Benchmark for analysis, modeling and control of ventilation systems in small-scale mine

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***Abstract*—This work presents a new experimental set-up constructed to analyze ventilation networks from a control point of view. The dynamic system is built with low-cost material and it is designed to reproduce, at a small scale, similar conditions of existing underground mines. Different types of sensors are tested and compared to measure the airflow in the branches of the flow network. The transfer function representation of a constructed ventilation system is computed based on experimental data. The benchmark is devoted to the study of air distribution networks in mines, but the analysis can be extended to different fluid networks.**

I. Introduction

The mining industry is considered as an important source of development for many countries. Due to its characteristics, underground mining is considered a dangerous activity, reporting a high rate of accidents each year. For this reason, several academic and industrial research works have been devoted to improving safety conditions in the underground mining operation.

The main aim of an underground mining ventilation system is to provide the correct levels of air to the different tunnels in the mine in order to dilute hazardous gases and contaminants in all the tunnels of the mine where workers are present [1]. Modern automation methods and the use of wireless sensor networks provide new openings for safety and performance in mining ventilation control [2]. In this context, the problem of controlling ventilation networks has been studied extensively and even some prototypes of air distribution in underground mining have been presented, see for instance [3], [4].

Steady-state description of ventilation networks has been performed using the Hardy-Cross method. The airflow in mine ventilation circuits is determined algebraically by combining graph theory and classical Kirchhoff's laws [5]. A non-linear dynamic lumped parameter model for mine ventilation systems has been introduced in [6], where a multi-variable control strategy was proposed for the linearized model. Hu, *et al.* [7] propose a model based on Kirchhoff's algebraic equations and the differential equation describing the airflow dynamics in the branch, to design a non-linear feedback controller for a mine ventilation system with the assumption of full equipment (actuators and sensors in all the network). This method was extended, controlling periodically forced fluid networks and including adaptive methods [8], [9]. A similar model was proposed by [10], including external perturbation in the system and designing an H_1 optimal controller. Sui *et al.* [11] introduce a control law based on feedback linearization and genetic algorithms to obtain optimal branch resistances values for complex networks.

The aforementioned works have studied the case of large-scale mining where there are sensors and actuators in most of the network branches. However, in small-scale mining, a typical scenario is a ventilation system with a reduced number sensors and actuators. For instance, a high rate of emergencies in the Colombian small-scale mining industry is related to the lack of monitoring and automatic control of ventilation systems [12]. Due to this fact, it is necessary to design control strategies for underground mines taking into account ventilation networks with limited resources.

This work describes a new experimental benchmark devoted to the study of small scale ventilation systems. The main purpose is to validate modeling and control strategies for flow distribution networks with limited instrumentation. In addition, structural properties of the network can be analyzed, *i.e.* generic observability and controllability, in order to correctly locate the sensors and actuators, or to relocate them (if it is necessary) as the network topology evolves. Whereas directed mainly to underground mining operations, the expected results can be also applicable to the ventilation of spaces such as intelligent buildings, nuclear waste repositories, commercial accommodation or vehicular networks. Other type of fluid networks like gas and water distribution networks and irrigation networks can be also analyzed in a similar perspective.

The paper is organized as follows: Section II describes the benchmark design, aspects related to the selection of sensors and actuators, and their location in the network is discussed. In Section III the experimental results are shown, the parametrization of the sensors is detailed and an identification method for the ventilation network is provided to design and implement a closed-loop controller. Section IV provides perspectives and future works foreseen for the experimental set-up.

II. Benchmark description

A small-scale benchmark to perform different tests in ventilation systems for underground mining is described in this section. Considering the size of a typical mine, a scale 1:500 has been selected in order to configure the cross-section of the tunnels. The different elements of the proposed benchmark have been selected taking into account the given scale. A brief description of the system components is provided in the following.

A. Actuator

To design the ventilation network it is necessary to drive the air flow in the system. We consider a typical centrifugal fan used in small underground mining, with a nominal power of 20 HP which delivers an air flow of 15 000m^3/h. Setting a scale of 1:500, we need a fan supplying an approximate air flow of 30m^3/h. This is achieved with a centrifugal fan powered at 12V$_{DC}$, with a nominal delivery of volumetric air flow of $27m^3/h$. The selected fan is shown in Figure 1.

