The 3rd China-Japan Conference on Mechatronics 2006 Fuzhou

(CJCM 2006 Fuzhou)

Sep.11, 2006 Fuzhou

Organized by
Soochow University of China
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Editors
Yan Shirong(China)
Rui Yannian(China)

福建科学技术出版社
FUJIAN SCIENCE & TECHNOLOGY PUBLISHING HOUSE

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图书在版编目（CIP）数据

中日第三届机电一体化学术会议论文集／严世榕等编. —福州：福建科学技术出版社，2006.9
ISBN 7-5335-2866-2

Ⅰ.中…　Ⅱ.严…　Ⅲ.机电一体化—国际学术会议—文集—英文　Ⅳ.TH-39

中国版本图书馆CIP数据核字（2006）第093044号

书　名　The 3rd China-Japan Conference on Mechatronics 2006 Fuzhou
编　者　Yan Shirong · Rui Yannian
出版发行　福建科学技术出版社（福州市东水路76号，邮编350001）
印　刷　福建地质印刷厂
开　本　889毫米×1194毫米　1/16
印　张　25.25
字　数　800千字
版　次　2006年9月第1版
印　次　2006年9月第1次印刷
印　数　1—400
书　号　ISBN　7-5335-2866-2
定　价　80.00元

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Research on the Adaptive Control Theory of Moving Robot Built on Extension Control Theory

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Abstract: Adaptive control theory has been a hot issue in automation research field, especially there are many problems eager to be solved as for the adaptive controlling of moving robot walking on complex road. This paper presents a new intelligent theory named "extension adaptive control" by combining adaptive control theory and extension theory. Adaptive control theory solves the issue of time invariant system and time slow variant system, while extension theory specifically solves the issue of time variant system and paroxysmal changes. Based on the extension adaptive control theory, this paper builds the dynamic model of moving robot, designs the adaptive controller, and the experiment indicates the robot is able to fit to the environment better compared with the traditional adaptive control.

Keywords: *Moving robot, Extension control, Adaptive control*

1 Overview

In the adaptive control of moving robot, there are many problems need to be solved. The traditional adaptive control theory is particularly used to solve the issues of time invariant system and time slow variant system, but it has no ability to deal with the problems in unpredictable or time fast variant events. That means it has poor adaptability. For example, the adaptive driving controller can change the direction and velocity which has been set by the designer when the robot is moving on a way of good condition. However when the road condition becomes poor or complicated, such as the level of curve or declivity is beyond the desired scopes, the performance of adaptive driving controller is unsatisfied. As for the above situation, usually only human can find the problems and how serious those problems are, and figure out new control strategies "on-line" to solve them. In other word, the control system has to employ more intelligent methods to control the unpredictable time variant system and accidents well.

Although artificial neural networks has some intelligence similar to man's brain, the delayed phenomena of dealing with the accidents on the complicated system is obvious. Sometimes it can not hand at all, while the best advantage of extension control is its good adaptability. This paper builds the extension adaptive control theory by combining the extension control theory and adaptive control theory, and tries to apply it to the moving robot.

2 Basic principle of extension control theory

Form the point of controlled subject, extension control theory can imitate the human's ability of generalizing, studying and solving contradicted problems to sort out the unpredictable and unexpected issues. It changes contradicted issues into compatible issues to figure them out. The inside mechanism is changing and replacing not containing and matching as in the traditional control theory. Extension control can imitate human's creativity better than the other current control theories.

According to the model, the most outstanding characteristic of the extension control is that it does not depend on the information of the control system structure, and does not need any mathematics models provided in advance. Therefore, it has no problem caused by scheduled models or structures that have implicit mistakes, which can be applied in those fields which are understood insufficiently or even completely unknown.

From the point of that method itself, the extension control is a kind of control method that combines fixed-quality and fixed-quantity together. Its fixed-qualitative analysis tool is extension analysis and extension transformation method that take basic-element as basis, while its fixed-quantitative analysis tool is connection function and excellent evaluate method that

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take extension sets as basis. It considers not only the quantity relation of control objects, but also the variety of their characteristics and conduct effects.

