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Creation of a Live Virtual Reality Model of Mining Environments from Sensor Fusion

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Abstract. This paper describes a generic technology for modeling in real time the various operations of surface mines. Based on various sensor fusion techniques and high-speed network, a virtual reality model of a mine capable of representing not only static infrastructures but also mobile equipment such as trucks and excavators is created. The modeling technique deal with a wide range of sensors such as survey data, satellite pictures, ore concentration, machine condition indicators, video, sound, real-time GPS locator, range sensor, etc. The model created allows for every piece of information to be displayed in context allowing for a better temporal and spatial correlation of events by mine operators, planners, and supervisors. Syncrude, a Canadian mining company located in northern Alberta, is planning to use this technology, not only to understand oil sands mining processes better, but also to give decision-makers better access to the timely, accurate information from the field that they need to make informed decisions.

1 Introduction

One of the goals of this project was to demonstrate that safe, effective and reliable monitoring and control of mine operations can be performed over satellite and terrestrial communication links, including the Internet [Gillett,1999][Lipsett,1998] using models created from various sensors located in a mine. Using this system, supervisors and planners can easily access information from equipment, such as production data and condition monitoring information anywhere around the world. With such a system, a specialist can remotely access data to solve a problem without having to be transported near the mining site, thus saving time and money.

The system uses the NRC Virtualized Reality toolkit developed especially for this type of application. The toolkit is an add-on to the SGI Performer library allowing for the direct connection between sensor data located on the Internet and a graphic action in the VR world. Based on this library, a generic viewer was developed allowing visualization of the multitude of information necessary to create an advance mining information management system.

The live 3D model of the mine used in this system is created from various sensor fusion techniques ranging from photogrammetry to dynamic 3D geometric modeling. This virtual reality model represents not only static infrastructures such as building and underground mine corridor, but also mobile equipment such as trucks and excavators. The modeling technique deal with a wide range of sensors such as survey data, satellite pictures, ore concentration, machine condition indicators, video, sound, real-time GPS locator, range sensor, etc.

Using this virtualized reality system, every piece of information is displayed in context allowing for a better temporal and spatial correlation of events. Syncrude, a Canadian mining company located in northern Alberta, is planning to use this technology, not only to understand oil sands mining processes better, but also to give decision-makers better access to the timely, accurate information from the field that they need to make informed decisions.

In the following sections, we will discuss the different aspects of this system from the point of view of model building, network data communication, sensor systems, system integration, and human factors.

2 Architecture of the System

The system is composed of five main sub-systems (Figure 1 shows a block diagram of the system):

- a modeling station,
- an observer station,
- an operator station,
- a data communication controller,
- an on board remote monitoring sensing system.

Each sub-system is connected via available terrestrial or satellite links possessing various levels of quality and speed over potentially great distances. To achieve this over any distributed system node, whether it is remote equipment, an operator station, or an observer station; the system must be capable of receiving data communications from any other system node in as timely manner as possible. Additionally, given the bandwidth and latency limitations of data communication links over large distances, the system must address the time differences that are inevitable between physical events and the corresponding received data.

The current implementation employs in-house server software using socket communication between the sensing elements and a central server residing on a dedicated PC. In the next version we will use CAVERNSoft [Leigh et al., 1997] from the Electronic Visualization Laboratory at the University of Illinois to form this communication backbone. This basic idea behind CAVERN consists of activating on every computer comprising the system an IRB (Information Request Broker) that create a virtual private network amongst them. Using this software, the interconnection of data communications between network nodes and the sharing of data that is of interest to several nodes is made transparent to the application software.

With this approach, the system interconnections are open and scalable to any number of network node entities. Furthermore, the actual physical layer of the communications network is left open. Data formats for the system are also open and determined by the producers of data.

