A Reference Model, Design Approach, and Development Illustration toward Hierarchical Real-Time System Control for Coal Mining Operations

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CONTENTS

ABBREVIATIONS

Coal Interface Detection	CID
Continuous Miner (Continuous Mining Machine)	CM
Elementary Move	E-Move
Executor	EX
Job Assignment Module	JA
Intelligent Machine System	IMS
Intelligent Machine Unit	IMU
Mobile Control Structure	MCS
National Institute of Standards and Technology	NIST
Planner	PL
Real-Time Control System	RCS
Sensory Processing	SP
State Transition Diagram	STD
Task Decomposition	TD
World Modeling	WM
U. S. Bureau of Mines	BOM
U. S. Bureau of Mines Testbed and Communication Network	BOM/NET

A Reference Model, Design Approach, and Development Illustration toward Hierarchical Real-Time System Control for Coal Mining Operations[1]

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1. INTRODUCTION

Coal, the nation's primary domestic energy resource, accounts for over 50% of the total domestic electric power generation [Sc 89][2]. The availability and the cost of coal are vital to U. S. economic competitiveness. Coal mine safety is one of the key factors affecting the cost of coal production. The objective of safety improvement is therefore a primary motivation for conducting research in the area of computer-assisted coal mining methods.

In the underground coal mining environment (figure 1), one of the most hazardous areas is in the vicinity of the coal face (where the coal extraction operation takes place). A major hazard is the potential for roof falls, especially with unsupported roofs. Methane, which is very combustible, is hazardous due to the heavy usage of high-voltage equipment (up to 9600 volts) and various electrical/electronic devices. Methane is also lethal when inhaled in sufficient concentration. Methane content in the air must

[1]This work is sponsored by the U. S. Bureau of Mines under Interagency Agreement (J0189027).
[2]Denotes the references listed at the REFERENCES section of this chapter.

be tightly monitored and controlled through coordinated ventilation and sensor systems. Moving personnel away from the coal face is of top priority in terms of mining safety.

Figure 1: Underground Coal Mining Using a Joy 14CM[3] Continuous Mining Machine (Courtesy of the Joy Technologies, Inc.).

It is preferable to keep mine operators in remote and safer areas where the roof has been reinforced, the wall has been sprayed with fire-retardation rock dust, and ventilation meets federal and state regulation requirements. The operators may remotely operate and control mining machines with the assistance of sensory information, for example, with the use of coal-rock interface detection or camera vision display of face activities. They may also elect to allow the machine to automatically perform the cutting tasks and assume only the monitoring duty themselves. All these possibilities suggest that a computer-assisted coal mining system is required.

One charter mission for the National Institute of Standards and Technology (NIST) has been the advancement of U. S. competitiveness[4]. The NIST Robot Systems

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[3]References to product and company names do not imply Government endorsement.
[4]Designated 23 August 1988 when President Ronald Reagan signed into law the Omnibus

Division has been researching and developing a generic Real-time Control System (RCS) hierarchical architecture [Ba 84] over the last decade and has been applying RCS to various large-scale real-time control problems. The first RCS application concerned laboratory robotics [Ba 79]. Later RCS applications include the NIST Automated Manufacturing Research Facility (AMRF) [Si 83], the NASA Flight Telerobot Servicer (FTS) [Al 87], and the Defense Advanced Research Projects Agency (DARPA)/NIST Multiple Autonomous Undersea Vehicle (MAUV) [Al 88]. The current RCS projects include a federally-funded Initiative for Intelligent Machine Systems, a submarine automation demonstration project funded by DARPA, and the Air Force Next Generation Controller (NGC) project.

The underground coal mining operation system control problem that the Robot Systems Division is investigating under the sponsorship of the U. S. Bureau of Mines is an ideal application for RCS. This chapter summarizes our first effort (1988 through 1990) in utilizing RCS as a reference model for the construction of a hierarchical coal mining real-time control system. The primary objective of this effort is to establish the reference model and to describe the design method. Coal mining is a very complex operation which typically involves equipment, personnel, and process plants distributed across hundreds of miles. This makes full implementation of a computer-assisted mining system a very large undertaking. The NIST contribution to this problem is focused on the development of a system design methodology. Such a methodology will facilitate incremental implementation and integration, leading to an integrated coal mining control system.

An overview of the mining environment, along with term definitions and a brief description of the U. S. Bureau of Mines (BOM) testbed, are presented (in appendices A and B, respectively) for those who are not familiar with them. A description of RCS as a reference model in dealing with complex real-time system control problems is given. Research on the application procedures for the reference models has been undertaken. Preliminary research results are described in this chapter as the task decomposition methodology. The application of this methodology is illustrated (sections 4 through 8). The emphasis of the illustration has been put on a Joy 14CM continuous mining

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Trade and Competitiveness Act and thereon renamed the National Bureau of Standards to National Institute of Standards and Technology.

machine [Jo 82], as this is in line with the current research focus of the United States Bureau of Mines, as described in [Sc 89].

2. A GENERIC REFERENCE MODEL

The NIST Real-time Control System (RCS) architecture has been proposed as a reference model for the real-time control of coal mining operations [Al 89]. RCS can be viewed as an intelligent machine system (IMS) capable of reasoning and judging through the interaction with its sensory systems and in turn driving its actuator systems to achieve goals . Figure 2 shows a functional model for such an IMS. An IMS model consists of multiple intelligent machine units laid out hierarchically and performing their assigned tasks intelligently. Interfaces to an IMS include its sensory and actuator systems, as well as human interaction channels. Human interaction can technically reach all the intelligent machine units which make up an IMS.

A functional model describes the functionality of a system, but does not necessarily describe the organization of the software processes to be implemented. Sections 4 through 8 illustrate the application of RCS to underground coal mining. In implementation, each intelligent machine unit may be programmed as a controller node and performs the intelligent functions described in figure 2.

The essential elements of RCS, or an intelligent machine system, are described in the following sections:

2.1 The Definition of Machine Intelligence

Machine intelligence can generally be defined as the machine's capability to sense, perceive, organize, reason, plan and execute. However, the extent of intelligence a machine can exhibit varies. The minimum and necessary criterion for the machine to be regarded as possessing intelligence is its capability to close loops on the tasks that it performs.

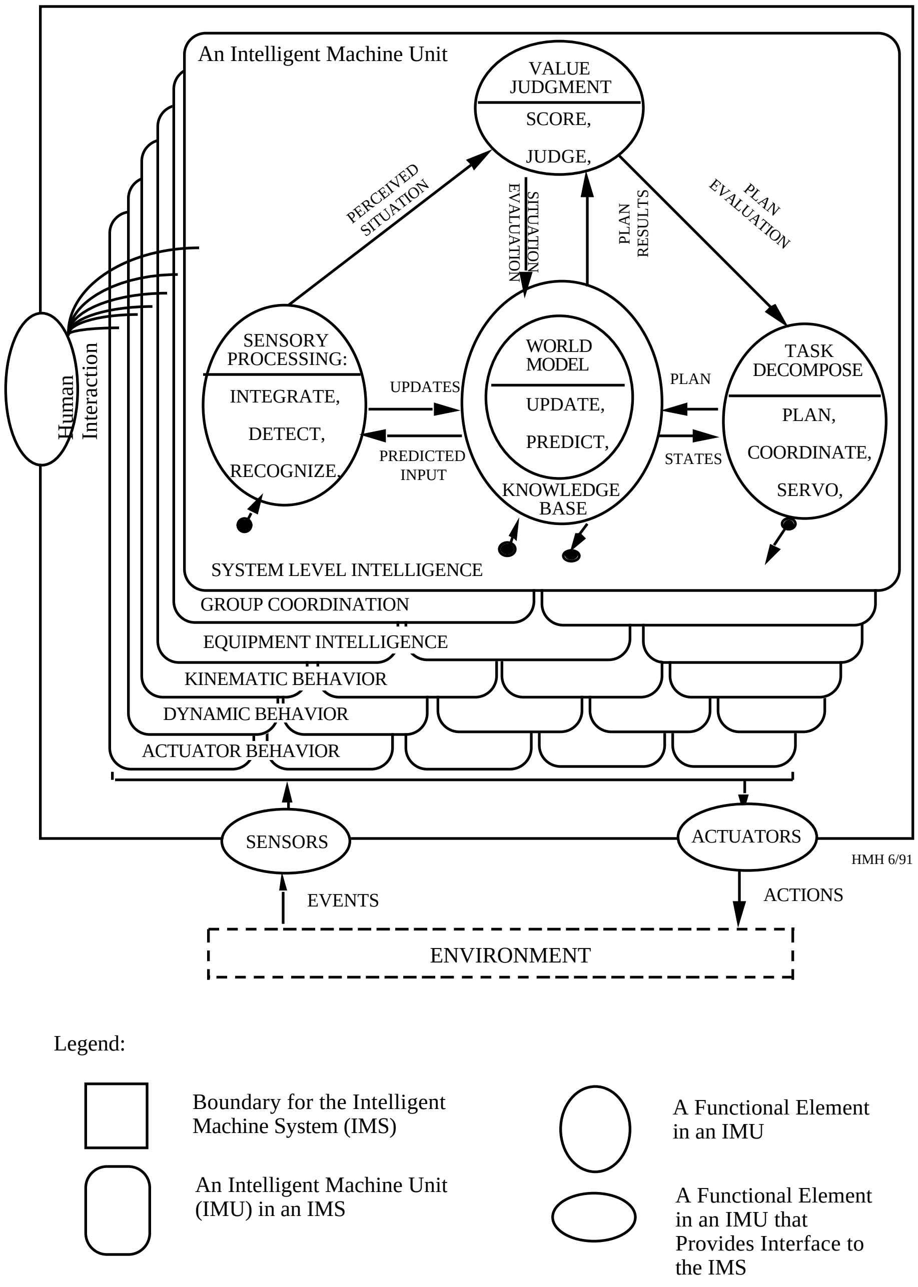

Figure 2: A Functional Model of an Intelligent Machine System

2.2 An Intelligent Machine Unit

An intelligent machine system consists of multiple intelligent machine units (IMU) organized hierarchically. Each unit is a self-contained entity performing assigned tasks through sensory interaction. An intelligent machine unit performs certain intelligent functions, namely sensory processing, world modeling, and value judgement (as described in sections 2.3 through 2.6) in its designated level of abstraction (section 2.8). All the units coordinate and communicate cohesively in a predefined model to achieve system goals.

2.3 The Task Decomposition Function

The RCS task decomposition (TD) function, as can be seen in figure 3, is responsible for planning and executing the decomposition of goals and/or tasks at each level of the system's hierarchy. Task decomposition involves both a temporal decomposition (into sequential actions along the time line) and a spatial decomposition (into concurrent actions by different subsystems). Therefore, it is sufficient to describe a task decomposition between any two successive levels as: the higher level sends down "what needs to be done," and the lower level generates "how it can be done." A brief description of the TD module is given below, whereas a more comprehensive discussion of the subject can be seen in [Al 89] and [Hu 90-1].

For the input task commands, the job assignment manager (JA) is responsible for selecting a proper execution command and partitioning the selected command into necessary spatially or logically distinct jobs to be performed by the corresponding physically distinct planners/executors.

Planning typically requires the evaluation of alternative hypothetical sequences of planned subtasks. The planner hypothesizes some action or series of actions. The world model predicts the results of the action(s). The value judgement module then determines the value of some evaluation function on the predicted resulting state of the world. The hypothetical sequence of actions producing the best value is then selected as the plan to be executed by the executor. State transition diagrams can be used to describe RCS plans.

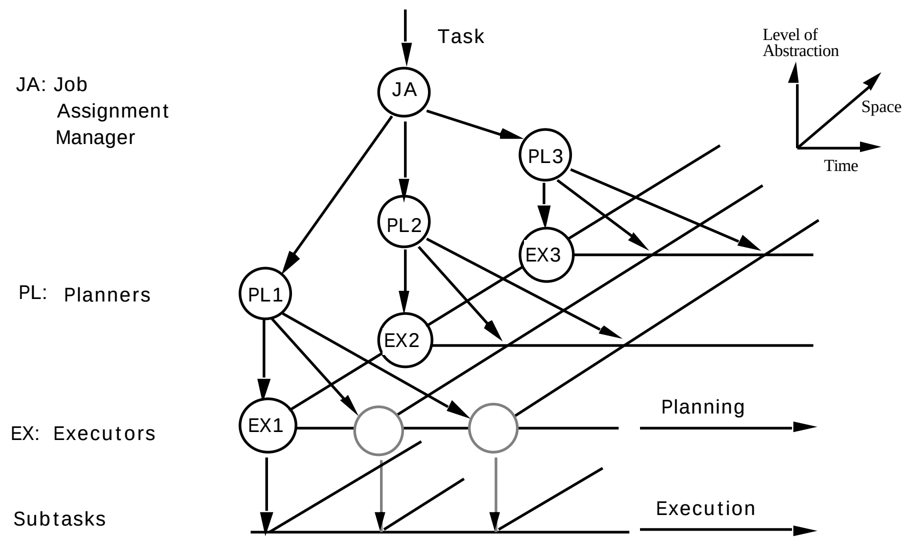

Figure 3: The Task Decomposition Function in a RCS Architecture

In general, an executor (EX) is responsible for successfully executing the plans prepared by the planners. The executor operates by selecting a subtask from the current queue of planned subtasks and outputting a subcommand to the appropriate subordinate IMU. The EX module monitors its feedback input in order to servo its output to the desired goal of the subtask activity.

Executor output also contains requests for information from the world model module and status reports to the next higher level in the TD module hierarchy.

2.4 The World Modeling Function and the Underlying Database

The major world model (WM) functions are to remember, estimate, and predict (see figure 4). The WM functional modules at various levels perform the following functions:

(a) Maintain the knowledge base, including the system's best estimated current state, possible future states, maps, lists of objects and events, and attributes of objects and events, and update it. The knowledge base is updated based on correlations and differences between model predictions and sensory observations (see figure 4). Such a knowledge base may be maintained as a distributed database.

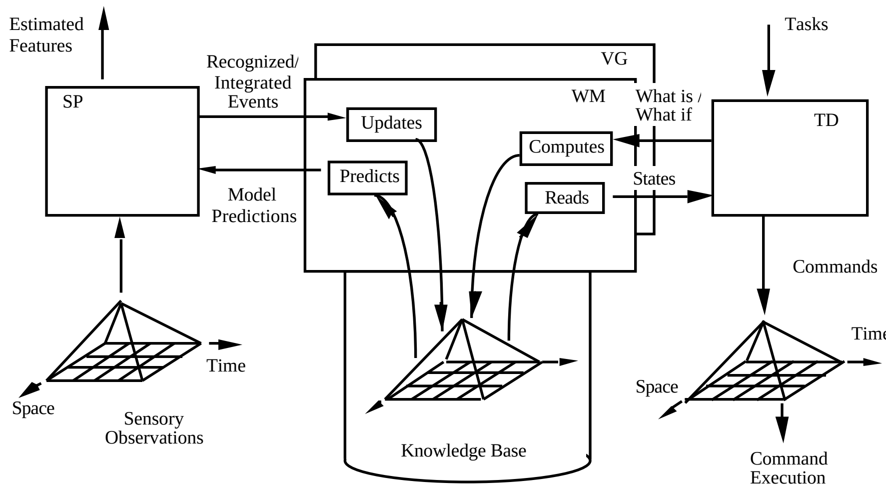

Figure 4: The World Model Function

(b) Provide predictions of expected sensory input to the corresponding sensory processing (SP) modules based on the state of the task and estimates of the external world.

(c) Answer "What is?" questions asked by the planners and executors in the corresponding level TD modules. The task executor requests information about the state of the world and uses the answers to monitor and servo the tasks.

(d) Answer "What if?" questions asked by the planners in the corresponding level TD modules. The WM modules predict the results of hypothesized actions.

2.5 The Sensory Processing Function

The sensory processing (SP) function recognizes patterns, detects events, and filters and integrates sensory information over space and time. As shown in figure 5, the SP function also consists of three sublevels which:

* compare observations with predictions
* integrate, correlate and difference over time
* integrate, correlate and difference over space.

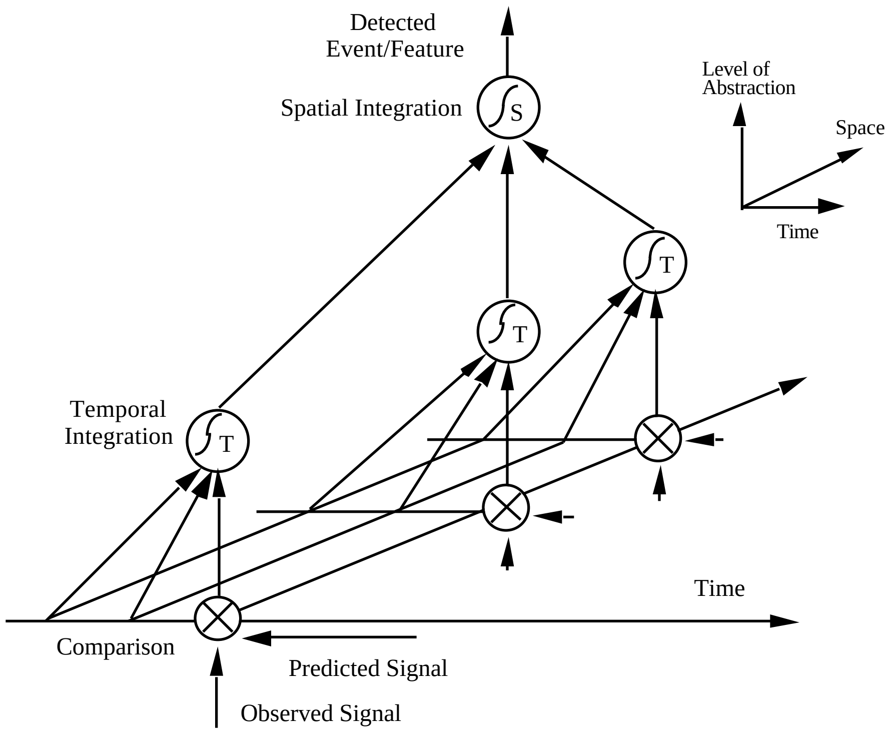

Figure 5: The Sensory Processing Function for an IMU: Comparison, Temporal Integration, and Spatial Integration

These spatial and temporal integrations fuse sensory information from multiple sources over extended time intervals. Newly detected or recognized events, objects, and relationships are entered by the WM modules into the world model knowledge base in global memory, and objects or relationships perceived to no longer exist are removed. The SP modules also contain functions which can compute confidence factors and probabilities of recognized events, and statistical estimates of stochastic state variable values [Hu 82].

