APPLICATION OF ARTIFICIAL INTELLIGENCE AND ASSOCIATED TECHNOLOGIES IN ACCIDENT PREVENTION AND WORK OPTIMIZATION: A CASE STUDY IN MINING INDUSTRY 4.0

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Abstract: The technological advancement in production methods, especially in the AI era, has gained increasing prominence in the mining industry, which benefits from these innovations in optimization and accident prevention at work. Thus, this study is based on a rigorous theoretical foundation to examine the use of these modernizations, associating their impacts on accident prevention and work enhancement, in addition to analyzing the current scenario and future perspectives of mining 4.0.

Keywords: **Technologies; IoT; Industry 4.0; Artificial Intelligence; Mining safety.**

INTRODUCTION

Occupational health and safety are of paramount importance across various sectors, with mining being a notable example. This activity exposes its workers to a wide range of risks, including physical, chemical, and environmental hazards. This sector is characterized by numerous hazardous activities necessary for the extraction of mineral resources from surface portions (open-pit mines) or even from subsurface portions of the Earth's crust (underground mines). It is noteworthy that the latter category carries even higher risks. According to estimates by the International Labour Organization (ILO), the mining sector is responsible for high rates of work-related accidents worldwide, both fatal and non-fatal (Wadsworth and Walters, 2019).

In the mining sector, specifically regarding worker health and safety risks, there are numerous broad and complex challenges to overcome. Preventive measures are necessary to reduce potential physical, psychological, and health damages caused by undesirable events, such as explosions and exposure to toxic substances, necessitating constant maintenance and monitoring of equipment and machinery (CDC, 2017). Technical, organizational, and regulatory deficiencies persist in the mining sector, keeping accident rates high. Mining companies are required by current legislation to take measures according to the operational conditions of each activity, thus mitigating the risks highlighted in these scenarios (Saleh and Cummings, 2011).

With the advent of Industry 4.0, a new perspective on risk management and control in mining has emerged. Cutting-edge technologies, such as big data, cyber-physical systems, the Internet of Things (IoT), and Artificial Intelligence (AI), are noteworthy. These innovations enable task automation, bringing greater efficiency to processes and safety gains for employees (Kagermann *et al*., 2013). AI, in particular, has achieved recent advancements that have led to greater prevention of workplace accidents, thanks to continuous monitoring through predictive risk analyses and decision-making capabilities in complex scenarios (Peres *et al*., 2020).

In the mining industry, artificial intelligence has provided significant improvements when applied correctly, enhancing occupational health for workers and environmental sustainability. Mineral Research, Drilling and Rock Blasting, Transport and Loading, and other areas within the broader field of Mining Engineering have shown a trend towards high integration with AI, whether in current or future applications. These initiatives have allowed for an upgrade in mine planning, optimizing company operations and minimizing errors in conducting operations (Costa *et al*., 2023).

In this context, this article focuses on investigating the application of AI and other advanced technologies in preventing workplace accidents and optimizing efficiency in the mining industry. These technologies are detailed concerning their integration into operational processes, aiming to improve worker safety and increase production. This study intends to contribute to the field of occupational safety and operational efficiency in the mining industry, offering insights into the main practices in the Mining 4.0

scenario and identifying existing gaps that require future research.

MATERIAL AND METHODS

The methodology employed in this study focused on a comprehensive and systematic literature review, aimed at investigating the application of artificial intelligence (AI) and other cutting-edge technologies in workplace accident prevention and better time management for production in the context of Industry 4.0, with an emphasis on Mining Industry 4.0. Initially, key terms were defined to guide the search for relevant literature, including "underwater mining", "space mining", "machine learning", "remote sensing", "predictive analysis", "Industry 4.0", "Internet of Things (IoT)", "big data", "smart mining", "industrial automation", "accident prevention in mining", "safety monitoring in mining", "working conditions in mining", "AI in mining", "mining", "mining safety", "work accidents in mining" and "technology in mining". The combination of these keywords, without restriction to a single language, aimed to cover all relevant aspects of the study, ensuring the identification of a wide range of sources. The literature search was conducted in academic databases and specialized websites recognized for their relevance and comprehensiveness in the field, such as Google Scholar, ScienceDirect, IEEE Xplore, SpringerLink, Science Direct, MDPI (Multidisciplinary Digital Publishing Institute), among others. To ensure the quality and relevance of the sources, rigorous inclusion and exclusion criteria were established: relevant and impactful studies in the Industry 4.0 mining sector were included, and opinion articles, studies with insufficient methodology, and publications outside the defined thematic scope were excluded. Data collection involved the identification, selection, and critical review of the articles found, evaluating each one for its contribution to the topic, methodology used, results obtained, and relevance to the mining industry. The extracted information was categorized and synthesized to identify patterns, gaps, and relevant insights. This methodological approach ensured a robust and comprehensive literature review, providing a solid foundation for understanding the application of technologies in workplace accident prevention and task optimization in Mining Industry 4.0.