The characteristics of combining fixed-quality and fixed-quantity together provided the fitting model for it handles various contradict problems in the process of control. The main characteristics of extension are dissipation, relativity, conjugation and containment.

2.1 Extension object-element model

A lot of control processes are the functions of time, influenced by many restriction factors. In order to predict the conditions of something in the future time and some characteristic values, at first extension analysis the formation reason of object-element variety described the conditions of the things.

Supposing that an object N in the time of t, the quantity value of characteristic c is $v(t)$, then

$$R(t) = [N(t), c, v(t)] \quad (1)$$

From the dissipation of object-element, $R(t)$ is used to describe the multi-dimensions dynamic object-element:

$$R(t) = \begin{bmatrix} N(t) & c & v(t) \\ & c_1 & v_{11}(t) \\ & M & M \\ & c_n & v_{1n}(t) \end{bmatrix} \quad (2)$$

Equation (2) reflects the possible value of $v(t)$ by researching the law of $v_{1i}(t)(i = 1,2,\cdots,n)$.

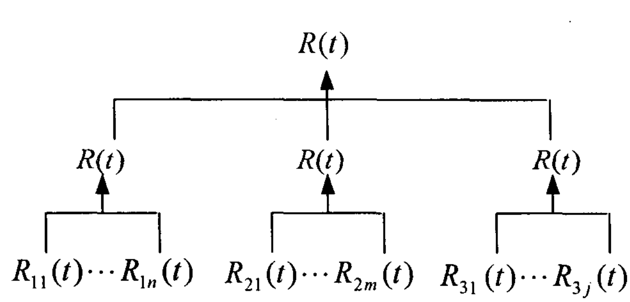
(2) From the relativity of object-element to analyze the correlation set $\{N_{2j}(t) | j = 1,2,\cdots,m\}$ about c of $R(t)$ and research the change of $v_{2j}(t)$ which brings conduction effect to $v(t) : v(t) = f_{2j}(v_{2j}(t))$ to depict the future state of $R(t)$.

(3) From the conjugacy of object-element,

$$\begin{aligned} N(t) &= reN(t) \otimes imN(t) = hrN(t) \\ &= apN(t) \otimes ltN(t) = ps_c N(t) \otimes ng_c N(t) \end{aligned} \quad (3)$$

Equation (3) researches the mutual transforming relations of conjugating of all parts to conclude the chose result of $v(t)$.

(4) From the implication of object-element, we can depict $R(t)$ as the epistasy object-element of implication relation.



Through the research of the quantity value state of $R_{11}(t)\cdots R_{1n}(t), R_{21}\cdots R_{2m}(t), R_{31}(t)\cdots R_{3j(t)}$, the state of $R(t)$ can be determined.

2.2 Extension adaptive controller structure

Robot in moving has the problems of the time variant and paroxysmal changes due to the complexity condition of the road. Since adaptive control is good at dealing with the time invariant system and time slow variant system and extension control is good at dealing with the paroxysmal changes and time fast variant system, we can combine two situations and let them exert their own advantages respectively. Then it come into being the extension adaptive control, its principle frame is shown as Fig.1.

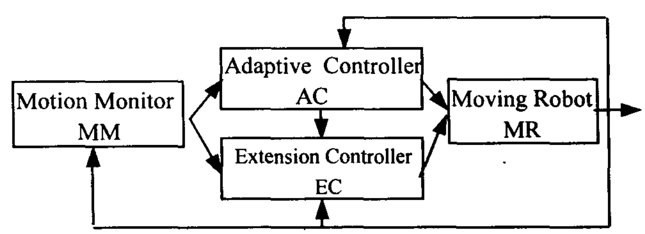


Fig.1 Extension adaptive control principle frame

This control system has three running states: EC separateness running, EC and AC simultaneity running, AC separateness running. Monitor MM takes care of the switch of those three running states.

Adaptive control system for complicated system is the series-wound or/and shunt-wound result of extension adaptive control units. The structure of extension controller is shown in Fig.2. Generalized object is equivalent model which includes actuate mechanism, controlled object, measuring device. The following five modules shown in Fig.2 are the main parts of the extension controller.

