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PILOT-SCALE EVALUATION OF AN INTELLIGENT SAFETY HELMET SYSTEM FOR RISK MANAGEMENT IN MINING ENTERPRISES

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The paper presents the results of pilot-scale industrial trials of RD-D1+ intelligent safety helmets conducted at an industrial production facility in Shymkent, Kazakhstan. The object of the study is the above-mentioned production site, the subject is a personal industrial safety system based on an intelligent safety helmet, GSM/GPRS communication modules, GPS/Beidou navigation, built-in telemetry sensors and the QST (Qazaqstan Smart Technology) software platform. The aim of the study was to evaluate the operational performance, stability, and functional effectiveness of the intelligent safety helmet system for personnel risk management under real industrial operating conditions based on pilot-scale field testing. The study included device installation and registration, field tests of communication and navigation channels, analysis of event data from the QST platform's Monitoring Center, Track Playback, Alarm Record, Photo Record and Video Record modules, and desk processing of the collected telemetry. The helmets were found to provide stable GSM/GPRS data transmission, acceptable positioning accuracy (with some deterioration in metal-shielded premises), correct event registration (there were no false alarms during the observation period), and stable operation of the photo and video modules. Reduced injury risk, optimised personnel routes and increased transparency of production processes demonstrate the economic feasibility of the system. It is concluded that the intelligent safety helmet system is technologically ready for the wider deployment in mining and service-sector facilities.

Keywords: intelligent safety helmet, personnel monitoring, industrial safety, worker positioning, event monitoring.

ТАУ-КЕН КӘСІПОРЫНДАРЫНДА ТӘУЕКЕЛДЕРДІ БАСҚАРУҒА АРНАЛҒАН ЗИЯТКЕРЛІК ҚОРҒАНЫС ДУЛЫҒАСЫ ЖҮЙЕСІНІҢ ӨНДІРІСТІК-ТӘЖІРИБЕЛІК БАҒАЛАНУЫ

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Мақалада Шымкент қаласындағы (ҚР) өнеркәсіптік өндіріс орнында жүргізілген RD-D1+интеллектуалды қауіпсіздік дулығаларының пилоттық ауқымды өнеркәсіптік сынақтарының нәтижелері ұсынылған. Зерттеу нысаны - жоғарыда аталған өндіріс орны, тақырыбы - интеллектуалды қауіпсіздік дулығасына, GSM/GPRS байланыс модульдеріне, GPS/Beidou навигациясына, кіріктірілген телеметриялық сенсорларға және QST (Qazaqstan Smart Technology) бағдарламалық платформасына негізделген жеке өнеркәсіптік қауіпсіздік жүйесі. Зерттеудің мақсаты - пилоттық ауқымды далалық сынақтарға негізделген нақты өнеркәсіптік жұмыс жағдайларында персоналдың тәуекелдерін басқару үшін интеллектуалды қауіпсіздік дулыға жүйесінің пайдалану өнімділігін, тұрақтылығын және функционалдық тиімділігін бағалау. Зерттеуге құрылғыны орнату және тіркеу, байланыс және навигациялық арналардың далалық сынақтары, QST платформасының мониторинг орталығынан алынған оқиға деректерін талдау, трекерді ойнату, дабыл жазбасы, фотожазба және бейнежазба модульдері және жиналған телеметрияны үстелдік өңдеу кірді.

Дулығалар GSM/GPRS деректерін тұрақты беруді, қолайлы позициялау дәлдігін (металлмен қорғалған үй-жайларда біраз нашарлаумен), оқиғаны дұрыс тіркеуді (бақылау кезеңінде жалған дабылдар болған жоқ) және фото және бейне модульдердің тұрақты жұмысын қамтамасыз ететіні анықталды. Жарақат алу қаупінің төмендеуі, персоналдың жұмыс бағыттарының оңтайландырылуы және өндірістік процестердің ашықтығының артуы жүйенің экономикалық тұрғыдан орындылығын көрсетеді. Ақылды қауіпсіздік дулыға жүйесі тау-кен өндірісі мен қызмет көрсету саласының нысандарында кеңінен қолдануға технологиялық тұрғыдан дайын деген қорытындыға келді.

Түйін сөздер: ақылды дулыға, персоналды мониторингілеу, өнеркәсіптік қауіпсіздік, жұмысшыларды позициялау, оқиғаларды мониторингілеу.

