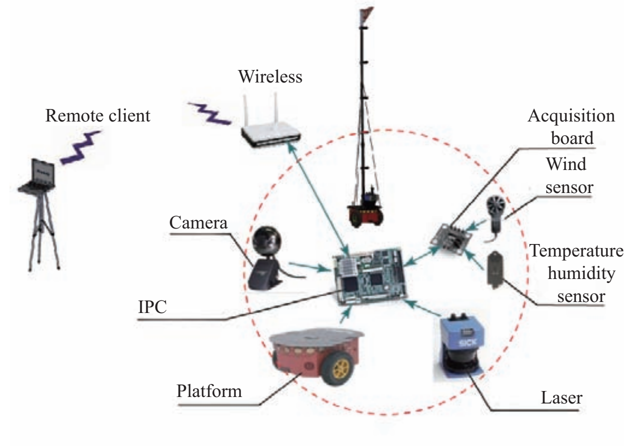


Fig. 3. The components of whole system

of important devices), and not suitable for human to access.

- The monitoring results may be affected by human factors.

To overcome the above drawbacks, we have built an intelligent monitoring system based on mobile robot (Fig. 2(a)). Mobile robots have been applied to various fields owing to their flexibility and autonomy. Their applications in intelligent monitoring become increasingly attractive [4], [5], [6]. Some corporations such as IBM and HP begin to develop their own monitoring systems. However, at present there are no general productions in the market. The system presented in this paper has strong versatility with a number of novel features, as will be stated below. It can be applied to monitor conditions for safety in various indoor environments.

II. System Development

As stated above, the development of our environmental monitoring system aims to improve monitoring efficiency during the process of collecting environmental parameters in large indoor spaces. In this section, we present the whole system including its components, control mode and software architecture, and features as well. The working principle and the post-processing system will be stated in the next section.

A. The System Components

A mobile robot, Pioneer 3-DX from MobileRobots, is employed as the main platform for carrying other components including an industrial personal computer (IPC), a laser range finder, a camera, various sensors for capturing the environmental parameters, and communication devices. The task of the robot is to fulfill the locomotion (navigation) of the whole system. The IPC is installed inside the robot, and communicates with the robot controller through USB2.0. It processes various navigation data and transports sensing data by communicating with the remote host computer. A SICK LMS-200 is employed as the laser ranger finder to implement localization, mapping, and autonomous navigation. It is mounted on the top board of the mobile robot, and also communicates with the IPC through USB2.0. A camera is mounted on the top of the SICK for monitoring the scenario when the robot is navigating. All sensors for measuring environmental parameters (currently 15 temperature and humidity sensors and 5 airflow velocity sensors) are distributed and fixed on a steel frame consisting of five horizontal rods and a vertical pole (see Fig. 2(c)). The interval between the horizontal rods is usually set to be 250 mm (may be adjusted easily as needs). Composing of three segments like one leg of a camera tripod, the vertical pole may shrink or extend. It is mounted on the deck of the mobile robot to support the sensor frame. The frame can be easily assembled or disassembled, bring convenience to the delivery of the monitoring system. The hardware of the system consisting of the above components are shown in Fig. 3.

B. The System Control Mode

The system adopts client/sever (C/S) mode. The robot acts as the server, the IPC and the remote monitor compose the client. The robot is an independent self-governing system, which communicates with the remote monitor through a wireless network. The advantages of C/S mode consist in that as server system, different robots can execute the same client software, and also different users can run different tasks on the same robot. These advantages will help system extension in the future.

C. The Software Architecture

From top to bottom, the whole software system can be divided into three layers. At the top layer, the remote client

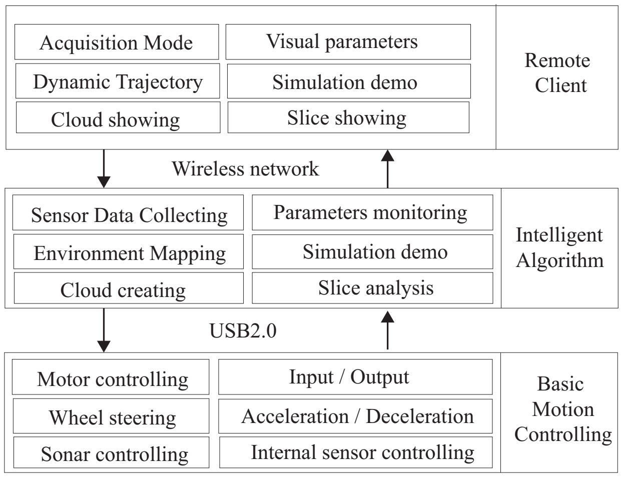


Fig. 4. Software system architecture.

