# An Inspection and Surveying System For Vertical Shafts

**Jared LeCras[1], Jonathan Paxman[1], Brad Saracik[1], Andrew Jarosz[2]**
**[1]Curtin University of Technology**
**Department of Mechanical Engineering**
**Bentley, Western Australia**
**[2]Western Australian School of Mines**
**Kalgoorlie, Western Australia**
***Email contact:* j.paxman@curtin.edu.au**

## Abstract

Underground mining operations usually require a number of vertical (or near vertical) shafts to allow movement of rock (ore) or air (ventilation) between different levels within a mine. In most cases such shafts are not easily and safely accessible for surveying and inspection. A reliable and safe method of shaft monitoring is required. The Vertical Opening Inspection System (VOIS) provides a solution to this problem, incorporating cameras, laser range sensors (LIDAR) and inertial sensors within a robust enclosure deployable via winch and cable.

This paper discusses the development of a second prototype (VOIS mk II), survey results from the first prototype (VOIS mk I), and plans for future work in the surveying of more general spaces within underground mines.

## 1 Introduction

The inspection of vertical shafts has posed difficulties for mining companies for a number of years. Ore passes are a particular concern, since the passage of rock through such shafts, and the impact of the surrounding stress-strain field result in the rapid erosion of shaft walls. Eroded shafts pose significant risks to continuity of mining operations, through the potential for unpredicted collapse of shaft walls. The need for a robust and accurate surveying and inspection tool is very clear.

The concept of the Vertical Opening Inspection System (VOIS) is very simple, and developed naturally from early crude attempts at shaft inspection which essentially involved deploying cameras into vertical shafts via winch. The system consists of a sensor payload (or pod) which is deployed down a shaft via a winch and cable, and a monitoring station at the top of the shaft, which displays data from the pod in real time as required and records the cable deployment via an optical encoder. The pod incorporates cameras for inspection of the shaft walls in a 360 degree arc; laser range sensors to precisely survey the cross section of the shaft as the pod is lowered; inertial sensors to facilitate estimation of the pose of the pod (particularly yaw); a computer to manage the sensor payload and log data; and supporting systems for power, control and communications.

This paper introduces the overall design concept of the Vertical Opening Inspection System, and gives a brief overview of the first prototype (VOIS mk I), which was used to successfully survey ore passes in the Perseverence mine in Leinster, Western Australia, and the Grasberg mine in West Papua, Indonesia. We also give an overview of the development of the second prototype (VOIS mk II). Future plans include the integration of the VOIS sensor payload with intelligent navigation and locomotion systems to enable the autonomous or semi-autonomous inspection and surveying of more general spaces in underground mining environments.

## 2 VOIS Mark I (first prototype)

The basic VOIS concept involves three major components:

1) deployment system
2) data sensing system (pod)
3) data collection and monitoring system

The deployment system for the first prototype (VOIS mk I) consisted of a winch and a hydraulic crane mounted to a modified light vehicle. The sensing system contained: power supply, communication systems, inertial measurement unit (IMU), stabilisation system (inertial gyroscope), video system and a laser range sensor (or LIDAR). A robust portable computer was used for system control and data collection.

An Auslog winch was selected as the main component of the deployment system. The winch was modified to include

1) a microprocessor controlled counter for indication of depth
2) slip rings to allow electrical and data connections to the rotating cable drum
3) data communication system
4) control pendant for winch drive

One kilometre of four-conductor steel armoured wire line was spooled onto the winch with a cable drum total capacity of 2 km. . A diagram illustrating the winch components is shown in Figure 1. A commercial hydraulic crane (Kevrek 700) was also acquired for pod positioning during deployment

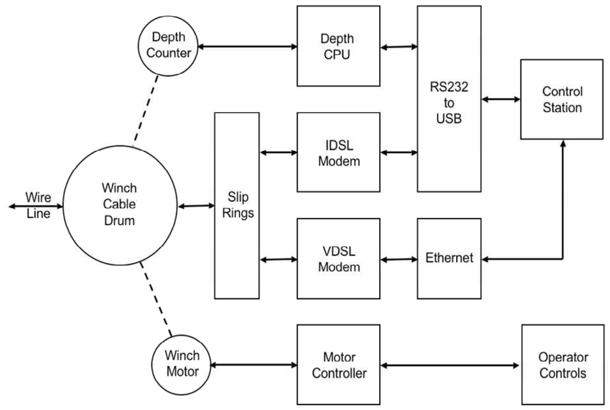


**Figure 1: Deployment and monitoring systems**

The pod system was comprised of four major subsystems, namely:

