The PLUTO Project: The Concept of a Virtual Tunnel Laboratory in the Experimental Mine 'Barbara'

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ABSTRACT

We have proposed a Virtual Tunnel Laboratory in the Polish Central Mining Institute Experimental Mine 'Barbara.' Mines and tunnels are critical infrastructure. They have unique environments due to their isolation from the surface and the constraints imposed by their surrounding. Mines and tunnels are also subject to unique threats from natural forces, operational and construction accidents and terrorism. Modeling and simulation can play a major role in minimizing the loss of life and catastrophic damage to the infrastructure from incidents such as fires and explosions. These models need to be verified with data from full scale realistic experiments. It is nearly impossible to conduct long-term experiments in an operational tunnel or mine. PLUTO, a web-accessible, virtual tunnel laboratory, capable of supporting a sophisticated sensor network located within 'Barbara,' can provide the ideal testbed for the required experiments.

KEYWORDS: *Virtual Laboratory, Remote Experiments, Underground Laboratory*

INTRODUCTION

Mines and Tunnels have been highly valued for thousands of years [1]. Substantial tunnels date back at least to the 8th Century BCE, when, King Hezekiel of Jerusalem, authorized a (1 m X 2 m) "new tunnel" through 765 feet of solid rock to connect Gihon Springs to cisterns within the city walls [2]. Mines involving tunnels also have long been of critical economic importance. For instance, in 14th century Poland, Wieliczka {"Magnum Sal"} generated over 30% of the Royal income, paying for the great Wawel Castle and the Krakow Academy {Jagiellonian University.[3] By the 16th century, Wieliczka had become one of the largest business enterprises in Europe, employing many hundreds and even had its own "pension plan." Wieliczka has remained important and expanded to 300 km of galleries and 2040 chambers, extending down to 327m.

Tunneling for vehicular or pedestrian transport seems to date from 220 BCE when a narrow tunnel was excavated at the Furlo Gorge for The Flaminian Way. This road runs from Rome north through the Apennine Mountains to the Adriatic coast at Fano. In 76 CE, Emperor Vespasian excavated a 38 m long, larger cross section parallel tunnel.

Chisel marks can still be seen in the rock walls of this tunnel (used by modern traffic).[4] However, transportation tunnels remained short and scarce until 19th century railroads required road-beds with small gradients, and new tunneling technologies involving compressed air, steam, and explosives such as nitroglycerine and dynamite made tunneling more practical (e.g. 6 km Hoosac Tunnel in western Massachusetts) [5].

Tunnels and mines have unique environmental, safety and security requirements
Tunnels and mines behave as unique micro-environments because they are nearly isolated from the general environment. Explosions and gases are confined by the walls, and the climate is isothermal (e.g. 14C, year-round in the Wieliczka mine). Consequently, experiments conducted on the surface will often not apply. Likewise, procedures developed on the surface for fire fighting, rescue or contaminant cleanup may not work well in mines and tunnels. Because of these differences, events that would be minimal on the surface, involving no or small loss of life, can become far more severe underground. This is especially true of fires, where the tunnel confines the heat and toxic combustion products and makes fire-fighting more dangerous and difficult.

This general principle has been long understood. For instance, in 1697 a fire that started in a wooden underground chapel of the Wieliczka salt mine in Poland led the royal commission to forbid the use of inflammable materials in the chapels and in turn resulted in the world renowned rock salt sculpture for which the mine is famous.

Modern examples of this effect include relatively minor vehicle fires (e.g. Chunnel)[6] or their cargo (e.g. Mt. Blanc) [7] that turned into raging infernos. This is a substantial problem, given the number of tunnels in use, and the vast number of vehicles that use them (the I-93 tunnel “Big Dig” in Boston is designed for 245,000 vehicles per day} [8].

In addition to accidents, tunnels face the threat of high explosives (e.g. London Underground) [9] and other attacks (e.g. the Tokyo Sarin attack) [10]. We need to know how to best detect these attacks early, perhaps prevent them, but at least respond to them as rapidly and efficiently as possible to save lives and return the transportation infrastructure to use.

But, one should not lose sight of the normal daily risks amid occasional disasters. In the USA alone, there are about 40 mining fatalities per year (USA NIOSH statistics, 1996-2000), a number which is far smaller than the early to mid 20th Century [11], but still leaves substantial room for improvement. Global fatalities are in the thousands [12]. The mining industry has one of the highest fatality rates of any industry.