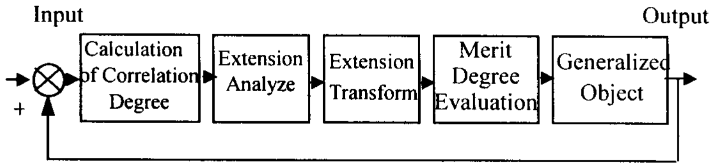


Fig.2 The structure of extension controller

3 Design of extension adaptive control system

3.1 Design of extension controller

(1) Establishing extension model for control: the key point is to find the core problem for control including control objectives and control conditions, then expressing them with basic-element (including object-element, matter-element and relation-element)

Supposing the control objectives and control conditions of walking robot are

$$R=\begin{bmatrix} robot-AC & velocity-c_1C & v_1 \\ & direction-c_2C & v_2 \\ & expection\cdot deviation-c_3C & v_3 \end{bmatrix}=\begin{bmatrix} A, & c_1 & v_1 \\ & c_2 & v_2 \\ & c_3 & v_3 \end{bmatrix},$$

$$r_1=\begin{bmatrix} robot-A, & weight-c_4 & v_4 \\ & imbalence-c_5 & v_5 \\ & actual\cdot deviation-c_6 & v_6 \end{bmatrix}=\begin{bmatrix} A, & c_4 & v_4 \\ & c_5 & v_5 \\ & c_6 & v_6 \end{bmatrix}$$

$$r_2=\begin{bmatrix} run\cdot conditions-B, & road\cdot condition-c_4 & v_4 \\ & bend\cdot degree-c_5 & v_5 \\ & environment\cdot disturb-c_6 & v_6 \end{bmatrix}=\begin{bmatrix} A, & c_7 & v_7 \\ & c_8 & v_8 \\ & c_9 & v_9 \end{bmatrix}$$

$r_1 \wedge r_2$ means that control object is to realize R in the condition of r, marked as follows:

$$P=R*r \qquad (4)$$

From the point of the control method based on characteristic model, the set of characteristic state is:

$$S=(c_1,c_2,c_3,c_4,c_5,c_6,c_7,c_8,c_9) \qquad (5)$$

(2) Calculation of correlation degree: establishing the extension set according to the core problem for control, and calculate the correlation degree $G(p)$. There are 3 states:

①$G(p)\geqslant 0$, it means that the control problem is compatible, and the control problem can reach the expected control objective by adaptive control method. It is adaptive control phase;

②When $-1\leqslant G(p)\leqslant 0$, it shows the control problem is the incompatible problem. If it is unable to make the incompatible control question turn into the compatible control question by adopting the adaptive method, but it can make the incompatible control question turn into the compatible control question through increasing extension control method, and then use the traditional adaptive control to reach ideal control, the whole process is the stage of "the adaptive control + extension control";

③When $G(p)\leqslant -1$, it shows the control problem is the incompatible problem, and the adaptive control doesn't work at all. This stage divides into two kinds of situations: One is it can make the incompatible control problem turn into the compatible control problem; the other is totally uncontrollable situation, which means it is unable to make the incompatible control problem turn into the compatible control problem even by extension control method.

(3)Extension analyze: according to the class of related degree, we can utilize the expansion rule, the conjugation rule and the conduction rule in extension control method to analyze the goal basic-element and condition basic-element, and then set up the basis of extension transfer.

(4)Extension transfer: according to extension analysis, we can establish the type of basic transfer and its mode of combination. Through the transfer of the goal basic-element and condition basic-element, we can make control strategy that can turn the incompatible control problem into the compatible control problem.

(5)Optimize evaluation: The quality of every control strategy is different, which is reflected by different control results. We must evaluate the strategy according to certain conditions before implementing the control strategy, so as to ensure that every control strategy can produce actual effects. The basic algorithms of the evaluation are:

①Confirming the strategy collections which will be evaluated;

②Confirming the weighing condition set;

③ Confirming the right coefficients of different weighing conditions ;

④Appraising at the first time: Using the condition that must be satisfied to appraise the control strategy;

⑤Setting related functions to calculate qualified degree of every control strategy;

⑥Calculating the qualified degree;

⑦ Calculating optimize degree of every control strategy.

