Mining ventilation control:
a new industrial case for wireless automation

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Abstract

This paper describes a new industrial case on wireless automation, for a large scale system with high environmental impact: the mining ventilation. *We do not pretend to solve the global control problem but rather propose a novel approach based on distributed sensing/actuation capabilities, which can be allowed by the installation of an heterogeneous network in the underground process. Several key issues, such as the centralized vs. decentralized control, the macroscopic physical models for the main components and the network structure, are introduced to motivate future research along this line. We particularly highlight new grounds for the development of global control strategies that would allow for the energy consumption optimization of this large-scale system.*

1. Introduction

Mining ventilation is an interesting example of a large scale system with high environmental impact where advanced control strategies can bring major improvements. Indeed, one of the first objectives of modern mining industry is to fulfill ecological specifications [1] during the ore extraction and ore crushing, by optimizing the energy consumption or the production of polluting agents. The mine electric consumption was 4 % of total industrial electric demand in the US in 1994 (6 % in 2007 in South Africa) and 90 % of it was related to motor system energy [2] (p.19). Another interesting figure is given in [3] where it is estimated that the savings associated with global control strategies for fluid systems (pumps, fans and compressors) represent 22.20 % of the total manufacturing motor system energy savings. This motivates the development of new control strategies for large scale aerodynamic processes based on appropriate automation and the consideration of the global system. More specifically, the approach presented in this paper is focused on the mining ventilation, as 50 % of the energy consumed by the mining process goes into the ventilation (including heating the air). It is clear that investigating automatic control solutions and minimizing the amount of pumped air to save energy consumption (proportional to the cube of airflow quantity [4]) is of great environmental and industrial interest.

Our approach strongly relies on distributed sensing and actuation capabilities. Traditionally, industrial control systems have relied on hardwired information flows between sensor, actuator and control nodes. Over the last decades, distributed control systems have seen a transition to communication buses, such as fieldbus and Ethernet technology, and there is currently a drive to take the next step in this evolution by moving to wireless communication. Increased efficiency and lower costs for installation and commissioning are important factors. There is also a large potential for major technological advances due to increased flexibility and mobility, which may lead to totally new system designs. Admittedly, wireless technology is already present in many manufacturing and process industries. Wireless links have since long been installed for long-range (100 m–1000 m) SCADA applications to cut costs. More recently, wireless LANs have been installed for applications with non-stringent communication requirements (e.g., logistics), but wireless instruments (temperature, pressure, etc.) are starting to appear on a smaller scale. In this paper, we investigate the benefits, in terms of control and safety, associated with wireless automation for the mining ventilation process.

Reconfigurability and wireless communication are key automation components for advanced mining ven-

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tilation control. The first issue is related to the variable topology of the mine (mobile process industry): after all accessible ore has been retrieved from a mine level, the extraction rooms are filled and a new level further down along the decline (which is a spiraling tunnel used by the trucks to reach the surface) is bored. All equipments, including the ventilation, have to be moved and re-configured in the new level. The second issue comes from the blasting and drilling operations in the extraction rooms, rendering the wiring infeasible in these areas. Wireless networks can also be used for improving the efficiency of other processes that are of importance in operating a mine, e.g., equipment (trucks and ventilation system) maintenance, people and equipment localization, voice communication and security.

The paper is organized as follows. The first section describes the mining ventilation process, actual automation and control objectives. In Section 3, we propose a new wireless automation architecture, which highlights the interest for model-based control using distributed measurements. This architecture naturally motivates the physical description of the airflow and the network architecture presented in sections 4 and 5.

2. Actual automation process and control objectives

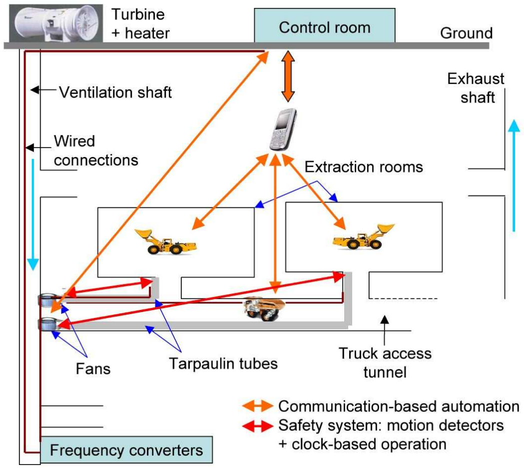

Figure 1. Mine ventilation process and actual automation.