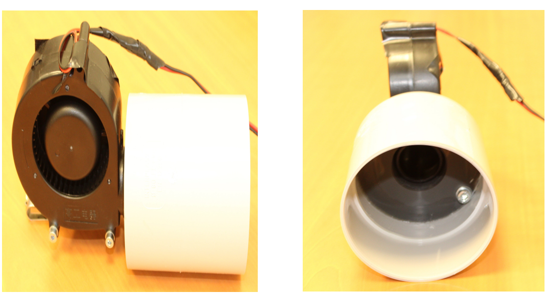

Figure 1. Fan adjusted to the network dimensions.

Once the maximum air flow for the network is specified, it is necessary to define the diameter of the pipe that will represent the tunnels of the ventilation network in the underground mining. The cross-sectional area for design in small underground coal mining is $3m^2$. Continuing with the ratio 1: 500 we need PVC pipes of 80mm diameter that corresponds to a cross section of 0.005m^2. An adaptation of the cross-section is thus necessary to couple the fan to the pipe, as shown in Figure 1.

The benchmark is first designed to work with a single actuator, but it is built with the flexibility to add more branches and fans to the network to analyze their effect on the dynamics of the system.

B. Sensors

For the measurement of the air flow in the ventilation network, a group of sensors is selected. Those sensors are evaluated in the steady conditions but also during their transient behavior. In order to compare different technologies, three different classes of sensors have been installed in the system: a hot wire sensor, a mass flow sensor, and a differential pressure sensor.

Hot wire sensor

Hot wire anemometers use a thin wire (on the order of several micrometres) electrically heated to some temperature above the ambient. As the electrical resistance of most metals is dependent upon the temperature of the metal, a relationship can be obtained between the resistance of the wire and the flow speed.

In order to correctly select the sensor's characteristics we define the operating range in the application. Taking into consideration the air flow delivered by the fan:

$$Q = 27\frac{m^3}{h}\frac{1h}{3600s} = 0.0075\frac{m^3}{s},$$

and a pipe diameter of $0.08m$ with a cross section of $0.005\ m^2$, the expected air velocity in the fan branch of the ventilation network when the fan is working at nominal power is:

$$V = \frac{Q}{A} = \frac{0.0075m^3/s}{0.005m^2} = 1.5\frac{m}{s}.$$

The sensor EE671 is selected to obtain a signal with the needed characteristics [13]. EE671 is a compact air velocity probe for HVAC applications. It operates on the hot-film anemometer principle and ensures high accuracy and excellent long-term stability. The flow sensing element is very robust and highly insensitive to contamination. The selected range is $0 - 5m/s$. The measured air velocity is available as linear voltage output in the range $0 - 10V_{DC}$. The sensor is shown in Figure 2.

Figure 2. EE671 hot wire sensor connected to a pipe.

Mass flow sensor

The mass air flow sensor measures the air flow passing through an engine with a spring-loaded air vane (flap/door) attached to a potentiometer. The airflow provides a proportional displacement in the mechanical vane. A voltage is applied to the potentiometer and a proportional voltage appears on the output terminal of the potentiometer in proportion to the angle the vane rotates. To determine the characteristics of the mass flow sensor, we consider the measurement equipment used in the injection systems of low power vehicles, taking into account its easy acquisition and low cost.

First, we look for mass flow sensors used in vehicles of low cylinder size, with a diameter of 80mm to facilitate the coupling with the network. Then, we define the amount of air required by a common vehicle, considering a vehicle of 1400 cc, gasoline engine without turbo, the efficiency factor of 0.8, working at 900 RPM, the amount of air needed can be computed as follows:

$$Q = K\ D_l\ RPM\ E_{ff},$$

where $K = 3e^{-5}$ is a constant for unit management, D_l is the displacement, defined as the total volume of the cylinders in an engine given in cubic centimetres, RPM represents the revolutions per minute and measures how many times the engine's crankshaft makes one full rotation every minute, E_{ff} is the engine efficiency. The obtained airflow through the engine is $30.24m^3/h$. With these parameters, a generic mass flow sensor is selected, with reference OEM 28164-37200, used in vehicles of the mentioned characteristics. The main constraint of the selected sensor is that there is no data sheet available. Trial and error measurements and other sensor are necessary for an adequate use. The sensor is shown in Figure 3.

