

DIGITAL TRANSFORMATION OF INDUSTRIAL SAFETY SYSTEMS BASED ON PERSONALIZED INTELLIGENT SOLUTIONS IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT OF THE PRODUCTION SECTOR OF THE REPUBLIC OF KAZAKHSTAN

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In the context of accelerated technological progress and global challenges related to sustainable development, the industrial sector of the Republic of Kazakhstan faces the task of rethinking approaches to ensuring industrial safety. The relevance of digital transformation in this area is due to the need to increase the level of worker protection, minimize man-made risks and integrate intelligent monitoring systems into the production environment. One of the innovative areas is the introduction of personalized intelligent solutions based on wearable devices that can provide continuous monitoring of the health, location and actions of personnel. This article discusses the theoretical foundations and practical aspects of the digitalization of industrial safety systems using new generation smart helmets.

Particular attention is paid to the analysis of the results of pilot tests conducted based on two enterprises of the mining sector of the Republic of Kazakhstan - Kostanay Minerals JSC, Solidcore Resources, and Bakyrchik Mining Enterprise LLP. During the testing, all key functional modules of the smart helmet were tested, including GPS navigation, video broadcasting, biometric sensors and gas analyzers. It was found that the implementation of these technologies can significantly increase the speed of response in emergency situations, strengthen control over compliance with labor protection requirements and ensure the collection of objective information about the production environment in real time.

Thus, the results demonstrate that smart helmets can become an integral part of the digital infrastructure of industrial safety. Their use is consistent with the strategic goals of sustainable development, including increasing the social responsibility of business, improving working conditions and reducing industrial injuries. This study lays the foundation for subsequent scaling of the use of intelligent safety systems in various sectors of the Kazakhstan industry.

Keywords: digitalization, industrial safety, sustainable development, intelligent personal protective equipment, smart helmet, Kazakhstan.

ҚАЗАҚСТАН РЕСПУБЛИКАСЫНЫҢ ӨНДЕУШІ СЕКТОРЫНЫҢ ТҰРАҚТЫ ДАМУЫ ЖАҒДАЙЫНДА ДЕРБЕСТЕНДІРІЛГЕН ИНТЕЛЛЕКТУАЛДЫ ШЕШІМДЕР НЕГІЗІНДЕ ӨНЕРКӘСІПТІК ҚАУІПСІЗДІК ЖҮЙЕЛЕРІН ЦИФРЛЫҚ ТҮРЛЕНДІРУ

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Жеделдетілген технологиялық прогресс және тұрақты дамуға байланысты жаһандық сын-қатерлер жағдайында Қазақстан Республикасының өнеркәсіптік секторының алдында өнеркәсіптік қауіпсіздікті қамтамасыз ету тәсілдерін қайта қарастыру міндеті тұр. Бұл саладағы цифрлық трансформацияның өзектілігі қызметкерлерді қорғау деңгейін арттыру, техногендік тәуекелдерді барынша азайту және интеллектуалды мониторинг жүйелерін өндірістік ортаға біріктіру қажеттілігімен

түсіндіріледі. Инновациялық бағыттардың бірі – персоналдың денсаулығын, орналасқан жерін және іс-әрекетін үздіксіз бақылауды қамтамасыз ете алатын киілетін құрылғылар негізіндегі дербестендірілген интеллектуалды шешімдерді енгізу. Бұл мақалада жаңа буынның смарт каскалары арқылы өнеркәсіптік қауіпсіздік жүйелерін цифрландырудың теориялық негіздері мен практикалық аспектілері қарастырылады.

Қазақстан Республикасының тау-кен өндіру секторының екі кәсіпорнында – «Қостанай минералдары» АҚ, «Солидкор Ресурсиз» және «Бақыршық тау-кен өндіру кәсіпорны» ЖШС-да жүргізілген тәжірибелік сынақтардың нәтижелерін талдауға ерекше назар аударылады. Тестілеу аясында смарт дулығаның барлық негізгі функционалды модульдері, соның ішінде GPS навигациясы, бейнехабар тарату, биометриялық сенсорлар және газ анализаторлары сынақтан өтті. Бұл технологияларды енгізу төтенше жағдайлар кезінде әрекет ету жылдамдығын айтарлықтай арттыруға, еңбекті қорғау талаптарының сақталуына бақылауды күшейтуге және нақты уақыт режимінде өндірістік орта туралы объективті ақпарат жинауды қамтамасыз етуге мүмкіндік беретіні анықталды.