1) Data Communications and Power Control
2) Gyro Stabilisation and Motion Data Collection System
3) Digital Video Capture and Control
4) Laser Scan Data Capture and Control

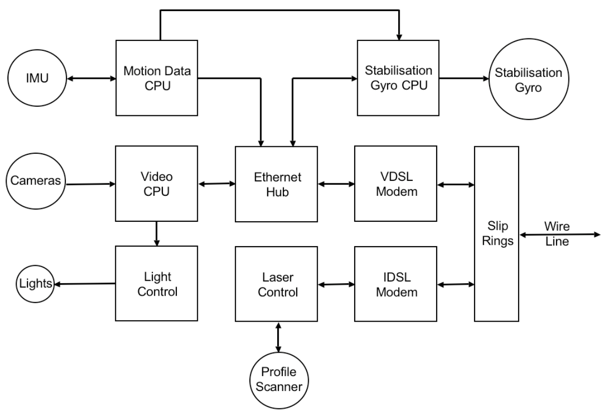


**Figure 2: Data sensing system (pod)**

The pod incorporated several embedded sub-processors to provide distributed control of the various functions as shown in Figure 2. The distributed processing allowed rapid independent development of the pod component systems. Standardised communications links (IEEE 1394, RS232, USB, and Ethernet) were leveraged to link the sub processors together into a fully functional system.

Testing of the initial system revealed that the pod underwent significant rotation when it was raised or lowered into a shaft. This issue was initially addressed by replacing the existing polyurethane coated Kevlar cable with a counter wound sheath wire line cable. This replacement significantly reduced the rate of rotation, but did not sufficiently eliminate the problem. A further reduction of pod rotation was achieved by incorporating a spinning inertial gyroscope (Kenyon KS-6) originally designed for stabilisation of cameras in film industry. To further improve pod rotational stability, a rotating coupling was constructed to allow unwinding of the suspension cable and to reduce imparting of torsional forces on the pod causing axial rotation. The coupling also required a slip ring assembly to maintain electrical connections between pod and cable.

The development of the first prototype (VOIS mk I) is discussed in more detail in [Langdon 2007, Jarosz 2008].

## 3 Initial Surveys

After successful completion of field tests in Kalgoorlie and at the Perseverence mine in Leinster, Western Australia, the equipment (winch and pod) was shipped to Grasberg Mine in Irian Jaya (West Papua), Indonesia. The system was deployed to inspect and survey four active ore passes. The Grasberg ore passes were characterised by a diameter of 3.1 – 5.5m and depths of up to 650m.

The mine manufactured a boom and a winch mounting plate for deployment of the system. The complete system was designed to fit into a loader LHD bucket. The pod was deployed through the open door of an ore pass hopper using a “tag” line to pull it up against the bottom of the boom. When inserted it was lowered down. Once the pod was deployed the LHD bucket was lowered to a stable position with the ore pass door left open.

The initial position (orientation) of the pod was surveyed, recording the position of the wireline and a laser spot projected radially from the top of the suspended pod. This manual calibration was repeated again at the completion of the ore pass survey, enabling the compensation for a drift in the estimation of yaw angle provided by the IMU.

During the ore-pass surveys the control computer collected and logged the following datasets:

- timestamped images produced by each of the five side facing cameras
- cable payout data starting from the top of an ore-pass (from the initial position of the pod as defined by the initial calibration procedure)
- the pod’s orientation (referred to the initial calibrated orientation of the pod)
- laser data in the form of radial distances measured to ore pass walls, with a one-degree horizontal resolution

The data was postprocessed to generate models in Surpac string format. This data format enables compatibility with mine design packages including Surpac Vision, Vulcan3D and Datamine Studio. The processing capabilities of these packages can be used by mine engineers to further manipulate the survey results into required formats: 3D models, point clouds, wire frames, solids and cross-sections.

Figure 3 shows the rendered survey from the Grasberg mine. Figure 4 shows the rendered results of two shafts surveyed twice at the Perseverence mine in Leinster. The rendered solids show the surveyed shafts at the time of the first survey, while the wire-frames show the shafts at the time of the second survey taken seven months later. The results show a very significant degree of erosion in both shafts.