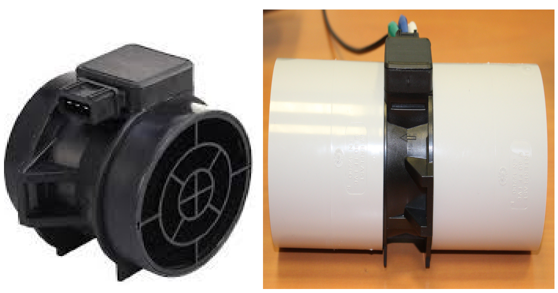

Figure 3. Mass flow sensor OEM 28164.

Orifice plate sensor

Orifice plate flow meters are differential pressure sensors mounted on a section reduction to estimate the mass flow rate. Then, can be used with gases, liquids, corrosive, and high temperature fluids. Applications include steam flows, boilers feed-water, and fluid flow rates in buildings water lines. For our application, the differential pressure is measured in a bypass configuration over a concentric orifice in order to derive the air flow in the main pass.

According to Bernoulli's energy equation and the law of continuity, the total flow head (dynamic velocity head and static pressure head) is constant. The increase in speed at the restriction causes a reduction in the static head. In general, the mass flow rate q_m measured in kg/s across an orifice can be described as follows:

$$q_m = \frac{\pi C_d}{4\sqrt{1-\beta^4}} \epsilon d_2^2 \sqrt{2\rho \Delta P}, \tag{1}$$

where C_d is the coefficient of discharge (dimensionless), β is the diameter ratio d_1/d_2, ϵ is the expansibility factor (1 for incompressible gases and most liquids), ρ is the density of the flow and ΔP is the differential pressure across the orifice. Figure 4 shows the diagram of an orifice plate sensor, where the reduction causes a change of velocity of the flow and a contraction, denoted as a *vena contracta*, with diameter d_{vc}.

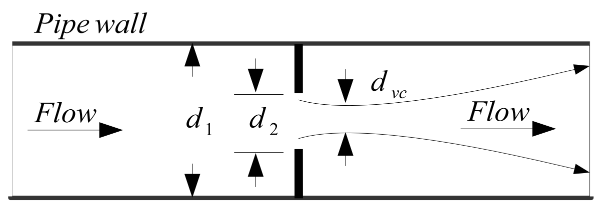

Figure 4. Schematic view of an orifice plate sensor.

Considering the airflow quantities provided by the actuator in the network, a sensor Sensirion SDP611 was selected [14]. This sensor has the following capabilities: accuracy better than 0.2%, excellent repeatability, even below 10Pa, calibrated and temperature compensated, flow measurement in bypass configuration provided by its thermal measurement principle [15].

C. Network

Once sensors and actuators were selected, the galleries or tunnels in underground mining can be represented by pipes of PVC of 80 mm in diameter. The design takes into account the functionality, namely, the capability to easily change the geometrical topology of the network, including the tunnel lengths and the network connections.

Using the sensors and actuators described before, a network has been built as shown in Figure 5, which represents the model described by Yunan Hu in [7], with 3 independent tunnels and a tunnel with the actuator.

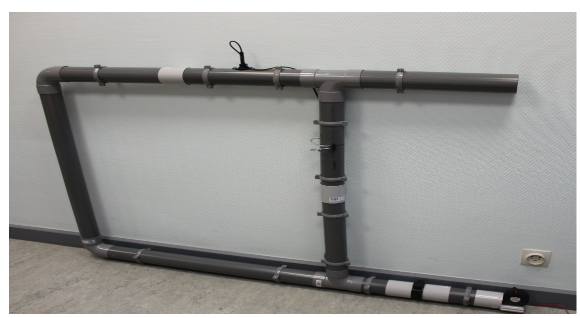

Figure 5. Benchmark: A ventilation network configuration.

D. Data Processing

A control unit is needed to process the signals provided by the sensors and make the required computations to regulate the actuators. Due to its price and technical specifications, an Arduino Mega 2560 board has been selected to be used as a data acquisition system [16].

In order to simplify the sensor connections and wiring management, a Mega IO expansion shield is installed [17]. The available micro SD slot in the IO expansion shield allows to save the experimental data for further analysis. Plug-play addition of new sensors is possible due to the header connectors of the IO shield.

