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International Journal of Thermal Sciences 44 (2005) 1098–1105

International Journal of Thermal Sciences

www.elsevier.com/locate/ijts

Performance improvement of indoor air temperature through state feedback decoupling, genetic algorithm; A study with LonWorks™ fieldbus

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Received 7 July 2004; received in revised form 21 March 2005; accepted 21 March 2005

Available online 23 May 2005

Abstract

Because variable air volume (VAV) air conditioning system has the feature of intense coupling among multi-loops, supply air temperature cannot follow the set-point value closely. Therefore, the precision and performance of indoor air temperature of VAV air conditioning system is influenced. In this paper, precision and performance of indoor air temperature of VAV system are highly improved through state feedback decoupling and genetic algorithm. The coupling between loop of supply air temperature and loop of indoor air temperature is eliminated in the method of state feedback decoupling. Besides, the controller parameters are optimized by means of inverse and genetic algorithm. LonWorks technology is adopted in VAV air-conditioning decoupling control system so that data can be exchanged among multi-loops. The experimental results show that performance of indoor air temperature of VAV system is improved effectively.

Keywords: Variable air volume; State feedback; Decouple; Genetic algorithm; Fieldbus

1. Introduction

VAV air conditioning control system is multi-variable, and has multi-control loops coupling [1]. Because of the coupling between loop of indoor air temperature and loop of supply air temperature, the precision and performance of indoor air temperature of VAV air conditioning system is influenced. For example, the change of chilled water flow rate effects the change of supply air temperature. Due to this, the indoor air temperature of room is also changed. Further, the change of supply air flow rate influences the indoor air temperature. Besides, it also causes the change of the air flow rate of the cooling coil. As a result, the supply air temperature is changed, and eventually affects the indoor air temperature continuously. In this paper, the coupling between loop of indoor air temperature and loop of supply air temperature is decreased or eliminated through state feedback decoupling technology [2,3].

Meanwhile, the controller parameters are designed through inverse and genetic algorithm. The relationships among the PID parameters and the roots of characteristic equation are found in the method of inverse deducing. This equation is the characteristic equation of closed loop control system. While designing the controller parameters, if the range of the roots is within the unit circle in the z-plane, then the closed loop control system is stable. But the roots in different groups affect the performance of the control system differently. In this paper the roots are optimized by the use of genetic algorithm [4,5]. The controller parameters are optimized by the combined effect of inverse and genetic algorithm.

Data must be exchanged between loop of indoor air temperature and loop of supply air temperature in VAV decoupling control system. Data exchanging between these two loops is very important for decoupling control system. Otherwise, it is difficult to realize the decoupling control

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2005.03.015

Nomenclature

A	matrix	
a_{21}	proportion coefficient	
A_a	heat transfer area of air side about the cooling coil	m^2
A_p	wall area of room	m^2
B	matrix	
b_{11}	proportion coefficient	
b_{22}	proportion coefficient	
C	matrix	
C_1	the first row of matrix C	
C_2	the second row of matrix C	
C_a	heat capacity of air	$J \cdot kg^{-1} \cdot {}^\circ C^{-1}$
C_c	heat capacity of cooling coil	$J \cdot kg^{-1} \cdot {}^\circ C^{-1}$
$c_{\max}$	maximum of each circulating calculation about genetic algorithm	
C_v	heat capacity of indoor air	$J \cdot m^{-3} \cdot {}^\circ C^{-1}$
C_w	heat capacity of chilled water	$J \cdot kg^{-1} \cdot {}^\circ C^{-1}$
E	matrix	
E^{-1}	inverse matrix of E	
F	matrix	
f_{avg}	average fitness about genetic algorithm	
f_i	fitness about genetic algorithm	
$f_{\max}$	maximum of fitness about genetic algorithm	
$G_0(s)$	transfer function matrix of controlled process	
$G_1(s)$	the first row of $G_0(s)$	
$G_2(s)$	the second row of $G_0(s)$	
$G_f(s)$	transfer function matrix	
H	matrix	
I	unit matrix	
J	object function about genetic algorithm	
K	matrix	
k_D	differential coefficient of PID controller parameter	
k_I	integral coefficient of PID controller parameter	
k_p	proportion coefficient of PID controller parameter	
L	length of each individual in population about genetic algorithm	
M_c	mass of cooling coil	kg
q_a	air flow rate of air side of cooling coil	$m^3 \cdot s^{-1}$
$q_{a,b}$	return air flow rate	$m^3 \cdot s^{-1}$
$q_{a,f}$	fresh air flow rate	$m^3 \cdot s^{-1}$
Q_m	heat of heat source in room	$J \cdot s^{-1}$
q_r	supply air flow rate of room	$m^3 \cdot s^{-1}$
q_w	chilled water flow rate of cooling coil	$m^3 \cdot s^{-1}$
S_{GA}	search space about genetic algorithm	
t	time	s
T_0	sampling period	s
T_1	time constant	s
T_2	time constant	s
U	input vector of controlled process	
u_1	chilled water flow rate	$m^3 \cdot s^{-1}$
u_2	supply air flow rate of room	$m^3 \cdot s^{-1}$
V	volume of room	m^3
x_1	supply air temperature	°C
x_2	indoor air temperature of room	°C
y_1	supply air temperature	°C
y_2	indoor air temperature of room	°C
Y	output vector	
z_{11}	root of equation of the closed loop	
z_{12}	root of equation of the closed loop	

