[115,4]111

"Advanced Robotics for Tunnelling"

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ABSTRACT

As part of its Advanced Technology programme, the DTI has introduced an Advanced Robotics initiative to assess economic benefits across a diverse range of application areas and to develop technological sub-systems which are not specific to a particular industry. The AR initiative has been spearheaded by the tunnelling collaborative group which has the prime objective of realising fully or semi-autonomous systems within 5 - 10 years. This tunnelling group has successfully completed both a Feasibility Study and a Project Definition Study (PDS) and is currently submitting a proposal to the DTI for the Project Realisation phase. The paper presents the conclusions from the Feasibility Study before detailing technical progress with the robotic elements from the PDS which include machine guidance and navigation, systems control and communications, system health and condition-based maintenance, as well as specialised sensors for such tasks as strata prediction. The paper continues to describe progress with the Project proposal which is to develop an integrated drivage system for mining which will comprise a machine with novel mechanical attributes to allow simultaneous cutting and support of roof.

1. INTRODUCTION

At the Versailles Economic Summit in 1982, it was agreed that further international scientific and technological co-operation would be required for the revitalisation and growth of the world economy. European countries were becoming increasingly concerned about their ability to compete in the markets of the world with the USA and Japan. One specialist area was termed Advanced Robotics (AR) with the twin objectives of encouraging the development of systems that can dispense with human work for difficult activities in harsh, demanding or dangerous environments. The AR Programme spans a broad spectrum of engineering and social application areas.

The DTI initiated an AR Programme to assess potential economic benefits across a diverse range of application areas. The AR initiative in mining was directed to tunnelling operations as these operations are common to coal mining and civil engineering. The DTI identified three major phases of work which aim towards the application of AR techniques to fully or semi-autonomous tunnelling systems within 5 - 10 years. Firstly, a fully-funded feasibility study to consider three different types of tunnelling methods and to recommend a preferred project on the basis of market requirements, technical risk, available technology and commercial potential. Secondly, a partially-funded PDS to detail research and development requirements, to appraise design studies and to consider the commercial viability of the tunnelling project. Finally, the project to be carried out by an industrial collaborative group must be prepared to provide development funds.

The UK AR initiative has been spearheaded by the Tunnelling Collaborative Group. British Coal carried out a feasibility study between October 1985 and April 1986; the objectives and conclusions of this study are summarised later. The tunnelling feasibility study prompted sufficient interest to establish a collaborative group to undertake the PDS stage. The PDS was undertaken between August 1987 and December 1988 with the report being accepted by the DTI in January 1989. The PDS addressed tunnelling with the emphasis on a systems approach and the objective of continuous operation. In essence, the PDS was an in-depth state-of-the-art review of advanced robotics technologies applied to the integration of tunnelling systems. Since 1989, a collaborative group led by Dosco Overseas Engineering has been formulating a proposal for a £5 M AR tunnelling system for development drivages in longwall mining. The thrust of the project is to develop and demonstrate an AR production tunnelling system which offers continuous operation through the integration of automated sub-systems. At the time of writing the proposal is being considered by the DTI.

2. FEASIBILITY STUDY

This study addressed the three concepts which cover the most widely used techniques of tunnelling, namely:

1. hard strata tunnelling utilising integrated cutting, loading and roof support machines.
2. hard strata tunnelling using separate plant to drill, blast, load and support the tunnel.
3. pipelines and tunnels in alluvial or weak sedimentary strata for services.

The DTI required that independent sub-contracts were let to assess the future market potential for tunnelling and to review the current state-of-the-art with Advanced Robotics. Additionally, visits were made and discussions held with most UK organisations who were considered to be potential collaborators. Visits were also made to relevant organisations and tunnelling operations in France, Germany and Norway.

The study concluded that the current world tunnelling market is approximately 10000 kilometres annually in civil engineering and mining of which the UK has about 1% of the civil and 6% of the mining market. The successful application of current automation and robotic technology could double the utilisation rate and reduce costs by 30% in a 5 year period. This improvement may increase the annual tunnelling market by 30 - 40%. Sufficient technology exists to produce viable, automated and semi-autonomous tunnelling systems within 5 years. The development of an autonomous system within 10 years will require significant further progress with research into AR techniques such as artificial intelligence, natural language interfaces and machine vision. The study proposed that a PDS should be carried out on a hard rock circular tunnel boring machine (TBM) integrated into a debris and supplies transport system.