An Arduino motor shield is installed to manage the actuators in the ventilation network [18]. The motor shield permits to manage the power levels demanded by the fan. The velocity of the fan can be controlled by means the PWM outputs available in the Arduino Mega 2560.

III. Experimental results

This section is devoted to the analysis of experimental results. First, the three sensors in the network are calibrated to obtain airflow measurements in m^3/h units. With the obtained measurements, a system identification of the ventilation network shown in Figure 5 is performed and a controller is installed to regulate the airflow in one of the branches.

A. Sensors calibration

The characteristics of each sensor are described in Section II. The linear response of the hot wire sensor $EE671$ allows to directly compute the air flow based on the pipe diameter and the measured air velocity. Connecting the sensors in series, as shown in Figure 6, and assuming that air is incompressible, (a reasonable assumption at the operating conditions), the volumetric flow rate through the three sensors is the same.

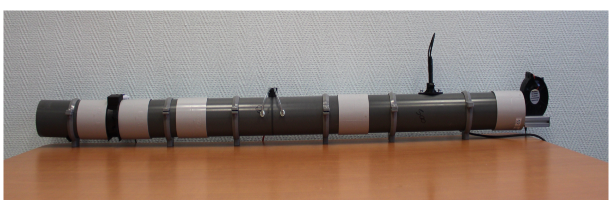

Figure 6. Sensors series

An H-bridge is used to vary the fan velocity by means a PWM signal. The hot wire sensor EE671 delivers a voltage, V_s, linearly proportional to the air velocity [13]. Knowing the radius of the pipe $r = 0.04m$, the cross section is $A = 0.005m^2$ the volumetric airflow can be calculated, $Q = k_s V_s A$, where the proportional constant $k_s = 0.5$ is related to the sensor resolution. The mass flow sensor provides a voltage signal, V_{MAF}, proportional to the mass of air passing through its section. Due to the mechanical components of the measuring device, low-range airflows do not produce a significant change on the measured voltage. The data sheet of this sensor is not available and other sensors are required for steady-state calibration. The orifice plate sensor offers the differential pressure P, generated by the reduction in the pipe. However, considering the pressure-flow relationship given by Eq. (1), the discharge coefficient in our application is unknown.

A set of experiments was realized to collect enough data and to perform a curve fitting. A linear regression was performed for the mass air flow sensor. Considering the quadratic relation between pressure and airflow, a second order regression was performed for the orifice plate sensor. The obtained results are shown in Figure 7.

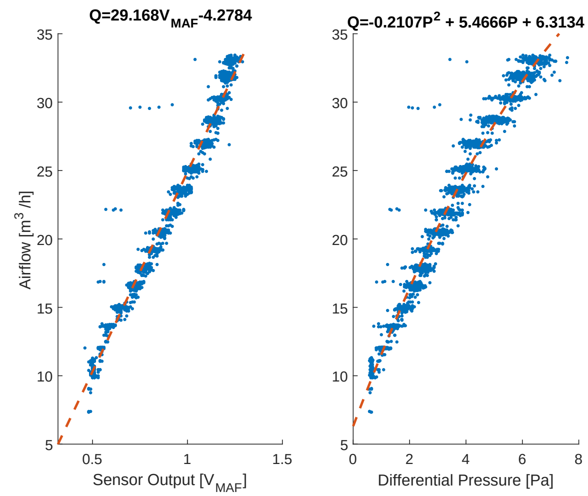

Figure 7. Calibration of the mass air flow sensor (left) and of the orifice plate sensor (right) using the hot wire measurement and a curve fitting method.

Finally, programming the computed polynomials in the measurement routine, we can obtain the signals of all sensors expressed in m^3/h. The outputs of the sensors at different operating points is shown in Figure 8. Despite of small differences all sensors now give comparable results. Note that the hot wire sensor has a better accuracy for steady-state while the other sensors have a faster response time and may thus be more appropriate to regulate the transient behavior of the flows.