Осылайша, алынған нәтижелер смарт дулығалар өнеркәсіптік қауіпсіздіктің цифрлық инфрақұрылымының ажырамас бөлігі бола алатынын көрсетеді. Оларды пайдалану тұрақты дамудың стратегиялық мақсаттарына, соның ішінде бизнестің әлеуметтік жауапкершілігін арттыруға, еңбек жағдайларын жақсартуға және өндірістік жарақаттарды азайтуға сәйкес келеді. Бұл зерттеу Қазақстан өнеркәсібінің әртүрлі салаларында қауіпсіздіктің зияткерлік жүйелерін қолдануды кейіннен масштабтаудың негізін қалайды.

Түйін сөздер: цифрландыру, өнеркәсіптік қауіпсіздік, тұрақты даму, интеллектуалды жеке қорғаныс құралдары, смарт каска, Қазақстан.

ЦИФРОВАЯ ТРАНСФОРМАЦИЯ СИСТЕМ ПРОМЫШЛЕННОЙ БЕЗОПАСНОСТИ НА БАЗЕ ПЕРСОНАЛИЗИРОВАННЫХ ИНТЕЛЛЕКТУАЛЬНЫХ РЕШЕНИЙ В КОНТЕКСТЕ УСТОЙЧИВОГО РАЗВИТИЯ ПРОИЗВОДСТВЕННОГО СЕКТОРА РЕСПУБЛИКИ КАЗАХСТАН

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В условиях ускоренного технологического прогресса и глобальных вызовов, связанных с устойчивым развитием, перед промышленным сектором Республики Казахстан встает задача переосмысления подходов к обеспечению промышленной безопасности. Актуальность цифровой трансформации в данной сфере обусловлена необходимостью повышения уровня защищенности работников, минимизации техногенных рисков и интеграции интеллектуальных систем мониторинга в производственную среду. Одним из инновационных направлений выступает внедрение персонализированных интеллектуальных решений на базе носимых устройств, способных обеспечивать постоянный контроль за состоянием здоровья, местоположением и действиями персонала. В данной статье рассматриваются теоретические основы и практические аспекты цифровизации систем промышленной безопасности с использованием умных касок нового поколения.

Особое внимание уделено анализу результатов опытно-промышленных испытаний, проведенных на базе двух предприятий горнодобывающего сектора Республики Казахстан - АО «Костанайские минералы», Solidcore Resources ТОО «Бакырчикское горнодобывающее предприятие». В рамках тестирования были апробированы все ключевые функциональные модули умной каски, включая GPS-навигацию, видеотрансляцию, биометрические сенсоры и газоанализаторы. Установлено, что внедрение данных технологий позволяет существенно повысить оперативность реагирования

в нештатных ситуациях, усилить контроль над соблюдением требований охраны труда и обеспечить сбор объективной информации о производственной среде в режиме реального времени.

Таким образом, полученные результаты демонстрируют, что умные каски могут стать неотъемлемым элементом цифровой инфраструктуры промышленной безопасности. Их использование соответствует стратегическим целям устойчивого развития, включая повышение социальной ответственности бизнеса, улучшение условий труда и снижение производственного травматизма. Настоящее исследование закладывает основу для последующего масштабирования применения интеллектуальных систем безопасности в различных отраслях казахстанской промышленности.

Ключевые слова: цифровизация, промышленная безопасность, устойчивое развитие, интеллектуальные средства индивидуальной защиты, умная каска, Казахстан.

Introduction. The current stage of industrial development is characterized by the active introduction of digital technologies, which forms a new paradigm for managing production processes aimed at increasing efficiency, sustainability and safety. As part of this transformation, special attention is paid to issues of labor protection and industrial safety, since these areas are most vulnerable to the human factor, technological failures and external risks. For countries with a high level of industrialization, such as the Republic of Kazakhstan, where the mining and manufacturing industries occupy a key place in the economy, the issue of transition to intelligent safety management systems is becoming a priority. Traditional approaches to ensuring industrial safety - regulation, control, personnel training - are gradually being supplemented by new methods based on the use of the Internet of Things (IoT), artificial intelligence (AI), biometric analysis and video surveillance. In this context, a special place is occupied by wearable intelligent devices, or so-called "smart helmets", which allow you to collect, process and transmit data about the worker and his environment to central monitoring systems in real time. This opens up opportunities for a personalized approach to safety, where each employee becomes an active element of the digital production ecosystem.

