International Journal of Applied Earth Observations and Geoinformation 108 (2022) 102710

Contents lists available at ScienceDirect

International Journal of Applied Earth Observations and Geoinformation

journal homepage: www.elsevier.com/locate/jag

The CNRIEEEMC: A communication-navigation-remote sensing-integrated ecological environment emergency monitoring chain for tailings areas

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ARTICLE INFO

Keywords:
Ecological Environment Monitoring
Emergency Response
Tailings Area
Communication-Navigation-Remote Sensing Integration
Service Chain
Workflow

ABSTRACT

Pollution from tailings areas often introduces serious animal- and plant-associated ecological disasters and can even endanger human health. Communication-navigation-remote sensing (CNR)-integrated monitoring is expected to play a key role in the assessment of ecological environments in tailings areas, but CNR integration has long been a challenge for emergency monitoring systems. To address this challenge, in this paper, a CNR-integrated ecological environment emergency monitoring chain (CNRIEEEMC) for a tailings area in Northwest China is proposed, designed and constructed. This study included (1) a summary of the ecological environment monitoring content in the tailings area and a proposal for the CNRIEEEMC mechanism; (2) a design of the execution model of the CNRIEEEMC for driving the integration of CNR resources to execute ecological environment monitoring tasks; and (3) a formal description method of CNRIEEEMC execution logic to implement routine and emergency monitoring in the tailings area. An experiment was carried out in a tailings area to verify the effectiveness of the proposed CNRIEEEMC method. This method provides a feasible framework for optimizing emergency monitoring schemes based on the integration of CNR resources and offer a basic structure for future automatic, intelligent ecological environment emergency monitoring, and also with important implications for emergency monitoring systems in other fields.

1. Introduction

The mining industry plays a very important role in the global economy, and mining is the economic foundation and pillar industry in many countries worldwide. Mineral resources are important for the survival and development of human society (Chen and Cheng, 2015). However, the development of the mining industry has also introduced many environmental problems. Tailings waste may cause air pollution, endanger rivers and soils, destroy the hydrological ecology, affect domestic, industrial and agricultural water, and even lead to the invasion of toxic elements and heavy metals into the food chain around the mining area (Tiwary and Dhar, 1994; Murciego et al., 2007). Thus, the presence of mine tailings poses a potential threat to humans.

Therefore, it is necessary to conduct ecological environments monitoring to ensure that the tailings area is safe. In the case of emergencies, critical information such as the status of infrastructure in tailings areas, land coverage changes, soil pollutant composition and water quality must be sensed in time. Fortunately, the development of communication, navigation and remote sensing technology provides an effective means for monitoring the ecological environments of mine tailings areas.

At present, there are more than 4,000 spacecraft in orbit, covering many fields, such as communication, navigation, and remote sensing (Union of Concerned Scientists, 2021). A large number of space-based Earth observation technologies are applied in environmental monitoring (Gao and Zhang, 2018; Sashikkumar et al., 2017; Hassan et al., 2019), pollution analysis (Zhang et al., 2018; Liu et al., 2020; Huang et al., 2020), water quality monitoring (Chen et al., 2020a, 2020b, 2020c; Pivato et al., 2019), land cover change detection (Schneider, 2012), disaster and emergency management (Abdalla and Li, 2010; Zhang et al., 2010), etc. However, when sudden disasters occur (e.g., earthquakes, landslides, dam breaks, etc.), satellite platform-based

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https://doi.org/10.1016/j.jag.2022.102710
Received 12 November 2021; Received in revised form 30 January 2022; Accepted 31 January 2022
Available online 17 February 2022

remote sensing monitoring is not yet sufficient to help with real-time emergency responses (Huang et al., 2017). Unmanned aerial vehicles (UAVs), based on their highly portable and flexible characteristics, are capable of carrying out emergency monitoring of cities, rural areas, grasslands and even mountainous areas with poor conditions (Kucharczyk and Hugenholtz, 2021). Therefore, to a certain extent, UAVs can help compensate for problems (e.g., observation lags, insufficient observation cycles, lack of capacity for real-time scheduling and observations, inability to acquire small and complex object details, etc.) associated with satellite-based remote sensing (Deng et al., 2018; Zmarz et al., 2018; Chen et al., 2020a, 2020b, 2020c; Yue et al., 2020; Shenbagaraj et al., 2021).

However, due to the relative isolation of these monitoring systems, real-time, comprehensive service requirements might not be met by these existing systems or their collaborations (Zheng et al., 2020b). Current monitoring systems (e.g., displacement monitoring, satellite-based remote sensing, UAV-based remote sensing and ground-based remote sensing, etc.) work independently and have not been combined to form a comprehensive, intelligent or integrated CNR monitoring method. Although technical research on CNR integration has rarely been conducted in practice, extensive research has been conducted on the integration of communication and navigation (Andriana et al., 2018; Gulyaev et al., 2016; Ye et al., 2021), communication and remote sensing (Shah et al., 2012; Deng et al., 2016; Guchhait et al., 2020), and remote sensing and navigation systems (Jin and Komjathy, 2010; Yu et al., 2014; Yi and Astin, 2015; Isioye et al., 2015).

Challenges still exist in CNR integration and mainly include the following: 1) existing CNR systems are independent, self-contained and work independently, and the independent resources can be utilized but they are usually time-consuming and labor-intensive (Zheng et al., 2020b); 2) the acquisition speed of space-based remote sensing technologies is usually slow, making it difficult to meet the real-time requirements of emergency monitoring (Huang et al., 2017); 3) real-time satellite scheduling and acquisition of satellite-based remote sensing resources for some applications (e.g., small areas, little and dynamic objects, etc.) are difficult (Guo et al., 2016); and 4) at present, there are no effective, scientific means of scheduling integration of CNR resources, leading to an increased waste of CNR monitoring resources (Zheng et al., 2020b). Currently, comprehensive, multilevel space-air-ground CNR observations are developing in a new direction toward heterogeneous observation networking systems with diverse functions, complementary orbits, a high intelligence, autonomous operation and an ability to be easily expanded (Li et al., 2021). However, to realize this highly intelligent space-sky-ground observation network, the associated systems must be supported by optimal, effective CNR integration technology.

To overcome these challenges and realize effective, CNR-integrated ecological environment emergency monitoring schemes, we proposed and established a CNR-integrated ecological environment emergency monitoring chain (CNRIEEEMC) for tailings areas by utilizing geoscience service computing technology. With the continuous progress of geoscience service computing technology, multiple geographic information services can be combined and integrated into more powerful service chains and workflows and applied to disaster response (Zhang et al., 2010; Tan et al., 2015; Tan et al., 2016), geo-problem solving (Chen et al., 2019; Tan et al., 2021) and geographic model building and sharing (Chen et al., 2014; Yue et al., 2015, 2016a, 2016b; Sun et al., 2019; Chen et al., 2020a, 2020b, 2020c). This method achieved orderly, proper and efficient scheduling of CNR resources for ecological environment monitoring in the tailings area. The main contributions of this paper are summarized as follows.