2.6 The Value Judgement Function

The value judgement function evaluates the current situation and potential future consequences of hypothesized actions by applying evaluation functions to current states and to future states expected to result from hypothesized actions. The evaluation functions define a set of values over the state-space defined by state variables (typically globally defined). These evaluation functions can be used to compute priorities, cost-benefit values, risk estimates, and pay-off values of states of the world. Thus, working together with the world model, the planners are able to search the space of possible futures and choose the sequence of planned actions that produce the best value of the evaluation functions. The executors are able to apply value judgments to moment-by-moment behavioral decisions.

2.7 The Information Flow Model

The information flow model across intelligent units is illustrated in figure 6.

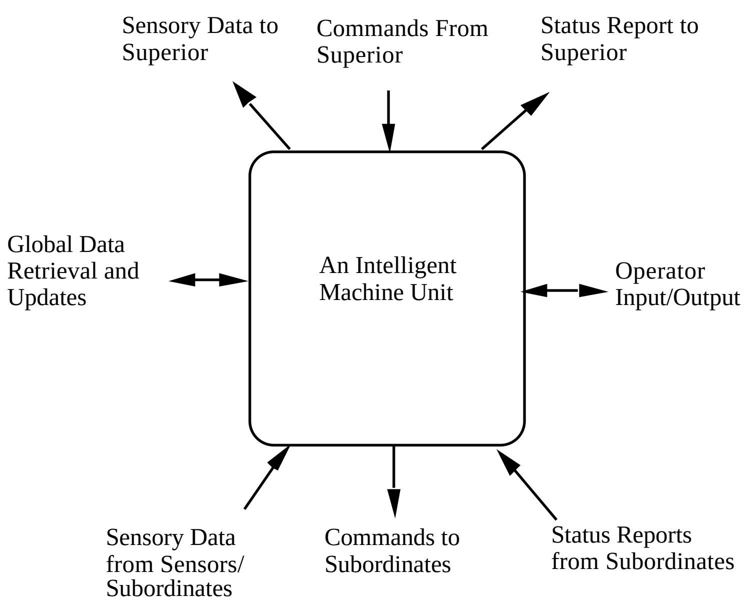

Figure 6: The Interface Model for an Intelligent Machine Unit

The other types of information flow, namely the information flow within the boundary of an intelligent machine unit, has been sufficiently described in figure 2 (the intelligent machine system functional model).

2.8 Level of Abstraction for Machine Intelligence Units

Intelligent machine units must be organized in a computationally stable and human understandable hierarchy. Transition of machine intelligence among the units at different levels must be smooth (as this is crucial to system stability and human understandability). A general philosophy for the formation of the RCS hierarchical levels (in order to achieve such smooth transitions) is described as follows:

(a) Facilitate Logical Decomposition of Tasks -- In executing a task, component dynamics should be computed before actuator commands can be generated. Kinematic consideration takes precedence over dynamic consideration. Therefore, RCS typically has a predefined actuator/servo level (level 1, or the lowest level) for performing actuator commands, a primitive level (level 2) for computing component dynamics, and an elementary-move (e-move) level (level 3) for computing kinematics. A more specific description is given later in this section.

(b) Achieve Consistency with Natural Spatial and Temporal Boundaries -- The existence of distinct physical entities dictates the need to have an equipment level in RCS. The fact that machines work together to form groups and groups coordinate to form super-groups dictates the need for multiple higher levels beyond the equipment level. In RCS, planning and response time intervals increase by roughly one order of magnitude per level (figure 7). This facilitates task planning and event summarizing, as well as smooth transition in task execution among different levels.

Figures 8 and 9, in combination, represent a control hierarchy for coal mining automation. In this hierarchy, a continuous miner (this term is used interchangeably with the term "continuous mining machine") is modeled as an equipment level controller. The major subfunctions of the continuous miner (CM) are modeled as its associated e-move level subsystems including guidance, coal cutting, etc., as shown in figure 9. The production level is created to deal with the large difference in planning

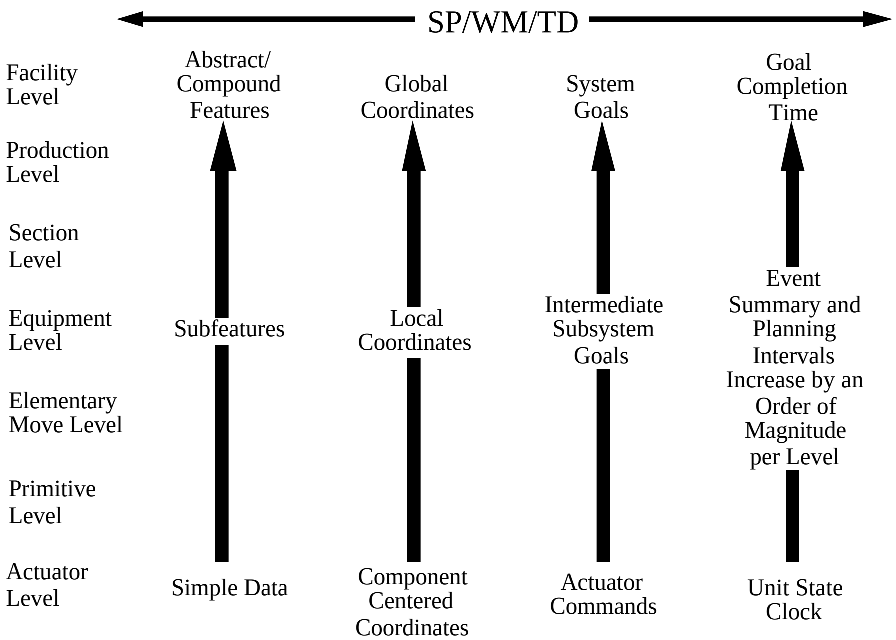

Figure 7: Transition in Temporal and Spatial Scales in a RCS Hierarchy

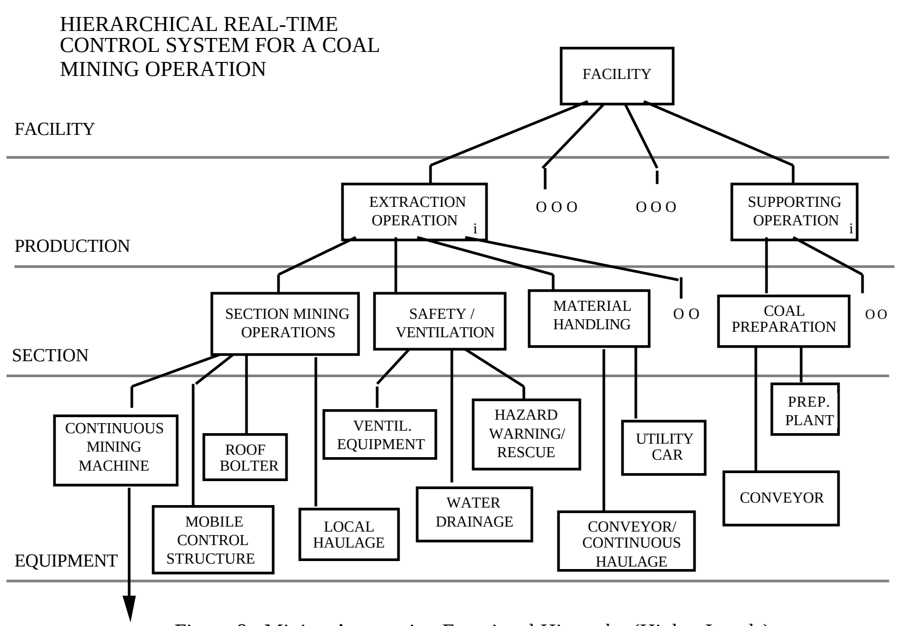

Figure 8: Mining Automation Functional Hierarchy (Higher Levels)

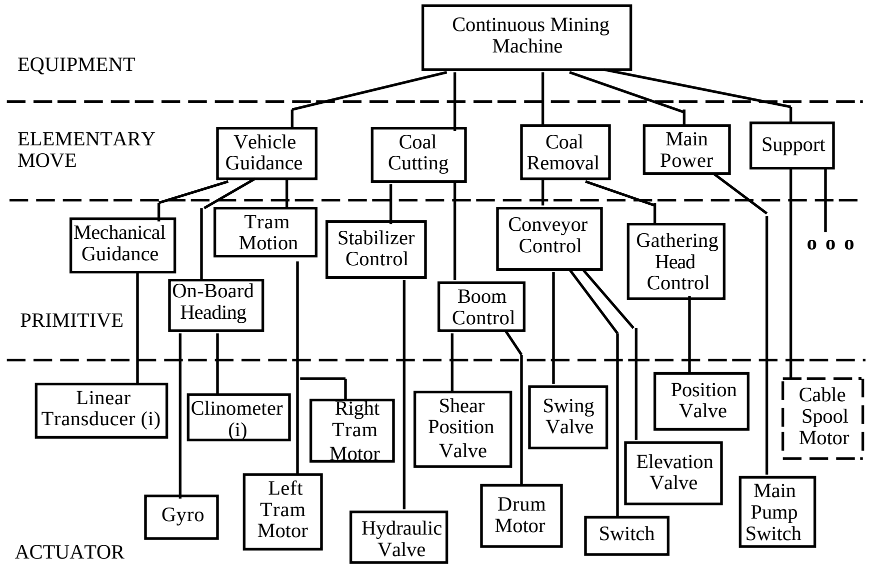

Figure 9: Mining Automation System Hierarchy (Lower Levels)

horizons between the section level and the facility level and to account for the fact that multiple extraction operations may run concurrently in a large coal mine.

The following levels are identified in RCS:

(a) Level 1 -- Actuator Level: The actuator level is the environment interaction level. The task decomposition function for this level is to generate electrical or hydraulic commands (for example, the cutting-drum motor motion control commands). The sensory processing function for this level is to receive signals from each individual sensor and process them, e.g., the gyroscope readings.

(b) Level 2 -- Primitive (Prim) Level: The primitive level is the dynamic control level. The task decomposition function for this level deals with all the dynamic computations, such as computing the maximum allowed time for a CM shear command. The sensory processing function includes sensory fusion from individual sensors and sensory data integration, which produces linear features for objects.

(c) Level 3 -- Elementary Move (E-move) Level: The e-move level is a kinematic control level. The task decomposition function at this level performs subsystem tasks, referred to as the "e-moves," that disregard force requirements (the reference to the mass of the bodies and the forces causing the motion differentiates kinematics from dynamics

[Ba 78]). As an input to this level, a navigation command might direct the CM to traverse from location A to B. In this case, the level above issuing the command is not concerned with how the navigation is done. Navigation commands are checked for obstacle avoidance, and collision free paths are generated. Other tasks (e-moves) are defined in terms of e-move subsystem actions on object features. All tasks are checked to be free of kinematic limits and singularities. For the sensory processing function, sensor data from each primitive level subsystem may be combined to produce surface features, feature distance and relative orientation, etc.

(d) Level 4 -- Equipment Level: The equipment level includes subsystems representing physical entities (e.g., a mobile control structure). However, multiple simple physical entities can be combined together to form a more significant physical entity which can then be modeled as an equipment level controller (subsystem). At the Marrowbone Coal Mine in West Virginia, scoop cars combine the functions of cleaning coal, spraying rock dust on mined surfaces, and transporting supply.

Tasks coming down to the equipment level are defined in terms of single pieces of equipment acting on single target objects (as compared to surface features at the e-move level).

(e) Level 5 -- Section Level: The section level subsystems perform coordinated group functions (this level can be referred to as the 'group level' in other RCS applications). For example, the section operation subsystem and the material handling subsystem perform tasks involving multiple pieces of equipment.

(f) Level 6 -- Production Level: The production level is an additional level created for systems either when the tasks are complex enough to require another level of decomposition between the top level and the group task level, or when there exist natural boundaries enclosing multiple 'group level' functions. In developing the hierarchy, it is envisioned that several extraction operations may be operating in parallel in a large coal mine, and each would need a 'set' of all section level subsystems.

(g) Level 7 -- Facility Level: The facility control level is the highest level that receives and executes overall mining operations orders, including compliance to mining plans.

2.9 Hardware

The hardware aspect of the RCS may include:

* the computer architecture, such as CPU boards and backplanes;
* the human interaction device specification (see section 2.10);
* the actuator system specification;
* the sensor system specification;
* the mechanical design;
* the physical arrangement of the workspace and the machine(s).

2.10 Human Interaction

Intelligent machine systems allow for human interaction at any level and at any "time" as long as such interaction is within restrictions imposed by synchronization and data integrity constraints. In other words, teleoperation, or "man in the loop" control, may be viewed as one mode of operation for intelligent machine systems. Human interaction may assume the following functions: control, observe, define goals, indicate objects, and edit programs and data.

2.10.1 Operator Interface

The operator interface provides a means by which human operators can observe, supervise, and directly control the mining equipment. Each level of the hierarchy provides an interface where the human operator can assume control. The task commands into any level can be derived from either the higher level TD module or the operator interface, or some combination of the two. Using a variety of input devices such as a joystick, mouse, trackball, light pen, keyboard, or voice input, a human operator can enter the control hierarchy to monitor a process, to insert information, to interrupt automatic operations and take control of the task being performed, or to apply human intelligence to sensory processing or world modeling functions such as entering or modifying a mining map. Advanced robotic hand controllers [Be 90] have also been developed which use the Bilateral Force Reflecting (BFR) control [Fi 90, Be 90] concept to efficiently perform dextrous control in teleoperation.

The operator interface terminals may also be used to provide output devices such as alphanumeric and graphic CRT's, printers, warning lights, or warning sounds. These output devices provide feedback to the operator and indicate the status of the systems and the result of the operator's intervention.

The operator interfaces also allow the human the option of simply monitoring any level. Windows into the global memory knowledge base allow viewing of maps of a section, geometric descriptions and mechanical and electrical configurations of mining machines, lists of recognized objects and events, object parameters, and state variables such as position, velocity, force, confidence levels, tolerances, traces of past history, plans for future actions, and current priorities and utility function values.

2.10.2 Design Considerations and Workload Analysis for Human Interaction Devices

Only properly-designed human input devices can enhance system performance, especially for intelligent machine systems that operate under hazardous or precision engineering environments. Human input device design considerations include fault tolerance, design redundancy, position/force bandwidth, and backlash. Fischer [Fi 90] gives an excellent discussion on this subject.

As previously described, humans can interact with essentially any module of a RCS. One factor affecting the design of human interaction is the workload that would be imposed on operators. Operator input must be entered in time so as not to delay (or even destabilize) the real-time system control. The types, amount, time of application and the locations (in the hierarchy) for human interaction and the physical layout of human interaction workstations must be analyzed so that coordinated and seamless human/machine operation can be achieved. Work load analysis methods (such as [No 88]) exist. Such methods may use matrices (of which one axis may represent task names and the other interaction channel names, as shown in figure 10) to label scores reflecting the relative amount of human activity and the degree of difficulty. These matrices may be used to develop a human interaction time series for analyzing human workload. The sampling periods for the time series may be made equivalent to the command execution time intervals. Richer time series (containing higher frequency information) may be obtained when multiple level commands are presented concurrently in the X-axis. A score higher than a user-specified threshold at any instance of time implies that either more interaction media are required, or the physical layout of the workstations may need to be re-configured to reduce the human interaction difficulty.

INTERACTION CHANNELS \ TASKS (Level of Involvement)	APPROACH FACE	SUMP	SHEAR	● ● ●
CONVEYOR TAIL JOYSTICK	0*	2	5	
JACK CONTROL SWITCH	1	0	4	
TRAM CONTROL BOX	5	5	4	

*Note: The numbers are for illustration only and may not reflect the actual situations.

Figure 10: An Example of Workload Analysis Matrix

3. The RCS Task Decomposition Methodology

There are different paradigms which can be used to develop software systems, such as information (data) modeling, object oriented design, functional decomposition [Co 91], or task decomposition. While different paradigms may be suitable for different types of problems, task decomposition based methods seem to be powerful for goal driven intelligent machine systems (systems that perform required tasks to achieve assigned goals). Therefore, a RCS task decomposition methodology is being developed to facilitate the implementation of the intelligent machine systems.

Note that in the RCS context, the term "task decomposition" has two layers of meaning:

* the characterization of system behavior in the design phase -- the task decomposition "methodology;"

* the execution of the defined tasks at each level of the hierarchy during the operation phase -- the task decomposition "function."

A Real-Time Control System (RCS) interacts with the environment at its highest level to receive a compound goal, and at the lowest level to act on the environment to achieve the goal. Internal to a RCS, hierarchical and heterarchical (within a level) task decomposition occur, both temporally and spatially. Task decomposition between any two successive levels may be described as follows: the higher level sends down "what needs to be done" and the lower level generates "how it is to be done."

The task decomposition methodology can involve an iteration of the following steps: establish the context, develop an organizational hierarchy, perform task analysis, and develop RCS plans. These steps are described in the following sections.

3.1 Establish the Context

In designing a RCS, the definition of context is the first step. Generally in this design step one seeks to achieve the following goals:

3.1.1 Define the System Objectives and the Problem Scope

The following questions must be answered first in designing an intelligent mining system:

* What are the typical highest-level tasks? Would they be as high level as "produce X tons of coal in Y months" or as low level as "perform a 5 meter cut?"
* What is the interface between the intelligent system and the environment? What are the sensor and the actuator systems involved?
* Which functionalities of the system are to be developed first? Is the automation of the CM of top priority? Is the automation of coal preparation plants of any priority?

* Does the physical equipment already exist, or is the specification or mechanical design of the physical equipment a part of the design?

