Automation and wireless control for mining ventilation

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Mining

Components:

- Blasting and drilling
- Transport: trucks or hoist
- Ore crushing
- Ventilation: 50% of the energy consumption – Mining = 4 (US) to 6% (South Africa) of industrial electrical consumption
BOLIDEN

- Mining and smelting company
- 3 500 MEUR turnover
- 4 500 employees
- 3 Swedish and 1 Irish mine

Garpenberg mine
- Mining since 9th century
- 1000K ton ore/yr
  - 58K Zn, 21K Pb, 0.56K Cu, 0.1K Ag, 0.2 Au
- 1 100 m deep
- 280 employees
I. Mining ventilation control
actual architecture

- Ventilation control = worst case ventilation design
- i.e. choice of the tunnels diameter / fans power depending on the trucks
- Operation at max power when extracting the ore
- No continuous air quality monitoring (scheduled)
- No WSN

![Diagram of mining ventilation control architecture]

- Turbine + heater
- Control room
- Ground
- Ventilation shaft
- Exhaust shaft
- Wired connections
- Extraction rooms
- Fans
- Tarpauline tubes
- Truck access tunnel
- Communication-based automation
- Safety system: motion detectors + clock-based operation
- Frequency converters
Potential wireless control architecture for mining ventilation

- **Centralized**
  - Fans with Embedded control
  - Phone and other communications
  - Frequency converters
  - Pressure sensors
  - Communication nodes / CO sensors

- **Decentralized**
  - Wireless networks:
    - Pressure sensors
    - Communication nodes / CO sensors
  - Wired Connections i.e. PLC
  - Control signals transmissions

Control room
Network Modeling: Platform of Services

Applications

- Security
- Ventilation Control
- Phone Calls
- Video Calls

Middleware of Services on the mobile gateways

- Safety

- Positioning
- Data Fusion
- Protocol Adaptation

Heterogeneous Networks

- IEEE 802.15.4
- IEEE 802.11
- Ethernet LAN
- Power Line
Control architecture and objectives

Objectives:
- Control air quality ($O_2$, NOx and CO) in extraction rooms at suitable level
  - Regulate turbine and heater to provide suitable airflow pressure at ventilation fans
  - Regulate ventilation fans to ensure air quality in extraction rooms
- Safety through wireless networking for personal communication and localization

Design constraints:
- Physical interconnections, actuators limitations and networking capabilities
- Sensing capabilities: $O_2$, NOx, CO and pressure and temperature
Plant models and control systems

- **Primary system:**
  - Flow model: compressible viscous flow (Navier-Stokes)
  - Regulated output: pressure at the fans locations
  - Actuation: turbine and heater
  - Sensing: pressure and temperature along vertical shaft
  - External inputs: fan boundary conditions, atmospheric conditions

- **Secondary system:**
  - Flow model: Incompressible, inviscid, adiabatic flow + empirical data
  - Regulated output: air quality
  - Actuation: fans
  - Sensing: air quality through WSN
  - External inputs: pressure in primary system, number of vehicles in the room
II. Primary System

- Turbine and heater (2nd and 1st order dynamics, respect.)
- Compressible viscous flow
- Estimation / observation based on pressure and/or temperature sensors
- Fans exhausts and regulated pressure
- Delayed measurements, bandwidth limitation
Physical model for the vertical shaft

- 2-D model:
  - conservation of mass, momentum and energy
  
  \[
  \frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \rho V \\ \rho E \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho V^T \otimes \nabla + \rho I - \tau \\ \rho V H - \tau \cdot V - k \nabla T \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
  \]

  - state-space expression
  
  \[
  \begin{align*}
  \frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho V) \\
  \rho \frac{D u}{D t} &= -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} \\
  \rho \frac{D v}{D t} &= -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} \\
  \rho D \left( e + \frac{V^2}{2} \right) &= \rho \dot{\theta} + \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) - \nabla \cdot (\rho V) \\
  &\quad + \frac{\partial (u \tau_{xx})}{\partial x} + \frac{\partial (u \tau_{yx})}{\partial y} + \frac{\partial (v \tau_{xy})}{\partial x} + \frac{\partial (v \tau_{yy})}{\partial y}
  \end{align*}
  \]

  - \( p = \rho R T \)
  - \( e = c_v T \)

  - + discrete boundary conditions (potential numerical instabilities)
0D, bond graph model

- Energy approach: equivalent to finite volume method → physically **consistent averaging** of the dynamics.

- Hypotheses:
  1. only **static pressure** considered in energy conservation;
  2. impulsive term negligible compared to **pressure in momentum conservation**;
  3. momentum dynamics simplified using Saint-Venant equations → **algebraic** relationship.

⇒ Algebro-differential model with **numerically robust** ODE description.
Resulting simulator

- Simulator properties:
  - ventilation shafts \approx 28\ control volumes (CV);
  - 3 extraction levels;
  - regulation of the turbine and fans;
  - flows, pressures and temperatures measured in each CV.

