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A MAJOR STEP FORWARD IN CONTINUOUS MINER AUTOMATION

David C Reid, Jonathon C Ralston, Mark T Dunn and Chad O Hargrave

ABSTRACT: Progress on a major research and development project undertaken by the CSIRO Mining Technology Group to advance the automation capability of continuous mining equipment in underground coal mining operations is described. The aim is to increase the overall rate of roadway development as well as providing a safer working environment for underground mine personnel.

The outcomes achieved at the half-way mark of this ACARP funded three-year research and development project are reported. Details of the technical developments undertaken towards demonstration of a "self-steering" capability to enable a Continuous Miner to automatically maintain a given mining heading and mining horizon under production conditions are provided. Reported outcomes include the means to accurately determine both the location and orientation of a Continuous Miner in real-time using a combination of a navigation-grade inertial navigation unit, Doppler radar and optical flow technologies. Comprehensive performance evaluations have been conducted using a scaled skid-steer mobility platform and results achieved to the present stage of the project indicate that the required automated self-steering functionality is achievable under production conditions. The project outcomes represent an important move towards achieving a step change improvement in underground roadway development practice.

INTRODUCTION

Continuous Miner (CM) automation has been identified by the Australian coal industry as essential to achieve a step change improvement in roadway development productivity. The research project reported in this paper covers one component of a larger research and development effort referred to collectively as CM2010.

Advances in longwall coal mine production in Australia have put pressure on roadway development rates, which have become a limiting factor in the coal production supply chain. Due to new technology and equipment, production rates from longwalls are increasing rapidly while roadway development improvements have generally been limited and incremental in nature. The Roadway Development Task Group (RDTG), established in 2005 by the Australian Coal Association Research Program (ACARP), is tasked with addressing this production bottleneck by means of research and development projects that will lead to new processes and technologies. The RDTG carried out a review of existing processes and technologies and charted a path forward for roadway development based on the introduction of new systems that could deliver the necessary improvements in production for both new generation longwalls and for existing mines. Based on this review, an extended research and development programme was initiated with broad industry support. This was formalised as the CM2010 roadway development strategy in 2008 with four major technology categories: remotely supervised continuous miner, automated installation of roof and rib support, continuous haulage and integrated panel services.

Current CSIRO research and development is focussed on the first of these technologies, a remotely supervised Continuous Miner., The primary goal is to deliver a "self-steering" capability that will enable a Continuous Miner to maintain 3D position, azimuth, horizon and grade control within a variable seam horizon under remote monitoring and supervision.

This research builds on previous research which demonstrated the practical application of advanced inertial navigation techniques for longwall automation (Reid, *et al.*, 2001; Reid, *et al.*, 2006). Despite the inherent time-dependent position drift associated with all inertial-based solutions (Savage, 2000), the longwall automation research delivered a commercial-grade system that achieved sustained position accuracy under full production conditions. The use of this enabling-technology for underground mining

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applications is covered by international patent and is targeted as an area of strategic research by the CSIRO Mining Technology Research Group (Hainsworth and Reid, 2000).

Progress to date in this CM2010 CM automation project, the technology solutions that have been developed, the experimental setup to evaluate the performance and the results achieved is described.

INERTIAL NAVIGATION TECHNOLOGY FOR MINING GUIDANCE

Central to achieving a practical inertial navigation solution for CM automation is the performance of the underlying inertial sensor technology – in particular the gyroscopes and accelerometers. The quality and technical sophistication of commercially available inertial technologies covers a wide range from Micro-Electro-Mechanical Systems (MEMS)-based devices used in mass consumer products such as mobile phones, automotive application such as air-bag control and satellite navigation aiding, through to fibre-optic and laser-based devices which are essential for high performance air, land and sea navigation systems.

Common to all inertial navigation systems, irrespective of the gyroscope and accelerometer technologies used, is the fundamental requirement to compute a positional translation by means of the numerical double integration of acceleration (as measured by the accelerometer sensors) and angular rotation by the single integration of angular rate (measured by the gyroscope sensors).