  If the equipment for the underlying system essentially exists, then a description of the equipment must be given, and one must design the system intelligence according to the machine capability. In this situation, the intelligent machine system design problem emphasizes the software aspect.

  If the equipment does not exist, the system design problem additionally includes the mechanical system design and the specification of actuator and sensor systems that will meet the system objectives.
* What are other constraints and the assumptions? For example, the federal and state regulations must be abided by.

3.1.2 Describe the Approach Selected to Achieve the System Goals

Scenarios are often developed to describe typical operational descriptions. Scenarios may be viewed as the pivotal statements relating the external physical system behavior to the internal machine intelligence description. Domain experts would develop scenarios describing how the physical equipment should operate to affect the environment and achieve goals. IMS experts design machine intelligence to command the equipment to operate accordingly.

3.2 Develop an Organizational Hierarchy

A first sketch of the system's architecture is developed to serve as a foundation for further design work. Such a hierarchy, shown in figures 8 and 9, takes into account the system goals, the environment, the existing facility, and other factors such as the pre-defined functional requirements for each of the RCS levels. The following is a set of guidelines for developing a RCS hierarchy.

3.2.1 Autonomy and Modularity

The RCS methodology emphasizes maximizing the autonomy and the modularity of all subsystems. To achieve subsystem autonomy and modularity, the hierarchy is developed so that each function (such as the conveyor control function at the primitive level, or the section mining operation at the section level) has a closed loop at the lowest practical level. By doing so, independent (autonomous) control modules are formed. Subsystems may themselves be composed of several hierarchical levels. Each level of functional decomposition includes sensory information input, data storage, data manipulation routines, state space models, control laws, and output commands. Sensors and actuators are connected through SP, WM, and TD modules to form a closed loop. At each level, a loop is closed through the SP, WM, and TD modules at that level, so that the control hierarchy forms a set of nested control loops. The loop bandwidth decreases about an order of magnitude per level from the bottom to the top of the hierarchy. Therefore, the autonomy and modularity guideline promotes self-sustained modules and locally maximized communication traffic as well as system extensibility.

By closing the loops at the lowest practical levels, changes in any module would have minimal effects on other modules. Without this autonomy and modularity approach, data queries may logically pass through longer routes [Hu 90-2].

3.2.2 Hierarchical Levels and Their Pre-Defined Functional Requirements

The hierarchical level definitions and their functional requirements established in section 2.8 laid out the skeleton of an intelligent machine system control hierarchy. Existing equipment can be placed on the hierarchy according to its functionality. Additional controllers can then be designed and added as the system control dictates.

3.2.3 System Goals

The goals for a system determine the top level of the hierarchy. NIST's viewpoint is that the ultimate goal for the coal mining industry is to have a functionally integrated coal mining system. Therefore, a facility control level is required as the highest level for the control system, as shown in figure 8.

3.2.4 Operation Requirements and Functional Coherence

The closely coupled face area operations in a coal mine dictate the need for a section mining operation subsystem at the section level to coordinate operations such as coal cutting (performed by CM's), coal haulage (performed by shuttle cars or continuous haulage units), bolting (performed by roof bolters), etc. In another example, the elementary move level is developed by observing the major operations of equipment (figure 9).

3.2.5 Concurrent Computing Timing Requirements and Software Module Size

The order of magnitude criterion (figure 7) may affect the development of the hierarchy by constraining the sizes of the software modules. It may not be suitable for the actuator level modules to be involved in heavy computation.

The synchronization requirements may also affect the hierarchy development. For example, in the continuous miner (CM), the fact that the cutting drum motor should be turned on before the machine can sump in the coal face implies frequent synchronization will be required. Therefore, these operations should be performed by two parallel subsystems belonging to the same parent subsystem.

3.2.6 Existing Facilities and Resources

The NIST research effort, as part of the U. S. Bureau of Mines (BOM) underground coal mining automation research project [Sc 89], must utilize existing equipment (the CM, laser range finders, gyroscopes, clinometers, etc., see [Sh 90]) specified by the BOM Pittsburgh Research Center [Sc 89]. This implies the existence of certain equipment and actuator level subsystems as a baseline for the development of the RCS. Other existing resources include software, such as BOM/NET (see section 4.2.1 and appendix B) communication protocol and the expert system machine diagnostic systems

[Mi 89]. As the system development effort evolves, software reusability and generic software components may become significant concepts in managing software resources.

3.2.7 The Coal Mining Environment

The complexity of coal seam formation may affect the requirements of the coal interface detection (CID) subsystems and algorithms, and in turn affect the structure of the hierarchy.

3.2.8 Other constraints

For the mining industry, low cost but effective and reliable devices are preferred over high cost, state-of-the-art computers or equipment.

3.2.9 Contradictions

Violations to the autonomy and modularity guideline can be seen when different guidelines are applied simultaneously. The BOM's laser system is used to provide range data for the continuous miner (CM), but it is physically located on the mobile control structure (MCS). The MCS has been defined as an equipment level subsystem in a RCS structure (parallel to the CM subsystem), which is consistent with the "hierarchical levels and their pre-defined functional requirements" guideline. However, this violates the "autonomy and modularity" guideline for not closing the guidance control loop at the e-move level. The CM vehicle guidance e-move subsystem has to get range information through the section level (a longer route), which coordinates the CM and the MCS.

3.3 Perform task analysis

Knowledge necessary to perform tasks, including the machine capability and the operational environment, is acquired and assimilated along the following lines: what are the activities each control module can perform, what are the associated constraints, and what is the information required to perform a given task? Task commands for each module at each level are developed in this design step.

In hierarchical real-time control, the system's overall goal or task is received at the highest level. The goal is decomposed into detailed tasks at lower levels and is executed by controllers at and for those levels. To achieve this, each level's functions must be identified first. Machine activities (and system activities at the higher levels) have to be defined specifically by means of a complete list of task commands. Task command definition involves the way each individual machine behaves, as well as the way machines coordinate among themselves. The combination of individual behavior and cooperative behavior specify the system's capability.

Task analysis seeks to resolve the following questions for a system and its subsystems: what tasks are implied, how can these tasks be performed, and what are the requirements and constraints of the system. In particular, when multiple subsystems are involved, the complexity of cooperative behavior makes the definition of system and individual machine activity even more necessary. Issues involved in performing task analysis are discussed in the following sections.

3.3.1 Spatial Coordination Strategy

The spatial coordination strategy determines how individually automated machines cooperate. The spatial coordination strategy is a crucial step in achieving system integration. One example is the alignment problem between a haulage unit and a continuous miner at the face area.

The criteria for the alignment may include the relative angle between the center lines of the machines, the clearance for the machines at their facing ends, and the CM conveyor boom positions. The alignment criteria are affected by the types of the on-board sensors as well as the type of haulage units used. If shuttle cars are used, then the coordination strategy would be defined as:

(a) Prior to cut: The shuttle car will make proper maneuvers to align to the CM. The minimum requirement for the shuttle car is to stay within the CM conveyor boom's reach, so that the CM conveyor boom can be positioned.

(b) During the cut: The shuttle cars will make simple maneuvers (such as straight forward or backward) to keep pace with the CM. The CM, while in its CUT-LOAD-PAUSE state, will activate a COAL-LOAD e-move command to swing the boom according to the actual alignment pattern to load the coal efficiently. A 'pause' signal will be sent to the CM if the shuttle car is not aligned properly.

See section 5.8 for the other case (when continuous haulage units are used).

3.3.2 Real-Time Planning vs. Predefined Script Planning

In a real-time planning application, the generic plans can be described in advance by using state transition diagrams, but the selection of plans and the computation of the target values for the involved state variables are done in real-time based on sensory feedback information. Replanning may also be necessary when the system does not approach the goal as expected by executing the preselected plan. On the other hand, a more primitive format for task planning is to have pre-defined scripts. Capabilities such as plan selection and replanning may not be available when a system is built using scripts.

3.3.3 Emergency Reaction Capability and Level of Intelligence

The emergency reaction capability of each machine when encountering unexpected problems has to be considered. Do all machines contain the same level of intelligence, or are there one or two dominant machines? For example, the haulage system may only be able to react to certain given commands whereas the CM is able to resolve more complex situations involving the haulage system, and may send commands to the haulage system to resolve the haulage system's problem.

3.3.4 Coordinate Reference Frames, Map Resolutions and Level of Abstraction

In RCS, higher levels are concerned with larger work areas but coarser resolution (figure 7). In general, at the higher levels, a global coordinate frame is used, and at the lower levels, machine centered local frames are used. In a global frame, further subclassification in terms of resolution typically is required for different levels. Therefore, successive transitions in coordinate frames and/or resolutions can be seen among different hierarchical levels. A mining operation can be specified by the production tonnage required at the highest level. Tasks are then decomposed at a lower level; to accomplish numerous subgoals, at some level a task may be defined in terms of commands to produce coal in a certain area of the coal seam, while at a lower level tasks are decomposed in terms of the coordinate positions where coal is to be cut. A mobile control structure coordinate system may be used at this level. At even lower levels, the mining sequences are defined as to the number of cuts to make, the number of sumps to make, all the way down to the amount of tram motor current needed for the tramming distances involved (refer to appendix B for more detail on the term "tram").

Lower-level tasks must also deal with functions to be performed in a three dimensional world. For example, lower-level coal mining tasks must be concerned with the height of the coal seam to be cut and with transforming commands from higher level tasks requiring the cutting of coal (of some thickness) into tasks defined in terms of an initial boom position angle and the number of degrees of shearing angle to cut.

RCS, in most cases, is flexible as to which reference frame each level should use. But the key point is that at the highest level, a global coordinate frame is used, and at the lowest level, the individual actuator coordinate frames are used. Developers should be aware that coordinate transformations are used throughout a RCS design in order to simplify computations and to facilitate sensor fusion and model matching.

3.3.5 Task Command Complexity for Different Levels

Similar to the above discussion in which higher levels are concerned with larger areas but coarser resolution, higher level tasks also cover a greater period of time but less spatial and temporal detail. The section level receives tasks which treat the mine section as a whole. Section level tasks contain all coal extraction related actions, such as continuous mining, bolting and haulage, and they are subsequently decomposed into equipment tasks. These activities for different equipment are coordinated by the section level. The equipment level receives tasks involving work to be performed on objects (coal, roof strata, etc.), by each machine (as an entity) in the section. The equipment tasks are decomposed into subsystem tasks (e-moves) and they are sent as inputs to the elementary move level. E-moves are symbolic commands expressed in terms of motion. Machine primitives (outputs from the e-move level) deal either with the same subsystems as the level above or with further decomposed subsystems, but they deal typically with shorter ranges. The outputs of the prim level may have the same or a finer scale (in complexity) compared to this level's inputs. However, they all have system dynamic characteristics attached as part of the command parameters. The actuator level converts primitive level outputs to action commands, such as opening a pilot valve to pressurize the cutter head hydraulic system, so that the shear operation can be activated. This valve will be closed when the desired shear angle is reached.

3.3.6 Existing Constraints, Existing Practices, and Flexibility

The existence of certain equipment dictates the existence of certain fixed tasks. Examples can be seen in the actuator level, where capabilities of the valves, motors, or sensors are basically fixed, and thus their definitions can be viewed as the descriptions that conform to the existing capabilities. Examples can also be seen in the primitive level, where the Joy 14CM tram control (machine movement control) can have only ten hard-wired commands. Regulations comprise another type of existing constraint. For example, at the section level, ventilation has to be set up before the CM can operate at the coal face. Therefore, these two task commands must have synchronization built in. Thus, the problem is bounded by existing constraints, but the designer is free to define tasks within these specified problem boundaries.

Existing mining practice may be used as a reference to identify task commands. For example, the sump-and-shear cycle (see section 5.6) is such a typical mining practice that the sump and shear commands described in this paper correspond to it. However, the reference model does not intend to entirely follow the existing practice. The RCS "section mining operation" (figure 8) subsystem is responsible for fewer pieces of equipment than a section foreman [Us 68]. The distinguishing criterion is the computing efficiency versus human control efficiency.

All these issues (sections 3.3.1 through 3.3.6) are addressed during the performance of task analysis. Each task command contains a set of parameters and a description (the coordination method, the coordinate frames, etc.) which can be used to develop RCS plans.

3.4 Develop RCS plans

Task commands defined above are used to develop RCS plans using state transition diagrams. These RCS plans describe how higher level tasks are decomposed into lower level tasks, and how the constraints for the commands are implemented as transition requirements among the different states.

3.4.1 The Description Language: State Transition Diagrams

State transition diagrams (STD's, see figure 11) are used in task decomposition, plan description, and machine activity description. One assumption of STD's is that the system's states will not change unless all transition requirements are met and that no action will take place until all activation prerequisites are met. Generally, there is a one-to-one correspondence among a 'state,' a 'command,' and an 'activity.' In other words, the system enters into a certain 'state' causing a corresponding 'command' to be executed and the corresponding 'activity' is exhibited. A similar one-to-one correspondence also exists between a 'transition condition' represented by a status data set and an 'event' occurring in the external world.

In a state transition diagram, a bubble with an enclosed name is used to represent a system's state (and the implied command to be issued to the next lower level). The edges with arrows pointing toward or away from a bubble are used to describe the system's state transitions. Together the bubbles and edges completely describe how the system is to enter, stay, and leave any particular state (by following the direction of the arrows). Each edge has a definition attached to it and is typically described internally by a condition list which contains multiple special flags, predicate function values, or other aspects of the system's status.

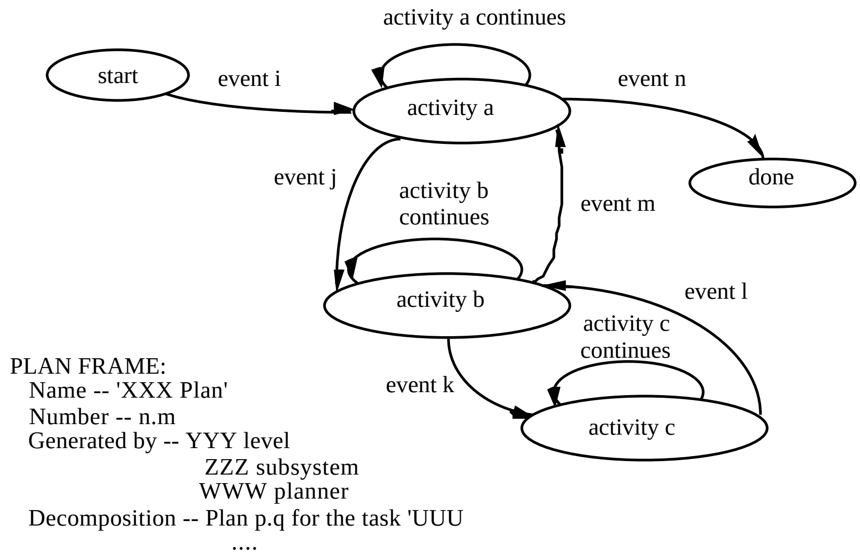

Figure 11: A State Transition Diagram

One general assumption in the state transition diagrams is that each command has a timeout limit. If the command can not be accomplished within the time limit, the system automatically branches out to a 'suspend' state and fault reports are issued. Proper actions need to be taken either by human intervention or by certain emergency recovery processes such as the executor emergency planning routines. The execution of the commands is also subject to interventions (generated by either human or computer) that prompt certain commands and send the system into alternate modes of operation.

3.4.2 RCS Plan

A RCS plan can be described by one or a series of STD's. The TD module for any controller has a job assignment (JA) manager and a planner (PL) which decompose tasks for the next lower level subsystems (or actuators) that it controls. The JA and PL generate (or select) plans for the subordinates. The commands in the plans are passed down sequentially by the executor (EX) associated with the JA/PL to the JA of the next lower task decomposition modules (or to the actuators).

3.4.3 Plan Frame

Each state transition diagram uses a plan frame notation which includes the following information slots to identify the plan (see figure 11):

* Plan Name -- The name of the command to be described by the current state transition diagram is used as the name for this plan.
* Plan Number -- The first segment is the number of the level which generates (not executes) the plan. It is followed by a dot and a second segment which is a serial number. More segments may be needed if the complexity of the system grows.
* Generated By -- The module generating the plan is described by
    - the name of the hierarchical level
    - the name of the subsystem
    - the name of the functional module.
* Decomposition -- This slot cross-references the commands associated with each state on the current diagram to the corresponding next lower level diagrams.

An optional "Description" slot can also be inserted to describe the activity.

4. METHODOLOGY APPLICATION: THE CONTEXT DEFINITION AND THE HIERARCHY DEVELOPMENT

The following sections (sections 4 through 6) illustrate the application of the RCS task decomposition methodology to an underground coal mining operation. This section defines the context of the application.

4.1 General Problem Definition and the Developed Hierarchy

A control hierarchy has been developed (shown in figures 8 and 9). A vertical swath is selected within the hierarchy to demonstrate the RCS development process. Such a swath includes (from the top down in the figures) the extraction operation controller, the section mining operations controller, the continuous mining machine controller, the vehicle guidance controller, the tram motion controller (see appendix B), and the tram motor controllers, with vehicle guidance being the focus.

A description of the main piece of equipment used in this process, a Joy 14CM continuous mining machine, is given in appendix B as part of the problem definition.

4.2 The Context for the Vehicle Guidance Controller

The primary responsibility for the vehicle guidance controller is to move the machine to desired locations. During the performance of vehicle guidance, problems including tread slippage along the lateral or rotational directions may be encountered. Vehicle guidance is a fundamental problem in that it interacts with other aspects of the machine control/mining process (such as the control of the conveyor boom and the cutter drum). Therefore, issues such as problem scope and developing a typical scenario all have to be resolved before task analysis can be performed.

4.2.1 Scope for Vehicle Guidance

Closed loop tramming for continuous mining machines may be categorized into the following two types: navigation (free-space tramming) and cutting. The current focus for free-space tramming is in the vicinity of the face area. Obstacle avoidance is assumed to be a human operator function. The current focus for cutting tasks is on the first pass of a cut (see appendix A).