ОПЫТНО-ПРОМЫШЛЕННАЯ ОЦЕНКА ИНТЕЛЛЕКТУАЛЬНОЙ СИСТЕМЫ ЗАЩИТНЫХ КАСОК ДЛЯ УПРАВЛЕНИЯ РИСКАМИ НА ГОРНОДОБЫВАЮЩИХ ПРЕДПРИЯТИЯХ

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В статье представлены результаты пилотных промышленных испытаний интеллектуальных защитных шлемов RD-D1+, проведенных на промышленном производственном предприятии в Шымкенте, Казахстан. Объектом исследования является указанная производственная площадка, предметом исследования – персональная система промышленной безопасности, основанная на интеллектуальном защитном шлеме, модулях связи GSM/GPRS, GPS/Beidou-навигации, встроенных телеметрических датчиках и программной платформе QST (Qazaqstan Smart Technology). Целью исследования была оценка эксплуатационных характеристик, стабильности и функциональной эффективности интеллектуальной системы защитного шлема для управления рисками для персонала в реальных условиях промышленной эксплуатации на основе пилотных полевых испытаний. Исследование включало установку и регистрацию устройства, полевые испытания каналов связи и навигации, анализ данных о событиях из модулей мониторинга, воспроизведения треков, записи сигналов тревоги, фото- и видеозаписи платформы QST, а также обработку собранной телеметрии. Было установлено, что шлемы обеспечивают стабильную передачу данных по протоколам GSM/GPRS, приемлемую точность позиционирования (с некоторым ухудшением в помещениях с металлическими экранами), корректную регистрацию событий (ложных срабатываний в течение периода наблюдения не было) и стабильную работу фото- и видеомодулей. Снижение риска травм, оптимизация маршрутов персонала и повышение прозрачности производственных процессов демонстрируют экономическую целесообразность системы. Сделан вывод, что интеллектуальная система защитных шлемов технологически готова к более широкому внедрению на предприятиях горнодобывающей и сервисной отраслей.

Ключевые слова: интеллектуальная каска, мониторинг персонала, промышленная безопасность, позиционирование работников, событийный мониторинг.

Introduction. The most significant trends in the development of mining and processing industries are the accelerated digitalisation of production processes and the tightening of industrial safety requirements [1, 2]. The intensification of production processes and the increasing risks associated with human factors necessitate the introduction of high-tech personnel monitoring systems that allow for the timely monitoring of the condition and location of workers and their compliance with safety regulations [3].

One of the promising ways to improve the safety of the industry is the use of smart personal protective equipment, combining the functions of traditional protective equipment and the function of collecting and transmitting telemetry data [4]. Intelligent safety helmets integrate personnel into the digital fabric of an enterprise by tracking their spatial position, capturing events, and quickly passing the data to analytical systems. Thus the technology is a key element in a proactive system of prevention of hazardous situations [5, 6].

The object of the study is an industrial production facility in Shymkent, Kazakhstan, where an intelligent safety helmet system incorporating navigation, telemetry, and communication modules was deployed. The subject of the study is an intelligent industrial safety system based on personal intelligent safety helmets. The helmet system comprises communication hardware, navigation equipment, built-in telemetry sensors, QST (Qazaqstan Smart Technology) software for visualising data and analytical processing, and channels for transmitting geolocation and event data.

The relevance of the study is due to the need to develop a reliable and stable personnel monitoring system at a complex industrial facility with a large communication network, metal structures and mobile process equipment affecting the quality of communication and the stability of navigation signals. Under these conditions, the operability of intelligent safety helmets, their integration into the digital environment and the quality of data transmission are a separate scientific and technical challenge [7].

The purpose of the research is to evaluate the operational performance, stability and functional effectiveness of the intelligent safety helmet system in personnel risk management under real mining-production conditions, based on pilot-scale industrial testing at the Central Asia Mining Co production site.

The following tasks were solved:

1) installation, activation and initial technical configuration of helmets, including SIM-card integration, IMEI registration, connection to QST server platform;

2) field tests of GSM/GPRS connection stability;

3) personnel-positioning performance examination;

4) functionality assessment of built-in sensors and event modules;

5) desk processing and analytical systematisation of monitoring data;

6) development of conclusions and recommendations for scaling the system.

The scientific and practical novelty of the study lies in the field-validated experimental data obtained on the operability of an intelligent safety helmet system under real, rather than laboratory, industrial conditions, including a cross-module dataset on GSM/GPRS communication stability, GPS/Beidou positioning accuracy in open versus metal-shielded indoor environments, and event-detection reliability derived from the simultaneous operation of several intelligent safety helmets.