(1) The ecological environment monitoring mechanism and content for the tailings area were proposed.
(2) A CNRIEEEMC execution model for the studied tailings area was designed, and according to the execution model, The CNR resources were seamlessly incorporated into the CNRIEEEMC.
(3) A formal description method of CNRIEEEMC execution logic was proposed, and CNRIEEEMC-based ecological environment monitoring in the studied tailings area was implemented.

2. The CNRIEEEMC in a tailings area

Frequent mining activities produce large amounts of waste in a mining area, and this waste pollutes the environment around the mining area and introduces the possibility for hidden dangers and disasters. Dust, nitrogen oxides, sulfur oxides and other harmful gases produced by mining operations damage the atmospheric environment in mining areas, causing respiratory problems for the people within the mining area and surrounding residential areas (Boyles et al., 2017). The liquid waste produced in mining areas seeps into rivers and groundwater, deteriorating the water quality in the mining area and affecting the industrial and domestic water use in the surrounding areas (Tiwary and Dhar, 1994). The accumulation of waste residues and the infiltration of liquid waste into the soil can cause heavy metal pollution in the soils, leading to the destruction of vegetation in mining areas and the deterioration of surrounding cultivated lands (Li et al., 2014). Mining also causes ground depressions and declines in some mining areas (Yang et al., 2019), leading to debris flows (Chen et al., 2008), landslides (Karagianni et al., 2018), tailings dam breaks (Lima et al., 2020) and other disasters. Therefore, conducting routine environmental monitoring and facilitating timely emergency responses to environmental disasters are very important for environmental protection and disaster protection in mining areas.

The research process utilized to realize the proposed CNRIEEEMC in a mine tailings area is shown in Fig. 1.

2.1. CNR-integrated ecological environment emergency monitoring mechanism and content

To implement CNRIEEEMC-based ecological environment monitoring in tailings areas, the ecological environment monitoring mechanism and content of the CNRIEEEMC were proposed and implemented in this paper, and the triggering conditions of emergency monitoring were defined.

2.1.1. CNR-integrated ecological environment monitoring content

The ecological environment monitoring content in the tailings area included routine and emergency monitoring content, including “Event”, “Data-acquiring device”, “Acquired Data” and “Analyzed Data”. The routine monitoring of tailings areas mainly included monitoring the deformation of tailings dams, water pollution and remote sensing changes in the tailings areas. The routine monitoring content in a tailings area is shown in Table 1.

In addition to routine monitoring, the monitoring content during ecological environment emergencies in the tailings area is shown in Table 2, and this information was designed to be sent to a command center to assist the authorities in making emergency disaster-related decisions.

2.1.2. CNR-integrated ecological environment monitoring mechanism

To monitor the daily dam displacement and water pollution values, monitoring was conducted, and automatic disaster alarms were triggered using alarm rules. Once a disaster event occurred that triggers an alarm, the emergency monitoring process initiated the collection, transmission and processing of ecological environment data. These data were sent back to the command center, where emergency decisions could made according to the emergency monitoring information received.

This paper designed an ecological environment monitoring

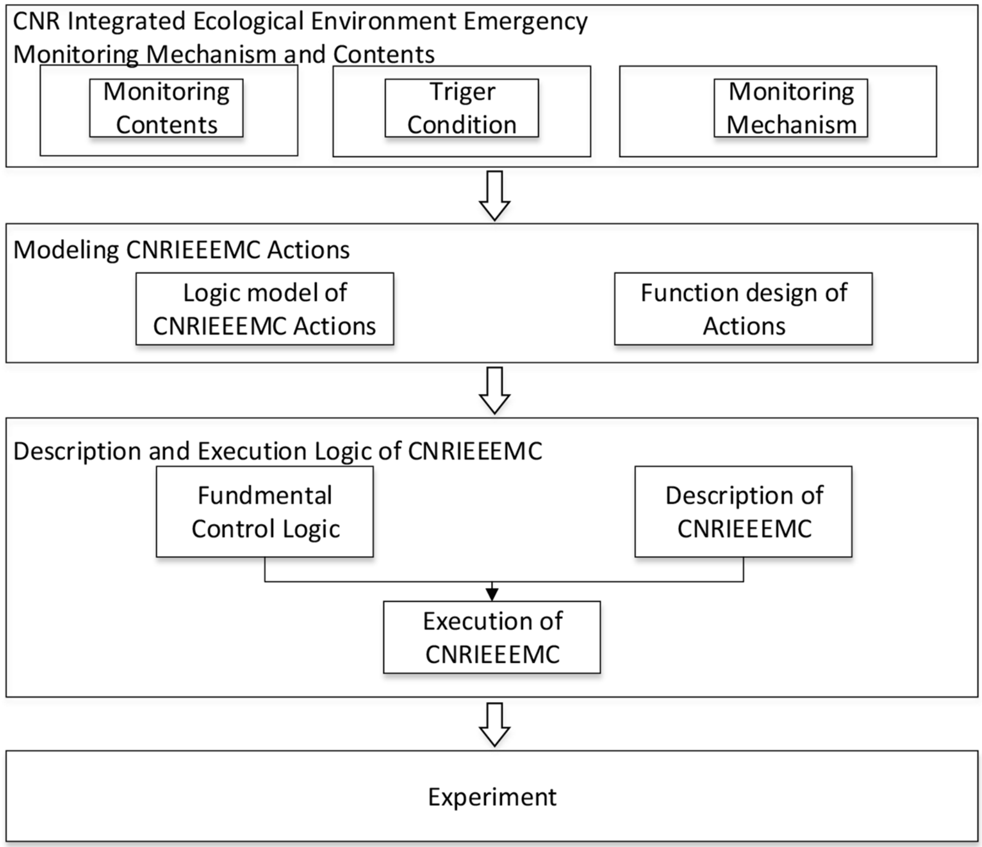


Fig. 1. Research process of the proposed CNRIEEEMC.

Table 1
Tailings Area Routine Monitoring Content.

Event	Data-acquiring device	Acquired Data	Analyzed Data
Dam deformation monitoring	Dam deformation monitoring station	Horizontal X direction displacement Horizontal Y direction displacement Vertical Z direction displacement	Dam deformation information
	Historical high-resolution remote sensing satellite imagery	Historical high-resolution remote sensing imagery Current high-resolution remote sensing imagery	Preliminary land cover change detection information
	UAVs, hyperspectral RS devices	Historical hyperspectral remote sensing imagery Real-time hyperspectral remote sensing imagery	Hyperspectral fine-resolution land cover change detection information
Water pollution monitoring	Water quality sensors	pH Conductivity Dissolved oxygen Chromium Manganese Copper Arsenic	Water quality report Water pollution report

mechanism for tailings areas that was divided into seven main steps. The basic structure is shown in Fig. 2.

In the process shown in Fig. 2, once the alarm threshold was exceeded, the dam displacement alarm or water pollution alarm was triggered.

The dam deformation monitoring station measured the displacement of the dam in the horizontal X direction, horizontal Y direction and vertical Z direction. The alarm rules are shown in Table 3.

Water pollution monitoring instruments mainly monitored the pH value, conductivity, and dissolved oxygen, chromium, manganese, copper, and arsenic concentrations, as well as other indicators. According to their intended water use purpose and monitoring index values, surface waters were divided into five categories. When the monitoring index value exceeded the standards for class-V water bodies, an alarm was triggered indicating that the water pollution exceeded the standards. The alarm rules are shown in Table 4.