These daily risks arise from floods, and geologically induced collapse and a variety of other problems. For coal mines, especially fires as the result of mining operations and their toxic gaseous byproducts such as carbon monoxide are second only to explosions as cause of miner fatalities (e.g. recent Sago West Virginia Mine Accident [13]).

IMPROVED MINE AND TUNNEL SAFETY AND SECURITY THROUGH EXPERIMENT

Many mining accidents could be prevented or mitigated by improved monitoring of the conditions within the mine and the surrounding rock. Similarly, fatalities due to accidental or intentional tunnel incidents can be reduced through development of better sensors, in-place fire fighting apparatus and ventilation systems. Even warning signals and communications for emergency evacuation can be made more effective through more realistic modeling of toxic transport and dispersion. In general, there is substantial scope for safety-related research in mines and tunnels

Assessing risk

There are a number of well developed methodologies for the formal risk assessment of structures, these range from freely available simple tools, such as CARVER2 [14], to highly sophisticated, tools used by the US General Services Administration to analyze blast susceptibility of thousands of buildings and which require extensive training.[15] Most of the core structural analysis models used for blast assessment assumes that the explosion is outside the structure and that the structure is above ground. Clearly, mines and tunnels subjected to internal explosions would be expected to behave differently.

Effective modeling and simulation requires – Ground-Truth for validation

To further reduce mining and tunneling risks, we need to model accidents and rescue/clean-up operations, so that we can learn and make our mistakes in simulations rather than real emergencies. This is especially true for transportation tunnels that are used by tens or hundreds of thousands of people per day. We need enough basic scientific and engineering understanding to quantify the risks to the tunnel and mine infrastructure and to develop appropriate countermeasures and mitigations.

Substantial amounts of data are needed to develop and verify sophisticated modeling tools. Unfortunately, taking an operating, busy tunnel out of service for even a brief time can be highly disruptive to global, national, regional commerce. Thus getting non-ordinary operational data is difficult to impossible, except under real anomalous (aka Crisis) conditions; but then there are invariably more urgent tasks than gathering supporting data, and rare that an experiment is ready to go.

Need for a dedicated TestBed

A facility is needed that can be instrumented for long-term and other data-intensive experiments. Beyond emergency situations, such a facility could lead to reliable models of transport, propagation, etc, that would be useful for improving the normal operation of mines and tunnels. One might expect improved ventilation systems, communications and sensor arrays to monitor conditions and potential threats. What is needed is a mine that can be dedicated to experiments along with support staff to assist researchers and an adaptable, secure, high capacity network infrastructure to allow international researchers to access their and supporting experimental data from remotely conducted experiments.

Poland's Experimental Mine 'Barbara' provides the TestBed solution

Figure 1 shows the entrance shaft to the Experimental Mine 'Barbara', the oldest part of the Central Mining Institute, the leading research organization in mine and industrial explosion safety in Poland, known all over the world. Figure 2 is a map of Poland showing the location of the Central Mining Institute. 'Barbara' is located in Mikolow less than 15 km from the Institute headquarters in Katowice, a big industrial city in south of Poland. Katowice is the center of a region with good transportation (two international airports Katowice and Krakow) and communications infrastructure (a major node on the Krakow to Poznań branch of POL-34/622, the Polish Research and Education Network).

Fig. 1. Mine 'Barbara.' Fig 2. Map of Poland showing Central Mining Institute

'Barbara' has been used for the following types of experiments:

1. investigating coal dust and methane explosions
2. investigating other organic dust explosions, including corn dust
3. testing explosion-proof dams of different thickness and construction
4. testing explosion-proof barriers: dust; water; barriers triggered by detectors
5. demonstrating coal dust explosions along with dust hazard control training

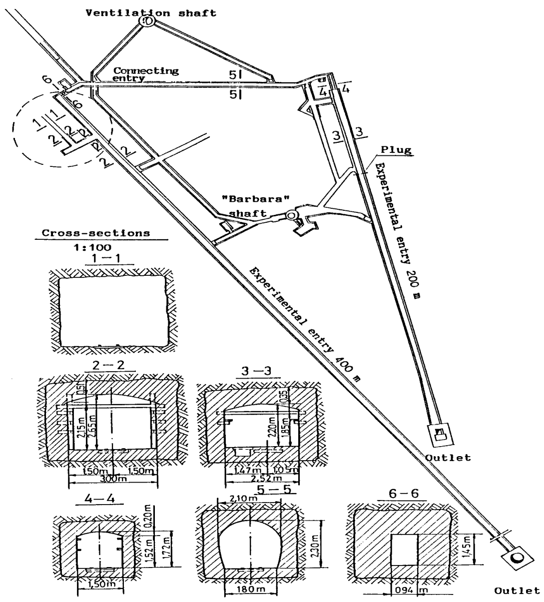
Description of the physical layout of the Experimental Mine 'Barbara'