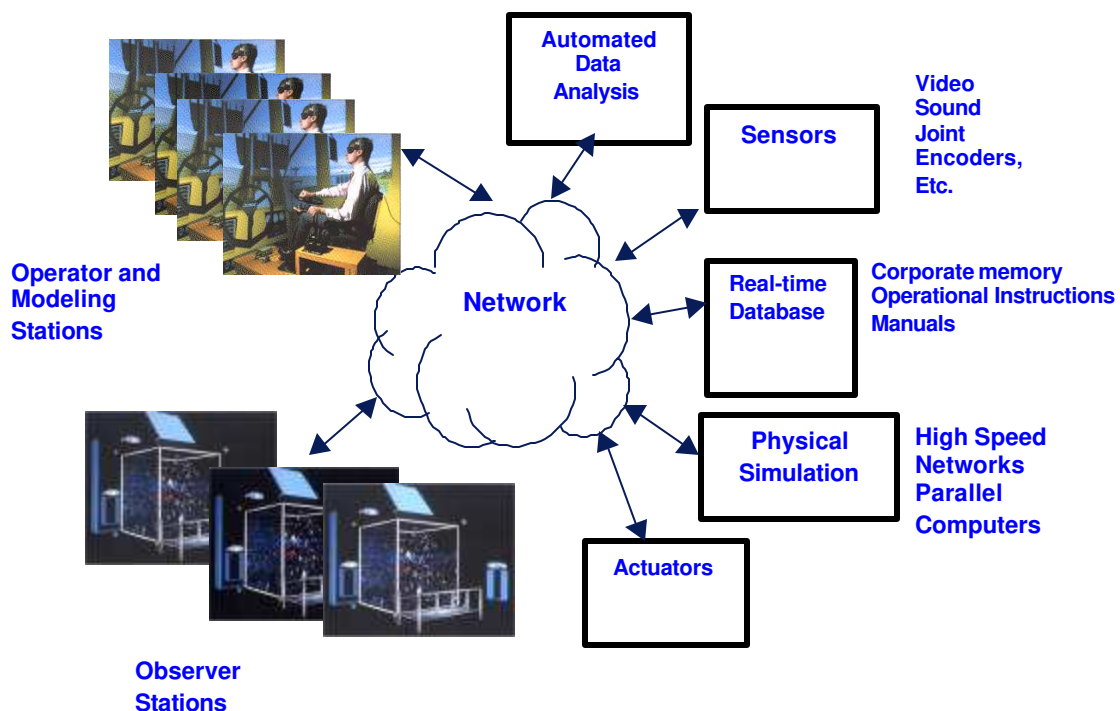


Fig. 1: Block diagram of the system

The data communications networks used in this prototype are based on Internet communication and employ RF data links at the remote work site to tie mobile equipment into the network. In order to vary the

network performance over a wider range for comparison purposes, an additional high-speed link employing a satellite to yield higher data rate communications between the operator station and the work site equipment, was used.

3 Modeling Station

In order to locate information in a geographic information system one must first create a 3D model of the mine terrain and infrastructures as well as dynamic objects populating this terrain such as excavators and trucks. Many techniques are used to create such models but most of these models must follow some basic criteria.

- The model must be accurate.
- The model must be easily interpreted.
- The model must be compatible with VR display systems.
- Each model should have various levels of detail.

The most common representation of a VR model is by the use of a scene graph technique [Wernecke, 1994]. Contrary to a pure geometrical representation where no optimization is possible, a scene graph can be optimized to hide various latencies of the display and communication system. This is because a scene graph is a structured representation of the various relationships between elements of a scene. A scene graph allows for easy propagation of properties along the hierarchy as well as allows the notion of level of details and context switching.

One of the most important and fundamental problems in VR modeling is the selection of the right level of detail (LOD). This requirement comes from a fundamental compromise between display speed and model complexity. By using a well designed scene graph one can hide various latencies such as display speed and communication load using techniques such as geometric and communication LOD and graph culling. This is an important consideration since a complete mine model can be extremely large.

To prepare the various models used in this system a modeling workstation combining various in-house and commercial software was developed. Realax Corporation developed the scene graph editor RxScene used in this project. This editor allows for easy graphic style editing of the scene graph and is truly compatible with the Performer library. In the next section, we will describe the various phases used to prepare the VR mine model.

4 Terrain Modeling

The mine terrain model was created from differential GPS survey data supplied by Syncrude. The precision of the data set was in the order of 20 cm. This is quite good considering the fact that the mine covers an area of approximately 5-km by 5 km. As one can see in Figure 2b, these data come in a relatively sparse form, usually because surveyors follow roads or the edge of a cliff. To transform the sparse data into a useful terrain model, we created a triangle mesh approximating the measured data. In order to do so, we used a 3D Delaunay triangulation algorithm [Edelsbrunner, 1998] implemented in a commercial software called WRAP supplied by Geomagic Inc. The software produced very good results and the resulting terrain model required minimal post-processing.

The second phase of the modeling project was to register a LANDSAT satellite picture against the terrain model (see Figure 2c). Using the road structures as our guide and a projective texture mapping software developed in-house, we were able to manually locate the correspondence between the terrain model and the texture. One can see in Figure 2b the resulting terrain model combining the satellite texture and the survey data. We also experimented with various automated registration algorithms [Weinhaus, 1997] but most of them did not produce results as good as the manual technique. The main reason is that it is hard to detect the same structures between the terrain model and the picture.

