Comparison of occupancy detection algorithms, methods of signals filtration and types of requirements expression for CO_2-based DCV systems

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ABSTRACT

The paper presents part of the outcomes from the project set up by the Polish Committee for Scientific Research and devoted to development of the recommended control strategies for Demand Controlled Ventilation (DCV) systems in Poland. The performance of both different CO_2-based occupancy detection algorithms for online demand controlled ventilation systems and different methods of digital filtration of signals have been studied. Additionally, the analysis covers three different procedures of adjusting ventilation rates according to the following ventilation standards: ASHRAE 62-2001, CEN CR 1752 and Polish standard PN-83/B-03430. Computer simulation was used to present the accuracy of the analysed algorithms.

INDEX TERMS

Occupancy detection; Demand controlled ventilation; Computer simulation

INTRODUCTION

In the last 15 years vital interest in Demand Controlled Ventilation (DCV) systems, especially based on measurements of CO_2 concentration, resulted in a number of studies. The interest was based on the assumption that adapting the ventilation rate to the actual demand may fulfil both goals of comfortable indoor environment and low energy consumption. All aspect of this type of ventilation from theory, through simulations and applications, up to case studies may be found in a large set of papers. For instance, extensive literature reviews were prepared by Raatschen (1990), Emmerich and Persily (1997) and Fisk and De Almeida (1998).

However, in the author's opinion, there is still some room to discuss the DCV system performance taking into consideration different detection algorithms (Sowa, 2001) and signal filtration methods. Moreover the recommendations may depend on the type of expressing requirement in ventilation standard. Typical ventilation requirements are described using one or a mixture of the following concepts: minimum ventilation rate per person, minimum air change rate and minimum ventilation rate per floor area. The undertaken researches took into consideration the following standards: ASHRAE Standard 62-2001 (ASHRAE, 2001), report CEN CR 1752 (CEN, 1998) and Polish Standard PN-83/B-03430 (PKN, 2000).

OCCUPANCY DETECION ALGORITHMS

Principles of online controlling of ventilation using CO_2 concentrations are based on the mass balance for CO_2. Assuming that people are the only source of carbon dioxide for the single room ventilated only with outdoor air the balance can be described by Eqn (1):

$$M \frac{\mathrm{d}C_{\mathrm{R}}}{\mathrm{d}t} = e_0 \cdot a \cdot P + \left(C_{\mathrm{OA}} - C_{\mathrm{R}}\right) \cdot \dot{m}_{\mathrm{OA}} \cdot \varepsilon_{\mathrm{AC}} \tag{1}$$

where M is the mass of air in the room, C_R is the CO_2 concentration (mass) in the occupied zone, e_0 is the average CO_2 generation rate (mass) of an occupant in reference activity, a is the

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activity level of the occupants in the space, P is the number of occupants, C_{OA} is the CO_2 concentration (mass) in the supply air, $\dot{m}_{OA}$ is the mass stream of outdoor air used to ventilate the room, ε_{AC} is the air change effectiveness and t denotes time.

Eqn (1) describes system behaviour in continuous time. However, due to sampling interval and properties of processor calculations, real estimation techniques have to use discrete time. The simplest occupant detection algorithm is based on the assumption that CO_2 concentration reached the state of equilibrium. Steady state detection algorithm was developed assuming that derivative $dC_R/dt = 0$. Using measurement data of the outdoor air flow rate and both outdoor and indoor CO_2 concentrations, the actual occupancy of a space in moment i can be estimated using Eqn (2):

$$P^i = \frac{\left(C_R^i - C_{OA}^i\right) \cdot \dot{m}_{OA}^i \cdot \varepsilon_{AC}}{e_0 \cdot a} \tag{2}$$

A more precise method of the occupancy detection is based on the approximation of the derivative (dC_R/dt) by the difference of CO_2 concentration in the occupied zone ($i - 1$ represents previous sampling point) divided by the sampling interval Δt

$$\frac{dC}{dt} = \frac{C_R^i - C_R^{i-1}}{\Delta t} \tag{3}$$

Using this assumption, Eqn (1) can be converted into discrete form:

$$P^i = \frac{\left(C_R^i - C_{OA}^i\right)\left(\dot{m}_{OA}^i + \dot{m}_{OA}^{i-1}\right)}{2 \cdot e_0 \cdot a} + \frac{\left(C_R^i - C_R^{i-1}\right) \cdot M}{\Delta t \cdot e_0 \cdot a} \tag{4}$$

Knowing the number of occupants, estimated by one of the described above algorithms, and taking into consideration existing limitations of the system, the mass stream of outdoor air for next step $i + 1$ can be adjusted according to Eqn (5):

$$\dot{m}_{OA}^{i+1} = \mathrm{MIN}\left(\mathrm{MAX}\left(P^i \cdot R_P \cdot \rho + R_B \cdot A_B \cdot \rho; \dot{m}_{MIN}\right); \dot{m}_{MAX}\right) \tag{5}$$

where R_P is the outdoor air requirement per person, R_B is the outdoor air requirement per unit area, ρ is the air density, A_B is the net area of the floor in the occupied zone $\dot{m}_{MIN}$ and $\dot{m}_{MAX}$ are lower and upper limits of the real ventilation system, respectively.