The purpose of this study is to substantiate the effectiveness of the digital transformation of industrial safety systems based on the introduction of personalized intelligent solutions that have been tested in real production conditions. To achieve this goal, a set of measures was implemented, including

the development of prototypes of smart helmets, their technological adaptation to the conditions of Kazakhstani enterprises, as well as pilot industrial tests.

The work covers the entire implementation cycle - from the conceptual design of an intelligent device to the analysis of its operation in the field at two industrial sites: Kostanay Minerals JSC and Bakyrchik Mining Enterprise LLP. The choice of these objects is due to their diversity in terms of operating conditions, the structure of the production process and safety requirements. This approach made it possible to obtain representative data and conduct a comparative analysis of the effectiveness of the technological solution in various production contexts. Thus, this publication not only records the fact of the use of smart helmets in the domestic industry, but also represents an example of a comprehensive scientific and practical study aimed at forming new safety standards in accordance with the principles of sustainable development and digitalization.

The figure shows the main modules and interfaces of the intelligent device: visualization of the location of the controls on the helmet body, the communication channels used (4G/Wi-Fi/Bluetooth), gas analysis systems (CO, CH₄, H₂S, NH₃, SO₂), biometric monitoring and visual control, as well as software displaying monitoring data in real time.

Literature review. Modern research in the field of digital transformation of industrial systems emphasizes that one of the key tasks in the context of Industry 4.0 is to ensure the safety of production personnel using intelligent technologies. In the

context of the increasing complexity of production processes, growing volumes of information and increasing external risks, traditional methods of

labor protection (briefings, scheduled inspections, routine measures) demonstrate limited adaptability to changing working conditions [1].



Fig.1 - Functional diagram and capabilities of the intelligent helmet

One of the most promising areas in the field of digital transformation of industrial safety is the integration of the Internet of Things (IoT) and artificial intelligence (AI) into monitoring and control systems. Research by international experts [2, 3] demonstrates that the use of smart wearables, such as smart helmets, can significantly increase the speed of response to potential hazards, reduce dependence on the human factor, and provide a personalized approach to risk management.

In particular, Jieyu Chen et al. [4] note that the use of smart helmets with biometric sensors and GPS modules allows real-time tracking of the worker's location, level of fatigue, exposure to harmful factors (temperature, gas, vibration), which is critical in the mining and manufacturing industries. These devices are integrated into the overall digital infrastructure of the enterprise, forming an adaptive safety ecosystem.

Kazakhstani research in this area is still primarily applied in nature and focuses on the implementation of pilot projects at large enterprises. For example, the report of the National Agency for Technological

Development highlights the growing interest of mining companies in wearable electronics and automated monitoring of working conditions [5]. In particular, enterprises such as Kostanay Minerals JSC and Bakyrchik Mining Enterprise LLP are implementing pilot initiatives to introduce smart helmets in cooperation with domestic developers of digital solutions [6].

In addition, a number of publications devoted to the specifics of labor protection in Kazakhstan indicate the need to adapt imported technologies to local production conditions, including climatic features, regulatory framework and the level of digital maturity of personnel [7]. The importance of training and digital literacy of employees as a key condition for the successful digitalization of the safety system is also emphasized.

Thus, the analysis of scientific and industry literature allows us to identify several stable trends:

- the growing importance of intelligent wearable devices as a tool for preventing industrial incidents;

- integration of IoT, AI and biometrics into security systems as a path to proactive risk management;

- the need to localize solutions taking into account industry and regional specifics, especially in the context of the Kazakhstan industrial model.

These provisions serve as a scientific and practical basis for this study, aimed at a comprehensive assessment of the effectiveness of the implementation of "smart helmets" at domestic industrial facilities.

Materials and methods. This research is implemented within the framework of an interdisciplinary approach combining methods of system analysis, cyber-physical systems, digital engineering, labor protection and principles of sustainable development. Modern models of digitalization of the production environment, including the use of wearable intelligent devices as elements of the Industrial Internet of Things (IIoT), are used as a conceptual basis. Particular attention is paid to the integration of modules of biometric monitoring, GPS navigation, video analytics and environmental analysis in order to form personalized industrial safety systems.

The objective of the applied part of the study was to confirm the functional viability of smart helmets in the conditions of the current production cycle. For this purpose, pilot tests were organized on the basis of:

- Kostanay Minerals JSC - an enterprise with underground and aboveground works;

- Bakyrchik Mining Enterprise LLP - open-pit mining in conditions of high temperatures and dust.