Greek symbols

α_a	heat exchange coefficient of air side about cooling coil	$W \cdot m^{-2} \cdot {}^\circ C^{-1}$
α_p	heat exchange coefficient about indoor air and wall in room	$W \cdot m^{-2} \cdot {}^\circ C^{-1}$
ρ_1	radius of polar coordinate in z-plane	
ρ_a	density of air	$kg \cdot m^{-3}$
ρ_w	density of chilled water	$kg \cdot m^{-3}$
θ_1	angle of polar coordinate in z-plane	
$\theta_{a,b}$	return air temperature	°C
$\theta_{a,f}$	fresh air temperature	°C
$\theta_{a,\text{in}}$	inlet air temperature of cooling coil	°C
$\theta_{a,\text{out}}$	outlet air temperature of cooling coil	°C
θ_c	temperature of cooling coil	°C
θ_p	wall temperature of room	°C
θ_r	indoor air temperature of room	°C
θ_s	supply air temperature	°C
$\theta_{w,\text{out}}$	outlet water temperature of cooling coil	°C
$\theta_{w,\text{in}}$	inlet water temperature of cooling coil	°C

algorithm. LonWorks technology is adopted to realize the data exchanging. It has many features including peer-to-peer communication; device level processions; and a network operating system for easy management such as remote services. In this paper, decoupling compensation coefficients between the two loops are handled as network variables (NV), a new concept adopted in LonWorks technology [6,7].

This paper presents a strategy that highly improves the controlling performance of indoor air temperature through state feedback decoupling, genetic algorithm and fieldbus such as LonWorks technology.

2. An outline of the studied VAV system

Fig. 1 is the schematic diagram of the studied VAV air conditioning system, which is mainly composed of six units such as air handling unit, fresh air valve, return air valve, exhaust air valve, VAV boxes and duct network.

After the return air has blended with the fresh air, the mixed air will enter the air handling unit. When the air temperature has dropped, the air is sent to the supply air duct by fan, and it then enters the room.

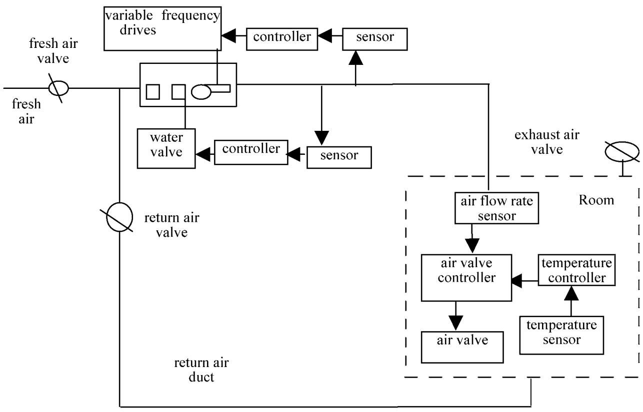

Fig. 1. Constitution of the VAV air conditioning system.

Control loop of supply air temperature: Supply air temperature is detected by the temperature sensor. Then it is compared with the set-point value. According to the difference between the actual value and the set-point value, the chilled water valve is adjusted by the controller, so that the supply air temperature is controlled.

Control loop of indoor air temperature: Indoor air temperature is detected by the temperature sensor. Then it is compared with the set-point value. According to the difference between the actual value and the set-point value, the supply air valve is adjusted by the controller, so that the indoor air temperature is controlled.

3. System model

There are two control loops in the studied system: One is the loop of supply air temperature, another is the loop of indoor air temperature. System model is established according to three steps. First, input variables and output variables are determined. Second, the relationships among input variables and output variables are deduced according to corresponding physical equations. Finally, the state equation is set up according to these relationships.

Input variables: chilled water flow rate (u_1), supply air flow rate of room (u_2). Input vector: $U = [u_1 \quad u_2]^{\mathrm{T}}$.
Output variables: supply air temperature (y_1), indoor air temperature of room (y_2). Output vector: $Y = [y_1 \quad y_2]^{\mathrm{T}}$.

The first describes the relationship between supply air temperature and chilled water flow rate. The second describes the relationship between indoor air temperature and supply air flow rate. These relationships are the basis of deducing state equation. The third describes the setting up of state equation based on the first subsection and the second subsection.

