Online Near Real-time Mine Disaster Monitoring System Based on Wireless Sensor Networks

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***Abstract*—An online automatic disaster monitoring system can reduce or prevent geological mine disasters to protect life and property. Global Navigation Satellite System receivers and the GeoRobot are two kinds of in-situ geosensors widely used for monitoring ground movements near mines. A combined monitoring solution is presented that integrates the advantages of both. In addition, a geosensor network system to be used for geological mine disaster monitoring is described. A complete online automatic mine disaster monitoring system including data transmission, data management, and complex data analysis is outlined. This paper proposes a novel overall architecture for mine disaster monitoring. This architecture can seamlessly integrate sensors for long-term, remote, and near real-time monitoring. In the architecture, three layers are used to collect, manage and process observation data. To demonstrate the applicability of the method, a system encompassing this architecture has been deployed to monitor the safety and stability of a slope at an open-pit mine in Inner Mongolia.**

***Index Terms*—geological mine disasters, wireless sensor networks, remote online monitoring**

I. INTRODUCTION

The exploitation of mineral resources commonly disturbs the stress regime of the rocks in and near the mine and this can lead to the release of groundwater. That groundwater and the changes in stress can then cause geological mine disasters, such as ground deformation and subsidence, mining district slope instability, landslide, collapse, debris flow, and other geological disasters [1]. Geological mine disasters not only threaten the personnel and equipment in the mine but can also can pose some risk to people living nearby.

Recently, wireless sensor networks (WSN's) have been used to support many important applications including global environmental monitoring, natural disaster prediction, and critical infrastructures protection. There are some locations where WSN's are being used in the field to monitor disasters successfully. For example, the Romanian Waters National Administration and Hidroelectrica Romania laid out flood monitoring sensors in the Danube River [2]. In addition, WSN's have been used for mined ground disaster monitoring [1, 3], and debris flow monitoring [4]. In remote, sensitive, or hazardous environments, because of their much higher spatial and temporal granularity [5], WSN's are much superior to conventional monitoring technologies. For example, an automated WSN system has been used for monitoring ground deformation on the Deception Island volcano, Antarctica, based on quasi real-time observations from Global Navigation Satellite System (GNSS) satellites [6].

It is not uncommon for mines to be located in regions that are harsh or dangerous (or both). Traditional artificial monitoring is low efficiency and high cost. It is difficult to monitor the precursors of mine disasters. This paper attempts to apply WSN's to promote the automation of online monitoring for geological mine disasters.

In general, the positions of sensor networks for mine ground disaster monitoring are relatively fixed. For disaster monitoring, different types of disasters commonly need different sensors. The sensors usually need to collect data either periodically or continuously. Among the types of sensors used, the two most common types for mine disaster monitoring are GNSS receivers and the GeoRobot. Both are very good at automatic online monitoring but each has advantages and disadvantages. Here a combined monitoring solution is presented integrating the advantages of both.

Automated mine disaster monitoring systems involve using a number of different procedures including sensors layout design, data transmission, data management, real-time data processing, and application services. To aid in realizing automatic online monitoring systems, the main contribution of this paper is to describe a three-layer architecture based on a WSN for mine disaster monitoring. To demonstrate this system, a mined ground deformation monitoring system based on the architecture is described. The system is an automatic online near real-time system.

The system is called a “near real-time” system because there are some intermediate steps that cause a delay between the time the observation data are obtained and the time the data are processed and available for inspection. For example, the middleware processing of the raw data, the transmission of the data from the RS-232 serial port to the (General Packet Radio Service) GPRS, and the transmission of the virtual sensor data over the Internet all take measurable amounts of time.

II. METHODS

A. *Combined monitoring with GNSS and a GeoRobot*

Ground deformation and displacement are regarded as precursors to geological mine disasters such as mine slope instability and surface subsidence. Data on the displacement of monitoring points on the ground is obtained by analyzing monitoring data from in-situ geosensors. Even a small displacement can be detected.