1. 46 m level underground galleries – see Fig. 3:
    1. Built for explosion experiments , with galleries of concrete (4 and 7,5 sq m cross-sections) able to withstand strong explosions
    2. well supplied with sensors designed for current explosion tests
    3. 400 m long gallery, with a cross section of 7.5 sq m
2. 30 m level underground galleries – see Fig. 4.
    1. Two kilometers of galleries (10 sq m)similar to functioning coal mine
    2. Longest galleries 300 m long.
    3. A large chamber (n) 75 m long and cross section of 18 sq m.
    4. Note: the 30 m level is more suitable for the non-explosive Pluto tests
3. Operational Capabilities and Unique Features
    1. "Barbara" is ideally suited for long-term, non-invasive experiments.
    2. At the moment, in Europe only the Experimental Mine Barbara is a suitable facility to conduct underground tests. Other research facilities like Tremonia in Germany have been or will eventually be closed.
    3. All galleries are supplied with energy, cables to sensors and data storage.
    4. Amount of air supplied can exceed 500 m^3 per minute.

Best uses of 'Barbara': underground facilities best suited to test smoke movement in tunnels or a tunnel network, to test different kinds of sensors

1. Due to reasons of safety and possible damage -massive fires are undesirable – explosions are less devastating being short lived events

2. Simulation of ventilation
3. Smoke movement
4. Testing of different kinds of sensors (eg smoke, presence of explosive or ,toxic gases)
5. Radio communications tests
6. Large scale explosions and small scale fires.



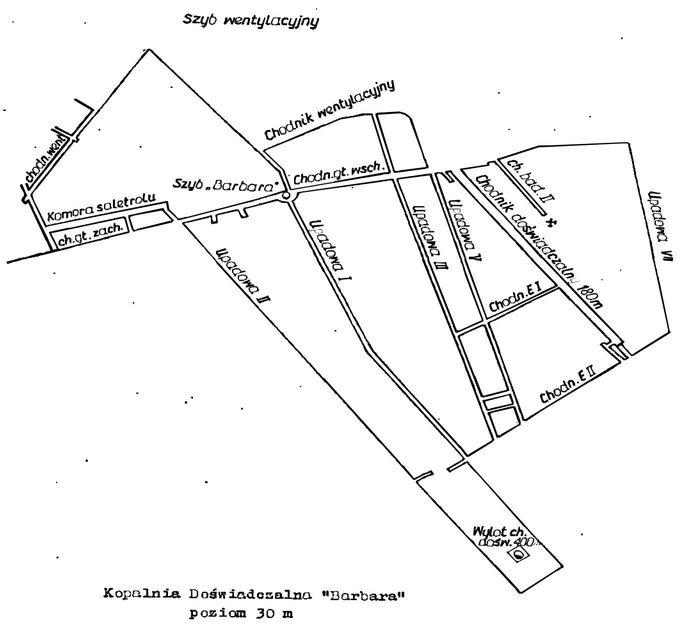


Fig. 3. Plan of Workings at the 46 m level with 400m long 7,5 sq m gallery for explosion tests. Fig 4. Plan of Workings at the 30 m level showing: ventilation shaft.(szyb went.); Main shaft (szyb Barbara); Experimental gallery (chodnik doświadczalny) 180 m long 5m X 1.5m high, concrete gallery; Other workings include: Upadowa (inclined gallery); Chodnik (gallery).

Some recent large scale explosion test data collected and processed is shown in Fig. 5.

PROJECT PLUTO AND ITS ANTECEDENTS

PLUTO concept

Project Pluto {Platform Laboratory for Underground and Tunnel Observations} is a secure and flexible, wide-band, Internet-accessible underground network. Pluto enables maximal value to be extracted from mine and tunnel security and safety-related experiments that could be conducted in the Experimental Mine 'Barbara.' The Pluto network and supporting ancillary facilities are configured to enable a distributed network of sensors, actuators and analytical instrumentation to be installed in the underground experimental galleries and chambers located at several levels.