The scope of the vehicle guidance controller is further defined by existing constraints and assumptions (they are also important references for the vehicle guidance controller to be integrated into the overall system [Sh 90]). The following pre-conditions apply in this vehicle guidance controller design:

* A coal haulage unit is available to transport coal to a main coal transportation conveyor system.
* No obstacle avoidance is involved.

* No Coal Interface Detection (CID) system [Sc 89] is employed. The formation of the coal seam to be cut is assumed to be regular and in extractable condition.
* The machine will pivot only to adjust its orientation (the term "yaw" is used interchangeably with "orientation"). Assume that the pivot action does not change the position of the machine.
* The pivot point for the machine is used as a reference for the machine position.
* The CM uses only the slow tramming speed for the purpose of simplicity.
* This vehicle guidance function must be integrated into the existing BOM testbed, BOM/NET (appendix B). The BOM/NET system includes a set of low level computer commands for tramming control. Therefore, the low level constraint for vehicle guidance is that its output should be compatible with the BOM/NET command structure and specification.

The vehicle guidance controller can assume additionally the existence of the following conditions if it is commanded to perform a cutting task:

* The coal seam has been surveyed and the cutting location identified. A cutting path coordinate system has been defined (see section 5).
* The machine is assumed to be located at the origin of the cut coordinates.
* Adequate machine power for the electrical, hydraulic and mechanical systems exists.

4.2.2 Scenarios for Vehicle Guidance

In order to accomplish navigation (free-space tramming) tasks, the continuous miner (CM) will be given goal position coordinates. The machine will then tram to the position through sensory interactive, closed loop control. Typical machine movements include pivoting and pointing the machine towards the position, and tramming-forward to approach the goal. Section 5.3 describes the error control issue.

For cutting tasks, the machine will receive a desired cut distance and repeat as many times as necessary a so-called sump-and-shear cycle. This includes the following primitive functions: approach the face, sump into the coal face by tramming forward, shear coal by moving the cutting drum down to the floor, gather the cut coal and move it to the rear of the machine, and cut the remaining coal on the floor while tramming in reverse (see sections 5 and 6 for definitions). Similar error control (as in free-space tramming) is used. However, more frequent correction activity is expected (due to the cutting process).

A combined scenario may include first a navigation task to move the machine to the coal face followed by a cutting task to extract the coal.

5. METHODOLOGY APPLICATION: TASK ANALYSIS

The discussion for a Continuous Miner (CM) and related section level and operation level task commands is included in this section. The description includes a minimum set of commands required for the system to perform automated operations. Therefore, the described task commands include:

* those commands that the current equipment is not capable of performing, but which are desirable for automation purposes; and
* those commands that are currently performed by human operators.

Some planned commands are listed without detailed description, either because the current equipment does not have such capabilities, or because more systematic investigation is needed before these tasks can be defined. In either case, they will be incrementally implemented as longer term project objectives.

5.1 General Coordinate Frame Transition

As described earlier, successive transitions in coordinate frames or resolutions can be seen among different levels in hierarchical control. Appendix A provides additional information defining the terms used here to describe the coal mining environment. The following is an example of such coordinate system transition:

* Panel/Room. At a higher level, a mine map may refer to objects such as panels (see appendix A). Further detail within a panel is not of concern at this level.
* Pillar ID, Entry Number. At a lower level, a map typically has a finer resolution. Objects within a room, such as a certain pillar or a certain entry, will be referred to.
* Representation of Pillars. At another level down, pillars may be represented in more detail. The shape of pillars may be represented in vectors (polygons) or in an array referring to a common coordinate system in a room.
* Path Coordinate System. A convenient way to simplify data manipulation is using local frames originating at the starting point of a cut or a free-space tramming task. See section 5.2 for more detail.
* Actuator Coordinate Systems. At the lowest level, actuators typically have their own local references, such as voltages or stroke of hydraulic cylinders.

5.2 Path Coordinate Frame

Since vehicle guidance is the focus of this application, its particular coordinate system is described in detail in this section. The vehicle guidance controller uses a local path coordinate frame originating at the starting point of either a cutting or a free-space tramming task to simplify computation. The vector from the starting point to the goal is used as the forward (or Y) axis (figure 12). The starting point for a cut is set at a point such that the cutter drum is about one meter away from the coal face. At this point any necessary (albeit minor) adjustment of the yaw of the machine can be made to allow the machine to line up with the direction of the cut.

5.3 Vehicle Guidance Analysis

Vehicle guidance is responsible for the motion control for the CM's. When the control algorithm is designed, the following questions have to be answered:

* How does the machine behave given its mechanical/electrical/hydraulic design?

- * What are the tasks that the machine must perform?
- * What is a natural hierarchical organization of those tasks?

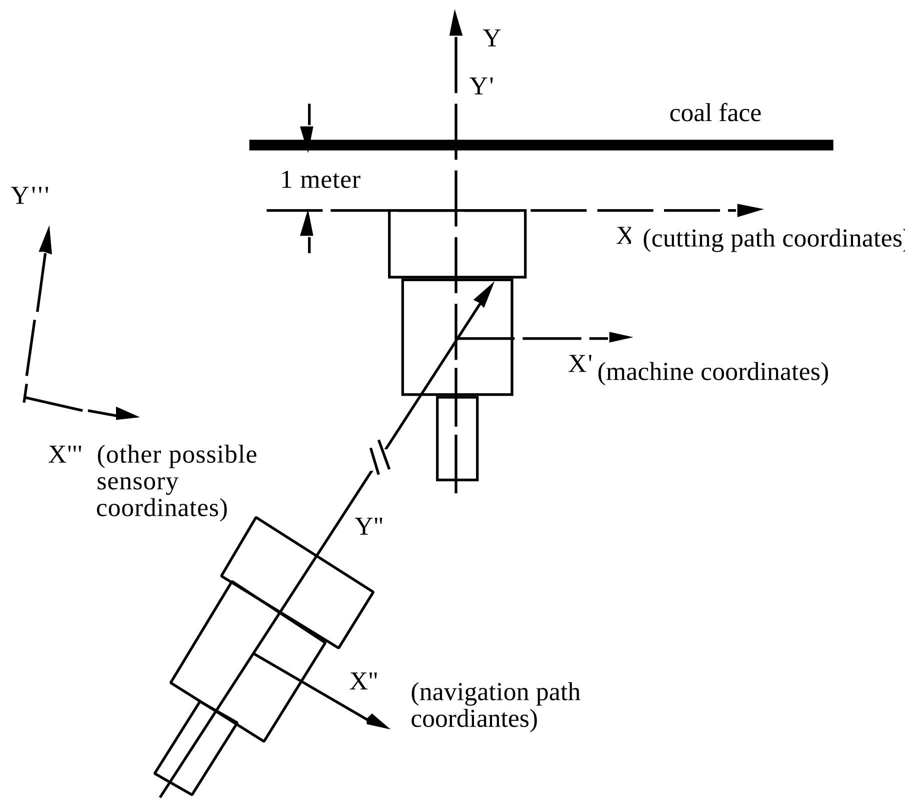

Figure 12: Different Local Coordinate Frames

In order to more fully characterize the performance of the vehicle guidance controller, some understanding is necessary concerning the sources and kinds of errors affecting control, the basic control strategy, and some related issues regarding the performance of the error control of the machine motion. Huang [Hu 91] gives an in-depth discussion of these issues, summarized in the following sections.

5.3.1 Problems Affecting Vehicle Guidance

Several environmental factors affect the performance of the vehicle guidance controller. Irregularities in the coal seams can cause machine motion control error.

Irregularities of concern include oblique grade of the floor (a few degrees) and anomalies (such as faults in the earth or rocks). A wet or muddy floor can also cause unpredictable machine motion, such as machine slip or slide, which is nonlinear and difficult to control.

Some physical system problems also contribute to machine motion error. In the CM, mechanical/electrical delay exists between issuance of a motion command and the actual motion of the tram motors [Sc 90]. Uneven speeds between two tram motors or uneven wearing conditions between two tread sets also cause control errors.

Communication failures in the network and problems in measurement error propagation [Ho 90-1] are additional sources of vehicle guidance errors.

Typical underground coal mining involves operating a bulky CM (see appendices A and B) in a tight space but without proximity sensing capability on all sides of the machine. This, combined with the above-mentioned environmental and physical system problems, can cause the machine to bump into pillars, ventilation brattices [St 83], or other obstacles.

5.3.2 Vehicle Guidance Error Control

Despite the fact that the problems identified in section 5.3.1 are rich enough to warrant the consideration of applying more advanced techniques such as on-line system identification [Bo 76, Ey 74] or adaptive control [As 84] as control solutions, for now, however, a simpler control strategy is chosen which will merely keep a tight control on the orientation (yaw) and the lateral deviation. In other words, the machine will be stopped any time that the yaw or lateral error gets beyond the specified value. A new course would be drawn from the current position to the goal and the corresponding commands will be issued and executed. This previously incurred error will be corrected as the machine proceeds along the new course (figure 13). Refer to [Hu 91] for more information.

One interesting characteristic in this vehicle guidance problem is that some "non-linear" factors may override the established control strategy in some situations. This simple control strategy was selected in the interest of balancing the need for accurate path planning against coal production efficiency (a trade-off between coal produced per hour and cutting precision).

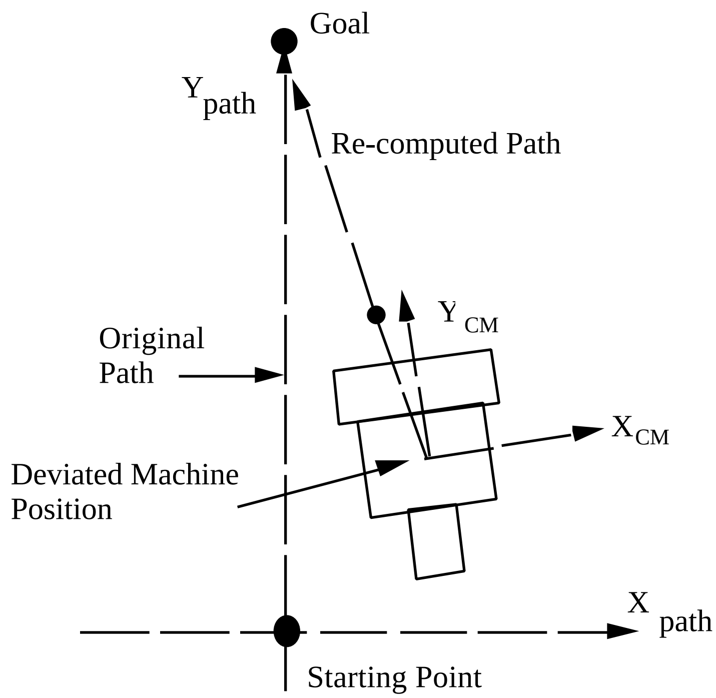

Figure 13: Adjustment of Path

Given the nature of the errors and uncertainties affecting the guidance controller and given the simple control strategy outlined above, certain issues arise as one seeks to minimize the adverse effect of the errors.

(a) Anticipative Control. As a first step approach, an anticipative type of control will be used [An 90] as the machine approaches the goal position or orientation. The TRAM-OFF command is sent with sufficient lead-time to allow the desired machine stop distance to be achieved (see figure 14).

(b) Boundary for Yaw-Error Control. Forward commands will cease when the orientation of the machine exceeds the error threshold, and the machine will pivot. There is a trade-off between the path-following accuracy that the controller can achieve and the frequency of tram, stop, and pivot commands required. Frequent error correction is highly undesirable from the standpoint of machine maintenance, power consumption, and coal production efficiency. A very tight yaw tolerance in a poor (slippery) operational environment may result in an inefficient "forward - stop - pivot-left - stop - forward - stop -pivot-right - stop" loop without advancing the machine significantly.

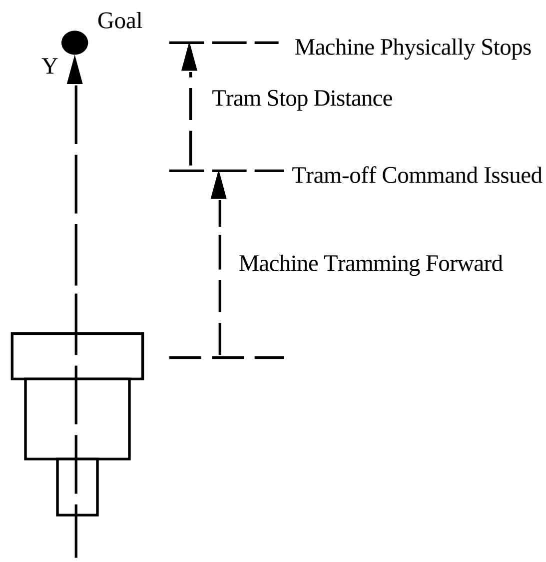

Figure 14: Approaching Desired Position During Forward Motion

(c) Effect of Operational Requirement on the Yaw Error Threshold. When the machine is farther off from the goal, yaw error is less critical since the machine has a longer time to correct for it. However, one must also realize that a yaw error accumulating over a larger distance translates into a larger lateral offset at the goal (arc equals angle times distance). A lateral deviation at a position closer to the goal means a larger pivot correction is needed, which in many situations may not be feasible since the machine must maneuver in very tight quarters.

Nonsymmetrical error boundaries may be required due to the environment constraints or the machine's mechanical conditions (e.g., one motor may be faster than the other).

(d) Acceptance Region for Goals (see figure 15). A safe requirement for establishing an acceptance region in a practical (non-ideal) mining environment [Hu 91] is that the whole region be larger than the worst-case stop distance. Once the machine is started in order to correct an out-of-region error, the acceptance region should be large enough to enclose the stop distance to allow the machine to physically stop after the tram-off command is received. Otherwise, corrective action might cause oscillation.

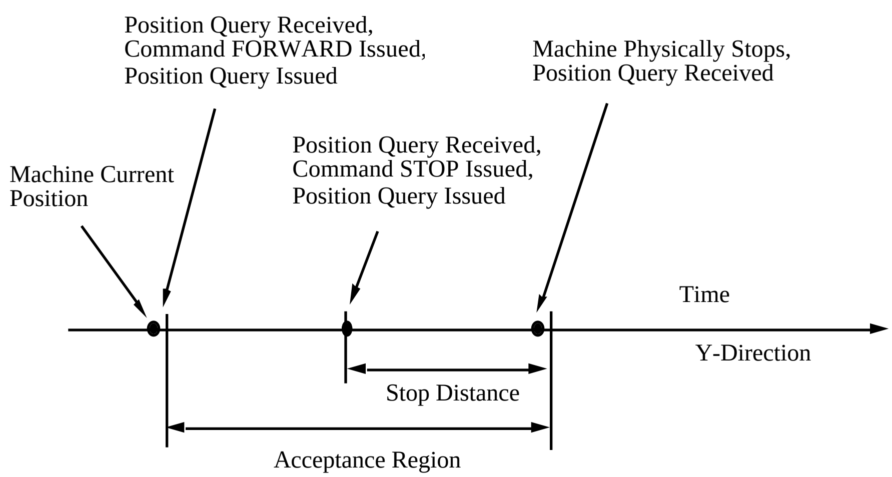

Figure 15: Acceptance Region, Sensory Data Sampling Period, and Mechanical Stop Delay

5.4 The Integration of BOM/NET Commands

BOM/NET (see section 4.2.1 and appendix B) includes a complete set of continuous miner (CM) primitive commands [Sh 90], as well as a set of commands for, and responses from, each sensor package (refer to figure 9 for the specific sensors). They are all implemented as message packets with a standard format so that they can be sent across the network [Sh 90] to their destinations. The BOM/NET commands are used in this chapter in defining the inputs to the actuator level for the following reasons:

* To preserve a coherent interface in a heterogeneous development environment (between the reference model research work at NIST and the computer-assisted coal mining research work at BOM).

- * In the RCS, the primitive level deals with system dynamics. In the BOM/NET protocol, commands specify dynamic characteristics for each actuator, such as velocity and maximum time limits. Therefore, a correspondence can be found between these two systems.

For these reasons, the BOM/NET CM commands are used as the prim level outputs from the RCS hierarchy. The BOM/NET commands are generally specified for each individual actuator, except for the tramming commands, where one command involves both tram motors (since this is how CM control switches are wired).

5.5 Level 1 -- Actuator Level

The output of the actuator level TD module contains electrical/hydraulic command signals to each actuator [Jo 82]. The input to this level is the primitive level output defined for each subsystem as described in the above section.

The following Joy CM actuator functions and function categories were derived from the Joy CM service manual [Jo 82] and BOM/NET Specification [Sh 90], where complete command names and formats are listed:

* Tramming
  - forward slow / fast
  - reverse slow / fast
  - left turn forward / reverse
  - right turn forward / reverse
  - pivot left / right

* Appendage Hydraulic Motions
  - conveyor tail up /down, left / right
  - shear up / down
  - stabilization jack up / down
  - gathering head up /down,

* Latching On/Off
  - pump motors
  - cutter head motor
  - conveyor
  - main control switch (safety relay)

5.6 Level 2 -- Primitive Level

As mentioned, the primitive level is also referred to as the dynamic control level. However, in the case of mining equipment, most controls are of the step function type (on/off or fast/slow). Therefore, the primitive level computations are much simplified [Hu 90-3]. Section 5.5 specified three categories of commands. For the tramming and the appendage commands, the prim level controller determines their range, rate, and maximum safety time, whereas for the latching commands, only the actions of 'on' or 'off' are needed.

The following sections (5.6.1 through 5.6.5) are organized according to the architecture as shown in figure 9.

5.6.1 Tram Motion Control Module

The main objective for the tram motion control is the performance of the closed loop control on the goal positions or orientations given by the vehicle guidance controller.

Path coordinate frames can be used for the continuous miner (CM) to perform tram motion control. However, a center-following approach may also be used in free-space tramming tasks. In such an approach, the desired wall clearance (proximity) is a predefined quantity. Since the wall surface is generally rough, range information must be defined statistically. Multiple readings in the vicinity are taken and a filtering process is used to compute the ranges. In some cases when the equipment needs a linear prediction over distances, such as for the trend of wall clearance, for the path of an object, or for the next key pose, a second stage filtering process (a time series type of analysis is a good candidate for this purpose) may be required. Filtered statistical range data will be used, and a cascaded filtering process is seen [Hu 82].