SIGNAL FILTRATION METHODS

In practice, measured values do not represent the real state but are interfered by a number of random factors. Estimations based on such data may propagate and increase the input noise in the system. Therefore, very often real control systems use signal filtration methods to reduce input noise as well as to reduce rapid unrealistic changes in the estimated parameters.

The signals may be smoothed using moving average, moving median, moving linear regression and more sophisticated methods like Kalman (Federspiel, 1994, 1995) or by the 'forgetting filter' used in the studies on CO_2-based DCV systems by Wang and Jin (1998) and Wang *et al.* (1999). The 'forgetting filter' performance can be described by the following equation:

$$y_{out}^i = \varphi \cdot y_{out}^{i-1} + \left(1 - \varphi\right) \cdot y_{in}^i \tag{6}$$

where y_{out} is the filter output, y_{in} is the filter input (the superscripts i and $I - 1$ represents the current and previous sampling point, φ is a forgetting factor.

SIMULATIONS

The performance of the described CO_2-based occupancy detection algorithms as well as signal filtration methods was studied using computer simulation with a 30-s time step. The input parameters used for the simulation described an existing conference room for 30 persons (floor area of 60 m^2 and volume of 170.5 m^3). Outdoor air, filtered and heated in cold periods, is supplied by four ceiling diffusers. An air conditioner mounted in the ceiling (100% recirculation) is responsible for cooling and additional mixing of air in the room. The control system allows changing the ventilation rate according to demands. On the other hand, the control system itself creates lower limitations for ventilation rate ($\dot{m}_{MIN}$ of 10% of the maximum value). Required ventilation rates and maximum ventilation rate supplied by the system are dependent on the ventilation standard and are summarized in Table 1.

Table 1 Ventilation rates in the analysed test room

Ventilation standard	Ventilation rate per person l/(s person)	Ventilation rate per area (l/s/m^2)	Maximum ventilation rate (l/s)
ASHRAE 62-2001	10	0	300
CR EU1752 (class B)	7	1.4	294
PN-83/B-03430	8.33	0	250

The most difficult task for occupancy detection algorithms is to truly recognize rapid entrance of a group of people into a room. Therefore, the algorithms and signal filtration methods were checked with the scenario of a sequence of rapid 10, 20 and 30 person entrances. Each occupation lasts 1 h and is separated by a 1-h break.

The simulation took into account that measurement data used for occupancy detection contain random errors. Pseudo-random normally distributed noise with 0 mean and standard deviation of 5 ppm modelled this phenomenon according to CO_2 concentrations. Additionally it was assumed that a similar noise of 0 mean and standard deviation of 1% of measured value is associated with flow measurements. The simulation checked the performance of 'forgetting filter' as well as moving average, moving median and mowing linear regression. The performance of Kalman filters was not covered in that part of the research project.

Normalized mean squared error (NMSE) was used as the criterion for the comparison of the methods. Table 2 presents the results of searching for optimal values of forgetting factors for dynamic algorithm. The similar analysis conducted for steady state algorithm showed that in all cases optimal forgetting factors were equal to 0. Taking this into consideration, NMSE was 0.6177 for ASHRAE 62-2001, 0.4222 for CR EU1752 (class B) and 0.5403 for PN-83/B-03430. Figure 1 presents the comparison of real and estimated number of people in the room without signal filtration and after optimized 'forgetting filtration' in the case when ventilation standard ASHRAE 62-2001 was used. Figures 2 and 3 present similar comparisons for the cases when the ventilation rate was adjusted according to report CEN CR 1752 and Polish Standard PN-83/B-03430.