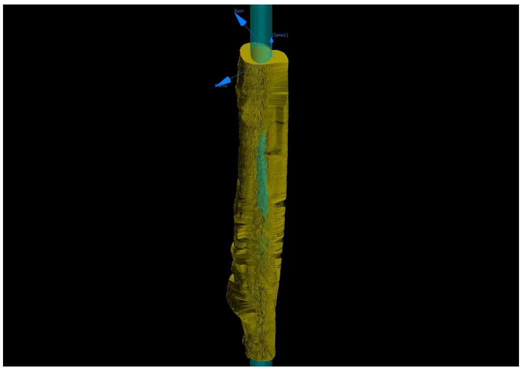

**Figure 3: Rendered survey from Grasberg mine**

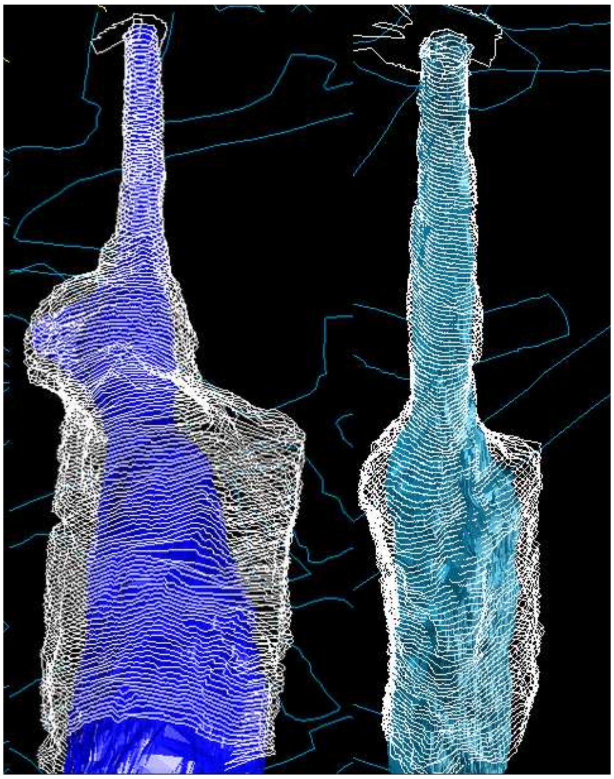

**Figure 4: Rendered surveys from Perseverence mine**

## 4 VOIS Mark II (second prototype) system development

An iterative development strategy coupled with readily available component selection COTS (Commercial off-the-shelf) was adopted during the design of both prototypes. Complete OEM (Original Engineering Manufacturer) assemblies were selected to meet the requirement of each sub system, such as inertial gyro stabilisation, IMU, 2D laser range finders and FireWire video cameras.

The VOIS mk II pod incorporates several design and component improvements over the original design. One goal of the version II design was to reduce size and weight of the package such that it could be transported more readily on standard air services. Key design changes are described in detail in the following sections.

### 4.1 Modular Design

The VOIS mk I pod had a diameter of 250mm and a length of 1.60m which posed some difficulties for air transportation. The single piece rigid frame also made upgrading or replacement of individual components rather difficult.

For VOIS mk II, a modular design approach was taken for the pod construction. Each functional unit is housed within its own module. A common power and communications bus runs down the length of the pod, and adjacent modules are connected together with common mechanical and electrical interfaces. This approach allows for modules to be removed or replaced seamlessly, and also for the order of modules within the pod to be changed if necessary. The only constraint on module order is that the power and communication module must be at the top of the pod, and the camera module must be at the bottom. It is usually preferred for the laser module to be adjacent to the camera module, in order that image textures can be accurately associated with the laser metric data.

The modular pod, with a diameter of 212mm and assembled length of 1120mm (shown in exploded form in figure 5) can be separated for transportation in flight cases. On-site assembly can be achieved with a single tool in less than five minutes. The assembled pod is sealed with a waterproof rubber cover prior to deployment.

### 4.2 Power Consumption

By far the most significant factor in the power budget of the mk I pod were the ten 20W halogen lights (4000 lumens total luminous flux) used to illuminate the shaft. The mark II pod used instead 20 Luxeon Rebel-Star LED modules with total power consumption of approximately 100W and luminous flux of 10800 lumens. The luminous efficacy of these lights is among the most power efficient available commercially, at over 100 lumens per Watt.