communicates with the middle layer through a wireless network, sends acquisition commands to the IPC, receives sensing data, and online demonstrates trajectory in 3D virtual space. A user can monitor environmental conditions at any position. It builds parameter clouds, detects changes of some regions visually by analyzing slice. Also it is capable of simulating data processing. The middle layer implements intelligent algorithms, being responsible for complex tasks such as navigation, localization, mapping, data collection, and communication. The bottom layer is responsible for basic motion control and sensor signal processing. The architecture is shown in Fig. 4.

D. Features and Functions

Consisting of above components and with the architecture, the monitoring system has the following features and functions:

- *Autonomous Navigation*: The system can move autonomously in various known or unknown indoor environments avoiding obstacles, conduct localization and mapping. According to demands, it can also define routes and measuring points, and then run along the pre-defined path.
- *Environment Monitoring*: While the robot navigates autonomously, the system transports 3-D environmental parameters and its state to the remote client real-time through a wireless network. At the same time the monitoring points will be displayed online. Different environmental conditions are represented by different colors. Users can monitor dynamic environmental conditions in 3-D virtual view (see Fig. 2(d)), analyze temperature cloud, humidity cloud, and airflow velocity cloud, and perform slice analysis.
- *Cloud Creating and Slice Analysis*: The cloud software receives monitoring data from the remote server, and create environment clouds. The distribution maps of environmental conditions are created after the monitoring process ends, which include temperature cloud, humidity cloud, and airflow velocity cloud. The distribution of each environment condition is represented by five layer clouds. Different areas are shown with different colors (e.g, the green represents low value and the red represents high value). Slice analysis is an intuitive approach. The user can slice the virtual 3-D space to analyze changes in environmental conditions. After observation mode and the section depth are set, the user can analyze the distribution of parameters in contiguous zone visually.
- *Visual View*: In addition to perception of above environment parameters, the camera mounted on the robot deck can capture environment video for remote user. The video will be stored in the robot and transported to remote monitoring client.
- *The Others*: light system, easy assembly/disassembly, and easy delivery.

III. Working Principle

A. Localization and Mapping

Simultaneous localization and mapping (SLAM) [11], [12], [13] is an important capability for system navigation. Although it is desired in many scenarios, it will affect efficiency of monitoring and processing in practical applications, since it consumes much time in extracting feature and associating data [14], [15]. In this paper, the purpose of our system is to monitor environment effectively, not on the issue of SLAM. In order to meet the needs of practical applications, and the IPC has sufficient resources to process environmental data, the system adopts off-line mapping. The system will first store the scanned data (with scan resolution of 0.5^0, range of 180^0). After scanning stops, it computes the stored data by the following formulas:

$$P = T * O, \tag{1}$$

given the rotation matrix T and the observation data O, to obtain the coordinate P of the scanned data in the global coordinate system. Many algorithms can be used for mapping. In our system, IPF (iterative point fitting) [16] algorithm is adopted to extract features owing to its efficiency. IPF is an iterative method, described as follows. For points in an area $A_s(p_a, \cdots, p_e)$, a line L_i is created between the first point $p_a(x_a, y_a)$ and the last one $p_e(x_e, y_e)$, and then the max Euclidean distance D_{max} from other points $p_k(x_k, y_k)$ to L_i is calculated in turn. Given a dynamic threshold D_f (may be adjusted to 0.15*L_i), if the following condition is satisfied,

$$D_{max} > D_f \tag{2}$$

then the area A_s is divided into two areas: $A_{s1}(p_a, \cdots, p_k)$ and $A_{s2}(p_k, \cdots, p_e)$. The interactive procedure continues until the above condition is not satisfied. In experiments, the environment is represented by geometry map, which mainly include coordinates of points and lines. Internal odometer and electronic compass are used to infer location. The system moves along a pre-defined path. If it meets obstacles, the

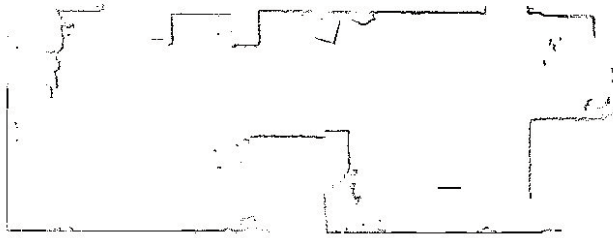


Fig. 5. Environment map

local path will be adjusted autonomously. Fig.5 is an example of environmental maps obtained by the robot in experiments.