In recent decades a large body of strapdown navigation theory, that builds a theoretical framework for optimally combining the inertial sensor data to compute 3D position and thereby a navigation solution has been developed. Even with the highest performance sensing devices, the nature of numerical integration means that position errors will accumulate and grow with time. In a free-inertial mode, where only purely inertial information is used, this position error will grow quickly even for a high performance system (Savage, 2000).

Given this inherent limitation to inertial sensor performance, practical inertial navigation solutions operate in an aided-inertial mode to limit the growth of these errors by taking advantage of external (non-inertial) information. The most convenient and commonly used strategy is to periodically correct the integration error build-up by taking advantage of times when the inertial system is stationary (i.e., in a non-moving position relative to the earth) to correct and recalibrate the internal velocity calculations. This simple and quite robust aiding strategy known as Zero Velocity Updating (ZUPTing) can be very effective but requires relatively frequent stops (typically every few minutes) for a short duration (typically about 10 s). With ZUPTing it is possible to reduce the position errors for a typical high performance system from nautical miles per hour to metres per hour.

Further improvements can be made by incorporating external aiding, for example, the addition of velocity sensing to internally allow the inertial navigation system to continually correct for sensor noise and integration error build-up by comparing internally computed velocity to the external source. This arrangement is shown in the block diagram of Figure 1. Conceptually, this approach can be thought to extend the ZUPTing strategy to non-zero velocity updating and is generally referred to as Vehicle Motion Sensor (VMS) aiding. VMS-aiding is a key requirement necessary to achieve a practical navigation solution for automated CM guidance.

VMS-aiding is commonly used with vehicle-mounted inertial navigation systems by utilising odometry signals from rotary encoders fitted to the vehicle wheels or drive train. This approach works well when the vehicle is travelling on a hard surface where wheel slip is minimal. On rough terrain wheel slip will quickly degrade the sensor performance to the point that it may be worse than without any VMS-aiding. Early in this project it was concluded that it would be necessary to develop accurate, reliable and practical *non-contact* odometry technology for CM automation, that is, a means of measuring vehicle motion relative to the surrounding environment without mechanical linkage from the vehicle or contact with the surface over which the vehicle is travelling.

A number of non-contact odometry technologies were considered, taking into account performance, robustness and general suitability to operate and survive in the hostile mining environment. Candidate technologies including scanning laser, optical flow and Doppler radar were identified as providing individual and complementary advantages.

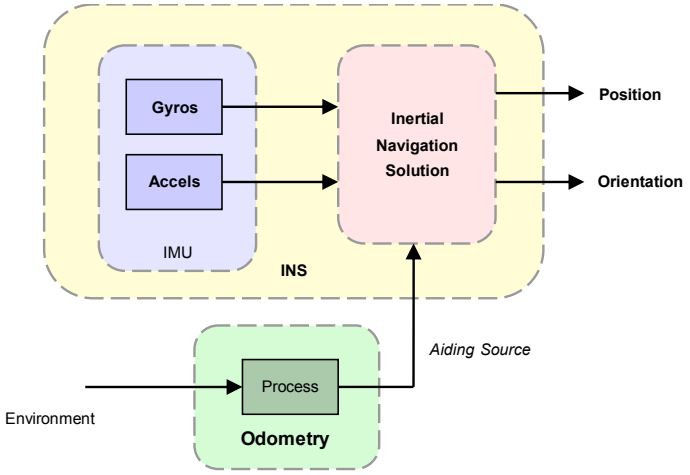

Figure 1 - Block diagram showing the relationship between the IMU sensors and the aiding source used to compute the navigation output

NAVIGATION SOLUTION PERFORMANCE: EXPERIMENTAL EVALUATION METHODOLOGY

The underlying performance of navigation-grade inertial navigation systems can be confidently determined from the technical specifications of the internal gyroscopes and accelerometers. Navigation system performance is often expressed in terms of nautical miles per hour position drift for pure-inertial operation and pointing accuracy which measures the ability of the system to resolve the gravitational vector and the rotation of the earth about the central axis.

The achievable navigation performance is much harder to analyse or predict when the motion of the mobile platform (CM in our case) is unconstrained and the motion of interest is small relative to the erratic motion resulting from significant background vibration and jolting. In this case the achievable performance depends greatly on the performance of the VMS-aiding sensors and the tuning of the internal signal processing filter parameters to match the vehicle motion and dynamics. For these reasons the performance of the complete navigation system needs to be assessed under realistic operating conditions.