2.2. Execution model of the CNRIEEEMC

We designed a CNRIEEEMC execution model, as shown in Fig. 3. According to the CNRIEEEMC execution model, a cyclic process that facilitates continuous monitoring was constructed, and 14 action processes was implemented (Table 5).

The monitoring diagram of the CNRIEEEMC execution model is shown in Fig. 4. Specifically, the environmental emergency response in tailings areas mainly involves dam displacement and water pollution emergencies. If a measured dam displacement exceeds the standard values, triggering an alarm, the dam deformation monitoring station must collect displacement information for the corresponding tailings dam in the horizontal X direction, horizontal Y direction and vertical Z direction; additionally, digital surface model (DSM) and orthoimage data for the tailings area must be collected through the use of a UAV. The

Table 2
Tailings Area Emergency Monitoring Content.

Event	Data-acquiring device	Acquired Data	Analyzed Data
Dam deformation monitoring	Dam deformation monitoring station	Horizontal X direction displacement Horizontal Y direction displacement Vertical Z direction displacement	Dam displacement information from real-time kinetic (RTK) measurements
	UAV tilt photogrammetry device	UAV tilt photogrammetry data	DSM DOM Slope Aspect 3D change detection
Water pollution monitoring	Water quality sensors	pH Conductivity Dissolved oxygen	Water quality report(handheld terminal)
	Water quality sensors, water quality analyzers	Chromium Manganese Copper Arsenic	Water pollution report(handheld terminal)
Air pollution monitoring	UAV-based Lora sensors	Temperature Humidity Flame Methane Carbon monoxide Benzene	UAV-based Lora sensors

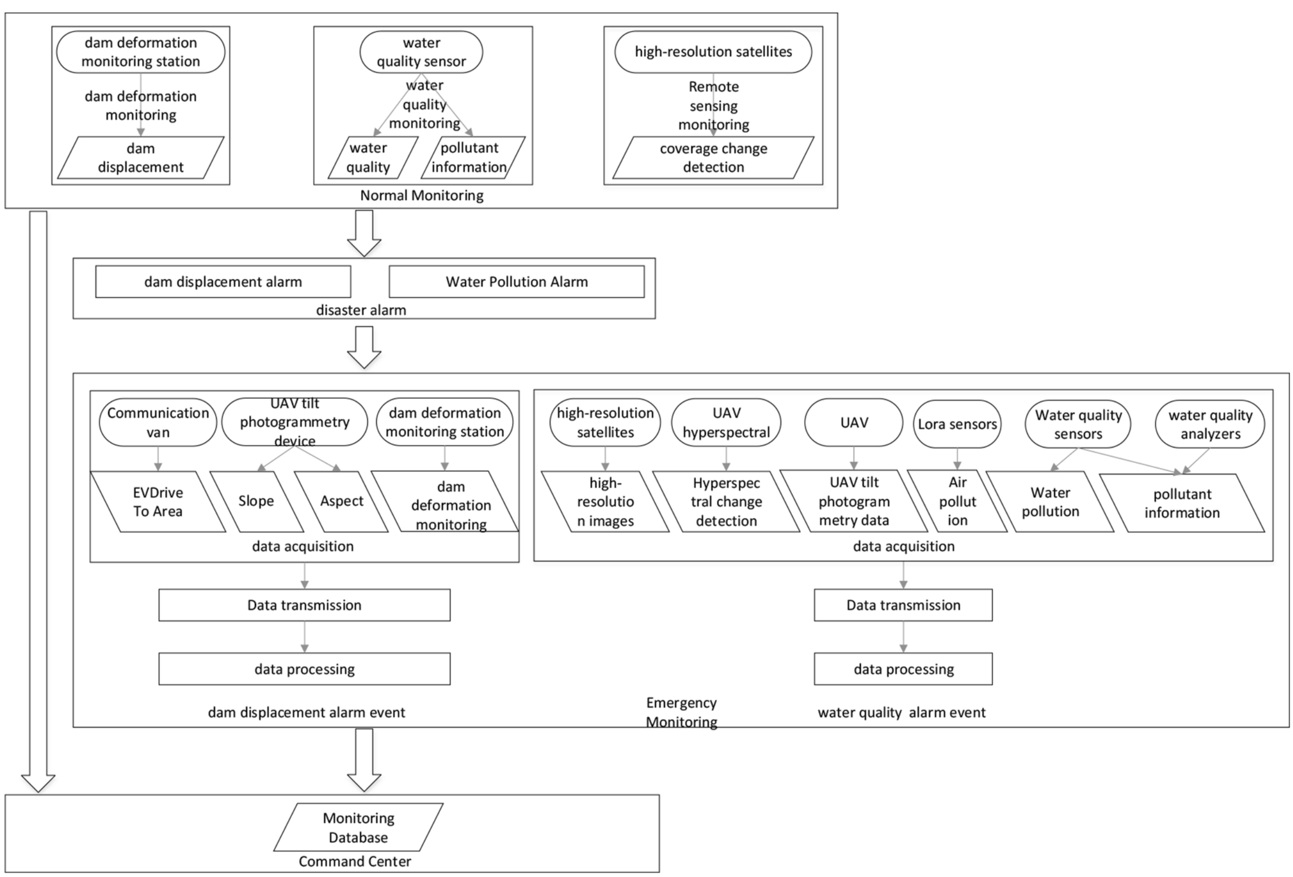


Fig. 2. CNR-integrated Ecological Environment Monitoring Mechanism.

Table 3
Dam Deformation Alarm Rules.

Monitored value	Displacement threshold
Horizontal X Direction	$\lvert DX\rvert \le 0.01$ m
Horizontal Y Direction	$\lvert DY\rvert \le 0.01$ m
Vertical Z Direction	$\lvert DZ\rvert \le 0.01$ m

DSM data are used for slope and aspect analyses of the tailings dam, and the dam displacement information, slope information, aspect analysis results and change analysis results are sent to the center to facilitate emergency measures in response to the dam displacement alarm. If the water pollution levels exceed the standard values, water quality monitoring personnel are sent to obtain water quality and pollutant monitoring data in the water pollution areas through the use of water quality

Table 4
Water Pollution Alarm Rules.

Monitored value	Class I	Class II	Class III	Class IV	Class V
pH	6 ~ 9				
Conductivity(μs/cm)	10 °C ≤ 3.6, 20 °C ≤ 4.3, 25 °C ≤ 5.1				
Dissolved oxygen(mg/L)	≥ 7.5	≥ 6	≥5	≥3	≥2
Chromium (mg/L)	≤0.01	≤0.05	≤0.05	≤0.05	≤0.1
Manganese (mg/L)	≤0.01	≤0.01	≤0.05	≤0.5	≤ 0.1
Copper (mg/L)	≤0.01	≤1.0	≤1.0	≤1.0	≤1.0
Arsenic (mg/L)	≤0.05	≤0.05	≤0.05	≤0.1	≤0.1

sensors and water quality analyzers, and the results are then sent to the center. At the same time, UAVs with air sensors onboard are used to measure air parameters in the tailings area to provide emergency response support.