A further significant power saving was achieved through the replacement of the 36W SICK LD laser sensor with two Hokuyo UTM-30LX sensors consuming a total of 17W.

The power savings in the mk II pod enabled the entire pod to be powered by three very compact 20 cell NiMH battery packs instead of the heavy Lead-acid batteries used in the mk I pod, while maintaining similar running times in excess of 30 minutes.

### 4.3 Pod Weight

Significant weight savings were achieved in the design of the mk II pod. This was due to four main factors:

- Replacement of Lead-acid gel batteries with compact NiMH pack, possible due to significant power savings achieved in the revised design.
- The use of aluminium as the primary material for the frame construction.
- Replacement of the SICK LD (weighing over 4kg) with the two compact and lightweight Hokuyo UTM-30LX sensors weighing 200g each.
- Use of a flexible rubber outer cover instead of heavier solid alternatives.

The assembled mk II pod now weighs approximately

20kg, compared to the 45kg mk I pod.

### 4.4 Wireless Communication

Communication between the pod and the control station was achieved in the mk I version of the system through a four-conductor steel wireline. This necessitated the transportation of a custom winch to the survey site at substantially higher cost. The mk II pod was designed around a wireless communication concept. To achieve this, high gain panel antennas (12 and 17dBi) were employed, along with high power transceivers (and further signal amplification if required). The wireless communication system was tested on the surface to a distance of 1km, and in an underground decline in the Mount Charlotte (KPMG) mine, Kalgoorlie to a distance of 850m, maintaining a constant data rate in excess of 100 kilobytes per second.

Removing the need for data cable also enabled the removal of the slip ring assembly. For the mk II pod this was replaced by a modified industrial swivel with O-ring removed to minimise friction.

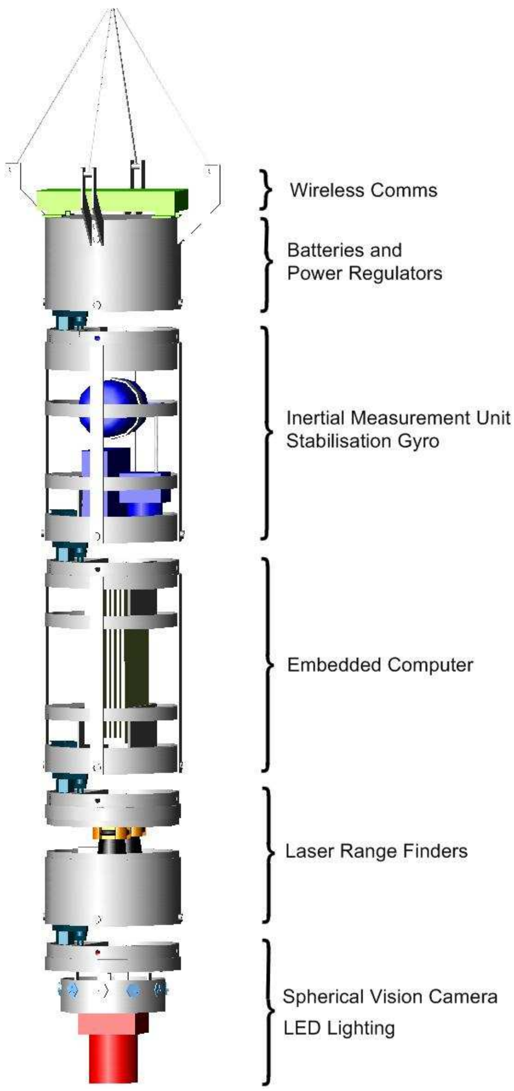


**Figure 5: Exploded view of mark II pod**

## 5 VOIS Mark II Components

The pod system is divided into five major components, namely:

- Data communications and power control
- Gyro stabilisation and motion data collection system
- Central processing and data storage
- Laser scan data capture and control
- Digital video capture and Lighting

Each pod component is completely modular and self contained, allowing the pod to be simplified or enhanced as the task specifies.

### 5.1 Data Communications and Power

Communication between the pod and monitoring system is achieved via a line-of-sight 802.11g network, aided by a 12dBi panel antenna on the pod and a 17dBi antenna on the surface.

The pod is powered by three 20 cell NiMH battery packs, with regulated 12V lines for the laser sensors and Kenyon gyro.