Routine prototype testing on underground coal mining equipment is impractical due to the logistics and statutory regulations governing the installation of electrical equipment in explosive atmospheres. For this reason a skid-steer remote-control vehicle, referred to as the Phoenix mobility platform, was adapted to provide a suitably realistic scaled mobile test platform. The Phoenix as shown in Figure 2 captured some of the CM dynamics in terms of motion profile, skid steer manoeuvring, wheel slip and jolting/vibration characteristics. In this figure one of the INS units under test can be seen mounted on top at the rear and the Doppler radar mounted on the front far corner angled down towards the ground. The optical flow sensor is mounted to the rear of the vehicle and is not visible in this view.

The Phoenix is also fitted with a high-accuracy RTK GPS using a CSIRO-located base station, which provides an absolute ground-truth position reference updated at twenty times per second with an absolute position accuracy of better than 2 cm RMS. These high accuracy absolute position data are used as a base line reference for all the navigation experiments on the Phoenix. In addition to the navigation system under test, the Phoenix is fitted with an embedded computer so that the vehicle can navigate to a mission plan under closed-loop control.

The design of the Phoenix means that the navigation experiments can be conducted on natural (i.e., un-paved) and rough terrain which provides more realistic conditions for evaluating the navigation and speed sensors.

Trials of the integrated CM navigation system are conducted along a 55 m natural bush track located on the grounds of the CSIRO research facility. The track has a loose-gravel surface in places and moderate uphill and cross-track grades. A satellite image of the test track is shown in Figure 3 with the start and end points shown and the straight line target path for the experiments indicated by the white line. The RTK GPS system is used to survey the absolute 2D coordinates of the start and end points used during these trials.

At the start of each trial the reference point on the Phoenix is placed on the start marker and the inertial navigation system is initialised with the absolute coordinates of the start location. The Phoenix is then instructed to autonomously navigate to the end coordinates using only vehicle position and attitude information provided by the inertial navigation system. The vehicle travels at a slow walking pace and in accordance with a pre-programmed mission plan periodically stops for a short duration and reverses for a short distance before moving ahead again. This motion profile approximates the motion of the CM production cycle and allows the inertial measurement unit to take advantage of Zero Velocity Updates.

Figure 2 - Phoenix skid steer vehicle used to evaluate the performance of the inertial navigation systems

Figure 3 - Natural ground test track used for inertial navigation system evaluation located on the grounds of the CSIRO research facility

Around the mid-point of the mission the vehicle is taken out of closed-loop control and is driven under manual (remote) control through a sharp left turn and a short distance off track. It is then driven back on track where closed-loop control is resumed. This manoeuvre simulates some aspects of a niche or cut-through construction which is another less frequent component of the CM production cycle. The vehicle automatically stops when it reaches the mission end point.

Multiple navigation trials as described above have been conducted over an extended period using various combinations of inertial and speed-sensing hardware.

EXPERIMENTAL RESULTS

Representative results from a recent navigation system performance trial follow. The start and end points for this experiment being approximately 55 m apart are shown superimposed on the satellite image of the track in Figure 3. As previously described, during each experiment navigation data from the navigation system under test is recorded and also used in real time to steer the Phoenix in a straight line between the nominated start and finish points including the periodic stops and reversing manoeuvres. For ground-truth validation, the actual path of the Phoenix is also recorded from the on-board RTK GPS system and this is shown as the blue trace in Figure 3 where the short departure from the straight path can be seen around the midpoint of the mission. Apart from this intentional departure it can be seen that the Phoenix tracked closely along the desired path.

More detailed analysis is presented in Figure 4 where it can be seen that the position error of the Phoenix throughout this mission is generally less than 0.1 m. Larger errors during the programmed reversing manoeuvre are due to deficiencies in the closed-loop control algorithms and not the navigation system. This is confirmed by observing that the vehicle regains correct track alignment once it begins to travel in the forward direction again. Relatively larger position errors near the end point reflect control system error as the vehicle experiences increased track cross-grade and vehicle slide-slip in this portion of the track.