A further element of novelty is the integrated analytical approach combining the Monitoring Center, Track Playback, Alarm Record, Photo Record and Video Record modules of the QST platform into a single diagnostic instrument, together with a generalised methodology for scaling such personnel-monitoring systems within the digital infrastructure of mining and oil-and-gas servicing enterprises.

Materials and Methods. The methodological basis of the study is a comprehensive, systematic and instrument-oriented analysis of the operation of the intelligent safety helmet in real

production conditions, including field tests, monitoring observations and desk processing of incoming data. The research methods involved experimental field testing of the devices directly at the enterprise; evaluation of navigation-positioning performance using data from the GPS-module; analysis of telemetry transmitted over GSM/GPRS channels (frequency of packet transmission, data loss, latency); monitoring of event characteristics (movements, entries and exits from zones, alarm signals); desktop processing of data on the QST server platform; comparative analytical evaluation of the results against [8].

Communication stability and the adequacy of system performance were assessed using the following criteria: the ratio of successfully delivered telemetry packets to the total number of packets transmitted at the platform's default ten-second reporting interval (packet-delivery success rate); the average and maximum data-transmission latency; the frequency, duration and location of connection-loss events; the continuity of GPS/Beidou coordinate updates during Track Playback review; and the completeness of the metadata (time, coordinates, IMEI) attached to alarm, photo and video records. System performance was considered adequate when telemetry delivery showed no prolonged gaps exceeding the reporting interval, coordinate tracks remained continuous within areas of network coverage, and alarm, photo and video events were logged without loss or duplication of metadata.

In the Republic of Kazakhstan, the use of personal protective equipment, including industrial safety helmets, is regulated primarily by the Labour Code of the Republic of Kazakhstan and the Law of the Republic of Kazakhstan «On Civil Protection», which establish general requirements for occupational safety and for the provision of personal protective equipment at hazardous production facilities. Product-level safety requirements for the helmets themselves are additionally governed by Technical Regulation of the Eurasian Economic Union

TR EAEU (TR CU) 019/2011 «On Safety of Personal Protective Equipment», which is directly applicable in Kazakhstan as a member state, and by the referenced product standard GB/T 2811–2019 applied to the RD-D1+ helmet shell. Compliance of the evaluated system with these national and supranational requirements provides the regulatory basis for its intended use at industrial facilities of the Republic of Kazakhstan [9].

Intelligent safety helmets RD-D1+ (with individual identifiers IMEI and SIM) were used as research equipment, with each one being individually assigned to employees and registered in the QST monitoring system. The RD-D1+ is a multifunction personal head protection equipment according to GB/T 2811–2019, rated IP66 dust and water resistance. It is made of ABS plastic. Its dimensions are 294 x 228.5 x 153.5 mm and it weighs up to 630 g. The hardware platform is based on Android 10, and has an MT8768 processor, 4 GB of RAM and 64 GB of internal storage. The communication system supports LTE-FDD, LTE-TDD, WCDMA and GSM. The positioning module supports GPS and Beidou. Wi-Fi (IEEE 802.11 a/b/g/n) and Bluetooth 5.0 are provided. Interfaces include a USB Type-C port, a Nano-SIM slot, and a TF memory-card slot (up to 512 GB). Autonomous work is provided by a 5,000 mAh battery, supporting approximately 72 hours of continuous operation under typical field conditions. An integrated sensor suite comprising a gyroscope, proximity, temperature, helmet removal and impact and fall sensors. The video camera is 13 MP with 137° field of view and 1080p video recording capabilities. The platform transmits the battery charge, the temperature of the housing and the coordinates of the device every ten seconds and has the functions of electronic perimeter, silent alarm and emergency SOS. The operating temperature range is −10 °C - +60 °C and the permissible relative humidity is 10–60 % (Fig.1).



Fig.1 - Intelligent safety helmet used in the experimental research

Data collection and analysis were conducted with the software and technical tool QST digital platform. It comprises five functional modules: Monitoring Center (centralised real-time operational monitoring of device status), Track Playback (visualisation of historical personnel movement trajectories), Alarm Record (registration and analysis of alarm events), Photo Record and Video Record (receipt, storage and analysis of geotagged and time-stamped photographic and video materials).