3.2 Adaptive controller design

The structure of the adaptive controller based on extension control is showed in fig.3.

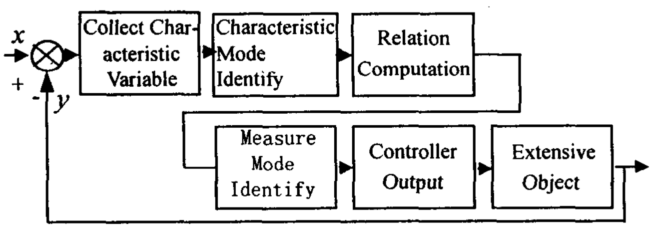


Fig.3 The structure of the adaptive controller

For simplicity, single variable system is considered here. Supposing x is the system set value, y is the extensive object output. And the system error is $\delta = x - y$. The error changing-rate is $\dot{\delta} = \mathrm{d}e/\mathrm{d}t$. According to the experienced data, the output variable of classic element and stanza element on δ and $\dot{\delta}$ are:

$$R_{0y} = \begin{bmatrix} y, & \delta, & (-\delta_{0m}, \delta_{0m}) \\ & \dot{\delta}, & (-\dot{\delta}_{0m}, \dot{\delta}_{0m}) \end{bmatrix}$$
$$R_y = \begin{bmatrix} y, & \delta, & (-\delta_m, \delta_m) \\ & \dot{\delta} & (-\dot{\delta}_m, \delta_m) \end{bmatrix} \quad (6)$$

According to equation (6) to establish extension set of output variable about δ and $\dot{\delta}$, the classification of measure mode are:

$$\begin{aligned} M_1 &= \{S | G_{\bar{x}}(S) \geq 0\} \\ &= \{S | \delta \in [-\delta_{0m} \delta_{0m}] \dot{\delta} \in [-\dot{\delta}_{0m} \delta_{0m}]\} \end{aligned} \quad (7)$$

$$\begin{aligned} M_2 &= \{S | G_{\bar{x}}(S) \geq 0\} \\ &= \{S | \delta \in [-\delta_{0m} \delta_{0m}] \cup \dot{\delta} \in [-\dot{\delta}_{0m} \delta_{0m}], \dot{\delta} \in [-\dot{\delta}_m, \delta_m]\} \end{aligned} \quad (8)$$

$$M_{21} = \{S | a_{i-1} \leq G_{\bar{x}}(S) \leq a_i\}, i = 1, \cdots, m,$$

And $-1 = a_0 < \cdots < a_{i-1} \leq a_i \leq \cdots \leq a_m = 0$

$$\begin{aligned} M_3 &= \{S | G_{\bar{x}}(S) \leq -1\} \\ &= \{S | \delta \notin [-\delta_{0m} \delta_{0m}] \dot{\delta} \notin [-\dot{\delta}_{0m} \delta_{0m}]\} \end{aligned} \quad (9)$$

And $M_1 \cup M_2$ is the control range of adaptive control's characteristic state S. The corresponding algorithms of controller output are:

$$u(t) = \begin{cases} u(t-1) & Q_{\bar{x}}(S) \geq 0 \\ -Q_{\bar{x}}(S) u_M \operatorname{sgn}(\delta) + \varepsilon & -1 \leq Q_{\bar{x}}(S) \leq 0 \end{cases} \quad (10)$$

$$\varepsilon = \begin{cases} Q_1 \int_0^t \delta dt & |\delta| \leq e \\ & others \end{cases} \quad (11)$$

And $u_M > 0$ is the amplitude of controller output, e is the minimal modifying value, Q_1 is constant, e is a small positive number.

Characteristic area $M_1 \cup M_2$'s control problem is the compatible problem,

$$M_1 \cup M_2 = \{S | Q(P) \geq 0\} \quad (12)$$

Measure mode in extension set only depends on classic area and stanza area of control characteristic variable, it doesn't need any information of mathematics model and structure of control system in advance. Therefore it can apply to control system which is insufficient known.