At present, GNSS receivers and GeoRobots used for ground deformation monitoring have achieved high precision and automation. Practice shows that GNSS technology plays a more and more important role in deformation monitoring that traditional measurement methods cannot match. With GNSS receivers and GeoRobots, systems have the virtues of continuity, real-time data transmission, and automation [7]. The GeoRobot is an in-situ sensor, also called an auto-total station, and is an integrated system that can perform automatic target recognition, automatic measuring of angles and distances, automatic target tracking, and automatic data recording. The GeoRobot's most important feature is automatically observing the targets after the initial observation with the help of some manual input by an operator. The GeoRobot greatly reduces the labor intensity of field measurements, improves efficiency, and provides real-time or near real-time observation data.

In general, the GNSS geodetic network requires at least three station points, and then, through data processing, high precision site coordinates can be obtained. A deficiency of GNSS is that the area to be monitored commonly needs many monitoring points, so many GNSS receivers are required. The cost of one GNSS receiver is high, so the total cost can be very high. In addition, if the monitoring area is small and the baseline is short, it is difficult to obtain coordinates with high precision.

In recent years, the GeoRobot has been used more often in the field of spatial monitoring. It is very widely used for monitoring buildings and dams. For example, the GeoRobot monitoring system has been successfully applied on the Whuchuan reservoir dam. There it is used for the completely automated monitoring of deformation of the dam exterior [8]. However, a GeoRobot is rarely used for mined ground deformation monitoring, the main reasons being that it is commonly difficult to locate the multiple GeoRobots within sight of each other. A GeoRobot network also has limited surveying scope. The need for station intervisibility means that the GeoRobot station points must be located within the monitoring area or near the area boundary. This means that if the stations must be moved now and then, their coordinates change. The GeoRobots cannot provide absolute coordinates for themselves like GNSS stations can.

The GeoRobot compensates for the inadequacies of the GNSS. Each monitoring point has a fixed reflecting prism as a sighting mark for the GeoRobot. The prisms are much less expensive than GNSS receivers. Therefore, a composite surveying system combining GeoRobots and GNSS has been designed. The basic principles of the surveying system are described below:

Three prism points are used to set up the GNSS receiving antenna. The three prism points are called the coincidence points for the prisms and GNSS receivers. Three GNSS receivers provide stable and high precision coordinates for the GeoRobot station point. The GeoRobot station point may be automatically updated through the three coincidence points. The specific updating procedure is discussed in detail in the literature [9]. The GeoRobot is responsible for automatically scanning the monitoring prism so that all monitoring prism points and the GNSS station points use the same coordinate system. In Fig.1, the GeoRobot is laid out according to the free station method and the GeoRobot station points can be located arbitrarily.

The position of the GeoRobot is flexible and the positions of the prisms can be changed at any time. The surveying system can obtain high precision coordinates with the support of the GNSS; the system has just become more complex than a GeoRobot alone. Now the prisms serve as a sensor nodes and the system can record ground deformation data automatically and online with the support of wireless networks.

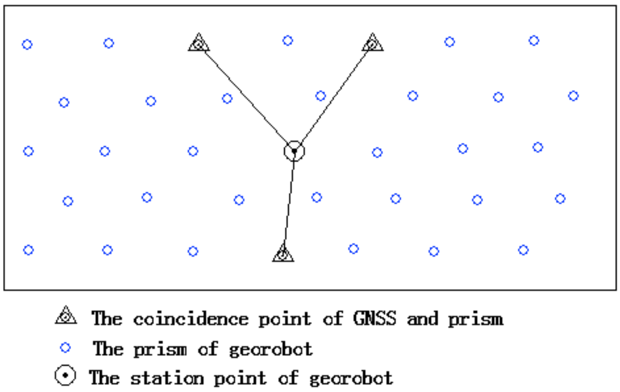


Figure 1. Schematic diagram showing the layout of a GeoRobot and GNSS surveying system

B. *Geosensor networks*

In recent decades, WSN's have influenced the field of geosciences in significant ways. WSN's are a collection of tiny, untethered, battery-powered, low-cost micro-electromechanical devices with limited on-board processing capabilities, storage, and short-range wireless communication links. The networks are based on radio technology and have sensing capabilities based on microsensors and sensor materials [10]. Geosensor networks (GSN) technology, which is largely at the research stage today, will add significant novel capabilities to modern geosciences. So-called GSN are specialized applications of WSN technology in geographic space that detect, monitor, and track environmental phenomena and processes [11].

