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ABSTRACT: The outcomes achieved at the completion of a major industry-funded project undertaken by the CSIRO Mining Technology Group to advance the automation capability of continuous mining equipment in underground coal mining operations are reported. The details of a practical steering and guidance solution for autonomous Continuous Miner operation employing novel inertial navigation aiding techniques are described. The results of navigation performance evaluation using a scaled skid-steer mobility platform completing three segments of a two-heading roadway development pattern under autonomous control are presented. These results represent a significant milestone in 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 specific research outcomes reported in this paper cover 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 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). Initial navigation results in this CM2010 CM automation project, including an introduction to the technology and the experimental setup used to evaluate the navigation performance has been previously presented in Reid *et al*., (2011).

This paper presents updated results of the CM navigation system which has been recently tested on an above ground coal surface over a two-heading roadway development mining pattern which covers a total path length of over 900 m.

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INERTIAL NAVIGATION TECHNOLOGY FOR MINING GUIDANCE

As described in Reid *et al.,* (2011) all inertial navigation systems compute 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 has been developed, that builds a theoretical framework for optimally combining the inertial sensor data to compute 3D position and thereby a navigation solution. 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 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.

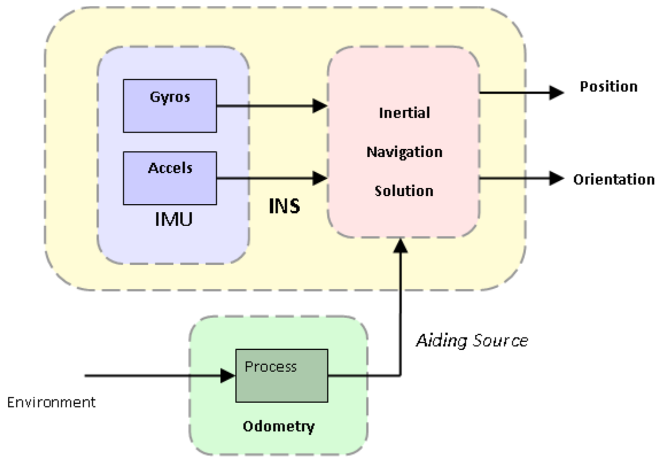

Figure 1 - Block diagram showing the relationship between the IMU sensors and the aiding source used to compute the navigation output

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. As reported in (Reid, *et al.,* 2011) much of the early project work focussed on the development of an 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.

Earlier in this project 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 radar were identified as providing individual and complementary advantages. Subsequent testing has shown that radar yields significant operation and performance advantages over the other technologies. Radar technology has been developed and further optimised during this project to provide a practical and extremely accurate aiding source that operates at very low velocity and low latency.

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 captures some of the CM dynamics in terms of motion profile, skid steer manoeuvring, wheel slip and jolting/vibration characteristics. In this figure the INS unit under test is mounted internally and the Doppler radar is mounted on the front far corner angled down towards the ground.

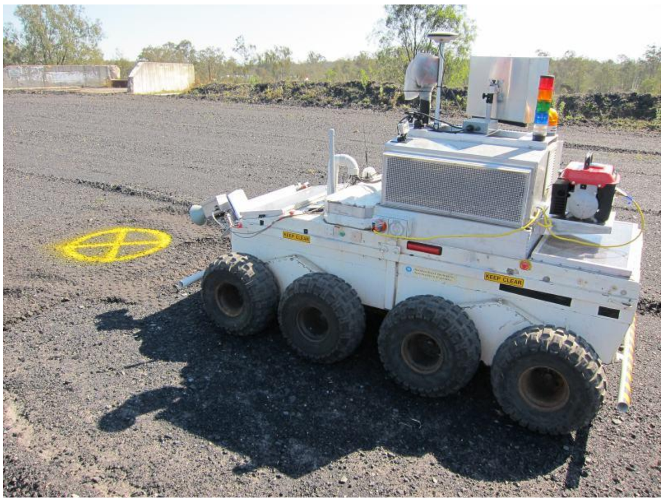

Figure 2 - Phoenix skid steer vehicle used to evaluate the performance of the inertial navigation systems

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 a 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 autonomously navigate to a mission plan under closed-loop control.