3.1. *Relationship between chilled water flow rate and supply air temperature*

Utilizing heat balance and mass balance relationships [8], Eqs. (1)–(3) can be obtained. Eq. (1) indicates that the heat change of heat exchanger equals to the difference between the decreasing heat of air and the increasing heat of chilled water. Eq. (2) indicates that the decreasing heat of air equals to the heat exchange between the air and the heat exchanger. Eq. (3) indicates that the inlet air temperature of heat exchanger equals to the product of the fresh air temperature and its percentage plus the product of the return air temperature and its percentage.

$$M_c C_c \frac{\mathrm{d}\theta_c}{\mathrm{d}t} = q_a \rho_a C_a (\theta_{a,\mathrm{in}} - \theta_{a,\mathrm{out}}) - q_w \rho_w C_w (\theta_{w,\mathrm{out}} - \theta_{w,\mathrm{in}}) \qquad (1)$$

$$q_a \rho_a C_a (\theta_{a,\mathrm{in}} - \theta_{a,\mathrm{out}}) = \alpha_a A_a (\theta_{a,\mathrm{in}} - \theta_c) \qquad (2)$$

$$\theta_{a,\mathrm{in}} = \frac{q_{a,f}}{q_{a,f} + q_{a,b}} \theta_{a,f} + \frac{q_{a,b}}{q_{a,f} + q_{a,b}} \theta_{a,b} \qquad (3)$$

From Eqs. (1)–(3), $\theta_{a,\mathrm{out}}$ can be described as Eq. (4) when $T_1 = \frac{M_c C_c}{\alpha_a A_a}$:

$$\frac{\mathrm{d}\theta_{a,\mathrm{out}}}{\mathrm{d}t} = -\frac{1}{T_1}\theta_{a,\mathrm{out}} + \frac{1}{T_1}\left[\frac{q_{a,f}}{q_a}\theta_{a,f} + \frac{q_a - q_{a,f}}{q_a}\theta_{a,b} - \frac{q_w \rho_w C_w}{q_a \rho_a C_a}(\theta_{w,\mathrm{out}} - \theta_{w,\mathrm{in}})\right] \qquad (4)$$

The proportion coefficient between $\frac{\mathrm{d}\theta_{a,\mathrm{out}}}{\mathrm{d}t}$ and q_w is $\frac{b_{11}}{T_1}$, b_{11} is described as

$$b_{11} = -\frac{\rho_w C_w}{q_a \rho_a C_a}(\theta_{w,\mathrm{out}} - \theta_{w,\mathrm{in}})$$

Because the relationship between $\frac{\mathrm{d}\theta_{a,\mathrm{out}}}{\mathrm{d}t}$ and q_a is nonlinear, it can be transformed into linear by the use of Taylor series at working point.

The proportion coefficient between $\frac{\mathrm{d}\theta_{a,\mathrm{out}}}{\mathrm{d}t}$ and q_a is $\frac{b_{12}}{T_1}$; b_{12} is described as

$$b_{12} = \frac{1}{q_a^2}\left[-q_{a,f}\theta_{a,f} + q_{a,f}\theta_{a,b} + \frac{q_w \rho_w C_w}{\rho_a C_a}(\theta_{w,\mathrm{out}} - \theta_{w,\mathrm{in}})\right]$$

3.2. *Relationship between supply air flow rate and indoor air temperature*

Utilizing heat balance relationship [8], Eq. (5) can be obtained. Eq. (5) indicates that the heat change of indoor air equals to the difference between the increasing heat and the decreasing heat of indoor air.

$$C_v V \frac{\mathrm{d}\theta_r}{\mathrm{d}t} = q_r C_v \theta_s - q_r C_v \theta_r + Q_m - \alpha_p A_p (\theta_r - \theta_p) \qquad (5)$$

Eq. (5) can be transformed into Eq. (6):

$$\frac{C_v V}{q_r C_v + \alpha_p A_p}\frac{\mathrm{d}\theta_r}{\mathrm{d}t} + \theta_r = \frac{C_v q_r \theta_s}{q_r C_v + \alpha_p A_p} + \frac{Q_m + \alpha_p A_p \theta_p}{q_r C_v + \alpha_p A_p} \tag{6}$$

Eq. (6) can be transformed into Eq. (7):

$$\frac{\mathrm{d}\theta_r}{\mathrm{d}t} = -\frac{q_r C_v + \alpha_p A_p}{C_v V}\theta_r + \frac{q_r}{V}\theta_s + \frac{Q_m + \alpha_p A_p \theta_p}{C_v V} \tag{7}$$

When $T_2 = \frac{C_v V}{q_r C_v + \alpha_p A_p}$, Eq. (7) can be transformed into Eq. (8):

$$\frac{\mathrm{d}\theta_r}{\mathrm{d}t} = -\frac{1}{T_2}\theta_r + \frac{q_r}{V}\theta_s + \frac{Q_m + \alpha_p A_p \theta_p}{C_v V} \tag{8}$$

The relationship between $\frac{\mathrm{d}\theta_r}{\mathrm{d}t}$ and θ_s can be transformed into linear by the use of Taylor series at working point, the proportion coefficient between $\frac{\mathrm{d}\theta_r}{\mathrm{d}t}$ and θ_s is $a_{21} = \frac{q_r}{V}$.

The relationship between $\frac{\mathrm{d}\theta_r}{\mathrm{d}t}$ and q_r can be transformed into linear by the use of Taylor series at working point, the proportion coefficient between $\frac{\mathrm{d}\theta_r}{\mathrm{d}t}$ and q_r is $b_{22} = \frac{\theta_s}{V}$.