RESULTS AND DISCUSSION

Remote Sensing (RS)

Remote sensing is defined as a crucial indirect geophysical technique in mining, involving the processing and interpretation of data obtained by aircraft and satellites about portions of the Earth's surface and subsurface, covering large geographical areas through the capture of electromagnetic energy resulting from interactions with matter (Khorram *et al*., 2012). This remote sensing can be conducted in two ways: active remote sensing and passive remote sensing, as shown in Figure 1 below.

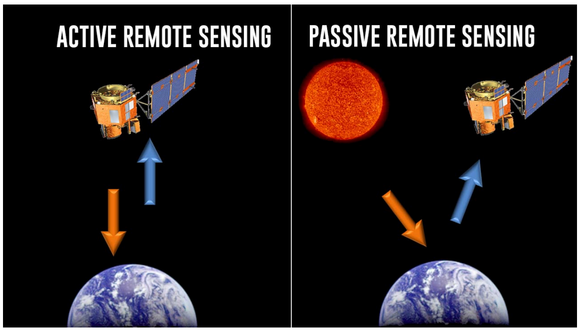

Figure 1. Types of remote sensing.

Source: Mukesh Sharma (2019).

Passive remote sensing is based on the detection of natural radiation emitted by the sun or thermal radiation emitted by the Earth and reflected by the Earth's surface, using means such as cross-track optical-mechanical scanners, also known as thematic mappers (TM). The TM directs the field of view at a right angle to the satellite's orbital path, and as it moves along the solar orbit, the mirror oscillates, reflecting the light captured by the sensor's lens to a set of detectors (which generate electrical signals) or spectrometers. These passive sensors are calibrated to specific wavelength ranges, separating this captured energy into short wavelength intervals (spectral bands), with each recorded as isolated images. These Landsat thematic mapper satellite images are used to locate potential mineral deposits, either by mapping geology, faults, and fractures indicative of deposits or by identifying spectral signatures of rocks altered by the percolation of hydrothermal fluids (Sabins, 1999). Additionally, such images provide the capability for environmental monitoring or rehabilitation of areas degraded by the mining industry, reinforcing the achievement of targets by these companies (McKenna *et al*., 2020).

In a formal agreement between NASA (National Aeronautics and Space Administration) and USGS (United States Geological Survey), the history of Landsat satellites began in 1972 with the launch of Landsat 1 (formerly ERTS-1), following a continuous line of launches. Each satellite is responsible for capturing various spectral ranges between bands, allowing the creation of multispectral images, which provide specific information for each portion of the Earth's subsurface and surface analyzed. Besides the satellites already in orbit, NASA intends to launch a new satellite, Landsat Next, by 2031, with an improved spatial resolution of 10m/pixel, indicating that this sector of remote sensing is constantly advancing (NASA, 2023).

With the advent of these satellites, there have also been improvements in their compartments, one of which is the type of sensor. Each sensor has bands, with the latest launched on Landsat 8, the TIRS (Thermal Infrared Sensor), featuring two thermal bands, allowing integration with "split window" algorithms commonly used to acquire surface temperature data (Climatologia RJ, 2024). Table 1 below provides relevant insight for a better understanding of the information from these data collection objects.

Table 1. Summary of information on the components and current status of Landsat satellites.

Satellite	Launch Date	Current Status	Sensors
Landsat 1	07/23/1972	Inactive (01/06/1978)	RBV and MSS
Landsat 2	01/22/1975	Inactive (02/25/1982)	RBV and MSS
Landsat 3	03/05/1978	Inactive (03/31/1983)	RBV and MSS
Landsat 4	07/16/1982	Inactive (1993)	MSS and TM
Landsat 5	03/01/1984	Inactive (11/22/2011)	MSS and TM
Landsat 6	10/05/1993	Inactive (10/05/1993)	ETM
Landsat 7	04/15/1999	Active (Reception interrupted in Brazil on 05/31/2003)	ETM+
Landsat 8	02/11/2013	Active	OLI and TIRS

Source: Adapted from Landsat - Portal Embrapa (2020).

From another perspective, there is also the so-called active remote sensing, which has two types of active sensors, namely LIDAR (Light Detection and Ranging) and radar sensors (Dong and Chen, 2017). According to Bachman (1979), active LIDAR sensors work by emitting laser pulses directed at the target of interest and measuring the time it takes for these pulses to return after being reflected, enabling high-precision distance calculation between the sensor and the target. This procedure begins when the short-duration laser pulse is emitted, hitting the target surface and reflecting back to the sensor, with the total time taken for the pulse to return being recorded. This time is multiplied by the speed of light to obtain the total distance traveled by the laser pulse, and since the distance is round-trip, dividing by two gives the real distance between the sensor and the target. Using a series of complex mathematical parameters and fundamental principles, Baltsavias (1999) sought to explain the relationship between laser range and scanning patterns, among other factors, for a better understanding of the creation of 3D maps by ALS (Airborne Laser Scanning). However, in a summarized manner, LIDAR (2002) explained that by repeatedly measuring the vertical distance from a LIDAR sensor mounted on a level-flying aircraft, a descriptive contour of the Earth's surface, whether soil or vegetation, is obtained. Bathymetric LIDAR sensors can measure elevations under shallow waters using medium wavelengths of 532 nm for greater penetration. More modern LIDAR sensors have scanning capabilities with rotating mirrors, generating detailed images across the range covered by the aircraft. Additionally, laser altimetry or LIDAR is characterized by higher accuracy in biophysical measurements and expansion for three-dimensional analysis (such as plant canopies or their topography, generating precise maps of their height, among other parameters), as well as greater precision in estimating the LAI (Leaf Area Index) and above-ground biomass. Furthermore, multiple beams and scanning systems facilitate biospheric, cryospheric, and hydrological processes, captured by the LIDAR system (Wang and Menenti, 2021). Wajs *et al*. (2021) analyzed the integration of the LIDAR system with the Riegl VMZ 400i measurement platform and a Velodyne LiDAR sensor in the SLAM (Simultaneous Localization and Mapping) approach based on MLS (Mobile LIDAR Systems) in an open-pit mine in Mikoszów (Lower Silesia, SW Poland), allowing the three-dimensional model of the pit to be constructed and updated in real-time, generating a high-resolution point cloud, which feeds big data databases in mines, within the context of mining industry 4.0. This information is used at all stages of open-pit mining operations and post-mining area management, enabling a sustainable approach to its use.

