OPTIMAL LQI-BASED CONTROL OF MULTI-ZONE UNDERGROUND MINE VENTILATION SYSTEMS USING FANS AND ADJUSTABLE DAMPERS

Tuxtamishova Malika
PhD Student Navoi Branch of the Academy of Sciences of Uzbekistan
E-mail: example@gmail.com

Abstract. This study proposes an optimal control framework for multi-zone underground mine ventilation systems using a Linear Quadratic Integral (LQI) controller. The approach coordinates ventilation fan rotational speeds and adjustable damper positions to regulate airflow distribution across underground working zones. A mathematical model is formulated considering airflow dynamics, aerodynamic resistance, and network interactions. The model is linearized around an operating point and represented in state-space form. Integral feedback is introduced to reduce steady-state tracking errors and improve disturbance rejection. The proposed methodology can be evaluated through MATLAB/Simulink simulations using airflow tracking accuracy, response time, stability, and control effort as performance indicators.

Keywords: Underground mine ventilation; Multi-zone ventilation; LQI controller; Optimal control; Airflow regulation; Ventilation fans.

INTRODUCTION

Underground mining operations require reliable and efficient ventilation systems to maintain safe working conditions, ensure an adequate oxygen supply, and remove hazardous gases, dust, and excess heat generated during mining activities. The ventilation system is one of the most important components of underground mine infrastructure because its performance directly affects occupational safety, operational efficiency, and energy consumption. In particular, methane accumulation, insufficient oxygen concentration, and the presence of harmful gases can create dangerous conditions for underground workers. Therefore, maintaining the required airflow distribution across different mining zones is an essential task in modern mine ventilation management.

Conventional underground mine ventilation systems are commonly operated using fixed-speed fans and manually adjusted ventilation doors. Although these approaches can provide basic airflow regulation, they may not respond effectively to changing operational conditions, such as variations in mining activity, tunnel resistance, airflow demand, and the opening or closing of ventilation branches. These limitations can result in unequal airflow distribution, excessive ventilation in some areas, and insufficient airflow in others. Such conditions may increase energy consumption and reduce the overall efficiency of underground ventilation networks. Consequently, the development of automatic control strategies for multi-zone mine ventilation systems has become an important research direction.

Previous studies have investigated mathematical modeling and automatic control of underground mine ventilation networks. Hu et al. (2003) developed a nonlinear mathematical model based on the physical characteristics of ventilation networks and studied nonlinear control techniques for airflow regulation. Rodríguez-Díaz et al. (2023) proposed a modeling and control strategy for small-scale underground mine ventilation networks using a reduced number of sensors and actuators. Their approach was based on a nonlinear dynamic model, a state-space representation, and a Linear Quadratic Integral (LQI) controller combined with a state estimator. Their study demonstrated that airflow in several underground branches could be regulated by adjusting the operating speeds of two main fans. It also

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highlighted the potential to reduce instrumentation costs while maintaining the required airflow conditions.

Despite these developments, the coordinated control of multiple ventilation zones using both fan speed regulation and adjustable ventilation dampers remains an important engineering problem. Simultaneous adjustment of fan operating conditions and damper opening positions can provide additional flexibility in distributing airflow among underground working areas. This approach can help maintain the required airflow in each zone while limiting unnecessary pressure losses and electrical energy consumption.

The mathematical representation of a multi-zone underground ventilation network can be developed using the principles of mass conservation and pressure balance. According to the continuity equation, the total airflow entering a ventilation junction is equal to the total airflow leaving that junction:

$$\sum_{j=1}^{n} a_{ij} Q_j = 0 \quad (1)$$

where Q_j represents the airflow rate in the j-th ventilation branch, a_{ij} is the corresponding network incidence-matrix coefficient, and n is the total number of branches.

The aerodynamic pressure loss in an underground ventilation branch can be described using the Atkinson resistance relationship:

$$\Delta P_j = R_j Q_j |Q_j| \quad (2)$$

where ΔP_j is the pressure loss in the branch, R_j is its aerodynamic resistance, and Q_j is the airflow rate. The aerodynamic resistance can be estimated as:

$$R_j = (\alpha_j L_j P_j) / S_j^3 \quad (3)$$

where α_j is the aerodynamic resistance coefficient, L_j is the tunnel length, P_j is the tunnel perimeter, and S_j is the tunnel cross-sectional area.