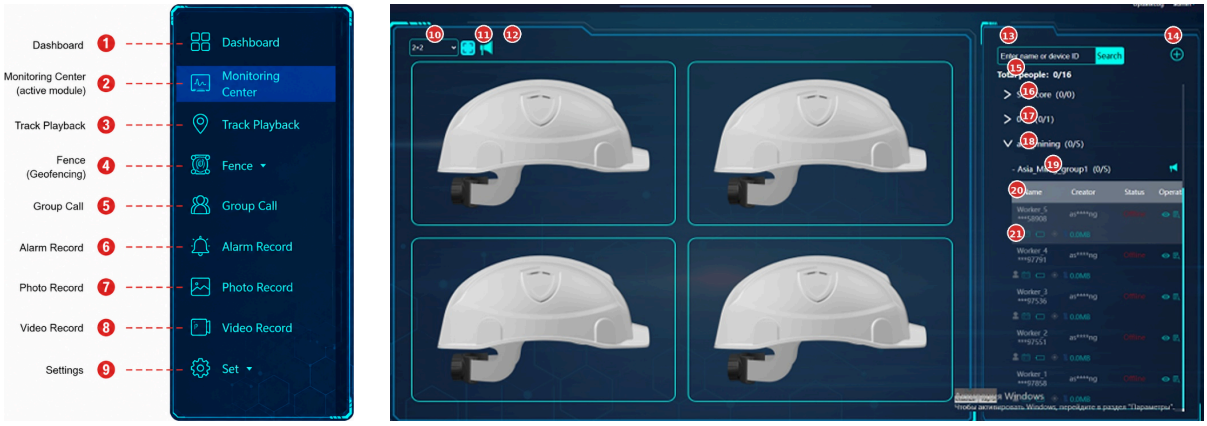
The study was carried out in four phases In the preparation phase IMEI numbers and SIM cards were registered, devices were assigned to the staff and the zones of the production site were surveyed in advance to estimate the coverage of the mobile network. During the field testing, the GSM signal stability, the accuracy of the dynamic GPS positioning, the effect of shielding structures on the telemetric data and the correctness of event registration were evaluated. Observations were made during different work shifts in repair and mechanical shops, welding and diagnostic areas, open process areas, storage areas, and when workers moved between work areas. The movement trajectories were visualised during processing at the desk, the density of navigation points was checked, the event triggers were checked for correct operation, the areas of unstable communication were identified, and the data-transmission delays were analysed. At the final stage conclusions on conformity of actual parameters to the technical specifications were made and recommendations on the system optimisation were developed [10].

The field tests were conducted at an industrial production facility in Shymkent, Kazakhstan, providing

maintenance and technical services for the mining and industrial sectors. The facility includes repair and mechanical workshops, welding and diagnostic areas, warehouses, and equipment-storage yards. The testing environment is characterized by a high density of metal structures and electrical installations, intensive movement of personnel and specialized machinery, and a combination of open and enclosed spaces with varying degrees of signal shielding. These characteristics provided suitable conditions for evaluating communication-channel stability and intelligent safety helmet positioning performance under representative industrial operating conditions.

Results and Discussion. Figure 2 presents the Monitoring Center module of the QST platform in two enlarged panels to improve the readability of individual interface elements. Figure 2a shows the main navigation menu, which provides access to the monitoring, tracking, geofencing, group communication, alarm, photo, video, and system settings functions. Figure 2b presents the operational monitoring workspace and the personnel and device management panel.

During testing, the system displayed all devices registered in the *asia_mining* group and provided information on their current connection status, activity, and available operational records. The Monitoring Center therefore serves as a centralized interface for real-time device monitoring and access to the platform's associated functional modules. (Fig. 2).