2.3. Formal description of the CNRIEEEMC execution logic

To implement ecological environment monitoring according to the CNRIEEEMC execution model, formal description of the CNRIEEEMC execution model was necessary. In this paper, XML was used to design and describe the environmental monitoring and emergency response workflow processes, and a group of fundamental control structures (Liu et al., 2007) (Fig. 5), such as the sequence structure (Sequence), looping structure, parallel split structure (AND Split), parallel join structure, exclusive choice structure (XOR split), simple merge structure and fault tolerant structure, were used. The XML-based formal description of the execution logic of CNRIEEEMC is shown in Fig. 6.

All CNR based actions listed in Table 5 are integrated into CNRIEEEMC via the formal description. The action set described in part 1 of Fig. 6 involves three specific actions, and it is necessary to perform routine monitoring. In part 2, if the extent of dam displacement triggers an alarm, the CNRIEEEMC executes emergency monitoring. Two *sequence* subsets are executed in the *AND* parallel structure under the corresponding sequence. In part 3, only one action is executed to update the dam displacement and water pollution monitoring data.

Based on the formal description of the execution logic of CNRIEEEMC, the specific parsing and executing algorithm are as follows:

(1) The relationships between a root node and its child nodes are used to support the traversal of the XML document. For example, when the *process* node is encountered, the child node *for* is obtained;

(2) Then, all *action* nodes in the *for* node are retrieved and judged to determine whether the *isalone* attribute of each *action* node is *false*. If it is *false*, it is considered a *part*; otherwise, it is considered an *action*, and the

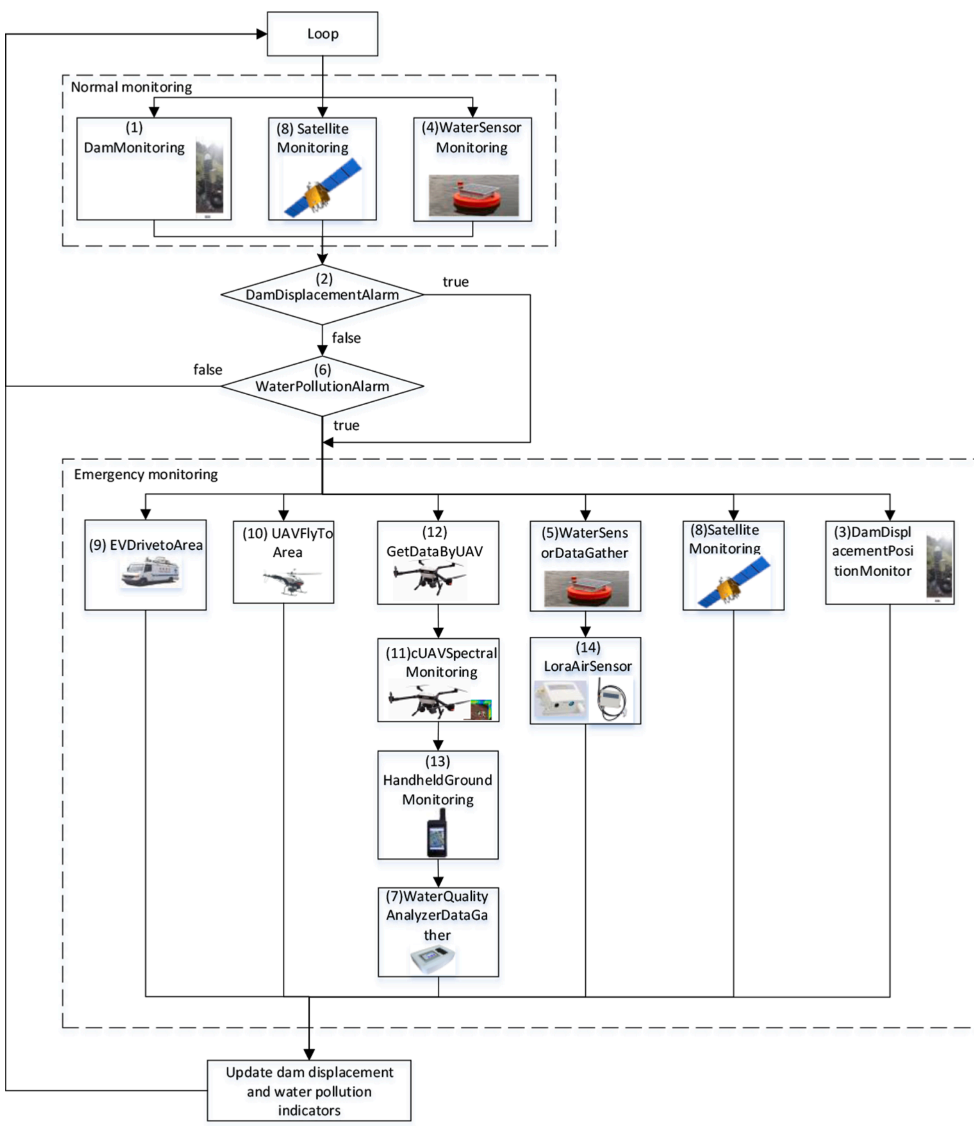


Fig. 3. CNRIEEEMC execution model.

Table 5
Actions of Routine and Emergency Monitoring Chains.

Action number	Action name	Action function	Device or platform	CNR role	Routine or emergency
(1)	DamMonitoring	Dam displacement routine monitoring	Beidou Positioning System	Communication & Navigation	Routine
(2)	DamDisplacementAlarm	Judge and trigger dam displacement alarm	Beidou Positioning System	Communication & Navigation	Routine & emergency
(3)	DamDisplacementPositionMonitor	Dam displacement emergency monitoring	Beidou Positioning System and RTK	Communication & Navigation	Emergency
(4)	WaterSensorMonitoring	Water quality routine monitoring	Water quality sensors	Communication & Navigation	Routine
(5)	WaterSensorDataGather	Water pollution data acquisition for pollution event	Water quality sensors	Communication & Navigation	Emergency
(6)	WaterPollutionAlarm	Judge and trigger water pollution alarm	Water quality sensors	Communication & Navigation	Routine & emergency
(7)	WaterQualityAnalyzerDataGather	Water quality analysis for pollution event	Water quality analyzer	Communication & Navigation	Emergency
(8)	SatelliteMonitoring	RS routine monitoring	High-resolution level-1 archive data	Communication & Remote Sensing	Routine & emergency
(9)	EVDrivetoArea	Dispatch emergency center vehicle to designated location	Communication van	Communication	Emergency
(10)	UAVFlyToArea	Dispatch UAV to fly to monitoring Area	UAV	Communication	Emergency
(11)	UAVSpectralMonitoring	UAV hyperspectral monitoring	UAV hyperspectral	Communication & Remote Sensing	Emergency
(12)	GetDataByUAV	UAV tilt photogrammetry data acquisition	UAV photogrammetry	Communication & Remote Sensing	Emergency
(13)	HandheldGroundMonitoring	Drive to collect ground-based data of monitoring points	Handheld data-acquiring terminal	Communication & Navigation & Remote Sensing	Emergency
(14)	LoraAirSensor	Lora sensor-based air monitoring	Lora air sensor	Communication & Navigation	Emergency