Mining ventilation is an active field of scientific research [4], mainly focused on equipment design according to operation specifications [5] or complex ventilation network topology [6]. A few works propose detailed mathematical modeling of the flows for extraction rooms [7] or underground shafts [8, 9] but, to the best of the authors' knowledge, dedicated models for real-time operation and ventilation control have not been studied yet. This is illustrated by the simplicity of the actual automation process presented in this section and further research along this line is motivated by the definition of new control objectives.

2.1. Vertical shaft and rooms ventilation

The global mine configuration is illustrated in Fig. 1. The ventilation is first achieved by a turbine and a heater connected on the surface to a vertical shaft. The heater is introduced (in winter time at least) to avoid freezing in the upper part of the shaft and the air is cooled down at high depths (more than 1000 meters) because of the geothermal effect (the temperature is increased by $1^{\circ}C$ every 30 m). We will refer to this part of the system as the *primary system*. From the ventilation shaft, fans located at each extraction level pump fresh air to the extraction rooms via tarpaulin tubes: this is the *secondary system*. Bad quality air naturally flows because of the pressure gradient from the extraction rooms back into the decline and to the exhaust ventilation shaft (similar but separate from the primary ventilation shaft).

The distinction between primary and secondary systems will be used in the following sections to divide the control problems. In fact, the primary system typically has a clear geometry while the secondary system is strongly varying in geometry (rooms are blasted every day), characteristics (tarpaulin tube length and shape) and disturbances (trucks) even within the same mine. Model-based control approaches can then be envisioned for the primary system while grey-box identification or more empirical methods should be preferred for the secondary one.

2.2. Today's automation architecture

In the actual architecture, the turbine is operated based on the flow pressure gradient and the heating depends on the external temperature. The system of fans is controlled based on the demand of airflow in different parts of the mine thanks to frequency converters, as presented in Fig. 1. This airflow demand is determined based on messages sent by the drivers to the control room using walkie-talkies, indicating their position (no automatic control, but maximum ventilation power during ore extraction) and which fan needs to be set to its maximum speed. Both turbine and fans are at least operated at low speed (no automatic localization system within the mine). There may also be an additional safety system that triggers the fan high-speed operation based on a motion detector placed at the room's entrance. The actual control architecture is then characterized by the absence of wireless sensing or continuous monitoring of air quality.

2.3. Control objectives

The overall objective of the mining ventilation control system is to provide for good air quality in the extraction rooms. For a future wireless automation supporting the ventilation control, it is also desirable to increase safety by using the wireless system for personal communication and localization. We specify the objective as the *control of air quality* (O_2, NO_x and/or CO_x) in the extraction rooms at different levels. Considering the distinction between the primary and secondary systems defined above, it is then suitable to fulfill a cascade control configuration with the following two objectives:

1. regulate the turbine and heater based on physical measurements within the vertical shaft to provide for a suitable airflow pressure at the location of the fans;
2. regulate the ventilation fans based on chemical sensors to ensure air quality in extraction rooms.

An additional system objective is to obtain *safety through wireless networking* for personal communication and localization. It should be noted that today's control architecture does not enable the fulfillment of these objectives, due to the lack of automatic control and sensing capabilities. The proposed wireless control architecture strives for fulfilling all the objectives listed above.