Figure 2 shows the units that comprise the automated disaster monitoring system described above. There are three basic subsystems in the automated online GSN monitoring system. The first is sensor resources. In Fig.2, The GNSS and the GeoRobot sensors are the subsystem responsible for gathering observation data from the sensors.

Near real-time data collection is another important feature to support time-sensitive environmental studies. This type of data collection requires a convenient yet reliable long-haul wireless communication link [12]. Therefore, the second subsystem is a wireless communication network, the unit responsible for transferring the real-time monitoring data to the data receiving center. In Fig.2, the GNSS and the GeoRobot provide a RS-232 serial cable for data transfer. This cable connects the port of the GNSS receiver and the GeoRobot to a GPRS converter module to convert the RS-232 data stream and initiate the wireless remote data transmission.

The third unit is the energy supply subsystem. Disaster monitoring systems need to be survivable in extreme environmental and weather conditions to enable long-term operation with limited human intervention. This makes energy harvesting and energy efficiency major design considerations. Batteries are the main power sources for the sensors. If the sensor resources require more power, different hardware that can harvest power from the environment such as solar panels can be used to supply power to the sensors and the 12V batteries through charge regulators.

Compared with traditional monitoring methods, automated GSN monitoring systems have two main advantages [13]: 1) They reduce the cost of labor associated with field surveying, and 2) they provide real time or near real-time observational data and automatically send the data. The latter feature avoids unintentional operator errors when recording and transmitting the data.

III. MINE DISASTER MONITORING SYSTEM ARCHITECTURE

A complete disaster monitoring system can not only provide real-time data collection but also achieve highly effective data management and generate valuable precursor data through data analysis. Thus, we propose an online monitoring architecture based on geosensor networks for mine disaster monitoring.

The overall architecture is shown in Fig.3. The architecture consists of a data sensing layer, a data service layer, and an application service layer. The detailed specifications of these three layers are described below.

A. *Data sensing layer*

The data sensing layer obtains periodic or continuous observational data through sensors in the monitoring area. A sensor is the most fundamental unit; a sensor system is an aggregation of sensors, attached to a single platform. A sensor or a sensor system may be abstracted as a sensor resource. A sensor network consists of a number of spatially distributed and communicating sensor resources. Sensor resources are the core of the sensor network, the “front end” of the monitoring system. The type of sensor and its role depend on the type of activity and objects to be monitored. More and more application fields are making use of these technologies. Sensor may be stationary or in motion and can gather data either from their own location or remotely.

The monitoring of geological disasters in mines commonly requires continuous real-time or near real-time observation. Continuous observation data can be transferred to the management department’s local area network (LAN) by mobile communication technology (e.g., GPRS).

B. *Data Service layer*

The data service layer mainly performs data storage, retrieval, [13], and data pre-processing. In general, there are two types of data generated by sensor networks. One is static data, such as data that describes the sensors characteristic information (sensor metadata); the other is the dynamic data, the data gathered by the sensor itself [14].