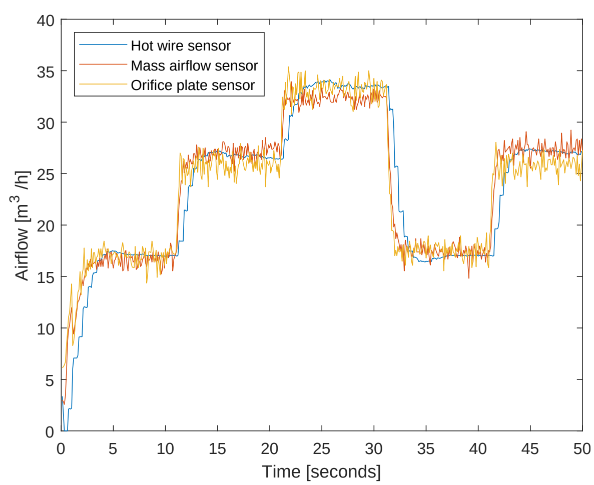

Figure 8. Comparison of the air flow measurements for the three sensors.

B. Identification and control of the ventilation network

A simple system identification method has been performed to the ventilation network shown in Figure 5. The duty cycle of the PWM to power on the fan is changed periodically at operating conditions $PWM \in [65\%,\ 80\%,\ 95\%]$. Experimental data is collected by means the hot wire sensor. A discrete transfer function is computed to represent the relationship between the PWM signal supplied to the fan denoted by $V_{fan}(t)$, and the volumetric airflow in a branch of the network measured by means the hot wire sensor $Q_1(t)$. A line search algorithm considering a sampling time $T_s = 0.1s$ allows estimating the following discrete plant:

$$\frac{Q_1(z)}{V_{fan}(z)} = \frac{0.0029}{1 - 0.88z^{-1} - 0.96z^{-2} + 0.87z^{-3}}. \tag{2}$$

The control aim is to regulate the volumetric airflow in the branch where the hot wire sensor is connected. Based on the model (2), a PI controller is designed to obtain a response with a settling time $t_s < 10s$ without overshoots in the closed-loop behavior. Let us consider a control fan voltage given by:

$$V_{fan}(z) = \left(K_p + \frac{K_i}{z-1}\right) e(z), \tag{3}$$

where $e(z) = Q_{ref}(z) - Q_1(z)$, and $Q_{ref}(z)$ is the set-up reference. From the given specifications, the constants of the discrete PI controller are: $K_p = 1.92$ and $K_i = 0.246$.

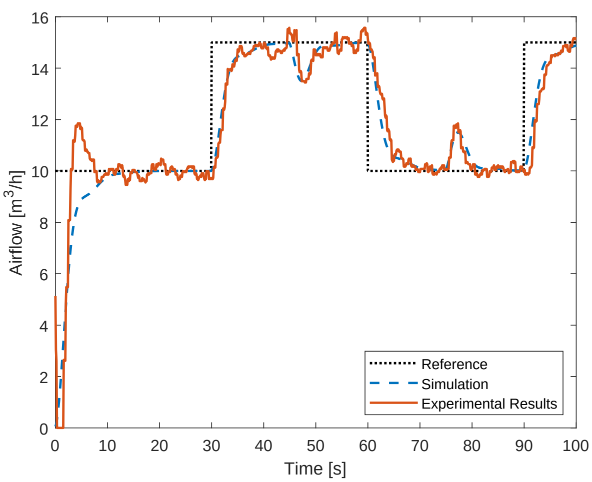

Figure 9. Controlled response of the airflow in the ventilation network.

The results are shown in Figure 9, the reference input (dotted line), simulation results (dashed line) and experimental results (solid line) are illustrated. The reference is a step signal periodically changing every 30 seconds between $Q_{r1} = 10m^3/h$ and $Q_{r2} = 15m^3/h$. In the simulation, a step disturbance of magnitude $d = -14$ is introduced at the system input at the instant $t = 45s$, and it is removed at the instant $t = 65s$. To represent the disturbance in the experiment, an obstruction reducing the diameter of the network exhaust to $40mm$ is used.

It can be noticed that the experimental results are similar to the simulated response. However, due to the non-linear characteristics of the physical system, the experimental closed-loop response has an overshoot in the transitory response of the step input reference introduced at the beginning of the experiment.

IV. Perspectives

This work is a starting point for an experimental set-up dedicated to the analysis of ventilation networks. In that sense, several possibilities for future work can be considered. This section is devoted to explore some of these possible research fields where the presented benchmark can be useful.