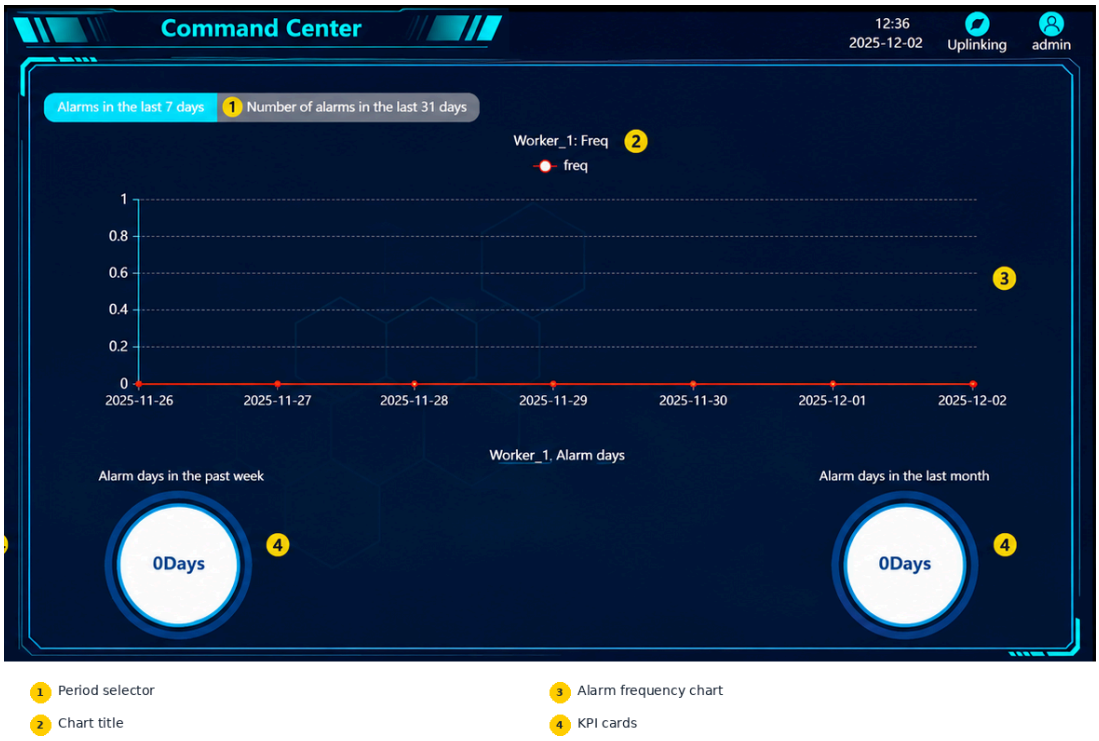


a) b)

Fig. 3 - Monitoring Center interface of the QST intelligent helmet platform: (a) numbered navigation menu and access to the main functional modules; (b) real-time monitoring workspace and personnel/device management panel

Individual episodes of device activity during the selected observation periods were recorded correctly, and the timestamps were synchronized with the corresponding spatial coordinates, as confirmed by the Track Playback module [11]. Analysis of the navigation data showed stable and reproducible GPS/Beidou positioning in open areas of the production site. In enclosed industrial facilities, positioning performance deteriorated due to signal attenuation, multipath propagation, and shielding by metal structures. The degradation was most pronounced in areas with a high density of metallic equipment and structural elements, where greater coordinate scatter and occasional short interruptions in the positioning track were observed. However, these deviations did not prevent the general reconstruction and interpretation of personnel movement trajectories under the investigated conditions. Precise quantitative determination of the positioning error would require comparison with reference coordinates obtained using an independent high-accuracy positioning system and was outside the scope of the present pilot study [11, 12] (Fig. 3.).

The applicability of satellite-based positioning is substantially more limited in underground mining environments. GPS/Beidou signals are strongly attenuated by the surrounding rock mass and are generally unavailable in underground workings, particularly at deep horizons. Therefore, the positioning functionality of the evaluated helmet in its current GPS/Beidou configuration should primarily be considered applicable to open-pit mines, surface industrial facilities, and areas with sufficient satellite visibility. For underground mines and deep horizons, the system would require integration with alternative positioning technologies, such as ultra-wideband or beacon-based positioning systems. Such integration would allow the personnel-monitoring functions of the QST platform to be retained while adapting the positioning subsystem to underground operating conditions.



a)