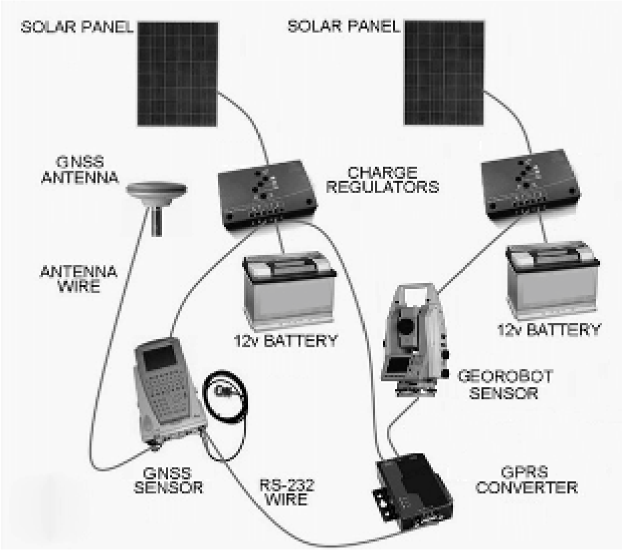


Figure 2. Basic units that comprise a typical automated monitoring system. Sensors that gather the observational data are not shown

The dynamic data is time-series data. Each sensor in the network produces dynamic streaming data in real time. The amount of data increases over time.

It is necessary to manage these data effectively by building a data management system to provide adequate protection and support. Distributed data management systems combined with web service technologies are an ideal solution to data management.

Before storage, the data commonly needs to be extracted from the raw sensor data, parsed, and in some cases have its format converted. All these operations must be performed by the data service layer. Data services installed on one server located at a data center may be able to respond to the requests from the applications through the internet.

C. *Application service layer*

The application service layer is the third important part of the disaster monitoring systems. Depending on the actual need, the application client can be a web client running web applications. In this configuration, the users interact with the data server through web browsers. The client can also be a desktop client running standalone desktop applications. No matter how it is configured, any client needs to connect to the database management system (DBMS) located at a data center through the internet. The client then sends data requests to the data service layer.

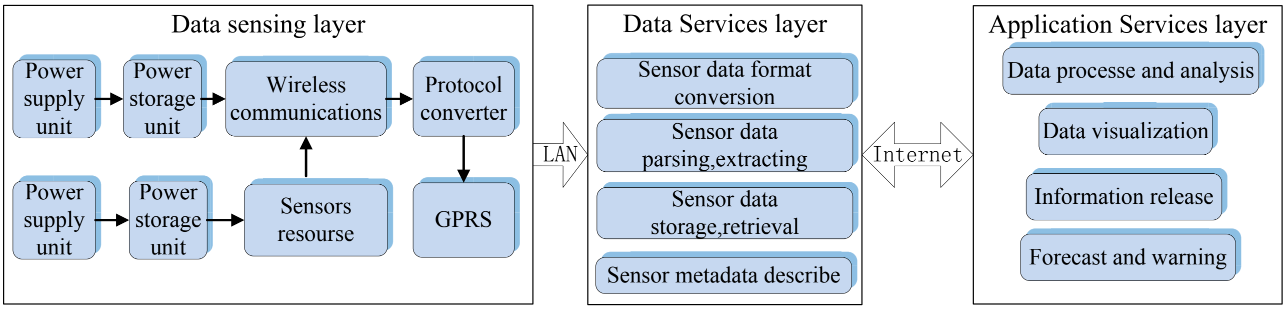


Figure 3. Overview of the mine disaster monitoring system architecture

In practice, through querying and analyzing, the sensor networks data that can effectively monitor the physical world. The application service layer is responsible for processing and analyzing data from the data service layer. The potential disaster may be predicted, forecast, and early warnings sent out based on the data analysis result supported by the client application. To realize the automatic publication of early warning information, an early warning module should be is deployed on the client. When the data processing results exceeds the defined threshold, the warning module will take the initiative and send warning information to the user by SMS or email.

IV. USE CASE: MINE DISASTER MONITORING SYSTEM

A mine disaster monitoring system (MDMS) was installed at a mine in Inner Mongolia. The area monitored is a slope generated by open-pit mining. Monitoring the stability of the different kinds of slopes produced by mining in near real time is very important to mine safety.

The following sections describe this largely self-contained, automatic MDMS that is based on the technology and architecture discussed in in Section II and III.