3. Proposed wireless control architecture

The proposed automation architecture is depicted in Fig. 2, where we introduced networked sensors in the vertical ventilation shaft, in access tunnels and in the extraction rooms. The sensors placed in the vertical shaft and in the access tunnels can make use of the existing wired connections, while those in the extraction rooms have to be wireless, due to the blasting activities. The exchange of sensor measurements and control signals can then be carried thanks to wired links as well as wireless communication. We can consider two control architectures:

1. a *centralized* strategy, where all the sensor signals are transmitted to the control room, where the control algorithms are run. This strategy allows for the global optimization of the energy consumption, at the price of a communication load due to the transmission of the control signals between the surface and the fans;

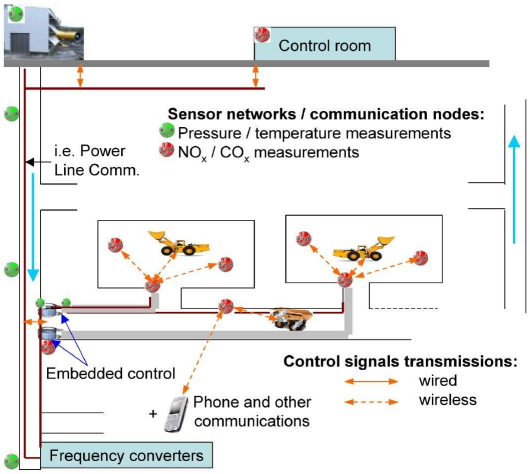

Figure 2. Proposed communication architecture.

2. a *decentralized* approach, where some intelligence is embedded at the locations of the fans and can adjust their regulation directly based on the chemical sensors measurements. This regulation is structurally sub-optimal but should be preferred as a first approach for its simplicity and the limited communication constraints.

Note that the control algorithm embedded at the fans location has to be relatively simple, due to the limited computation capabilities, while we can develop more advanced control strategies for the algorithms run in the control room.

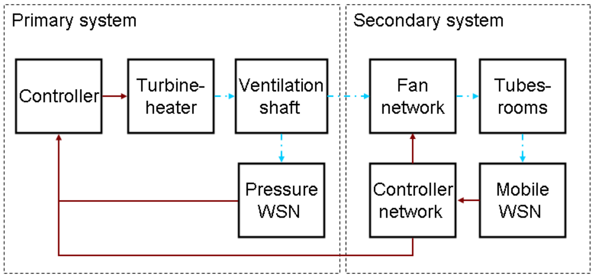

Figure 3. Block diagram description of the control setup, including communications (—) and airflows (− · −).

Based on the decentralized control approach, the ventilation system can be described in two parts: one fixed installation, which is the primary air supply from the ground via a vertical shaft, and the secondary system, a mobile network of fans. This distinction results in the block diagram description proposed in Fig. 3, where both the physical (airflow) and communication (wired and wireless) interconnections are presented. This description includes the existing systems as well as key elements of the advanced technological solutions presented in this paper. The different subsystems are detailed in the next section.

4. Physical description of the airflow

The aim of this section is to provide for a physical description of the airflows involved in the mine ventilation, following the distinction between the primary and secondary systems. The interconnection between the two subsystems is the pressure at the fans location, and is a key parameter to investigate the relative efficiency of the turbine with respect to the fans to ensure that the room gas concentration is within safety bounds.

Indeed, the extraction rooms ventilation is increased by increasing either the turbine or the fans actuation. The first solution is associated with energy losses due to the turbulent behavior of the flow in the vertical shaft while in the second case energy is lost in the tarpaulin tubes. The turbine and fans efficiency also has an important role. A major difficulty from an optimal control point of view, which motivates the physical description proposed in this section, is then to find the distribution of the energy spent in the actuation that maximizes the rooms ventilation.

4.1. Flow in the primary system

The flow dynamics of the primary system are governed by the Navier-Stokes equations, including the compressibility, viscous losses and thermodynamic effects, due to the large mass flow rate and the length of the shaft considered. The exogenous inputs are the surface boundary conditions (set by the heater and turbine) and the vertical shaft has to provide the fans with an appropriate flow pressure, which is then the regulated output. The geometry of the shaft is well known, which implies that we can determine a precise associated physical flow model. Depending on the desired precision level, *potential*, Euler or Navier-Stokes equations can be used. A pedagogical description of the flow aerodynamics can be found in [10] while more advanced material, including the computational aspects, is available in [11]. For example, the following conservative form of the Navier-Stokes (NS) equations can be used to describe the primary system