### 5.2 Central Processing and Data Storage

An embedded computer is used for central processing and data storage. Timestamped data from the IMU, spherical camera and laser range finders are received by the computer and stored to the solid state drive.

### 5.3 Gyro Stabilisation and Motion Data

The Z-axis rotation of the pod is stabilised using an inertial spinning mass gyro used for film camera stabilisation. The commercial Kenyon KS-6 gyro is mounted in the centre of the pod. Pod orientation is estimated by an Xsens MTi mounted above the stabilisation gyro. The timestamped inertial data is logged to the embedded computer via USB, and stored for post processing.

The Xsens unit contains MEMS (micro electrical-mechanical systems) accelerometers, gyroscopes and magnetometers, and produces pose estimates via an embedded Kalman filter. Magnetic data is not currently used for the pose estimate of the VOIS pod, since we cannot be certain of the variation of magnetic field with depth.

The orientation of the pod is precisely measured before and after each survey, allowing the drift of the yaw angle to be estimated and corrected in post processing.

The Xsens unit may be replaced by a laser ring gyroscope in future versions of the pod, dramatically reducing gyroscopic drift and consequently improving the accuracy of the pose estimate.

### 5.4 Laser Scan Data Capture and Control

Laser scanning is accomplished by two Hokuyo UTM-30LX 2D laser range finders each with a field of vision of 270˚, together covering the full 360˚ view required. These lasers scan at a rate of 40Hz and timestamp the data before sending via USB to the embedded computer for storage.

Laser points are accurate to approximately +/-50mm at ranges up to 10m.

Some difficulties can be encountered when there is substantial moisture inside a shaft to be surveyed. The passage of air in ore passes can cause a fog to develop inside shafts in humid climates, which may prevent the lasers from correctly registering the shaft walls. If this occurs, it is necessary to temporarily block the bottom of the shaft with a "plug" of ore. Experience has shown that fog usually dissipates within 30 minutes of blocking the pass.

### 5.5 Digital Video Capture and Lighting

Video images are collected using a Point Grey Research Ladybug 2 spherical vision camera. This unit contains six 0.8 megapixel cameras in a fixed calibrated enclosure, covering at least 60% of the full sphere. The Ladybug is mounted at the bottom of the VOIS pod, such that one camera is pointed in the "forward" direction (down the shaft) and five are pointed at the shaft wall, covering the full 360º perimeter of the pod.

The image from the forward facing camera is streamed to the monitoring station on the surface, and is primarily used to ensure that the pod does not collide with unexpected obstacles in the shaft. The images from the side facing cameras are logged for inspection of the ore pass and for final model rendering. Camera power and communications are handled via an IEEE 1394 (FireWire) bus to the embedded computer. 20 Luxeon Rebel Star LED modules producing 540 lumens each are used to illuminate the cavity during the survey. Compressed and timestamped images are logged at a rate of approximately three frames per second.

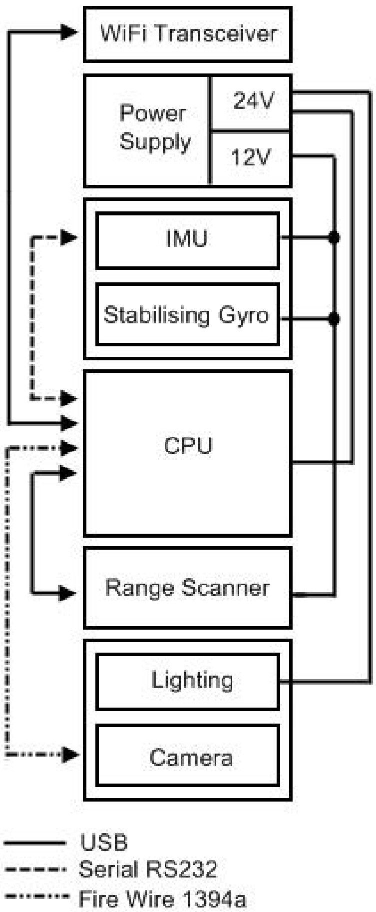


**Figure 6: Data sensing system (pod)**

### 5.6 Software

Data logging and streaming is accomplished via the open source Player/Stage system [Gerkey 2003]. A Player server running on the pod embedded computer logs the laser, image and IMU data using custom drivers. The forward facing camera and current laser scan are streamed to the monitoring station at a reduced frame rate sufficient for monitoring the current position of the pod.