3. PROJECT DEFINITION STUDY

British Coal as lead organisation had the dual responsibility of establishing the functional structure of the Group and defining the objectives for the PDS. Its role is unique in that although it has sole responsibility for the contract with the DTI, it is also a contributing collaborator and has to reflect the majority view of the collaborators.

The tunnelling collaborative group comprised 8 group members; Dosco and Howdens are essentially tunnelling equipment manufacturers, HSDE and Moog Controls manufacture control and communication technology equipment, Lilley Construction is a tunnelling equipment user whereas British Coal (HQTD), ERA and BP are predominantly R&D organisations. British Coal had to agree the allocation and scheduling of resources and to match available expertise to project requirements. Inevitably, this liaison proved to be an iterative and time consuming process. Also the group had to progress a Collaboration Agreement which specified contractual obligations and IPR.

Project objectives are to significantly increase the utilisation of tunnelling systems from the current figure of less than 25% and to reduce manpower by 50%. The feasibility study has identified that the major delays to the cutting operation are attributable to the support of roof, services extension, planned and unplanned downtime, and logistic failures. The PDS was therefore to define and specify the features of an integrated cutting, loading and supporting system which within 5 years will utilise AR techniques to increase the application and economics of tunnelling projects.

3.1 Machine Designs

It has proved necessary to modify the feasibility study recommendation to automate a hard rock TBM because of a conflict of interests between Dosco and James Howden; the former markets boom-type roadheading machines whereas the latter services the civil market and wishes to automate a full-face machine. The feasibility study identified that the various methods of cutting did not constitute a major delay to tunnelling systems so it was acceptable to consider both types of machine with the expectation of progressing common robotic elements. These respective machines both produce circular drivages and are shown in Figures 1 and 2.

Figure 1 shows Dosco's latest boom-type roadheading machine which generates a 6 m diameter tunnel at an advance rate of 2 m/hr in strata of medium strength. This performance corresponds to an advance rate of 14 m/day with a cutting head utilisation of 30% requiring 13 men/shift. As it is not expected to significantly increase the hourly advance rate, increased performance will derive from a cutting head utilisation of 60%. The robotic machine will require instrumentation to minimise pick wear, provide strata prediction, allow remote supervision and monitor mechanical, electrical and hydraulic components. Primary support of roof is a shield which needs to be advanced with fast cycle times. The robotic machine will require an independent control system to handle and sequence permanent support sections whether they be concrete or steel.

James Howden wishes to automate a full-face TBM that is similar to the one being used to bore the 4.8 m service tunnel for the Channel Tunnel project. The automated machine will have a similar