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\mathbf{V}\\ \rho E\end{bmatrix}+\nabla\cdot\begin{bmatrix}\rho\mathbf{V}\\ \rho\mathbf{V}^T\otimes\mathbf{V}+p\mathbf{I}-\tau\\ \rho\mathbf{V}H-\tau\cdot\mathbf{V}-k\nabla T\end{bmatrix}=\begin{bmatrix}0\\ 0\\ \dot{q}\end{bmatrix}$$

where ρ, $\mathbf{V}$, p and T are the density, velocity vector, pressure and temperature, $\otimes$ is the tensor product of two vectors, τ is the shear stress vector (which depends on the velocity gradient), $H = E + p/\rho$ is the total enthalpy, E is the total energy per unit mass, k is the thermal conductivity and $\dot{q}$ is the incoming heat flux. Note that specific care has to be taken in the discretization of the partial differential equations, due to the associated computational complexity and nonlinearities in the dynamics.

The airflow in the vertical shaft is mainly turbulent, implying that *Direct Numerical Simulation* should be used to solve the time-dependent NS equations. However, this method is typically out of reach for industrial applications and approximate methods, such as *Large Eddy Simulation*, *Reynolds Averaged Navier-Stokes* or *Thin Shear Layer Approximation*, should be preferred [11]. Advanced model-based control strategies then have to be preceded with appropriate model simplification and real-time computation analysis.

4.2. Flow and pollutants in the secondary system

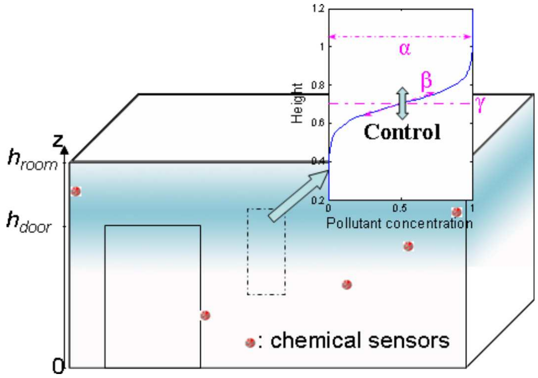

Figure 4. Stratification and sigmoid description in extraction rooms.

The description of the flow and pollutants in the secondary system is greatly simplified due to the uncertainties previously mentioned, induced by the complexity of the chemical processes and by the variable geometry of the rooms. Indeed, precise physical description would not be relevant in that case and we will focus on a functional model of the flow chemical properties. The airflow in the tarpaulin tubes is considered inviscid, incompressible and adiabatic, and can then be considered as a time-delay τ_{tarp} (the time needed for a change of the mass flow rate due a modification in the fan actuation to reach the extraction room). The pollutant (CO_x or NO_x) volumic tarpaulin concentration profile $c(z,t)$ (mainly set by the gas buoyancy and resulting in a stratification of bad quality air at the ceiling), where $z \in [0; h_{room}]$ is the height in the extraction room, h_{room} is the room height and t is the time, is approximated with the sigmoid distribution

$$c(z,t) = \frac{\alpha(t)}{1 + e^{-\beta(t)(z-\gamma(t))}}$$

where $\alpha(t)$ is the amplitude, $\beta(t)$ is the dilatation and $\gamma(t)$ is the inflection point of the distribution. This is illustrated in Fig. 4.

Note that any function can be approximated with the desired precision level by a sum of such sigmoid functions: we suppose here that one curve is sufficiently accurate for control purposes and considering the system uncertainties. This simplified modeling approach was proposed for distributed systems involving smooth transport phenomena in [12] and is detailed in [13], where a grey-box identification method allowing for the distinction between transient and steady-state behavior, the use of a switched model and the conservation of global physical properties is proposed. This method was successfully applied to the modeling of temperature profiles in Tokamak plasmas and validated with experimental results.

The shape parameters α, β, γ can be related to the global parameters (room temperature and pressure, number of trucks and engines power, etc.) with an appropriate identification method and the dynamics can be introduced with the global conservation of mass

$$V \frac{dC(h_{room},t)}{dt} = \dot{m}_{in} - C(h_{door},t) S_{tarp} \nu u_{fan}(t - \tau_{tarp})$$

where V is the room volume, $C(h,t) \doteq 1/h \int_0^h c(z,t)dz$ is the averaged volumic concentration up to the height h, $\dot{m}_{in}$ is the incoming pollutant mass rate due to the engines (we neglect human contribution) given by appropriate specifications, h_{door} is the height of the room door, S_{tarp} is the cross section of the tarpaulin tube and u_{fan} is the airflow speed provided by the fan, scaled by a constant ν (flow momentum losses due to the tube geometry). We supposed here that there is no pollutant in the tarpaulin tube and that the flow in the room is incompressible.