For active radar sensors, the operation is slightly different, relying on the use of microwave waves to form images of the Earth's surface. This method is quite effective and useful in conditions where optical or thermal sensors are inefficient, such as in cloudy areas, penetrating cloud cover. Additionally, this sensor is sensitive to the presence of water, making it valuable for analyzing the structural characteristics of vegetation and surface moisture conditions. The principle of radar imaging works by emitting microwave pulses, capturing, and recording their reflection back to the antenna, with the geometry and composition of the body of interest influencing the strength of the emitted pulse. Since the spatial resolution of radar images is equivalent to the ratio between the wavelength and the antenna length, the synthetic aperture radar technique is used, synthesizing a long antenna while the image is processed, generating high-resolution images crucial for descriptive ecosystem studies. These radars are also used to map geological features and monitor seasonal changes in sea ice, with global use possible for satellites such as Europe's ERS-1 and ERS-2, Japan's JERS-1 and Canada's RADARSAT. These sensors operate in various frequency bands and wavelengths within the microwave range, each suitable for different applications (Waring *et al*., 1995). Table 2 addresses the characteristics of the bands, showing relationships between their wavelength and frequencies, obtaining different information.

Table 2. Distinction between microwave remote sensing radar bands.

Band	Frequency (GHz)	Wavelength (cm)	Applications and Uses
X	8 - 12	3.8 – 2.4	Urban monitoring, ice and snow, weather monitoring, low penetration in vegetation cover
C	4 – 8	7.5 – 3.8	Land use, agricultural monitoring, deforestation, ice, ocean and maritime navigation
S	2 – 4	15 – 7.5	Biomass, forest management, soil moisture, geology and hydrology
L	1 – 2	30 – 15	Soil moisture, glaciers, geophysical monitoring, biomass and vegetation mapping; inSAR (Interferometric Synthetic Aperture Radar)
P	0.3 - 1	100 - 30	Deeper penetration capabilities, landslides, erosion, archaeology, and wetlands

Source: Adapted from GISGeography (2024).

For Ponomarenko and Pimanov (2017), the integration of SAR (Synthetic Aperture Radar) radar with information analysis technologies was significant, involving the use of this data for geodynamic monitoring and operational forecasting of hazardous phenomena in mining areas. More specifically, this integration enabled the monitoring of technogenic deformations, enhancement of mining production safety through dynamic data updates (data acquisition and flexible visualization). Escayo *et al.* (2022) evaluated the potential of the Sentinel-1 radar satellite in improving mines for C-band radar image processing of the Riotinto mine from 2015 to 2017, identifying previously unknown deformation zones. Additionally, the authors proposed a future evaluation to integrate Sentinel-1 with the mine's control system, improving not only its safety but also the sustainability of essential mineral resources. Parameters such as incidence angle, dielectric properties, polarization of the transmitted radar signal's electromagnetic vector, wavelength, surface roughness, and penetration are essential for determining radar image characteristics (Dong and Chen, 2017).

Submarine and Space Mining

The mining industry in marine environments has developed specialized underwater mining technologies for extracting mineral resources, such as polymetallic nodules with high potential for copper, nickel, cobalt, and rare earths, essential for manufacturing electronics and green technologies, located remotely thousands of square kilometers from the seafloor and being transported to a ship for surface transportation (US Department of Commerce, n.d.). The International Seabed Authority (ISA) has played a crucial role in regulating mining activities in underwater regions, implementing regulations for exploration and extraction of resources in international areas (ISA, 2024). NOAA (National Oceanic and Atmospheric Administration) employs high-tech underwater mining technologies, including remotely operated vehicles (ROVs) and automated excavation and extraction systems, as shown in Figure 2. These ROVs have been used since the 1960s for other purposes, reaching current times where they are used to explore mineral deposits in marine environments, collecting geological and environmental data for greater accuracy and safety in the process. ROVs are remotely operated in extreme marine environments with high pressure and lack of light, where direct human intervention would be impossible, and are equipped with high-resolution cameras, sensors, and manipulator arms, which enable all the work for extraction with high precision. Furthermore, these vehicles are controlled by cables connected (tethers) to the controlling ship, providing them with operational commands and power, while the ROVs provide data through these wires (NOAA, n.d.). NOAA projects highlight the economic potential of underwater mining and also the need for thorough approaches to mitigate environmental risks, showing that this area presents high complexity for the exploration of mineral deposits.