Previous navigation trials along a 55 m natural bush track have been report in (Reid, *et al.*, 2011). Since then more elaborate and field-realistic experiments have been conducted which map out the path of a CM throughout three sections of a two-heading roadway development mining plan with a total path length of approximately 900 m. This mining pattern is shown in Figure 3.

These experiments have been conducted at the Ebenezer decommissioned surface coal mine nearby the CSIRO research facilities west of Brisbane. A large ex-stockpile area with a remnant coal surface was prepared and mapped-out with the two-heading plan as shown in the aerial view of the test site in Figure 4.

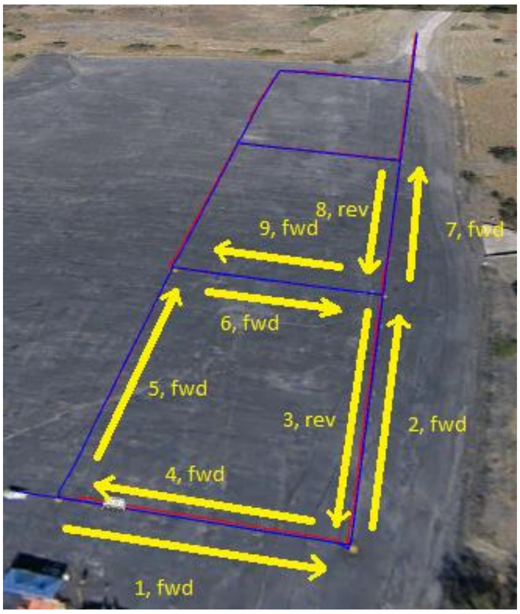

Figure 3 - Image showing two-heading roadway development mining plan

Figure 4 - Aerial view of Ebenezer test site with waypoints and mining plan shown

For each of these experiments the Phoenix test vehicle control system was pre-programmed with the coordinates of the 2-heading mining plan and the associated speed/direction profiles. The vehicle was then positioned at the starting point which the navigation system fully aligned and calibrated. The vehicle was then enabled to automatically navigate through the pre-programmed mine plan with regular brief stops to allow the navigation system to ZUPT. The vehicle velocity profile throughout this 60 minute mission is shown in Figure 5.

RTK differential GPS data were recorded throughout the experiment to provide a baseline reference to determine the performance of the navigation system. The ground survey markings also provided a general visual measure of performance during the experiment. One of these yellow circular ground marks can be seen ahead of the Phoenix in Figure 2.

In these experiments a two-stoke petrol generator was installed on brackets rigidly connected to the inertial navigation mounting plate. With the generator running during the experiments this arrangement provided a more field-realistic condition to test the sensitivity of the navigation system to background vibration, especially during ZUPTing periods.