3.3 Intelligent control switch design

How to set up the switch function in intelligent control monitor is the key problem in the adaptive control system design. The switch function is based on relating function of the extension set. Considering the single variable control system, supposing that f is a control feature, $[a, b]$ is the range of adaptive control about control feature f, $[c, a]$ or $[b, d]$ is the pre-warning range or dangerous range $([a,b] \subset [c,d])$ of adaptive control and extension control, then set up the relating function:

$$q(v) = \begin{cases} -\rho(v, [a,b]) & v \in [a,b] \\ \rho(v, [a,b] / [\rho[a,b] - \rho(v, [a,b])]) & v = \notin [a,b] \end{cases} \quad (13)$$

where, $\rho(v, [a,b]) = |v - 0.5(a+b)| - 0.5(b-a)$,
$\rho(v, [c,d]) = |v - 0.5(c+d)| - 0.5(d-c)$

The value of relating function $Q(v)$ has the following features:

(1) $q(v) \geq 0$ if and only if $v \in [a,b]$;

(2) $q(v) \in [-1, 0]$ if and only if $v \in [a,c] \cup [b,d]$;

(3) $q(v) \leq 1$ if and only if $v \notin [c,d]$;

(4) $q(v) = 0$ if and only if $v = a$ or $v = b$;

(5) $q(v) = -1$ if and only if $v = c$ or $v = d$.

The value of $q(v)$ indicates: the transition of control strategy is going at extreme point of $[a,b]\subset[c,d]$.

For any $v\in(-\infty,+\infty)$, control switch function is defined as:

$$Q=\begin{cases} adaptive \quad control & Q(P)\geq 0 \\ extension \quad adaptive\ control & Q(P)\in(-1,0) \\ extension \quad control & Q(P\leq -1) \end{cases} \quad (14)$$

where $Q(P)=q(v)$

Based on the apriori information, the interval $[a,b]\subset[c,d]$ is determine, which makes it easy to build the above control switch function.

This control switch function is much simpler compared with those control forms based on fuzzy mathematics or grey mathematics. It needs no complicated transition calculation or statistical evaluation of large amount of collecting samples, and its meaning is much more intuitionistic.

If α is the transverse dip angle of walking robot (unit: degree), $[a,b]=[-5,+5]$, $[c,d]=[-10,+10]$, then the above control switch function means:

(1)when the transverse decline angle of walking robot doesn't exceed 5 degrees $(q(v)\geq 0)$, it is in the range of adaptive control and adaptive control can be used to realize the stability of walking robot.

(2)When the robot's transverse decline angle is between 5 and 10 degrees, $q(v)\in[-1,0]$, it is in the extension adaptive control pre-warning range, that means the ground slope is larger. Robots can walk stably by using the extension adaptive control. When the robot adopts the adaptive control, (adjusting the walk direction, the speed and transverse inclination with the adaptive pilot steel), it need to start the extension control device to get extension control in some level.

The goal is to improve the walking stability of the robot, that is

$$T=\begin{bmatrix} \text{improvement}, & \text{controlled member} & \text{the stability of the walking robot} \\ & \text{controlled device} & \text{walking robot} \end{bmatrix}$$

According to the extensible analytical method, we can easily get the following extensible transposition by emanative thinking and the hypogynous implicit tactics.

①Moving the center of the counterweight of the robot to the reverse direction of decline, the action is written as H_1;

②Keeping balance by swing its arms, is written as H_2;

③Reducing or increasing the speeds is written as H_3;

④Reducing or increasing its step length is written as H_4;

Any of above can adjust the center of the counterweight of the robot to improve the walking stability of the robot, that is,

$$H_1 \vee H_2 \vee H_3 \vee H_4 \Rightarrow T$$

(3) When the robot's transverse decline angle over 15 degrees, $q(v)=-1$, the adaptive control will be useless.

The extension control works better in the condition when $q(v)\in[-1,0]$ in the online real-time control. The off-line or artificial control works better in the condition when $q(v)\in[-1,\infty]$.

4 The experiment result

In experiments the walking robot was placed on the platform with the grid with certain inclination randomly. It let the robot has the ability of making decision by itself. The experiment scene is as Fig. 4 shows.