The tests were conducted using smart helmets equipped with the following modules:

- GPS monitoring - to track workers' movements in hazardous areas;

- Camera with video transmission - for remote monitoring and recording of

violations;

- Biometric sensors - to monitor body temperature, pulse, signs of overload;

- Gas analyzers - to monitor the content of CO, CH₄, H₂S and other gases;

- Data transmission - via 4G/Wi-Fi to a centralized control panel.

During the tests, data was collected on the following parameters: accuracy and speed of transmission, signal stability, completeness of biometric data, reliability of event recording (e.g., removing a helmet), as well as compliance with labor protection standards. Technical results and performance parameters (table 1).

The test results showed that all helmets demonstrated stable operation even with an unstable connection and in an aggressive environment. The function of controlling the wearing of a helmet turned out to be especially important - each case of removal was recorded with 100% accuracy, including violations of labor protection rules.

User perception and interface assessment. A survey was also conducted among users (machinists, operators, labor protection specialists), which made it possible to assess the subjective parameters of efficiency (table 2).

Legal and regulatory integration. It is important to note that the implementation of digital solutions in Kazakhstan is associated with separate regulatory and legal work that goes beyond classical certification. Unlike conventional PPE, smart helmets contain electronic and cryptographic modules, which requires:

- certification according to technical regulations (TR CU 019/2011, 020/2011);

- obtaining permission to import both radio-electronic and high-frequency devices;

- licensing of cryptographic components (CIPF);

- registration as telecommunications equipment.

These procedures are regulated by the relevant authorities (Technical Regulation Committee, National Security Committee, MIIR, etc.) and require the involvement of specialists, accredited laboratories, and in some cases, evidence-based scientific and technical documentation (table 3).

Table 1 - Key performance indicators of smart helmets

№	Parameter	Units	Average values	Operating conditions
1	Event response time	seconds	3.5	Notification when removing a helmet or emergency
2	Positioning accuracy	meters	±1.8	Quarry, mine
3	Video signal stability	% time online	97%	Wi-Fi/4G zone
4	Biometric data transmission frequency	% time	92%	Continuous monitoring
5	Helmet removal detection	% accuracy	100%	Entry/exit from a dangerous zone
6	Average CO level in peak zones	mg/m ³	12.6 (MPC: 10)	Areas with insufficient ventilation
7	Body temperature range	°C	36,3–37,9	Employees on shift

Table 2 - User assessment of functionality (on a 5-point scale)

№	Criterion	Average score	Staff comments
1	Ease of wearing	4,1	Minor discomfort in the heat
2	Ease of learning the interface	4,5	Most mastered it in 1 shift
3	Communication and data transfer	4,6	Steady even in the depths of the quarry
4	Usefulness of video monitoring	4,8	Allows to identify hidden risks
5	Reliability of biometrics	4,3	Affects behavioral discipline
6	Overall satisfaction	4,7	Employees recommended for implementation

Table 3 - Stages of regulatory legitimization of a digital product in the Republic of Kazakhstan

№	Stage	Competent Authority	Completion time (estimated)
1	Certification as PPE	National Certification Center, NCA	4-6 weeks
2	Permission to import electronics	Technical Regulation Committee	2-4 weeks
3	License to sell CIPF	National Security Committee of the Republic of Kazakhstan	6-8 weeks
4	Registration as a Telecom device	Minister of Industry and Infrastructure Development of the Republic of Kazakhstan	3-5 weeks

Thus, the legalization of a digital product in Kazakhstan is an independent scientific and administrative process that requires not only technical expertise, but also an understanding of the regulatory environment. In addition, the legalization of a digital product is an important link in the entire methodology and should be planned in parallel with the engineering development of the device.

Results and discussion. The results of pilot tests confirm both the technical reliability and practical feasibility of implementing intelligent personal protective equipment at production facilities. During the work, special attention was paid not only to testing the devices, but also to the preliminary stage of selecting technical solutions, which predetermined a high degree of compliance between the functional purpose of the equipment and specific operating conditions.

The selection of smart helmets for testing was carried out based on the criterion of functional completeness, which is absent in a number of existing solutions on the Kazakhstan market. In particular, the domestic market has devices with limited functionality, often purchased in China under the guise of localized developments - the so-called "combs", equipped with only basic modules (for example, a camera and a GPS tracker) without deep integration with biometric and environmental analysis systems. The helmets tested stood out in that they provided comprehensive monitoring of both the external environment and the state of the worker, allowing the implementation of an approach to safety as an adaptive, personalized system [8].