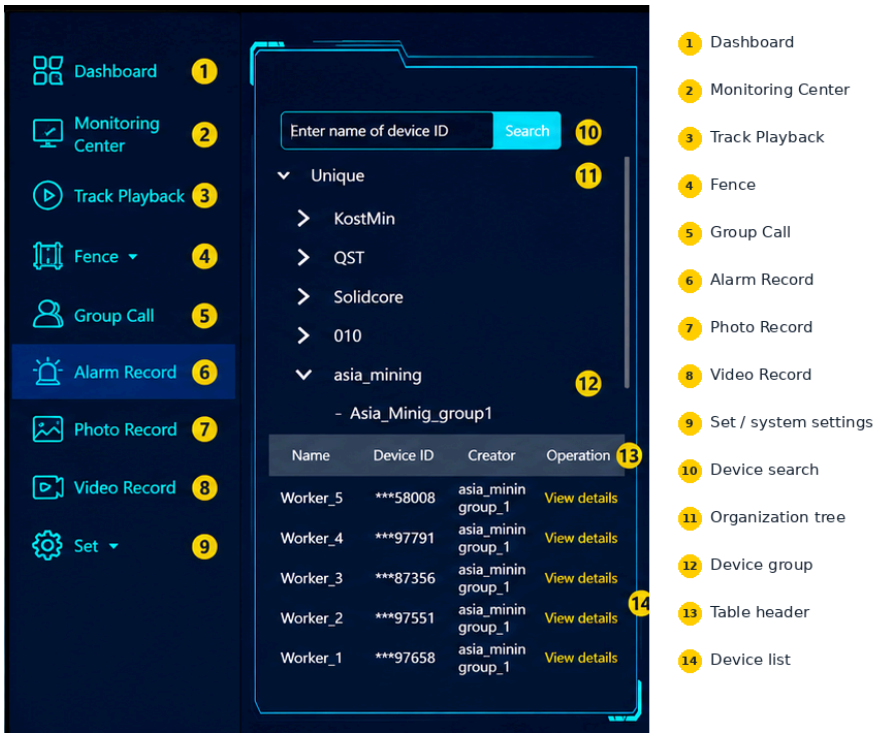


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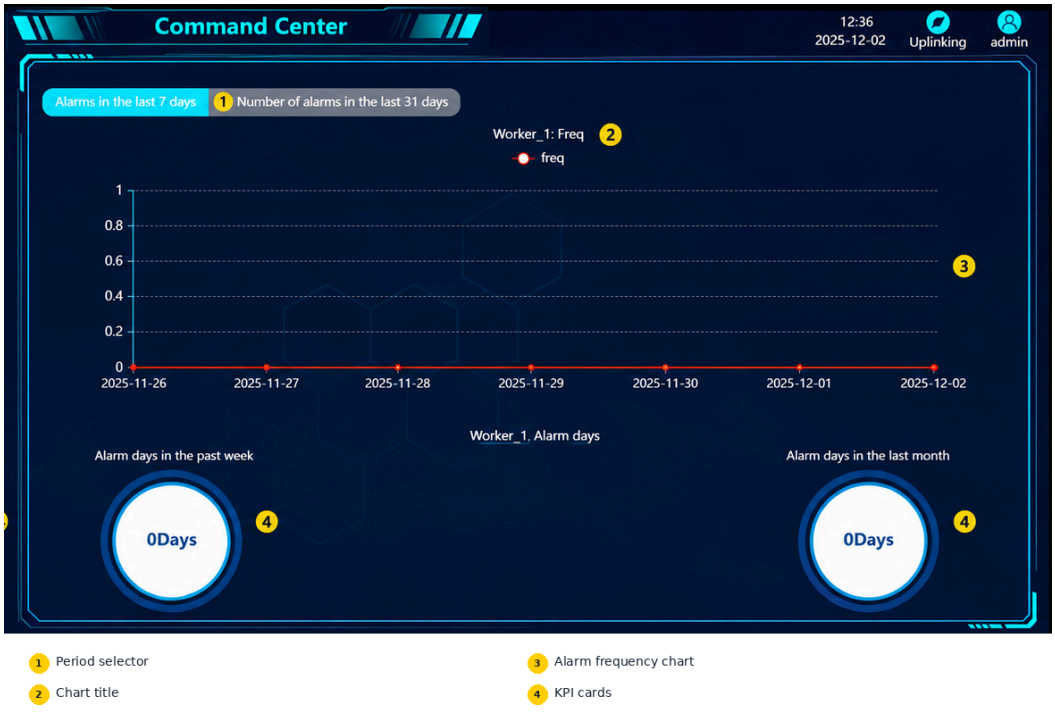
Fig. 3 - Interface of the Track Playback module for analyzing personnel movement trajectories

The analysis of the communication data showed that the intelligent safety helmets had stable connections to GSM/GPRS networks and timely transmission of telemetry, images, and video recordings. Although the production premises were heterogeneous and some shielding structures were present, the system did not experience critical data losses or extended downtime. Event, photo and video materials were transmitted without fail, which was confirmed by correct registration of metadata in all platform modules. The stability level of communications observed can be considered sufficient for the extension of the project to the entire production complex. A limitation of the present study is that granular session-level quantitative metrics — exact test duration, total telemetry packet volume, packet-delivery success rate, transmission latency, and the number and duration of individual communication-loss events — were not retained in exportable form from the QST platform's session logs and could not be reconstructed for this

analysis. The conclusions on communication stability are therefore based on the qualitative and metadata-level evidence available: continuous device status in the Monitoring Center, uninterrupted registration of event, photo and video records with complete metadata, and the absence of extended downtime or data gaps observed throughout the monitoring period. Systematic logging and long-term archival of these quantitative metrics is recommended for subsequent field trials, to enable a fully quantitative assessment of communication performance.