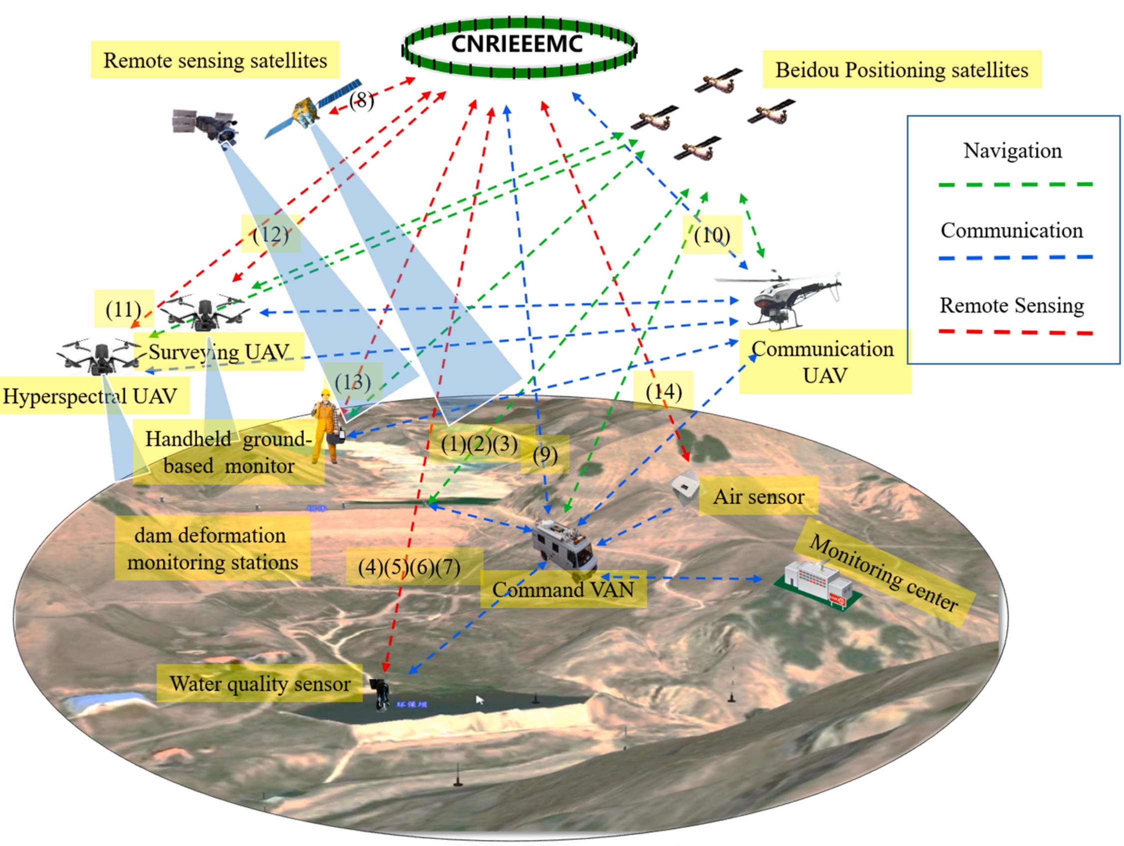


Fig. 4. Diagram of CNRIEEEMC driven monitoring.

CNRIEEEMCE model directly interprets its content;

(3) For each *part*, the child node is traversed. If it is an XOR node, the child node *sequence* is traversed. If each node under the *sequence* node is an AND node, all *sequence* nodes under that node are traversed until the *isalone* attribute of all *action* nodes under that *sequence* node are true; otherwise, the *action* node is traversed until the *isalone* attribute of the *action* node is *true*;

(4) Finally, the specific *actions* are interpreted and executed according to the logical control processes

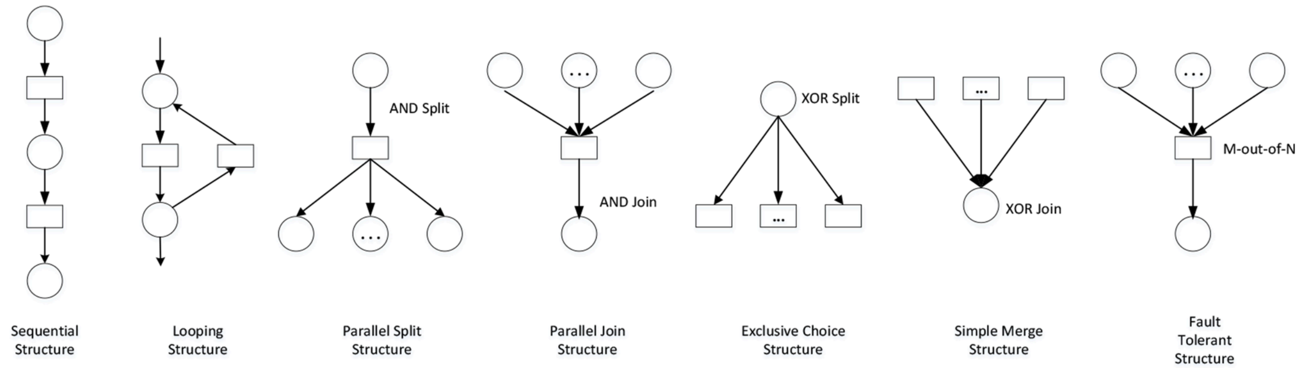


Fig. 5. Fundamental control structure.