Fig. 4 The stability experiment of the extension adaptive controlled robot

The software is based on Visual Basic 6.0. It scans the surroundings through the CCD on the head of the robot, processes the imagines and employs it as the reference for the software program to make decision. The experiment performance (shown in Table 1) indicates the effects are much better than adaptive control theory to be employed only.

Table 1 Stability comparison between adaptive control and extension adaptive control

Control the way / Sport Parameter	Adaptive Control	Extension Adaptive Control
The road faces an O of inclination	5	5
The road faces an O of inclination	10	10
Run about the speed (cm/ min)	300	300
Stable time (s)	30~50	10~12

5 Conclusion

(1) The adaptive control mainly employed to solve the problems of time invariant system and time slow variant system. Adaptive control can't solve the problems of time fast variant and unexpected or paroxysmal system.

(2) Extension control is not good at dealing with the time invariant system and time slow variant system, but good at dealing with the time fast variant and unexpected or paroxysmal system.

(3)Extension adaptive control contains the advantages of adaptive control and extension control both. It can not only solve the problems of the time invariant system and time slow variant system but also the problems of the time fast variant and unexpected or paroxysmal system.

(4) The experiment of controlling walking robot by extension adaptive control method proves that it has better stabilization and adaptability compared with the traditional adaptive control method.

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Development of a Fire Detector with Multiple Smell Sensors

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Abstract: This paper is concerned with the development of a new type of home-use fire detector which is used to predict the fire breaking as early and accuracy as possible in order to prevent the aged person from failing to escape. Fire burning tests are carried out within a 90 cm^3 chamber and the smell signals in burning are measured by several gas or smell sensors which are set in the chamber. The whole process of fire burning tests is observed and recorded by two CCD cameras. A simple data processing method for predict the fire breaking is proposed based on a massive amount of burning experiment results. The experimental results show that using the smell sensors of TGS2600 and TGS2602 is an efficient way to detect the fire breaking with the proposed algorithms. Finally a new home-use fire detector, which consists of two smell sensors (TGS2600 and TGS2602) and a microprocessor and etc, is designed for practical use in a house.

Keywords: *Fire breaking detection, Fire detector, Smell sensor, Data processing algorithm*

1 Introduction

Nowadays, in order to protect goods and life, the fire detection systems are used world wide. However at the present time, fire detectors showed poor features with regard to detection speed and reliability. Conventional fire detectors were based on the sensing of physical parameters such as particle density and temperature. However, those parameters vary with the materials and status of combustions, which adds difficulty to conventional detectors [1]. To secure human lives against abrupt fire, buildings require advanced technologies and monitoring system for fire detection. Multi-criteria/multi-sensor approaches have been investigated with various degrees of success [2]. Few studies have provided results, which clearly demonstrate the performance improvements of the new multi-criteria approaches, compared to threshold alarm smoke detectors. Modern fire detectors show good detection capabilities in the case of test fires as well as in genuine fires, but the rate of false or unwanted alarms is quite high. An advanced fire detector system should be based on a combination of a high sensitivity sensors fitted with various environment and rapid responds to the abrupt changes. The more automatic fire detectors are installed, the more serious becomes the false alarm problem. There are various possible means available for reducing the false alarm rate, i.e., (1) professional design of the hardware for fire detectors, (2) the use of multi-sensor fire detectors, (3) the use of advanced detection algorithms to various environments.

The purpose of this study is focused on the development of a simple and sensitive fire detector for general household life support. According to the recent statistics, fatalities caused by fire are mainly of the aged persons because of failing to escape. Prediction of the fire breaking as possible at an early stage will prevent fatal accident from the fire. In this study, the fire burning experiments are carried out for investigation of the smell and smoke during substances burning by the measurement with the sensors, such as air contaminant sensor, carbon monoxide sensor, hydrogen sensor and etc. Since TGS2600 sensor has high sensitivity to gaseous air contaminants such as hydrogen and carbon monoxide which exist in cigarette smoke, and TGS2602 sensor has high sensitivity to low concentrations of VOCs such as toluene emitted from wood finishing and construction products in office and home environments, these two sensors are mainly taken into account in this paper. Furthermore, a data processing method, simply using difference analysis to the signals from two sensors, is proposed and described in detail. The experimental results show that the sensors TGS2600 and TGS2602 have good potential for detecting fire breaking. Finally a simple fire detector, consisting of two sensors and a microcontroller and etc, is designed for the practical use in office and home environments.