Table 2 The values of normalized mean squared error (NMSE) and the optimized forgetting factors for the dynamic algorithm

Ventilation standard	Dynamic algorithm			
	NMSE	Optimal forgetting factors (min NMSE)		
		measured CO_2 concentration	measured flow volume	detected occupancy
ASHRAE 62-2001	0.06375	0.5593	0	0.4221
CR EU1752 (class B)	0.06288	0.5640	0	0.4205
PN-83/B-03430	0.06312	0.5601	0	0.4217

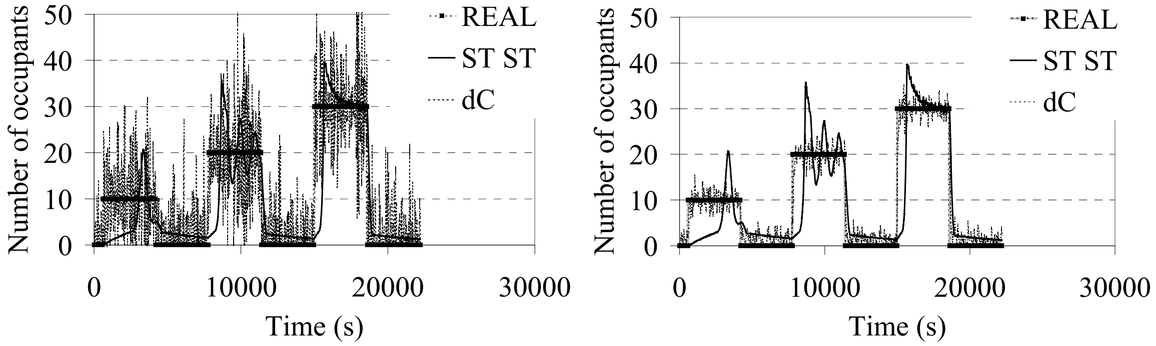

Figure 1 The comparison of real and estimated number of people in the room without signal filtration (left) and after optimized filtration (right) (ventilation standard ASHRAE 62-2001).

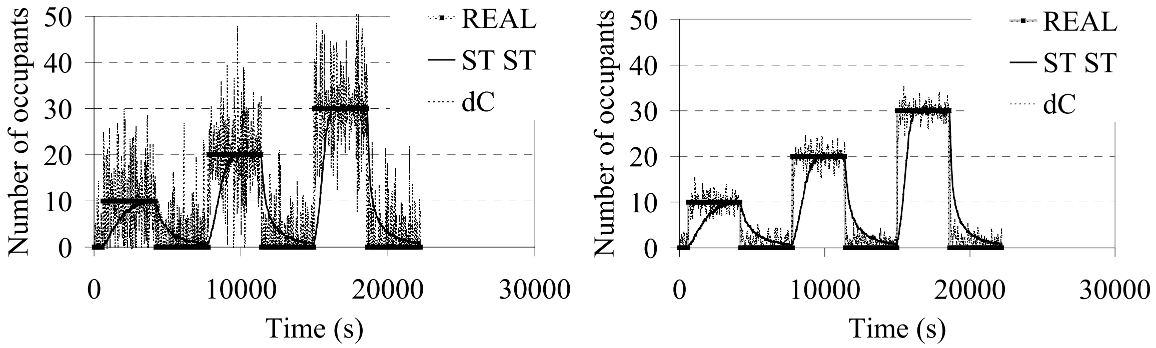

Figure 2 The comparison of real and estimated number of people in the room without signal filtration (left) and after optimized filtration (right) (report CEN CR 1752).

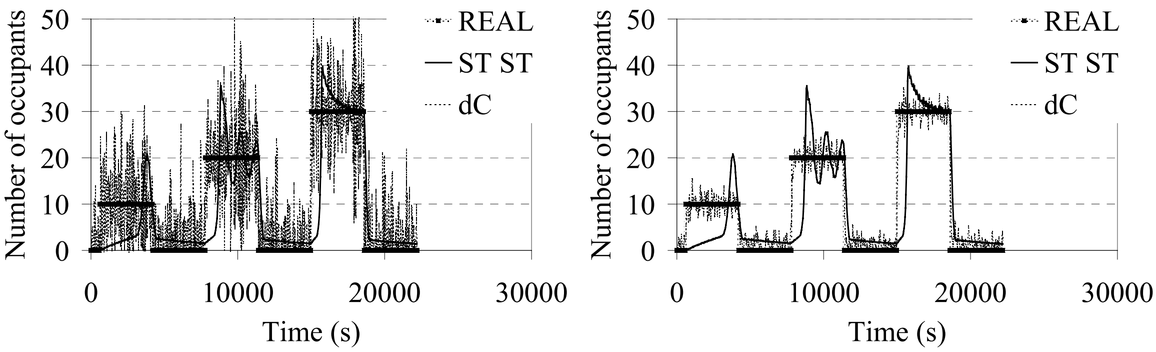

Figure 3 The comparison of real and estimated number of people in the room without signal filtration (left) and after optimized filtration (right) (ventilation standard PN-83/B-03430).