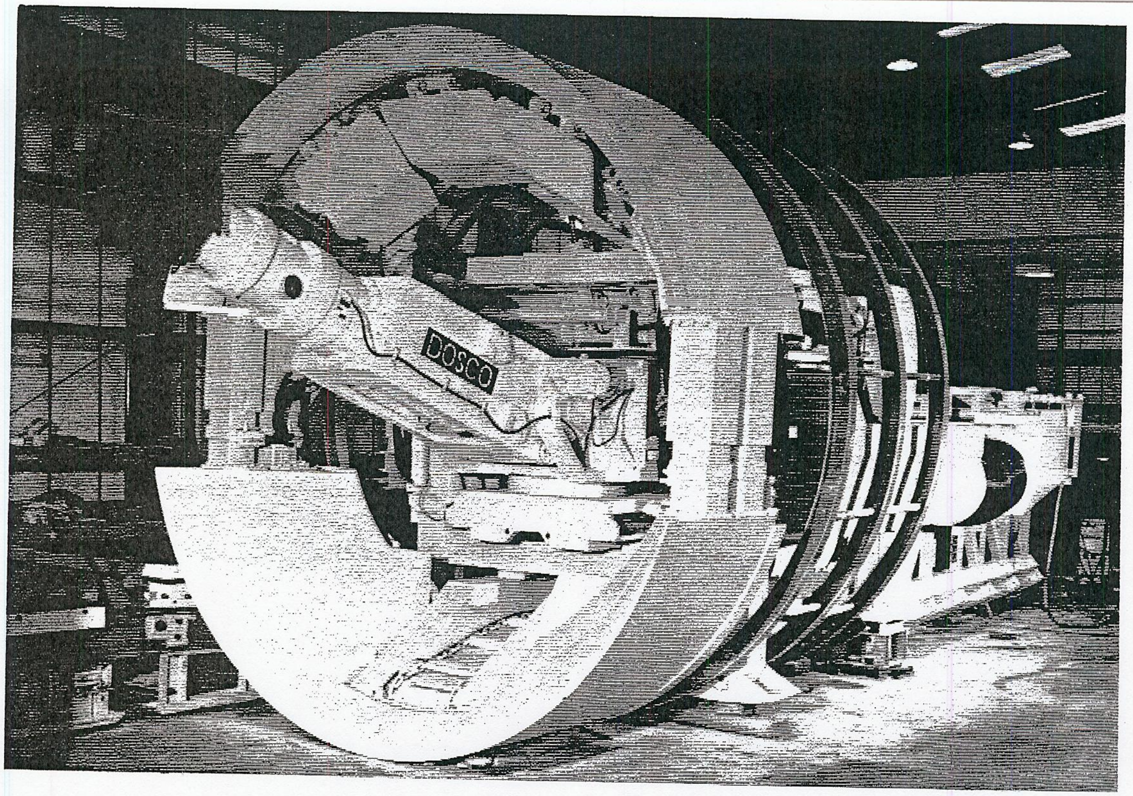

Figure 1 : Dosco CTM

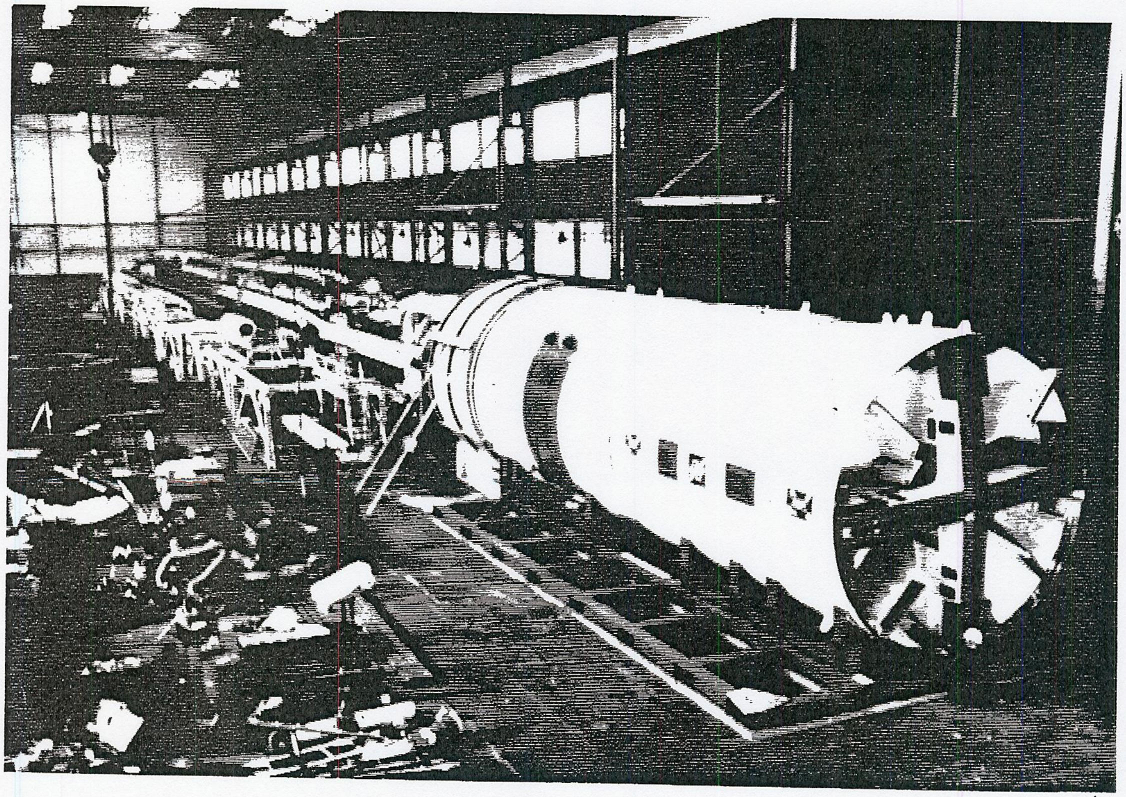

Figure 2 : James Howden TBM

performance requirement to the Dosco machine. However, disc wear is unlikely to be a problem given that the strata below the sea-bed is chalk marl. The cutting heads, steering and drive systems will be electrically powered so these facilities will require monitoring and there is a need for load control. Strata prediction ahead of the TBM is also a requirement; at present Howdens allow 8 hours/day for maintenance and testing the immediate strata ahead with a probe drill.

3.2 Guidance Navigation and Load Control

The robotic tunnelling machine requires highly accurate and continuous datum related to the tunnel line, grade and distance. Current laser-based reference systems achieve the required centre-line accuracy but suffer from the need for frequent repositioning and re-alignment. Inertial guidance systems suffer from drift unless frequently updated, are expensive and cannot currently achieve the required accuracy. The scanning laser technique appears to provide most promise although accuracy is currently a limitation and further development work is required.

The total concept of load control is contentious, particularly where relaxation of machine advance rate is the means of control. Hence, the concept of optimisation of 'applied energy' and 'wear and tear' for the maximum rate of advance has been proposed with the main objective being to 'tune' the machine to the rock conditions. There are a number of available developments involving the measurement of motor slip, torque, thrust or machine vibration.

3.3 System Integration & Communications

The tunnelling system should be considered equivalent to a manufacturing process in which the product is the tunnel. This integrated system will exercise hierarchical control via a management supervisory system communicating with 2 main sub-systems. An overall schematic of the integrated system is given in Figure 3. The machine sub-system will control functions in the vicinity of the machine, each function may need its own intelligence to be able to stand-alone and to communicate with its sensors via a high speed field bus.
The outbye sub-system will control secondary transport management, materials scheduling, services extension and debris disposal. The management supervisory system will communicate bi-directionally with both sub-systems and supervise all operations.

3.4 Specialised Instrumentation

An exhaustive study of methods of strata prediction indicated that no commercial sensor is available for direct application to a tunnelling system which requires information at a range of at least several metres ahead. Hence purpose built equipment is required, based wherever possible on existing developments. For example, ground probing radar is showing some promise, particularly since it does not need to be in direct contact with the rock. This type of sensor is more likely to be applied to a boom machine and a prototype could be constructed to meet a range of 5 - 10 m in shales.

Vision systems were studied for application to inspection, manipulator control, guidance and safety. Nothing was seen to be