2 Experiments

The burning experiments were carried out within a 90 cm^3 chamber. Test fires are located on the bottom at the center of the chamber. Sensors are placed on the coping. In addition, in order to monitor the fire condition, two CCD digital cameras were setup near by. Paper, calico and etc were used as materials for combustion which have smoke before burning. The size of these materials is 15 cm × 10 cm (four pieces and overlapped). Figure 1 shows the experimental environment.

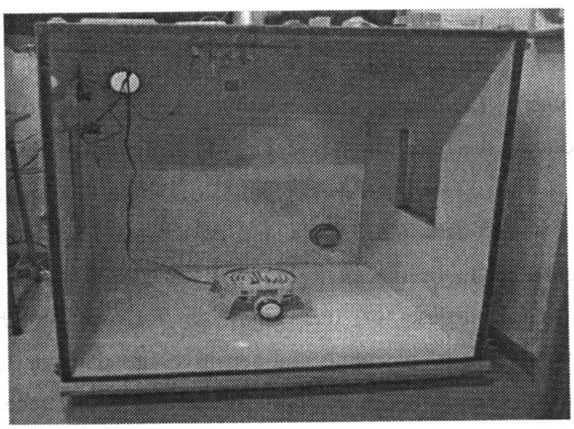

Figure 1 Photo of the experimental environment

For the experiments, we use the Evaluation modules (AM-1-2600 and AM-1-2602) of TGS2600 sensor and TGS2602 sensor respectively. The signals were recorded by a data acquisition system (NR-2000, Keyence) and the data was saved as CSV file format.

As for experimental environment, the experiment was performed through an obturator by closing the door and blocking the hole on the back of the test room. For observing material's burning condition, it can be snapped by the CCD digital cameras. Furthermore, peculiar situations were recorded. Hereinafter sensor output of these peculiar situations will be used to signal processing algorithms for fire detection.

From burning experiments, we could get the similar differential curve although their original curves have a little difference from each other. Paper is used for explaining material's burning in this paper.

Figure 2 shows the time responses of two smell sensors TGS2600 and TGS2602 corresponding to three peculiar situations described by snapshots as Figs. 2(a) to (c). It is obvious that two sensors simultaneously respond to situations but there are a little different speed and path characteristics. Furthermore, it is obvious that two output curves react just on smoke out, however they do not give any information for the fire. So the raw curves can not be used for fire detection. As a result, in order to extract the feature of the fire, the signal processing method might be needed. Then, it will give a solution for fire detection.

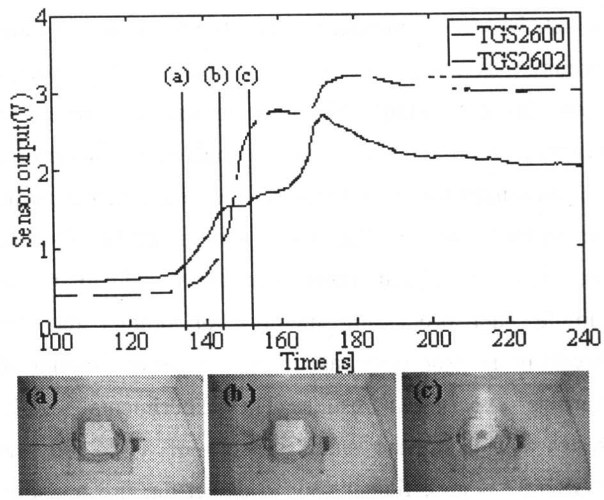

Figure 2 Time responses of the sensors TGS2600 and TGS2602. (a) smoke out, (b) start burning, and (c) high intensity in burning

3 Signal processing

The additional use of the selected gas sensors requires algorithms that are more sophisticated and complex than the simple threshold rule. The algorithms should be able to identify fire signatures from measured multi-dimensional sensor responses and eliminate the disturbing event situations. The algorithms consist of a pre-processing, a differential coefficient analysis and feature extraction, and fire detection method. For data analyzing, we use MATLAB software as the analysis tools.