Modelling

A non-linear model based on the power conservation approach and bond graph theory is expected to be validated by means the proposed benchmark.

Future works include the theoretical formalization of a control oriented model in a state-space type representation taking into consideration the non-linear relation in the fluid flow dynamics and the conservation laws appearing in the ventilation network. The modeling procedure should be simple in order to include the changes of the network geometry in a straightforward manner.

Also, system identification of the ventilation network parameters can be considered. Based on the conservation laws and a state-space representation, the model parameters of a large ventilation network can be identified with a limited number of measurements.

Structural Systems

Modeling a system from the structural point of view allows to capture most of the structural information available from physical laws and from the decomposition of the system into subsystems. It provides a visual representation which makes clear the structure and allows to study properties which depend only on the structure, almost independently of the value of the unknown parameters. These unknown parameters are in general functions of the physical parameters. The computational burden is low and allows to deal with large-scale systems, specially if they are sparse [19]. In this framework, a structural analysis is intended to be performed, considering the typical evolution of the geometrical topology of underground ventilation systems. The conditions to preserve (or to loss) observability and/or controllability whereas the number of branches and nodes in the mine increase can be analysed.

In addition, a structural analysis could provide a minimization in the number of sensors and actuators that should be installed in the mine to have an observable and controllable system. The optimal location of sensors and actuators is also a problem to study.

Infinite Dimensional Systems

Ventilation systems are designed to maintain appropriate environmental conditions for the workers inside the mine. Regulating the airflow at the different levels is not the only aim, and we also wish to dilute dangerous gases as CO_2 and NO_x, and regulate temperature and humidity. The use of partial differential equations is considered to study and simulate the transport of heat, contaminants or humidity along the ventilation network [20]. A 0-D approximation of the 1-D transport (with advection and sink) including a time-delay system has been proposed in [21], [22], and shown to be efficient as a reference model for feedback control of the large advective flows appearing in the mining ventilation problem. A time-delay model for fluid flow networks, leading to a classical state-space representation with delays to take into account the transport phenomena in the pipes of the network is presented in [23]. Injection of CO_2 and/or mist, as well as the addition of heat to the fluid network can be easily implemented to the proposed benchmark. Thus,with the installation of additional measurement equipment, the analysis and validation of models describing the fluid dynamics and the transport phenomena can be performed, considering the infinite dimensional framework.

Design of Control Systems

The non-linear nature of the fluid dynamics and the obtained high-order models related with the ventilation network systems, make the design of automatic control systems for this class of process particularly challenging. The problem becomes even more difficult when the number of actuators and sensors is limited, a common scenario in small-scale underground mining industry.

The main aim of the introduced benchmark is to develop and validate suitable control systems for ventilation systems in small-scale mines. In addition, the use of observers to estimate the state variables of the system should be considered. In order to overcome the delay effects existing when the transport phenomena in included in the modeling, the use of prediction-based controllers could also be considered.

V. Conclusion

This work introduced a new benchmark to deal with the problem of modeling and controlling networked ventilation systems in the subsurface mine industry. The benchmark has been built taking into consideration the flexibility as an important issue. It is then possible to make modifications in the geometry of the network in an easy way and to study the effects of the topology evolution in the network dynamics and properties. Three different types of sensors where installed to compare the different measurement instruments for airflow in the network. A simple methodology to normalize the measurements is provided and experimental data acquisition is used to perform a model identification and obtain a linear dynamical model of the ventilation network.

The results expected from the proposed benchmark are devoted to the analysis of ventilation systems, but they can be extended to systems of conservation laws with different fluids.

References

[1] M. J. McPherson, *Subsurface Ventilation and Environmental Engineering*. Dordrecht: Springer Netherlands, 1993.

[2] E. Witrant, A. D'Innocenzo, G. Sandou, F. Santucci, M. D. Di Benedetto, A. J. Isaksson, K. H. Johansson, S.-I. Niculescu, S. Olaru, E. Serra, S. Tennina, and U. Tiberi, "Wireless ventilation control for large-scale systems: The mining industrial case," *International Journal of Robust and Nonlinear Control*, vol. 20, no. 2, pp. 226–251, jan 2010.

[3] J. M. Salamanca, J. J. Niño, and A. F. Pérez, "Análisis de diferentes estrategias de control automático aplicadas a un prototipo didáctico para el estudio de la ventilación de minas subterráneas," *Revista ingeniería Investigación y Desarrollo*, vol. 14, no. 2, pp. 6–10, 2014.