Leng *et al*. (2021) discussed the development of deep-sea mining systems and technologies or Digital Ship Management (DSM), to address future resource scarcity, focusing on the role of the deep-sea mining vehicle, known as Deep Sea Mining Vehicle (DSMV). Dynamic analysis, modeling methods, track characteristics, collection systems, interaction with deep-sea sediments (up to 600m), performance, control strategies for adapting to deep operations, are some of the main parameters the author sought to address in his article, presenting DSMV prototypes and underwater tests, in the search for manganese, concluding that there is a need, due to technological progress and bionic inspiration, for a balance between environmental and financial viability of mining in these environments. Fluid dynamics challenges associated with underwater mining are also recurrent, involving physical processes such as sediment plume dynamics, being of utmost importance for assessing environmental impacts. Other factors such as theory, numerical modeling, laboratory experiments, and field tests favor understanding the environmental and operational factors that influence sediment dispersion, and although advances have been made in this area, deep studies in fluid mechanics are still necessary to mitigate environmental impacts (Peacock and Ouillon, 2023).

Liu *et al*. (2023), in a bibliographic review of 70 years on deep-sea mining, highlighted the mechanics of underwater rocks, which are affected by external structures and conditions, besides the challenges in developing efficient mining equipment. The collection system varies according to the mineral type, being: polymetallic nodules (PMN) collected by mechanical and hydraulic systems and the excavation of polymetallic sulfides (PMS) involving terrestrial mining methods. While the submarine mining vehicle (SMV) operates under high pressure and other adverse parameters, requiring factory technological integration, the surface support provides power, control, dehydration, and ore transportation, ensuring operational safety and efficiency. However, the recurring impacts of deep-sea and ocean mining are little known, making it crucial to integrate with big data systems, AI, and automation, providing robustness for the operation of these vehicles in these environments.

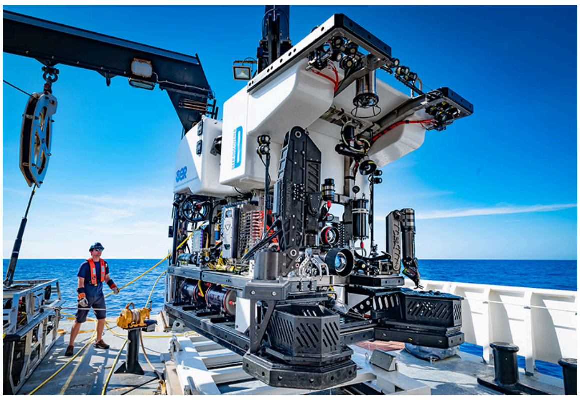

Figure 2. Example of an ROV, the Deep Discoverer, recovered after 19 dives.

Source: NOAA (2019).

Space mining is emerging as a futuristic and innovative field, utilizing advanced technologies such as robots, driven by the growing interest in exploring and utilizing resources available on asteroids (Asteroids, 2022), the Moon (Cooper *et al*., 1998; Moon, 2019), and even Mars (Mars, 2023). This field presents a solution to terrestrial resource scarcity and a new economic frontier. NASA and the European Space Agency (ESA) have been investing in research and technological developments to enable the extraction of minerals in space. NASA proposed the technique of "optical mining," which involves the use of concentrated solar energy for extracting and processing materials from asteroids, moons, and planets, facilitating the synthesis of water, oxygen, propellants, and asteroid materials. Conversely, the ESA has promoted a competition to develop advanced mining solutions, whether on Earth or in space, aiming to encourage innovations that enable sustainable extraterrestrial resource extraction (NASA, 2017; ESA, 2021). Both initiatives assess the significance of space mining in a sustainable context, minimizing dependence on terrestrial resources, with the intent to facilitate humanity's expansion beyond Earth, ensuring crucial resources for its subsistence and innovating the economy and logistics of missions in this area.

In addition to these organizations, studies in the literature have evaluated the feasibility of exploring these aforementioned spaces. Sommariva *et al*. (2020) analyzed a private economic model for lunar ice exploration for oxygen and hydrogen production, finding it unfeasible due to the negative Net Present Value (NPV) caused by uncertainty and extended periods without revenue. Another model analyzed was a public-private partnership, showing high profitability in simulations, based on the premise that the government conducted a successful prospecting mission. The author also emphasized the importance of government lunar prospecting missions to reduce costs and risks for private companies, being crucial for obtaining information, resulting in more effective exploration.