3.1 Signal pre-processing

A pre-processing is necessary to compensate for sensor drifts and to reduce sample-to-sample variation and disturbances (noises) that affect the measurement process. For this purpose, a filter and a normalization process have been performed [3].

3.1.1 Low pass filter

The signals acquired from sensors often include some noises, and they make disturbance for data analysis. Noises generated by ambient variations, i.e., in humidity, temperature variation and etc, and by surface variations, i.e., in the transduction mechanism of metal-oxide sensors. Noises have often been cited as a limiting issue in the accuracy of sensors. In order to reduce these noises and high frequency noise induced by electronic heater control, the dynamics of surface reactions and semiconductor contact effects, we used a 3rd-order Butterworth low pass filter with a cut-off frequency of 2.5 Hz.

3.1.2 Normalization

Data normalization is a method to normalize all of the data from each sensor into the same range, and then all of the data can delimit into the range of [0, 1], i.e., let the maximum and minimum of sensor output data be y_{max} and y_{min}, respectively. Then the normalized data x will be given as:

$$x(t) = \frac{y(t) - y_{min}}{y_{max} - y_{min}} \quad (1)$$

3.2 Differential coefficient analysis and feature extraction

Differential coefficient analysis and feature extraction are necessary to extract appropriate information characterizing fire situations and can be defined as a transformation of the pre-processed sensor signals. Differential coefficient analysis can reflect the changes of the things. For this experiments Differential coefficient analyzed data z of each sensor respond is defined as follows:

$$\dot{z}(t) = \frac{\Delta x(t)}{\Delta t} \quad (2)$$

where Δx is the output difference of sensor response of two different times, and Δt is the increment of the times. We defined Δt = 1 second, hereinafter, the differential curve of each sensor was introduced respectively.

3.2.1 Differential curve of TGS2600 sensor

TGS2600 sensor has two peaks in the differential curve. We compared the time (T_p) when the first peak comes out with the time (T_b) of start burning, the mean value and the standard deviation of (T_p-T_b) are summarized in Table 1. It obviously shows that T_p and T_b are almost the same time, i.e., the peak comes out when start burning, although there is a little deviation which might be caused by person operations and etc.

Table 1 Mean value and standard deviation of time

Material	Mean value (s)	Std. dev. (s)
Paper	1.4	2.1
Calico	1.2	1.3

Figure 3 shows the differential curve of TGS2600 sensor after data normalization. When smoke density increases, the differential curve ascends, at the first peak region of the curve, fire comes out, and start burning, then differential curve descends, and the second peak of differential curve is caused by carbon monoxide CO, because we have compared it with another CO sensor (Cosmos Co.), and the peak comes out at the same time.

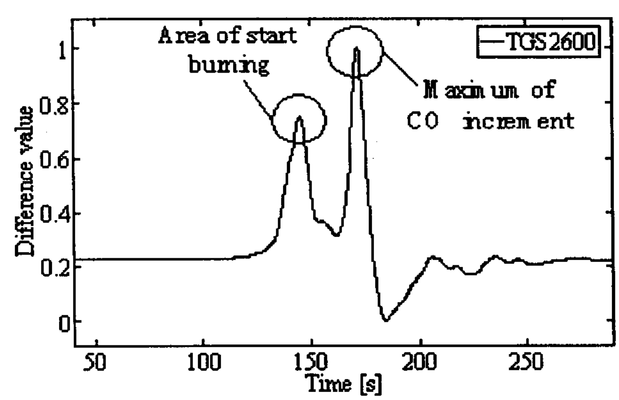

Figure 3 Differential curve of TGS2600.

3.2.2 Differential curve of TGS2602 sensor

TGS2602 sensor has one peak in the differential curve, this time, we compared the time (T_k) when the peak comes out with the time (T_h) when the burning is in high intensity, the mean value and the standard deviation of ($T_k - T_h$) are summarized in Table 2. It obviously shows that T_k and T_h are almost the same time, i.e., the peak come out when the burning is in the high intensity stage. Figure 4 shows the differential curve of TGS2602 sensor after data normalization.