3.3. The establishment of the state equation

The state equation describes the state of a dynamic system in terms of a set of state variables. The variables are those variables that determine the future behavior of the system when the present state of the system and input signals are known. The basis of the state equation is the physical equations among output variables and input variables [2,3]. According to the analyzing of the first subsection and the second subsection, the following can be deduced:

State variables: x_1 is supply air temperature, $x_1 = \theta_{a,\mathrm{out}} = \theta_s$; x_2 is indoor air temperature of room, $x_2 = \theta_r$.
Input variables: u_1 is chilled water flow rate; u_2 is supply air flow rate of room.
Output variables: y_1 is supply air temperature; y_2 is indoor air temperature of room.

State equation is described as Eq. (9):

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}-\frac{1}{T_1} & 0\\ a_{21} & -\frac{1}{T_2}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\frac{b_{11}}{T_1} & \frac{b_{12}}{T_1}\\ 0 & b_{22}\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

$$\begin{bmatrix}y_1\\ y_2\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} \tag{9}$$

In Eq. (9)

$$A = \begin{bmatrix}-\frac{1}{T_1} & 0\\ a_{21} & -\frac{1}{T_2}\end{bmatrix}, \qquad B = \begin{bmatrix}\frac{b_{11}}{T_1} & \frac{b_{12}}{T_1}\\ 0 & b_{22}\end{bmatrix}$$

$$C = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, \qquad Y = \begin{bmatrix}y_1\\ y_2\end{bmatrix}, \qquad U = \begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

Through deducing, Y can be described as Eq. (10):

$$Y = C(sI - A)^{-1}BU \tag{10}$$

In Eq. (10), matrix I is unit matrix.

The transfer function matrix of controlled process $G_0(s)$ can be described as Eq. (11):

$$G_0(s) = C(sI - A)^{-1}B \tag{11}$$

Through deducing, $G_0(s)$ can be described as Eq. (12):

$$G_0(s) = \begin{bmatrix}\frac{b_{11}}{T_1 s+1} & \frac{b_{12}}{T_1 s+1}\\ \frac{a_{21}b_{11}T_2}{(T_1 s+1)(T_2 s+1)} & \frac{b_{22}T_1T_2 s+(a_{21}b_{12}T_2+b_{22}T_2)}{(T_1 s+1)(T_2 s+1)}\end{bmatrix} \tag{12}$$

4. The structure of the state feedback decoupling control system

Fig. 2 is the schematic diagram of the state feedback decoupling control system. In Fig. 2, U is the input vector, $U = [u_1 \quad u_2]^{\mathrm{T}}$; Y is the output vector, $Y = [y_1 \quad y_2]^{\mathrm{T}}$. U can be described as $U = K \cdot x + H \cdot v$. The objective and function of state feedback decoupling control system is to transform the transfer function matrix $G_f(s)$ of the system in Fig. 2 into a diagonal matrix through designing the matrix K and H. Thus, the coupling between loop of indoor air temperature and loop of supply air temperature is eliminated, and air conditioning system is decoupled.

The transfer function matrix of system in Fig. 2 can be described as Eq. (13):

$$G_f(s) = C(sI - A - BK)^{-1}BH \tag{13}$$

$G_1(s)$ is the first row of matrix $G_0(s)$; $G_2(s)$ is the second row of matrix $G_0(s)$; $d_i = \min\{$the order difference between denominator and numerator of elements in $G_i(s)\} - 1$; $d_1 = 0$, $d_2 = 0$. C_1 is the first row of matrix C; C_2 is the second row of matrix C.

Matrix F can be described as following:

$$F_1 = C_1 A^{d_1+1} = [1 \quad 0]\begin{bmatrix}-\frac{1}{T_1} & 0\\ a_{21} & -\frac{1}{T_2}\end{bmatrix} = \begin{bmatrix}-\frac{1}{T_1} & 0\end{bmatrix}$$

$$F_2 = C_2 A^{d_2+1} = [0 \quad 1]\begin{bmatrix}-\frac{1}{T_1} & 0\\ a_{21} & -\frac{1}{T_2}\end{bmatrix} = \begin{bmatrix}a_{21} & -\frac{1}{T_2}\end{bmatrix}$$

$$F = \begin{bmatrix}F_1\\ F_2\end{bmatrix} = \begin{bmatrix}-\frac{1}{T_1} & 0\\ a_{21} & -\frac{1}{T_2}\end{bmatrix}$$

$$E_1 = \lim_{s\to\infty} s \cdot G_1(s) = \begin{bmatrix}\frac{b_{11}}{T_1} & \frac{b_{12}}{T_1}\end{bmatrix}$$

$$E_2 = \lim_{s\to\infty} s \cdot G_2(s) = [0 \quad b_{22}]$$

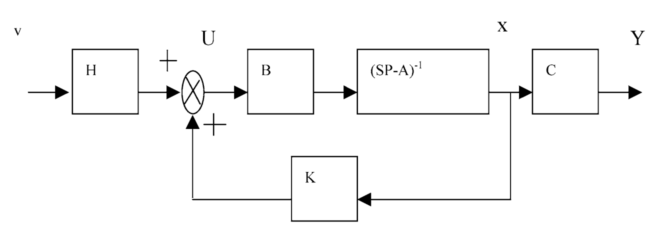

Fig. 2. Decoupling system of state feedback.