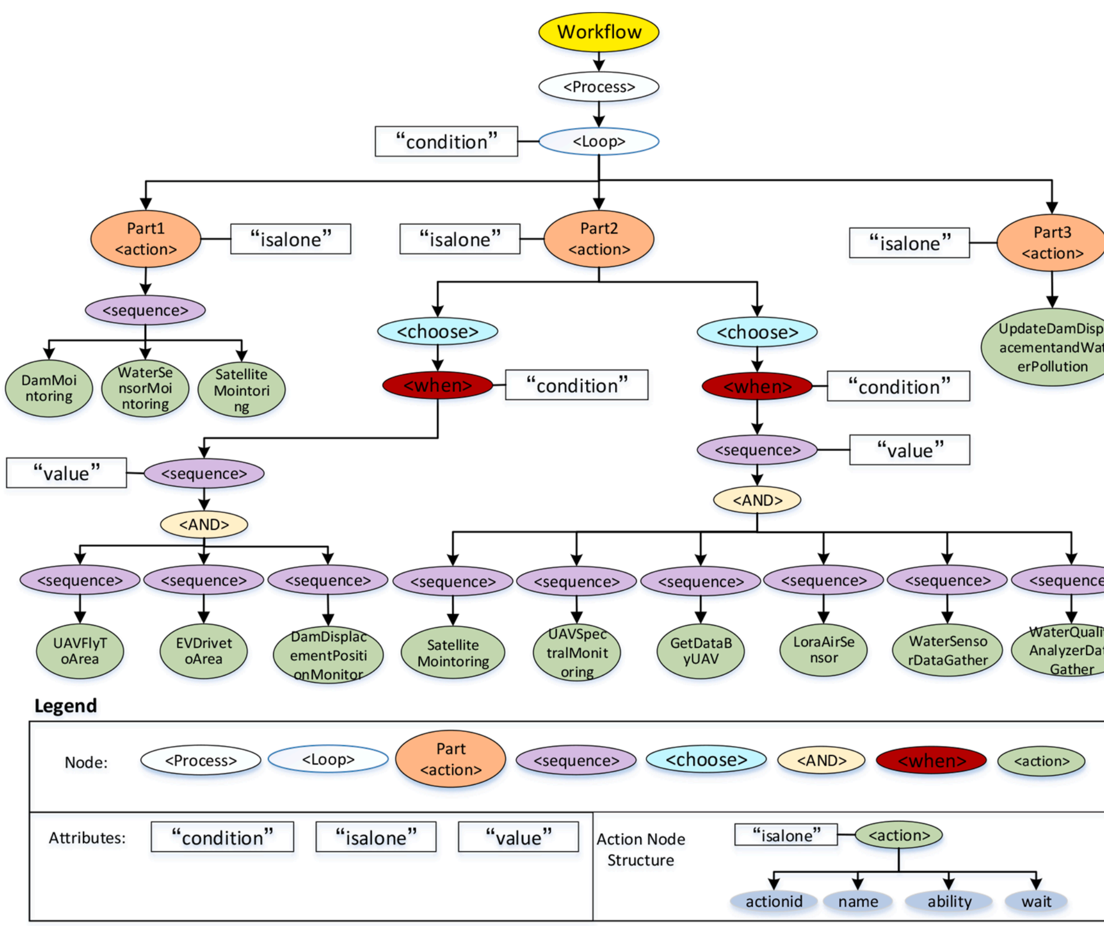


Fig. 6. XML formal description structure of the execution logic of CNRIEEEMC.

3. Experiment

3.1. Experimental area

In this paper, an experiment was carried out in a mine area in Northwest China. The mine is located in the upstream region of the Yili River, as shown in Fig. 7 (a). In this region, there are dense river networks, vast beaches and 200,000 ha of freshwater swamps. Therefore, the region is of ecological significance to Northwest China and even to Central Asia. Sixty-three kinds of minerals have been found in this area, including 20 kinds of proven reserves. A total of 48 deposits of various types have been found, including 6 large deposits, 14 medium deposits and more than 300 ore occurrences. The dominant minerals in this area are coal, gold, iron and manganese (Gao et al., 2021). In this study, a mine in this region was selected as the experimental area in which the CNRIEEEMC research was carried out.

A large amount of slag is produced during mining in the studied mine, and this slag is discharged into the tailings area, as shown in Fig. 7 (b). A tailings dam is located at the bottom of the tailings area, and under the tailings dam is the Small Asi River, which is a tributary of the Yili River. If serious geological disasters (e.g., mountain torrents, earthquakes, or landslides) occur, they pose dam breaking or cracking risks, sewage may infiltrate into the tailings reservoir, and sewage containing an excess of heavy metals (e.g., gold or arsenic) may seep outside of the dam, causing pollution in the Small Asi River, resulting in excessive heavy metal concentrations in the Yili River and even affecting aquatic

Region of Yili River

A tailings area

Fig. 7. Experimental area.

environments in neighboring region. Therefore, it is necessary to strengthen the routine ecological environment monitoring of this tailings area to ensure that the dam body remains safely intact and that heavy metal sewage does not flow into the Small Asi River. Conducting efficient ecological environment emergency monitoring in tailings areas in case of disasters is thus very important work.

3.2. CNRIEEEMC implementation

In the process of monitoring the ecological environment of a mine, selection of a type of CNR technology equipment is conducted according to the CNRIEEEMC method proposed in Section 3. The communication equipment resources utilized herein included a mobile emergency communication center van, a communication satellite and a communication UAV; the navigation equipment included a Beidou positioning system, dam displacement monitoring stations, handheld terminals, water quality sensors, water quality analyzers, and airborne air pollution sensors; and the remote sensing equipment included a UAV hyperspectral spectrometer, a UAV mapping camera, and a remote sensing satellite. Information on the equipment used in the CNRIEEEMC is shown in Table 6.

During the routine monitoring period in the CNRIEEEMC experiment, the monitoring chain drove the navigation system to monitor the dam deformation. The dam displacement information was mainly obtained via the dam deformation monitoring stations. The water quality change information was obtained through a water monitoring sensor network, and preliminary information detecting ground object coverage changes was obtained via remote sensing monitoring. When the monitored index values exceeded certain thresholds, the corresponding alarm was triggered. In this experiment, if the displacement in the horizontal X direction of the dam exceeded 0.01 M, the alarm was triggered. If the arsenic content in the water body in the tailings area exceeded 0.1 mg/l, the water pollution alarm was triggered. Thus, according to the CNRIEEEMC method proposed in this study, ecological environment emergency monitoring was carried out in the tailings area.

3.3. Experimental results

Based on the CNRIEEEMC proposed in this study, a CNRIEEEMC platform was constructed. Fig. 8 (a) and 8 (b) show the CNRIEEEMC platform, which can conduct the execution of the CNRIEEEMC in real time.

During routine monitoring, the dam deformation monitoring station collects and stores dam displacement information every four hours. The collected dam displacement information is shown in Fig. 9 (a). The routine monitoring processes driven by the CNRIEEEMC enabled the platform to obtain real-time dam positioning information, and the system triggered an alarm when the displacement magnitudes exceeded the predetermined threshold values. The process by which water pollution was monitored mainly considered the water quality and pollutants of the water environment in the tailings area through fixed water quality sensors in the environmental protection ponds (as shown in Fig. 9 (b)). During the routine monitoring of the tailings area, Gaofen-1 remote sensing images after 2018 (Zhu et al., 2018), Gaofen-2 images after 2015 (Shi et al., 2020), Landsat remote sensing images after 1995 were acquired periodically and are shown in Fig. 9 (c) and 9 (d). Further change detection was carried out to obtain the preliminary ground feature coverage change detection information, as shown in Fig. 9 (e).

Once an alarm was triggered, the CNRIEEEMC entered the emergency ecological environment monitoring process. First, the CNRIEEEMC drove the communication van to the predetermined location and dispatched the UAV to fly to an airspace where its signal could cover the involved area, as shown in Fig. 10 (a). Then, a UAV was dispatched to acquire the DSM and orthoimage data of the tailings area via tilt photogrammetry, and these data were then processed and visualized on the platform (as shown in Fig. 10 (b)). Based on the DSM data, the slope (as shown in Fig. 10 (c) and slope direction (as shown in Fig. 10 (d)) could be obtained. The hyperspectral remote sensing data and classification and change detection results obtained by the hyperspectral mapping UAV driven by the CNRIEEEMC are shown in Fig. 10 (e). With the support of the communications UAV, emergency monitoring personnel on the ground could carry a handheld terminal (as shown in Fig. 10 (f)) to collect ground photos and spectral information (as shown in Fig. 10 (g)). The monitoring results of the air pollution sensor onboard the UAV are shown in Fig. 10 (h).