The third phase of the terrain modeling process was to add the ore concentration as an overlay. In most mining operations a series of regularly spaced drillings are performed in a rectangular manner over the

region to be excavated. The drillings positions are determined using a differential GPS (DGPS) system in a central mine coordinate system. Each drilling core is then analyzed for bitumen concentration as a function of depth. The resulting data set is a volumetric map of ore concentration. In order to create a color map of the ore concentration for a given terrain condition, a color texture was generated and overlaid over the terrain model. Since each ore concentration datum is not really on a regular volume, an interpolation algorithm was implemented to estimate the ore concentration over a regular volume of size 20 m x 20 m x 20 m. From the resulting structure one can then slice the volume of data to any depth and produce a high-density texture map used to create the overlays. The slicing surface is the terrain model at its current depth. An update of the texture can be performed as new estimates of the terrain shape are computed. One can see in Figure 2a the various layers of the ore data and in Figure 2b the texture map over the terrain model.

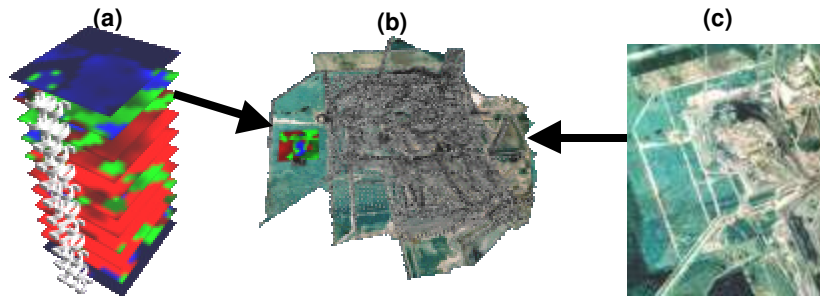


Fig. 2: Model creation process for the north mine model. (a) Ore concentration data, (b) Final model with survey data overlaid, and (c) LANDSAT picture of the region

The last part of the modeling technique consists on optimizing the geometry for VR viewing. Techniques such as dividing the terrain model in smaller sections to optimize the culling process and the transformation of the LANDSAT texture into Clip Texture to minimize the usage of texture memory were used.

5 Modeling Outdoor Infrastructures

In the next phase of model creation, we will describe how to create a 3D representation of the mine infrastructures. In order to start the modeling phase; we first need to get the exact position of the footprint of each building. This is usually performed using the DGPS system. Using this footprint, one can model the building using photogrammetric techniques. Photogrammetric techniques compute the 3D position of a point in an image relative to the camera from two or more pictures taken from different locations. It is beyond the scope of this paper to describe photogrammetric methods in detail. One can refer to the large body of work in this field to get more detailed information [Brown,1976] [ElHakim,1997].

Before any measurement is performed, one must first calibrate the camera to determine all the internal calibration parameters such as pixel size, lens distortions, etc. Once the camera is calibrated, we need to be able to determine from a common point in the image, the orientation of the camera and the 3D position of the points selected. If some of these 3D points correspond to the footprint of the building as measured by the DGPS, a rigid transformation between these points is computed and applied to the rest of the measurements. The resulting data set is in the central coordinate system of the mine and can be easily integrated with the terrain model.

The last phase of the model building process consists of using these measurements to create a series of textured polygons representing the main features of each building. The textures are extracted from the pictures by using a back projection algorithm [El-hakim, 1998]. This is the lengthiest part of the modeling process. If one wants to model a building with a large amount of detail, one has to spend a long time extracting the measurements for each of these features. In this project, we used in-house software called ShapeCapture. In Figure 3, one can see a 3D-textured model of the NRC M50 building created by ShapeCapture software.



Fig. 3: 3D textured model of NRC building created by ShapeCapture.

6 Modeling Equipment

So far, we only dealt with the static part of the model. However, we also need to model the equipment. Contrary to the static part of the model such as the terrain or the infrastructure which do not have any dynamic section, the equipment models must have moving sections that need to be actuated.

One technique to model such systems is to start from a drawing and use an advanced modeling software such as 3D Studio MAX to build a geometric representation of the equipment, i.e., model separately, every moving parts. Once each moving part of the equipment is built, we can then connect them topologically by using a scene graph technique. One can see in Figure 4 the 3D model of the Hitachi EX200 excavator used in these experiments and in Figure 5 a section of the scene graph representing the model.

