Inertial Navigation: Enabling Technology for Longwall Mining Automation

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ABSTRACT

This paper describes recent advances in the development of an integrated inertial guidance system for automation of the longwall coal mining process. Significant advances in longwall automation are being achieved through an industry sponsored project which targets productivity and safety benefits. High performance inertial navigation systems are being successfully employed to accurately measure the three-dimensional path of the longwall shearer. Novel techniques have been developed which take advantage of the partially constrained motion of the shearer to correct and stabilise the inertial-based position measurement system. Accurate measurement of shearer position is a fundamental requirement for automated face alignment which involves controlling the shearer path in the horizontal plane. Automated face alignment represents a breakthrough in achieving the greater goal of practical and reliable automated longwall coal mining.

1. INTRODUCTION

Recent advances in the development of an integrated guidance system for automation of the longwall coal mining process using inertial navigation techniques have been made by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, Mining Automation group. Longwall mining is used extensively worldwide and accounts for over 80% and 50% of underground coal production in Australia and the USA respectively.

Modern longwall mining operations have been optimized to the point where manual operation of the process limits the future development of this mining method. In addition, the necessarily hands-on approach to the mining process exposes the operators to hazardous working conditions. In 2001 the Australian coal industry provided major *Landmark* funding to the CSIRO to develop a longwall mining automation system to the level of "on-face observation". This project builds on previous successes in highwall mining automation [1]. More *Landmark* details can be found at the project website [2]. The first major component of the *Landmark* project is the demonstration of automated longwall face alignment. This achievement alone will yield significant productivity and safety benefits across the industry. An international patent covering this technology development has been granted to CSIRO [3].

Details of the longwall mining process and the need for automation are presented in Section 2. Section 3 describes the automated face alignment system and the use of stabilized inertial navigation techniques.

2. THE LONGWALL MINING PROCESS

Longwall coal mining is a full extraction mining process in which large panels of a coal seam up to 5m thick are completely mined. An indicative longwall panel is 250m wide by 2000m long. The longwall mining system used in this process is comprised of three main components: a shearer, an armoured face conveyor (AFC) and a roof support system.

A longwall shearer as shown in Figure 1, is up to 15m long, weighs 90 tonnes and typically extracts a one metre slice of the coal seam as it travels back and forth across the panel along rails attached to the AFC. A portion of the roof support system and AFC can also be seen in Figure 1. The roof support system can have over 180 individual hydraulic support modules which collectively provide temporary support of the roof material above the extracted coal seam. The load capacity of each support can exceed 1000 tonnes.

As the shearer moves across the coal seam, large hydraulic push rams attached to the roof support modules progressively advance the AFC and associated shearer rails behind the shearer in a snake-like manner. The solid

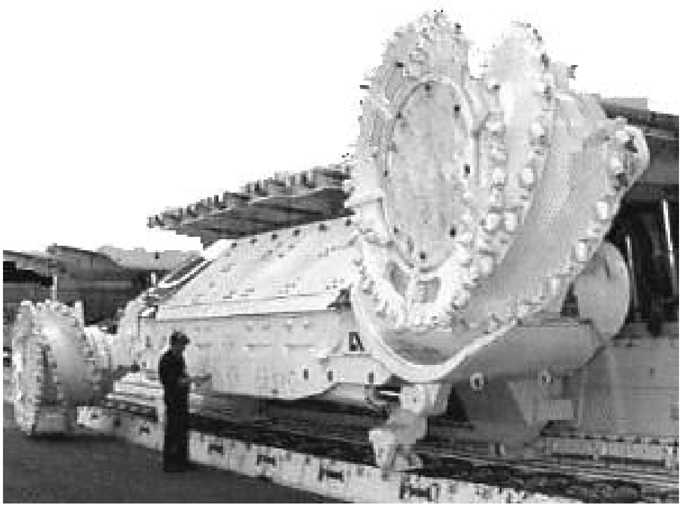

Figure 1: A longwall shearer showing the leading and trailing drums. A portion of the roof support canopy and armoured face conveying is also visible.

line in Figure 2 shows the shape of the AFC in plan view at a given point in time with the ‘snake’ behind the moving shearer. The dotted lines describe the theoretical path of the shearer for a commonly used ‘bi-di’ shearing mode. In this mode a ‘shuffle’ is required at each end of travel to advance the end portions of the AFC. As the longwall equipment progresses in this manner, the roof material collapses into the void left behind the advancing system.