The tram motion controller can have additional responsibilities including the determination of the turning method (pivot or one tram halted) and the determination of the tramming speed (slow or fast), but they are beyond the scope of this chapter (see section 4.2.1).

The following are the tram motion control input commands for the CM at the primitive level; they also correspond to the names of planes which carry out the commands at the primitive level:

CM-STRAIGHT

This command is used primarily in navigation (free-space tramming) to move the machine to a specified location. This command will refer to a path coordinate system computed in the e-move NAVIGATE-TO-Zi command. Future enhancements to this program include a decision making process, either through human interaction or rule-based inference, to determine whether to use the forward or the reverse mode of operation to approach the goal.

CM-PIVOT

This command is used when pivot is needed (primarily during navigation tasks) to point the machine towards the goal. Future enhancements to this plan can include a post-pivot position verification and correction.

APPROACH-FACE

This command generally means to move the machine forward to have the cutter drum in contact with the coal face. There are two situations where this plan is used:

* at the beginning of a cutting task,
* after the CUSP-REMOVAL task during a cut (see later in this section for definition).

The first step the machine performs during a cut is to approach the coal face coincident to the direction of the cut (see section 5.2 for the reference coordinate frame). The precision of the direction is important to the straightness of the whole cut. The stabilization jack is lowered (before the machine trams forward) to provide a more stable platform during cutting operations. Because of precision requirements, the yaw error and the lateral deviation of the machine are tightly monitored and controlled. The operator enters an error specification according to factors such as floor condition, since, on a slippery floor, it may not be possible for the controller to achieve path accuracies that are possible under drier conditions. The completion of this task is defined as when the cutter motor current exceeds a pre-defined threshold. This occurs, under normal conditions, soon after the cutter drum makes contact with the coal seam.

The CM is required to re-approach the coal face after each CUSP-REMOVAL task. In this situation, the precision of the direction is not as critical, which means the maximum allowed error may be larger. A specification for the desired distance may be used (instead of the cutter current threshold) as the task completion criteria.

SUMP

Sump means pushing the turning cutter drum into the coal face by the force of forward tramming while maintaining the height of the drum. The first increment of the sump distance (approximately 15 centimeters, per discussion with the BOM researchers [Ho 90-2]) is critical to the straightness of the whole sump and is the only time during the execution of a SUMP command that the yaw of the machine is controllable. Afterwards the machine is allowed to sump in, without control of yaw, for its entire desired distance.

The cutting height measured from the floor must be given. The height will be converted to a drum angle in this level. Note that usually an initial-approach-to-the-face command precedes the sump command, hence this parameter may serve only for checking purposes.

SHEAR

This command requires close coordination with the boom control module (discussed in section 5.6.2). After the cutter drum is sumped into the coal, the coal can be excavated by shearing down the rotating drum (see the DRUM-TO-ANGLE command in the following section). Lateral or yaw deviation may be severe due to the large cutting force involved, yet no attempt will be made to correct the error so that static friction force may be maintained on the treads. An exception exists when the cutting reaction force is large enough to push the machine away from the face. During such circumstances, forward motion may be applied to re-engage the machine in the coal so that shearing can resume.

CUSP-REMOVAL

A cusp (a ridge of coal) can be left on the floor due to the geometry and the shearing-down motion of the cutter drum. The cusp must be removed. The machine performs a reverse motion while the cutter is turning at roughly the floor height (see the command above). The goal point for this command is the location where the last sump started. The yaw error is not monitored since, from a production efficiency standpoint, there is no point applying a lot of corrective action for relatively small amounts of coal. In other words, the machine trams reverse with an expectation that the goal point can be reached without yaw control. This is due to the fact that there is much less coal to cut, the reacting force is in turn much smaller, and, as a result, the machine is less likely to slip.

If the machine can not proceed because of an obstacle (see section 5.3.1), the guidance controller will not attempt to remove any remaining coal. Whether or not the cusp removal is completed, the controller will perform a pivot motion in an attempt to re-orient the machine to prepare for the next sump-and-shear cycle.

5.6.2 Boom Control Module

DRUM-TO-ANGLE

This command is used in coordination with the SHEAR command discussed in the above section. This command moves the rotating drum to a desired shearing angle to excavate the coal. A cusp may be left on the floor due to the shape and the angular motion of the drum.

Normally the cutter shears down to the floor. In this case, the shearing height (angle) is the same as the sump height (angle). However, under certain conditions the cutter may shear down lower or higher in order to follow the coal seam, to make more room for machine maneuvers, or because rock may exist at the floor.

5.6.3 Stabilizer Control Module

JACK

This command moves the stabilization jack to a desired angle. However, other sensory feedback methods can be suggested due to the fact that it appears difficult for the upper-level planner to compute, in advance, a precise jack target angle. Servo loops such as sensing the CM inclination or sensing the jack hydraulic pressure may be considered. Several factors, stated below, have to be taken into account in performing such servo function:

(a) In the current CM hydraulic circuit, a relief valve [Jo 82] with a manufacturer's preset relief pressure is installed to protect the maximum line pressure in the circuit. It is still a good safety measure to monitor the stabilizer hydraulic pressure during the jacking operation and/or to use it as an auxiliary control variable in the servo loop.

(b) When shearing starts and the cutting force is applied, not only does the jack hydraulic line pressure increase, but the inclination of the continuous miner (CM) also may change. These both have to be taken into account when the upper level (e-move) stabilization planner computes and sends down the inclination setting criteria. A continued monitoring of these two parameters during the whole sump-and-shear cycle may be necessary.

(c) The target inclination angle may not always be set at zero degrees. It must be determined by the coal seam variation and by anomalies on the floor (rocks, for example).

The requirements for the inclination information are also discussed in the e-move level STABILIZE command.

5.6.4 Gathering Head Control Module

GATHERING-PAN-SETTING

The desired gathering pan elevation must be set before the CM can gather the cut coal or perform free-space tramming.

Note that the switch function for the gathering head is controlled by the conveyor switch (refer to the e-move level corresponding reset command for more detail).

5.6.5 Conveyor Control Module

CONVEYOR-SETTING

This command can be used either to reset the coal removal subsystem for various tasks or to align the conveyor boom to the haulage unit after the haulage unit reaches the CM. The following parameters are involved:

* latching: on/off of the conveyor motion;
* swing_angle: the relative angle from the previous position. Set the boom to the CM center line when performing a navigation task, or set it to the middle of the swing angle when performing an alignment for loading.
* elevation_angle: the target elevation angle, with the reference being at the lowest conveyor position, corresponding to the desired conveyor tail height. This angle would be zero degrees for a navigation reset. For aligning the tail to the haulage unit, the target elevation angle would be a fine tuning value relative to the highest position (refer to the e-move level discussion). At the higher levels, absolute coordinates would be used to specify the interface requirement (the height of the conveyor boom) so as to properly transport the coal from the CM to the haulage unit. However, in lower level maneuvering, the locally centered elevation angle information is used.

CONVEYOR-TAIL-LOAD

This command is used to move the tail to load the coal on the haulage unit. The following parameters are involved:

* elevation: the necessary relative elevation angle if coal builds up on the haulage unit.
* range: the relative boom swing range (horizontally) to load the coal efficiently.

5.7 Level 3 -- E-Move Level

The elementary movements (e-moves) that the CM is capable of performing (i.e., the inputs to the e-move level) are discussed in this section. E-moves are coordinated subsystem motions designed to achieve some key positions, and/or orientations (a typical key position is a corner where the CM is to make a turn) [Al 88]. The length of the path for an e-move is typically the distance that can be directly observed by the on-board sensors.

Outputs from the e-move level such as motion paths generated for all appendages have been checked to be free of collisions and singularities. Navigation paths, expressed in terms of intermediate goal points, are obstacle free and optimized (shorter distance, less traffic, better floor condition, etc.).

Since the main power control subsystem and the support subsystem (figure 9) involve only the actions of switching on and off, it may be assumed that there is no need for a prim level and therefore the e-move level directs its outputs to the actuator level.

5.7.1 Initialization

POWER-UP

Turn on the pump motor. By doing so both the hydraulic circuits and the electrical circuits are charged up, so that both systems become controllable. The charging status of these circuits should be monitored and the existence of non-recoverable error signals would result in a shut down of the machine.

The following five commands are executed to perform all necessary initialization/test procedures for all the CM subsystems when the machine is started.

COAL-CUTTING-SUBSYSTEM-INITIALIZATION

COAL-REMOVAL-SUBSYSTEM-INITIALIZATION
GUIDANCE-SUBSYSTEM-INITIALIZATION
MAIN-POWER-SUBSYSTEM-INITIALIZATION
SUPPORT-SUBSYSTEM-INITIALIZATION

The initialization work includes component availability verification, component calibration, information base initialization, etc. The initialization must be completed without error before an extraction or a navigation operation can begin.

5.7.2 Guidance Control Module

GUIDANCE-SUBSYSTEM-RESET

This command is executed so that the subsystem becomes ready to perform any tramming related tasks. Depending on the task types, the affected sub-components vary. For example, to perform global navigation, the mechanical guidance subsystem (figure 9) may need to be retracted.

NAVIGATE-TO-Zi

This is a plan allowing for the movement of a CM in non-cutting situations. The goal points for this command are a series of key points (Zi) which route the CM to its destination. These points define a piecewise linear approximation of the trajectory. The distance between two consecutive points is typically limited to correspond to on-board sensor ranges.

Two of the major planning functions normally performed at the e-move level, namely kinematics computation and obstacle avoidance, are performed by human operators at this stage. In other words, when an operator sends a goal position to the vehicle guidance controller, he or she must make sure that this position can be reached by the mining machine and that intermediate planning is neither needed nor intended.

At the beginning of this task, the GUIDANCE-SUBSYSTEM-INITIALIZATION command will verify the current position information stored in the computer. The goal position will also be entered (possibly from an operator input channel). The controller then computes a vector from the machine's current position to the goal, assuming there is no obstacle in between. The angle between the current machine yaw and the goal vector will be computed and used as a transformation angle. The reference for the machine will be transformed to a new coordinate system that uses the goal vector as the Y-axis. Such planning activity normally results in a plan consisting of a pivot action to point the machine to the goal position and a forward motion to move the machine to the goal.

A future enhancement to this plan is the ability to determine whether to use the forward or the reverse mode in approaching each goal position. Criteria for making such a decision may include power/time efficiency, physical constraints along the path, and the need to set up a convenient orientation for the next following task.

BOX-CUT

A cut typically requires the machine to cut in two passes [Appendix A]. A box cut refers to the first pass. A box-cut plan receives a goal (5 meters, for example). This goal is translated to the goal coordinates, (0, 6, 0), in the path coordinate system. The machine then cyclically performs a series of primitive commands (defined in the previous section) in order to do the work of cutting coal. A clean-up task to clean up loose coal on the floor may be required but is currently not included in the plan. This series of operations executes in cycles until the 5-meter cut distance has been reached. The operator needs to be able to suspend this plan at any stage, record the status, and resume the operation as desired. One occasion to suspend the operation occurs when the haulage unit is full.

BACKOUT

This command is used primarily when the machine has finished its five meter cut and needs to get back to the origin of the path coordinate frame. This command is designed to be highly user-interactive at this stage, expecting that problems may arise during the course of long-distance reverse tramming. It is desirable that such user interactions become part of the machine's planning capability in the future. The cutter drum will be raised before the machine trams in reverse.

5.7.3 Coal Cutting Control Module

COAL-CUTTING-SUBSYSTEM-RESET

The cutter motor should be commanded 'off' for the navigation tasks and 'on' for the extraction tasks. The drum is reset to its middle height in a navigation task and is usually reset at the cutting height[5] for a sump-and-shear operation. Typically the cutting height is the coal seam thickness, unless more machine clearance is needed or a loose roof needs to be removed [Be 87]. The jack is set to high during navigation, and can be set to low for cutting tasks.

STABILIZE

This command lowers the hydraulic stabilization jack to provide a counteracting force during a shearing cycle. The planner at this level has to compute the stabilization requirements for the primitive level JACK command based on the following information: coal seam variation, floor formation and grading, counteracting force requirement during the shearing cycle, and the maximum hydraulic line pressure (see the discussion in section 5.6.3). The primitive level controller will then servo according to this derived criterion (represented either as a CM inclination or others) to stabilize the machine. This level would only consider 'whether the CM is stabilized.'

5.7.4 Coal Removal Control Module

COAL-REMOVAL-SUBSYSTEM-RESET

The conveyor motor switch position needs to be properly selected. When this command is used to reset the subsystem for navigation tasks, the conveyor is set to 'off'; for the extraction operations, the conveyor is turned on.

The conveyor boom would be set to the lowest position for a navigation task and the highest for a cutting task. Another alignment command will be discussed later to make necessary adjustments to the height. The CM's are designed so that the conveyor boom normally can not go below the height of normal haulage units (see COAL-LOAD

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[5]In some mining practice, a sump from the bottom may alternatively be used for more efficient production.

e-move for exceptions). At this level, the unit of 'meter' is used. It will be converted into an actuator angle as an input to the primitive level.

The horizontal angle of the conveyor boom also needs to be set. A typical position would be at the CM centerline. As above, the later alignment command may make more adjustments to the boom angle. This angle will be converted to a relative amount of swing for the conveyor boom as an input to the primitive level.

The gathering pan height needs to be set. For navigation, the gathering pan will have to be in its raised position. For cleaning up coal, it will be kept at a floating (on the floor) position [Be 87].

COAL-REMOVAL-SUBSYSTEM-ALIGN

This command is used prior to the cutting operation. Typically the haulage system would approach the CM and the two machines perform an alignment operation (refer to the corresponding command in the equipment level for more detail). The definition of the alignment pattern determines the conveyor boom swing angle during the coal loading operation. This will be explained in the next COAL-LOAD command.

The height of the CM conveyor boom for a proper alignment defined in the global frame needs to be specified. Although the equipment level planner computes a nominal target value for the height, the local ground situation can affect the relative heights between two machines and therefore the target value will be computed on-line. The conveyor boom would be placed at the middle of the swing range for a proper alignment.

COAL-LOAD

This command directs the conveyor boom to load the coal during the extraction operation. The first step is to check the coal removal subsystem reset and the alignment requirements as discussed before. A replan to re-invoke those commands may be necessary if the requirements are not met. The next step is to compute a conveyor boom swing pattern according to the actual haulage system alignment. A boom elevation pattern according to the haulage capacity, in order to load the cut coal efficiently, should also be computed. The better the alignment is defined and accomplished, the easier swing angles can be derived. However, this may mean a very difficult machine maneuver (to achieve such precise alignment). Another approach is to compute the swing and the elevation angles in real-time (sensory interactive) by measuring the constantly changing alignment angles as the machines move. Such computation models would be installed in the world model.

Note that due to local ground situations, it is not always possible to elevate the conveyor boom high enough and jamming the boom is fairly common [Be 87].

As required, the world model may include a mathematical model to compute the conveyor swing patterns for the system to achieve the fastest and most evenly distributed haulage loading.

5.7.5 Support Control Module

CABLE-TENDING

This may be a required task for a fully automated machine, but for the present the required actions are taken by human operators.

5.8 Level 4 -- Equipment Level

This section discusses the input commands for the continuous mining machine controller residing at the equipment control level.

START-UP-CM

Electrically and hydraulically power the CM so that it becomes controllable.

MACHINE-TEST

This command is used in the initialization period to verify machine health. The actions include a static shift-start check as suggested in the CM service manual [Jo 82] (for part wear assessment), and the checks as discussed in the next section (the section level). Machine calibration and data base initialization will also be performed.

CM-RESET

Depending on which plan is to be executed, the CM has to be reset accordingly.

ALIGN-TO-THE-HAULAGE-SYSTEM

The criteria for the alignment may include the machines center line relative bearing, the clearance at the facing ends, and the CM conveyor boom positions. The alignment criteria are affected by the types of on-board sensors as well as the type of haulage systems used. If a continuous haulage unit is used, the coordination strategy may be defined as:

(a) Prior to cut: The continuous haulage unit would physically engage with the CM. The CM will then position the boom to complete its ALIGN-TO-THE-HAULAGE-SYSTEM task.

(b) During the cut: The CM COAL-LOAD e-move command will swing the boom and load the coal. Fault conditions may occur in the continuous haulage unit: the system may become jammed, it may be stretched to its limit, it may come in contact with corners as it turns, etc. In these situations, the required action for the continuous haulage unit is to stop and send a pause signal to the CM.

See section 3.3.1 for the other situation (when shuttle cars are used).

CUT-LOAD-PAUSE

This task essentially sends commands to all its subsystems (figure 9) to perform a cut (see the corresponding plan in section 6 for the specific command sequence). It also coordinates with the haulage unit for removing the coal from the face area.

If shuttle cars are used to transport the coal, generally several car loads are needed for a cut. A 'pause' parameter can be used. When the 'pause' has a value of '1,' the haulage unit is not available. The CM has two options under this situation: wait and do nothing, or cut without loading to a maximum allowed amount and load the coal when the haulage unit becomes available again. These options are defined as different commands which can be seen below. It is assumed that during the waiting period the CM is not required to stop the cutting drum, the gathering head, and the conveyor. The value of 'pause' can be supplied by the haulage unit through the world model control hierarchy.

The cutting approach angle relative to the coal face must be given. For a straight cut the cutting angle is 90 degrees relative to the face, whereas for a cross cut the cutting angles will be a series of incrementing angles (a cross cut pattern can be found in the reference [An 89]). Note that research [Li] has shown that, in order to make a more efficient cross cut, the CM should make a straight cut beyond the intended intersection then back up to make the cross cut.

CUT-NO-LOAD-PAUSE

This command directs the CM to continue cutting during a wait for the haulage unit. There is a maximum amount of coal it is able to cut before the loose coal prohibits the CM from advancing. The receipt of a 'pause' signal means that the haulage system has become available again. The cutting process would be stopped to allow the CM and the haulage system to realign.