$$E=\begin{bmatrix}E_1\\E_2\end{bmatrix}=\begin{bmatrix}\frac{b_{11}}{T_1} & \frac{b_{12}}{T_1}\\ 0 & b_{22}\end{bmatrix}$$

$$E^{-1}=\begin{bmatrix}\frac{T_1}{b_{11}} & -\frac{b_{12}}{b_{11}}\frac{1}{b_{22}}\\ 0 & \frac{1}{b_{22}}\end{bmatrix}$$

$$H=E^{-1}=\begin{bmatrix}\frac{T_1}{b_{11}} & -\frac{b_{12}}{b_{11}}\frac{1}{b_{22}}\\ 0 & \frac{1}{b_{22}}\end{bmatrix}$$

$$K=-E^{-1}F=-\begin{bmatrix}\frac{T_1}{b_{11}} & -\frac{b_{12}}{b_{11}}\frac{1}{b_{22}}\\ 0 & \frac{1}{b_{22}}\end{bmatrix}\begin{bmatrix}-\frac{1}{T_1} & 0\\ a_{21} & -\frac{1}{T_2}\end{bmatrix}$$

$$K=\begin{bmatrix}\frac{1}{b_{11}}+\frac{b_{12}}{b_{11}}\frac{a_{21}}{b_{22}} & -\frac{b_{12}}{b_{11}}\frac{1}{b_{22}}\frac{1}{T_2}\\ -\frac{a_{21}}{b_{22}} & \frac{1}{T_2 b_{22}}\end{bmatrix}$$

The transfer function matrix of decoupling system in Fig. 2 can be described as following:

$$G_f(s)=C(sI-A-BK)^{-1}BH$$

Through calculating

$$G_f(s)=\begin{bmatrix}\frac{1}{s} & 0\\ 0 & \frac{1}{s}\end{bmatrix}$$

In the above deducing, the transfer function matrix $G_f(s)$ is transformed into a diagonal matrix, so that the coupling between loop of indoor air temperature and loop of supply air temperature is eliminated, and VAV air conditioning system is decoupled.

5. Designing of the controller parameters

5.1. PID parameters vs the roots of characteristic equation

The controlled process is transformed into $G_f(s)$ through state feedback decoupling. The transfer function between indoor air temperature and supply air flow rate is $\frac{1}{s}$. The transfer function of zero-order hold is $\frac{1-e^{-T_0 s}}{s}$, T_0 is the sampling period of indoor air temperature—supply air flow rate loop.

$$G_r(z)=Z\left[\frac{1-e^{-T_0 s}}{s}\frac{1}{s}\right] \tag{14}$$

Eq. (14) can be transformed into Eq. (15):

$$G_r(z)=\frac{T_0}{z-1} \tag{15}$$

The transfer function of PID controller of the supply air flow rate-indoor air temperature loop is $D_r(s)$:

$$D_r(s)=k_p+\frac{k_I}{s}+k_D s \tag{16}$$

$\frac{k_I}{s}$ in Eq. (16) can be changed by means of bilinear transformation ($s=\frac{2}{T_0}\frac{1-z^{-1}}{1+z^{-1}}$);

$k_D\cdot s$ in Eq. (16) can be changed by means of backward difference ($s=\frac{1-z^{-1}}{T_0}$);

Eq. (16) can be transformed into Eq. (17):

$$D_r(z)=k_p+\frac{k_I T_0(z+1)}{2(z-1)}+\frac{k_D(z-1)}{T_0 z} \tag{17}$$

$$D_r(z)=\left[\left(k_I T_0^2+2k_D+2k_p T_0\right)z^2+\left(k_I T_0^2-2k_p T_0-4k_D\right)z+2k_D\right]\times\left[2T_0 z(z-1)\right]^{-1} \tag{18}$$

$$D_r(z)G_r(z)=\left\{\left[\left(k_I T_0^2+2k_D+2k_p T_0\right)z^2+\left(k_I T_0^2-2k_p T_0-4k_D\right)z+2k_D\right]\times\left[2T_0 z(z-1)\right]^{-1}\right\}\frac{T_0}{z-1} \tag{19}$$

$$D_r(z)G_r(z)=\frac{\frac{k_I T_0^2+2k_p T_0+2k_D}{2T_0}(z-x_2)(z-1)}{z(z-1)}\frac{T_0}{z-1} \tag{20}$$