[4] K. Wang, J. Shuguang, W. Zhengyan, and S. Hao, "Intelligent safety adjustment of branch airflow volume during ventilation-on-demand changes in coal mines," *Process Safety and Environmental Protection*, vol. 111, pp. 491 – 506, 2017.

[5] H. Cross, "Analysis of flow in networks of conduits or conductors," *University of Illinois Engineering Experiment Station*, no. 286, 1936.

[6] N. Petrov, M. Shishkin, V. Dmitriev, and V. Shadrin, "Modeling mine aerology problems," *Journal of Mining Science*, vol. 28, no. 2, pp. 185–191, 1992.

[7] Y. Hu, O. I. Koroleva, and M. Krstić, "Nonlinear control of mine ventilation networks," *Systems & Control Letters*, vol. 49, no. 4, pp. 239–254, jul 2003.

[8] O. I. Koroleva and M. Krstic, "Averaging analysis of periodically forced fluid networs," *Automatica*, vol. 41, no. 1, pp. 129 – 135, 2005.

[9] O. I. Koroleva, M. Krstic, and G. W. SchmidSchonbein, "Decentralized and adaptive control of nonlinear fluid flow networks," *International Journal of Control*, vol. 79, no. 12, pp. 1495–1504, 2006.

[10] S. Zhu, Z. Jiang, K. Zhou, G. Peng, and C. Yang, "The characteristics of deformation and failure of coal seam floor due to mining in Xinmi coal field in China," *Bulletin of engineering geology and the environment*, vol. 73, no. 4, pp. 1151–1163, nov 2014.

[11] J. Sui, L. Yang, and Y. Hu, "Complex fluid network optimization and control integrative design based on nonlinear dynamic model," *Chaos, Solitons & Fractals*, vol. 89, pp. 20–26, aug 2016.

[12] J.-M. Salamanca, O.-O. Rodriguez-Diaz, A. A. Fernández, and J. J. Niño, "Modernisation of the underground coal mining sector in Colombia – a proposal from the academy," in *Underground Mining Technology 2017*. Sudbury, Canada: Australian Centre for Geomechanics, 2017, pp. 523–532.

[13] *Application note for EE671: HVAC Miniature Air Flow Transmitter*, V2 ed., Sensovant, December 2017.

[14] *SDP600 Series: Low-cost Digital Differential Pressure Sensor*, V1.9 ed., Sensirion, July 2015.

[15] *Application Note for SDP600 Series: Mass Flow Temperature Compensation & Sensor Selection Guide*, V2 ed., Sensirion, August 2013.

[16] "Arduino Mega 2560 rev3," https://store.arduino.cc/arduino-mega-2560-rev3, accessed 2019-02-13.

[17] "Mega IO expansion shield v2.3," https://www.dfrobot.com/-wiki/index.php/Mega-IO-Expansion-Shield-V2.3-(SKU:DFR0165), accessed 2019-02-13.

[18] "Arduino motor shield rev3," https://store.arduino.cc/arduino-motor-shield-rev3, accessed 2019-02-13.

[19] J.-M. Dion, C. Commault, and J. van der Woude, "Generic properties and control of linear structured systems: a survey," *Automatica*, vol. 39, no. 7, pp. 1125 – 1144, 2003.

[20] G. L. Danko, "Subsurface flow and transport process model for time dependent mine ventilation simulations," *Mining Technology*, vol. 122, no. 3, pp. 134–144, 2013.

[21] E. Witrant and N. Marchand, *Mathematical Problems in Engineering, Aerospace and Sciences*. Cambridge Scientific Publishers, 2008, ch. Modeling and Feedback Control for Air Flow Regulation in Deep Pits.

[22] E. Witrant and K. Johansson, "Air flow modeling in deepwells: Application to mining ventilation," in *Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on*, 2008, pp. 845–850.

[23] D. F. Novella-Rodriguez, E. Witrant, and O. Sename, *Recent Results on Nonlinear Delay Control Systems*, ser. Advances in Delays and Dynamics. Springer, 2016, vol. 4, ch. Control-Oriented Modeling of Fluid Networks: A Time-Delay Approach.