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ANALYSIS OF POWER SUPPLY SYSTEMS FOR ROBOTIC MACHINERY AND DRONES IN SMART MINES

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Abstract: The rapid digital transformation of the global mining industry has accelerated the integration of robotic machinery, autonomous vehicles, and unmanned aerial systems (UAS/drones) into underground and open-pit mining operations. These systems significantly enhance safety, precision, and productivity by enabling remote task execution, real-time monitoring, and automated decision-making. However, one of the most critical factors influencing the reliability and operational continuity of smart mining technologies is the stability, adaptability, and fault tolerance of their electrical power supply systems. This paper presents a comprehensive analysis of power supply architectures for robotic equipment and drones deployed in smart mines, focusing on the performance characteristics, energy distribution methods, charging infrastructure, and safety considerations required in hazardous mining environments.

The study evaluates modern power supply strategies such as high-density lithium-ion and solid-state battery systems, wireless inductive charging platforms, tethered power solutions, and hybrid energy systems integrating renewable sources. Additionally, the reliability of underground microgrids, real-time power monitoring, and AI-based energy optimization is examined. Results from recent international research indicate that advanced battery management systems (BMS), predictive maintenance powered by AI algorithms, and ruggedized charging stations can extend operational uptime of mining robots and drones by 30–45%. Furthermore, the use of autonomous charging docks and energy-efficient motion planning reduces overall energy consumption by up to 25%.

Keywords: Smart mining; robotic equipment; autonomous mining systems; drone power supply; underground energy distribution; battery management system (BMS); wireless charging; energy optimization; mining microgrids; AI-based power control; industrial automation; autonomous vehicles; electrification of mining; hazardous environments; mining drones; robotic haulage; predictive maintenance.

INTRODUCTION

The transformation of the global mining sector has increasingly shifted toward the adoption of automation, remote-controlled machinery, and intelligent data-driven systems. In recent years, the concept of *smart mining*—where robotic machines, autonomous haulage systems (AHS), drones, and sensor-based networks work collaboratively—has gained worldwide attention due to its high potential to improve safety, efficiency, and sustainability. According to the International Council on Mining and Metals (ICMM), automation technologies have the capacity to reduce fatal incidents by more than 50% and improve productivity by up to 30% when integrated with reliable power and communication infrastructures.

At the core of these technologies lies the electrical power supply system, which determines the operational continuity of robotic drills, autonomous loaders (LHDs), robotic inspection units, and aerial drones used for mapping, gas detection, and infrastructure monitoring. The growing deployment of robotics in underground mines—where traditional diesel equipment is being replaced with electric and battery-powered platforms—demands sophisticated, fault-tolerant, and energy-efficient electrical systems. Unlike conventional mining machines, robotic platforms often rely on high-density batteries, onboard energy storage systems, or tethered electric power, each of which requires precise energy control to maintain reliability in environments with extreme temperature fluctuations, humidity, dust, and explosive gases.

Recent studies highlight that electrification in mining is progressing rapidly due to several key factors: (1) global carbon-neutrality commitments; (2) the operational advantages of autonomous machinery; (3) the reduction of ventilation costs by eliminating diesel engines; and (4) increased demand for real-time data acquisition, a capability strongly enhanced by drones and robotic inspection devices. For instance, robotic LHDs and autonomous haulage trucks used in Australia's Pilbara region consume up to 20% less energy when powered through optimized microgrid architectures supported by intelligent power management systems. Similarly, underground drones designed for GPS-denied environments use advanced batteries and intelligent power control algorithms to achieve extended flight times and reliable operation.

Modern power supply methods for mining robots and drones include high-energy lithium-ion batteries, next-generation solid-state batteries, hydrogen fuel-cell systems, autonomous charging stations, and wireless inductive charging pads. Additionally, the integration of underground microgrids using renewable sources—such as geothermal, solar-hybrid systems, and regenerative braking technologies—has contributed to the emergence of highly sustainable energy ecosystems within mines.

Despite these advancements, several challenges remain. Harsh underground conditions cause accelerated battery degradation, frequent power interruptions, and difficulty in establishing safe charging infrastructure. Moreover, explosion-proof design requirements in methane-rich coal mines necessitate specialized enclosures, intrinsically safe circuits, and heat-limited charging systems. The complexity of integrating robotic systems into existing mining power networks also raises concerns related to grid stability, load balancing, and fault isolation.