The Moon is targeted for space mining due to its high potential for resources such as water ice, rare metals, and elements for fuel production, which can be exploited to support space missions and future colonies. However, advanced technologies and automation systems adapted to the lunar environment are necessary, characterized by low gravity, extreme temperature conditions, and abrasive lunar dust, as well as international regulations for lunar mining, as evidenced in Table 3, allowing for the sustainable exploration of this natural satellite (Peacock, 2017). Figure 3 depicts a model of an autonomous and versatile robotic vehicle designed to operate in extraterrestrial environments, featuring six articulated legs that enable it to walk, climb, and roll on uneven surfaces, developed by the Jet Propulsion Laboratory (JPL), a research and development center located in Pasadena, California, managed by the California Institute of Technology (Caltech). These rovers have energy storage options such as fuel cells and batteries, with fuel cells combining hydrogen and oxygen generated from water obtained through lunar mining to produce electricity, with the water resulting from the process being reused. These cells have high energy density associated with low maximum power, while batteries have high power. Thus, the design of these MIT vehicles uses a hybrid system, with fuel cells continuously charging the high-power batteries, and these batteries being used for maneuvers that require a high amount of energy, such as climbing steep terrain.

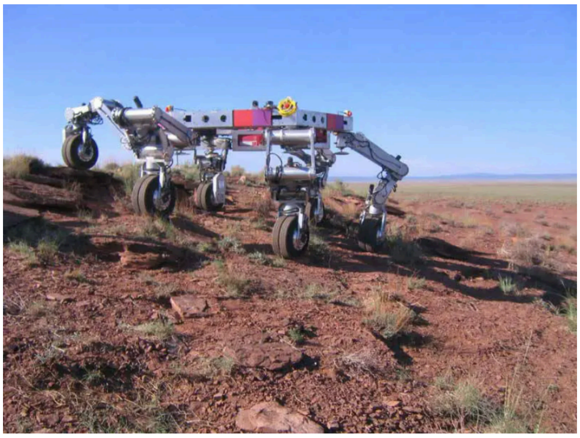

Figure 3. ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) vehicle.

Source: The ATHLETE Rover - NASA (2008).

Helium-3, found in the lunar regolith and implanted by the solar wind, is a valuable resource for nuclear fusion fuel (FA and JIN, 2007). He-3 is crucial for solving the emerging global energy crisis, being a clean and efficient alternative that generates large amounts of energy. On Earth, this isotope of the chemical element helium is extremely scarce, unlike the lunar environment, where it is abundant due to the lack of atmosphere. Samples from the Apollo missions or data from NASA satellites have already revealed the large quantities of this isotope on the Moon, identifying it even in specific regions such as Mare Tranquillitatis and South Pole Aitken. Furthermore, there are estimates that evaluated the extraction of He-3 from the Moon and its transportation to Earth, consuming 1,895,809 GJ and producing 5,369,656 GJ, with supplying energy to the fusion reactor being the most energy-demanding process (Matar, 2021).

Lava tubes or pyroducts are geological formations related to the flow of lava during volcanic activity, revealing empty tunnels when the lava is drained. On Earth, these tunnels are well known in various shield volcanoes, recording formation processes such as inflation and supercrust. However, pyroducts on Mars and especially on the Moon are much larger than those on Earth, evidenced by skylights and collapses in volcanic regions, associated with techniques such as gravimetry and radar. These formations provide protected and stable environments on the lunar surface for human colonization missions (Sauro *et al*., 2020). In this context, Carrer *et al*. (2024) discussed the discovery of a lunar cave conduit (likely a lava tube) identified by Ground Penetrating Radar (GPR) in the Mare Tranquillitatis region (Figure 4). This conduit is accessible from a surface pit and could serve as a shelter against lunar climatic adversities, protection from micrometeorites, a shelter for humans, and storage for equipment, as well as reducing the costs and challenges associated with constructing artificial habitats in this environment.

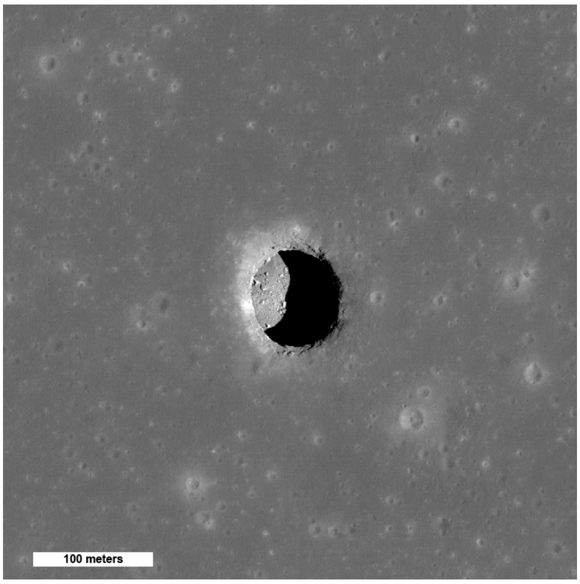

Figure 4. High Sun Narrow Angle Camera Image of Mare Tranquillitatis Pit Crater by the Lunar Reconnaissance Orbiter (LRO).

Source: NASA's LRO Finds Lunar Pits Harbor Comfortable Temperatures - NASA (2022).

Table 3. Main International Laws Governing Outer Space.