The complete longwall system is a mobile semi-autonomous underground mining machine weighing in excess of 700 tonnes. Currently, each of the three main equipment components operates under largely independent and proprietary control systems.

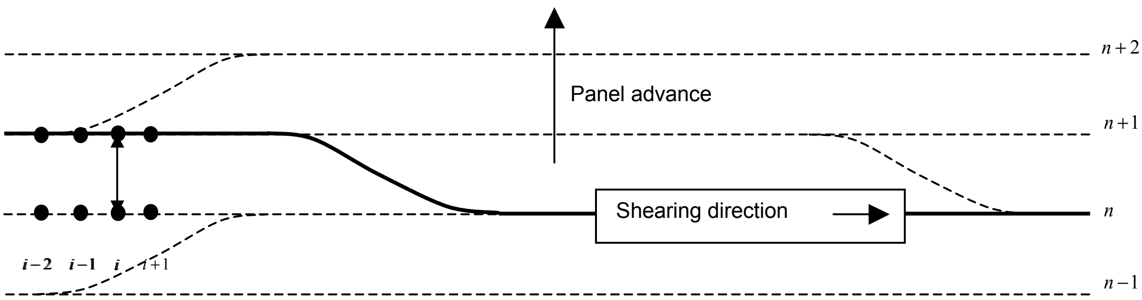

Figure 2: Schematic of shearer path and AFC profile in plan view for a commonly used shearing mode. The advancing AFC (solid line) bends to form a ‘snake’ behind the moving shearer. In this shearing mode, the shearer path (dashed line) ‘shuffles’ at each end of travel.

2.1 The Need for Automation

Full automation of the longwall mining process has always held the lure of increased productivity but more recently is being driven by issues of occupational health and safety. The presence of hazardous gases, respirable dust and the inherent danger of personnel working in close proximity to large mobile mining equipment is becoming increasingly unacceptable.

There have been many attempts worldwide over a number of decades to achieve full automation of the longwall mining process [4]. Equipment manufacturers have invested heavily in ongoing development of their respective proprietary control systems and yet, to date, personnel are still required to routinely work in hazardous production areas and to manually control the mining process.

Previous automation attempts have in large part been stymied by the inability to accurately determine the three-dimensional path of the longwall shearer as it systematically progresses through the coal panel. Without this information there is no absolute reference for controlling the motion of the equipment and reliable, sustained automation can not be achieved.

Automated face alignment is a major deliverable of the *Landmark* project. Face alignment refers to the process of maintaining a desired path for the shearer in the horizontal plane as it 'slices' across the coal face. In order to minimize mechanical stresses on the mining equipment and maximize production, the face is generally required to be straight and at a specified geodetic heading nominally orthogonal to the direction of panel progression.

Face alignment is currently achieved by manually aligning the position of the AFC and each roof support module with reference to a string line deployed across the face for the purpose. This adjustment is typically required about every eight hours of operation and is both time consuming and largely non-productive.

3. AUTOMATED FACE ALIGNMENT

Automated face alignment is achieved by controlling the incremental advance of the each of the AFC supports using the horizontal position information from an inertial navigation system (INS) mounted on the shearer as it travels along the AFC. As shown in Figure 2, the AFC at the ith support located behind the moving shearer is advanced a distance d from the nth to the n+1th incremental position so as to achieve the desired face profile. The required advance distance d is computed from the shearer horizontal path information gathered by the INS during the n-1th pass.

In control theory terms the desired face profile, which also describes the absolute geodetic heading, is the control system set point. The desired face profile is typically a straight line but other non-straight profiles could be advantageous under certain geological conditions. The control system output is the proportional control of the AFC movement via the roof support system. Negative feedback is provided by the shearer-mounted INS which measures the three-dimensional position of the shearer at closely sampled points across the face. Position error in the AFC proportional control is represented as a system disturbance.

Due to INS processing requirements, shearer position data is batch processed at the end of each full face traverse so that the profile corrections made during the n+1th shear cycle are computed from data gathered throughout the nth cycle.