CLEAN-UP-PAUSE

This command can be executed after the above command when there is loose coal on the floor that may require the CM to turn to different angles in order to clean up all the loose coal. If problems occur (e.g., the shuttle car is full) before the floor is clean, a 'pause' signal will be received and the CM will pause and wait. Note that totally asynchronous cutting and loading actions may form and they need to be avoided.

NAVIGATE

A destination (a global position in the mine) where the next operation will take place must be given.

CM-SHUT-DOWN

There are different shut down devices installed on the Joy 14CM mining machine such as circuit breakers, main switch, emergency switch, and panic bar. Any of these can be switched to activate a shut down.

CUTTING-BIT-MAINTENANCE

A currently non-existent capability, required actions are assumed to be taken by human operators.

5.9 Level 5 -- Section Control Level

The section control level handles face area production and related functions, including coordinating each individual machine's activities and summarizing the production status. Although the section level controller is not intended to be a replication of a conventional 'section foreman' [Bu 68], similarities can be seen.

The following commands are the inputs to the section mining operations controller residing at the section control level:

SECTION-INITIALIZATION

This task is applicable only when a new section or a new mining plan is started; afterwards, a SHIFT-START-INITIALIZATION task can be used.

The work in this task includes:

* Count the required resources designated by the upper levels.
* Derive the starting locations for the machines. For example, in a five-entry development, send the entry #3 coordinates to the machines.
* Route shuttle cars according to 'right' and 'left' designations when applicable [St 83].

A satisfactory summary report from the above procedures, plus other requirements such as resource availability and production goal achievability at the end of the initialization period, should set the system to the ready state.

SHIFT-START-INITIALIZATION

The idea of a 'shift' serves as a natural intermission point for work such as preventive maintenance, equipment exchange, or production analysis to be performed. Subsequent adjustments may be needed (these cause changes in the state variable values). Consequently, the changed state variable values have to return the 'ready' condition before the next shift starts.

The following are some possible procedures that either exist or can be designed for evaluating the readiness of the shift:

* A calibration procedure that compares the test commands and the sensory feedback to evaluate the readiness of each piece of equipment. Some of the I/O channels on the CM controller are used to provide diagnostic information, such as the main pump pressure information. The CM will not become controllable unless the main hydraulic pressure is up.
* A background statistical analysis algorithm using the on-line machine operation data to provide long-term machine health trend prediction.
* An expert system [Mi 89] for diagnosing the CM's electrical system, mechanical system, or hydraulic system problems.
* A machine start up sequence.

More comprehensive initialization procedures can be designed. However, since not all the required information is available, enhancement of this initialization task is left as future implementation work.

SHIFT-END-WRAP-UP

Equipment may be commanded to backout after completing the last task in a shift for a routine check. Some equipment may be scheduled to retreat for a major overhaul. Summary reports are generated.

ROOM-AND-PILLAR-ADVANCE-IN-AREA-#R

The section planner at this level will derive a mining plan and send down a decomposed cutting sequence to all involved equipment.

The '#R' referred to here is only a general representation for any planned mining area. The formal data structure and data description for the mining area need to be designed as part of the world model. In such a design, both the computation efficiency and current convention (the way mine operators and engineers describe their mining plans) will be taken into account.

EMERGENCY-SHUT-DOWN [Jo 82];

This command is activated in response to equipment health, human safety, or environmental condition warning generated by the monitoring system. Action is taken to stop production in time to avoid a hazard and to send the machines into a safe idle or shut down state.

EQUIPMENT-RELOCATION

Equipment can be relocated for purposes such as maintenance, replacement, or safety backout.

The world model support for this section mining operations controller would include a timing analysis model for machine coordination, such as shuttle car (if they are used) changeout timing [St 83]. The world model support would also include Federal and state regulations as well as a map of the mine section(s) with a proper resolution.

5.10 Level 6 -- Production Control Level

The following commands are the inputs to the extraction operation #i controller residing at the production control level. Only those commands that are related to the previously discussed lower level commands are included:

VIRTUAL-CELL-FORMATION

One responsibility for the production control level is to allocate required resources so that the production goals can be achieved. A 'virtual cell' [Mc 82] is formed as a work unit and will be managed by the section control level controller.

PRODUCTION-OPERATION

The production goal for the i'th extraction operation subsystem, in terms of tonnage, and the extraction method (such as room-and-pillar or long-wall) must be included.

5.11 The Resulting Task Tree

A task tree, shown in figure 16, describes the decomposition of the higher level tasks to the lower level tasks. The primitive level output commands are decomposed as

CM machine commands. It is not our intention to have all of the tasks completely decomposed here. One vertical thread (depicted horizontally here) is decomposed thoroughly to illustrate the RCS development process.

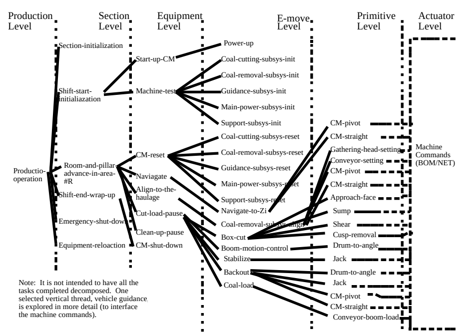


Figure 16: The Task Tree

6. METHODOLOGY APPLICATION: THE RCS PLANS

A series of illustrative RCS plans in hierarchical order has been developed to show the successive task decomposition process. Bubbles are shaded to indicate that they have been decomposed in this paper:

6.1 A Production Level Plan

The PRODUCTION-OPERATION plan (figure 17).

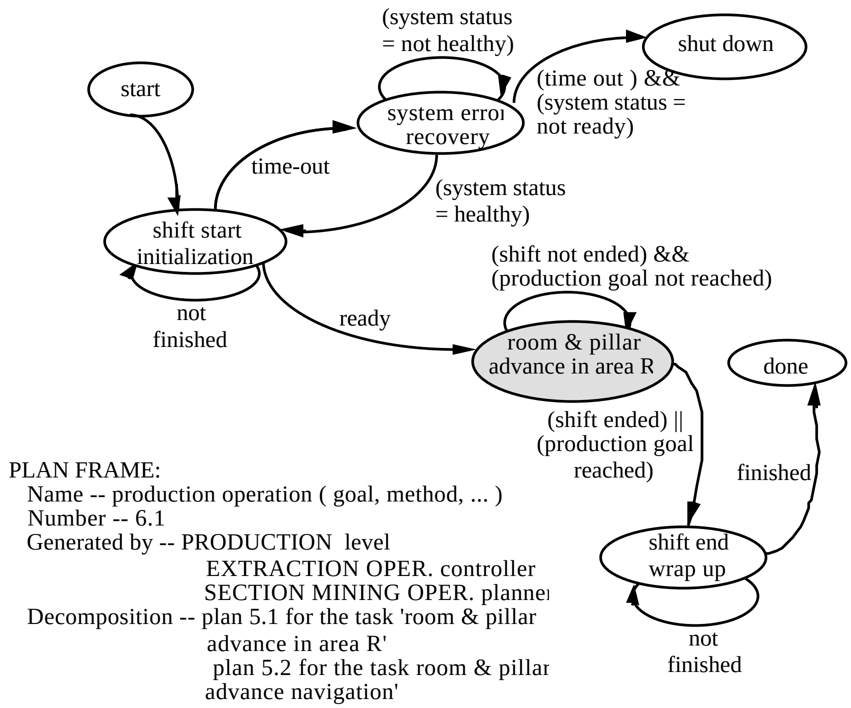


Figure 17: A Production Operation Plan

This plan is generated by the section mining operation planner residing in the production level (figure 8) extraction operation #i controller.

* Operator Interface: The operator may enter a cutting goal for a shift and a desired location Z in area #R.
* Prerequisites: Resources are all allocated.
* Execution: The first step of this plan is a shift start initialization. Detected inconsistencies such as equipment non-readiness would be allowed a certain time to recover. At the end of this period the executor would decide whether to proceed to the next step on the normal plan, or to do one of the following two tasks due to un-recoverable system faults: perform emergency planning, or suspend operation altogether and report the status to the facility level planner. After the initialization finishes satisfactorily, the next task to be carried out is a ROOM-AND-PILLAR-ADVANCE-IN-AREA-#R. The criterion to end this task is that either a shift has come to an end or the production goal has been

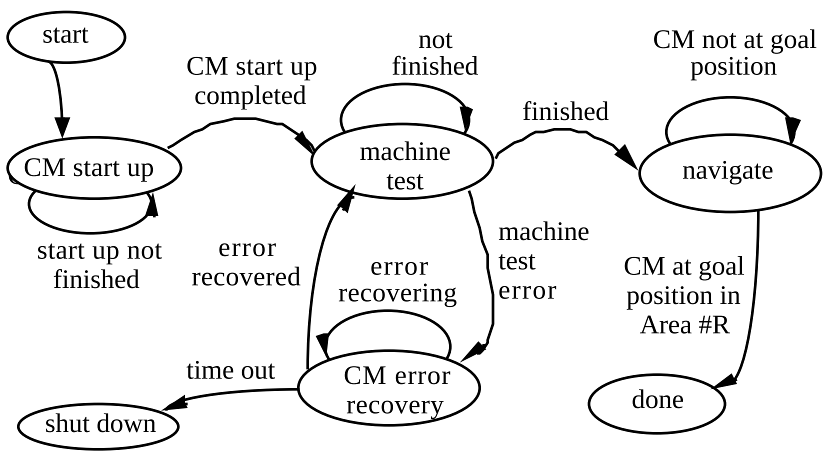
met. Afterwards, a SHIFT-END-WRAP-UP task is executed before the plan is completed.

* Completion: This plan is completed when the shift is completed.

6.2 Section Level Plans

The ROOM-AND-PILLAR-ADVANCE-IN-AREA-#R command is decomposed into the following plan 5.1 and plan 5.2.

The ROOM-AND-PILLAR-ADVANCE-NAVIGATION plan (figure 18).



PLAN FRAME:
Name -- CM room & pillar advance navigation
Number -- 5.1
Generated by -- SECTION level
SECTION MINING OPERATION controller
CM planner
Decomposition -- None

Figure 18: A Room & Pillar Advance Navigation Plan

This plan is generated by the CM planner residing in the section mining operation controller of the section level.

* Operator Interface: The operator may need to be able to set the intermediate goals for a given destination. He may also need to be able to modify the points during the navigation.
* Prerequisites: The CM is assigned to a particular section mining operation.
* Execution: This plan starts with a machine test and a start-up procedure followed by a navigation task to reach a more specific location in that area. The "specific location" has a resolution that is of about one order of magnitude finer than that of "area #R," as a result of the hierarchical decomposition.
* Completion: This plan is completed when the CM reaches position Z in area #R.

The ROOM-AND-PILLAR-ADVANCE plan (figure 19)

This plan is generated by the CM planner residing in the section mining operation controller of the section level.

* Operator Interface: The operator may need to be able to observe the alignment operation and determine this operation's completion status for the involved equipment.
* Prerequisites: The CM is at the desired location in area #R, otherwise the above navigation plan may be activated first.
* Execution: The conveyor boom at the rear of the CM is to be aligned with the haulage unit first (this means the haulage system has to be in place already), then the CUT-LOAD-PAUSE activity can begin. Pause signals can be generated and can happen in various situations. For example, if the haulage unit is away, full, jammed, or has other problems. The conditions for the CM to exit the cut state are that either the cutting distance is reached or an external pause signal is received. In the former case the system goes into a 'wait' state, and in the latter case the plan is completed.
* Completion: This plan is completed when the cutting goal for a shift is achieved.

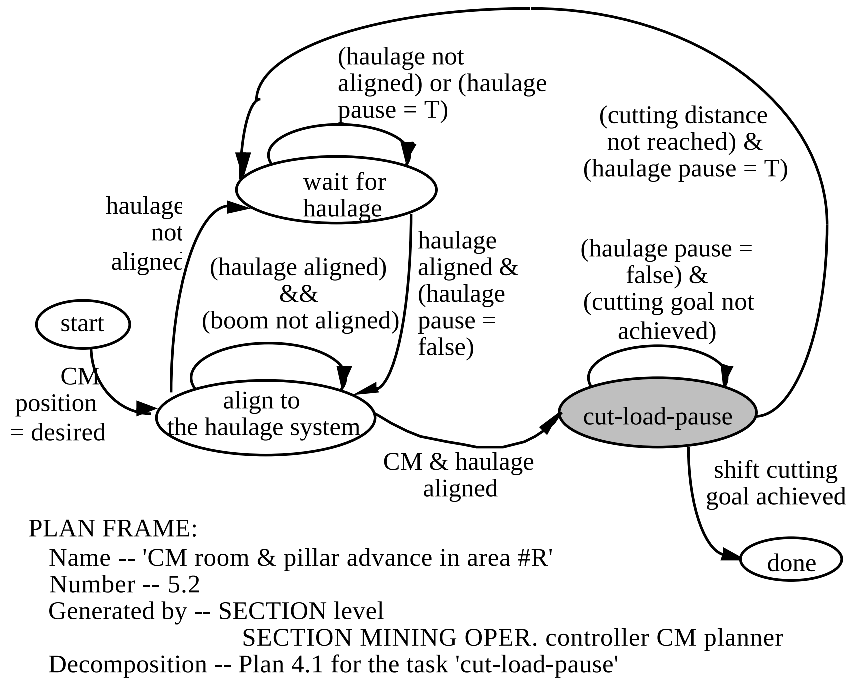


Figure 19: A Room & Pillar Advance Plan

6.3 Equipment Level Plans

The CUT-LOAD-PAUSE plan (figure 20).

- Operator Interface: The operator may be asked to enter or modify the length of the cut. The operator needs to be able to suspend this plan at any stage, record the status, and resume the operation as desired.
- Prerequisites: This plan receives a goal. The CM is at the path coordinate origin.
- Execution: A BOX-CUT command is executed by the vehicle guidance controller to perform the first pass of a cut. A BOOM-MOTION-CONTROL command and a STABILIZE command are executed by the coal cutting controller when necessary. A BACKOUT command is executed when the box cut is completed. A SLAB-CUT command is then executed to complete a cut.
- Completion: A box cut is completed when the desired cut is completed.

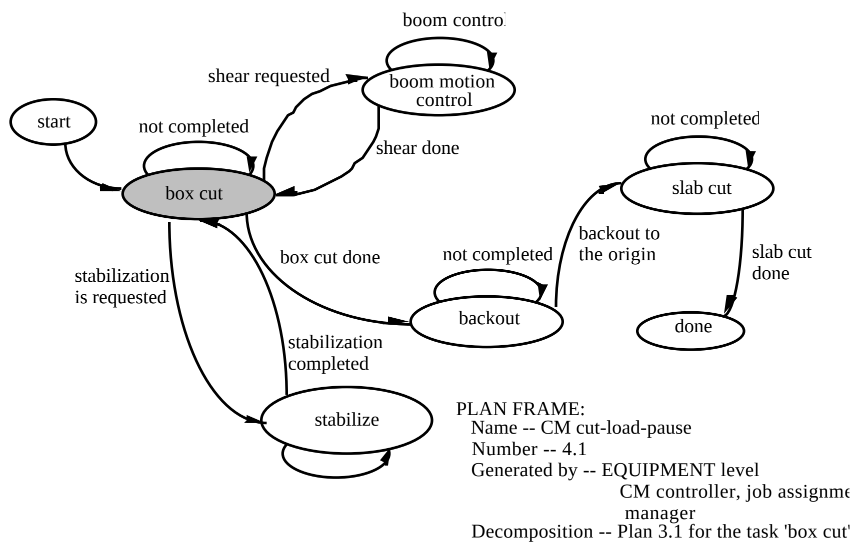


Figure 20: A Cut-Load-Pause Plan

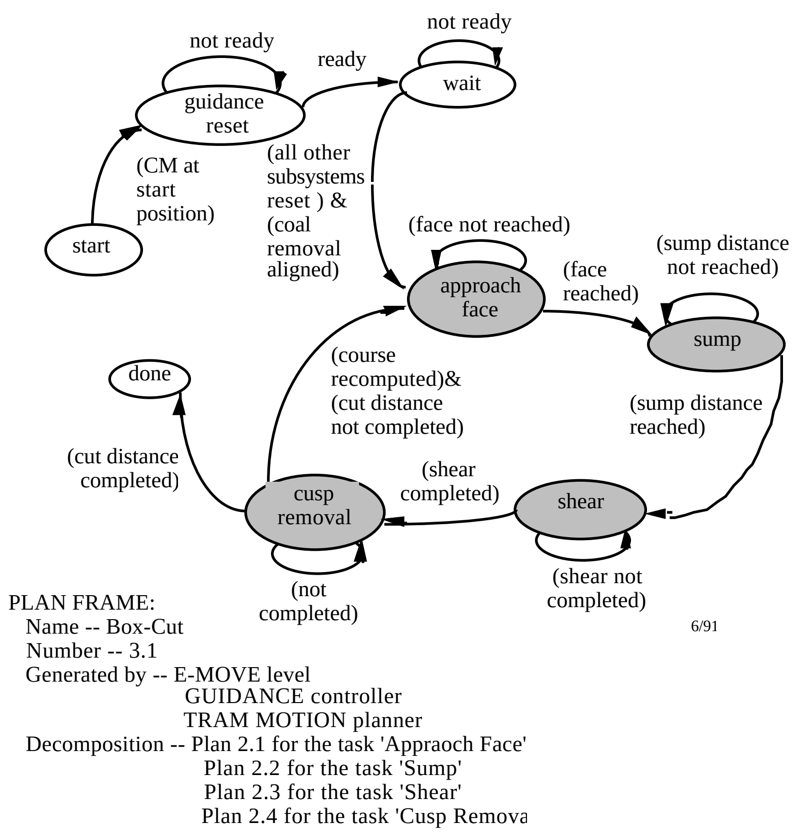


Figure 21: A Box Cut Plan

6.4 E-move Level Plans

The following two RCS plans describe the two e-move commands defined earlier. Each of the states in the diagrams corresponds to a pre-defined primitive command.

The BOX-CUT Plan (figure 21).