3.4. Discussion

Through experiments, the effectiveness of the CNRIEEEMC can be verified. In the long-term, routine monitoring process, the monitoring chain conducts routine monitoring and controls the remote sensing and navigation equipment to ensure that the dam deformation, water body quality and land cover changes are continuously monitored in the tailings area. Once any dam displacement values or heavy metal values in the water body are found to have exceeded the threshold values, the CNRIEEEMC drives the emergency monitoring response in the tailings

Table 6
Environmental emergency monitoring device information.

Device or platform	CNR role	Function	Description
Mobile emergency command van	Communication	Emergency command and data transmission relay	A vehicle equipped with an emergency command communications system
Communication satellites	Communication	Satellite communication	Short-message communication based on a Beidou communication satellite.
Communication UAV	Communication	Communications relay	Emergency communication between a handheld terminal and a communications van is realized through airborne communication relay
Handheld water quality terminal	Communication & Navigation	Collect and analyze water quality data at designated points	The handheld terminal uses Beidou positioning to obtain navigation information and upload the collected water quality and location information to the emergency system
Handheld ground-based monitor	Communication & Navigation & Remote Sensing	Collect ground-based data of monitoring points	The handheld terminal uses Beidou positioning to obtain navigation information and upload the collected surface feature spectrum data, photo and location information to the emergency system
Fixed water quality monitor	Communication & Navigation	Tailings area water quality monitoring	Monitors water quality via sensors in tailings area.
Dam deformation monitor	Communication & Navigation	Dam deformation monitoring	Dam deformation monitoring based on high-precision, Beidou differential positioning technology
High-resolution RS satellites	Remote Sensing	Remote sensing monitoring to obtain a high-resolution satellite map of the mining area	High-resolution Gaofen-1, Gaofen-2, Landsat RS image was processed based on deep convolution neural network, SVM and etc.
Surveying UAV	Communication & Remote Sensing	Tilt photogrammetry data acquisition	DJI M600 UAV is equipped with a mapping camera to complete tilt photogrammetry to produce DSM and DOM data via Pix4D
Hyperspectral UAV	Communication & Remote Sensing	Hyperspectral information acquisition	DJI M600 UAV is equipped with a hyperspectral camera to acquire hyperspectral image and process the data based on a deep convolutional neural network algorithm (Zheng et al., 2020a)

area to not only realize the effective scheduling of communication resources but also to drive the navigation and remote sensing resources to complete emergency monitoring in the tailings area, thus supporting monitoring of potential dam deformations, water quality, ground scene, spectrum and air pollution, as well as other indicators, to facilitate emergency monitoring in the tailings area. The proposed CNRIEEEMC not only effectively designs monitoring tasks and mechanisms to assess the ecological environment in the tailings area, facilitates the orderly occurrence of ecological environment monitoring, and enables universal and reproducible ecological environment monitoring, but it also programs a monitoring workflow with the potential to support fully automatic and intelligent monitoring.

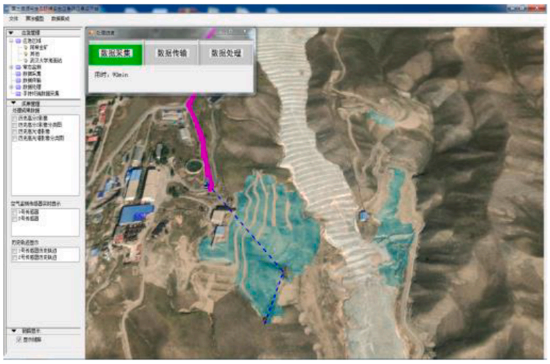
However, the existing methods do not support the integration of the various CNR resources we have mentioned in Table 6, and the CNR resources worked independently during conducting the ecological environment monitoring in the experiment area. Hence, when with the existing methods, once the alarm was triggered, the monitoring team needed to analyze the situation of the experiment area, and schedule the CNR resources according to expert experience or the predefined instructions manually to conduct ecological environment monitoring.

Via the implementation of the CNRIEEEMC, the monitoring efficiency can be significantly improved compared to those of existing methods because the proposed method can programmatically perform monitoring tasks. The human resources and time requirements of the data acquisition and emergency response processes in the experimental area are shown in Table 7.

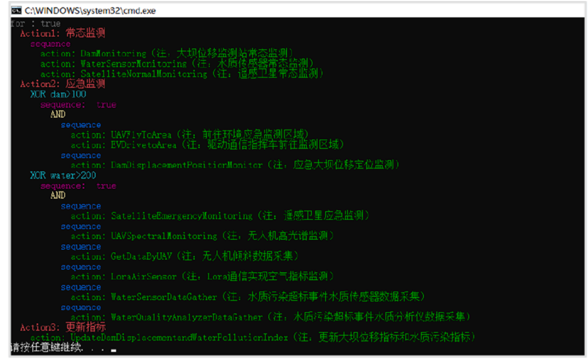
The advantages of the current CNRIEEEMC method were mainly reflected in the efficiency of the corresponding emergency monitoring processes and the human resources advantages in the emergency decision-making process. As shown in Table 7, due to these shortcomings in emergency decision making, existing emergency monitoring methods usually required more than 4 h in the same experimental area, while the proposed method could take only 2 h or less, which is particularly critical for emergency monitoring. In addition, in the decision-making process of the emergency monitoring system, the proposed method needed only one person to operate the CNRIEEEMC system. The terminals executed the corresponding actions to complete the monitoring tasks according to the commands that were automatically sent by the CNRIEEEMC platform. In contrast, existing methods required more than 4 people with professional knowledge and experience to make decisions together to complete ecological environment monitoring, which is time-consuming and labor-intensive. We can also see that the human resource requirement in the emergency monitoring execution stage in the experimental area was not reduced in the new method, mainly because until now, manual assistance has been needed to operate the monitoring facilities involved; thus, the intelligence and automation ability of the CNRIEEEMC needs to be strengthened, and these recommendations are particularly critical for emergency responses in specific situations, especially in toxic environments.

4. Conclusion

Mineral resources play an important role in human society, but mining pollution and resulting regional and watershed pollution

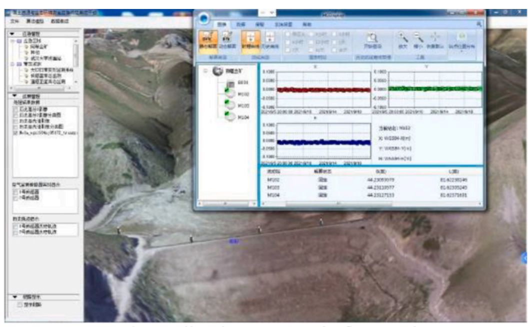


(a) CNRIEEEMC user interface



(b) CNRIEEEMC execution monitoring

Fig. 8. CNRIEEEMC platform.