A. Framework and function of the MDMS

The sensors for this MDMS consist of three GNSS receivers and sixty-five prims of GeoRobot. Figure 4 show the framework and function of the MDMS. A data center receives observation from the sensors through a wireless communication system. Sql Server 2008 software (Microsoft Corporation, Redmond, USA), a relational database management system (DMS), was deployed in the data center to manger the observation data and respond to user request.

The MDMS was completed with a client application that supports GIS components. This function module is mainly responsible for data processing and detailed analysis to identify abnormal phenomena on the slope.

B. Data preprocessing subsystem

Near real-time online data processing is symbolic of a mature application for an automatic monitoring system. To achieve this goal, we developed the corresponding data preprocessing middleware based on sensor data types. Data preprocessing subsystem consists of two different middleware routines.

The format for data from different sensors is not exactly the same. GeoRobot observation data includes distance, horizontal angle, and vertical angle from each of the prisms. The GNSS receives continuous observation data from satellites; these are big data and the data structure is complicated. The DMS does not need to record all the raw data so we may develop middleware to preprocess the raw data. Some sensor manufacturers provide their own data processing middleware. For example, the GeoMos middleware(Leica, Switzerland) was provided by the manufacturers of the GeoRobot. GeoMos software completes angle and distance error processing and also corrects distance measurements for pressure and temperature. Another piece of middleware named GeoGNSS is responsible for parsing and extracting the GNSS observation data, detecting abnormal data [15], and resolving the baseline.

After the raw data are processed, the data are termed intermediate data. The intermediate dataset is considerably smaller. The smaller dataset is then stored to reduce the load on the DMS and to make it easier to transfer the data via the internet when a remote user requests data from the sensor database. Figure 5 shows the data stream from sensor to end user. Observation data and timestamps are passed to the client application for further processing and analysis.

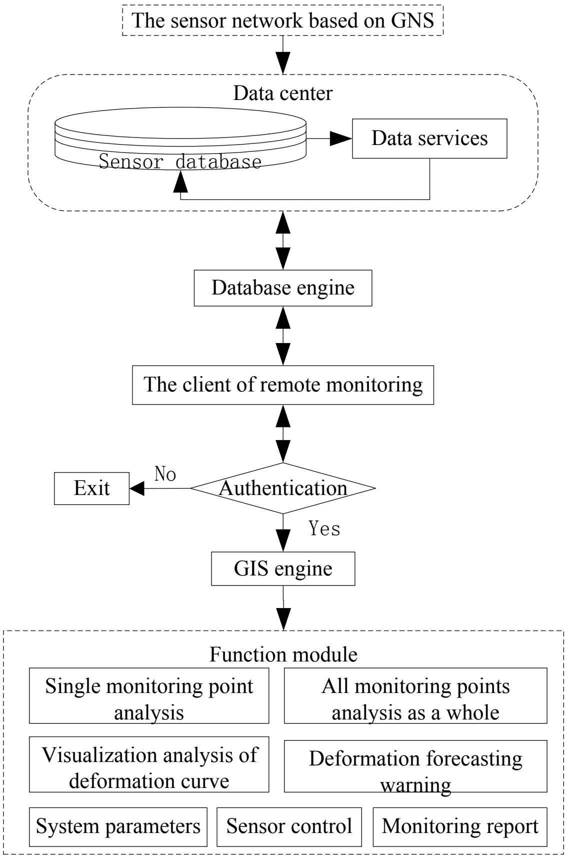


Figure 4. Flow chart showing the framework of the MDMS installed at an open-pit mine in Inner Mongolia