For a ventilation branch equipped with an adjustable damper, the effective resistance depends on the damper opening position. A simplified representation is:

$$R_j,\text{eff}(\theta_j) = R_j,\text{tunnel} + R_j,\text{damper}(\theta_j) \quad (4)$$

where θ_j denotes the damper opening position. The damper resistance varies with its opening degree and therefore affects the airflow distribution in the corresponding zone.

A simplified dynamic relationship for a ventilation branch can be expressed as:

$$dQ_j/dt = K_j [\Delta P_j,\text{fan} - R_j,\text{eff}(\theta_j) Q_j |Q_j|] \quad (5)$$

where K_j is the inertial coefficient of the ventilation branch and ΔP_j,fan is the pressure generated by the fan. This relationship describes the interaction between fan-generated pressure, tunnel resistance, damper position, and airflow dynamics.

MATERIALS AND METHODS

This study investigates the optimal control of a multi-zone underground mine ventilation system using ventilation fans, adjustable dampers, and a Linear Quadratic Integral (LQI) controller. The proposed system consists of interconnected underground tunnels divided into several ventilation zones. Each zone is characterized by its airflow demand, aerodynamic resistance, and ventilation requirements.

The research methodology involves developing a mathematical model of the ventilation network, determining the operating parameters of fans and dampers, and designing an LQI-based control algorithm. Fan rotational speed and damper opening position are used as control variables to regulate airflow distribution across the underground zones.

The main parameters considered in the proposed ventilation system are presented in Table 1.

Table 1. Main parameters of the multi-zone mine ventilation system

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Parameter	Description	Unit
Q_i	Airflow rate in zone i	m^3/s
ω_i	Fan rotational speed	rpm
θ_j	Damper opening position	%
R_j	Aerodynamic resistance	Ns^2/m^8
ΔP	Air pressure difference	Pa
Qref	Required airflow reference	m^3/s

The LQI controller is designed to minimize airflow deviations from reference values while maintaining stable system operation. The controller simultaneously adjusts fan speeds and damper positions to achieve the required airflow in each ventilation zone.

The proposed control strategy is evaluated using MATLAB/Simulink simulations. System performance is assessed based on airflow regulation accuracy, response time, disturbance rejection, and energy consumption. The simulation results are used to evaluate the effectiveness of coordinated fan and damper control in improving the safety and energy efficiency of underground mine ventilation systems.

RESULTS AND DISCUSSION

The proposed LQI-based control strategy is intended to improve airflow regulation in multi-zone underground mine ventilation systems. The coordinated operation of ventilation fans and adjustable dampers provides an opportunity to distribute airflow according to the ventilation requirements of individual mining zones.

The main expected result of the proposed control system is improved airflow tracking accuracy. By adjusting fan rotational speeds and damper opening positions, the controller can compensate for variations in airflow demand and changes in aerodynamic resistance. The integral component of the LQI controller helps eliminate steady-state tracking errors and maintain airflow close to the desired reference values.