- Case study:
  - turbine rotational speed increased from 260 to 280 rpm at \( t = 1000\) s;
  - 1\textsuperscript{st} level fan not operated, 2\textsuperscript{nd} level fan goes from 0 to 150 rpm at \( t = 2000\) s and 3\textsuperscript{rd} level fan operated at 200 rpm;
  - CO pollution injected at \( t = 500\) s during 80 s in 3\textsuperscript{rd} level;
  - measurement of flow speed, pressure, temperature and pollution at the surface and extraction levels.
Simulation results

- Physical and chemical airflow properties:
  - pressure losses = energy losses;
  - rooms ventilation rate = physical interconnections and importance of a global control strategy;
  - temperature: geothermal effect and fans compression;
  - pollutant transport: time-delay effect;

- Computation time $34\times$ faster than real-time.
First results on feedback control

- (P)I control based on surface measurements (blue) vs. surface + bottom (red)
- Down pressure tracking ($1.1 \times 10^5$ Pa)
- Promising improvements with down pressure measurements
- Sensitivity to initial conditions and destabilizing effect of P control motivate more advanced control methodologies
Model reduction: on-line parameter estimation & TdS

- General formulation:
  - estimate $c(t)$, $d(t)$, $r(t)$ and $s(t)$ in **single variable** 1-D model

$$\frac{\partial \tilde{p}}{\partial t} = c(t) \frac{\partial \tilde{p}}{\partial x} + r(t) \tilde{p} + s(t) \xi(x) \Delta p_{fan}(t) \eta_{fan}(t)$$

  from distributed pressure and perturbation measurements;
  - cost function

$$J(\theta, t) = \frac{1}{2} \int_0^\infty \| p_{meas}(\theta, t) - \tilde{p}(\theta, \theta, t) \|^2_2 \ d\theta.$$  

  - minimized using **stochastic gradient** and Gauss-Newton method, with online sensitivity computation (ODE)

$$\frac{d}{dt} \left[ \frac{\partial \tilde{p}}{\partial \theta} \right] = \frac{\partial}{\partial \tilde{p}} \left[ c(t) \frac{\partial \tilde{p}}{\partial x} + r(t) \tilde{p} \right] \frac{\partial \tilde{p}}{\partial \theta} + \left[ \frac{\partial \tilde{p}}{\partial x} \tilde{p} \xi(x) \Delta p_{fan}(t) \eta_{fan}(t) \right].$$
The proposed simplified model is promising for control purpose but the estimation algorithm needs to be robustified.
Time-delay formulation

- The PDE model (homogeneous convective-resistive)

\[
\frac{\partial}{\partial t} c(t, x) + v(t) \frac{\partial}{\partial x} c(t, x) = r(t, x) c(t, x)
\]

\[
c(t, 0) := u(t) \quad c(0, L) := \psi(L)
\]

Is equivalent to the delay differential equation

\[
\dot{\xi}(t) = v(t) \left[ u(t) - u(t - \theta_f) e^{r\theta_f} \right] + r\xi(t)
\]

⇒ Reduced model equivalent to a time-varying delay system: significant and exact model reduction for control!
III. Secondary system

Fans with Embedded control

Control signals transmissions

Phone and other communications
A. system and model

- System to be controlled

![Diagram of a ventilation system with labels for Fresh air, Main ventilation shaft, Fan, Tarpaulin tube, Embedded Control, Distributed measurements, and wireless multi-hop network. The diagram includes a graph for pollutant concentration with axes labeled for height and pollutant concentration.]
Tropical orchids growing: from plume to stratified flow
• Model of the system
  ➢ Physical delay in the tarpauline tube:
    \[ \tau_{tarp} (t) \approx \frac{L}{u(t) + \sqrt{r_y T(t)}} \]

  ➢ Chemical concentration of pollutant \( j \):
    \[ c_j (x,t) = \frac{\alpha_j (t)}{1 + \exp(-\beta_j (t) \cdot (z - \gamma_j (t)))} \]

  ➢ Shape parameters dynamics:
    \[
    \begin{bmatrix}
    \dot{\alpha}_j (t) \\
    \dot{\beta}_j (t) \\
    \dot{\gamma}_j (t)
    \end{bmatrix} = E^+ [\dot{m}_{j, in} (t) - B_j u_{fan} (t - \tau_{tarp}) - D_{jk}] 
    \]

  ➢ Chemical reactions in mass conservation:
    \[ \dot{m}_j (t) = \dot{m}_{j, in} (t) - \dot{m}_{j, out} (t) - \dot{m}_{j, chem} (t) \]

  ➢ Experimental WSN multi-hop delay
    [Witrant & al., CCA’07]:
    \[ \tau_{wsn} (t) = h(t) F + \sum_{i=1}^{h(t)} (\alpha_i + \beta_i) \]
Using linear controllers?