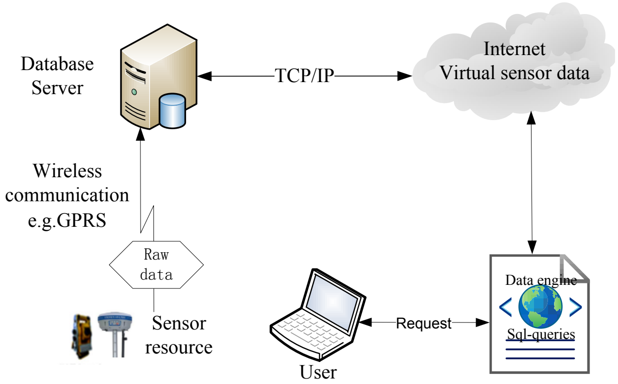


Figure 5. Schematic diagram showing the flow of the data stream from sensor to user (data consumers)

The DMS not only manages the intermediate data but also stores sensor metadata (such as each sensor's unique identification code, type, and parameters). The intermediate data and observation timestamps for every sensor are encapsulated into a new virtual sensor [14, 15] where no physical sensors are available. The data center is considered a virtual sensor network.

C. *Client application*

The client application is the third important part of the MDMS. The client may request intermediate data from DMS at any time. Because the MDMS holds a great variety of complex data, a GIS component was used to allow data visualization with graphics operations such as panning and zooming. To view of the data and the monitoring system targets, the user may choose different data processing models for data analysis. For example, the use may choose to view Kalman filtering [18, 19] or space-time Kriging interpolations [20]. These data processing models are not described in this paper. Figure 6 shows the main interface of the client application for the MDMS. Figure 6(a) shows the selected prisms, Fig.6(b) shows the deformation curves for those prisms, and Fig.6(c) shows a table with the cumulative displacement for every prism.

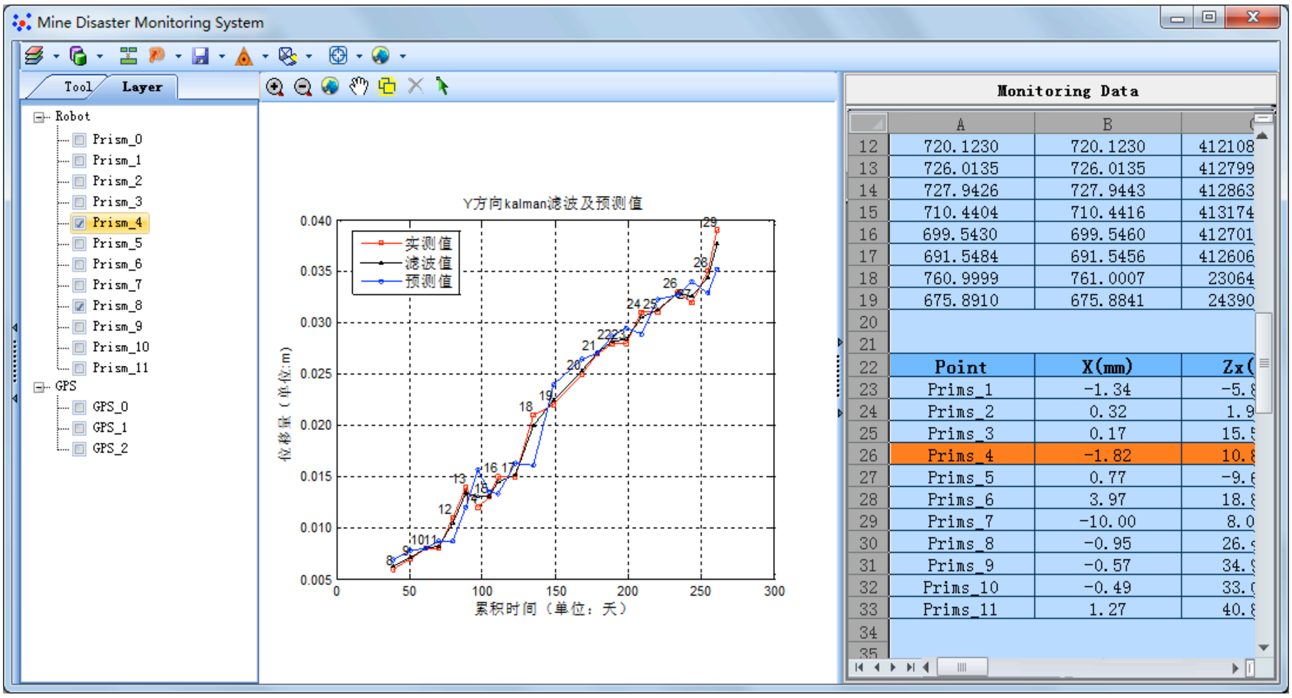
When the MDMS is in operation, if the analysis results exceed pre-defined threshold values, an early warning will be issued. For instance, for the slope being monitored at the mine, the MDMS will send an alert by SMS if three points' coordinates change by more than 20 mm or the elevation changes are more than 3 cm at a certain observation timestamp. These thresholds may be set through the application software.