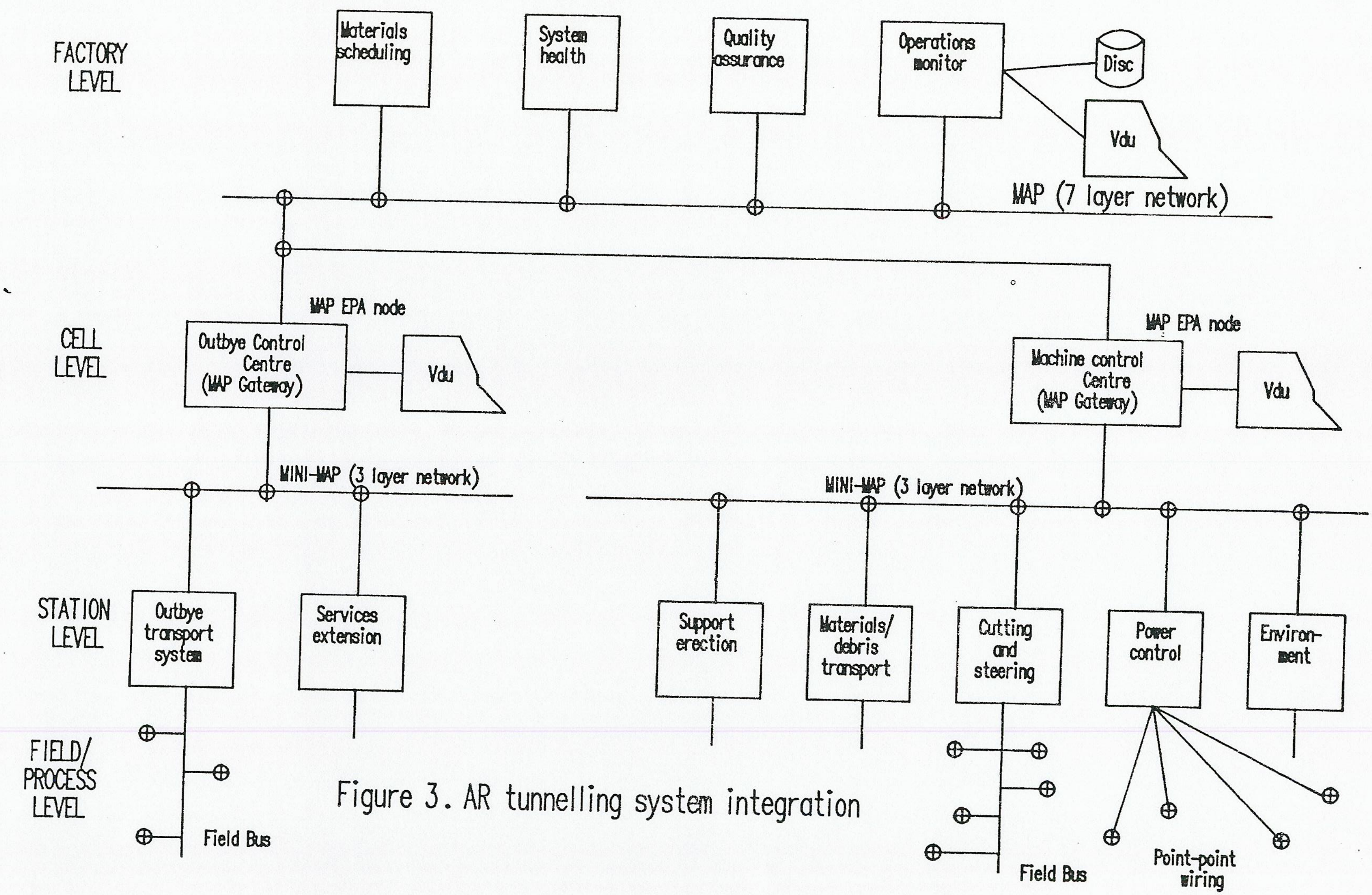

Figure 3. AR tunnelling system integration

directly applicable for remote monitoring apart from the use of cameras for inspection and collision avoidance. The special circumstances in tunnels such as inadequate lighting, dust and water will require specialised development which is unlikely to spin off from other industries. A development for vision systems would undoutably exceed the time scale of the project.

Robot manipulator sensors will be required for even the simplest tasks envisaged; tactile and proximity sensors are likely to be the most important to assist the manipulator in its first objective to reach and grasp objects. No suitable tactile sensor is commercially available but current multi-element types could be adapted using the most recent sensing materials such as conductive elastomers and forroelectric polymers. Proximity sensors based on ultrasonic sound or infra-red are common, inexpensive and accurate for ranges of less than 2 m. Adaptation for the mining environment and further development for longer ranges is required.

3.5 PDS Recommendations

The conclusions of the study start from the premise that firstly, a large world market for tunnelling exists and will be claimed by the most efficient operator and secondly, correct utilisation of tunnelling systems is low and that a programme of AR technical improvements would lead to an increase of both market and efficiency. A further programme of work is recommended with short (5 year) and long (10 year) projects.

The first phase of the short term project should use existing equipment to build and hold trials of a tunnelling system using a machine with automated concrete segment erection, machine guidance and navigation and sequential advance. The outbye services would include proprietary conveyor control, vehicle monitoring equipment and a materials scheduling system. Robotic systems required for this phase would use existing robot controllers and although most of the automated sub-systems would be independent, some attempt would be made to integrate data gathering. In parallel with this first phase, second phase projects should commence to address cutter tool wear measurement, continuous directional drilling techniques, strata prediction and load control. Within 5 years, the project should aim to demonstrate an integrated tunnelling system with semi-autonomous operation.

The long term project is highly speculative and depends on customer requirements and the success of the short term project. Therefore, the only projects to start immediately should be those related to full strata prediction and 'smart' sensors.