DISCUSSION

Extensive practical evaluation of inertial system performance using the Phoenix mobility platform has yielded important information towards delivery of the final system. Firstly, the results obtained indicate that an inertial based approach indeed represents a valid means for deducing real-time vehicle position. This sensing capability is an essential component for any robust closed loop automated control system, and a very practical requirement in the development of a guidance solution for underground mining equipment. Secondly, the results obtained clearly demonstrate that the performance of navigation-grade inertial measurement systems can be greatly improved by taking advantage of position or motion information that is available within or outside the inertial frame of reference.

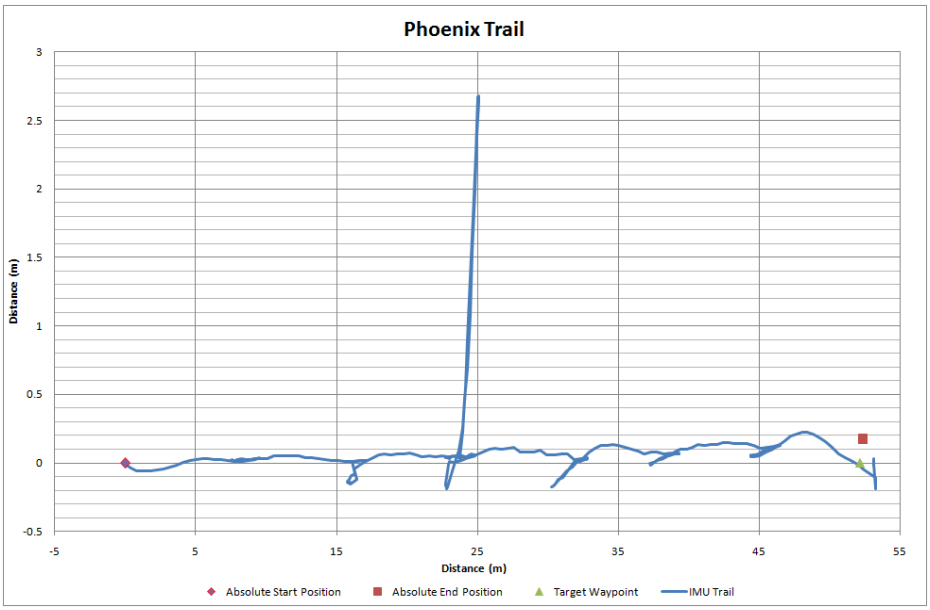

Figure 4 - Analysis of 2D position error as measured by the on-board RTK GPS equipment. The position of the Phoenix under INS-only guidance is in close agreement with the RTK GPS supplied position. Note that the excursion in the centre of the plot was an intentional manually instructed departure from the nominal desired path to demonstrate correct control system return behaviour

Further developments of the guidance system have yielded a novel approach to inertial navigation aiding using vehicle speed sensing, which has greatly improved the overall performance of the inertial navigation system. This has involved the use of non-contact speed sensors which are integrated with the inertial navigation algorithms to provide accurate ZUPTing and VMS-aiding to achieve significant performance improvement.

Extensive field campaigns have provided a measure of understanding and confidence with regards to achievable position measurement with the current system. This has been undertaken using the Phoenix vehicle which has provided a convenient experimental test platform to evaluate the complete navigation system performance under CM-like motion and operating conditions. The test vehicle is fitted with on-board RTK GPS to provide sub-centimetre ground truth reference data. Importantly, the experimental results to date have shown that sub-decimetre 2D position accuracy can be achieved with a suitably-aided inertial navigation system over a 55 m track length.

Research is continuing on the further development of the non-contact speed sensing technology to ensure accurate and robust operation over the wide range of operating conditions encountered in roadway development. Further intensive evaluation is required to assess the assumption that there are periods when the CM is sufficiently stationary to permit ZUPT aiding.