Profile correction values are calculated as shown in Figure 3. The correction values (solid arrows) at positions corresponding to each roof support module are normalized to be zero at points where no correction is required (point D) and negatively valued elsewhere. For each increment of panel progression the required advance distance at each roof support module is then computed by the roof support control system as the addition of the correction value and a constant default advance distance (typically 1m). A correction of zero at all points across the face will result in the longwall progressing the default distance. This strategy ensures that the mining process can continue under open loop control during periods where the correction information is unavailable.

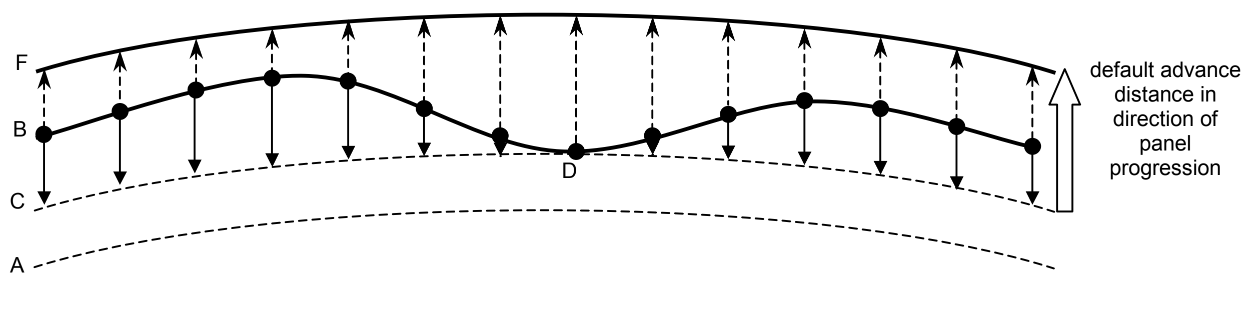

Figure 3: Diagrammatic representation of the relationship between the desired face profile (dashed line A or C), actual face profile (heavy solid line B), normalised position correction values (solid arrows), required advance distance (dashed arrows) and the resulting face profile (solid line F). The desired face profile is generally straight although can be non-straight as indicated in this example.

An example of the shearer path under open-loop control as measured by the shearer mounted INS is shown in Figure 4. It can be seen that the vertical path, as projected onto the vertical plane, is consistent across the multiple shear cycles as the shearer follows the natural undulations in the coal seam. The horizontal component as projected onto the horizontal plane highlights the departure in the face profile from the desired straight line due to accumulated position errors in the open-loop face alignment control system. It is interesting to note that at the time this data was collected, the longwall operators assessed the face profile to be straight by visual inspection.

In the automated face alignment system these accumulated position errors are minimized by systematically adjusting the AFC movement at each roof support module. Full underground trials of the automated face alignment system are planned for second half of 2003 at Beltana Colliery, NSW Australia.

The overall performance of the automated face alignment system is critically dependent upon the accuracy and precision of the INS. The longwall automation system has been developed around high performance military-grade inertial navigation equipment with better than 0.5mil pointing accuracy.

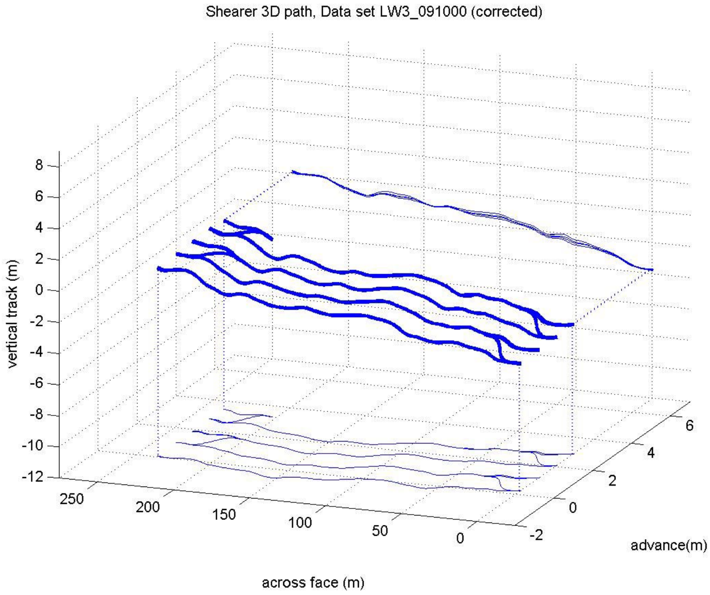

Figure 4: Three-dimensional path of the moving shearer throughout a number of shear cycles as measured by the INS.