(a) dam displacement information

(b) Fixed water quality sensors

(c) Historical high-resolution RS images

(d) Recent high-resolution RS images

(e) Preliminary ground feature coverage change detection

Fig. 9. Acquisition of routine monitoring data with the CNRIEEEMC.

seriously impact human health. Although monitoring methods with multiple means currently exist, these methods do not have any comprehensive or integrated observation abilities and instead acquire data independently through various means before finally summarizing and analyzing the data. Up until now, monitoring research has also been conducted independently, and the utilized methods have not provided an effective unified or coordinated means for environmental monitoring and have had difficulty realizing automated, intelligent emergency

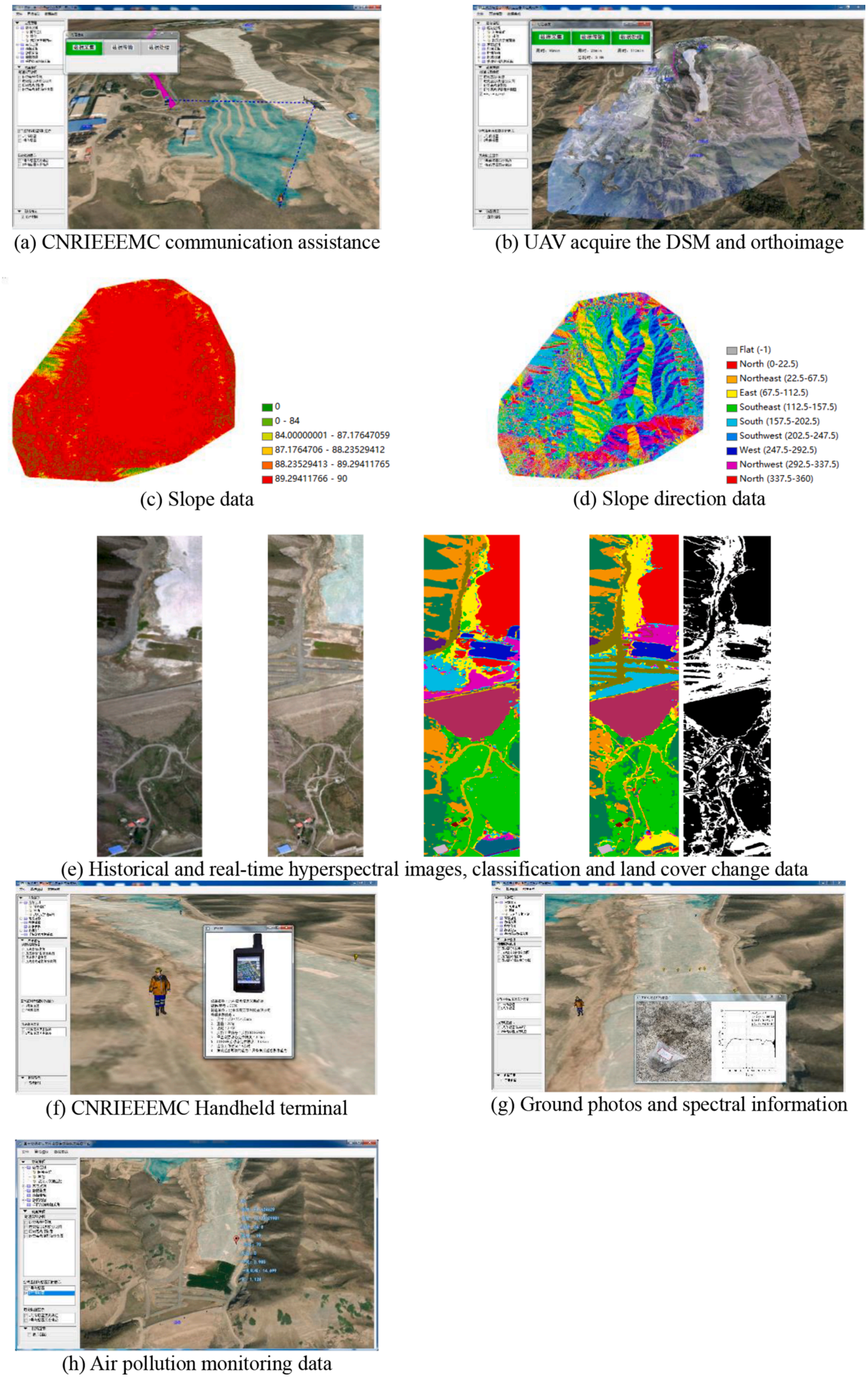


Fig. 10. Acquisition of emergency monitoring data with the CNRIEEEMC.

monitoring. Moreover, these methods might not fully or effectively schedule space-sky-ground monitoring resources or CNR resources for timelier, more automatic and more efficient ecological environment emergency monitoring. To form a comprehensive, CNR-integrated, space-sky-ground monitoring method, this paper proposed a construction method for a CNRIEEEMC that integrated communication, navigation and remote sensing resources, established the routine and emergency monitoring chain models of the ecological environment in a tailings area, and realized the process and automated execution of the environmental monitoring chain in the tailings area. The monitoring results were visualized in the software platform, providing a clear, efficient emergency monitoring method for tailings areas and other ecological environments. These experiments showed that the CNRIEEEMC proposed in this paper achieved routine and emergency

Table 7
The Comparison of CNRIEEEMC with existing methods.

Monitoring task	Existing emergency monitoring methods	CNRIEEEMC
Time consumed in the emergency monitoring of the ecological environment in the experiment area	More than 4 h	Less than 2 h
Human resources required in the emergency monitoring decision making process	More than 5 experts	1 person
Human resources required in the emergency monitoring execution	More than 10 people	More than 10 people

ecological environment monitoring in tailings areas and integrated and visualized the monitoring results through the use of a virtual platform. This study can help optimize current environmental monitoring mechanisms or methods, especially when the communication technologies, remote sensing methods, equipment, personnel, features and objectives involved in emergency monitoring systems are diverse and complex. In such circumstances, it is difficult for existing environmental monitoring methods to manage and schedule a variety of monitoring resources effectively. The CNRIEEEMC proposed herein enables all the current experience and knowledge to be organized and utilized under the guidance of the monitoring chain. Therefore, with this process, environmental emergency monitoring can be conducted in an orderly manner.

Although this study provides an effective and predefined automatic organization workflow for ecological environment emergency monitoring, CNR resources must still be manually operated in the proposed framework. To date, the proposed method does not have the ability to intelligently or automatically dispatch or organize various resources. Therefore, in future research, we plan to improve the intelligence and scheduling abilities of the proposed method for ecological environment emergency monitoring and realize a fully intelligent CNRIEEEMC.

CRediT authorship contribution statement

Xicheng Tan: Methodology, Data curation, Writing – original draft, Software, Investigation. **Jinguo Jiao:** Visualization, Software, Data curation. **Yanfei Zhong:** Conceptualization, Methodology, Supervision. **Ailong Ma:** Data curation, Writing – review & editing, Validation. **Yanyan Xu:** Supervision. **Zongyao Sha:** Writing – review & editing, Supervision. **Fang Huang:** Investigation. **Yuting Wan:** Data curation, Validation. **Wenzhuo Hu:** Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by the National Science Foundation of China (NSFC) [Grant ID: 41871312], National Key Research and Development Program of China [Grant ID: 2017YFB0504202], Fundamental Research Funds for the Central Universities [Grant ID:2042019kf0226], Hubei Natural Science Foundation [Grant ID: 2017CFB433], and Open Research Project of The Hubei Key Laboratory of Intelligent Geo-Information Processing [Grant ID: KLIGIP-2017A09].

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