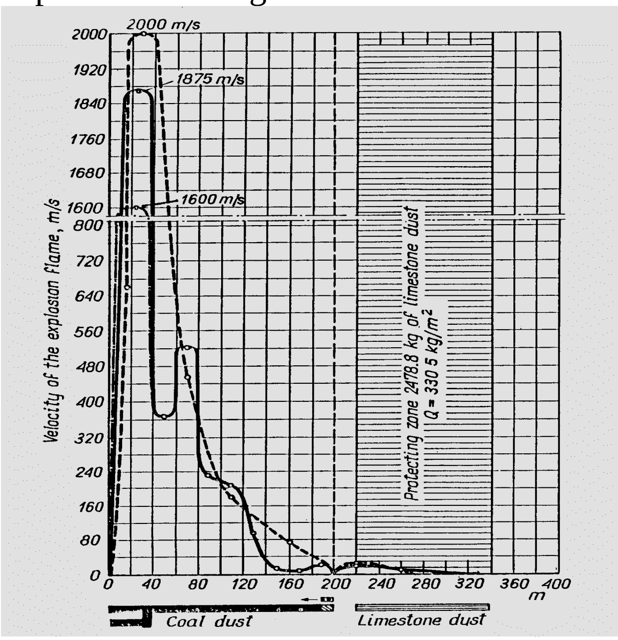


Fig. 5. Example of processed data from recent explosion tests

Antecedents

Project Pluto's spiritual ancestry is NEPTUNE {North-East Pacific Time-series Undersea Networked Experiments}[16], an underwater power and fiber-optic network with major sponsorship by the US the National Oceanographic Partnership Program and National Science Foundation, the Canada Foundation for Innovation and the British Columbia Knowledge Development Fund. NEPTUNE is designed to provide land-based research laboratories and classrooms with high-speed Internet access to real-time data from long-term, as well as transient observations, robotic vehicles and serves as a sensor test-bed.

Neptune participants, who have been developing key technologies such as web services, gridware and the combined power/communications nodes have written, "The ubiquity of the Internet and other communication technologies coupled with the decreasing cost and size, and increasing capability, of diverse sensors and communications systems, is resulting in a major paradigm shift in environmental science and engineering. Increasingly, spatially extended, intelligent, interacting sensor webs are seen as the appropriate tools for studying complex real-world systems. ….These facilities, their real time information flow, and the data repositories associated with them, will empower entirely new approaches to science. In addition, ocean observatories will enable educational-outreach capabilities that can dramatically impact understanding of, and public attitudes toward, the ocean sciences."[17]

PLUTO

Similarly, PLUTO will provide a means for remote users to observe and interact in real-time with transient and long-term experiments being conducted in 'Barbara.' PLUTO provides a means to extend this "new computational science and engineering" concept to the "underworld." Beyond collection of data however is interpretation. Already we can centrally collect data from multiple instruments {see fig. 5, plot of dust explosion} and compare the observations to simple models and theory. More sophisticated analyses and more detailed models will only increase the demand for large multi-sensor data sets.

Pluto is designed to enable critical experiments involving, mine and tunnel safety and security to be carried out in 'Barbara' in Poland and monitored and controlled remotely over a secure web-based access. The data from these experiments can in turn be used to fine-tune simulations of full-scale events in operational mines and tunnels.

PLUTO, just as NEPTUNE should provide a significant educational benefit as well as the research focus. The Central Mining Institute has partnered with a number of Polish universities and technical schools. In the future as Poland becomes more and more part of the research infrastructure of the EU, one can anticipate additional partnering among EU, NATO and other countries with similar interests in mines and tunnels (e.g. L-Surf).

To accomplish its goals, PLUTO will require advanced wideband, real-time-capable data acquisition, wired and wireless networking, high-speed, high-capacity, long-term archiving and sophisticated access control to insure security and safety. In order to implement this concept we have assembled a partnership including:

ISS – Institute of Control Systems -- one of Poland's leading organizations in network information systems, information security, automation systems

University of New Hampshire -- Institute for the Study of Earth, Oceans, and Space

National Infrastructure Institute – Center for Infrastructure Expertise

Central Mining Institute – leading-edge research in; modeling explosions; experimental coal dust, methane explosions; testing explosion-proof dams and explosion-proof barriers dust, training in the field of dust hazard control

Gdansk University of Technology -- Faculty of Electronics, Telecommunications and Informatics -- Department of Geoinformatics