The performance of other signal filtration methods, checked for 3, 5 and 10 last input signals (averaging from 1.5, 2.5 and 5 min periods), is presented in Tables 3 (steady state algorithm) and 4 (dynamic algorithm).

Table 3 The performance of traditional signal filtration methods in the case when the steady state algorithm was used for occupancy detection (local minimums are bolded)

Type of filtration function	Ventilation standard								
	ASHRAE 62-2001			CR EU1752 (class B)			PN-83/B-03430		
	No of sampling points *k*			No of sampling points *k*			No of sampling points *k*		
	3	5	10	3	5	10	3	5	10
Average	0.8554	1.0654	1.4691	0.5310	0.6359	0.8826	0.9745	1.1221	1.5951
Median	0.8756	1.0929	1.5333	0.5329	0.6405	0.8981	0.9887	1.1432	1.6631
Linear regr.	0.6567	0.6575	0.7823	0.4286	0.4268	0.4589	0.7688	0.7589	0.9803

Table 4 The performance of traditional signal filtration methods in the case when the dynamic algorithm was used for occupancy detection (local minimums are bolded)

Type of filtration function	Ventilation standard								
	ASHRAE 62-2001			CR EU1752 (class B)			PN-83/B-03430		
	No of sampling points *k*			No of sampling points *k*			No of sampling points *k*		
	3	5	10	3	5	10	3	5	10
Average	0.0717	0.1141	0.2654	0.0706	0.1131	0.2640	0.0716	0.1141	0.2655
Median	0.1116	0.1726	0.3312	0.1189	0.1774	0.3301	0.1131	0.1743	0.3311
Linear regr.	0.2412	0.0972	0.0829	0.2329	0.1003	0.0856	0.2386	0.0968	0.0822

DISCUSSION

The performed tests showed that measured data containing random noise influences the performance of occupancy detection algorithms differently. As the steady state algorithm is not dependent on previous estimations the noise of the input data is not amplified and therefore the system does not require the signal filtration. On the contrary, the dynamic algorithm based on the measurements in two consecutive time points is very sensitive for the input noise associated with CO_2 concentrations. This is because the occupancy detection algorithm described by Eqn (4) contains the difference between CO_2 levels in two consecutive time points, while ventilation rate, another measured factor, is already averaged in the equation. NMSE used as the criterion showed that among the tested methods of signal filtration the 'forgetting filtration' gave the best results. Other filtration methods also improve the estimation but not as effectively as 'forgetting filter'. In that group of filters the moving average gave the best results. From the results in Tables 3 and 4 the most effective was short averaging (in the conducted analysis for three points; only in cases of linear regression for five points we obtained better results). It should be pointed out that in spite of the sensitivity to noise associated with CO_2 measurement the dynamic algorithm better detects the occupancy.

It is worth pointing out that taking into consideration the type of standards, the most accurate estimations are obtained for report CR 1752. The reason of this phenomenon is caused by the fact that a constant part of the required ventilation rate not associated with occupancy reduces the system oscillation. Faster response by the steady state algorithm can be explained by higher ventilation rates at low occupancy.

CONCLUSION AND IMPLICATIONS

The presented study showed that when measured data contain random noise, not only different detection algorithms and type of expressing requirement in ventilation standard but also the method of signal filtration influences occupancy detection algorithms and in consequence DCV system performance. The necessity of effective signal filtration for the dynamic algorithm of occupancy detection was clearly shown.

Although the performance of two algorithms, three types of ventilation requirements and 10 variants of methods of signal filtration have been checked carefully in an idealized virtual world, the results may not be the same in reality. Of course, due to differences in CO_2 emissions, imperfect mixing of air in the room and time delays connected with pollutant transport there may be certain differences between the developed models and experiments in real DCV systems. However, it is expected that the basic conclusions from this part of the study would be valid also in the real. The experimental verification of the simulations is currently performed.

Adapting the ventilation rate to the actual demand is one of the most promising ideas of comfortable and energy efficient ventilation. As typical ventilation requirements are described by minimum ventilation rate per person, development of effective algorithms of occupancy detection is the crucial element for the implementation of DCV systems. The developed strategies verified and tuned during the experiments in the real control systems may provide an effective way of CO_2-based DCV control system for the rooms when there is no other source of CO_2 other than people.

ACKNOWLEDGEMENTS

The study is part of a project 8 T07G 004 21 funded by the Polish State Committee for Scientific Research.

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