Regulation	Year	Main Objective	Reference
Outer Space Treaty	1967	Establish basic principles for the exploration and use of outer space, including the Moon and other celestial bodies	U.S. DEPARTMENT OF STATE, 2009
Treaty on the Non-Proliferation of Nuclear Weapons	1967	Prohibit tests or launches of nuclear weapons in Earth's orbit or on celestial bodies	Documents on Disarmament 1967 – UNODA, [n.d.]
Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space	1968	Ensure rescue and assistance to astronauts in distress and the safe recovery of space objects	Rescue Agreement, 2024
Convention on International Liability for Damage Caused by Space Objects	1972	Encourage the exploration and use of outer space for peaceful purposes	D71981, 1973
Convention on Registration of Objects Launched into Outer Space	1976	Register objects launched into space	Registration Convention, 2024
Moon Agreement	1984	Regulate the activities of countries on the Moon and other celestial bodies, declaring them as the common heritage of mankind	UNOOSA, 2024

European Code of Conduct for Space Debris Mitigation	2004	Mitigate the creation of space debris associated with the promotion of safe space operations practices	European Code of Conduct for Space Debris Mitigation, [n.d.]
U.S. Commercial Space Launch Competitiveness Act	2015	Allow the exploration and use of space resources by American citizens and companies	US CONGRESS, 2015
Guidelines for the Long-term Sustainability of Outer Space Activities (LTS Guidelines) adopted by the Committee on the Peaceful Uses of Outer Space (COPUOS)	2019	Promote the long-term sustainability of space activities	Guidelines for the Long-term Sustainability of Outer Space Activities, [n.d.]

Based on the technical and financial parameters of asteroid, lunar, and Martian mining projects, a comparison of these locations can be made, considering their dynamic nature, architecture, and economy. In this regard, the Moon and Mars become more financially promising for mineral exploration, being more attainable with the recent and future integrations of applied technologies and knowledge (Zacharias *et al*., 2011).

Augmented Reality (AR) and Virtual Reality (VR) in Mining

The increasing complexity of activities related to mining has required investments in employee training to improve the efficiency of the operation and maintenance of the systems involved. The safety of the people involved must be a top priority in all organizations, and for this, the use of special methodologies is necessary. In this context, the large area of the Internet of Things (IoT) stands out, with its subfields Augmented Reality (AR) and Virtual Reality (VR) (Shafique *et al*., 2020).

AR consists of technologies that enable the overlay of information and virtual objects onto the real environment viewed by the user. Therefore, through devices such as smartphones, special glasses, or tablets, it allows the manipulation of various information: data, videos, images, photos, animations, and texts. This facilitates and enhances the quality, efficiency, and operational safety of the tasks, as more detailed and accurate information is taken into account for their execution (Brümel, 2013; Machado *et al*., 2020). Figure 5 shows a real example of the use of AR in the context of electrical maintenance.

Figure 5. Use of augmented reality in electrical maintenance.

Source: Automation (2024).

Figure 6 presents the sequence of information involved in augmented reality devices.

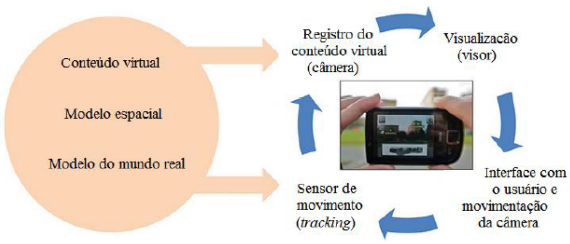

Figure 6. Information flow in an AR system.

Source: Adapted from Schmalstieg e Hollerer (2016).

In turn, VR refers to advanced interface technologies, utilizing computational resources that enable real-time navigation and interaction with a three-dimensional virtual environment. The association of augmented reality with virtual reality allows for safer virtual training for workers (Hernández and Pérez-Ramírez, 2016).

The practical applications of AR and VR in the maintenance of equipment in mining companies have been highlighted. Rocha (2021) explored a mobile AR application aimed at access and safety guidance for operators and maintainers of electrical substations. Through the 3D modeling of a simplified electrical substation, evaluating the user experience and defining the requirements to be used in synthesizing the final prototype application. As a result, the projection of physical arrangements and equipment of an industrial substation at the Ponta da Madeira Maritime Terminal (São Luís-MA) was obtained in VR, subsequently developing an AR using Unity 3D and Vuforia for the Android platform, enabling the reading of tags installed on substation equipment, determination of recommended PPE, safe working distance, and display of essential parameters of electrical panels.

Smart Mining

Aiming to improve the low ore grades due to the high demand for mineral resources, the integration of technologies in Mining 4.0, such as IoT, automated drones, 3D printing, among others, is of fundamental importance (Skenderas and Politi, 2023).