Firut Data Communications, Katowice

The University of Maine -- Department of Computer Science – Ayers Island Homeland Security Lab

Poznań Supercomputing and Networking Center – developers of VLAB [18]

Potential interested parties:

1. Operators of existing major tunnels in EU, USA and Asia including:
    1. Chunnel
    2. Big Dig, MBTA, MTA, METRO, London Underground
    3. Trans Alpine rail and road tunnels
    4. Japanese rail and road tunnels
2. Builders and Designers of new tunnels
3. Operators of existing and planned mines
4. Mine Safety Regulatory Bodies
5. Transportation and other R&D organizations responsible for safety and security including:
    1. John A. Volpe National Transportation Systems Center of US DOT
    2. Swedish Fire Research Center
    3. National Infrastructure Institute (NII) and European Infrastructure Institute (EII)
    6. Infrastructure disaster planning and recovery entities including
    4. FEMA
    5. EU Emergency Management organization

IMPLEMENTING PLUTO

PLUTO links physical experiments in 'Barbara' and associated computational simulations to experimenters and students worldwide. In addition, PLUTO supports limited access to certain elements of from anywhere on the Internet via a public web site.

For example, consider simulating the explosion of a "dirty bomb" within a tunnel or mine. The physical experiment might consist of the detonation within the Explosion Galleries of a small amount of explosive mixed with a short half-life radioisotope. There would be a number of phases of data collection 1) Initial -- transport of the radioisotope by the blast front; 2) Aging -- the radio isotope is spread further by the ventilation system (before it can be shut down) and subsequently by natural ventilation; 3) Clean-up -- a particular clean-up procedure is implemented; 4) Return to "normal operations" -- residual radioactivity maybe further spread by vehicles and ventilation. The data from this experiment could be used to drive the parameters in a computational simulation of the explosion of a "dirty bomb" inside the "Chunnel" and the associated clean-up and return to service. The combined data could be made available to a team developing an improved tunnel wall decontamination solvent. If necessary, further experiments could be designed to ensure that the clean-up procedure was not overly dangerous.

The Implementation of PLUTO involves both hardware and software / web services

Hardware features:

Provides: a capable backbone Mine Network to which analytical-type instruments, sensors, and actuators can be attached through wired (including fiber) and wireless LANs; High capacity Internet connection to the Experimental Archive and global Internet connections to the computational simulations and the end users with their visualization portals. The Mine Network will be segmented gallery by gallery to allow research groups that have specialized requirements to customize their section of the network.

Software / web services:

- Software segmentation of the network with per-segment access control and VPN (virtual private network) support.
- End-user access to data visualization and as appropriate control through portals
- Supervisory portals enabling overall monitoring, experiment control {both physical and computational experiments} and support as required

Hardware components:

- Sensors, Instruments and Actuators with local (within the Mine experimental areas) signal conditioning, data acquisition and storage as required
- Wired and wireless networks within the Mine
- Mine Backbone network – provides both real-time-data and communications
- Archive – hosts database of experimental parameters and data
- Primary Internet Interface
- Local Control Interface
- User's PC's – provide visualization and control access remotely

Software components:

- Local Network Monitoring
- Web services to support remote access
- Network Security

Core requirements [TBD] by consultation with prospective experimenters

Sources of inspiration

- Coastal and deep-ocean cabled observatories such as NEPTUNE, ORION and Martha's Vineyard Coastal Observatory Project, with demonstrated capabilities for supporting diverse equipment with persistent data collection
- MIT Ilab [19] and other remote access to instrumentation demonstrations
- VLAB developed by the Poznań Supercomputing and Networking Center to provide users with: Remote access to complex and expensive laboratory research equipment; User-customized Dynamic Measurement Scenarios; Digital Science Library; Data storage and management; Educational potential; Workgroup collaboration tools [20]

Approach to implementation

- Use Off the shelf hardware and software where ever possible
- Use Open source software and networking where ever possible
- Allow for special requirements to support potential experiments in mine environment
- Provide for adequate security of access to experimental network

DISCUSSION AND CONCLUSION

Since real testing of mines and tunnels is virtually impossible, we have proposed a solution using 'Barbara.' Realization of this concept requires an integrated and collaborative approach founded on NEPTUNE and VLAB. There are significant business issues that need to be addressed and significant opportunities to leverage existing technologies such as Single Engine Biometrics and Pattern Recognition.

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