3.1 Stabilised Inertial Navigation System

Inertial navigation systems are subject to position drift with time mainly as a result of the numerical double integration required to compute three-dimensional position from three axis acceleration. Dead-reckoning techniques using external odometry can be used to improve short term position stability but systematic drift can still occur if the incremental motion of the INS is not exactly along the measured geodetic heading. High performance INS, such as the military-grade units used in this project, typically use GPS aiding to correct this inherent drift. This integrated approach combines the short term accuracy of the INS with the long term stability of GPS to provide accurate and stable position measurement.

In the underground mining application GPS is not available and so other bias correction strategies need to be developed. Without effective bias correction the INS derived shearer path may diverge (or converge) in both the horizontal and vertical components [5]. An example of this divergence is apparent in the uncorrected data shown in Figure 5 which represents the same portion of shearer travel shown in Figure 4. In Figure 5 it can be seen in the horizontal and vertical planes that the nominally parallel paths of the shearer throughout each cycle are divergent.

INS stabilisation techniques generally rely on externally available position or velocity information such as GPS, vehicle odometry or zero velocity updates (ZUPTs). In the *Landmark* project INS stability has been achieved by recognising the (almost) closed-path of shearer travel throughout each shear cycle. In normal mining operations the horizontal closing distance for each cycle is either fixed or can be independently determined. This information is used in the automated face alignment system to back-correct the shearer path at the completion of each shear cycle. Similarly, back-correction in the vertical plane can be achieved based on manually surveyed levels which are generally available at the panel boundaries.

By utilising this closed-path information, the uncorrected data of Figure 5 can be back-corrected to yield the result shown in Figure 4. This correction strategy yields an accurate measurement of the three-dimensional path of the shearer at the completion of each shear cycle and ensures the long-term stability of the INS measurement system.

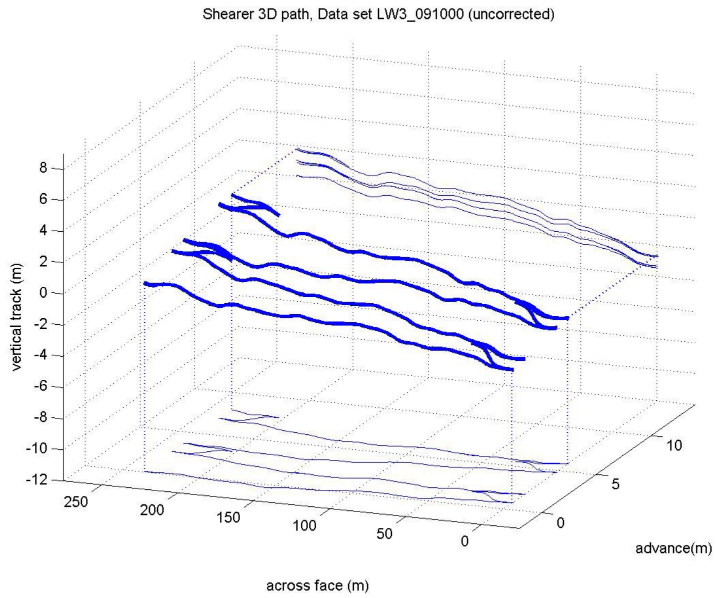

Figure 5: Three-dimensional path of the moving shearer throughout a number of shear cycles as measured by the INS without bias correction. Divergence in the shearer path due to this bias is apparent.

4. SUMMARY

Longwall mining accounts for a large portion of underground coal production worldwide. The industry is seeking ways to improve productivity and safety for mining personnel. Significant advances in longwall automation are being achieved through the industry sponsored *Landmark* project. A major deliverable of this project is automated face alignment which promises productivity and safety benefits to the industry.

Inertial navigation techniques are being successfully employed in this project to accurately measure the three-dimensional path of the longwall shearer. INS provides the enabling technology for automated face alignment that is paving the way towards full automation of the longwall mining process. Techniques have been developed to ensure the long-term position stability of the INS.

References

[1] D. C. Reid, D.W. Hainsworth and R. J. McPhee, “Lateral Guidance of Highwall Mining Machinery Using Inertial Navigation”, 4th International Symposium on Mine Mechanisation and Automation, pp B6-1—B6-10, 1997.

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