While it can be expected during roadway development that there will be periods during the mining/bolting cycle when the CM is not tramming, the platform is generally not strictly stationary. Background vibrations, platform jolting and slippage due to reaction forces all constitute low level motion to the inertial measurement unit. Under a strict ZUPTing interpretation this low-level motion will either prevent the INS from entering a ZUPTing mode or if forced to do so may degrade the navigation performance

One way to deal with the practical realities is to adjust the internal signal processing filters so that the INS is less sensitive to this background "noise". The trade-off here is that the navigation system will be equally less sensitive to legitimate small motion and this will lead to some degradation in navigation performance. Further testing and evaluation will be necessary to better understand and quantify the possible system degradation due to this non-ideal ZUPTing condition.

SUMMARY

With the support of the Australian coal industry, CSIRO is currently involved in a major continuous miner automation research and development project. Effort so far has demonstrated a guidance capability based on high performance inertial navigation technologies coupled with novel aiding strategies. Practical performance limits for core instrumentation have been identified. Extensive evaluations have been conducted on a scale mobility platform to identify and validate real-time system behaviour. Work continues to improve the underlying accuracy and performance towards and integrated solution.

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REMOTE TELE-ASSISTANCE SYSTEMS FOR MAINTENANCE OPERATORS IN MINES

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ABSTRACT: Complex technologies such as fully automated and semi-automated equipment and teleoperated machines are being introduced to improve productivity in mines. Consequently, the maintenance and operation of these complex machines is becoming an issue. There is a growing interest in industry in the use and development of technologies to support the collaboration between a local worker and a remote helper to deliver expertise to guide the local worker in undertaking maintenance and other activities. The productivity of the future mine relies on the effective delivery, of remote guidance. ReMoTe (Remote Mobile Tele-assistance), a mobile augmented reality system for remote guiding, has been developed at CSIRO as part of the work in the Transforming the Future Mine Theme.

INTRODUCTION

In the industrial and mineral extraction fields, complex technologies such as fully automated and semi-automated equipment or teleoperated machines are being introduced to improve productivity. Consequently, the maintenance and operation of these complex machines is becoming an issue. Operators/technicians rely on assistance from expert in order to keep their machines functioning. Personnel with such expertise, however, are not always physically located in close proximity to the equipment/machine. They are often in a major metropolitan city while the technicians maintaining equipments are in rural areas, where industrial plants or mine sites may be located. There is a growing interest in industry in the use and development of technologies to support the collaboration between a local worker and a remote helper. For example, in telemedicine, a specialist doctor may guide remotely a non-specialist doctor or a nurse (Palmer, *et al.*, 2007); in remote maintenance, an expert may be guiding remotely a technician through the task of repairing a piece of equipment (Kraut, *et al.*, 2003). Communication means that have been used for this purpose include telephone, email and basic video conferencing. It is generally accepted that augmented reality technology is very useful in maintenance and repair applications (Lapkin, *et al.*, 2009).

ReMoTe is a remote guiding system developed for the mining industry. ReMote was designed to support the mobility aspect of maintenance workers. In ReMoTe, the expert, when guiding remotely a worker, uses his/her hands not only to point to remote location - "grab this" - but also to demonstrate how to perform a specific manual procedure. The potential of applying a non-mediated hand gesture communication, a proven effective technique of communication, in the field of wearable augmented reality is explored. A review of the literature on augmented reality (AR) remote guidance systems used in industry is followed by some initial results of ReMoTe testing and a short description of future work.

AUGMENTED REALITY REMOTE GUIDING SYSTEMS FOR MAINTENANCE

Automated AR based remote guiding systems

Augmented reality (AR) systems have been developed since 1990 to assist maintenance workers in various industries in conducting their tasks. In order to minimize the risk of errors, relevant information was projected onto the machine in real time (using AR) to assist operators in repairing the machine. One key benefit of the use of AR is that the attention of the operator is on the maintenance task not on the system delivering the help. Many studies were conducted in the early 2000 to evaluate the benefits of AR in the area of maintenance. Identifying the exact location of the required intervention helps reduce the transition between tasks (Henderson and Feiner, 2009), AR based guiding is better than paper based instruction for guiding an assembly task (Wiedenmaier *et al.*, 2003), leading to a reduction in the number of errors. When comparing paper based instruction and AR based guiding, the AR based guiding system allow users to stay on task; there is no need to switch attention to a piece of paper to look for specific information and hence a reduced cognitive load (Henderson and Feiner, 2009).

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