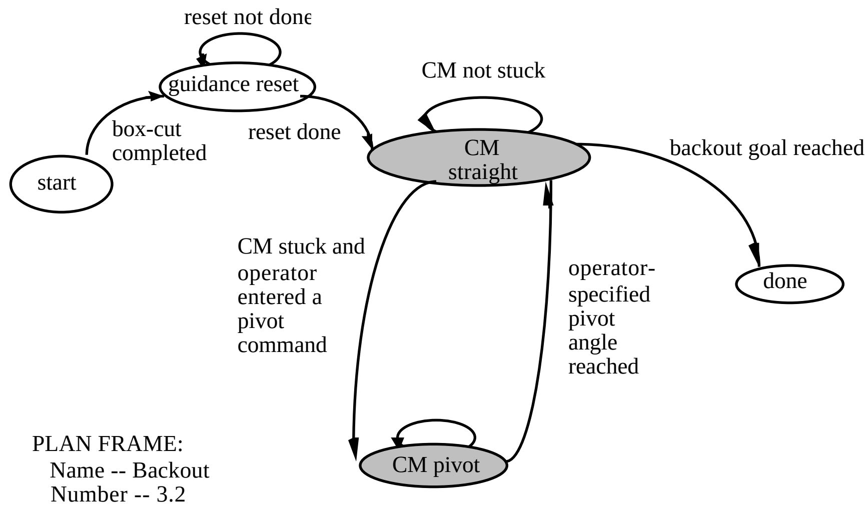
* Operator Interface: The operator may be asked to enter or modify the length of the cut. The operator needs to be able to suspend this plan at any stage, record the status, and resume the operation as desired.
* Prerequisites: A BOX-CUT plan receives a goal. The CM is at the path coordinate origin.
* Execution: The machine perform a series of sump-and-shear cycles.
* Completion: A box cut is completed when the desired distance is achieved.

The BACKOUT plan (figure 22).

* Operator Interface: An operator will be asked to enter the error tolerances in the yaw and the X directions at the beginning of the execution of this command. He will also be asked to enter a pivot direction and the accompanying pivot amount when the machine is stuck during the course of tramming backwards.
* Prerequisites: The machine has completed a cusp removal operation, the stabilization jack has been raised, and the cutter drum has been raised.
* Execution: The basic operation is tramming in reverse. Errors in the X and yaw directions will be corrected according to the operator specification. As described above, the operator will be involved in error correction when the machine gets stuck.
* Completion: The command is executed successfully when the machine is back to the origin of the path coordinate reference frame.

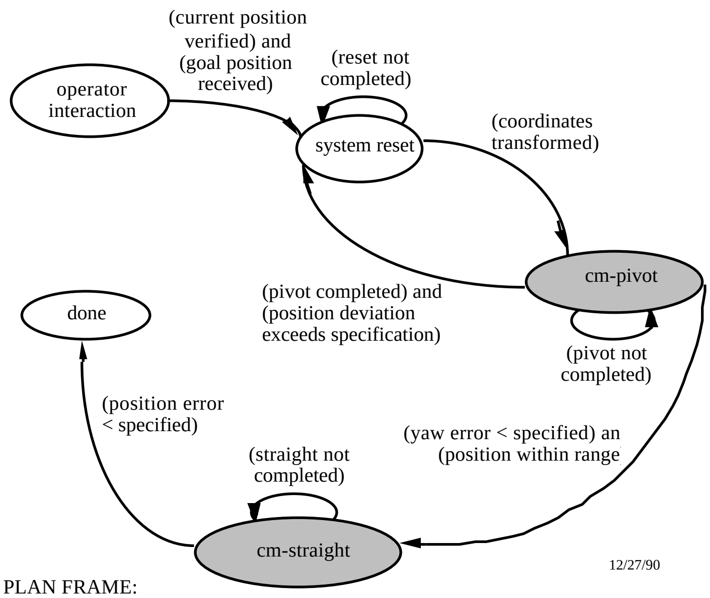
The NAVIGATE-TO-Zi Plan (figure 23).

* Operator Interface: The operator may be asked to enter or modify the goal position. The operator needs to be able to suspend this plan when he sees unexpected obstacles and reenter new goal positions to avoid obstacles.



PLAN FRAME:
Name -- Backout
Number -- 3.2
Generated by -- E-MOVE level
GUIDANCE controller
TRAM MOTION planner
Decomposition -- Plan 2.5 for the task 'CM straigh
Plan 2.6 for the task 'CM pivo

Figure 22: A Backout Plan



PLAN FRAME:
Name -- Navigate-to-Zi
Number -- 3.3
Generated by -- E-MOVE level
GUIDANCE controller
TRAM MOTION planner
Decomposition -- Plan 2.5 for the task 'CM straigh
Plan 2.6 for the task 'CM pivot

Figure 23: A Free-Space Tramming Navigate-to-Zi Task

* Prerequisites: This plan receives a goal. The CM is at the path coordinate origin.
* Execution: The machine typically computes the error in yaw, transforms its reference to the new path coordinates (see the corresponding plan description in section 5), then performs a straight and a pivot movement.
* Completion: This plan is completed when the given goal is achieved.

6.5 Primitive Level Plans

The following RCS plans describe the primitive commands defined earlier. Each of the states corresponds to a pre-defined lowest level CM machine command [Sh 90], except that the required tram-off commands between any two successive different tramming motion commands are not shown for simplicity. In other words, a transition from a TRAM-FORWARD command to a PIVOT-LEFT command implies a TRAM-OFF command in between.

Note that the state transition requirements (shown along the edges, or the arrowed lines) in the following diagrams are described but not specified. The numerical values for those requirements (for example, the maximum yaw error allowed) should be computed according to the error control strategy described in section 5.3. These values may be computed either in advance or on-line in the world model.

The APPROACH-FACE plan (figure 24).

* Operator Interface: The operator will be asked to enter or modify (optionally) the maximum errors allowed along the yaw and the X axes. Since vehicle accuracy is crucial to the whole cutting task, the maximum yaw deviation allowed should be kept as small as feasible.
* Prerequisites: The vehicle guidance controller needs to verify that the machine is at the origin of the path coordinates before this primitive command can be executed (see section 5.2 for more detail).

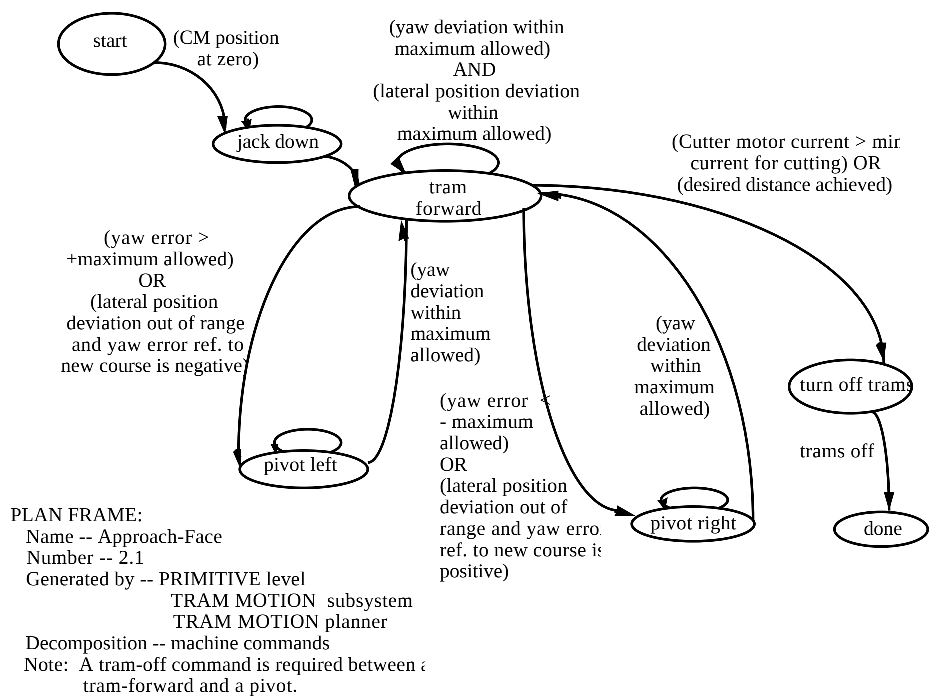


Figure 24: Approach Face

* Execution: Upon verification of its position, the machine will lower the stabilization jack[6] to the floor in order to increase the support to the machine. The machine will then perform a forward motion along the goal vector to approach the face. Pivot motion will be required if the yaw deviation gets larger than the specified limit. In such cases, the forward command will be stopped and a corrective pivot command will be issued. PIVOT-LEFT and PIVOT-RIGHT are two distinct states in the diagram. The machine will come back to the forward motion once the yaw correction is completed and the pivot command has been stopped. The same corrective activity will also be required when the lateral deviation exceeds the specified amount. However, in this situation a revector algorithm will be used first to compute the new goal vector and the accompanying required amount of yaw correction in order to re-position the machine toward the goal.
* Completion: This command is completed when either the cutter motor current exceeds the pre-specified threshold or the desired distance has been achieved.

The SUMP plan (figure 25).

* Operator Interface: The operator will be asked to enter or modify (optionally) the maximum errors allowed and the sump completion criteria (see the "completion" factor below).
* Prerequisites: The cutter drum must be at the cutting height, in contact with the coal, and turning.

[6]The extent of the use of the jack seems to vary, depending on floor conditions. The authors assume in this chapter that the floor can be slippery and therefore the jack is to be lowered at the beginning of the APPROACH-FACE plans, and raised at the end of the SHEAR plan.

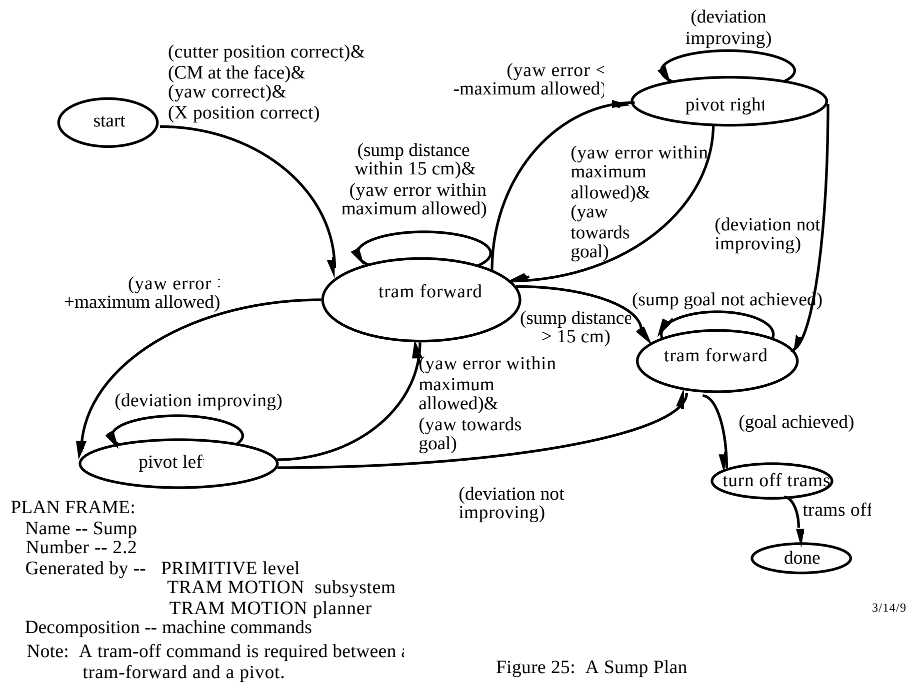


Figure 25: A Sump Plan

* Execution: The machine will perform a tram forward motion. As described in section 5, during the first 15 centimeters of a sump, the orientation of the mining machine will be closely monitored. A forward command will be stopped and a pivot command will be issued to correct for the yaw error once the error exceeds the specified limit. No corrective action will take place once the drum sumps in for more than 15 centimeters.
* Completion: One can conclude a sump when the gathering pan butts against the coal face.

The SHEAR plan (figure 26).

* Operator Interface: None. The maximum errors allowed in the X and Y directions may be specified in advance in a data file since they are not expected to be changed frequently.
* Prerequisites: A sump has been completed.
* Execution: The cutter drum will shear down to remove coal from the face. The yaw error will not be monitored. A large error in the Y direction may indicate

that the mining machine has been pushed out of the coal face by the counter reacting force. In such case a tram-forward command will be issued to re-engage the cutter drum to the face in order to complete the execution of the shear command. The stabilization jack will be raised after a shear is completed.

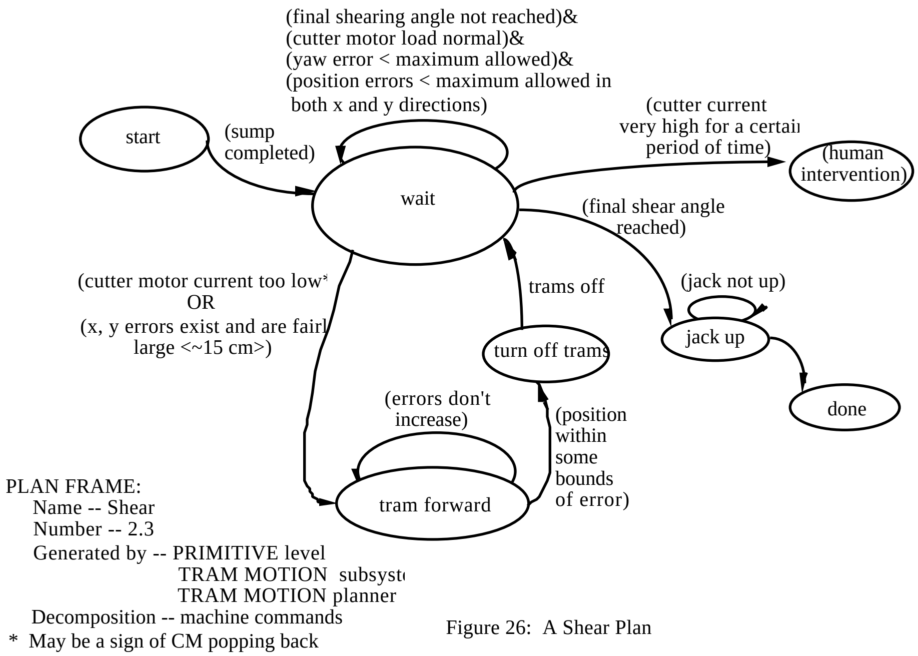


Figure 26: A Shear Plan

* Completion: Generally the cutter drum will shear down to the floor height (see section 5.6 for other situations). The tram motors will be turned off once a sump is completed.

The CUSP-REMOVAL plan (figure 27).

* Operator Interface: None.
* Prerequisites: A shear has to be completed.
* Execution: The machine will tram in reverse for a distance equivalent to the last sump distance without monitoring the yaw error. Cusp left on the floor from the last sump-and-shear cycle can be removed by the turning cutter drum, set at the floor height.

After the machine is back to the desired position or gets stuck before achieving that position, a pivot command will be issued to attempt to point the machine to the goal for the cut.

* Completion: This command is completed when either the machine has pointed itself to the goal and is ready for another cycle or the cutting goal has been accomplished.

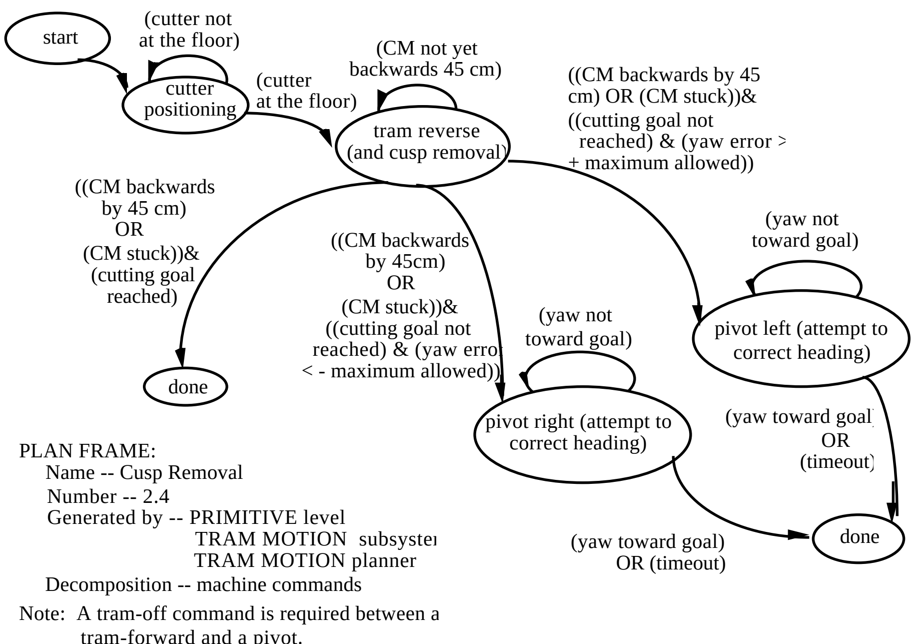


Figure 27: A Cusp Removal Plan

The CM-STRAIGHT plan (figure 28).

* Operator Interface: Error specification will be entered as in most other primitive commands.
* Prerequisites: The machine is up and operational. The stabilization jack is raised. The cutter drum is not at the floor height. There are no obstacles along the path.
* Execution: This command will receive a goal position from the e-move level. Forward motion and error checking are the main activities in this command. All the error checking will be in reference to the new coordinates, which also implies that the sensory data must be transformed before being used.

* Completion: This command is completed after the machine reaches the goal position.