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The automation of mining equipment, such as excavators and off-highway trucks, has demanded the application of artificial intelligence in their management. Operations that were previously conducted by employees are, in some mining companies, automated and controlled by sophisticated programs (ENG, 2024). AZIZ *et al.* (2020) evaluated the concept of IIoT (Industrial Internet of Things), being essential in industrial automation, including in the mining industry. Through a partnership with Boliden for lifecycle exploration in mining and evaluation of current IT (Information Technology) practices in the industry, the challenges to be solved with a specific IIoT architecture for mining were explored, aiming to solve interoperability and data exchange problems. Therefore, the implementation of this architecture would be effective when integrated with technologies such as OT/IT applications, IoT devices, cloud and edge computing, middleware, big data, and business applications, as well as opening margins for future research, especially regarding edge and fog computing (a highly complex topic in terms of the introduction of microservices and IoT-based systems). Additionally, advances in virtualization techniques are crucial for solving challenges related to edge computers, with this area still needing standard solutions like in cloud computing. Figure 7 below explores the existing IIoT elements (cloud-based or not), developing an advanced integrative structure in the direction of the IIoT Analytics Framework, in order to summarize the layers involved in IIoT and Advanced Analytics processes, as well as to be reused in future IIoT mining projects.

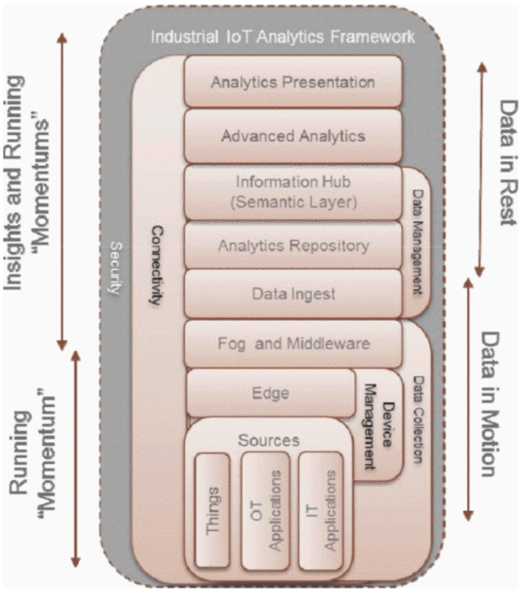

Figure 7. IIoT Analytical Integrative System.

Source: DE MOURA *et al.* (2017).

Advanced projects involving Arduinos are already being tested, such as the project proposed by Eldemerdash *et al.* (2020), consisting of an automated helmet system with applications for workers in the mining industry, integrated with XBee transmitters, 9V battery, LCD I2C module, Arduino connected to 3 LEDs, as well as DHT11 and MQ 2 Arduino sensors for hardware circuit implementation. This enables the detection of dangerous gases captured by the miner's helmet, as well as designing a monitoring system to update the control room with real-time data, among other functionalities (Figure 8).

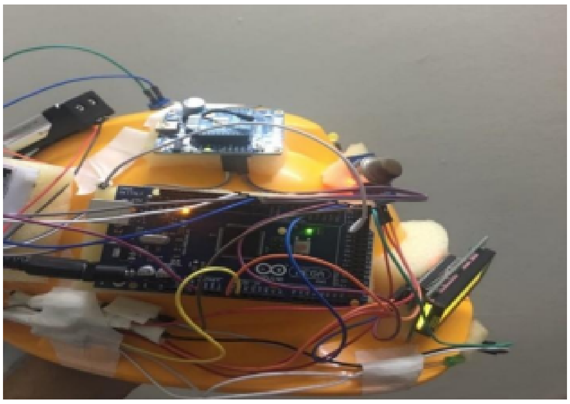

Figure 8. Helmet with Arduino integration for application in the mining industry.

Source: Eldemerdash *et al*. (2020).

IoT allows for the connection of vehicles and electronic devices together on the network, while IIoT, a subfield of IoT, enables the production of goods and the development of smart industries. A concept related to these areas is blockchain, which is defined as a set of data consisting of three main parts: the block, the chain, and the network. Among the main applications of blockchain in IoT and IIoT, electric vehicles, big data, and cloud storage open avenues for applications in the mining industry, reaffirming the importance of this concept for the industry (Wang *et al*., 2020).

Predictive maintenance has been fundamental for the development of Industry 4.0 in mining activities, commonly referred to as Predictive Maintenance 4.0 (RIHI *et al*., 2022). Predictive Maintenance or PdM, heavily relies on IoT, which is empowered with data science, enabling the digitization of physical actions and connecting humans with machines, aiming for greater effectiveness in intelligent operations. The focus of PdM on hardware and software for remote sensing of the health status of monitored equipment is the main focus of this area, including upstream and downstream activities of data collection and maintenance work execution, also requiring the integration of cost-benefit models that include the impact of PdM on total asset management (Compare *et al*., 2019). The following benefits of this type of maintenance can be highlighted: the possibility of planning interventions on detected faults before equipment breakdowns, resulting in significant cost reductions; increased physical availability of equipment; early detection of potential failures in critical equipment; reduced risk of accidents; performance analysis of operations, allowing for adjustments and consequently increased operational efficiency (Bousdekis *et al*., 2019).