A complete kinematics model of the excavator has been developed, allowing a fully articulated model that can be controlled and animated by data coming from either a control device (a joystick here) or from sensor data measured from the real excavator (joints positions sensors in this case). The animation is performed by associating to each moving joint a dynamic coordinate system that is connected virtually to a sensor. Using this technique, we had to create many new scene graph nodes to accommodate all sorts of new functions. Using this technique one can replace the texture of a polygon by video images coming from an active video camera called REMCAM located on the network, or change the color of a hydraulic actuator as a function of its pressure. In fact, one can map any sensor to any property defined in the scene graph as long as a transfer function is supplied. Added to the excavator model were also hot points allowing for data queries and the activation of video clips or the replay of engine sounds. The system can also allow data browsing through the drawing of the excavator or display maintenance reports. All these functions were also represented as part of the excavator scene graph.

7 Observer and Operator Stations

The benefit of this system for surface mining is that personnel can observe, and in real-time, the status and productivity of equipment, thus providing greater awareness about the ongoing mine activities. The observer station is a prototype version of a display environment in which mine information (payload, machine condition, and other parameters) is shown in the context of the equipment modeled in the virtual environment. An observer can look at the location of a fleet of mobile equipment within a global world model to observe overall mine operations, or zoom in on a specific on-board system, such as an engine. Sound bites and video clips are incorporated to add to reality of the visualization. From the hardware point-of-view the observer station is composed of a large back-projected screen system of 8' x 10' in dimension. The projector is an Electrohome 9500LC producing an image with SXGA resolution at 260 lumens. An Infinite Reality Engine refreshes the stereo images of the virtual environment every 1/10 of a second. Linked to this graphic supercomputer is a local high-speed network connecting various PC computers in charge of sound, communication, video, and user interface.

A lot of attention has been given to the design of the user interface (UI), since it is a key factor when

comes time to evaluate the usefulness of a product. The design criteria used here are the ease of use and the ease of learning. For that purpose, we developed a keyboardless, two-handed UI that combines a mouse and a three DOF joystick that are used in parallel.

Two mutually exclusive operator modes (monitoring and control) are possible and can be selected by using the mouse. In the monitoring mode, the joystick is used to navigate in the environment while the mouse is used to display information about the instrumented machines by clicking on specific parts of them. The clickable parts are highlighted to indicate their function when they are brushed by the mouse, i.e. when the mouse cursor is over them, as illustrated in Figure 4 (virtual query system). The highlighting style indicates the function of the object, which can be either to query and display information about it (sensor information or others), or to toggle between the monitoring and the control mode. Also, in the monitoring mode, the pose of the trucks and the excavator are displayed by placing the avatars in the same pose as the real ones.