B. Data Collecting

Gathering module consists of three parts, namely sensors, data converter and data collector. While robot begins to navigate autonomously, IPC sends request commands to capture card by distance interval or by time interval (not be less than 1s), and then the capture card transports sensor data to IPC (Fig. 6(a)). The robot motion will affect sensing airflow velocity of the environment, so the system stops for a few seconds to collect the airflow velocity data. The location of a collecting point is calculated by following formulas:

$$c_x = x + 0.5 * l * sina, \quad (3)$$

$$c_y = y - 0.5 * l * cosa, \quad (4)$$

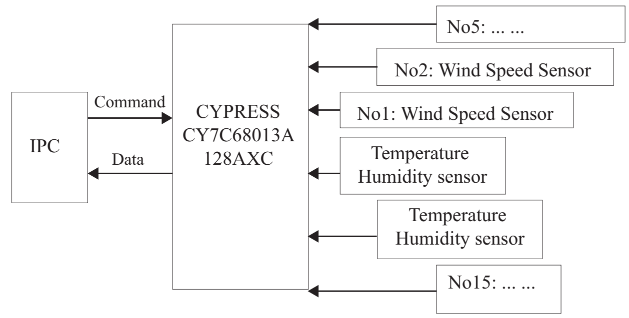
$$c_z = z_j, \quad (5)$$

where (c_x, c_y, c_z) is the location of collecting point, (x, y) is the robot current position, a is the robot current direction, l is the length of rod and z_j is height. The formatted data are vectors in the form of $[x, y, a, L_j, T_j, H_j, M_j, \cdots, L_{16}, A_{16}, \cdots, L_i, A_i, \cdots, L_{20}, A_{20}]$, where L_j is the position of the j-th temperature sensor, T_j is the corresponding sensed value, H_j is the position of the j-th humidity sensor (integrated with the temperature sensor), M_j is the corresponding sensed value, L_i is the position of the i-th airflow sensor, and A_i is the corresponding sensed value. The formatted data are transported to the post-processing system. Fig. 6(b) shows the data flows of the whole monitoring system.

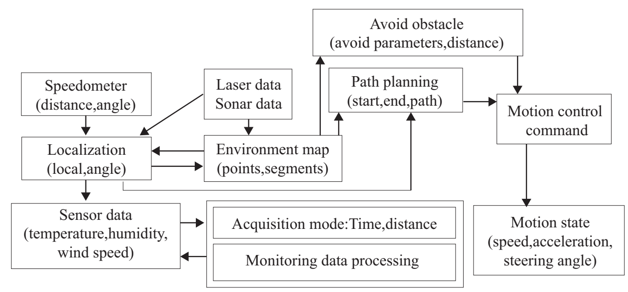
C. Post-processing System

A post-processing system is developed to be responsible for receiving monitoring data from the robot through a wireless network and providing visual analysis. It has three work modes, namely online monitoring, offline analysis and demonstration.

- *Online Monitoring*: An operator can edit the 3-D virtual space (e.g., the coordinate origin, space size and grid size), adjust color table, edit Z-depth, choose data-collecting mode. The system dynamically displays the monitoring data. By the visual data, it is easy to obtain motion trajectory and environment conditions at any points. Different colors represent different environmental conditions (Fig. 2(d)).