Wang (2016) analyzed the concept of Intelligent Predictive Maintenance (IPdM), also introduced in the context of Industry 4.0, which is based on several key techniques such as:

Cyber-Physical Systems (CPS): basic units in the system responsible for transferring the physical world to the virtual, with their development characterized in three stages. The first generation of CPS involves identification technologies such as RFID tags, enabling the unique identification of objects, as well as their storage and analysis requiring provision as a centralized service. The second generation of CPS is equipped with sensors and actuators with limited function ranges. The third generation of CPS allows for data storage and analysis, being equipped with multiple sensors and actuators, and being network-compatible.

Internet of Things (IoT): allows "things and objects" to interact with each other and cooperate with their smart components to achieve a goal.

Internet of Services (IoS): enables providers to offer their services via the internet and access them through various channels.

Big Data and Data Mining (DM): in addition to storing a large amount of data in databases, data mining enables the analysis and discovery of patterns, rules and knowledge, allowing for correct decision-making at the right time and place.

The use of AI and machine learning has elevated the mining industry to a new level, being applicable in areas such as efficiency and safety for autonomous vehicles (AVs) and predictive data analysis. Additionally, AIs have facilitated the independent operational process of machines, predictive maintenance, and process optimization, synthesizing large volumes of data into useful information for management. Companies like SafeAI and Caterpillar demonstrate the significant benefits of AI applicability, resulting in increased productivity and reduced operational costs, ensuring a more efficient and safe future in mining (In the mine, 2024). Other uses for AI also include topics for application in UAVs (Unmanned Aerial Vehicles), such as low-cost multirotor systems in the mining industry, integrating UAV technologies, AI, and MR (Mixed Reality) for mine surveillance and rehabilitation, as well as greater safety, efficiency, and sustainability of mining operations (Stothard and Shirani Faradonbeh, 2023).

A concept of great importance that emerges in the context of Mining 4.0 in the era of AI is sustainable mining (Figure 9), integrating AI with green mining technologies, expanding the potential for promoting ecological practices. In this sense, efforts in ESG (Environmental, Social, and Governance), such as collaborative efforts between government, the mining industry and academia, are essential, aiming to encourage technological research and policy improvements (Chen *et al*., 2024).

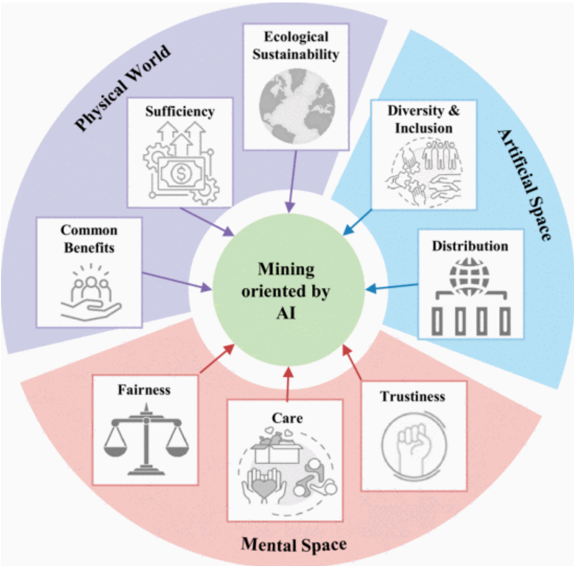

Figure 9. Schematic of parameters for AI-guided sustainable mining.

Source: Chen *et al*. (2024).

CONCLUSION

The present study aimed to highlight the importance of emerging technologies in the context of Industry 4.0, specifically in Mining 4.0 in the AI era, addressing fundamental aspects such as Remote Sensing, Submarine and Space Mining, Augmented and Virtual Reality, and Intelligent Mining, which involves broad and advanced concepts such as IoT, Big Data, Data Mining, Cyber-Physical Systems, among others.

For remote sensing, the study revealed the wide range of related techniques, involving the use of electromagnetic waves from low to high frequencies for various purposes, with some of the main ones being the monitoring of areas degraded by mining, improved efficiency in covering large areas for geological detections or even meteorological monitoring, resulting in increased safety and operational optimization, as this technique is characterized by being an indirect geophysical method, obtaining data through the processing of satellite or aircraft images.

In the field of submarine mining, technological advances are promising, given the complexity of the environment. The integration of big data, AI, and automation, as well as the use of equipment from other operations, such as ROVs, whose use dates back to the 1960s for other purposes, is essential to overcome operational and environmental challenges in this area, which is still somewhat less advanced than others, such as space mining, which already has numerous projects and prototype models, many of which are led by NASA. Space mining is crucial due to the intense search for minerals, aiming to minimize mineral exploration on Earth or even fuels for nuclear fusion, such as Helium-3, present in high quantities on the Moon. This isotope is often related to cleaner and more fundamental energy for the future of humanity, intensifying the space race among major powers, such as the USA and China primarily.

Cutting-edge technology concepts, such as IoT, AI, big data, and data mining in particular, are associated with augmented and virtual reality, as well as connections with predictive equipment analysis in mining, ensuring greater safety in operations, as well as increased efficiency and optimization of operational activities in the mine.

Future trends point to a continuous evolution of these technologies, with the development of more sophisticated systems in mining, always seeking to reduce the time required for a task along with an integration of greener mining and increasingly technological and autonomous aspects in all areas.

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