- Test of a linear controller: PI tuned to regulate CO at 0.028

Very satisfactory!! But….
• But, changing the reference to 0.035…

Non linearities of the system have to be carefully taken into account
B. NLMPC: Receding horizon control

- Control objectives:
  - Regulate the level of pollutants: \( y_j(t) \rightarrow y_{j,\text{des}} \)

- Constraints to be satisfied:
  \[
  \forall j, \quad \max_j y_j(t) \leq \bar{y}_j 
  \]

- Control tuning parameters:
  - \( N \): prediction horizon, long enough for transient behavior
  - \( N_u \): number of degrees of freedom: precision vs. complexity
  - \( \lambda \): weight control effort vs. tracking performances

Open loop: control

Computation:

\[
\min_{\{u_i, i=1, \ldots; N_u\}} \int_{\tau=kT}^{kT+N} \left( (\hat{y}_j(\tau) - y_{j,\text{des}}(\tau))^2 + \lambda u_{\text{fan}}(\tau)^2 \right) d\tau 
\]

with \( u_{\text{fan}}(\tau) = u_i, \quad \tau \in \left[ kT + (i-1) \frac{N_u}{N}, kT + i \frac{N_u}{N} \right] \)

Computed from prediction model
• Problem: robustness against pollutant emissions predictions
→ Need of a closed loop structure

Scheduling algorithm based on prediction model (maximum value of the delay)

MPC with on-line solution of successive optimization problems
Simulation results

• Unconstrained case, tuning of the control law (1)

\[ N_u = 2, \quad \lambda = 10^{-7} \]

\[ N_u = 2, \quad \lambda = 10^{-5} \]

Increase in \( \lambda = \)
• decrease in fan power
• increase in pollutant
• Unconstrained case, tuning of the control law (2)

\[ \text{Nu} = 2 \text{ (continuous line), Nu} = 5 \text{ (dotted line)} \]

Increase in Nu:
• more reactive control
• Increased computational effort (often untractable online)
Robustness against pollutant prediction error (50% underestimated): if infeasibility then unconstrained and decrease $\lambda$.

- Constrained case (1)
  
  - $y_{j,\text{des}} = 0.025$, with a bound constraint $y_j \leq 0.028$
  
  Due to constraints, the successive solution of optimization problems may lead to infeasibility.

  Development of a « reaching feasibility again » strategy:
  
  - Try to solve the constrained scheduling algorithm with $\lambda = 10^{-5}$ (strategy 1).
  
  - If unfeasible, solve the unconstrained scheduling algorithm with $\lambda = 10^{-7}$ (strategy 2).

  If impossible, allow high control efforts to reach feasibility again as soon as possible.
• Constrained case (2)
  \[ y_{j,\text{des}} = 0.025, \text{ with a bound constraint } y_j \leq 0.028 \]

\[ N_u = 2, \quad \lambda = 10^{-7} \]

\[ N_u = 2, \quad \lambda = 10^{-5} \]
• Robustness of the control law
  ➢ Worst case experiment: pollutant emissions 50% underestimated

Very satisfactory, thanks to the closed loop and the « reaching feasibility again » strategy
C. Hybrid Control Strategy

- Affine hybrid model
Safety Control

• Automatically verify if \textit{for a given control strategy} the hybrid automaton satisfies Safety and Comfort properties
  
  – Unfortunately, model checking is in general undecidable even for affine hybrid automata
    
    $\Rightarrow$ construct an abstraction of a hybrid automaton with affine dynamics, which preserves temporal properties expressed by CTL and TCTL formulae (temporal logics constraints)
      
      – The abstract model belongs to a subclass of timed automata, called \textit{durational graph}
• Example
  – Automatic verification procedure on the hybrid model using the following set of thresholds
    • \( gl_1 = 0.2955, \ gl_2 = 0.5 \times 10^{-3}, \ gl_3 = 0.0885 \ [Kg/m^3] \)
    • \( gh_1 = 0.2975, \ gh_2 = 2.5 \times 10^{-3}, \ gh_3 = 0.091 \ [Kg/m^3] \)
  – the original hybrid system is safe and the maximum time of uncomfortable air quality is bounded by 62 s
D. Comparison between the two approaches

• Test case
Regulation efficiency

- **MPC:**
  - direct trade-off regulation efficiency vs. Energy min.
  - better ratio
- **Threshold:**
  - easy tuning
  - find the tighter band for the guards
Robustness

• MPC: wrt. Model error
  – underestimated values for the prediction of the pollutant sources (1 truck)
– 20% underestimated gain
• Thresholds: 80/90 % → 85/95 %
Computational complexity

• Thresholds:
  – O(1) complexity,
  – comparisons betw. meas. and safety thresholds
  – can be embedded on WSN

• MPC:
  – time consuming (1500s in 10 minutes with Matlab 2007a on a Pentium IV, 2.80GHz)
  – hard optimization problems
Conclusions

• Complex test case with multiple dynamics:
  – Transport / PDE for primary
  – Nonlinear / hybrid for secondary
  – Communication associated with WSN/PLC
  ➢ Challenge for RT models and interconnection

• Numerous associated control issues, with significant possible improvements

• Results applicable to environmental applications
  – Ventilation control: intelligent buildings, flow transport
  – Transport in heterogeneous media: plasma, firns, bread
  – Distributed sensing and actuation
References


• S. Olaru, G. Sandou, E. Witrant, and S. Niculescu, "Receding horizon climate control in metal mine extraction rooms", *IEEE CASE 2008*. Invited paper.