The main advantage of this model is first associated with the use of shape parameters, allowing for on-line identification methods that are not affected by the fact that a sensor network provides for measurements at different locations at each sampling time. Furthermore, the fact that the regulated output (i.e. the height of the bad quality air layer h_r, which should be kept above the engines and humans level) is a scalar directly provided by $c(h_r, t)$.

4.3. Interconnection and actuation

In the ventilation system architecture described above interconnection issues clearly arise: the *turbine* and *heater* interconnect the atmosphere with the primary ventilation shaft, while the *secondary fans* interconnect the primary ventilation shaft to the extraction rooms via the tarpaulin tubes. Moreover, turbine, heater and secondary fans are the main actuation devices for the mining ventilation process.

Consistently with the description of the flows, the physical variables that take part in the interconnections are air pressure, temperature, density and gas concentration. Their mathematical models cannot be easily formalized by a general differential equation, but the data sheet of the commercial devices can be used to derive an approximation of the dynamical behavior of the system. As an example, consider a secondary fan. Let P be the air pressure upstream to the fan (in the primary ventilation shaft), u_{fan} the airflow downstream to the fan, ΔH the fan static pressure and $\dot{\theta}$ the fan speed (our control variable). Technical fan data sheets (such as Fig. 4 in [5]) relates the fan static pressure ΔH to u_{fan} for different values of the fan speed $\dot{\theta}$. The air pressure P in the primary ventilation shaft affects the fan performance curves by increasing u_{fan} for a given $\dot{\theta}$. If we assume that in the proximity of the fan the air temperature is constant and the airflow is incompressible, the airflow is only due to pressure difference and added energy (through $\dot{\theta}$), and the interconnection writes as

$$u_{fan} = f(P, \Delta H^{-1}, \dot{\theta})$$

where $f(\cdot)$ is the technical mapping and ΔH^{-1} expresses the inverse proportionality relationship.

5. Sensors and communication network

The sensor and communication network is primarily intended to provide support for exchange of measurements and commands among various elements of the ventilation control system. Nevertheless, once the feasibility of the whole networked control system will have been assessed and the related benefits will have been appreciated, the network can evolve in order to provide support for advanced services, such as phone calls, regular tracking of people and trucks in a potentially dangerous environment through localization and advanced sensing (e.g. video), and others.

5.1. Basic architecture

The basic architecture includes fixed wireless sensor nodes along the vertical shaft in the primary system and mobile wireless sensor nodes in the secondary system. Operation of the latter nodes is of major interest when trucks are working within the extraction rooms. This sensing (lower tier) network has to be complemented by a communication network portion, which is in charge of delivering information over longer ranges, up to controllers and actuators. As more opportunities can be considered in this regard, the following two alternatives can be here envisaged.

5.1.1. Uniform radio technology. Let us assume that the same radio technology (e.g. IEEE 802.15.4) is used in the whole system, both in the lower (sensing) tier and in the interconnection portion. In this case interaction with the existing mining infrastructure is minimal and we can devise two major patches of nodes: one for the primary system, which appears as an ad-hoc multi-hop network with fixed topology, and one for the secondary system, which appears as an ad-hoc multi-hop network with partially varying topology. Topology variation may in a shorter time scale be induced by movements of trucks within an extraction room or when they move along tunnels and/or from one room to another. The set of (relaying) nodes installed along the tunnel can be fixed and located at proper distances in order to provide continuity of radio coverage along the whole tunnel. On a longer time scale, the topology variation might be essentially related to the size of tunnels and the number of extraction rooms: as the mining extraction works progress, the tunnel length and the number of rooms increase, with the consequent increase in the wireless network size. This certainly induces an impact in scalability of solutions, since a larger size implies larger number of hops, longer delays and larger traffic to be supported by relaying nodes. Finally, it should be pointed out that in this architecture the mobile nodes might not be subjected to severe energy constrained operations, since they can either rely on local power generation mechanisms or be maintained by people when they come to ground level. On the contrary, the nodes deployed on the tunnel sides might be battery powered or provided with energy scavenging, but not able to benefit from typical recharge facilities.