V. CONCLUSIONS AND OUTLOOK

This paper presents a composite solution, a surveying system combining the advantages of the Global Navigation Satellite System (GNSS) with a total surveying station, a GeoRobot. The composite solution is flexible and convenient. We then describe the components that can be integrated with the composite solution surveying system to form a geosensor network to be used as an automated mine disaster monitoring system(MDMS), a system to monitor ground movements. To make full use the system, we present a three-layer system architecture for seamless integration of the GeoRobot and GNSS sensors. Every layer plays a different role. The data sensing layer controls the network of geosensors distributed in the monitoring area, the data service layer provides data management and finishes the raw data pre-processing, and the application layer finishes the data processing, analysis, and visualization of the data.

To demonstrate the applicability of our proposed system, we installed a remote near real-time online MDMS in an open-pit mine in Inner Mongolia to monitor the stability of a slope. At present, we do not control the sensors on this MDMS but we plan to add that capability in the future. For example, when heavy rain starts to fall, the GeoRobot sensors will be automatically started by a control service. To make this happen, we plan to add weather sensors to the system. In addition, we will update and add new services based on new sensor web technologies [21, 22].

We are also considering configuring the existing MDMS to be an open research infrastructure for use by mine disaster researchers and slope stability engineers who have no access to their own real-time data. A secure web site is being developed. This web site will be available to interested researchers who may obtain near real-time observation data so that they can carry out experimental studies and set up new applications running on their own web sites or desktop clients.



Robot
- ☐ Prism_0
- ☐ Prism_1
- ☐ Prism_2
- ☐ Prism_3
- ☑ Prism_4
- ☐ Prism_5
- ☐ Prism_6
- ☐ Prism_7
- ☑ Prism_8
- ☐ Prism_9
- ☐ Prism_10
- ☐ Prism_11

GPS
- ☐ GPS_0
- ☐ GPS_1
- ☐ GPS_2

	A	B	C
12	720.1230	720.1230	412108
13	726.0135	726.0135	412799
14	727.9426	727.9443	412863
15	710.4404	710.4416	413174
16	699.5430	699.5460	412701
17	691.5484	691.5456	412606
18	760.9999	761.0007	23064
19	675.8910	675.8841	24390
20			
21			
22	Point	X(mm)	Zx(
23	Prims_1	-1.34	-5.
24	Prims_2	0.32	1.9
25	Prims_3	0.17	15.
26	Prims_4	-1.82	10.
27	Prims_5	0.77	-9.
28	Prims_6	3.97	18.
29	Prims_7	-10.00	8.0
30	Prims_8	-0.95	26.
31	Prims_9	-0.57	34.
32	Prims_10	-0.49	33.
33	Prims_11	1.27	40.
34			
35			

Figure 6. Screen shot showing the client application interface for the mine disaster monitoring system software. a) The names of the prisms selected. b) Three deformation curves for the selected prisms.The red curve ,bule curve and black curve shows the measured values ,the predicted values and the filtered value of cumulative displacement, respectively. The horizontal axis is cumulative time(d),and the vertical axis is cumulative displacement.c) Cumulative displacements for the selected prisms.

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