4. PROJECT REALISATION

Since early in 1989, four of the original collaborators have been committed to progressing the AR initiative based on a coal mining application to the project realisation stage. They are Dosco, Moog Controls, British Coal and ERA Technology with the collaborative group being strengthened by Southampton University to provide specialist experience in vibrational analysis and NEI to design the machine's power control systems.

There are two fundamental means of extracting coal at depth, one being the longwall method practised in the UK and the other being the 'room and pillar' method predominately practised in the USA. Both methods require the drivage of development tunnels for access to the coal seams and, in the current economic climate, it is essential that the tunnelling machines drive these tunnels in-seam, quickly and cheaply. In-seam drivages ensure that the machines continually mine coal (as opposed to some rock) and high drivage rates ensure fast face changeovers. Fast, reliable changeovers mean that the number of production faces operating at any one time can be kept to one or two; therefore, in coal mining worldwide, there is a need for development drivage to attract the same priority as coalface production. A continuous miner is a machine which has existed for many years, which produces rectangular in-seam tunnels. Clearly, the role of this machine is becoming increasingly important and there is a need to improve its performance and reliability through automation and AR techniques.

4.1 Project Objectives

Contrary to its name, the operations of the continuous miner are far from continuous, given the need to stop cutting in order to support the roof. There are two totally different means of supporting the roofs of in-seam drivages, one being based on steel arches which are designed to yield and the other being based on roof bolts which are designed to re-inforce the roof by bolting into competent strata. Recent advances in technology have promoted bolting as a fast, efficient and cheap method of roof support which will dominate future coal mining worldwide. Dosco has therefore identified a market opportunity to develop a machine which will provide continuous operation and the support of roof via bolting. The AR programme represents an excellent opportunity to develop a robotic machine with a worldwide market potential. Some of the robotic features will be equally applicable to some civil projects. The DTI is considering a proposal to automate such a machine at a total cost over £5 M and spanning 5 years to achieve a 100% improvement in performance coupled with semi-autonomous operation.

4.2 Mechanical Features

The AR machine will have to provide both sufficient power and mechanical stability to allow simultaneous operations of cutting and bolting. The machine will have at least 4 bolting stations which will need a stable platform to achieve the required accuracies of hole depth, width and position.

The development of a truly continuous miner needs to be parallelled by an equally continuous haulage system to remove the coal. Current fixed conveying systems suffer from stoppage for extension and the use of shuttle cars mitigates against continuous production. Other haulage systems which offer versatility and flexibility require manual control.

The AR machine also has to be manoeuvrable and able to negotiate turns as there is frequent need to develop cross-cuts. Consequently, the haulage system will need to be automated so that it is equally capable of forwards or backwards movement. Also, the mechanical design of the machine will have to accommodate additional instrumentation, particularly in the hydraulic circuits, to achieve the desired machine availability.

4.3 Robotic Features

The robotic continuous miner will need to comprise many of the sub-systems previously described in the PDS such as machine navigation, automatic support of roof, materials scheduling, product disposal, system health monitoring and communications. Given the change in type of tunnelling application, load control and materials scheduling systems will not be primary requirements.

Robotic elements central to the success of the project are as follows:

i) the development of manipulators and robot controllers for an unstructured environment;
ii) the automation of the roof bolting process;
iii) the development of condition-based maintenance using expert systems;
iv) the development of special sensors for the hazardous environment, such as strata prediction;
v) the provision of systems integration to international standards.

Items i) and iii) are especially challenging; there is a need to develop the technology of robotic multi-axis manipulators from an ordered, well-defined factory environment to the unstructured, hostile mine environment and the need to develop expert systems operating in real-time to monitor the condition of machine elements such as cutter wear, hydraulic circuits and system health.

5. CONCLUSIONS

The paper describes the progress of a collaborative group with an AR for tunnelling initiative as part of the DTI's AR programme. The studies have addressed various AR Technologies applied to a number of different tunnelling applications at different stages during the collaboration. The common theme is one of systems integration which is seen to be applicable to all tunnelling projects, whether mining or civil. The proposal under consideration by the DTI is both challenging and speculative but, equally, there is an excellent opportunity for the UK to increase its tunnelling market share.

6. ACKNOWLEDGEMENTS

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