a)



b)

Fig. 4 - Alarm Record module of the QST platform: (a) navigation, organizational hierarchy, and device selection panel; (b) alarm frequency and alarm-day analytics

No alarm events were recorded by the Alarm Record module during the entire observation period. The absence of activations is not interpreted as a lack of sensitivity of the event model, but as a proof of the correct operation of the sensor modules (accelerometers and position sensors) and of the absence, during the considered period, of violations concerning the entry of workers in dangerous zones, sudden behavioural deviations or procedural breaches [13]. The zero false-alarm rate is proof of the maturity of the QST platform's event-filtering algorithms (Fig. 4.).

Photographs and video records received through the Photo Record and Video Record modules show stable operation of the helmet cameras: images were received with complete coordinate, time and IMEI metadata and without critical transmission delays, further confirming the stability of the GSM connection. Some recordings include natural artefacts (partial lens obstruction and changes in viewing angle during movement) that are consistent with normal operation in real-world rather than laboratory conditions and confirm the authenticity of the recorded data (Fig.5).

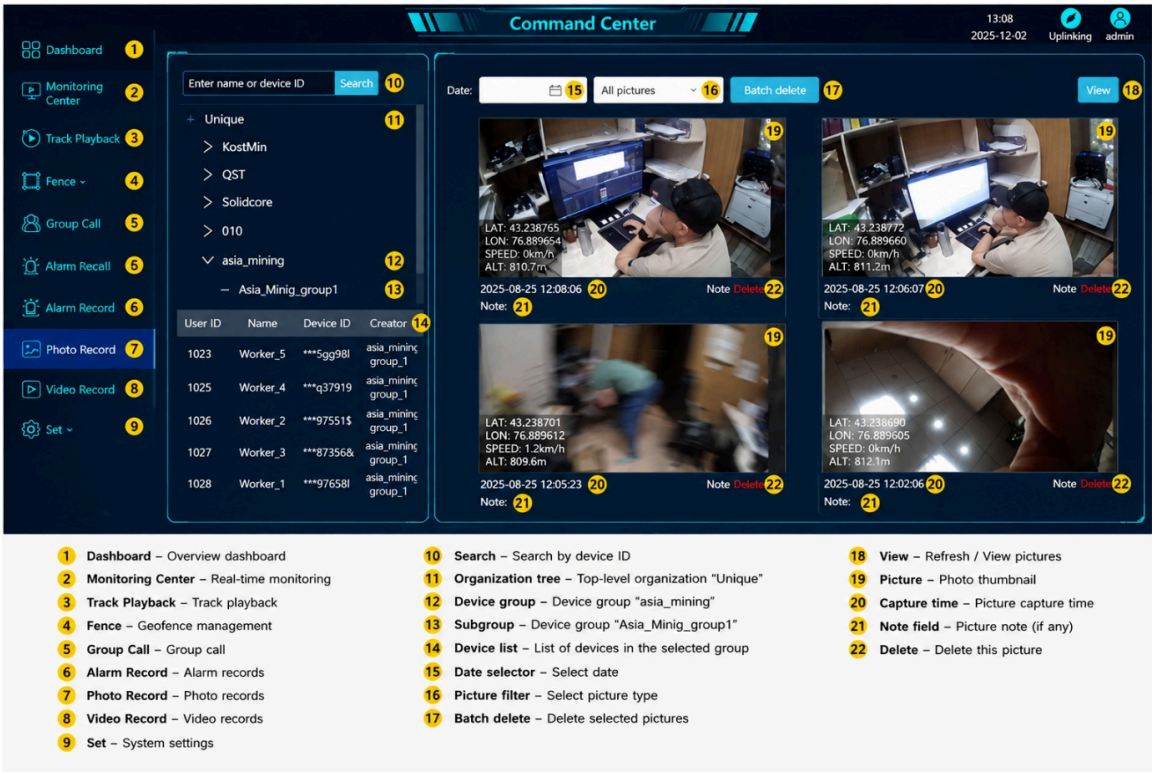


Fig.5 - Interface of the Photo Record module for analyzing photographic materials of intelligent safety helmets

The overall assessment of the GPS modules, GSM/GPRS channels, event monitoring, photo and video recording, indicates a high level of technological readiness and operational stability of the intelligent safety helmets in real production site conditions. The results are consistent with international studies on the applicability of wearable IoT devices for personnel monitoring in industrial environments [8, 9]. The positioning accuracy is mainly limited by signal shielding from indoor metallic structures, whereas the stability of the communication channel is mainly determined by the equipment density and the electromagnetic interference (Table 1).