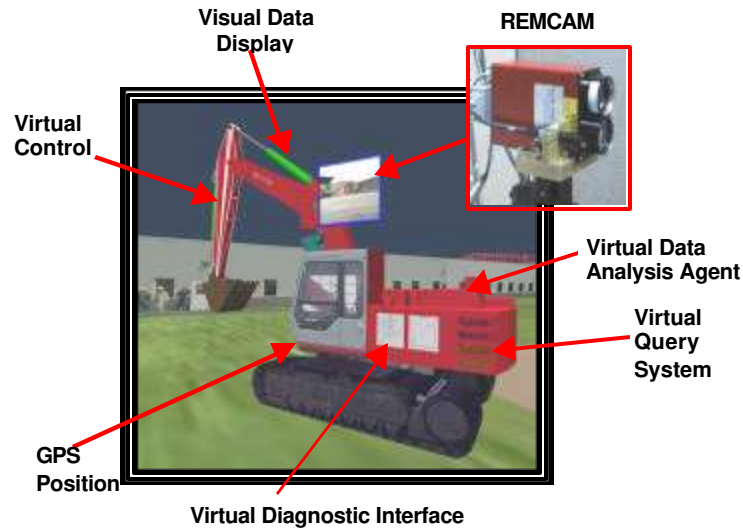


Fig. 4: Virtual Avatar of the Hitachi EX200 excavator

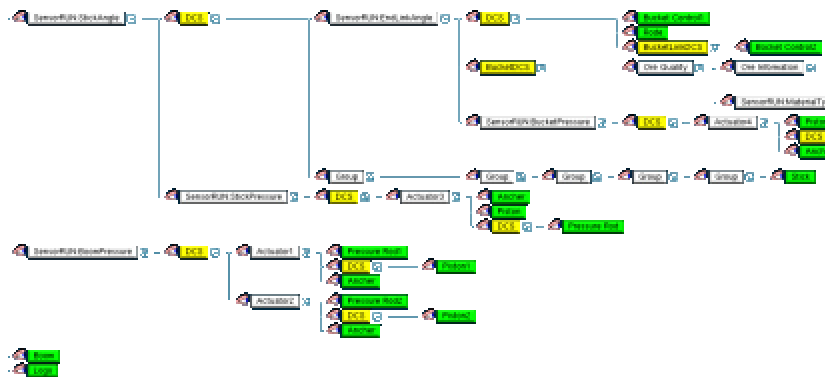


Fig. 5: Section of the scene graph representing the excavator

In the control mode, the joystick is used for the rate control of the virtual excavator joints in either joint or coordinated control mode [Withney, 1969]. The operator chooses the type of control mode (joint or coordinated) by clicking on a different mouse button. The coordinated control mode allows the direct control of the bucket motion instead of having to coordinate the movement of each separate joint of the excavator. It has been implemented in order to help novice users for the control of the excavator since it has been shown that this control mode significantly improves their initial performance compared to the traditional joint control [Lapointe, 1999]. Once that the virtual excavator is positioned correctly, the operator push the joystick's trigger to transmit joints positions of the virtual excavator through the network

to the real excavator. The real excavator then uses a local position controller to position itself accordingly to the virtual excavator pose, before sending back an acknowledgement signal to the operator station. It is important to note that both the monitoring and control mode require a calibration of the virtual world with the real one.

9 Data communication controller

In complex and distributed systems such as the one developed here, the management of the communication infrastructure becomes critical for initialization, maintenance, and failsafe performance of the system. Within the virtual private network, the current system prototyped here employs a network bulletin board implementation which all network nodes use to post their latest status. In this way, any node that requires data from other nodes can check their status using the bulletin board and thereby avoid the bandwidth overhead associated with the use of embedded heartbeat data and regular dedicated heartbeat packets.

The processing of all the incoming data from the mine site also required the development of a central local communication controller that is exclusively used by the observer station. This controller is in charge of data synchronization, logging operation, dealing with obsolescence, data validity, formatting, firewall, and allow to separate display from communication issues.

9.1 On-board remote monitoring sensing system

The remote equipment system for the Hitachi EX200 excavator was retrofitted with remote-control capabilities using their CAN-networked Genie II controllers and a number of sensors installed to provide condition indicators for overall machine health monitoring. The sensors are used to measure hydraulic pressure, joint angles, motor speed, temperature, position from GPS, etc. One particular sensor monitors the acoustic characteristics of various portions of the machine using an acoustic anomaly detection function. This sensing function also samples audio segments for playback at the observer station. A digital camera returns up-to-date images of the workspace and a laser range is used to create local terrain model. These two imaging sensors are mounted on a remotely controlled pan-tilt unit. Using this REMCAM system (see Figure 4), video images can be texture-mapped onto polygonal surfaces measured by the time-of-flight range sensor.

Local control of the machine is accomplished with a local version of a script executor called PACE from Dynacom. This script executor issues commands to the robot control computer (RCC). The RCC communicates via a CAN bus to drive the Genie II controllers and collect machine sensor data for networked transmission back to the observer stations.

Communication between this mobile equipment and the internet-based data communication network can use in-house radio modems or digital cellular telephone modems. The RCC also gathers machine status and sensor data for trending and performance evaluation, by using wireless Ethernet modems for data transmission between the machine and local area network hardware.

10 Conclusion

This prototype system demonstrates that by using a combination of high-speed network, virtual reality displays, and advanced sensor technology, one can create a tool that will help decision-makers make informed decisions on the daily operations of a complex industrial site. This technology however is only at its early stage and many research challenges must be solved before such a system becomes fully operational in a mine.

One of these research challenges will be in the collection and transmission of data from a large fleet of mobile mining machines distributed over a large territory. For a large operation, each piece of equipment should transmit their current location and all vital data necessary for maintenance and process optimization through wireless communication. In the mine of the future, there will be a need to develop

advanced wireless communication networks capable of dealing with this mass of information.

The second challenge is the collection and modeling of the current information available on the site. The next generation of virtualized reality systems should be able to connect to existing databases and should automatically extract the pertinent information in a form that is compatible with its internal representation.

The third challenge consists of developing new algorithms capable of automatically updating the central model from new knowledge about the site. For example:

- update of the terrain model as a function of digging from multiple-sources,
- addition of new equipment,
- correction and validation of information,
- addition and registration of various sensing modalities: ex: infrared sensor + range sensor.

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