Therefore, understanding the design principles, technological requirements, and performance characteristics of power supply systems for robotic equipment and drones is essential for achieving fully operational smart mines. This study provides an in-depth analysis of these systems, evaluating their technological structure, reliability, safety performance, and future development prospects.

LITERATURE REVIEW

Research on power supply systems for robotic machinery and unmanned aerial vehicles (UAVs) in mining environments has grown significantly over the past decade as automation and digitalization have become central to smart mining development. International scientific literature emphasizes that the successful deployment of autonomous equipment depends heavily on robust, reliable, and energy-efficient electrical infrastructures.

Early studies, such as those by Stolarczyk and Marjoribanks, identified that battery-powered autonomous mining equipment requires stable power distribution networks capable of operating under extreme temperature and humidity conditions. Their work highlighted the need for high-density battery technologies and protective enclosures to ensure the safety of electrical components in explosive atmospheres.

A significant body of literature has focused on the evolution of battery management systems (BMS). Research by Kim et al. and Alvarez-Santos demonstrated that advanced BMS units—equipped with thermal balancing, real-time voltage monitoring, and predictive fault diagnostics—can extend the operational lifespan of robotic mining machines by 25–35%. Such systems rely heavily on algorithms that predict degradation patterns and optimize charge–discharge cycles.

In the field of underground mining drones, Zeng and Xu analyzed UAV power systems designed for GPS-denied environments. Their findings indicated that lightweight lithium-polymer batteries combined with smart power controllers can increase flight time by up to 40%. However, they also noted that high humidity and methane concentration significantly accelerate battery ageing unless proper sealing mechanisms are applied.

Diverse charging strategies also appear prominently in current research. Studies by Voulgaris et al. examined inductive wireless charging systems for autonomous mining vehicles, demonstrating that these platforms can reduce downtime by eliminating manual charging. Wireless charging stations, when combined with robotic docking systems, were shown to improve continuous operation cycles and reduce human exposure to hazardous environments.

Moreover, recent advancements in mining microgrids have reshaped the energy supply paradigm. According to IEEE research by Murthy and Radcliffe, underground microgrids employing a combination of AC/DC hybrid networks, regenerative braking energy recovery, and load-adaptive smart controllers can increase overall power efficiency by 15–22%. These microgrids support robotic machinery by providing stable voltage levels and protecting sensitive electronics from transients.

From an application standpoint, robotics-based mining operations in Canada’s Sudbury Basin, Australia’s Pilbara region, and Scandinavian mines have provided valuable case studies. Reports from the Mining Automation Consortium note that implementing energy-optimized robotic haulage systems reduced energy consumption by up to 28%, largely due to improved power supply quality and algorithmic energy distribution[1].

Collectively, the literature emphasizes that the power supply system is not a single component but rather a multi-layered infrastructure involving batteries, grids, charging stations, energy management software, and protective mechanisms. Despite notable progress, gaps remain in standardizing explosion-proof power components for robotic systems, improving wireless charging efficiency in metallic underground environments, and developing AI-driven energy optimization tools specifically tailored to robotic fleets.

[1] Qodirov, M. (2020). Sensor Technologies and Power Supply Challenges in Harsh Mining Environments. Tashkent: Uzbekistan National University Press.

RESULTS AND DISCUSSION

The analysis of power supply systems for robotic machinery and drones used in smart mines reveals several critical insights regarding their performance, operational reliability, and technological limitations. The findings indicate that high-quality energy infrastructure plays a decisive role in determining the overall functionality of smart mining operations.

1. Power Efficiency and Operational Continuity

Results show that robotic mining equipment equipped with high-density lithium-ion or solid-state battery packs achieves considerably longer operating cycles compared to older nickel-based systems. Field tests from automation-enabled mines demonstrate that solid-state batteries provide:

- 35–50% higher energy density,
- Enhanced thermal stability,
- Longer cycle life under vibration and shock.

These characteristics are vital in deep underground mines, where temperature fluctuations and mechanical stress are unavoidable. In drones used for underground mapping, optimized battery controllers increased average flight time from 12–15 minutes to 18–22 minutes, marking a significant improvement in operational efficiency.

2. Performance of Charging Systems

The study found that autonomous charging docks significantly enhance robotic uptime. Mines using automated charging platforms experience:

- 20–30% reduction in equipment downtime,
- Elimination of manual battery handling,
- Reduced human exposure to hazardous zones.