Based on the above deducing, the characteristic equation can be described as Eq. (21):

$$z^2-z+\frac{T_0(k_I T_0^2+2k_p T_0+2k_D)}{2T_0}(z-x_2)=0 \tag{21}$$

z_1 and z_2 are the roots of Eq. (21). The following 4 equations can be worked out (Eqs. (22)–(25)):

$$1-\frac{1}{2}\left(k_I T_0^2+2k_p T_0+2k_D\right)=z_1+z_2 \tag{22}$$

$$\frac{-x_2(k_I T_0^2+2k_p T_0+2k_D)}{2}=z_1 z_2 \tag{23}$$

$$-\frac{k_I T_0^2-2k_p T_0-4k_D}{k_I T_0^2+2k_p T_0+2k_D}=1+x_2 \tag{24}$$

$$\frac{2k_D}{k_I T_0^2+2k_p T_0+2k_D}=x_2 \tag{25}$$

Through deducing, k_{D1}, k_{p1} and k_{I1} can be worked out as Eqs. (26)–(28):

$$k_p=\frac{1}{T_0}(z_1 z_2-z_1-z_2+1) \tag{26}$$

$$k_I=0 \tag{27}$$

$$k_D=-z_1 z_2 \tag{28}$$

From the above analysis, the relationships among k_D, k_p, k_I and z_1, z_2 are directly found out. If z_1 and z_2 are within the unit circle in z-plane, the closed loop control system is stable. But z_1 and z_2 in different groups influence the performance of the control system differently. Accordingly, z_1 and z_2 should be optimized.

5.2. Optimizing z_1 and z_2 in the method of genetic algorithm

z_1 and z_2 are within the unit circle in z-plane. Different z_1 and z_2 influence the performance of the control system differently. Accordingly, z_1 and z_2 should be optimized. After z_1 and z_2 are optimized, the optimizing controller parameters could be obtained. Genetic algorithm is a nice method for optimizing z_1 and z_2.

The basic ideas of optimization method are: First, encoding of the optimization problem in a binary string. Second, random generation of a population, which includes a genetic pool representing a group of possible solutions. Third, reckoning of a fitness value for each subject. It will directly depend on the distance to the optimum. Fourth, selection of the subjects that will mate according to their share in the population global fitness. Fifth, genomes crossover and mutations. Sixth, starting again from point 3. Finally, the optimization solution can be found out.

In order to satisfy the transformation, z_1 and z_2 are transformed into polar coordinate forms as the following:

$$z_1 = \rho_1 \cos\theta_1 + i\rho_1 \sin\theta_1$$
$$z_2 = \rho_1 \cos\theta_1 - i\rho_1 \sin\theta_1.$$

The range of ρ_1: $0 < \rho_1 < 1$; the range of θ_1: $0 \leqslant \theta_1 \leqslant 3.1416$.

Step 1: The transformation from the solution space (Π) to genetic algorithm search space (S_{GA}):

$$\Pi = (\rho_1, \theta_1) \implies S_{GA} = (f_1, g_1)$$

Step 2: The transformations from f_1, g_1 to ρ_1, θ_1 are described as Eqs. (29) and (30):

$$\rho_1 = \rho_{1\min} + [\rho_{1\max} - \rho_{1\min}]\frac{f_1}{2^{d1} - 1} \tag{29}$$

$$\theta_1 = \theta_{1\min} + [\theta_{1\max} - \theta_{1\min}]\frac{g_1}{2^{d1} - 1} \tag{30}$$

In Eqs. (29) and (30), $d_1 = 10$, $\rho_{1\min} = 0$, $\rho_{1\max} = 1$, $\theta_{1\min} = 0$, $\theta_{1\max} = 3.1416$:

$$\rho_1 = 0 + [1 - 0]\frac{f_1}{2^{10} - 1}$$

$$\theta_1 = 0 + [3.1416 - 0]\frac{g_1}{2^{10} - 1}$$

the length of each individual in population is $L_1 = 20$.

For example, $\Pi = (0.04203, 1.89172) \implies S_{GA} = (43, 616)$.

Gene locus:

1	2	3	4	5	6	7	8	9	10
0	0	0	0	1	0	1	0	1	1

f_1

11	12	13	14	15	16	17	18	19	20
1	0	0	1	1	0	1	0	0	0

g_1

Bit string: $S_{GA} = 00001010111001101000$

Step 3: Object function J can be described as Eq. (31):

$$J = \sum_{k_{ad}=1}^{300} \left[r(k_{ad}) - y(k_{ad})\right]^2 \tag{31}$$

In Eq. (31), k_{ad} is the sampling time of indoor air temperature—supply air flow rate control loop. $r(k_{ad})$ is the set-point of indoor air temperature—supply air flow rate control loop. $y(k_{ad})$ is the output of indoor air temperature—supply air flow rate control loop.

The object of the genetic algorithm is to search the minimum of object function J. The fitness f_i must be satisfied with 2 conditions: (a) $f_i \geqslant 0$; (b) the optimizing direction of the object function is the direction of increasing fitness. Fitness f_i can be described as Eq. (32):

$$f_i = c_{\max} - J \tag{32}$$

In Eq. (32), $c_{\max}$ is the maximum of each circulating calculation, so $f_i \geqslant 0$. Meanwhile, the direction of searching minimum of J is the direction of increasing fitness f_i.

Step 4: In genetic algorithm space, the initialized population is produced randomly; the amount of individuals is 20.

Step 5: To search maximum of fitness $f_{\max}$ and to search average fitness f_{avg}.