(a) Sensor data flow



(b) Data flow of monitoring system

Fig. 6. Data flows of the whole monitoring system

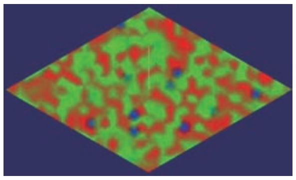
- *Offline Analysis*: In this mode, the operator can analyze the monitoring data by visual methods, create clouds of temperature, humidity and airflow velocity. The distribution maps M^e is related to robot trajectory R^t and sensor measurement O^t, by following formula:

$$M^e = F(R^t, O^t), \quad (6)$$

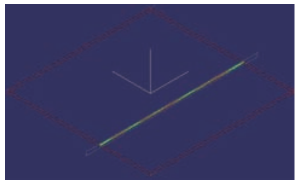
  If the observation mode of sampling points is adopted, the distribution maps will be created, or the slice analysis will be made. Different view direction and different section depth can be adjustable for facilitating comparison.
- *Demonstration*: In this mode, it is possible to simulate visually the whole monitoring process. Before simulation, the sampling rate should be set. It will help the operator to learn the procedure of analysis.

IV. Experiments and Results

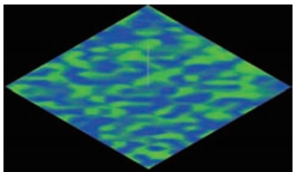
The intelligent monitoring system has been tested frequently in practical environments, including communication rooms and large computer barns. The tests have lasted for several months to verify system stability. The experiments show that the system is efficient and stable. The system performance is shown in Table. I. The results of experiments include the environment map, monitoring trajectory, environmental parameters, temperature cloud, humidity cloud, airflow velocity cloud, and slice analysis. From the clouds, we can easily observe the distribution of environment parameters



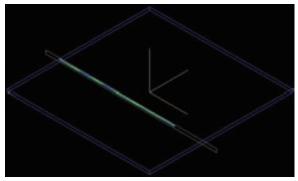
(a) Temperature cloud



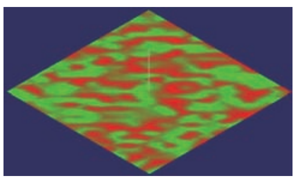
(b) Temperature slice



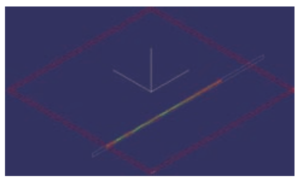
(c) Humidity cloud



(d) Humidity slice

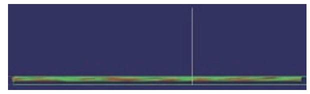


(e) Airflow cloud

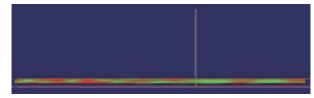


(f) Airflow slice

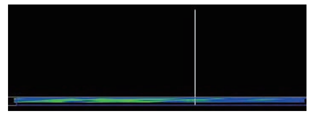
Fig. 7. The distribution maps of environmental conditions and slice analysis (interpolated sample points are selected, parallel to YZ plane, i.e. south-westbound, and the section depth is adjusted to 0.3.)



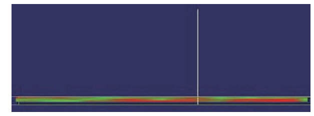
(a) Temperature, Depth=0.5



(b) Temperature, Depth=0.3



(c) Humidity, Depth=0.37



(d) Airflow, Depth=0.63

Fig. 8. The environmental cloud slices in different section depths.

TABLE I
THE PERFORMANCE OF SYSTEM

System Performance	Description
Motion speed	≤ 1.6 m/s
Capability of temperature measurement	$-20^0 \sim 100^0$, res. $\pm 1^0$
Capability of humidity measurement	$0 \sim 100\%$, res. $\pm 5\%$
Capability of airflow measurement	≥ 0.2 m/s.
Work environment	$0 \sim 60^0$C
Max measuring height	2.5 m
Max measuring weight	1 m
Physical size and weight	$s < 00$ mm; $w < 15$ kg
Continuous work time	≥ 3 hrs, 220 V charge

in global regions (Fig. 7(a), (c) and (e)). We can slice the 3D environment clouds (see Fig. 7(b), (d) and (f)). And different view directions can be chosen. It can be quickly and easily to observe whether the environmental conditions are normal or not.