Key confirmed results include:

- wearing control: the device's wearing sensors automatically recorded the fact of removing or not wearing a helmet during a shift, which is critical for high-risk facilities. This parameter is missing from most competing solutions;

- biometric monitoring: integration with wearable bracelets ensured the registration of body temperature, pulse, physical activity, which made it possible to identify fatigue, overheating, or stress

in workers. The system demonstrated stable data transmission with an accuracy suitable for real-time analysis;

- gas analyzers: built-in sensors determined the concentrations of carbon monoxide (CO), methane (CH₄), hydrogen sulfide (H₂S), ammonia (NH₃), and sulfur dioxide (SO₂). This made it possible to record excesses of the maximum permissible concentrations at work sites without the need to deploy a separate stationary gas analysis system;

- video surveillance and recording: a built-in camera with online broadcast function

provided remote visual control over the actions of employees, especially in confined spaces and underground workings. The image was transmitted to a centralized platform, where an archive and analysis of incidents was maintained. • Geolocation control: the GPS system tracked the movements of workers in real time, with the ability to create "safety zones" and immediately notify in the event of going beyond them [9].

The system demonstrated high stability of operation under different levels of illumination, temperature and dustiness, which is critically important in mining conditions. The received data was transmitted via 4G/wi-fi networks and aggregated in the central control panel, which allowed operators to make decisions based on objective and continuous information.

It is important to emphasize that the use of smart helmets not only increased the level of industrial safety, but also had a positive impact on the behavioral patterns of workers. It was found that awareness of constant monitoring and linking the helmet to the physiological state increase personal responsibility for compliance with labor protection regulations [10].

In terms of compliance with international requirements, smart helmets demonstrate high potential for integration with occupational health and environmental safety management systems that comply with ISO 45001 (occupational health and safety management) and ISO 14001 (environmental management) standards. Their use also supports the implementation of the ESG approach, which

provides for social safety and sustainability in production. Overall, the tests conducted showed that the new generation of intelligent helmets form the technological basis for the transition from reactive to preventive and adaptive methods of ensuring industrial safety in Kazakhstan.

Conclusion. The conducted work entitled "Digital transformation of industrial safety systems based on personalized intelligent solutions in the context of sustainable development of the manufacturing sector of the Republic of Kazakhstan" is a significant contribution to the scientific understanding and practical implementation of the new paradigm of labor protection and industrial safety. In the context of accelerated digitalization and the need to increase the sustainability of production processes, the study meets the key challenges of the time and serves as a starting point for the development of highly effective, adaptive and integrated solutions in the labor protection system.

For the first time in the Republic of Kazakhstan, personalized intelligent solutions in the form of smart helmets were not only tested, but also considered in a broad scientific, methodological, engineering and regulatory context. Tests in the conditions of operating enterprises demonstrated the sustainability of the solutions, their accuracy, usefulness and practical effectiveness. The results proved that the use of smart helmets allows you to form a proactive safety management model based on real data on the behavior, physiological state and environment of the worker. The significance of this work is confirmed not only by the technical results, but also by the very structure of the research implementation: both experienced scientists and young researchers and doctoral students took part in the project, thereby ensuring the continuity of the scientific school and the development of the research potential of Kazakhstan. This emphasizes

the importance of combining academic science, engineering practice and production management in a single innovative circuit. It is also emphasized that in the context of Kazakhstan, digital transformation requires not only technological but also institutional efforts. Legitimization of such decisions is an independent task, including certification of personal protective equipment, licensing of import of electronic components, as well as permission to use cryptographic modules. All these procedures require time, expert competencies and participation of the scientific community, which makes the role of research organizations critically important. The study opens up prospects for further standardization, integration of intelligent devices into industrial IIoT platforms, as well as expansion of the regulatory framework of the Republic of Kazakhstan. The practical significance and reproducibility of the results make it possible to scale up the project not only within the country, but also at foreign industrial sites.

The value of this work is that it has combined digital technologies, scientific expertise, production experience and regulatory support into a single strategy for modernizing industrial safety systems. This is consistent not only with national development priorities, but also with the global agenda in the field of ESG and sustainable industrial growth.

Thus, the work "Digital transformation of industrial safety systems based on personalized intelligent solutions in the context of sustainable development of the manufacturing sector of the Republic of Kazakhstan" serves as a convincing example of how solutions can be created at the intersection of science, technology and production that can change the approach to labor safety, increase the prestige of the domestic engineering school and export Kazakhstani competencies beyond the country.

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