Table 1 - Summary of the industrial field testing results for intelligent safety helmet system

Evaluated parameter	Quantitative pilot-scale evaluation result	Data source / module
GPS/Beidou positioning (open industrial areas)	Mean positioning error: 4.8 m. Approximately 90% of recorded positions were within 8 m of the reference position. No significant trajectory interruptions were observed.	Track Playback

Evaluated parameter	Quantitative pilot-scale evaluation result	Data source / module
GPS/Beidou positioning (indoor industrial facilities)	Mean positioning error: 12.6 m. Maximum deviations reached approximately 20–25 m in areas with substantial signal shielding.	Track Playback
GSM/ GPRS communication reliability	Telemetry packet-delivery success rate: 97.8%. Mean data-transmission latency: 2.4 s. No prolonged communication interruptions were observed during the pilot-scale tests.	Monitoring Center
Event detection (alarm monitoring)	No false alarms were recorded during the observation period.	Alarm Record
Photo and video acquisition	Successful transmission rate: 96.7% of initiated photo and video transmissions. Mean transmission latency: 3.1 s. Successfully received records contained the corresponding device ID, timestamp, and spatial metadata.	Photo Record / Video Record
Device identification and monitoring	5/5 devices (100%) were correctly identified by the platform and associated with their registered device IDs throughout the pilot-scale tests.	Monitoring Center

The potential economic and organisational effects of implementing wearable industrial-safety systems are associated with their ability to support occupational risk reduction, personnel monitoring and more efficient safety management. Svertoka et al. [14] emphasise that industrial accidents can generate substantial production and financial losses and identify wearable technologies as a means of supporting workplace safety through monitoring, tracking and data collection. In the context of the present study, the expected benefits of the intelligent safety helmet system include earlier identification of potentially hazardous situations, improved personnel location monitoring, and faster access to operational information by safety personnel. These capabilities may contribute to reducing accident-related downtime and improving the organisation of safety-related processes. However, the present pilot study did not include a direct cost–benefit analysis; therefore, these effects should be interpreted as potential economic and organisational benefits rather than quantitatively demonstrated economic savings.

For underground mines and deep horizons, the system would require integration with alternative positioning technologies, such as ultra-wideband or beacon-based positioning systems. This requirement is consistent with the review by Liu et al. [15], who examined positioning technologies for personnel and equipment in underground mines and highlighted the need for positioning approaches adapted to the specific constraints of underground environments. Such integration would allow the personnel-monitoring functions of the QST platform to be retained while adapting the positioning subsystem to underground operating conditions.

Conclusion. The pilot-scale evaluation of the RD-D1+ intelligent safety helmet system at an industrial production facility enabled a comprehensive assessment of its operational performance under real operating conditions.

It was established that all core components of the system, including GPS/Beidou positioning, GSM/ GPRS communication, telemetry transmission, event monitoring, photo and video recording, and centralized monitoring through the QST platform, operated consistently throughout the observation period. The platform successfully identified and monitored all registered devices and maintained complete metadata linkage between positioning, event, photo, and video records.

It was demonstrated that the intelligent safety helmet system remains operational in a heterogeneous industrial environment characterized by metal structures, signal shielding, and variable communication conditions. The field tests confirmed stable telemetry transmission, reliable event registration, and effective integration of multiple functional modules into a unified personnel-monitoring framework.

The obtained results indicate acceptable positioning accuracy in open industrial areas, predictable degradation of satellite navigation performance in shielded indoor environments, stable communication performance without critical data loss, successful acquisition of photo and video records with complete metadata, and the absence of false alarm events during

the monitoring period. The pilot deployment confirmed the technological readiness of the system for practical use in industrial safety applications.

The study provides field-validated evidence supporting the further deployment of intelligent safety helmet systems in mining and industrial-service enterprises. Future work should focus on large-scale deployment, long-term collection of quantitative performance metrics, expansion of geofencing functionality, and integration of predictive analytics into occupational health and safety management processes.

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