The test experiments are described in details as follows. In the experiments, according to the size of network device cabinets, main collecting points will be set in the environment map. The map processing is off-line, but the others are online. To ensure real time, the system will create environment map firstly, and then navigate online, locating itself and avoiding obstacles. The robot moves autonomously along a path. When dynamic obstacles appear, the robot will avoid them according to the signals from the sonar sensors, and adjust partly the pre-define path. By this way, the monitored area will recovered quickly by trajectory. The height of the measured room is about 3m, and the area is more than 300 square meters. The distances between two adjacent cabinets are almost equal and the width of one cabinet is about 1m (Fig. 2(c)). The distance mode is adopted in the experiments, and the step is set to 1.5m. Since the moving robot may affect measuring airflow velocity, in order to ensure measuring accuracy, the robot stops for five seconds, and then continues. In order to avoid robot vibration due to the tall frame carrying sensors, the motion velocity of the robot is set to 0.8 m/s (the maximum speed is 1.6 m/s). Three wires are used to keep the frame stable. Testing results indicate that the robot moves smoothly in normal velocity and acceleration.

A. *Measuring Results*

The whole process of monitoring takes about 20 minutes. Measurement data are divided into five layers, and each layer includes three sets of temperature and humidity data, one set of airflow velocity. Statistics results show that the environmental condition is normal (Table. II). The trajectory is shown in Fig. 2(d), and the distribution map will be analyzed in the following section.

B. *The Distribution Maps of Environmental Conditions and Slice Analysis*

The map of environmental conditions are composed by the clouds of temperatures, humidities and airflow velocities, with which slice analysis may be conducted.

- *Temperature Cloud*: In the distribution map of temperature, different areas are shown in different colors. The

TABLE II
THE RANGE OF MEASURING DATA

Parameters	Temperature (°C)	Humidity (RH)	Airflow velocity (m/s)
Measuring range	$25 - 41$	$0.15 - 0.3$	$0.5 - 7$

TABLE III
SAMPLE AT A GIVEN LOCATION

Sample number	280
Sample position	[14.284, 14.926, 0.8]
Temperature (^oC)	31.2, 28.2, 29.7
Humidity (%)	24.1, 23.9, 19.4
Airflow velocity (m/s)	3.8

whole area is covered by three colors (Fig. 7(a)). The temperature in most areas are between 33^oC and 36^oC, the temperatures in some dispersion areas are between 36^oC and 40^oC, and the temperatures in a few small areas are between 30^oC and 32^oC. If the operator is interested in some areas, the temperature at specific position can be obtained by pressing sample point in the 3D view (Table. III). Fig. 8(b) shows that the change of temperatures are very clear in continuous region, but well-distributed. The observation mode is set as follows: interpolated sample point is chosen, section depth is set to 0.3. However, when the section depth is adjusted to 0.5, slice result shows that temperature changes in continuous region are not clear, mostly concentrated between 35^oC and 36^oC (Fig. 8(a)). In temperature clouds, the red is defined for dangerous area, some solutions should be set up for high temperature area.

- *Humidity Cloud*: The humidity cloud shows that the humidity is well-distributed, which is between 0.15 and 0.3. It is normal for the devices. Fig. 8(c) shows that humidity changes in the continuous areas are not well-distributed, and the humidities in the left areas are higher than those of the right areas, when the section depth is adjusted to 0.37. Also analysis in other continuous areas can be done by adjusting section depth.

- *Airflow Cloud*: The minimum airflow velocity triggering airflow sensors is 0.2m/s. Fig. 7(e) shows that the distribution is uneven at the first layer in space. Colors are great contrast in different regions. Maybe because of cooling fan, airflow velocity in some areas are higher than others. Fig. 7(f) shows that the change of airflow velocity in the continuous areas is not well-distributed. When the section depth is adjusted to 0.63, compared to the right areas, the airflow velocity in the left areas are lower (Fig. 8(d)). Appropriate flow rate is beneficial for environmental safety.

V. CONCLUSIONS

Most existing methods for monitoring indoor environments are lack of generality, not flexible, and the process of monitoring is tedious. To overcome the drawbacks, a monitoring system has been developed based on mobile robotics. Compared with the conventional monitoring methods, the mobile robot-based monitoring system is more efficient. The system has the following features: autonomously monitoring, tracing motion trajectory and displaying visually the monitoring results, creating environmental clouds and slice analysis. These features give rise to the ability to adapt to various indoor environments and make the operation process more convenient. It has been shown that autonomous mobile robots can be applied for practical applications in industrial environments.

In this paper, a visual environmental monitoring system is proposed. We describe the system designs, the working principles and the experiments, and then discuss the monitoring results. The experiments have verified the good performance of our system in practical environments.

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