Step 6: If $f_{\max}$ and f_{avg} are the expected solutions, then the calculation ends. Otherwise, go to the next step.

Step 7: In genetic algorithm space, the population of next generation is produced by the operation of genetic algorithm, and they are decoded to solution space.

Step 8: Go to step 5.

6. Implemental study with LonWorks technology

LonWorks technology is one of the most important fieldbus technology. The advantages of the LonWorks open system include:

- The ability for owners and integrators to choose amongst best-of-breed, off-the-shelf components selected from among different manufacturers for both initial installations and enhancements down the road that are not tied to one manufacturer's closed technology.
- Lower system costs since the ability to choose fosters greater price competition.
- Less complexity and fewer failure points through the elimination of gateways to bridge between sub-systems.
- Lower cost deployments because it is faster to deploy interoperable products than non-interoperable products.
- The modularity of open systems enables changes and expansion to occur in a less-costly and less-complex manner.
- Lower life-cycle costs, particularly from an operations and maintenance perspective.

Network variable is an important concept of LonWorks technology. The data exchange among different node devices of LON network is realized by network variables. It is suitable that decoupling compensation coefficients between loop

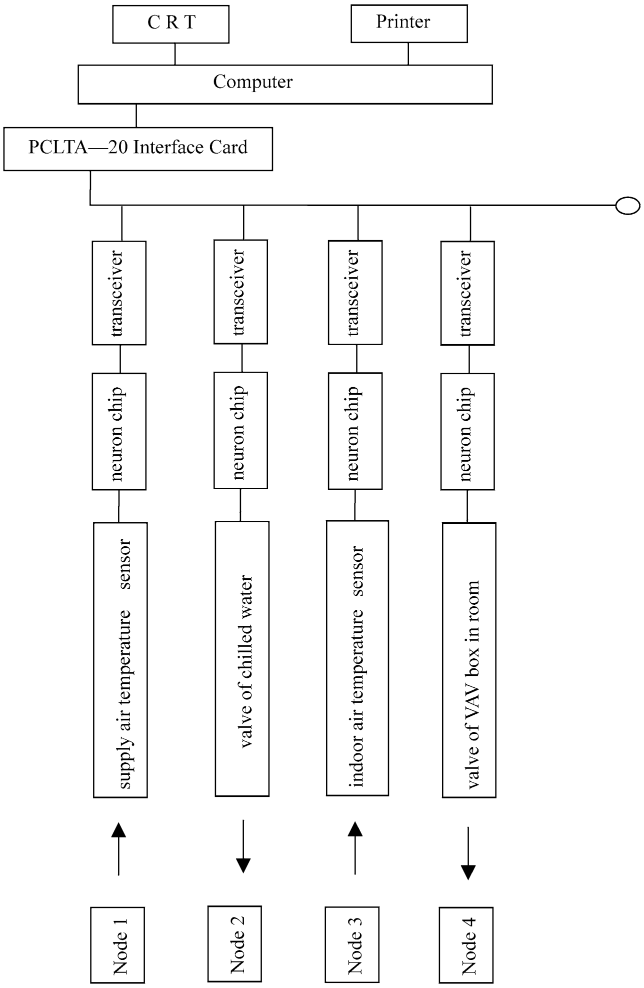

Fig. 3. The schematic of decoupling control system of VAV air conditioning by LonWorks technology.

of indoor air temperature and loop of supply air temperature are handled as network variables of LonWorks technology. Fig. 3 is the schematic diagram of decoupling control system realized by LonWorks technology.

This system has 2 control loops. The first loop is loop of the chilled water flow rate—supply air temperature; the second loop is loop of the supply air flow rate of room—indoor air temperature of room. The link between input network variable and output network variable is described as Table 1. Types, units and ranges of these user defined network variables are described as Table 2.

This control network system has 4 nodes.

Node 1 is the sensor node of supply air temperature. Its output network variable is:

nv_satp_out (the measured value of supply air temperature).

Node 2 is the control node of the chilled water valve. Its input network variables are:

nv_satp_in (the measured value of supply air temperature),

Table 1
Link between input network variable and output network variable

nv_satp_out (node 1)	⟷	nv_satp_in (node 2)
nv_b12H_out (node 2)	⟷	nv_b12H_in (node 4)
nv_b12K_out (node 2)	⟷	nv_b12K_in (node 4)
nv_iatp_out (node 3)	⟷	nv_iatp_in (node 4)
nv_b21H_out (node 4)	⟷	nv_b21H_in (node 2)
nv_b21K_out (node 4)	⟷	nv_b21K_in (node 2)