A custom GUI on the monitoring station displays camera and laser data along with depth and orientation, and facilitates basic control over elements of the pod including the lighting and spinning gyro.

**Figure 7: Assembled pod**

## 6 Future Work

The work discussed in this paper is a first step towards an autonomous survey tool suitable for general underground mining environments. VOIS was selected as a starting point due to the simple motion required. The two degrees of freedom (one translational and one rotational) can be accurately measured and recorded allowing each 2D laser scan to have a precisely known origin. Registration of these scans into an overall model is then a straight forward process using standard mine surveying software.
The challenge is to extend this concept to six degrees of freedom (three translational and three rotational). The

research proposed by our group involves the development of sensor fusing algorithms capable of producing empirical 3D maps of extensive environments. High accuracy, large scale 3D maps are vital to the mining industry for tasks including mine planning management, equipment navigation and monitoring of mine safety.

### 6.1 State of Industry

Current technology in this field is capable of producing high fidelity scans from a single point of origin, but has difficulty in generating a coherent integrated map from multiple points of origin. Registering these scans to produce large scale models is a post processing task that requires the exact position of each scan origin to be precisely measured, usually through the use of survey equipment. This time consuming process prevents the mapping of dynamic, dangerous or distant environments and requires excessive, highly trained human resources.

### 6.2 Proposed Research

The proposed research will focus on the automation of the 3D scan registration process by producing a sensor payload that scans and registers the acquired data to produce fully rendered, large scale 3D models. Through the use of 3D laser scanners, pieces of the overall model are created. These pieces are then combined through the use of feature extraction and matching algorithms to register the individual scans. The starting point for the scan registration process is provided by a single camera simultaneous localisation and mapping (SLAM) system that tracks movement between scans resulting in a known scan location. The result will be a high accuracy, large scale, empirical 3D model that is also rendered using the camera frames recorded between scans.

There are additional benefits of producing a hybrid range-and-bearing and bearing-only Simultaneous Localisation and Mapping (SLAM) platform for surveying. An autonomous or semi-autonomous mobile surveying platform will need real time localisation between scans. Single camera bearing-only SLAM can be computed at the frame rate of the camera, producing low accuracy, but real time, results. Alternatively, 3D laser SLAM produces high accuracy results but only when it intermittently collects data. Combining these approaches will result in a system that uses bearing only SLAM while moving, but when stopped validates its location using the higher accuracy 3D laser point cloud registration. This additional decrease in uncertainty will reduce the frequency needed for loop-closing navigation.

Research will include an investigation into the use of features extracted from laser intensity data to register individual scans to the overall model. Other areas of focus include the reduction in localisation uncertainty through the use of a hybrid SLAM system. Low uncertainty localisation will establish the origin of each 3D laser scan as a start point for the registration algorithms, reducing processing time and allowing real time model creation.

## References

[AP, 1993] *Ore collapse kills 4 miners*, Associated Press Newspaper article, August 12th 1993.

[Gerkey 2003] Gerkey, B. P., Vaughan, R. T and Howard, A. *The Player/Stage Project: Tools for Multi-Robot and Distributed Sensor Systems*. In Proceedings of the International Conference on Advanced Robotics (ICAR 2003), Coimbra, Portugal, 30 June – 3 July, 2003.

[Jarosz 2008] Jarosz, A., 2008. *Development of Inspection System for Evaluation of Ore-passes at Grasberg Mine, PT Freeport, Indonesia*, Proceedings, The 21st World Mining Congress & Expo, Krakow, Poland, 7 - 11 September 2008.

[Logan et al., 1993] A. S. Logan, E. Villaescusa, V. R. Stampton, M. A. Struthers and M. L. Bloss. *Geotechnical instrumentation and ground behaviour monitoring at Mount Isa*. In Proceedings of the Australian Conference on Geotechnical Instrumentation and Monitorng in Open Pit and Underground Mines, 21-23 June 1993: ed. T. Szwedzicki. 321-329, 1993.

[Langdon 2007] Langdon, J. and A. Jarosz, 2007. *Gyro Stabilised Vertical Opening Inspection and Surveying System*, Proceedings, Mine Planning and Equipment Selection (MPES 2007), Bangkok, Thailand, 11-13 Dec 2007.