5.1.2. Hybrid wired-wireless architecture.. Since the whole system setup foresees the presence of some cabling, e.g. for power delivery to fans along the primary system, and for connecting entrance detectors in rooms in the secondary system, it seems interesting to investigate exploitation of power line communication (PLC) devices for setting up the interconnection network. This scenario is implicitly accounted for in Fig. 5, which depicts a hybrid wired-wireless architecture with proper gateways at the interfaces between network segments operating with different technologies.

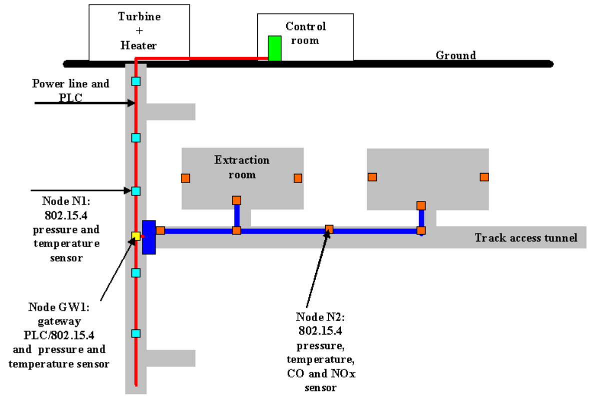

Figure 5. Sketch of the basic network architecture.

5.2. Advanced architecture with heterogeneous radio technology.

A more advanced solution relies on a heterogeneous radio technology, by introducing e.g. IEEE 802.11 in ad-hoc version in order to provide larger bandwidths and longer hop-ranges in the wireless relaying part of the secondary system. This kind of architecture resorts on the fact that mobile entities can be considered as non energy-constrained and are then able to support power expensive wireless radio technologies. This solution explicitly accounts for the presence of mobile gateways and introduces shorter-term topology variation also in the interconnection portion of the wireless network deployed in the secondary system.

5.3. Performance modelling

We are concerned with a multi-hop network, where the communication path from the emitter to the receiver is composed of a time-varying number of nodes $n(t)$. For each node, denoted by $i = 1 \dots n$, we can consider the following sources of delay:

- time to wait before sending a data packet α_i, which is typically a random variable;
- time F to forward a data packet to a given neighboring node, which is constant and includes the propagation and transmission delays;
- if an Automatic Repeat reQuest (ARQ) protocol is present, time β_i induced by the ARQ, which retransmits the packet for a predefined number of time if no acknowledgement is received.

The end-to-end delay can then be expressed as follows:

$$\tau(t) = n(t)F + \sum_{i=1}^{n} (\alpha_i + \beta_i) \qquad (1)$$

This model is illustrated e.g. with the randomized protocol proposed in [14], where the routing, MAC and sleeping discipline are designed in such a way that the energy consumption of the network is optimized. The protocol is based on a routing, MAC and duty cycling algorithm that allow for satisfying constraints on latency and error rate. Such a protocol dynamically organizes topology in clusters according to the traffic load, channel conditions, energy consumption, and delays from source to destination. Since the protocol design approach is representative of a class of protocols for wireless automation, we take it as a reference for modelling purposes and also as a candidate for network design. With this protocol, α_i depends on the exponentially distributed wake up rate, whose average value $\mu_{c,i}$ is constrained by a function of the traffic rate, packet loss probability and requested error rate. Note that, since $n(t)$, α_i and β_i are subject to random variations, the end to end delay clearly results in a random process.

Conclusions

In this work, we presented *mining ventilation control* as a novel industrial case for wireless automation, where the energy consumption minimization is motivated by environmental and economical issues. This optimization objective, associated with safety requirements, led to the definition of a new automation architecture, based on a global control approach and the use of distributed sensing and actuation capabilities. The physical model and network architecture were consequently described, to introduce the necessary background for model-based control approaches and the use of wireless sensing capabilities.

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