Table 2
Types, units and ranges of network variables

	Type	Unit	Range
nv_satp_out (node 1)	float_type	°C	0.0–30.0
nv_satp_in (node 2)	float_type	°C	0.0–30.0
nv_b12H_out (node 2)	float_type	$m^3 \cdot s^{-1}$	0.0–0.3
nv_b12H_in (node 4)	float_type	$m^3 \cdot s^{-1}$	0.0–0.3
nv_b12K_out (node 2)	float_type	$m^3 \cdot s^{-1}$	0.0–0.3
nv_b12K_in (node 4)	float_type	$m^3 \cdot s^{-1}$	0.0–0.3
nv_iatp_out (node 3)	float_type	°C	0.0–50.0
nv_iatp_in (node 4)	float_type	°C	0.0–50.0
nv_b21H_out (node 4)	float_type	$m^3 \cdot s^{-1}$	0.0–0.1
nv_b21H_in (node 2)	float_type	$m^3 \cdot s^{-1}$	0.0–0.1
nv_b21K_out (node 4)	float_type	$m^3 \cdot s^{-1}$	0.0–0.1
nv_b21K_in (node 2)	float_type	$m^3 \cdot s^{-1}$	0.0–0.1

nv_b21H_in (the compensation coefficient of the second loop to the first loop, it is caused by H matrix),
nv_b21K_in (the compensation coefficient of the second loop to the first loop, it is caused by K matrix).

Its output network variables are:

nv_b12H_out (the compensation coefficient of the first loop to the second loop, it is caused by H matrix),
nv_b12K_out (the compensation coefficient of the first loop to the second loop, it is caused by K matrix).

Node 3 is the sensor node of indoor air temperature of room. Its output network variable is:

nv_iatp_out (the measured value of indoor air temperature of room).

Node 4 is the control node of the VAV box valve in room. Its input network variables are:

nv_iatp_in (the measured value of indoor air temperature of room),
nv_b12H_in (the compensation coefficient of the first loop to the second loop, it is caused by H matrix),
nv_b12K_in (the compensation coefficient of the first loop to the second loop, it is caused by K matrix).

Its output network variables are:

nv_b21H_out (the compensation coefficient of the second loop to the first loop, it is caused by H matrix), nv_b21K_out (the compensation coefficient of the second loop to the first loop, it is caused by K matrix).

7. The experimental results

This paper improves the control performance of indoor air temperature in VAV air conditioning system through state feedback decoupling, genetic algorithm and LonWorks technology. Fig. 4 is the response curve of indoor air temperature without improvements. Fig. 5 is the response curve of indoor air temperature with improvements. In these figures, "r" indicates the set-point curve, while "y" stands for the measured curve. The root mean square of difference between the set-point curve and the actual curve in Fig. 4 is 0.39; while the root mean square of difference between the set-point curve and the actual curve in Fig. 5 is 0.14. Obviously, the actual curve is more close to the set-point curve through improving method. Precision of the indoor air temperature is highly improved. This is due to two reasons. One of them is that the coupling between the indoor air temperature and the supply air temperature is eliminated, so that the supply air temperature no longer affects the indoor air temperature. Another reason is that the PID parameters of the controller are optimized.

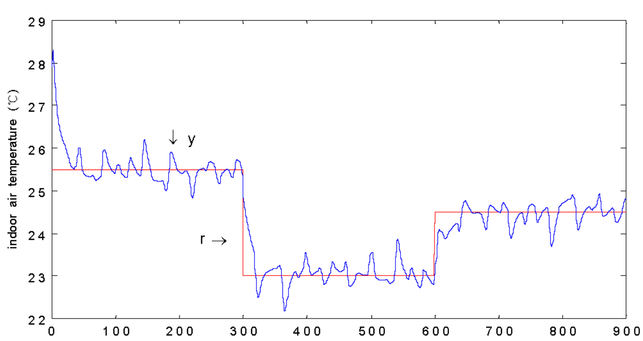

Fig. 4. Response curve of indoor air temperature without improvements.

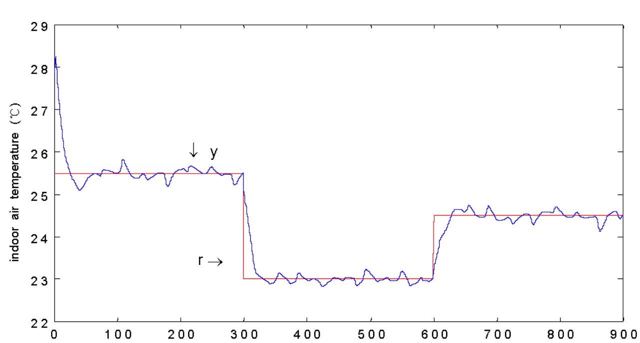

Fig. 5. Response curve of indoor air temperature with improvements.

8. Conclusion

The combination of the state feedback decoupling, genetic algorithm and LonWorks technology can improve the control performance of indoor air temperature in VAV air conditioning system effectively.

State feedback decoupling is a good method for eliminating the coupling between loop of indoor air temperature and loop of supply air temperature.

The combination of inverse deducing and genetic algorithm is an effective way to optimize the controller parameters of air conditioning system.

It is suitable that decoupling compensation coefficients between loop of indoor air temperature and loop of supply air temperature are handled as network variables of LonWorks technology.

The advantage of the method discussed in this paper is that it can improve the performance of indoor air temperature of air conditioning system, while the limitation of the method is that the computing workload is vast, but it is easy for high speed processor.

Acknowledgements

The research work presented in the paper is financially supported by Education Department of Shaanxi Province, China.

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