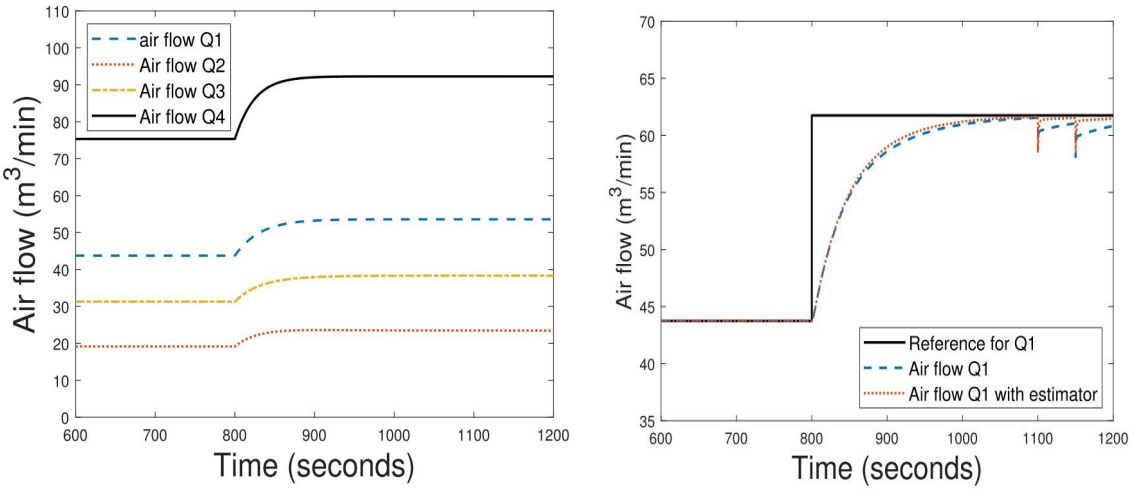


Figure 1. Simulation results of the LQI-based underground mine ventilation control system: (a) airflow dynamics in four ventilation branches; (b) tracking performance of the reference airflow and estimated airflow in Zone 1.

Another important aspect is disturbance rejection. Changes in ventilation demand, tunnel resistance, and operating conditions can affect airflow distribution throughout the network. The proposed controller

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is designed to compensate for these disturbances by coordinating the control actions of fans and dampers. This approach can improve the stability of airflow in different underground working zones.

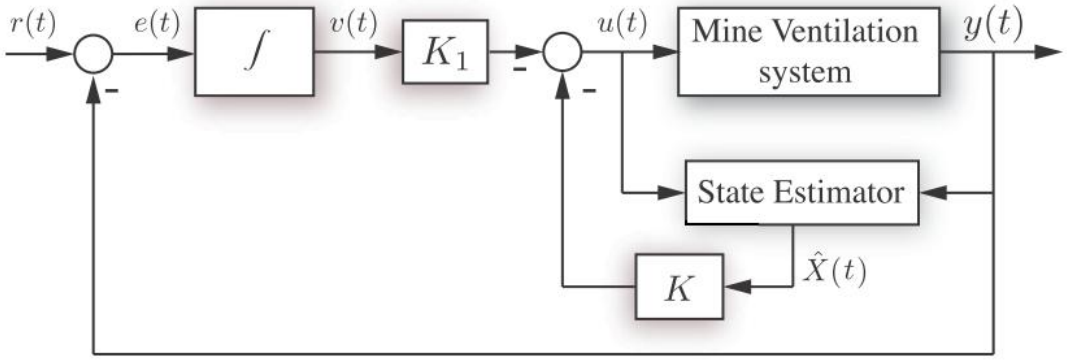


Figure 2. Block diagram of the observer-based LQI control system for underground mine ventilation network.

The energy efficiency of the ventilation system is also considered. Conventional ventilation systems may consume excessive energy when fans operate at constant speeds regardless of actual airflow requirements. The proposed control strategy provides the possibility of adjusting fan operation and damper positions according to the required ventilation conditions, potentially reducing unnecessary energy consumption.

The performance of the proposed approach should be evaluated using MATLAB/Simulink simulations. Particular attention should be given to airflow tracking accuracy, settling time, overshoot, disturbance rejection, and total control effort. A comparison between conventional control and the proposed LQI strategy will help determine the effectiveness of coordinated fan and damper regulation.

Overall, the proposed methodology provides a mathematical and control-system framework for intelligent management of multi-zone underground mine ventilation networks. The integration of fan speed regulation, adjustable dampers, and LQI control offers a potential solution for improving airflow distribution, operational stability, and energy efficiency. Experimental or simulation-based validation using actual mine parameters is required to quantify these improvements.

CONCLUSION

This study presents an optimal control approach for multi-zone underground mine ventilation systems based on a Linear Quadratic Integral (LQI) controller. The proposed methodology integrates ventilation fan speed regulation and adjustable damper control to maintain the required airflow distribution across different underground working zones. The mathematical modeling approach considers airflow dynamics, aerodynamic resistance, and the interaction between ventilation branches. The LQI controller provides a systematic method for reducing airflow tracking errors, improving system stability, and compensating for external disturbances through integral feedback and state estimation.

The proposed approach provides a foundation for developing intelligent and energy-efficient underground mine ventilation systems. The coordinated control of fans and dampers can improve airflow distribution, reduce unnecessary ventilation energy consumption, and maintain appropriate ventilation conditions in different mining zones. MATLAB/Simulink modeling can be used to further evaluate the controller's performance under different operating conditions. Future research will focus on experimental validation using real mine ventilation parameters, optimization of controller weighting matrices, and investigation of the influence of changing aerodynamic resistance and ventilation demand on overall system performance.

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