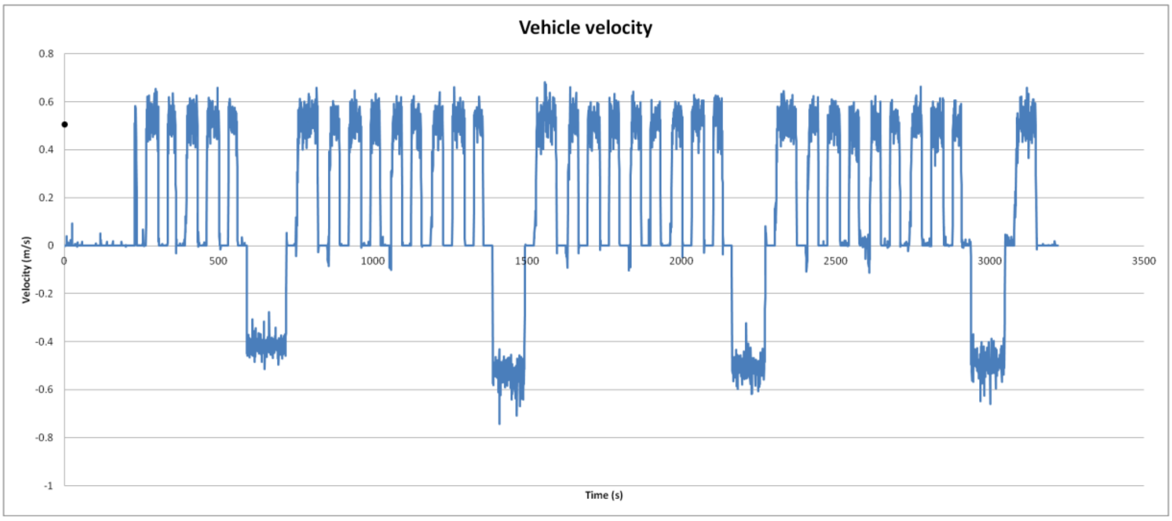

Figure 5 - Phoenix velocity vs time plot to indicate the ZUPTs and forward/reverse motion during the two-heading mining plan

EXPERIMENTAL RESULTS

Representative results from a recent navigation system performance trial at Ebenezer test site as described in the previous section indicated that the primary measure of system performance is given by comparison between the inertial navigation derived position estimate and the RTK DGPS measurement. The 2D position errors (orthogonal components of along track and cross track) for one recent experiment are shown in Figure 6. This result is indicative of three other similar experiments. As can be seen from this plot the overall error is typically less than 200 mm and importantly the error does not tend to increase with time over the 70 min duration of this experiment. The position at the furthest point of travel has reduced to approximately 200 mm. The beneficial effects of ZUPTing can be seen by the reduction in position error corresponding to times when the Phoenix is stationary. Furthermore it was observed that the path travelled by the Phoenix, which turned on each waypoint twice, is consistently accurate around the independently marked points.

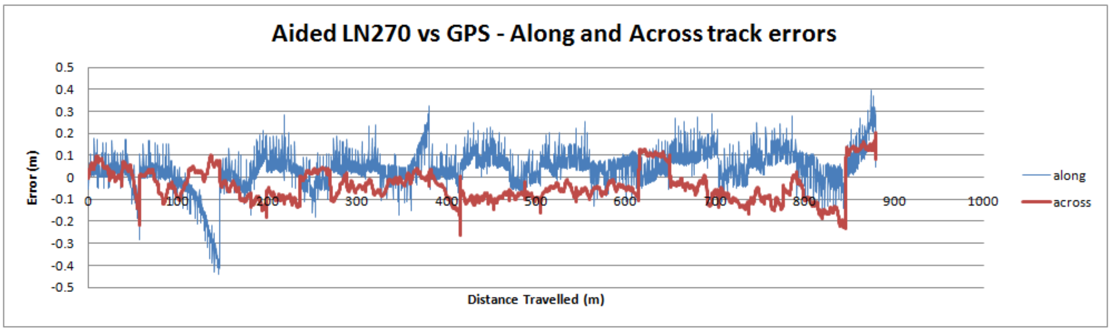

Figure 6 - 2D position errors (orthogonal components of along track in blue and cross track in red) between the inertial navigation system and on-board RTK GPS equipment

DISCUSSIONS

Extensive practical evaluation of the performance of a VMS-aided inertial system in mine-realistic above-ground experiments using the Phoenix mobility platform travel in a two-heading roadway development mining plan over a total distance of approximately 900 m has yielded encouraging results

The results obtained indicate that custom-designed radar can provide accurate and timely velocity measurement necessary to achieve a practical VMS-aided inertial navigation system for automated control of a Continuous Miner in a roadway development application. Furthermore the robust non-contact nature of the radar technology and the field proven reliability of strapdown inertial navigation technology could provide the complete hardware solution for this application.

Research is continuing on the further development of the radar non-contact speed sensing technology to improve the robustness and measurement reliability by means of multiple sensors. It is expected that this approach will overcome the known limitations of this technology when the target is reflective such as pooled water.

SUMMARY

With the support of the Australian coal industry, CSIRO is currently involved in a large-scale continuous miner automation research and development project. A major outcome of this project to date has been the demonstration of a practical CM guidance system which combines high performance inertial sensors with custom-developed radar. This guidance system has been demonstrated using the Phoenix mobility platform at a decommissioned coal mine and has achieved a position error of generally less than 20 cm over a 70 minutes mission which followed three segments of a two-heading mining plan with a total path length of over 900 m.

Work continues to improve the underlying accuracy and reliability leading to full underground trials on a production mining system.

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