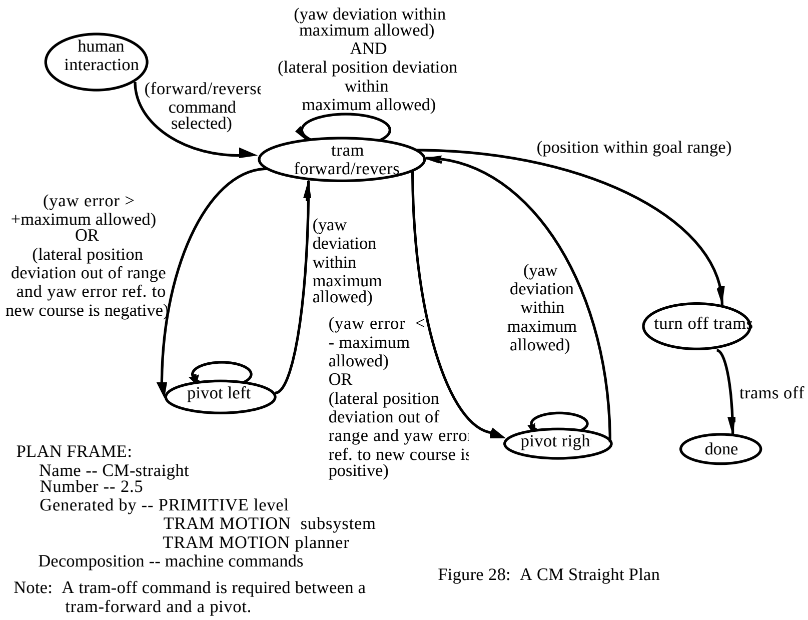
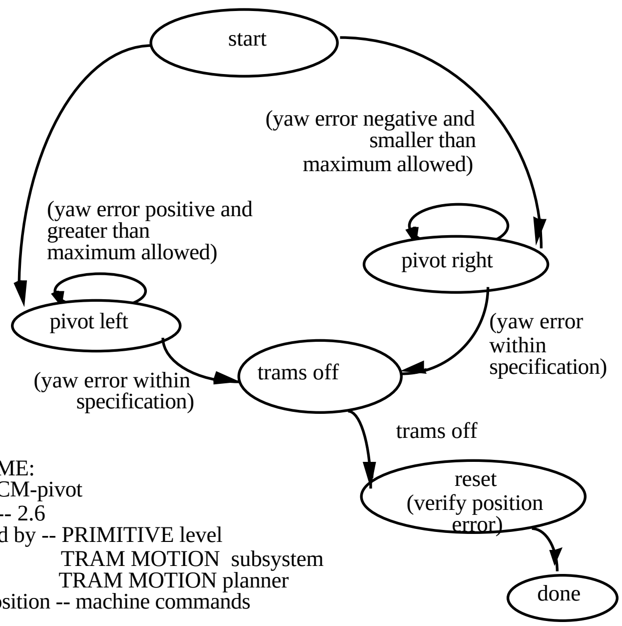


Figure 28: A CM Straight Plan

The CM-PIVOT plan (figure 29).

* Operator Interface: Error specification will be entered as in most other primitive commands.
* Prerequisites: The machine is up and operational. The stabilization jack is raised. The cutter drum is not at the floor height. There is no obstacles along the path.
* Execution: This command will receive a goal position from the e-move level. Pivot motion and error checking are the main activities in this command.
* Completion: This command is completed after the machine points itself to the goal.



PLAN FRAME:
Name -- CM-pivot
Number -- 2.6
Generated by -- PRIMITIVE level
TRAM MOTION subsystem
TRAM MOTION planner
Decomposition -- machine commands

Note: A tram-off command is required between a tram-forward and a pivot.

Figure 29: A CM-Pivot Plan

7. DISCUSSION ON THE IMPLEMENTATION OF OPERATOR CONTROL INTERFACE LEVELS

As described, the operator can interact with the system at any level of the hierarchy. If he enters the task decomposition hierarchy in the middle the actuator level, he must use individual joint position, rate, or force controllers.

If the operator enters the task decomposition hierarchy above the actuator level (input to the actuator level), he can use an appendage controller to perform resolved motion force/rate control or he can use function buttons to activate or deactivate subsystems or movements.

If the operator enters above the primitive level, he can simply indicate safe motion pathways, and the mining control system will compute dynamically efficient incremental movements.

If the operator enters above the e-move level, he can graphically or symbolically define key positions, or using a menu, call for elementary cutting head or machine transport movements (e-moves) such as NAVIGATE-TO-Zi or BOX-CUT. This may be done using an interactive graphics display with a joystick, mouse, track ball, light pen, or voice input.

If the operator enters above the equipment level, he can indicate objects and call for tasks to be done on those objects, such as CM-RESET or CUT-LOAD-PAUSE. This may be done using cursors and graphic images overlaid on video images.

If the operator enters above the section level, he can reassign mining machines to different mine sections, insert, monitor, or modify plans that describe equipment task sequences, define coal preparation, etc.

If the operator enters above the production level, he can re-configure all mining priorities, change mining requirements, enter or delete jobs, and change the mining operations schedule.

The operator control interface thus provides mechanisms for entering new instructions into the various control modules or program selection or execution sequences. This can be used on-line for real-time supervisory control, or in a background mode for altering autonomous mining plans before autonomous execution reaches that part of the plan. The operator control interface can also provide look-ahead simulation of planned moves so as to analyze the consequences of a prospective motion command before it is executed.

8. COMPUTER PROGRAM DESIGN AND IMPLEMENTATION

Computer software for the vehicle guidance has been implemented. Basically each plan (command) is implemented as an independent software module. The implementation was done using the C language. State pointers and the switch/case structure are used to describe the finite state plans. A main program is capable of executing any tasks (e-move or primitive) selected by an operator. A central command processor recognizes new motion commands (as opposed to the repetitive ones) as well as sensory data requests and sends them to the communication node processor. E-move level command reset is achieved by using a single 'task_type' pointer variable for the commands. This variable may have possible values of 'navigation' or 'cutting.' Depending on the value, one of the pre-defined data records (storing all the required information corresponding to that task type) will be selected and used. For example, if the task_type is 'navigation,' then the reset data record can read:

```
coal_cutting_subsystem_reset_to_nav
    {   switch = off;
        drum_angle = default;
        jack_position = lifted;}
```

Details of this implementation can be seen in [Hu 91].

9. SUMMARY

A generic reference model and a task decomposition methodology for the hierarchical real-time coal mining system control have been presented. The generic reference model, also referred to as the NIST RCS, comprises intelligent machine units laid out hierarchically according to their level of responsibility. These intelligent machine units coordinate according to the pre-defined control flow and information flow models to perform system tasks.

The task decomposition methodology emphasizes a systematic and generic approach for developing RCS applications. The iterative system development steps have been introduced. Each of these steps has associated with it a set of guidelines.

A control hierarchy, a set of task commands, and a vertical swath of RCS plans have been developed for illustrating the development process. The emphasis has been placed on the mining machine guidance. The resulting architecture is capable of receiving a high level coal production command, decomposing it to lower level commands, and eventually issuing machine actuator commands to achieve the production goal.

This work is by no means complete; many enhancements to this generic model and the task decomposition methodology will be considered in the future. Ongoing research at the NIST Robot Systems Division has been focused on the following areas:

* To produce a more comprehensive intelligent machine systems theory.
* To develop more systematic world modeling and sensory processing models.
* To derive a more elaborate system development methodology.
* To investigate software tool environments for the support of RCS system development, including a generic control module template.

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REFERENCES

[Al 87] Albus, J. S., *et al.*, "NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)," NBS Technical Note 1235, National Bureau of Standards, U. S. Department of Commerce, July 1987.

[Al 89] Albus, J., *et al.*, "Mining Automation Real-Time Control System Architecture Standard Reference Model (MASREM)," NIST Technical Note 1261 Volume 1, National Institute of Standards and Technology, U. S. Department of Commerce, May 1989.

[An 90] Anderson, D.L., "Laser485.c," Computer Program, Bureau of Mines, 1990.

[As 84] Astrom, K. J. and Wittenmark, B., Computer Controller Systems, Theory and Design, Prentice-Hall Information and System Sciences Series, Prentice-Hall, Inc., Englewood Cliff, N. J., 1984.

[Ba 84] Barbera, A. J., *et al.*, "RCS: The NBS Real-Time Control Systems," Robotics 8 Conference and Exposition, Detroit, MI, June 1984.

[Ba 79] Barbera, A. J., *et al.*, "Hierarchical Control of Robots Using Microcomputers," Proceedings of the 9th International Symposium on Industrial Robotics, Washington, DC, March 1979.

[Bo 76] Box, G. P. and Jenkins G. M., Time Series Analysis, Forecasting and Control, 1976.

[Bu 68] U. S. Bureau of Mines, A Dictionary of Mining, Minerals, and Related Terms, 1968.

[Co 91] Coad, P., and Yourdon, E., Object-Oriented Analysis, Yourdon Press Computing Series, Yourdon Press, Englewood Cliffs, New Jersey, 1991.

[Ey 74] Eykhoff, P., System Identification, Parameter and State Estimation, John Wiley & Sons Ltd., New York, N. Y., 1974.

[Fi 90] Fischer, P. and Daniel, R., "Specification and Design of Input Devices for Teleoperation," Proceedings of the 1990 IEEE International Conference on Robotics and Automation, Cincinnati, Ohio, May 1990.

[Ho 90-1] Horst, J. A., "An Application of Measurement Error Propagation Theory to Two Measurement Systems Used to Calculate the Position and Heading of a Vehicle on a Flat Surface," NIST Interagency Report NISTIR 90-4434, National Institute of Standards and Technology, U. S. Department of Commerce, 1990.

[Ho 90-2] Horst, J. A., "John Horst's Phone Conversation of March 23, 1990 with Tim Matty, a CM 'Expert' at BOM PRC," Telephone Conversation Notes, March, 1990.

[Hu 91] Huang, H., *et al.*, "A Motion Control Algorithm for a Continuous Mining Machine Based on a Hierarchical Real-Time Control System Design Methodology," Journal of Intelligent and Robotic Systems, in process, Kluwer academic publishers, Dordrecht, The Netherlands, 1991.

[Hu 90-1] Huang, H., "A Hierarchical Real-Time Control System for Use with Coal Mining Automation," Fourth Conference on the Use of Computers in the Coal Industry, the West Virginia University, Morgantown, West Virginia, June 1990.

[Hu 90-2] Huang, H., "Hierarchical Real-Time Control Task Decomposition for a Coal Mining Automation Project," NIST Interagency Report NISTIR 90-4271, National Institute of Standards and Technology, U. S. Department of Commerce, March, 1990.

[Hu 90-3] Huang, H. and Quintero, R., "Task Decomposition Methodology for the Design of a Coal Mining Automation Hierarchical Real-Time Control System," The Fifth IEEE International Symposium on Intelligent Control, Philadelphia, PA, September 5 - 7, 1990.

[Hu 82] Huang, H., "Suppressing the Nonstationary Portion of the Transient Response in Digital Simulation," Master's Thesis, The University of Texas at Arlington, Arlington, Texas, 1982.

[Jo 82] Joy Machinery Company, Technical Service Manual, Joy 16CM Miner, 1982.

[Li] A. D. Little, Inc., "A Theoretical Mathematic Analysis of Turning Capability of Full Faced Continuous Mining Machines," Notes Obtained from Schnakenberg, G., U. S. Bureau of Mines.

[Mi 89] Michell, J., "Diagnostic Maintenance Expert System for the Hydraulic Subsystem of a Continuous Miner," IEEE Transactions on Industry Applications, Vol. 25, No. 5, September/October 1989.

[No 88] North, R. A. and Riley V. A., "W/INDEX: A Predictive Model of Operator Workload," NATO AGARD Symposium, Orlando, Florida, 1988.

[Sa 89] Samet, H., The Design and Analysis of Spatial Data Structures, Addison-Wesley Publishing Company, Inc., New York, New York, 1990.

[Sc 89] Schnakenberg, G., "Underground Coal Mining Automation Research (Room and Pillar Mining) Justification and Research Program Plan," Ver. 1.1, Bureau of Mines, United States Department of the Interior, August 24, 1989.

[Sc 90] Schnakenberg, G. and Sammarco, J., "Joy 14CM Machine Test Data," U. S. Bureau of Mines Internal Document, September 28, 1990.

[Sh 90] Schiffbaur W. H., *et al.*, "Computer Network for Continuous Mining Machine (Joy 14CM) Control -- Documentation of Node Functions and Communications," U. S. Bureau of Mines Internal Document, April 1990.

[St 83] Stefanko, R., Coal Mining Technology, Theory and Practice, Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, New York, 1983.

Appendix A: OVERVIEW OF UNDERGROUND COAL MINING ENVIRONMENT

A typical underground coal mining environment is described for those readers less familiar with the common terminology. Only aspects of the underground mining environment relating to tramming control will be covered (figure A.1) [St 83, Bu 68]:

* Panel: a large block of coal (usually rectangular) to be extracted which is separated from the next panel by leaving a long rectangular pillar of unextracted coal between panels. The long unextracted pillar is a safety precaution to prevent the collapse of the coal roof over any more than one panel in the event of a cave in.

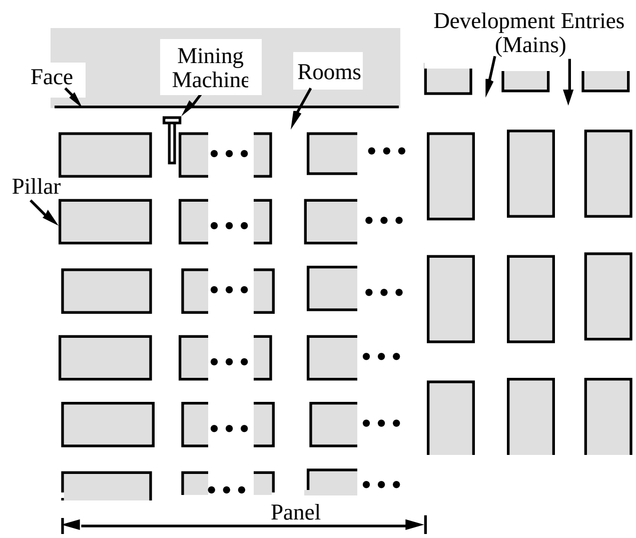

Figure A.1: A Room-and-Pillar Mining Environment

* Pillar: generally means a small (compared to panel) block of unextracted coal, 36 meters or less in length and 4.5 to 18 meters in width. As long as they are of sufficient size and separation from one another, pillars (along with roof bolts) help keep the roof of the mine from caving in.
* Face: the front of the coal seam where cutting operations occur.
* Entry: a passage way in a panel where coal has been extracted [Bu 68], typically 9 to 14 meters in width. Entries can be used as haulage roads,

transportation roads, or ventilation paths. Entries are formed by removing coal and leaving pillars that are nominally rectangular in shape.

* Cut: The action that the mining machine takes to excavate a block of coal (see [Hu 91] for a discussion on the size of a cut). Usually the mining machine cuts in two passes to achieve a desired width of a cut (typically the width of an entry). The first pass may be referred to as a box-cut, and the second pass may be referred to as a slab-cut.
* Room-and-Pillar Mining: a mining method that also features the development of main entries at both sides of a panel. Coal is extracted forming rooms [St 83] with pillars left. Pillars may be extracted at a later stage in a retracting operation. Sizes of pillars and width of entries may vary depending on the roof support and the transportation support requirements.

Appendix B: THE JOY 14CM CONTINUOUS MINER

Continuous mining machines (see figure B.1) are used in room-and-pillar mining. The major components of a Joy 14CM continuous miner (CM) of concern include (figure B.1):

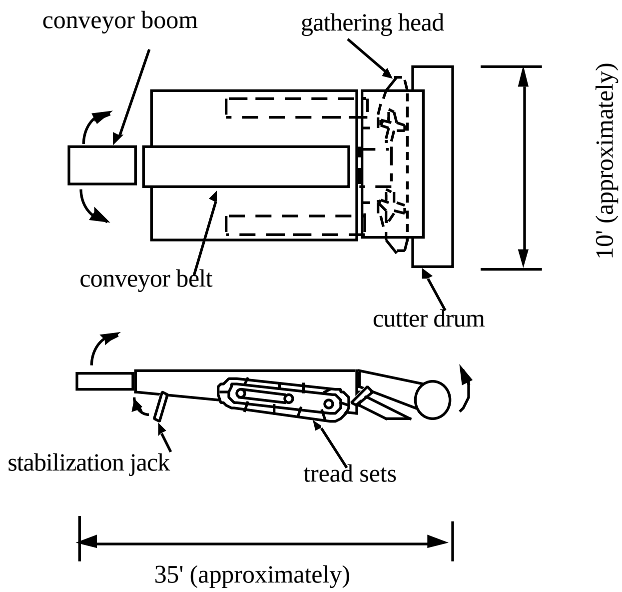

Figure B.1: The Major Components of a Continuous Miner

* A Tramming Subsystem: A tram motor driving a tread set exists on both sides of the machine. Generally, the motion of the CM's is referred to as "tramming," (e.g., tram-forward, tram-reverse) and the control of the machine motion can be referred to as "tram control."
* A Cutter Drum: A hydraulic actuated cutter boom extends out at the front of the machine. Attached to the front of the boom is an electrically operated cutter drum. Replaceable cutting bits are installed at the surface of the cutter drum which fracture the coal as the drum is pushed into the coal face while turning.
* A Gathering Head Subsystem: This subsystem is located at the bottom of the front end of the machine. A gathering pan can be set to float on the floor. The

gathering head, using a rotary motion, scoops the coal inward onto the gathering pan. A conveyor belt is behind the gathering head and moves the coal to the rear of the machine.

* A Conveyor Subsystem: The conveyor extends from the gathering head to the rear of the machine. An adjustable position conveyor boom forms the end of the conveyor system. It can move from right to left as well as up or down. Coal is dumped from the conveyor boom onto a haulage unit behind the CM.
* A Stabilization Jack: This hydraulic jack provides a stabilizing force to counter-balance the cutting force.

The continuous mining machine has ten tram control commands: slow/fast speed forward, slow/fast speed reverse, pivot left/right, turn left/right forward, and turn left/right reverse. These are open-loop commands. Execution of any of these commands can be terminated by either a stop command (implying the tram control loop is closed at a higher level where the sensory information is processed), or by a condition that some maximum time has expired (a safety time-out condition associated with this command).

The U. S. Bureau of Mines has been implementing a computer control system testbed [Sh 90]. This testbed is a distributed network linking the continuous mining machine, various sensor systems (length and angle measuring systems and a gyro, see figure 1), and an operator console which are all nodes on the network. This testbed can generally be referred to as BOM/NET [Sh 90].