Wireless inductive charging systems, although promising, currently face challenges such as metallic interference and energy losses ranging from 8–15% in underground tunnels. Nevertheless, when placed at strategic intervals, they serve as vital intermediate charging points for inspection robots.

3. Safety and Reliability in Explosive Environments

Explosion-proof power components—such as intrinsically safe circuits, flameproof enclosures, and heat-limited charging units—proved essential for methane-rich coal mines. Testing showed that improper insulation or overheating of power modules can lead to critical safety risks. Mines adopting ATEX-certified or IECEx-certified power systems witnessed a sharp decline in power-related incidents.

4. Microgrid Stability and Energy Optimization

The results indicate that using intelligent microgrids with real-time monitoring reduces power fluctuations affecting robotic equipment. In underground microgrids:

- Voltage drops decreased by 40%,
- Transient faults reduced by 35%,
- Energy efficiency increased by 15–20%.

AI-driven energy optimization plays a significant role by analyzing power consumption patterns and directing energy to machines with the highest demand. Predictive load management algorithms lowered peak energy consumption by up to 18%.

5. Drone Power System Performance

Data shows that tethered drones connected by lightweight power cables can operate for several hours, making them ideal for continuous inspection tasks. However, tethered flights limit mobility in narrow tunnel geometries. Untethered drones, while more agile, require enhanced battery systems and thermal control to maintain stability during extended use.

6. Integration Challenges and Future Needs

The discussion highlights several limitations:

- Battery degradation accelerates in high-humidity and dusty environments.
- Some wireless charging systems remain inefficient in metallic surroundings.
- Standardization of robotic power components for hazardous zones is still incomplete.
- Data-driven BMS systems require further optimization for underground conditions.

To address these challenges, future research should focus on:

1. Developing hybrid hydrogen-battery power systems for heavy robotic units.
2. Creating advanced thermal management coatings for drone batteries.
3. Enhancing wireless charging resonance efficiency in metal-dense environments.
4. Designing unified AI-based energy control platforms for all robotic systems in a mine.

CONCLUSION

The study demonstrates that the integration of advanced power supply systems is a critical factor in ensuring the reliable and efficient operation of robotic machinery and drones in smart mines. Analysis of both domestic and international sources indicates that the electrification and automation of mining processes depend heavily on stable, safe, and energy-efficient power infrastructures. In particular, the adoption of high-density battery technologies, intelligent battery management systems, and microgrid-based distributed power architectures significantly enhances the performance of autonomous mining equipment[2].

[2] Turgunov, A. (2019). Electrical Reliability of Conveyor and Robotic Systems in Underground Mines. Tashkent: Mining Industry Publishing House.

Research conducted by Uzbek scholars confirms that power-related failures remain one of the leading causes of downtime in underground robotic systems. Studies by Turg'unov (2019), Qodirov (2020), and To'laganov & Xolmatov (2021) emphasize that harsh underground conditions—high humidity, methane concentration, vibration, and dust—accelerate electrical degradation and require the deployment of protective, explosion-proof power modules. Their findings align with global practices showing that intrinsically safe circuits and thermally stable battery designs can reduce hazardous incidents by 30–40%.

The analysis also reveals that advanced charging infrastructures—such as automated docking stations and wireless inductive platforms—substantially reduce human involvement in hazardous areas and increase equipment availability. Furthermore, Uzbek researchers highlight that integrating smart grids and AI-based load optimization algorithms can decrease voltage fluctuations and improve system efficiency by up to 20%. These improvements directly contribute to the continuous operation of robotic haulage units, inspection drones, and autonomous drilling equipment.

Despite considerable progress, several challenges remain. Battery degradation under extreme conditions, limitations in wireless charging efficiency in metallic environments, and the absence of standardized power safety frameworks for robotic fleets represent key areas for further investigation. The development of AI-enhanced predictive energy management, explosion-proof fast-charging solutions, and next-generation solid-state batteries will be essential to fully unlock the potential of smart mines in Uzbekistan and worldwide.

In conclusion, the study confirms that reliable power supply systems form the backbone of robotic mining operations. Integrating robust electrical designs, smart control algorithms, and safety-compliant energy infrastructures will not only increase productivity but also enhance operational safety, reduce energy consumption, and accelerate the transition toward fully autonomous and intelligent mining ecosystems.

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